Sea Level Rise and Its Socio-economic Impacts: A Case Study in Mumbai, India

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Abstract Coastal zone supports flora and fauna biodiversities and is endowed with a wide variety of habitats. Both marine and terrestrial processes have their influence on coastal zones. As coastal zones are often under pressure from both anthropogenic activities and natural processes, coastal zones are one of the most fragile, dynamic and productive ecosystems. Sea Level Rise (SLR) is a by-product of climate change on a global scale. Though climate change has happened in the past, the rate of current levels of change is unparallel and cannot be explained, without highlighting human contribution as a major reason. Global commerce and trade relies heavily on historic marine transportation routes and port cities. In the era of globalization, sea-level rise becomes a significant concern at individual, local government as well as to global economy levels. India has a coastline measuring upto 7515 km. Around 35 percent of Indians live within 100 km of the Indian coast. Given the varying levels of sea rise predictions, it is important to understand the concentration of population in the coastal regions, and they will become the victims of adverse effects of sea-level rise. The paper focuses on sea-level rise (SLR), its effects on coastal communities and socio-economic impacts in India, with a special focus on the island city of Mumbai.

Keywords Sea level rise · Global warming · Displacement · Urban infrastructure · Biodiversity · Mitigation

1 Introduction

In a phenomenon unprecedented in 65 million years at least, the ocean has absorbed about 30 per cent of the anthropogenic carbon dioxide, resulting in ocean acidification and changes to carbonate chemistry. Survival, calcification, growth, development and abundance of a broad range of taxonomic groups (i.e., from algae to fish) are at risk with substantial evidence of predictable trait-based sensitivities. There will

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be a wide range impacts on marine organisms, ecosystems, as well as sectors such as aquaculture and fisheries due to ocean warming and acidification (corresponding to global warming of 1.5 °C of global warming) (IPCC 2018). The coast is defined as a spatial zone where land, sea and atmosphere interact and influence each other continuously. Both marine and terrestrial processes have their influence on coastal zones. As they are often under pressure from both anthropogenic activities and natural processes, coastal zones are one of the most fragile, dynamic and productive ecosystem. Coastal zone supports floral and faunal biodiversity and is endowed with a wide variety of habitats such as coral reefs, mangroves, sea grasses, sand dunes, mudflats, salt marshes, estuaries, lagoons etc.

In Indian scenario, as per Rao et al. (2008), frequent tropical cyclones and associated floods and tidal surges occur regularly in coastal Andhra Pradesh leading to loss of life and property in the region. An area of about 565 km^2 would be submerged under the new low-tide level along the coastal Andhra Pradesh, if the sea level rises by 0.59 m as predicted by IPCC (2007). The 2004-tsunami that devastated the Indian coasts underlined the role of geomorphology and coastal slope in sea level rise. At Nagapattinam in the southern state of Tamil Nadu, the low swales behind shore-parallel dune ridges claimed several lives due to lateral flows from tidal inlets or breaches in dune ridges. Longer penetration of tsunami inland due to gentle slope of the coastland was also observed (ISRO 2012). ISRO also calculated the Coastal Vulnerability Index for the state of Gujarat, which in on the west coast of India, and found that geomorphologically only 29.24 per cent of the coast represented by rocky/cliffy and indented sections comes under very-low to low categories, while 34.53 per cent of the Gujarat coast is very high to high vulnerable and 36.04 per cent of Gujarat coast is moderate vulnerable.

Studies (IPCC 2013; Parris et al. 2012; Sweet et al. 2017) suggest that the average rate sea-level rise of 3.4 mm per year is observed in globally, which will increase in the coming decades. According to the U.N. Atlas of the Oceans (2016), eight of the ten most populous cities—Tokyo, Mexico, Mumbai, Sao Paulo, New York, Shanghai, Lagos, Los Angeles, Calcutta and Buenos Aires—are in coastal regions. The paper focuses on sea-level rise (SLR), its effects on coastal communities and socio-economic impacts, with a special focus on the island city of Mumbai.

2 Sea-Level Rise (SLR)

According to the National Oceanic and Atmospheric Administration (NOAA 2017a, b, c, d), there is variation in sea-level rise, as some coastal communities experience a greater increase in sea level. As per Mimura (2013), there are two significant causes to global sea-level rise: thermal expansion and the melting of land-based ice. Complicated geologic processes such as isostatic rebound and groundwater pumping are also to be attributed for the same (Eggleston and Pope 2013). Since the beginning of the twentieth century, global sea surface temperatures have increased at an average rate of 0.13 °F per decade (1901–2015; NOAA 2016). Though climate change has

happened in the past, the rate of current levels of change is unparalleled and cannot be explained without bearing in mind human contribution as a major reason (NCA 2014). NOAA (2015) estimates that 90 per cent energy of heat-trapping greenhouse gases has been stored in the ocean and as water warms, it expands. The other main cause of global sea-level rise is the melting of land-based ice sheets, mainly found on Greenland and Antarctica. Their melting can lead to sea-level rise in metres, as together they contain more than 99 per cent of the freshwater ice on Earth (NSIDC 2018). Tropical storms, prolonged rain, fluctuations in ocean currents and moon phases also play an important role in the spatial-temporal variability in the height of the ocean other than thermal expansion and the decay of glaciers.

Sea level can be divided into three broad categories according to the variations in the range of temporal and spatial scales. These are occurrences of sea-level extremes associated with storm surges and tides, Global Mean Sea Level (GMSL) and the regional variation about this mean. Since the late nineteenth century, GMSL has been rising at low rates of change that characterized the previous two millennia (Church et al. 2013). Instrumental drift in the observing satellite system (Watson et al. 2015) and volcanoes (Fasullo et al. 2016) may be the reasons for slowing in the reported rate over the last two decades (Cazenave et al. 2014), accounting for the former results in rates (1993 to mid-2014) of between 2.6 and 2.9 mm yr-1 (Watson et al. 2015). Thermal expansion, glacier and ice-sheet mass loss, as well as fresh water storage on land, are the main contributors towards the same (Church et al. 2013; Watson et al. 2015), and their attribution is dominated by anthropogenic forcing since 1970 ($15 \pm 55\%$ before 1950, $69 \pm 31\%$ after 1970) (Slangen et al. 2016).

As per IPCC (2018), by the end of the century, GMSL rise will be around 0.1 m less in a 1.5 °C world as compared to a 2 °C warmer world. Up to 10.4 million fewer people are exposed to the impacts of sea level globally in 2100 at 1.5 °C as compared to 2 °C. Reduced sea-level rise will enable greater opportunities for adaptation though the sea-level rise will continue beyond 2100, as instabilities exist for both the Greenland and Antarctic ice sheets that could result in multi-metre rises in sea level on centennial to millennial timescales.

From Fig. 1, we can observe the estimated, observed and predicted global sea-level rise during the period 1800–2100. Different colour bands reflecting different data are red band—1800–1890—estimates from proxy data; pink band—uncertainty; blue band—1880–2009—shows tide gauge data; and green band—1993–2012—satellite observations. The figure predicts future scenarios of SLR ranging from 0.66 to 6.6 ft in 2100.

3 Concentration of Population in the Coastal Regions

Given the varying levels of sea rise predictions, it is further more important to understand the concentration of population in the coastal regions, as they will become the victims of adverse effects of sea-level rise.

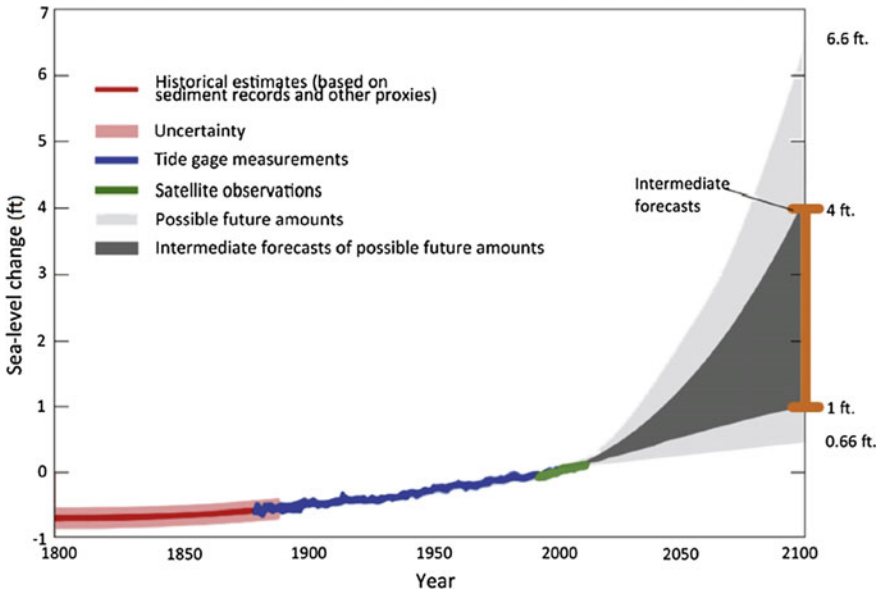

Fig. 1 Sea-level rise predictions. *Source* Khan (2018)

(1) Favourable climatic conditions—Coastal zones have moderating influence of land and sea breezes and the temperature rage also remains low.
(2) Contact point settlement—coastal habitats are also termed as contact point settlements, as they are located at such a place, where the residents were involved in more than one primary economic activities such as fishing as well as agricultural.
(3) Favourable locations during colonial period—coastal locations were developed as ports for import-export of materials. The colonial rulers found it safer to reside, as the local people were unknown to them. The colonial rulers built forts and isolated themselves from the local people. The coastal climate was moderate, and it was easier for colonial rulers to assimilate with the new environment.
(4) Legacy of the colonial period—underdeveloped/developing countries depended on the developed countries for the technological support in colonial era. When the developing countries became independent, they used the infrastructure developed by the Europeans. The port cities became million cities due to internal migration. Impact of these cities spread along with the coast e.g. the sphere of influence of Mumbai extends from Dahanu in the north to Alibag in the south along the coast of Arabian Sea.
(5) Development of tourism—tourism is considered as invisible export and contributes substantially to the developing countries like Singapore and Mauritius. Many new tourist destinations developed along the coast, thus increasing the concentration of population in the coastal areas.

(6) Migration—as the port cities developed at a rapid pace, the influx of migrants to cater to industries also grew. As port cities have limited space to grow horizontally, they started to grow vertically by construction of skyscrapers. But the cost of living became exorbitant, leading to the creation of slums, where the majority of the migrant population settled.

Indian port towns like Kolkata, Chennai, Mumbai, Kochi, Vishakhapatnam were commercial hubs during mercantile period. During the colonial period, their growth became more rapid, as they were the transport linkages with rest of the country to source out raw material. With the growth in quaternary economic activities such as service sector post-liberalization, the yesteryear port cities like Chennai, Kolkata and Delhi developed into metropolitan cities, while Mumbai achieved the status of a megalopolis. All the states on the west coast of India have more than 35% of its population living in urban area, while on east coast there is a gradual progression in urban population among states (Census 2011).

4 SLR and Coastal Communities in India

In India, coastal zones have gained importance because of high productivity of its ecosystems, exploitation of renewable and non-renewable natural resources, concentration of population, industrialization, discharge of waste effluents and municipal sewage and growth of recreational activities. Land–ocean interaction in the coastal zone produces a varied set of landforms and organisms having special forms of adaptation. The coastal processes largely operate within 10 m above or below and a few kilometres landward and seaward of the shoreline. The coastal regions are highly vulnerable to storm surges, tsunamis and inland floods, due to their low-lying nature and extremely gentle gradients (ISRO 2012). Coastal zones face the most direct impact of the sea-level rise around the world as they fringe the world oceans and are low lying. The sea-level rise leads to accelerated erosion, shoreline retreat, saltwater intrusion into coastal groundwater, aquifers, inundation of wetlands and estuaries and creates threats to historical and cultural resources as well as infrastructure (Pendleton et al. 2004).

India has a coastline measuring upto 7515 km. Around 35% of Indians live within 100 km of the Indian coast (ISRO 2012). The Indian coast can broadly be divided into two parts: the west coast facing the Arabian Sea and the east coast facing the Bay of Bengal. The coastal areas are in the states of Gujarat, Maharashtra, Goa, Karnataka, Kerala, Tamil Nadu, Andhra Pradesh, Odisha, West Bengal and in the union territories of Daman & Diu, Lakshdweep Islands, Puducherry, Andaman and Nicobar Islands. The western coastal plains are submerged coastal plain; hence, it is a narrow belt and provides natural conditions for the development of ports and harbour. On the other hand, the Eastern coastal plains are emergent coastal plain and their continental shelf extends upto 500 km into the sea; hence, it is difficult to develop good natural harbours and ports in this region. This also makes them more prone to

be affected by disasters like tsunami, storm surge and cyclones. The coastal plains of India are covered by fertile soils on which different crops like rice and coconut are grown. In view of its economic importance, the Indian coast has several big and small ports. Fishing is an important occupation in southern India, while low-lying areas of Gujarat are famous for producing salt. Kerala backwaters and Goa beaches are important tourist destinations.

5 Mumbai—A Historical Geography

The area known as Mumbai, then Bombay, consisted of a small archipelago in a harbour on the west coast of India. The number of distinct islands was open to interpretation since large areas were underwater at high tide and during the monsoon season (June to September), when water discharged from Thane and Panvel Creeks to raise the harbour's sea level. At other times, it was possible to cross between the islands on foot. This space contained a range of ecosystems: While some areas were entirely submerged, others consisted of mangrove forests, tidal flats and artificial salt pans. In 1661, Bombay was transferred by Portuguese to the English Crown in the treaty accompanying the marriage of Charles II and Catherine of Braganza. In 1668, the crown transferred the islands to the East India Company. The modern assumption is that seven islands existed: Colaba, Old Woman's Island, Bombay, Mazagaon, Parel, Worli and Mahim. The area today, after extensive reclamation, covers sixty-five square kilometres (Riding 2018) (Fig. 2).

Maharashtra State, barring a few centres, is as poorly developed as many industrially backward states in the country. This concentration is the result of historical forces. The British developed Bombay as the centre of their trade and also developed port in its natural harbour. By the middle of the nineteenth century, Bombay was the unrivalled trading centre in the whole India. Even traders from older centres, like Surat, migrated to Bombay in this period. As in the case of all cities developed to foster colonial trade, the transport network, specifically the railways, was developed with Bombay as the centre, and the city thrived at the expense of its hinterland. Agglomerative forces came into play leading to the growth of industries and diversified it in and around the city. This process continued unchecked till the 1960s, when the State Government intervened to limit further growth of industry in Bombay. Government policy, together with dispersing forces like soaring rents and factor prices, and labour trouble, led to the spill over of industry towards the suburbs at first and, later, to the nearest large urban centre of Pune.

6 Impact of SLR on Mumbai

As the population in developing countries continued growing and many people were living in high-risk, coastal locations, sea-level rise can have significant physical,

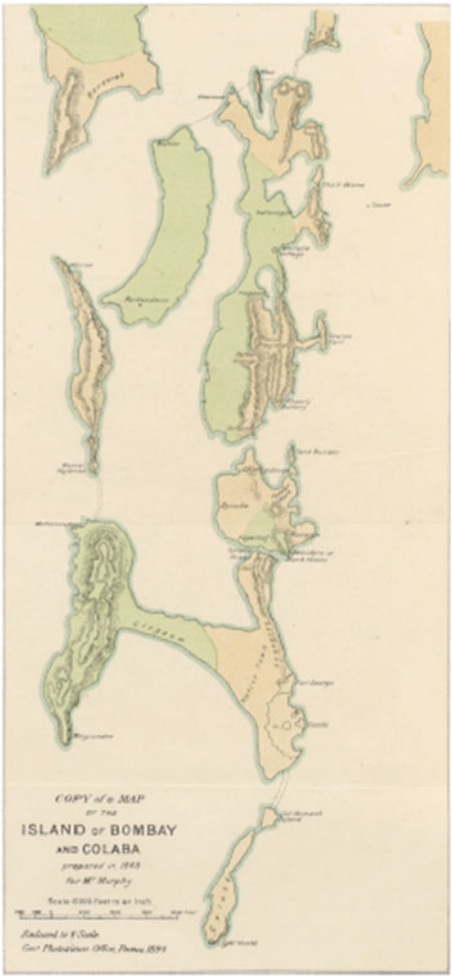

Fig. 2 Islands of Bombay.
Source Riding (2018)

health, social, economic and environmental consequences on both individuals and communities (Alderman et al. 2012).

Mumbai is termed as the economic capital of India. It is home to major financial institutions such as Reserve Bank of India, the National Stock Exchange of India, Bombay Stock Exchange and also to many of the corporate headquarters and commercial establishments. As per Census (2011), the population of Mumbai is 1.2 million, a large section which still resides in slums. As most of the Bombay city is reclaimed, the water stagnation is a major problem during monsoons. During high tides, the sea water is many a time above the sea level, and hence the storm water drainage is not able to function to its full capacity leading to flood-like situation in the city.

(1) **Health**

World Health Organization (WHO 2009) reports that flooding is expected to occur more frequently in the coming decades because of climate change and sea-level rise. According to Watts et al. (2015), the sea-level rise represents a significant public health concern. Flooding and health issues, such as water-borne diseases; respiratory diseases, such as asthma; vector-borne infections; skin rashes; and malnutrition are all interlinked (Rose and Akpinar-Elci 2015; Reponen et al. 2010), along with psychological issues such as depression, emotional trauma and anxiety (Akpinar-Elci et al. 2018; Bei et al. 2013). Increased incidence of respiratory diseases have been associated with floods, as many communities and houses are left damp, which often results in moulds and mouldy smells (Rose and Akpinar-Elci 2015; Mendell et al. 2011) and a reduction in quality of life (Reponen et al. 2010). It is often observed that the local administration is criticized for its failure to predict as well as respond to flood situations, despite it being a regular occurrence during monsoons. The health infrastructure in the city is usually strained due to excessive population, such floods exert undue pressure on the medical services.

(2) **Economic**

Being a commercially developed megalopolis, many of the corporate houses from India and abroad have their headquarters in the city. Post liberalization the economic development of Mumbai city is supported by a massive infrastructure development. The creation of Bandra Kurla Complex (BKC), restructuring of Special Electronics Export Processing Zone (SEEPZ) at Andheri, creation of business district at Mindspace, Malad was channelled to decentralize corporate offices from South Mumbai. But still several trading zones are located in South Mumbai like cloth market at Kalbadevi, electronic market at Grant road, gold and diamond market at Zaveri Bazar, utensils and tools market at Loharchawl. One of the biggest leather industry in located at Dharavi as a cottage industry in the slums. Shifting elsewhere is not commercially viable to them, as they pay very low rent. Sea level rise will lead to permanent inundation of these areas over a very long time horizon, leaving billions of rupees worth investment obsolete. In a city where currently a large workforce is involved in secondary to quaternary economic activities, this incurs a great economic cost.

(3) **Displacement**

Coastal communities are more densely populated and rapidly growing in population (Neumann et al. 2015). Koli community, which is one of the original inhabitants of Bombay Islands, live in a settlement called “koliwada” near the sea. Versova, Madh, Marve, Colaba, Trombay and Worli are some of the larger koliwadas in Mumbai. Fishing is a major source of livelihood among the members of this community. As their boats are on the beach, the settlements have formed right next to the sea and often during high tide the waves crash on the walls of the dwellings. Over the years, regular flooding during monsoon has started to occur in the koliwadas, as storm water from land and sea water merge in these areas. As these koliwadas are right next to the sea, they fall under Coastal Regulatory Zone (CRZ) due to which construction or repair becomes difficult. This has lead to several unauthorised constructions mushrooming in

the koliwadas. But as the sea level rises, the settlements are shrinking in size and leading to relocation of the population (Kotak 2018).

(4) **Infrastructure**

To create multi-modal transport linkages construction of multiple flyovers, express ways, metro & mono railways, skywalks have been carried out in Mumbai as support to the economic boom post liberalization. East-West suburbs connecting link roads like Jogeshwari-Vikroli Link Road (JVLR), Ghatkopar-Mankhurd Link Road (GMLR), Santacruz-Chembur Link Road (SCLR), under construction Mulund-Goregaon Link Road (MGLR) and Sion-Bandra Link Road (SBLR) have been built over the years at a great cost and new residential areas have mushroomed along these link roads. As sea level rise has an impact which will only be visible in the long term, no specific measures are in place to take care of the same. Over the years, Municipal Corporation of Greater Mumbai has installed five pumping stations are Irla, Haji Ali, Cleveland, Lovegrove and Britannia (Reay Road). The work on Gazdarbadh, Mahul and Mogra pumping stations are at various stages of completion (Pinto 2017). But these are only effective in short-term disruptions like flooding in monsoon and are not sufficient to mitigate sea level rise. Further, the government has planned coastal road on the entire west coast from Colaba (South Mumbai) to Virar (Extended Western Suburb) and statue construction in the sea, which will require reclamation of land thereby advancing sea level rise in other parts of the city. Mumbai's southern part was once habited by colonial officials to a great extent which led to construction of several heritage structures and art deco style building viz. the Royal Opera House, Asiatic Building, Horniman Circle and the famed Gateway of India. Sea level rise can lead to irreparable damage to this glorious historical inheritance.

Sea-level rise also impacts hazardous waste management. Sea-level rise would place waste management sites in the floodplain, exacerbating the impacts of a storm or landfall tropical storm. Exposure to toxic waste can increase the risks of toxicity of the liver and kidney as well as cause cancers (EPA 2018).

(5) **Biodiversity**

Seventy percent of the world's wetlands are in coastal regions which include salt swamplands, mangrove woodlands and sludge flats, which are highly vulnerable and very susceptible to changes in the environment (Spencer et al. 2016). A model was developed Spencer et al. (2016) by to assess the biophysical and socio-economic impacts of sea-level rise and wetland environments. The study estimated that if the sea level rose 50 cm up to 59 per cent of all coastal wetlands would be inundated, while in case of a higher sea-level rise scenario (110 cm), the statistic would increase to 78 per cent. Chowdhury and Behera (2015) has studied the changes in mean sea level with the help of tidal gauge stations located at Mumbai, Kandla, Cochin and Hiron Point (Bangladesh). The Mumbai station has a data for over 100 years, which has provided some significant findings. Figure 3 clearly shows that over the past century the average sea level rise has been more than 100 mm at Mumbai station, which is also consistent with the global estimate of 1–2 mm/ year (IPCC 2013).

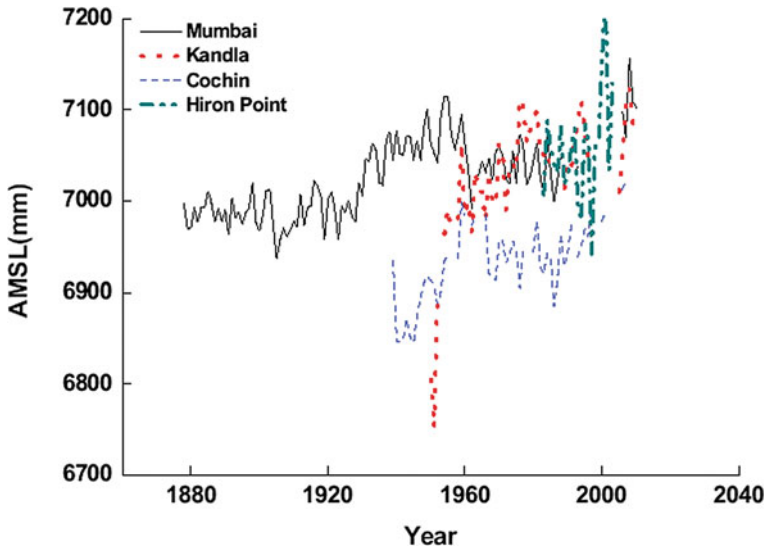

Fig. 3 Average Mean Sea Level (AMSL in mm) at master stations

Mumbai, due to its peculiar peninsular shape, has mangroves on all the sides. These mangroves prevent erosion of soil and inundation by sea water by reducing wave action. They also absorb carbon dioxide. However, in recent years due to reasons like unauthorised reclamation of land, high salinity of water, blockage of intertidal region, coastal pollution, the mangrove cover is depleting (Chatterjee 2018).

7 Adaptation and Mitigation

Sea-level rise (SLR) is a a by-product of Climate Change on a global scale. It is a reality which has to be accepted by the world and adaptive measures need to be placed in this regard. Due to lack of space in urban areas, the damage of SLR will be to a greater extent in urban area, while in rural areas shifting of settlement to higher grounds will be required. As land availability is comparatively more in rural areas, the land inundated by sea water can be used for aquaculture, desalination of water, salt pans.

In terms of mitigation, building of sea walls or barriers is a practice that has been done for a long time for the both areas, below and above the sea level. In Mumbai, such examples of creating barriers with the help of tetrapods can be seen at Colaba, Nariman Point and Marine Drive. But these are rather expensive and may not be economically feasible option for a developing and underdeveloped countries (TNN 2001). The sea walls can be constructed in height for the immediate future and

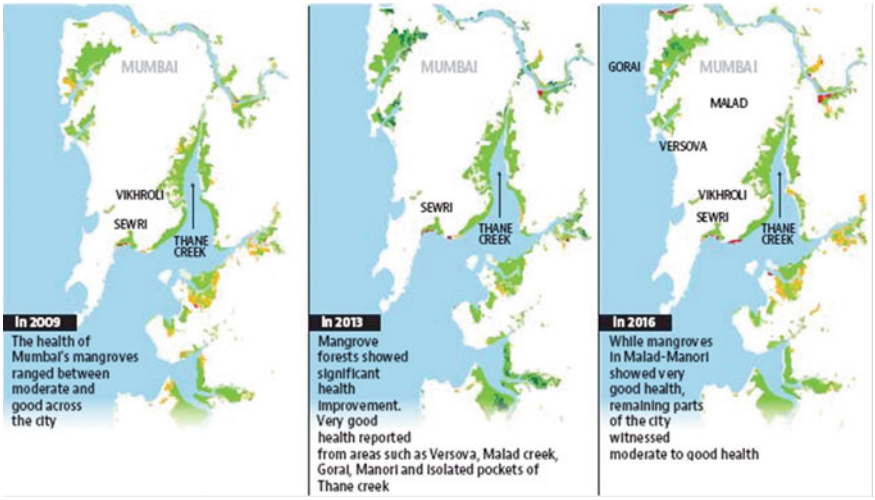

Fig. 4 Changes in Mangrove cover *Source* Chatterjee (2018)

designed to accommodate future increases in height. Dredging, creating off-shore barrier islands and reshaping ocean floors are some of the measures which can also be considered. Extending the wetlands by increasing the mangrove cover is also a good way to mitigate the SLR as mangroves can prevent further encroachment by the sea and at the same time keep alive the biodiversity in the area (Wong 2015).

Physical and digital model simulation and analysis should be carried out in order to study the segment of the ocean basin adjacent to the low-lying coastal area threatened by sea-level rise. An initial mapping of the regional seabed with historical data regarding currents and tides should be carried out with the objective of designing and engineering a hydrological system that would allow an increased volume of flow through the shallow water region, while limiting sea-level rise in the low-lying coastal area. Oceanographers, marine scientists, engineers and regional planners can collectively engage in limiting the adverse effects of sea-level rise (Wong 2015). With the technological advancement of the current world, tools like geographical information system and remote sensing can be used to generate scientific models and data, respectively. E.g. the figures (Figs. 4 and 5) depict the Landsat remote sensing data regarding changing mangrove cover at Thane creek, which is part of the east coast of Mumbai.

8 Conclusion

Research suggests that continued sea-level rise in the coming century is very likely, despite attempts to reduce greenhouse gas (GHG) emissions through agreements such as the Kyoto Protocol or more recently the Paris Climate Accord (Levermann

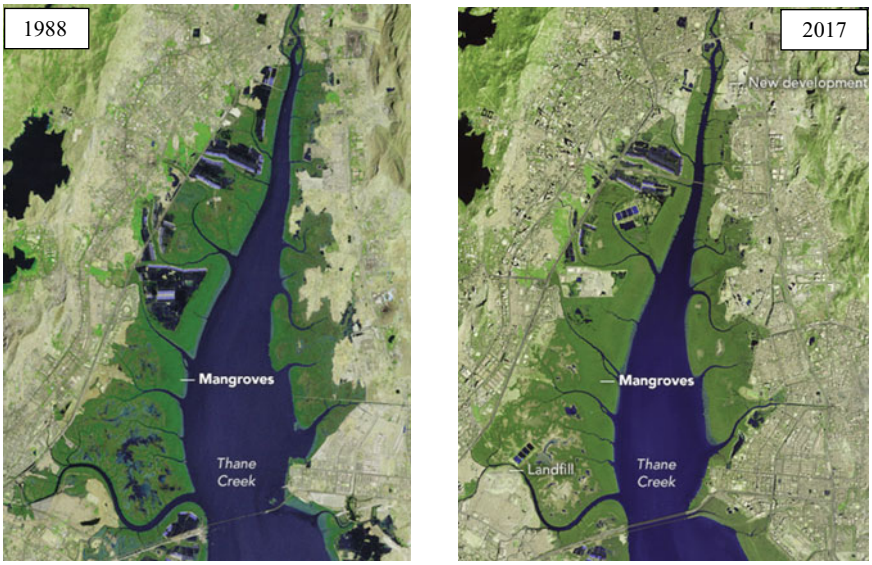

Fig. 5 Changes in Mangrove cover at Thane creek 1988 and 2017 *Source* NASA (2018)

et al. 2013). The concerns and impacts of climate change and sea-level rise on coastal communities around the world vary to a great extent (Schulte et al. 2015). Geisler and Currens (2017) estimated that 1.4 billion people could be displaced globally as a result of climate change by 2060.

Global commerce and trade rely heavily on historic marine transportation routes and port cities. In the era of globalization, sea-level rise becomes a significant concern at individual, local government as well as to global economy levels. Hence, both worldwide collaboration and localized strategies are very much required to address the challenges of sea-level rise. Following are some of the measures which could be taken into account for the same:

- The rate of sea-level rise may be slowed down by reducing the concentration of heat-trapping, greenhouse gases (GHG) in the atmosphere.
- Retrofitting or reconstruction of infrastructural facilities like roadways, drainage systems, homes and businesses may need to be carried out to reduce the impacts of sea-level rise.
- Successful implementation of counter-measures to sea-level rise will require cooperation, trusting partnerships and locally focused adaptation strategies like investment in green infrastructure and nature-based solutions, revising zoning strategies, construction of dikes and sea walls, improved drainage infrastructure, and inward migration.
- Capacity building of coastal communities and reducing the impacts of sea-level rise on global level will also require international research and worldwide organizational support.

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