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By

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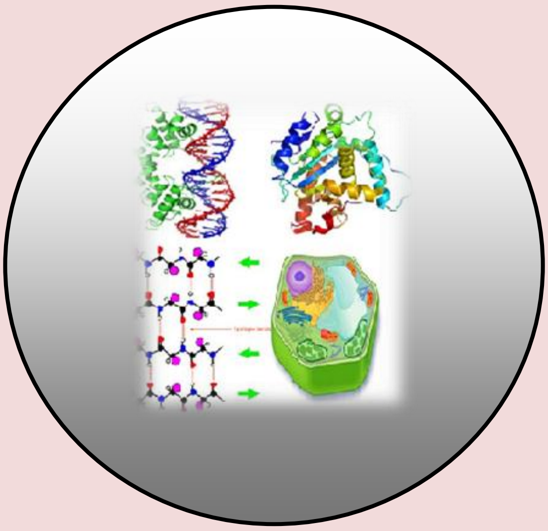

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REVIEW ARTICLE

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Climate Change Related Sea-Level Rise (SLR) Impacts on Social, Economic and Environmental Sectors and Adaptation Measures: A Short Review

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ABSTRACT

Rising sea level is one of the most catastrophic consequences of climate change and a major threat to social, economic, and environmental sectors worldwide. Sea-level rise (SLR) is the average increase in the level of the world's oceans. This article is a short review of SLR impacts on various social, economic, and environmental sectors including i. Wetlands and biodiversity, ii. Water resources, iii. Agriculture, fisheries, and aquaculture, iv. Public health, v. Assets and Infrastructure; and vi. Adaptation measures. SLR would cause significant losses of the world's coastal wetlands and its biodiversity (tiger habitats in Bangladesh and India, endemic species (mainly plants) in isolated islands in the world; and drowning of coral reefs in Atlantic and the Indian Ocean). It will further cause contamination of surface and groundwater with salt, salinization of rice lands (rice lands in Vietnam, Bangladesh, and Myanmar) and freshwater aquaculture facilities, and an increase of cholera outbreak and salinity-tolerant mosquitoes. The other impacts are damage to coastal infrastructures and assets. The risks of SLR should be incorporated in all current and future social, economic, and environmental development projects. Community awareness and education on the SLR would be vital to face the risks resiliently.
Keywords: Climate Change, Sea-Level Rise, Impacts, Biodiversity, Wetlands, Corals, Fisheries, Water, Rice, Human Health, and Infrastructure.

INTRODUCTION

Rising sea levels is one of the most catastrophic consequences of climate change/ global warming and a major threat to coastal habitats and coastal communities worldwide. Sea-level rise (SLR) is the average increase in the level of the world's oceans. There are three ways in which global warming is causing sea levels to rise (Figure 1)

- Thermal expansion of the oceans (*major cause).*
- The melting of glaciers, ice caps and ice sheets.
- Ice loss from Greenland and West Antarctica.

Global warming or increases in temperatures (due to an increase in the concentrations of greenhouse gases (GHGs)) cause the oceans to warm and expand in volume inducing a rise in the sea levels. Furthermore, warmer climate facilitates melting of glaciers, ice caps and ice sheets causing further addition of water to the oceans. In fact, the major cause of SLR is the thermal expansion of the oceans which contributed substantially in recent time (1993-2003: 3.1 mm/year) (IPCC, 2007).

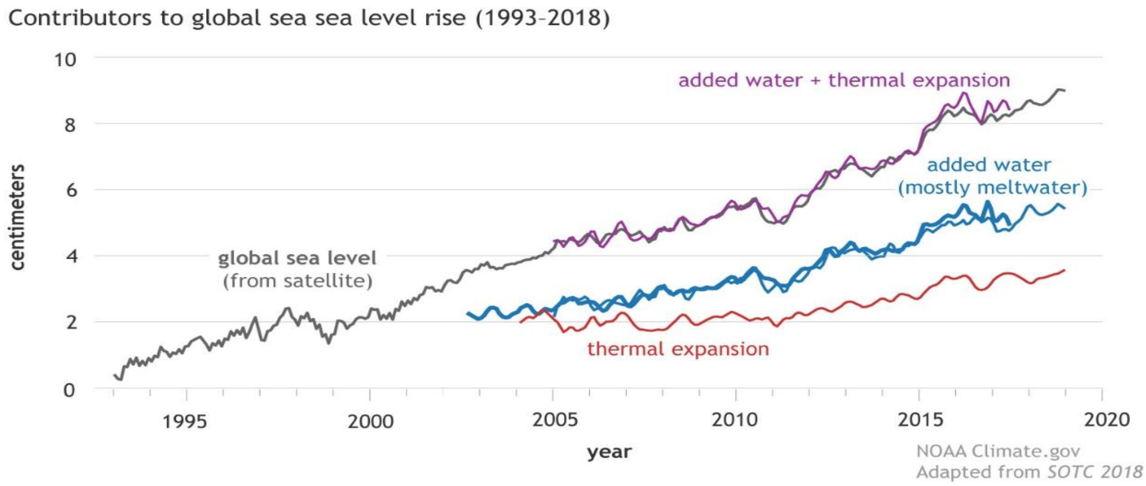

Figure 1. Observed sea level since the start of the satellite altimeter record in 1993.

Black line- satellite altimeter record, blue line- added water (glacier melt); purple line (thermal expansion). Source: (NOAA, 2018, Climate. Gov. Graphic, adapted from Figure 3.15a in State of the Climate 2018).

The recent projection on SLR is based on Representative Concentration Pathways (RCP) introduced by the Intergovernmental Panel on Climate Change (IPCC). Based on the four RCPs (RCP2.6, RCP4.5, RCP6, and RCP8.5), the global mean sea level could rise in the range of 0.28 to 0.98 m by 2100 (Table 1). RCPs are greenhouse gas (GHG) concentration trajectories (not emissions) adopted by the IPCC for its Fifth Assessment Report (AR5).

Table 1. Projections of global mean sea-level rise in meters relative to 1986-2005. (based on thermal expansion calculated from climate models) (IPCC, 2013; Wong et al., 2014, page 369).

Representative Concentration Pathway (RCP)	CO_2 concentration (ppm) Year: 2100	Mean sea level rise (m) Year: 2100
RCP 2.6 (low)	421	0.28-0.61 (0.44)
RCP 4.5 (medium)	538	0.36-0.71 (0.53)
RCP 6.0 (medium-high)	670	0.38-0.73 (0.55)
RCP 8.5 (high)	936	0.52-0.98 (0.74)

Sea-Level Rise Impacts

SLR will cause significant impacts on wetlands and its biodiversity, water resources, agriculture, fisheries and aquaculture, public health, assets and infrastructure and displacement and migration. Sections 2.1 to 2.5 discuss in detail the impacts of SLR on various sectors.

SLR Impacts on Wetlands and Biodiversity

SLR can cause significant impacts on coastal wetlands. Coastal wetlands including salt marshes, mangroves, and intertidal areas are sensitive to SLR since they are closely linked to sea level.

They provide flood and storm protection, waste assimilation, nutrient cycling functions, food production (nursery areas for fisheries), nature conservation (habitat for wildlife) and other ecosystems services. It has been projected that most losses of coastal wetlands may occur from a rise of 0.2 m sea level. A 1.0 m SLR may cause significant losses (25-46 %) of the world's coastal wetlands (Nicholls et al., 1999). Dasgupta et al*.,* 2009 assessed the vulnerability of SLR to wetlands of 84 developing countries; results of which show that 28 % of wetlands in Vietnam, Jamaica and Belize would be inundated by a 1.0 m SLR. Other developing countries, where wetlands will also be most affected are Qatar (21.75 %), the Bahamas (17.75 %), Uruguay (15.14 %), Mexico (14.85 %), Benin (13.78 %) and Taiwan (11.70 %). As a specific example, a 1.0 m SLR may cause complete losses of the Sundarbans mangroves (UNESCO World Heritage site) of Bangladesh and India resulting in the loss of heritage, biodiversity, and fisheries. The Sundarbans is the home of the iconic Royal Bengal Tigers (*Panthera tigris tigris*) (World Bank, 2000) and recent research revealed that a 28.0 cm SLR will cause a decline of 96 % tiger habitat in the Sundarbans (Table 2, Loucks et al*.,* 2010). In addition, the distribution and habitat of the important cetaceans, the Ganges river dolphin, *Platanista gangetica* preferring lower salinity may also be affected (Smith et al., 2009). Furthermore, SLR may cause replacement of the most dominant, freshwater-loving important trees in the Sundarbans, Sundari trees (*Heritiera fomes*) by salt-tolerant trees such as Goran (*Ceriops decandra*, *C. tagal*) and Keora (*Sonneratia apetala*) (World Bank, 2000). A recent study projected that SLR would cause significant biodiversity loss in biodiversity "Hot Spots" Islands in the world (see Case study 1).

Table 2. Remaining tiger habitat in the Sundarbans mangroves, Bangladesh with increasing sea levels (0-28 cm) (Loucks et al., 2010).

Sea level rise (cm) (baseline year 2000)	Total tiger habitat available (km^2)	% of habitat loss/ decline (compared to 2000)
0 cm	4,175 km^2	0 %
4 cm	4,169 km^2	0.14 %
8 cm	4,021 km^2	3.69 %
12 cm	3,697 km^2	11.45 %
16 cm	2,946 km^2	29.43 %
20 cm	1,771 km^2	57.58 %
24 cm	674 km^2	83.86 %
28 cm	159 km^2	96.19 %

Case study 1. Sea-level rise would cause significant biodiversity loss in biodiversity "Hot Spots" Islands in the world.

Bellard et al., 2014 assessed the impact of SLR on the 4,447 insular/isolated islands biodiversity (plants, birds, reptiles, mammals, amphibians, and fishes) in 10 biodiversity 'hot spots" in the world. The 4,447 islands located in the ten geographical areas are as follows: the Caribbean Islands (723), Japanese Islands (400), Philippines (670), East Melanesian Islands (414), Polynesia-Micronesia (597), Sundaland (795), Wallacea (571), New Caledonia (44), New Zealand (120), Madagascar and the Indian Ocean islands (113). The researchers assessed the impacts of projected SLR (1, 2, 3 and 6 m) on these 10 islands and the number of endemic species would potentially be affected by habitat submersion due to SLR for each taxon (i.e. plants, birds, reptiles, mammals, amphibians, and fishes). The findings of this research are highlighted below:

- The 1 m SLR would entirely submerge 267 islands (out of 4,447) and 6 m SLR would entirely submerge 845 Islands (out of 4,447).
- Most of the species predicted to be lost are plants.
- The 1 m SLR scenario would threaten (the risk of extinction) 26 plants, one bird and one reptile species, whereas the 6 m SLR (worst case scenario) would threaten (i.e. the risk of extinction) 300 plants, eight birds, 18 reptiles, six amphibians, two mammals, three fishes.
- Three hotspots displayed the most significant loss of insular habitat are the Caribbean islands, the Philippines and Sundaland, representing a potential threat for 300 endemic species.

SLR Impacts on Water Resources

Saline intrusion caused by rising sea-level (an invasion/ intrusion of seawater into freshwater and brackish areas) would cause the most significant impact on coastal groundwater resources (freshwater aquifers) along low-lying coasts. Freshwater aquifers in coastal areas are used for drinking water. Therefore, saltwater intrusion due to SLR would thus be a serious problem both at the regional and global level since 80 % of the world's population live along the coast and utilize local aquifers for their water supply (Kibria et al., 2016). Furthermore, SLR is projected to increase the frequency of storm surges resulting in inundation of thousands of kilometres of coastlines along the world's oceans. As a consequence, the saline water can flow down submerged and storm-damaged water supply wells. This will cause to contaminate both boreholes in inundated low-lying areas as well as the surrounding coastal aquifers (Carlson et al., 2007). Due to extensive coastline and many river deltas, two countries Bangladesh and Vietnam are the "hot spots" for SLR and salt water intrusion (Norwegian Institute of Bioeconomy Research, 2017). The major impacts of SLR on water resources are highlighted below:

- Will cause saltwater contamination and saltwater intrusion into estuaries, streams, rivers, land and coastal aquifers,
- Will cause salinization of surface and groundwater quality (chloride contamination),
- Will reduce the thickness of the freshwater lens on atolls (coral reefs) of the Pacific and the Indian Ocean *[Note: freshwater lenses float on top of the saltwater* (Verruijt, 1968),
- A threat to water infrastructure (threat of flooding and damage to water infrastructure) and the operation of drinking water, wastewater and stormwater utilities.

SLR Impacts on Agriculture, Fisheries and Aquaculture

Agriculture: SLR would cause loss of agricultural land due to flooding of lands and intrusion of seawater (Table 3.), as a result, agriculture in the low-lying coastal area or adjacent to deltas may be affected (Rosenzweig and Hillel, 1995, Nicholls et al., 2007, Kibria et al., 2010). It is projected that a 1.5 m of sea-level rise in Bangladesh (#1 climate risk 'hot spot' country in the world) may flood about 16 % of the country's land area (22,000 km^2) (*https://scied.ucar.edu/sea-level-change-bangladesh)* of which southern coastal sub-regions are more vulnerable where rice production could be unsuitable (Yu et al., 2010). In fact, significant rice land is projected to be inundated in many countries, most notably in Southeast Asia, South Asia, and East Asia (e.g. Vietnam, Egypt, Myanmar, and Bangladesh) (Dasgupta et al., 2009). Rice is a major staple crop of half of the world's population and may result in a food security crisis in those regions/ countries if SLR increases in the line of projections (see the Table 3 for the projected loss of crop/rice land in various vulnerable countries due to SLR). High levels of salt in agricultural soil/ irrigation water make it difficult for rice and other crops to absorb water and necessary nutrients (*https://www.nibio.no/nyheter/food-security-threatened-by-sea-level-rise*). Rice growth is suppressed, and rice yields can significantly reduce in a saline environment. Moreover, saline water can injure rice varieties (symptoms of salt injury: stunted growth, rolling of leaves, white tips, drying of older leaves, grain sterility and yield reduction). Rice is only moderately tolerant to salt, and yields are reduced when salinity goes >2 ppm (parts per million) (IRRI, 2007, Wassmann et al., 2009, Kibria et al., 2013).

Fisheries and aquaculture: SLR may cause loss of areas such as mangroves which act as nursery and breeding areas of aquatic organisms (fish, shrimp) that supply seeds for aquaculture. It may cause loss/ shift of natural breeding grounds of native freshwater fish species and loss of areas available for freshwater aquaculture. SLR can damage nests of shorebirds, sea turtles, hermit crab and cause the drowning of coral reefs impacting biodiversity, tourism, and other economic benefits (see case study 2 for the drowning of coral reefs due to SLR).

One positive impact is that SLR will create new areas for brackish water fish/shrimp aquaculture. For instance, Black tiger shrimp production (*Penaeus monodon*) will significantly increase in coastal areas of Bangladesh (Hassan and Shah, 2006) due to SLR.

Table 3. Loss of cropland due to sea-level rise (SLR) (as % of rice cropland lost to inundation) (data from Chen et al., 2012).

Regions/ SLR	1 m	2 m	3 m	4 m	5 m	Remarks
Bangladesh	0.54 %	1.25 %	2.77 %	5.33 %	8.34 %	Major impacts on rice land from 2 m to 5 m SLR.
China	0.03 %	0.05 %	0.07 %	0.1 %	0.13 %	
Egypt	1.72 %	2.23 %	2.76 %	3.29 %	3.87 %	Major impacts on rice Land from 1 m to 5 m SLR.
India	0.02 %	0.04 %	0.08 %	0.13 %	0.18 %	
Indonesia	0.18 %	0.34 %	0.6 %	0.96 %	1.41 %	
Japan	0.3 %	0.82 %	1.62 %	2.76 %	4.28 %	Major impacts on rice land from 3 m to 5 m SLR.
Korea DRP	0.03 %	0.06 %	0.14 %	0.26 %	0.43 %	
Myanmar	0.85 %	1.41 %	2.49 %	4.35 %	6.44 %	Major impacts on rice land from 2 m to 5 m SLR.
Pakistan	0.01 %	0.02 %	0.04 %	0.08 %	0.11 %	
Philippines	0.12 %	0.19 %	0.32 %	0.48 %	0.66 %	
South America	0.03 %	0.06 %	0.09 %	0.12 %	0.16 %	
Taiwan	0.33 %	0.57 %	0.85 %	1.2 %	1.53 %	Major impacts on rice land from 4 m to 5 m SLR.
Thailand	0.12 %	0.35 %	0.84 %	1.57 %	2.36 %	Major impacts on rice land from 4 m to 5 m SLR.
USA	0.001 %	0.003 %	0.003 %	0.003 %	0.003 %	
Vietnam	5.53 %	9.5 %	13.28 %	16.15 %	18.15 %	Most impacted country, major impacts on rice land from 1 m to 5 m SLR.
West Africa	0.02 %	0.03 %	0.05 %	0.07 %	0.09 %	

Case study 2. SLR will cause the drowning of coral reefs (Atlantic and the Indian Ocean)

A very recent study published in 'Nature' journal (Perry et al., 2018) revels that SLR would elevate water depths above coral reefs in more than 200 tropical western Atlantic and Indian Ocean reefs. The study assessed the magnitudes of future reef submergence using the recent and projected rates of SLR under different Representative Concentration Pathway (RCP) scenarios. The research projected that most reefs would be incapable of growing quickly enough to compensate for rising sea levels triggered by global warming. SLR would be additional stress on coral reefs which are already under stress due to coral bleaching (due to thermal and ocean acidification) where frequent coral mortality can be expected. SLR would cause less coral growth (reef degradation). The study found that the tropical western Atlantic and Indian Ocean coral reefs are predicted to experience increases of over 0.5 m of water depth by 2100. The significant water depth increases projected above these reefs by 2100 under both RCP4.5 and RCP8.5 scenarios are as follows:

- **SLR in coral reefs in the tropical Western Atlantic:** RCP 4.5: 16-66 cm (average 40 cm), RCP 8.5: 16 to 104 cm (average 60 cm), the study covered corals reefs in *Florida and the Greater Antilles* (Florida, Puerto Rico, Grand Cayman), *Northern Lesser Antilles* (St Croix, St Maarten, Anguilla, Barbuda, Antigua), *Meso America* (Belize, Mexico), *Leeward Antilles* (Bonaire).
- **SLR in coral reefs in the Indian Oceans:** RCP 4.5: 14-72 cm (average 47 cm), RCP 8.5: 22 to 112 cm (average 71 cm), the study covered corals reefs in *East Africa* (Kenya, Mozambique), *Western Australia* (Ningaloo), *Western Indian Ocean* (Seychelles), *Central Indian Ocean* (Maldives, Chagos)] (Perry et al*.,* 2018).

It should be mentioned here that coral reefs are famous for housing biodiversity/ fisheries, attracting tourists, bringing in the economic benefits to coastal communities and acting as natural breakwaters (sea walls), protecting the shorelines and human-built infrastructure from storms. Many of the small Pacific Island nations depend on coral reef fisheries for 90 % of their animal protein needs and for livelihoods (where there is a limited agricultural alternative) (Kibria et al*.,* 2017).

SLR Impacts on Public Health

SLR can increase the risk of cholera in many countries including Bangladesh since cholera bacterium, *Vibrio cholerae* survive longer in salinity ranges of 2.5 ppt to 30.0 ppt and need sodium ion (Na^+) for growth (Borroto, 1998). Cholera has a sea stage during which copepods (tiny animal called zooplankton) act as host organisms. It (cholera-carrying copepods) lives in salt or brackish waters (Craig, 2010). During the last 50 years or so the major cholera epidemics that have occurred originated in the coastal region (Colwell and Huq, 2001), therefore SLR may increase the risks of cholera outbreak in those coastal areas where SLR is projected to increase (Sarwar and Khan, 2007). SLR may also lead to increased breeding of salinity-tolerant mosquitoes such as *Anopheles* spp. and C*ulex* spp. For instance, soon after the Asian tsunami in December 2004 (which caused intrusion of saline water into inland), *Anopheles sundaicus* increased in density in the Andaman and Nicobar Islands, and freshwater mosquitoes, *A. stephensi* and *A. culicifacies*, were found breeding in brackish water bodies in India and Sri Lanka (Ramasamy and Surendran, 2011). Though most mosquito vectors breed in freshwater, however, some species do breed in brackish/ saline waters. Therefore, an expansion of brackish- and saline water bodies in coastal areas due to SLR can increase the density of salinity-tolerant mosquito vectors and cause freshwater mosquito vectors to adapt to brackish water habitats (Ramasamy and Surendran, 2011). Rising sea levels due to global warming can influence the spread and transmission of salinity tolerant, *Aedes* spp. (dengue virus bearing mosquitoes) in coastal areas (Ramasamy and Surendran, 2012).

SLR Impacts on Assets and Infrastructure

Commercial and residential buildings/ houses, industrial facilities, airports, sea and river ports, hospitals, schools, and other economic and social infrastructures (roads, hospitals, tourist places, oil refineries, mosques, churches, temples, pagodas) which are close to the coast will be at risk due to SLR. For example, in Australia, between 157,000 and 247,600 existing residential buildings are at risk of inundation with an SLR of 1.1 m (Australian Government, 2016). SLR may raise coastal water tables potentially impacting water supply infrastructures, such as septic tanks, sewer systems, basements, causing instability of swimming pools, tanks, and some other sub-surface structures. Stormwater pipes and drainage assets will also be exposed to the impacts of rising sea levels and may not be adequate to accommodate future changes in extreme rainfall and storm surges and groundwater inundation and may cause sewage overflows (de Almeida and Mostafavi, 2016). SLR may cause loss of areas such as mangroves that provide protection of assets and infrastructure and coastal villages from waves/ storm surges/ cyclones (mangroves acting as a natural sea wall).

Adaptation Measures to Reduce SLR Impacts

More than 70 % of the world's population lives in the coastal plains and many of the nations that are most vulnerable to SLR does not have the resources to adapt to or prepare for it, such as small Island nations, Africa, South, Southeast and East Asia. The adaptive measures that can be undertaken to cope with SLR or reduce the risk of SLR are highlighted below:

- Convert SLR affected agriculture/rice lands to brackish water fish and shrimp farming facilities.
- Promote/grow salt-tolerant rice varieties in affected areas.
- Harvest rainwater/ or install rainwater tanks in house/home (in SLR prone areas).
- Rebuild new roads and bridges to a higher elevation and design new coastal drainage systems with wider pipes to incorporate future SLR.
- Replant and restore mangrove trees to protect assets.
- Implement flood insurance programs

CONCLUSION

SLR would cause significant impacts on social, economic, and environmental sectors (Figure 2). There is projected to be significant losses of the world's coastal wetlands and its biodiversity [(e.g. freshwater loving trees and tiger habitats in the Sundarbans mangrove in Bangladesh and India (Table 2), endemic species (mainly plants) in isolated islands of the Caribbean, Japan, Philippines, East Melanesian, Polynesia-Micronesia, Sundaland, Wallacea, New Caledonia, New Zealand, Madagascar and the Indian Ocean (case study 1)]. SLR will cause the drowning of coral reefs in more than 200 tropical western Atlantic and Indian Ocean reefs (case study 2). Coral reefs support fisheries and act as natural breakwaters (sea walls) protecting the shorelines and human-built infrastructure from storms. Many of the small Pacific Island nations depend on coral reef fisheries for 90 % of their animal protein needs and for livelihoods.

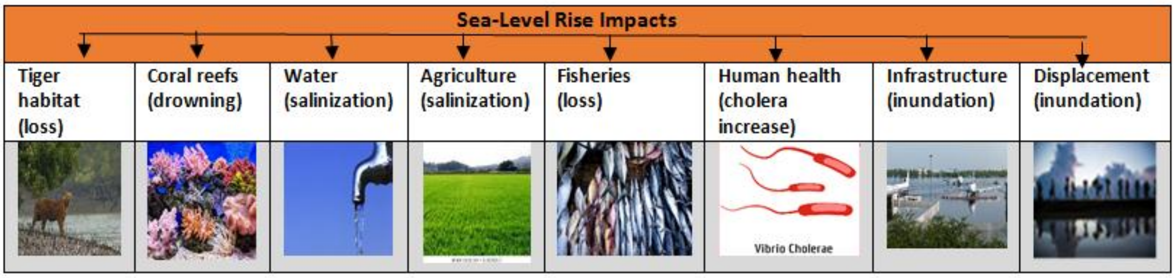

Figure 2. Key social, economic, and environmental sectors that would be affected by sea-level rise.

SLR will further cause intrusion of saltwater into estuaries, streams, rivers, land, and coastal aquifers, and salinization of surface and groundwater quality (thus a threat to water security due to contamination of drinking water with salt). SLR would further cause loss of agricultural land such as rice lands in Vietnam, Bangladesh, Myanmar (Table 3). Rice is a major staple crop of half of the world's population and may result in a food security crisis. SLR may cause loss of areas such as mangroves (nursery and breeding areas of fish, shrimp) and loss of areas available for freshwater aquaculture.

SLR can increase the risk of cholera (since cholera bacterium survives longer at higher salinity) and transmission of salinity tolerant mosquitoes in coastal areas. Commercial and residential buildings/ houses, industrial facilities, airports, sea and river ports, hospitals, schools etc which are close to the coast will also be at risk due to SLR. Therefore, the risks of SLR as a risk should be incorporated in all current and future social, economic, and environmental development projects. Community awareness and education on the SLR would be vital to face the risks resiliently. Government and private sectors should formulate appropriate policies and time-scheduled action plans to reduce emissions of GHGs, that cause climate change and result to sea-level rise.

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