4

RESULTS AND DISCUSSIONS

On completion of study, the output from research on the captioned subject has been presented in this chapter. Sustaining with the objectives of research as set out under Chapter-I (Introduction; Para 1.4 i, ii, iii & iv precisely); the 'Predictions', 'Study Results', 'Consequences' & 'Proposals' have been abridged in Paras 1, 2, 3 & 4 respectively in this chapter. As per the computerized output based on the method stated in Chapter-III, i.e., after simulation run in state of the art software MIKE 21of DHI, the climate change induced Rise in Sea Level city has been found at Mumbai. The consequences thereupon have been thoroughly discussed in the sections to follow.

4.1 Predictions

Even if India's total emissions are allowed to increase, the existing target is "2°C-compatible", as far as warming is concerned, which as per the Paris Agreement is in range of global effort's fair share. In the existing literature, Mumbai has been ranked at a very high position amongst top few cities in the world that are vulnerable to Rise in Sea Water Level [*Abadie et al. Ocean and Coastal Management 193(2020).105249*].

Projected Rise in Sea Water Level till 2100 globally is apprehended to be within 1.3 m to 1.9 m in various literature [11], [14], [23]. With 1 m global Rise in Sea Water Level in 2100 a linear interpolation shows SLR at Mumbai in 2050 as per IPCC's report [28].

The output from one simulation model under IPCC AR5 revealed that risein sea level at Mumbai may be **1.24 m, in 2100** under "Business-as-usual scenario" (the high-emission within RCP 8.5 [66].

It is projected that in a scenario of low emission, relative to the level in 2000, rise in sea level **by 2050** will be **30 cm** and **by 2100** will be **69 cm**, whereas in scenario of high emission will be **34 cm in 2050** and **111 cm** in **2100** in [82].

As per expert judgements, total predictions of increase in Sea Level, considering contributions both from thermal expansion in ocean & from melting of ice the low ended projections till 2050 is likely to be from 16 to 49 cm), and for high ended projected till 2050 H is likely to extend up to 61 cm [98]. Rise in Sea Level s due to contribution of increasing melting of icebergs in Polar Regions in 21st century remains highly uncertain and difficult to be quantified. In the high emission scenario by 2100rise has been projected to be upto 2 m or more [82].

It is found that there are doubts in assessing the Rise in Sea Level. The greatestuncertainty lies on how much the ice is going to melt and that too how fast it may. There are repeated warnings on the issue from different corners and

moreover there is large fluctuation in the figures up to what level globally the sea can rise.

In the said perspective of uncertainties, indicating any particular projection becomes unreliable. For this study the assumption made for Rise in Sea Level neither should be very pessimistic nor very optimistic, however has to be a reasonable one. Itis predicted that in the event substantial chunk of the polar icebergs melts into ocean due to Global Warming several thousand Gigatonnes of water may even raise the Sea Level globally by unexpected few meters at the top of this century or beyond. The widely varying predictions sufficiently raises doubts and indicates voids in in scientific information which means that the process which contributes to Rise in Sea Level is not very clear [47].

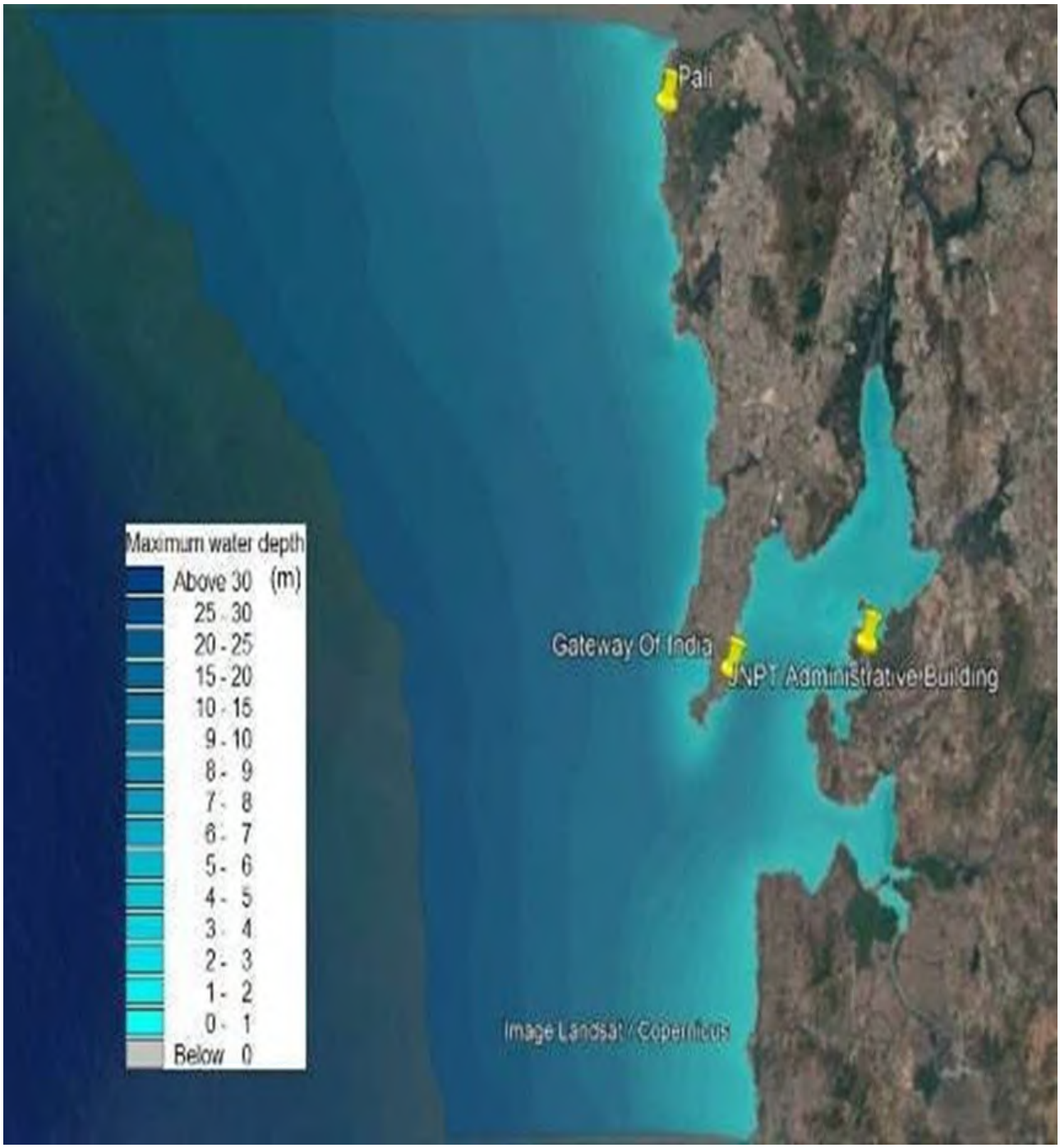


Figure 4.1: Point of study (Gateway of India) (Latitude/Longitude = 18.9220° N, 2.8347° E)

4.2 Study Results

The results obtained from the methods adopted in Climate Change Tool of MIKE 21 FM HD as explained in Chapter-III for the Rise in Sea Level at Mumbai coast during 2050 against respective scenarios are presented using IPCC AR4's method & Grinsted's method.

4.2.1 Variation in Water Level (Tides) [2020-2050]

At the location shown in Figure 4.1 (study area), the maximum and minimum tide level has been calculated from Global Tide Model which as obtained from MIKE are shown in Figures 4.2 and 4.3 sequentially.

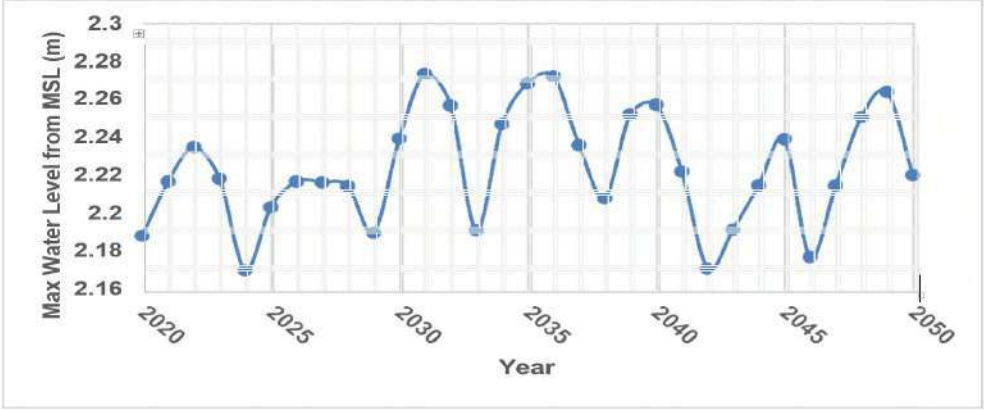


Figure 4.2: Tidal water level variation in lowest Tide from 2020 to 2050

Rise: 2.22009 m - 2.18815 = 0.03194 m = 3.19 cm

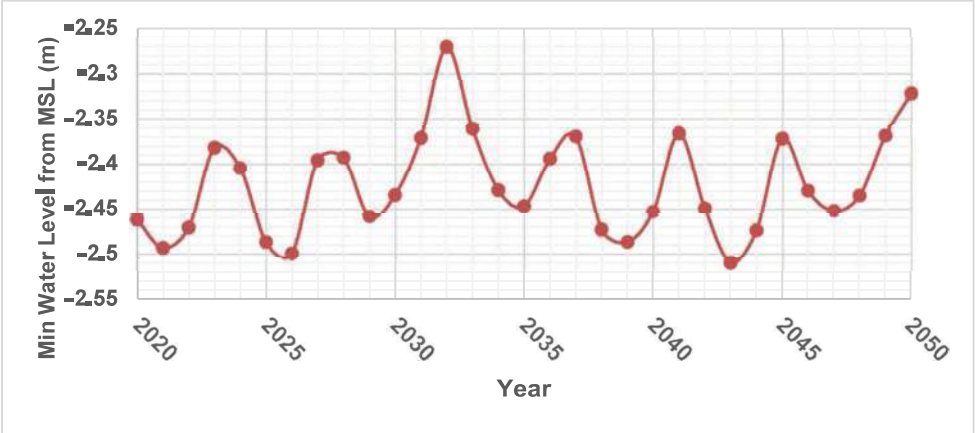


Figure 4.3: Tidal water level variation in HWL from 2020 to 2050

Rise: 2.32246 - (-2.46224) = 0.7847m = 7.8 cm

So, Tidal Rise will be in the range from 3.19 cm to 7.8 cm ..... [A]

The respective inundation map for the rise in tides for 2020 and 2050 are furnished in Figures 4.4 & 4.5.

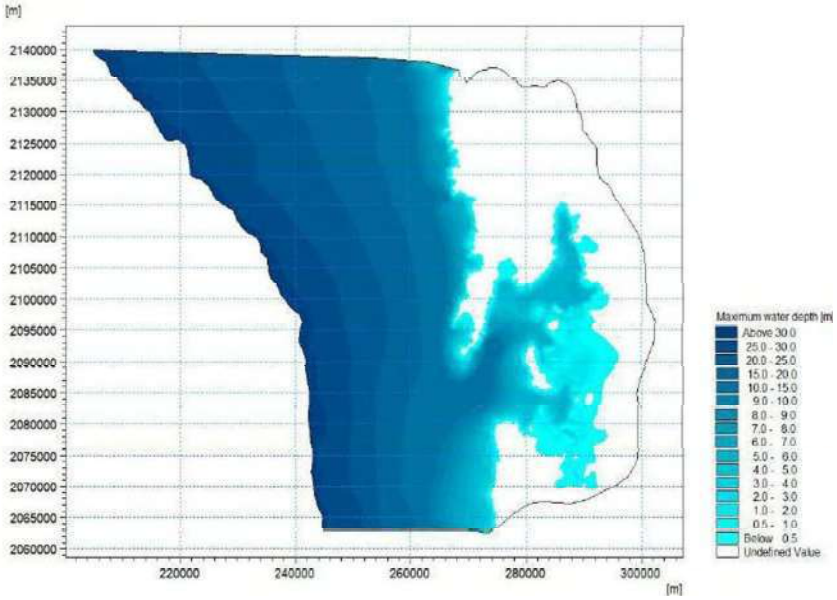


Figure 4.4: Maximum water depth (m) inundation in 2020

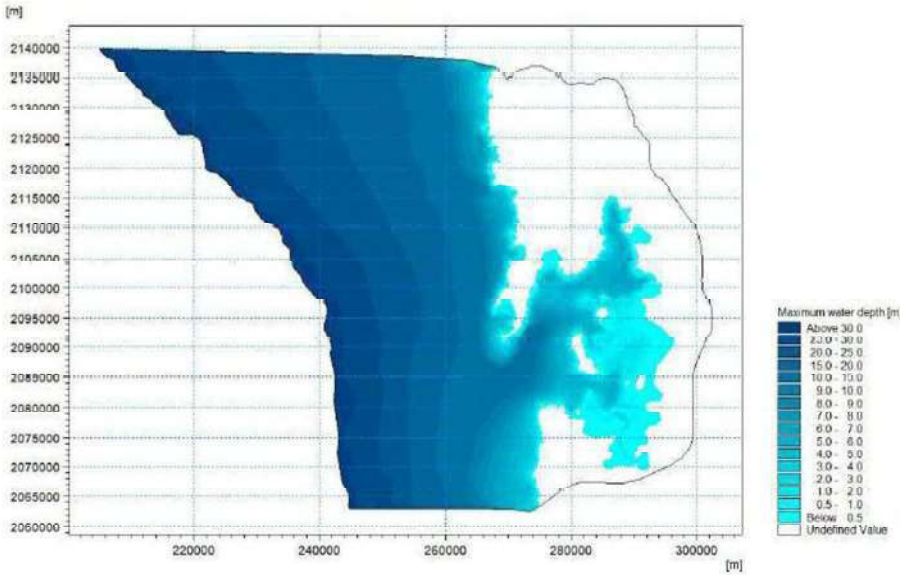


Figure 4.5: Maximum water depth (m) inundation in 2050

Similar inundation maps for variation in tides as obtained from MIKE Software for 30 years i.e., for 2021 to 2050 are attached in Appendix-I.

4.2.2 Increase in Sea Level affected by Changes in Climate[2020-2050]

4.2.2.1 Results from MIKE

The MIKE 21 FM HD model's climate change tool was run to find the Sea Level Change in 2050 to generate inundation and its areal extent for the study area. The co- ordinate of Gateway of India under the given Boundary condition was given as inputfor the considered Climate Change Scenarios under IPCC AR4 and Grinsted 2009 i.e., for SRA1B, SRA2 and SRB1.

The scenario-wise absolute results for respective emission scenarios for 2050 as obtained from the stated two methods as obtained from the software are presented in Table 4.1, summarized in Table 4.2 after simulation, relative variations appraised in Figure 4.6 through histogram, and plotted in a scatter diagram in Figure 4.9 successively one by one.

It is seen from the above chart that the Rise in Sea Level can vary within values of 0.156 m to 0.431 m depending on the various methods and the hypothesis considered therein. It is extremely difficult to ascertain which particular scenario will be in vogue at Mumbai in 2050.

Table 4.1: Prediction of Rise in Sea Water Level by 2050 (from Software)

Methods	1.75	1.65	1.29	Temp ^{0}C Rise
	SRA1B	SRA2	SRB1	Scenario
	Projected increase in SeaWater (m) by 2050			Reference
IPCC AR4	0.179	0.162	0.156	Meehl et al. (2007) [72]
Grinsted 2009	0.415	0.421	0.370	Grinsted et al. (2009) [11]
Horton 2008	0.249	0.254	0.223	Horton et al. (2008) [13]
Vermeer 2009	0.431	0.431	0.395	Vermeer and Rahmstorf (2009) [14]

Figure 4.6: SLR Data – Scenario vis-a-vis Methods

From the perspective of Paris Agreement Compatibility, the temperature rise at Mumbai can be reasonably considered well below 2^0C but not much above 1.5^0C with regional development in scenario A2 (Heterogeneous economics in direction of regional conditions & Rapid growth in world population) [75]. Based on the said elucidations, under Temperature rise of 1.65^0C in SRA2 scenario; Grinsted's methodis considered to suit (rise in temperature 2nd highest amongst the values in Table 4.1) and hence along with IPCC AR4's method, Grinsted et al.'s 2009 method [11] is accepted as the result.

As obtained with MIKE software and detailed in Table 4.1 it is found that the absolute rise ranges from 0.156 m to 0.431 m in different methods, nevertheless these values cannot be directly added to find the Rise in Sea Level as the relation is nonlinear, instead it depends on many factors such as boundary conditions, terrain elevation and Manning's co-efficient. The computer screenshots regarding results of the simulated maximum water level for Sea Level in 2050 obtained from MIKE softwareare presented in Figures 4.7 & 4.8 for 2020 & 2050.

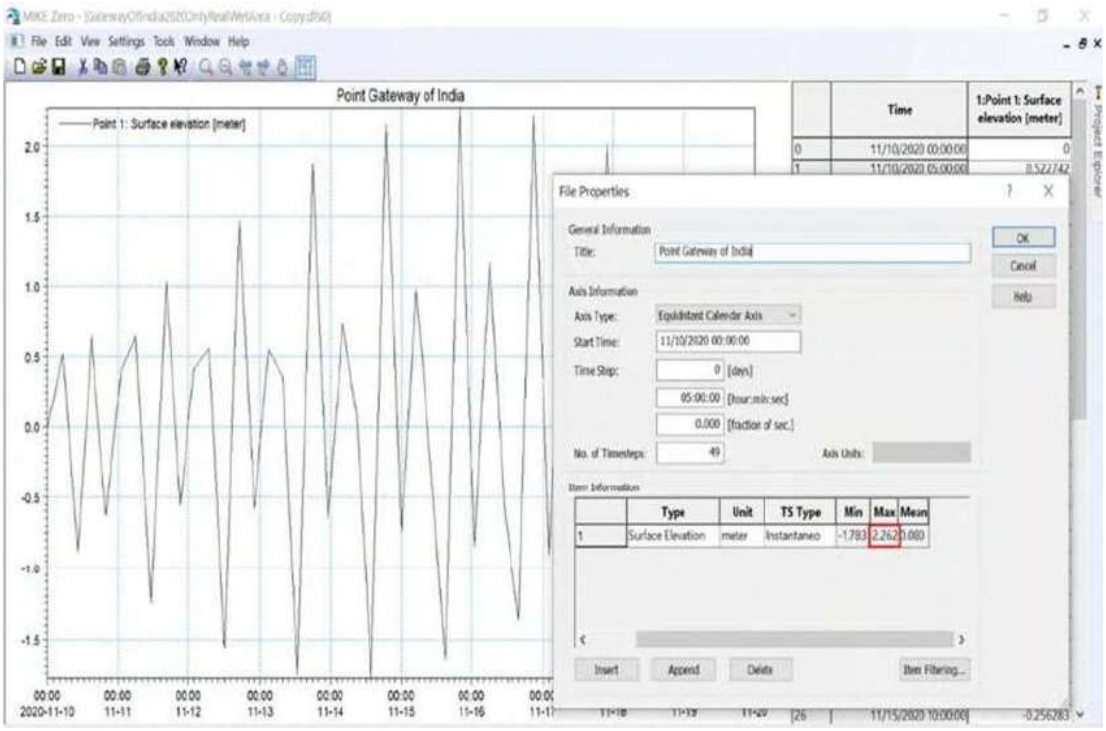


Figure 4.7: Base Sea Water Level at Gateway of India (base model) 2020

Amongst the two methods i.e., IPCC AR4 and Grinsted's one, the highest value of maximum water level under scenario A2 is **2.657** m above mean sea level. Maximum water level in original or base model (in 2020) was **2.262 m**. The rise of Sea water level in different scenarios as per the considered two methods is tabulated below in Table 4.3. The Software after further simulation provides a Rise in Sea water Level amounting to 395 mm (Table 4.3) only from Climate Change angle, mainly by focusing on temperature rise.

Hence, as an impact of Climate change as obtained from the simulation donein MIKE, (the increase in the mean sea level globally) ΔSLG for this study may be considered anywhere between 0.148 m and 0.395 m.

The highest one is considered as **0.395 m ..... (P)**

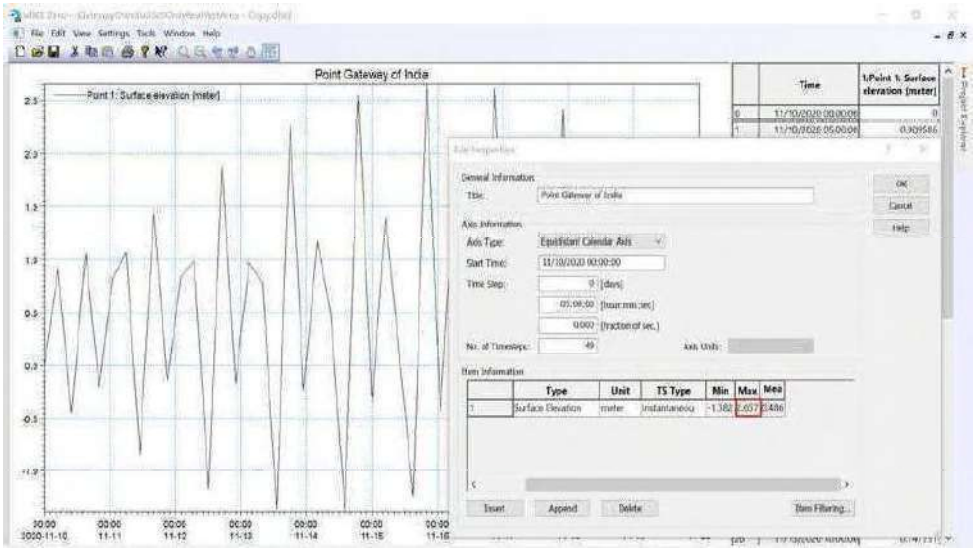


Figure 4.8: Raised Sea Water Level at Gateway of India 2050 [SRA2, Grinsted]

Table 4.2: Maximum water level at the Gateway of India			
Methods	**Maximum water level from MSL (m) at the Gateway of India in 2050**		
	SRA1B (RCP6.0)	**SRA2**	**SRB1 (RCP.5)**
IPCCAR4	2.431	2.415	2.410
Grinsted 2009	2.651	2.657	2.609
Temp ^{0}C	1.75	1.65	1.29
Maximum water level in original or base model (in 2020) = 2.262 m			

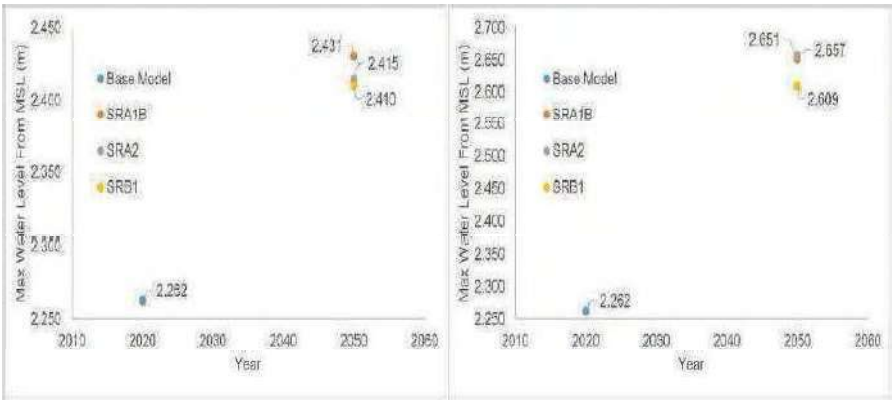


Figure 4.9: Sea Water level at the Gateway of India in 2050 considering IPCC AR4 method (Left) and Grinsted2009 (Right)

The following sea level inundation maps (Figure 4.10 (“a” to “g”) were obtained from DHI's MIKE.

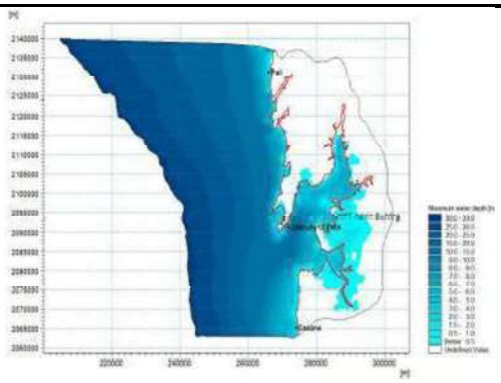


Figure 4.10 (a): Original model setup,2020

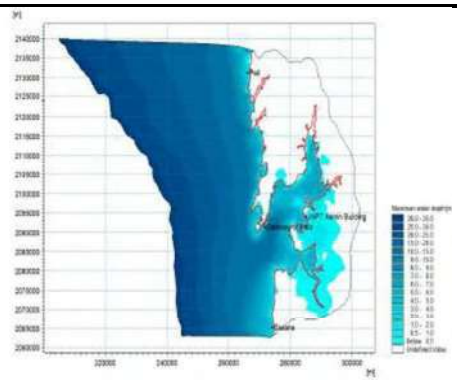


Figure 4.10 (b): IPCC AR4SRA1B2050

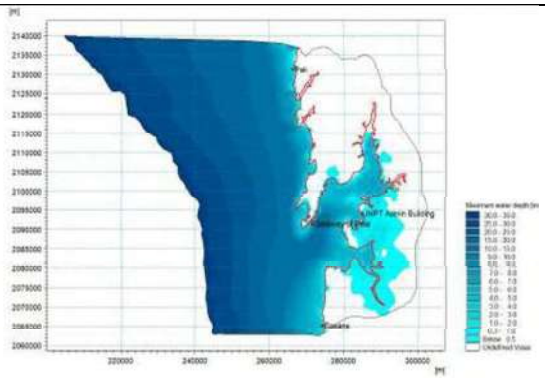


Figure 4.10 (c): IPCC AR4SRA2 2050

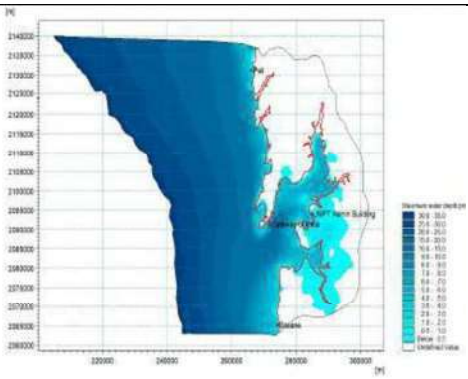


Figure 4.10 (d): IPCC AR4 SRB1 2050

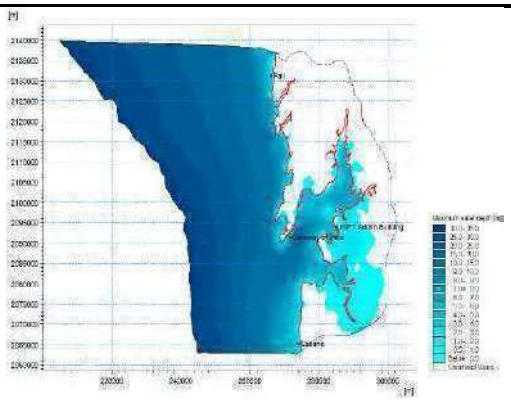


Figure 4.10 (e): Grinsted2009 method and SRA1B 2050

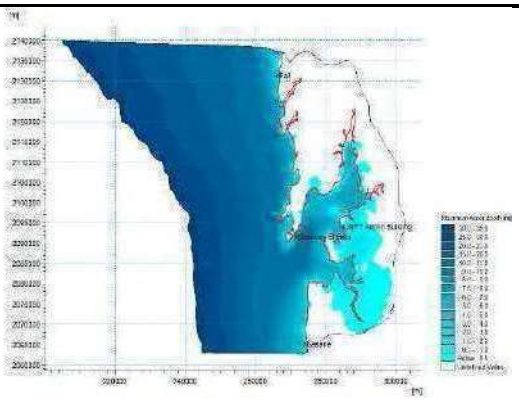


Figure 4.10 (f): Grinsted2009 method and SRA2 (2050)

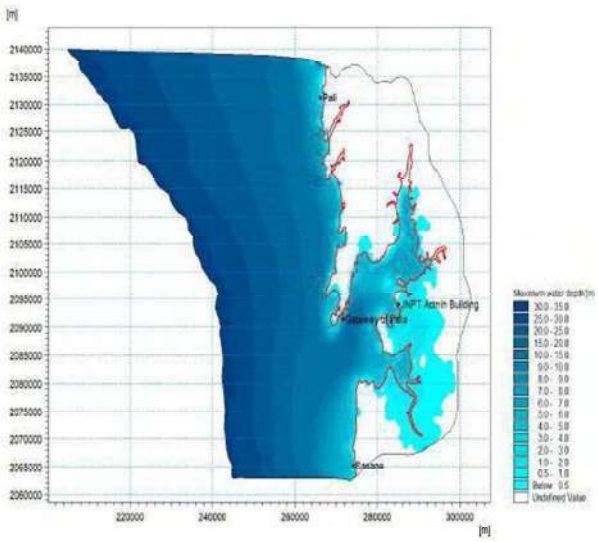


Figure 4.10 (g): Grinsted 2009 method and SRB1 emission scenario, 2050

Table 4.3: Effective Sea Level Rise from 2020 to 2050			
Temp ^{0}C Rise	1.75	1.65	1.29
Scenario→	**SRA1 B**	**SRA2**	**SRB1**
Method ↓	Increase in Sea Level for Changes in Climate		
IPCC AR4	0.169	0.153	0
Grinsted2009	0.389	**0.395**	0

4.2.2.2 Projected Rise in Sea Level considering additional factors

Predictions in Relative Rise in Sea Level for a specific location are found by adding contributions from the pertinent components at the local, regional and global level for any particular study area.

These components are then combined using following equation [79]:

$\Delta RSL = \Delta SLG + \Delta SLRM + \Delta SLRG + \Delta SLVLM$

Where,

- ΔRSL = Relative change in Sea level
- ΔSLG = Global mean sea water level i.e., 0.395 m

- ΔSLRM = variation in level of sea from mean sea level for factors relatedto meteo-oceanographic changes

- ΔSLRG = differences in the sea level at regional level for changes in gravitational forces

- ΔSLVLM = variation in water level at sea for sinking or upheaval of land

Regional spatial variations of sea-level differences [79] comprise:

a) ΔSLRM (Meteo-oceanographic factor) with components of changes in the rate of expansion in ocean from heat, variations in ocean circulation & variations in long-standing wind and pressure in atmosphere.

b) ΔSLRG (Variations in gravity field of the Earth at regional level) arising out of melting of ice (resulting to dispersion of mass).

c) ΔSLVLM (Vertical movements of land) (lift and subsiding) due to changes in geology arising out both human- induced and natural causes.

a) Meteo-oceanographic factors ΔSLRM

These factors, include variations in Earth's regional gravity field and lift and subsiding of land both from human-induced and natural causes. Dastgheib & Ranasinghe (2014) from UNESCO-IHE studied relative Rise in Sea Level at south of India. In the study area within the latitudes of 10^0-11.3^0 North and longitudes 78.15^0-
79.45^0 East, relative to 1990 the Relative Rise in Sea Level by 2100 was found as 0.87 m (highest) and -0.03 m (lowest) respectively [86].

However, during this study, reliable predictions of the potential RSLR at Mumbaitill 2050 for this factor was not available at present and so the effect could not be considered and hence ignored.

b) Variations in Earth's regional gravity field (ΔSLRG)

Traditional gravitational acceleration (**g**=9.8 m/s^2), due to the joint outcome of gravitation as well as the Earth's rotational outward radial force for the entire planet used to be presumed to be persistent. Earth was considered as one homogeneous sphere with hypothetical ocean layer with same gravitational force called the 'geoid'.In reality, at the surface of the planet from place to place the gravitational force actually varies from a maximum of 9.83 meters (32.2 ft) per second every second at poles and a minimum of 9.78 meters (32.2 ft) per second every second at Equator. ESA's satellite named GOCE observes the changes in level of sea arising out of changes in the climate and associated melting of ice-sheets. This satellite is equipped with obtaining precision results up to 0.000000005 **g** (**g** = 9.8 m/s^2) [88]. ΔSLRG is believed to be added to accurately project the Relative Rise in Sea Level for a specific location. Melting of ice from Icebergs and Glaciers are relatively recent.

Variations in Earth's regional gravity field (ΔSLRG) because of melting of ice (redistribution of mass) particularly for Mumbai is not readily available in public domain and hence could not be considered in this study.

c) Change due to vertical land movement ΔSLVLM

Mumbai being a reclaimed city, the settlements (vertical movement of land) can take 100s to 1000 years and may be very slow. The perfect data could not be obtained. However, it all depends on the local consistency of soil underneath, the load thereupon, and the rate of groundwater extraction. The relation between load upon land and the expected settlement thereby is given in Figure 4.11.

Rao et.al. (2021) studied that the settlement in and around lower Parel

could be more than in Central Mumbai. Most of the areas in the city are close to or belowthe mean sea level, excepting the hilly areas, which means the city more vulnerableto flooding during high tide and heavy rainfall. The soil character in Mumbai is mostly sandy being close to Arabian Ocean, and at some of suburban areas alluvial and loamy soils are also present.

Figure 4.11: Relation between SLR and Sinking of Land Mass in Coastal Cities [78]

Mumbai lies in Seismic Zone 3. Subsidence of land in Mumbai due any form geo-morphological deviations, relating to the structure of the earth's crust or due to human-induced events needs to be studied continuously to comprehend the future variations on Earth's surface. The is another efficient tool monitoring ground surface displacement with millimeter level accuracy. Recent observations through Persistent Scatterer Interferometry (PSI) method from Sentinel-1 shows the following range of subsidence in respective places from 2016 to 2019 on approximately 85 sq. km urban area of Mumbai [87].

- 80 mm at Wadala
- 60 mm at the merging point of Ghatkopar-Mankhurd Link Road & Sion Panvelexpressway
- 40 mm at Virar region

Upheaval up to 80 mm has been observed from 2016 to 2019 in the Adaigoan area.

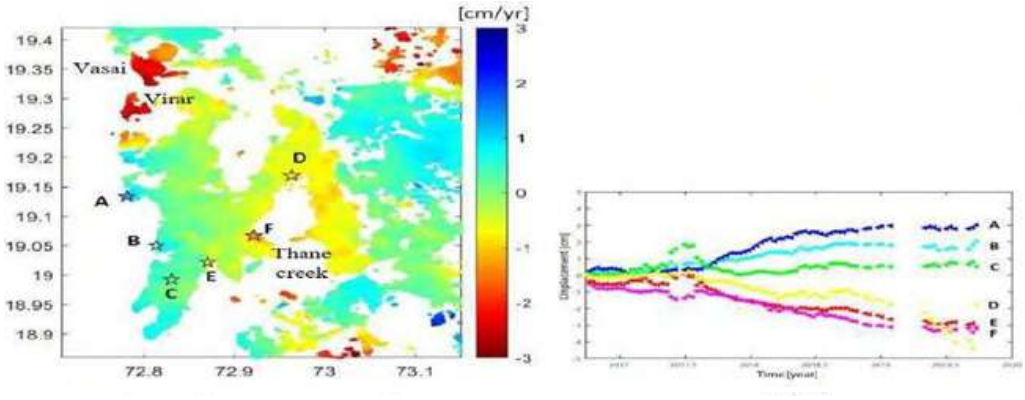


Figure 4.12 Displacement analysis over Mumbai city

[Uplift at points (A, B, C) in west of the city, whereas subsidence indicated at points (D, E, F) close to the Thane creek] [87]

Velocity map of deformation of the Mumbai city derived using (WabInSAR)Wavelet based (InSAR) Interferometric Synthetic Aperture Radar technique, shows subsidence of 0 to 10 mm/year at the around the Thane creek (Figure 4.12) [87]. Taking the reference from Sentinel-1's observations, on an average 10 mm/year means in coming 30 years it can go up to 300 mm till 2050 [87].

Figure 4.13: Original configuration of Mumbai [77]

Originally the Mumbai city consisted of seven islands under Portuguese colonial rule came to the British in 1661 and the British made the city with reclaimed connections (shown in black in Figure 4.13) [77].

The reclaimed (black connected parts Figure 4.13) must have settled during the last few centuries. Due to random pressurized developments in the city of Mumbai, for obvious reasons it can be well understood and reasonably presumed that the compaction and consolidation of earlier reclamations have not been done with surcharge load after PVD driving.

In a recent project by Port of Singapore Authority for construction of the 4th Container Terminal reclamation of 90 ha of land was done by driving Prefabricated Vertical Drains on Marine Clay with an allowance of Rise in Sea Level of 300 mm (considered in design and settlement allowance as 300 mm) after 20 years. Overall ground settlement (excluding earthquake) shall not exceed the values below.

Area	Maximum total overall ground settlement [Contemporary Industry Practice #]		
	After 2 Years	After 5 Years	After 20 Years
All Areas	100 mm	150 mm	300 mm

[# Source: Design Criteria- Contract Document- Dredging and Reclamation Works -Fourth Container Terminal at JNP - Cullen Gromit & Roe - January 2015]

Regarding change in vertical land movement as it depends on tectonic movements and the amount of extraction of groundwater for human usage the following needs to be mentioned here. As a matter of fact, Mumbai nowadays is frequently found in list of cities threatened by change in climate.

Sinking of city due to groundwater extraction also adds to the increase of Level at Sea. The relation between rise in sea level and sinking has been recorded by Erkenset al [78] where it is stated that Land subsiding can exceed global

absolute rise sea- level (SLR) with a multiple of 10. In this study, the minimum settlement, which can happen till 2050 can be conservatively assumed as:

$$\Delta SL_{VLM} = 200 \text{ mm} \ldots\ldots (Q)$$

4.2.2.3 Net Finding

Since MIKE 21 FM HD's Climate Change Tool during simulation has already considered effect of all possible parameters like Temperature rise, appropriated emission scenarios as per inbuilt capacity of the software separately rise in tidal leveltill 2050 as obtained from Global Tide Model up to 7.8 cm has not been separately added in the result obtained from climate change tool.

Hence,

$\Delta RSL = \Delta SLG + \Delta SLRM + \Delta SLRG + \Delta SLVLM$

$= 395 + 0 + 0 + 200 \text{ mm} = 595 \text{ mm}$

In absence of other data for a) & b) above we can consider SLR at Mumbai during2050 to be (P) + (Q) =395+200 =**595 mm (Say 600 mm)**

A Canadian team studied the temperature rise and Rise in Sea Level for few cities including Shanghai, Mumbai and Rio De Janeiro under A2 scenario (business as usual) and B2 scenario (sustainable path). They predicted rise in sea water level rise upto 1/2 meter (500 mm) at Mumbai in 2050 [86], the same value corroborates with McKinsey India sources who announced that in 2050 Mumbai will see a rise insea level amounting to 0.5 m. (*Mumbai first, Indian Express February 28, 2020*).

From the above study the net findings are:

- Tidal Rise at Mumbai will be in the range of 3.1 cm to 7.8 cm in 2050 and SLR solely due to Climate Change (Effect of Temperature Rise) at Mumbai during 2050 will be 595 mm.

- This is only a rough estimate as the effect of surge can be much higher in high wind and wave conditions and extreme weather events.

Hence, the expected SLR at the coast of Mumbai till 2050 due to impact of Climate Change only, for all *practical purposes* is considered in the order of magnitude of ***600 mm*** as a finding of this study, which can be considered as a reasonable value.

4.3 Consequences

1. The Rise in Sea Level will affect the Port and Harbour Operations and Navigational Operations for Passenger Vessels in various parts of Maharashtra including Mumbai and Navi Mumbai.
2. The present Deck Elevation Level for MbPT and JNPT the two Major Ports of India are at +7 m when the High Tide Level is +4.42 m above Chart Datum. The relation betweenChart Datum and MSL is presented in Table 4.4.
3. Because of the predicted increase in Sea Level, the free board at Jetties / Berths in the Ports will reduce and slam forces may develop on the jetty decks, which is not desirable.

4. The present provision for Deck Elevation Clause 6.3.7 of IS 4651 Part- V 1980 states:

   "The required deck elevation of cargo terminal is related to optimum position of the cargo transfer equipment to cater to two extreme situations, that is, with the largest vessel in light displacement condition at high water and with the smallest vessel fully laden at low water. The deck elevation should normally be at or above highest high- water spring plus half height of an incident wave at the berth location plus a clearance of 1 m".

5. There will be severe inundation and flooding in the city when the derived Rise in Sea Level will happen along with usual heavy rainfall during high tide, which may further increase because of surges from extreme weather events like cyclone and storm. Such a situation will jeopardize the life in the city, in all respects.

Table 4.4: *Chart Datum vs. Mean Sea Level (Source: Mumbai Port Trust)*

Tidal Level	**Higher (+) or Lower (-) Chart Datum**	**Higher (+) Or Lower (-) MSL**	**After Rise in Sea Level 600 mm Above MSL in 2050**
Recorded Highest High Water	+5.38 m	+2.87 m	+3.47
Spring Tides – Mean High Water	+4.42 m	+1.91 m	
Neap Tides–Mean High Water	+3.15 m	+0.64 m	
Level of Mean Sea Level	+2.51 m	0.00	+3.110
Neap Tides–Mean Low Water	+1.86 m	-0.65 m	
Spring Tides–Mean Low Water	+0.76 m	-1.10 m	
Recorded Lowest Low Water	-0.44 m	-2.95 m	
Recorded Highest Low Water	+2.74 m	+ 0.23 m	

4.4 Proposals

4.4.1 Port Infrastructure

- For future design of Jetties in Mumbai region during 2050 and beyond, a provision for an additional 600 mm and more has to be created. The Clause 6.3.7 in IS 4651 (Part V) may have to be revisited/changed and additional provisionsbe made.

- There shall be related changes in fixing height of Fenders.

4.4.2 Port Superstructure (Operational Aspects)

Also fixed cranes have to be replaced by Luffing cranes wherever possible, till free board remains available to the deck of a jetty/berth, to accommodate the diurnal changes between High and Low Tides. This will have serious effect on the design and handling capacity of the cranes. The efficiency of ports (moves per hour) is also likely to be affected. This will have a direct impact on economy of country.

4.4.3 Coastal Regulation Zone (CRZ)

Rise in Sea Level will also affect the current Coastal regulation zone notification,issued by MoEF regulate activities at the coastal area. Up to 500 m of the coastal land from the HTL (Level of High Tide) Line and along estuaries, backwater and rivers, banks of creeks, which face tidal fluctuations, up to 100 m, fall under Coastal Regulation Zone. Excluding the ocean part, this notification restricts the setting up of industries in the inter-tidal zone and the land part. Coastal regulation zone notification 2019 for maintaining sustainability, based on scientific principles, counts for change in climate and Rise in Sea Level. Up to 50 m and 200 m from the high tide line (HTL), CRZ areas have a no development zone. For CRZ area between 12 nautical miles seaward and low tide line, MoEF is authorized to oversee CRZ clearance. In other areas State level monitoring is

allowed. For all islands, this notification also advises a no development zone till 20 m.

Due to Rise in Sea Level as the HTL will be affected, it is opined that the findings of the subject research will invite consequential changes in CRZ regulations in future.

4.5 Limitation of the study

1. The initial Flexible mesh model for calculating rise in Tide level from Global Tide Level has the following limitations. The following recommendations should be considered to improve the accuracy of the model performance.

    - It is highly recommended to use higher resolution DEM (10 m DEM or less) for better and accurate results for the area inundated. The current 2D models are based on globally available low-resolution DEM (SRTM 30 m).If high resolution DEM is available then the bathymetry can be modified and can be included in the 2D models (MIKE 21 Flow Model FM).

    - Detailed calibration of the model is highly recommended for the better prediction.

    - Simulated inundation extent for the validation and calibration should beverified against flood photos and anecdotal records if available.

    - One limitation lies with the modeling that the 2D model has no provision to account for ground water and it is not having any provision to simulate between the aquifer and flooding. System also doesn't have any module for the network simulation with flood. These could give a better accuracy in estimation. These limitations influence

mostly the predicted flood situation during flood rise and recession, and not the main portion of the flood period.

2. The Climate Change Tool of MIKE has been applied on a single co-ordinate of Gateway of India. The Zone of Consideration has been for a length of about 67km on the sea shore. It is assumed that even for the points shown in Pali and Sasane the result will not differ much. The mesh has been generated upto about 30 to 50 m from the shore. The depth of water has been considered up to a bathymetry up to 30 m water depth.

3. The effect of rivers and estuarine flow has not been considered.

4. In the calculation the effect of wind has not been considered. Obviously, the effect of wave has also not been accounted for. Hence, the impact of splashing of waterto the real extent cannot be calculated correctly.

5. In this study the data from altimetry has not been compared for ratification.

6. The effect of heavy rainfall or extreme weather event like Tauktae has not been considered, which will further aggravate the scenario of flooding. A storm surge up to 4 m could happen (IMD Bulletin, 15-05-2021), which would have added much to inundation, in the event of landfall at Mumbai. Occurrences of storm can happen more frequently due to escalating Global Warming.

7. Variations in Earth's regional gravity field (ΔSLRG) has not been considered

4.6 Exclusions

The obtained result does not include effects of surge, tsunami or waves and storms. The result has not considered any effect of cyclone also. Because of sea water up to a depth of around 50 m in the Arabian Sea getting warm to the tune of 50^0C, occurrences of extreme weather event including cyclones ending with Nisarga, Taukte in recent years are becoming common every year. Frequent recurrences are likely to happen in future and those Cyclones will be more frequent and powerful [100]. Tauktae Cyclone (May 17, 2021) was fifth-strongest cyclone recorded in the Arabian Sea, had there been landfall at Mumbai coast, the storm surge reached 4 m (13 feet) at the headof the bay (IMD).

- Such serious extreme weather is not within the purview of this research and detailed study has not been undertaken.

- In this study detailed examination of inundation for increase in Rise in Sea Level and the disturbances on city's civic life and public health have not been elaborated but touched upon only.

A map from Climate Central showing inundation in 2100 is appended here for comparison of our obtained result (Figure 4.14).

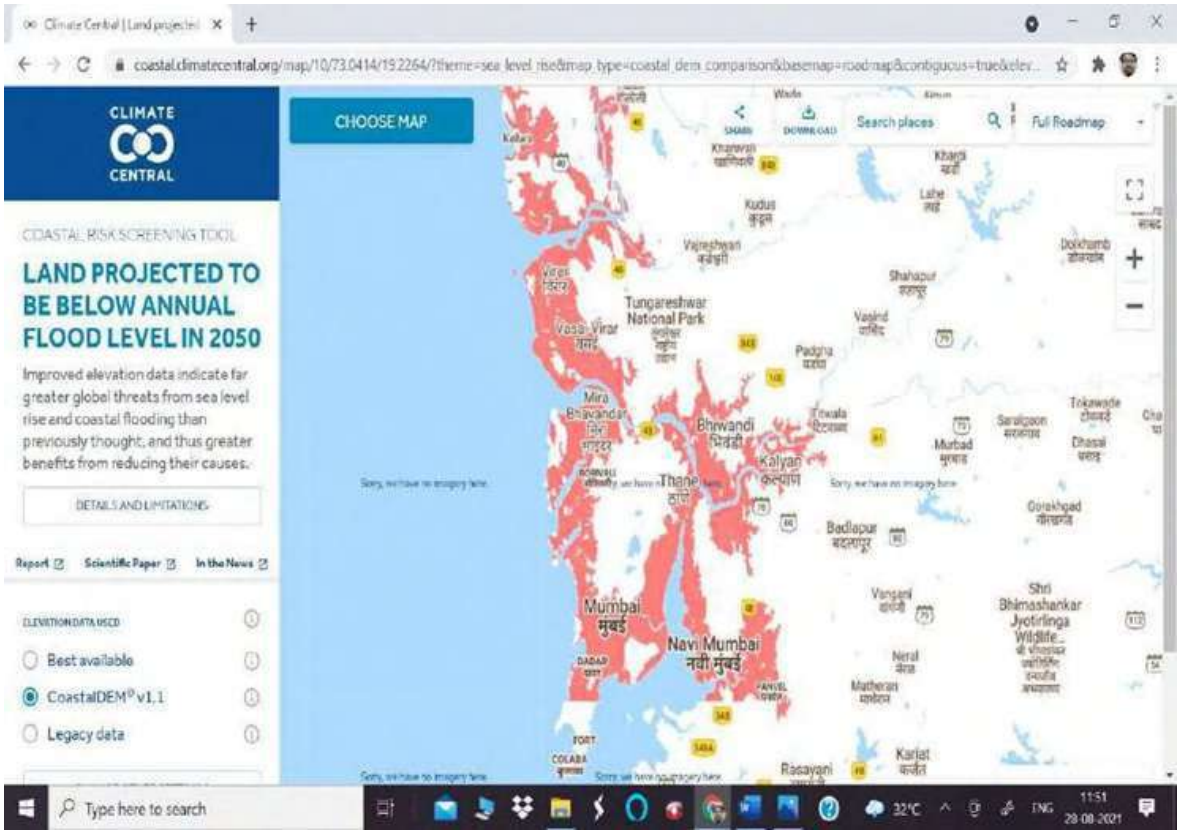


Figure 4.14: Relative SLR in 2050

(Study Area: Inundation in 2050 as per Climatecentral.org)

4.7 Discussions

IPCC's Reports what we already know and can see in the world around us (i)moisture loss due to extreme heat during wildfires, (ii) huge floods due severe rain events and (iii) cyclones due to changes between temperatures of sea and land.

Undoubtedly the threat of climate change is imminent and the future may be dangerous.

Before the onset of the monsoon in 2021, in India itself, two severe cyclonic storms happened more or less back-to-back –Taukte on western coast, and Yass oneastern coast. Undoubtedly climate change is the perpetrator for the Extreme Weather climates (frequently occurring).

Not only in India, Germany experienced severe floods losing more than 100 people. Canada recorded its highest-ever temperature when hit by a deadly heatwave, which is said to have killed many. Last year, northern Australia

was devastated by forest fires.

SSPs (Shared Socio-economic Pathways) are being cast as significant parameters for the latest models in climate considered in IPCC (AR6). SSPs are to explore how greenhouse gas emissions be affected by societal choices and therefore, how the Paris Agreement climate goals be accomplished.

Global warming in 2100, ranging from 3.1^0C to 5.1^0C above pre-industrial levels, is considered as "business as usual" world in SSPs. It is already well accepted that "well below 2^0C" Paris targets will hardly be possible. As emissions will continueto rise, the relative efficiency of the natural cleaning system known as 'sinks' viz. the oceans, forests and soils will go down in the coming years. By now we would have already breached the 1.5°C warming, without these sinks. It is confirmed that we canno longer lose time in finding new explanations not to act, for keeping promises of net zero by 2050.

As technologies are available to disrupt the current fossil fuel-driven industrial system, reduction of greenhouse gas emissions in 2030 by 45-50% below the 2010 level and reaching net-zero by 2050 is a need of the hour in our world. Really hard drastic actions are needed. While China emits some 10 Gt/CO2 and the US 5 Gt/CO2, India is emitting some 2.6 Gt of CO2 annually and considered as the third highest annual polluter of CO2 in the world.

Even if business-as-usual scenario continue in India, India till now emits less than what US is emitting, and India's emission would be one-third of China at 2030. In spite of the awareness amongst various nations, continuous research and real time follow up by advanced countries through altimetry studies from dedicated satellites, recurring sporadic incidents of dangerous weather events, the upshot and consequences of change in climate will have many uncertainties to be accuratelypredicted.

The following are affirmed by the latest IPCC Assessment Report 6:

- The world might be racing towards a temperature rise of 1.5°C by 2040;
- Undoubtedly, human activities are the main trigger for climate change; and
- The efficiency of the sinks to absorb emissions is going down

For the calculated Rise in Sea Water Level of about 600 mm a map showing possible shoreline retreat considering the derived SLR during High Tide is drawn(Figure 4.15) with the help of GIS Mapping merging with DEM of Mumbai City. However, Tidal Rise, may vary after 30 years due to Gravitational Changes. Prima Facilely the extent of water logging for SLR only in High Tide is envisaged which will be a critical danger of inundation, the city is going to face.

4.8 Review of the result based on Contemporary ResearchReports and Tools

The result obtained through our analysis from MIKE 21 software has been compared with contemporary research reports and tools under A. (IPCC), B. (NASA) & C. (COFU).

A. IPCC AR6

IPCC AR6 Report on climate change published on August 09 2021, in-betweenthe period of this research study. The IPCC Sixth Assessment Report introducedShared Socio-economic Pathways (SSPs), new categories ranked by carbon dioxide [93]. As per IPCC, approximately about a dozen of India's coastal cities of India spread across the country having Ports are likely to face the wrath of going underwater because of increase in risk of rising levels at sea.

The parameters for the respective scenarios i.e., SSPs include perceptions describing alternative developments patterns for projected socio-economic changes up to 2100 in our globe, which is used to assess scenarios greenhouse gas emission with newer policies on climate as stated hereunder.

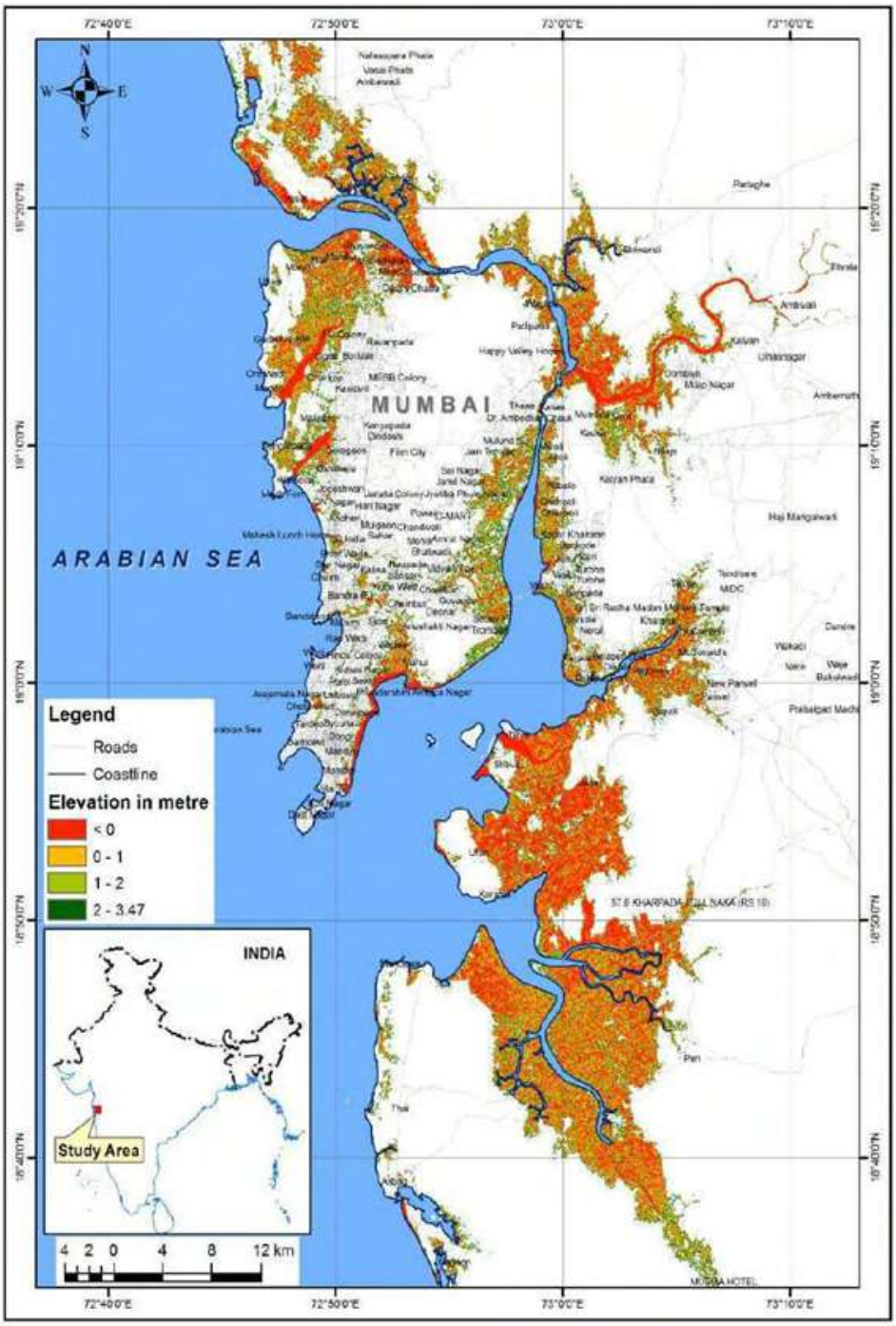


Figure 4.15: Probable intrusion of Sea Level inside Shore against Rise in Sea Levelof 600 mm at High Tide in 2050 due to Climate Change Only

(The Screenshots from Software Mike and Inundation Charts are in Appendix I.)

1. Sustainability: SSP1

Over all places developments will respect environmental limitations and progress in a prevalent manner, toward a maintainable path. Inequality in both across and within countries will be reduced by commitment to achieving development. Consumption would be moderated with lower material growth and lesser intensity on energy resources.

2. Middle Approach: SSP2

Technical trends grow in traditional manner and society would follow profitable path. Although there will be overall advancements, environmental condition will deteriorate and affect the intensity of resource and energy. Income inequality will continue or lethargically improve where need for lessening vulnerability to changes in climate will remain.

3. Regional Rivalry: SSP3

Increase in individualism, enhanced emphasis on safety, creating indigenous controversies, which will drive nations to decreasingly concentrate on indigenous subjects. Strong environmental declination in some regions due to low transnational precedence for addressing environmental enterprises.

4. Inequality: SSP4

Largely inadequate investments with growing difference in money making event and political power, leading towards more disparities both within and across countries. The energy sector differentiates worldwide with funding in carbon induced drives alongwith lower sources of carbon energy. Conservational programs will concentrate around high- and middle-income zones.

5. Fossil-fueled Growth: SSP5

The globe hinge on competitive market places, origination and participating cultures to yield a quick technical progress and expansion of anthropoid wealth as the route for maintainable progress. Factors leading to fast development in global finance when population rises and drops in the 21st century. Original problems in climate like pollution are positively controlled. Confidence in the capability to efficiently accomplish societal and environmental schemes, together with geo-engineering if necessary.

The SSP figure 'x' united to anticipated radiative forcing 'y. z' denoted by SSP 'x-y. z' in 2100 as stated in the Table 4.5.

SSP x-y.z	**Scenario *Likelihood***	**Estimated warming 2041-2060**
SSP1-1.9	CO_2 emissions cut to net zero around 2050	1.6 °C
SSP1-2.6	CO_2 emissions cut to net zero around 2075	1.7 °C
SSP2-4.5	CO_2 emissions continue until 2050 and then declinebut notattaining net zero by 2100	2.0 °C
SSP3-7.0	CO_2 emissions double by 2100	2.1 °C
SSP5-8.5	CO_2 emissions triple by 2075	2.4 °C

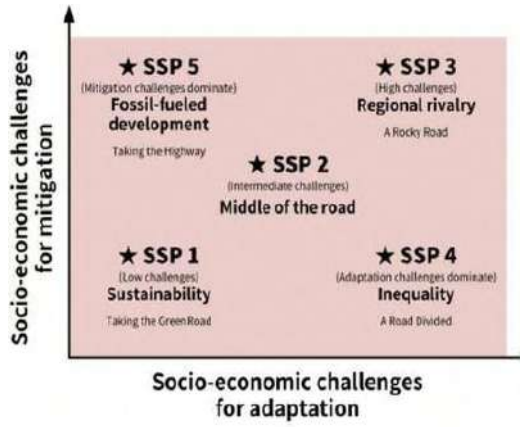
Table 4.5: SSP x-y. z

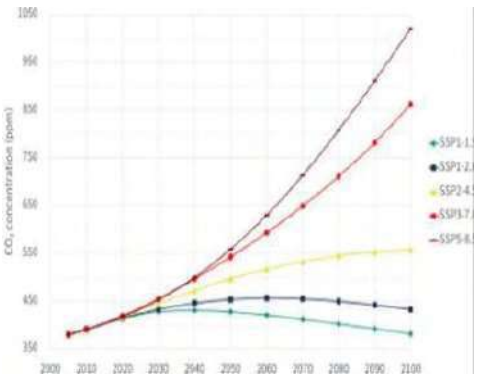
The predictable scenarios of socio-economic changes up to 2100 global, termed as **SSPs ('Shared Socio-economic Pathways')** are utilized to predict emission scenarios as per the changes in Policy. The CO2 concentrations in different SSPs across the century [93] are presented in Figure 4.16.

B. NASA's sea level projection tool

IPCC's report on Changes in Climate, 2021 is based on data from satellites and ground instruments and simulations computer.

NASA's Team on Changes in Sea Level has used same projections to build a prediction tool for sea level which visualizes future Rise in Sea Level, which will benefit planning of infrastructure at coastal regions according to Rise in Sea Level.





SSPs mapped to mitigate/adapt	CO_2 concentrations across 21st century by SSP

Source: Shared Socio-economic Pathways [Wikipedia]

Figure 4.16: CO_2 concentrations in different SSPs across the century [93]

NASA's sea level projection tod can exhibit sea levels in future under several scenarios both greenhouse-gas-emission and socio-economic Thescenarios include a business-as-usua scenario' aongwith an "acceleratedemission scenario' and low- emission scenario' in future'

Regional mean sea level will also rise to adversely- NASA's sea levelprediction tool predicts similar threat for Mumbai with risk of being submerged by 2050.

The initial projections based on the current trends [101] revealed that the following cities will be submerged under a water depth as shown hereunder.

City	Submergence (ft)	City	Submergence (ft)
Chennai	1.87 ft	**Mumbai**	**1.90 feet**
Tuticorin		Okha	1.96 ft
Visakhapatnam	1.77 ft	Kandla	1.87 ft
Cochin	2.32 ft	Bhavnagar	2.70 ft
Mangalore	1.87 ft	Paradip	1.93 ft
		Khidirpur	0.49 ft

Figure 4.17 shows a screenshot from NASA's sea level projection tool.

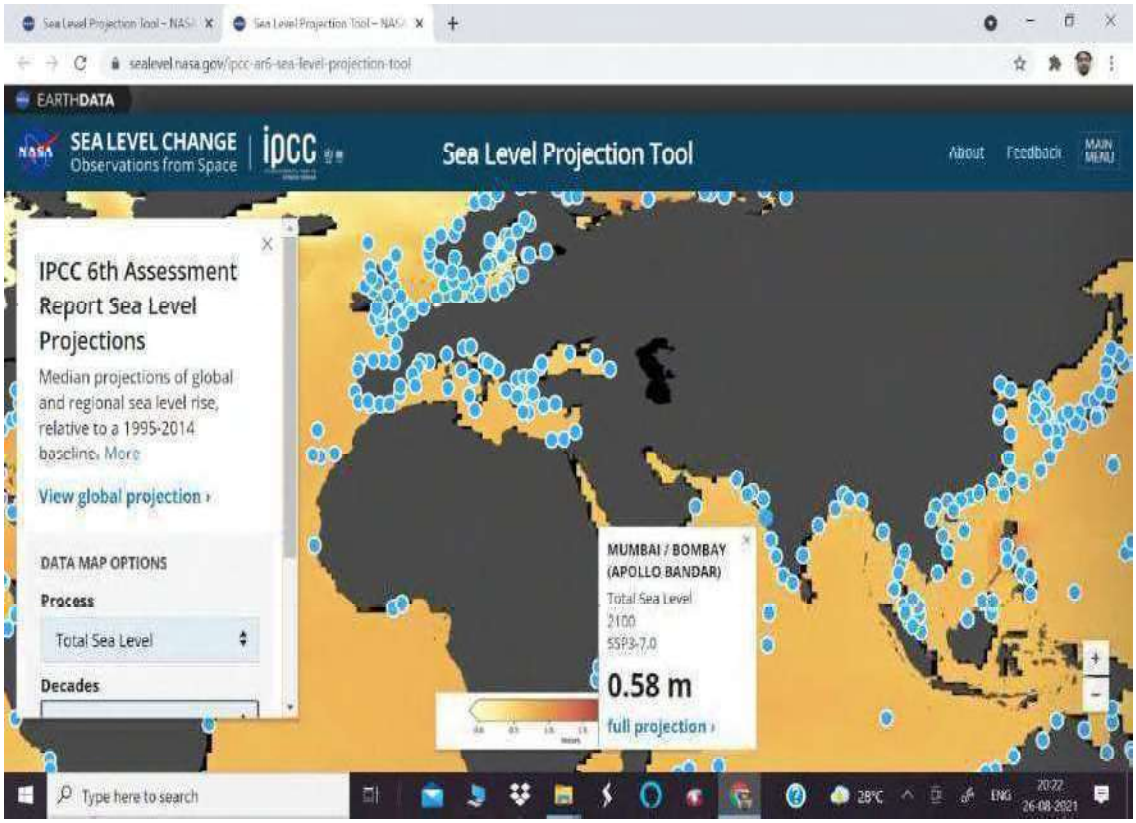


Fig 4.17: Projection from NASA Sea Level Tool

C. Coastal Futures (CoFu), IHE- Delft

Professor Roshanka Ranasinghe from Netherlands created Coastal Futures (CoFu) viewer, released on 11 October, 2021. Figure 4.18 shows a screenshot from CoFu sea level projection tool. This CoFu tool also is versatile in many aspects. The tool provides the status of the following considering the SSP scenarios 1-1.9, 1-2.6, 2- 4.5, & 3-7.0.

i. Changes in Regional Sea Level

ii. Extreme Level of Sea

iii. Coastal Flooding

iv. Shoreline Change

v. Extreme Waves

Comparing the results based on SRAlB, SRA2 &SRBl scenarios in IPCC AR4 and AR5 with the speculations in A, B & C above, it is seen that the predicted temperature rises (SRA2:1.05^0 C) till 2050 remains within a similar range (SSPl. 1.9: 1.6^0 c to SSP2• 4.5: 2° c) in AR6 with minor differences.

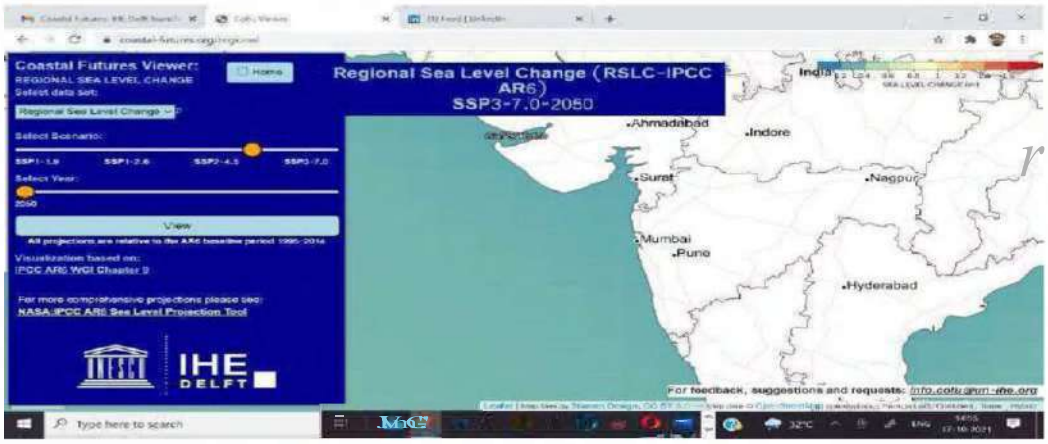


Fig 4.18: Projection from CoFu Tool (IHE Delft)

The Rise in Sea Level result obtained through MIKE 21 (0.595m) *[Para* 4.2.2.3] can be compared with the predictions (@ Mumbai) displayed in (i) NASA tool (1.90 ft or 0.579 m i.e., 0.58 m) [Fig 4.17] and (ii) CoFu tool

(Regional Rise in Sea Level 0.40 m) for SSP2 · 4.5 (2^0 c in 20 50) [Fig 4.18] to

assess its efficacy.

4.9 UNCERTAINTIES:

Because of ongoing melting of ice in glaciers in polar region huge quantity of additional melt water is also likely to largely contribute to further Rise in Sea Level. Despite huge development in related technologies, particularly in Altimetry measurements through satellites and Remote Sensing, the exact Rise in Sea Level till now remains too difficult to be determined correctly.

According to sources from INCOIS, Hyderabad, potential vulnerability at Mumbai coast falls under Very high-risk zones (Surge height > 5m), from the point of view of storm surge.

The obtained result 0.600 M closely matches with NASA's Climate Change Projection Tool result at Mumbai for 2050 i.e., 1.90 ft. Hence, it can be concluded that the severity of Sea Level is very crucial and the results obtained in the analysis is reasonable.

Nevertheless, there is a huge magnitude of indistinctness regarding the possible harm in the mass of the ice blocks which will affect amount of resultant risein Sea Level in future (Abedin et al.) [33]. In reality uncertainties in Rise in Sea Level remains as predictions from various studies are dissimilar (Garner et al.) [47]. An insight into the cumulative assessment of uncertainties in SLR has been assessed by Chakraborty et al. [94].

A very complex interplay of the physical climate related parameters from coastalareas, causes the rise in sea level, increase in storm surge, erosion and flooding. One way to measure the effect of Rise in Sea Water Level at the shore in any coastal cityis CVI (Coastal Vulnerability Index) at the place.

Vulnerability is calculated by considering various parameters by different

scientific group, some of which have been mentioned in Chapter IIA group of semi- quantifiable parameters consisting five geological variables viz. (i) shoreline change,
(ii) altitude, (iii) slope, (iv) geomorphology and (v) coastal bathymetry; three physical variables viz. (i) rise in sea water level, (ii) heights of wave and (iii) tidal variations alongwith four socio-economic variables viz. densities of (i) population, (ii) tourist density (iii) fisher folk and (iv) LULC proposed for Mumbai by Pramanik et al. [95], is well acknowledged.

The low-lying topography at Mumbai region is highly susceptible to inundation and erosion at coast due to Rise in Sea Water Level. Demolition of mangroves, filling waterways with debris, huge conversion of land due to massive construction activities, too much urbanization and inadequate drainage has made the region further vulnerable to inundation. The impacts of anthropogenic factors are extremely important to be quantified. Whatever may be the value of SLR predicted till mid-century at Mumbai, the fact remains that the city is already flooded every monsoon. The largestflood so far recorded was on July 26, 2005 an unanticipated 944 mm of rainfall in 24 hours poured alongwith a simultaneous high tide of 4.48 m [96].

The flooding type at Mumbai is different from river (fluvial) floods. Flooding happens from pluvial factors as city is having inadequate drainage facility. In Mumbai, during local rainfall the required lead time is not available like floods in the rivers, whichflows to a downstream area. in case of drainage congestion. Accumulated surface waters throughout the storm get drained out during 10 to 12 hours of low tide at (-) 2.0 below the MSL. At the drainage outfalls of the city there unfortunately is tidal inflow regularly. The level of a big stretch of the coast at Mumbai is near to 3.00 m and many lowland areas in suburbs of this Island city are only about 2.25 m & upto 3 m higher from MSL. Being tidal locking period high in this very old city, smooth drainage facilityis absent nor there is any scope to develop ponding facility [97].

On the other hand, whatever unsavory it might be Rise in Sea Level and also waves and storm are practically unavoidable in future. So, city is expected to suffer and our concern is to reduce the suffering to the extent possible, for which further research by a dedicated task force is necessary.

An impressive Inundation Map due to Rise in Sea Level because of Impact of worldwide Warming is presented in Figure 4.19, which will provide an idea of the areas,which may be inundated in 2050.

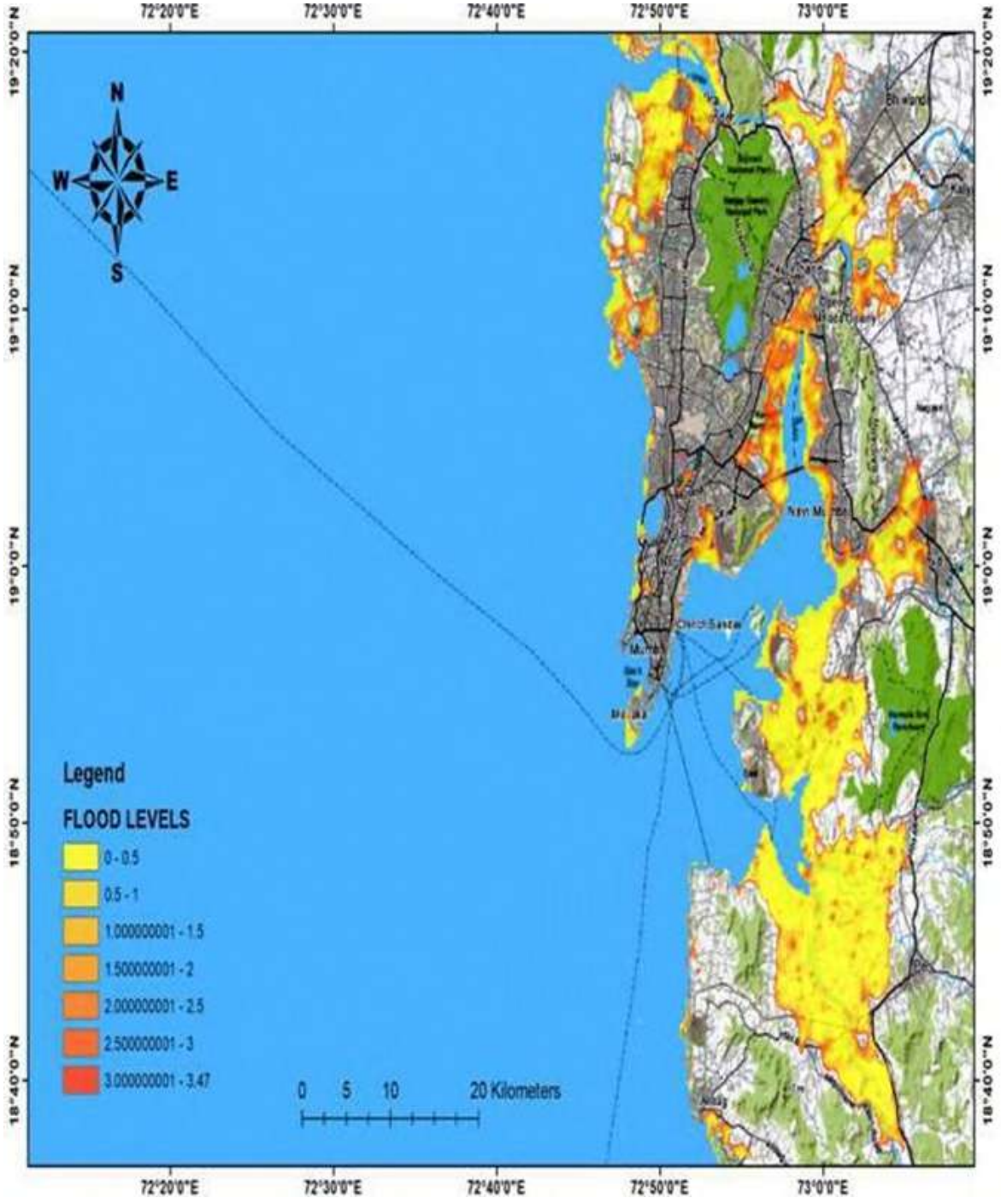


Figure 4.19: Impressive Inundation MAP Due to Climate Change Only (2050)