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# **Sea Level Rise and Coastal flooding in Urban Area: The Case of Chittagong City Corporation**

S. M. Gubair Bin Arafat

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**BRAC Institute of Governance and Development (BIGD)**

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By

S. M. Gubair Bin Arafat

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## Acronyms

AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
CCity	Chittagong City
DEM	Digital Elevation Model
FAR	First Assessment Report
GIA	Glacial Isostatic Adjustment
GIS	Geographic Information System
GSLC	Global Sea Level Change
IPCC	Intergovernmental Panel on Climate Change
MICRODEM	Microcomputer Digital Elevation Models
MSL	Mean sea level
RSLC	Regional Sea Level Change
SAR	Second Assessment Report
SLC	Sea Level Change
SLR	Sea Level Rise
TAR	Third Assessment Report
TGICA	Task Group on Data and Scenario Support for Impacts and Climate Analysis
UNEP	United Nation Environmental Protection

## Executive Summary

Sea level rise differs among coasts across the globe due to inherent differences in physical settings and human activities. Projection on relative changes in the sea level is important to understand the possible impacts on the coastal areas. It is particularly necessary in the case of urban centres which are located at close proximities to the shore for the assessment of the vulnerability of life, livelihood and infrastructure to the sea level rise. The scope of this study includes making projections on the probable extent of relative sea-level rise in the coastline of Chittagong coast and its bearing on industries in Chittagong which is the second largest city and the commercial capital of Bangladesh. In doing so, this study followed a multistage approach. In the first stage, a relative sea level change was projected for the next 85 years as per the guideline document provided in Nicholls et al. (2011). In the second stage, the inundation map was developed for Chittagong City Corporation by using Digital Elevation Model data on MICRODEM software platform. In the last stage, land cover change was estimated based on the inundation map. The results show that Chittagong city is going to experience a 0.99m relative sea level rise by the year 2100. The analysis considered three scenarios for the projection - the minimum rise of 1 m, the maximum of 3 m and a 12 m rise (including the occasional 9 m storm surges) in order to inform decision makers the extent of impact under various scenarios.

# 1. Introduction

## 1.1 Background

Climate change is now an evidence backed fact (IPCC, 2007). Sea level rise is one of the impacts of climate change. Sea level is the base level for measuring elevation and depth on earth (Cazenave and Llovel, 2010; Milne, 2009). Prolonged observation is required to precisely measure the sea level and its changes. Mean sea level (MSL), which is generally used as a proxy to the actual sea level, is defined as the average of the sea level by accounting for daily oscillations of rise and fall of tides (Emanuel, et al., 2004) and is based on the records of long-time seasonal cycles (Pugh, 2004). Sea-level is generally used as synonymous to MSL.

Sea level rise (SLR) has become a global concern as it threatens to inundate the low-lying areas, and increases the frequency of flooding, exacerbating the coastal erosion, acceleration of wetland loss, and intrusion of saltwater into estuaries and freshwater aquifers (Cazenave and Llovel, 2010). The consequences will be disastrous for Bangladesh due her to large population size and land scarcity - about 50% of the country's land lies below 8m elevation (Broadus, 1994). SLR will seriously effect human settlements especially in densely populated cities and residential areas which are located on low lying coasts (Paskoff, 2009). In urban areas, the potential impact of SLR includes intense flooding and submergence, enhanced intrusion of saline waters, drainage congestion problems, etc (Paskoff, 2009). However, appropriate planning and action towards adaptation and mitigation based on the considerations of possible impact may minimize the adverse effects of SLR on urban areas. Anticipatory measures could minimize the impending problems and lower the costs of mitigation measures.

Our understanding of the global sea-level changes has evolved with increasing scientific interventions and endeavours. In the first IPCC reports (AR1, 1993) the projection of GSLC was estimated 0.6 m for the year 2100 which has been revised in subsequent Second (1995) and Third (TAR, 2001), and fourth assessment report (AR4, 2010). The recent fifth assessment report (AR5, 2014) predicts a rise in global sea level between 0.28 and 0.98 meters. However, while uncertainties remain large in prediction, Meehl et al., (2007) argued that IPCC underestimated the SLR rate by not considering ice sheet melting factors. Rahmstorf (2007) estimated the SLC rate and found a higher range (between 0.06 and 1.8 m for the year 2100). In the following year, Pfeffer (2008) reported a higher rate of Greenland and Antarctica ice sheet melting and estimated the range as 0.07 to 2 m for the year 2100. His calculations considered the uncertainty, sensitivity and risks associated with ice melting, which is termed as H++.

Though there is an agreement on the rate of global sea level change, but the extent of the impact of SLR and the mechanism of their unfolding are debated issues. Sea level will not change uniformly across the globe. It will vary across regions depending on the natural and human induced aspects which contribute towards relative sea level (RSL) changes. The sea level as observed from any particular shore is called the relative sea level of that shore (Church et al., 2010; Drange et al. 2012). RSL is important for planning and designing long-life infrastructures, especially in the coastal urban areas (Richter et al., 2012) where populations and infrastructure are susceptible to RSL and coastal flooding. It is also important to understand as to what extent changes in the RSL may affect urban centers.



Chittagong, the second largest city of Bangladesh, has an extent of about 100 sq. km on the coast of the Bay of Bengal. Being a port city, it has become the commercial capital of the country with a population of about half a million (Majumder, 2007). The city has many important infrastructures including an airport, divisional administrative headquarter, naval academy, railway zone headquarter, many industries and business doorway for export and import goods. It is located in the hilly regions that branches off from the Himalayas - the city has unique undulating low-height hilly topography with small hillocks scattered all over the town (Banglapedia, 2005). The city's land is locked by the Bay of Bengal on the west, the Karnafuli River on the south and hills on the northern and north-southern proximities.

Impact assessment is the necessary first step in any effort to reduce the vulnerability of coastal urban centers. An inundation map based on the possible changes in RSL is essential in this pursuit. This map helps identify the resources and infrastructures of the urban areas susceptible to RSL change. Anticipatory measures can be planned to minimize the expected impacts which lower the costs of putting into place the adaptation and mitigation measures.

## **1.2 Literature review and scope of the study**

The literature review was limited to the studies conducted on sea-level changes at national and local levels. Among the important national studies, UNEP (1989) estimated a 1.5 meter rise in the sea level by 2100. Department of Environment, Government of Bangladesh (1993) estimated 0.3 – 0.5m rise in the sea level by 2005 (Shwal et al., 2013). The Storm surge modular, Flather and Khandker (1993), considered a 2m rise in sea-level by 2100. World Bank (2000) estimated 1 meter rise by 2100. Based upon a dozen Global Climate Models, National Adaptation Programme for Action (NAPA, 2005) projected a 0.88m rise in sea level. However, these estimations are not recent and most of them are based on the Third Assessment Report (TAR) of the IPCC published in 2001.

Despite the diversity in physical and local settings of the Bengal Delta, most of the existing studies on SLR are generalized for entire Bangladesh without clear indication on the dynamics of the RSL changes and how any changes in RSL will affect any particular urban centre (Brammer, 2014). A recent prediction, however, shows a 28cm rise on the eastern coast (Sundarban) of Bangladesh (Loucks et al., 2010) while, based on observational data, Morner (2010) argued that there was no sea-level change in the Bengal delta due to heavy erosion. These reports lack not only on the coverage of urban centres in the coastal area but also in the development of projection by considering the relative aspects of sea level change. On the contrary, this study aims to bridge the gaps by developing an inundation model for the most important coastal urban centre in Bangladesh – Chittagong. It looks at the changes in RSL and impact thereof on Chittagong city. The study will assist scientists, engineers and policy makers in planning adaptation and mitigation options against the RSL in the area.

## **1.3 Research question**

To what extent will the relative sea level change in the coast of Chittagong and how will it contribute to the land cover changes in Chittagong city?

## **1.4 Aim of the Study**

The aim of the study is to develop relative sea level rise scenarios for the next 85 years and to prepare an inundation map of Chittagong city to identify the extent of potential impacts on the city.

## 1.5 Objectives of the Study

- I. To develop scenarios of the relative sea level changes in Chittagong, Bangladesh for 2100.
- II. To develop an inundation model to identify lands under risk of coastal flooding.
- III. To identify the areas in Chittagong City Corporation where land use may change due to sea-level rise.

## 2. Methodology of the study

In line with the objectives, the methodology has been developed in three stages in order to identify the lands in Chittagong City Corporation which are susceptible to coastal inundation - (1) methodology for the constructing scenario of relative sea-level changes for the next 85 years, (2) methodology for the development of an inundation model to identify the areas in the city prone to flooding under scenarios developed in the first stage and (3) methodology for the development of a map of land cover changes in Chittagong city under inundation scenario with respect to RSL rise in Chittagong coast. In the first stage, relative sea-level change scenarios for Chittagong coastal area is constructed, and in the second stage, an inundation model is developed. In the third stage, land covers change is identified. The following Figure 2.1 explains the stages of the study in details.

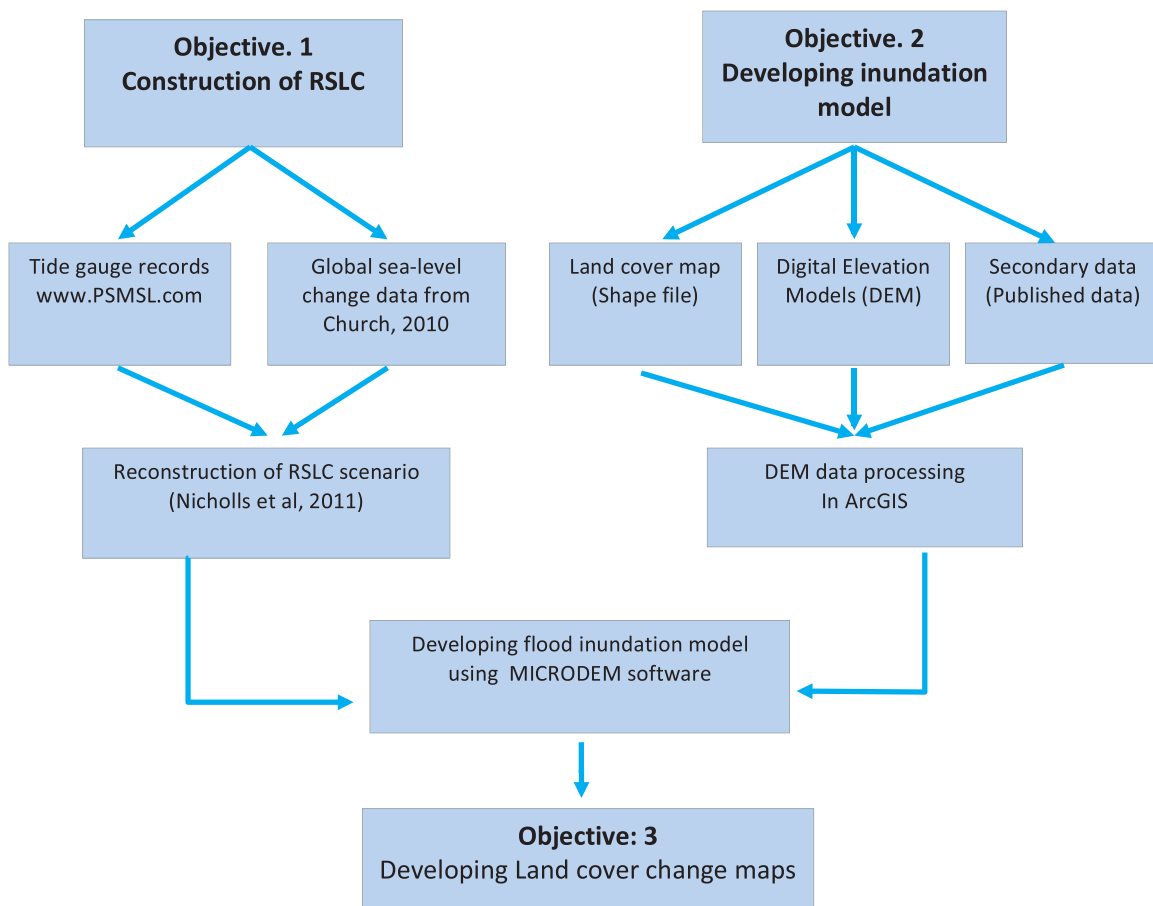


Figure 1.1: Flow chart of the Methodology

## Stage 1: Construction of RSL changes Scenario (Objective 1)

In order to attain the first objective of the study, we adopted the guideline documents (Table 2.1) published by Nicholls et al, in 2011. The guideline document demonstrates the step-by-step processes of constructing RSL changes by downscaling from the estimation of future global sea-level changes. Sequentially, we accounted for influential local factors such as thermal expansion, gravitational effect, and natural and human induced land uplift and subsidence. The guideline provides options for constructing RSL changes at three levels - detailed, intermediate and minimum. Inadequacy of data for detailed RSL change assessment was not possible. Hence, we carried out an intermediate level assessment for Chittagong city in this study.

Sea level component		Level of assessment		
		Detailed	Intermediate	Minimum
Socio-economic scenario		Downscaled SRES scenario <sup>1</sup> or other relevant local scenario	Global SRES (or baseline <sup>2</sup> )	
Global sea-level change (including ice melt)	SL <sub>G</sub>		IPCC AR5 (and H++ for impact studies)	
Regional sea-level change	SL <sub>RM</sub>	Meteo-oceanographic driven deviations from individual models in AR% for appropriate scenario	Scaled up local deviations from A1B diagram in AR4 (Figure 10.32): use pattern scaling equation or software e.g. SimCLIM	Use ±50% (based on HULME <i>et al</i> 2002)
	SL <sub>RG</sub>	Correction for gravity effects	Scale predictions according to MITROVICA et al. (2001, Figure)	Assume globally uniform eustatic sea-level rise.
Natural vertical land movement	LM <sub>N</sub>	Detailed local observations e.g. GPS, long time series local tide gauge or relevant geological data <sup>3</sup>	Regional patterns of land motions inferred from geological data/ GIA model estimates	Assume no change
Human induced vertical land movement	VLM <sub>H</sub>	Analysis of subsidence potential and relevant human actions <sup>4</sup>	Assume arbitrary changes based on geological setting	Assume no change
Changes in storm surge		Detailed local modeling using Regional models or statistical downscaling driven by climate models	Run sensitivity study with no change in storminess component, then range of increase over 50/100 year period <sup>5</sup>	Assume no change

Table 1.1: Guideline to construct relative sea level change scenarios (After Nicholls et al, 2011)

The sea level components which will contribute in the future sea-level change, including changes in the carbon emission rate and rate of temperature rise, thermal expansion of ocean surface and influx of additional water from Greenland, Antarctica and mountain caps are adjusted with the RSL of Chittagong City corporation. The components were estimated by downscaling from global to regional scale. Based on the above actors, relative sea-level change was estimated by using the following SL Equation:

$$\text{DRSL} = \text{DSL}_G + \text{DSL}_{RM} + \text{DSL}_{RG} + \text{DSL}_{VLM}$$

Where,

$\Delta\text{RSL}$  is the change in relative sea level

$\Delta\text{SL}_G$  is the change in global mean sea level

$\Delta\text{SL}_{RM}$  is the regional variation in sea level from the global mean due to metero-oceanographic factors

$\Delta\text{SL}_{RG}$  is the regional variation in sea level due to changes in the earth's gravitational field

$\Delta\text{SL}_{VLM}$  is the change in sea level due to vertical land movement

### **Step 1: Construction of scenarios for future SLR**

According to the guideline by Nicholls et al (2011) projections of the changes in sea level can be constructed for the next 100- year period. We downscale it for the next 85 years i.e., for the year 2100. The sum of global and regional components gave RSL.

### **Step 2: Global sea level change**

Global-mean sea level change (SLG) is expected to be primarily due to (1) thermal expansion of the ocean as it warms, (2) the melting of small glaciers and ice caps due to human-induced global warming, and (3) changes in the mass balance of the Greenland and Antarctic ice sheets (IPCC, 2007). The estimated projection for SLG ranged from 18 to 59cm for 2100 (IPCC, 2007). However, the guideline suggested considering the H++ scenario which accepts 2m as a maximum limit of global SLR for the next century.

### **Step 3: Regional Changes**

#### **a) Thermal expansion (Meteo-oceanographical effects) ( $\text{SL}_{RM}$ )**

The regional pattern of thermal expansion was approximated by using a pattern-scaling method developed by integrated assessment modelling system called SimCLIM, which produces scaled scenarios for regional sea-level rise (Nicholls et al, 2011). The model is developed by MEEHL et al., (2007). See details in annex 2.1.

#### **b) Gravitational effects ( $\text{SL}_{RG}$ )**

Glacier melting in Antarctica or any other places will change the global eustatic – the changes of global sea levels due to changes in either the volume of water in the world oceans or net changes in the volume of the ocean basins. The distribution of net contribution will be irregular and will vary depending on the distance from the source of melting. In order to adjust with gravitational effect in RSLC, we used the model developed by Mitrovica et al., 2001. See details in Annex 2.2.

### **c) Natural Vertical Land movements (SL<sub>VLM</sub>)**

Estimation of the vertical movement of land is important to measure local effects on RSL changes. Vertical movement of land is a natural process that varies across countries and regions due to Glacial Isostatic Adjustment (GIA), which is an elasticity driven continuous rebound of land. The effect of elasticity of land has been modelled by Peltier (2011) in order to measure the natural vertical land movement based throughout on an ice model (ICE-5G v1.3). The earth model was VM2 with a 90 km lithosphere. It shows GIA reading for different tide gauge points. The GIA effect for Bangladesh is measured on Charchanga tide gauge point. Glacial Isostatic adjustment data was collected from ([www.psml.org/train\\_and\\_info](http://www.psml.org/train_and_info), 2011). See details in Annex 2.3.

### **d) Human Induced Land Movements (VLM<sub>H</sub>)**

Human-induced subsidence is another local effect on changes in RSL which needs to be estimated in sea-level impact studies. Subsidence happens due to heavy groundwater withdrawal, land erosion and depositions. Tide gauge data is used to measure the rate of subsidence and extrapolated for the next 85 years. Tide gauge data for Bangladesh was collected from the Permanent Service for Sea-level Change ([www.psml.com](http://www.psml.com)). See Details in Annex 2.4.

### **e) Changes in storm surges**

Tropical cyclones are usually destructive and they affect Bangladesh and its adjoining areas. The wind associated with cyclones cause abrupt surges of water waves which we call storm surges. As the global climate is changing, extreme events such as storm surges will hit the shorelines more frequently with higher severity (IPCC, 2007). As storms come and go in the coastal zone, large storm surges eventually phase with sufficiently large tides to produce new record water levels. Considering the frequency an additional sea-level rise has to be added (Lowe et al, 2001). See Details in Annex 2.5.

### **f) Storm surge elevation**

Storm surges strike the coast with the raised sea-level. In order to adjust for SLR, an additional sea-level rise to be added to the historical maximum height of storm surges (Lowe et al, 2001). For Chittagong city, historical evidence on surge height has taken in to consideration as if the future storm surge with raised sea level could be projected. See details in Annex 2.6.

### **Stage 2: Developing inundation model (objective - 2):**

High-resolution satellite images are essential to develop an inundation model. There are also several steps involved.

#### **Step 1: Selection of satellite image**

In this study, Digital Elevation Model (DEM) with 15 meter cell size was used. We digitised selected branch mark points from topographic map of Bangladesh to use as primary data set. Accuracy of the DEM was verified at 10 selected points on ground. See details in Annex 2.8.

#### **Step 2: Selection of software for modelling inundation**

In this study, we used Microcomputer Digital Elevation Models (MICRODEM), which is a computer based inundation model that considers 2, 4 and 8 directional cell connectivity. It is a Geographical Information System (GIS) that processes digital elevation data. This software was developed by Professor Peter Guth at the Department of Geography at US Military Academy in 1986.

### **Stage 3: Developing of inundation map (objective 3):**

Impact of RSL changes on coastal inundation in Chittagong City was estimated by using a land-use map that showed five broad land use types - settlement, water bodies, forest, road and railway and open space. Important features which are economically valuable such as industrial export processing zone, sea port, airport and business centres are grouped into the settlement category. All build up areas were labelled as settlement, trees as forest, and any space without trees was categorised as open space. Saline water, fresh water, man-made and natural water bodies were simplified into the group 'Water bodies'.

### **2.1 Limitations of the Methodology**

Some limitations were inherent to each step of the methodology. However, the most noticeable limitation was in the methods used to construct the SLR. There is no unique global mean, and local tide gauge data are unevenly distributed with significant variation in the relative sea-level change records. The inundation model lacks incorporation of the local and regional effects of sea-level changes. Models are characterised by a fixed representation based on land elevation and are unable to represent the effects on future shorelines arising from sediment accumulation, land subsidence, erosion or other dynamic processes. They usually capture an average with the local adjustments. The models are also unable to incorporate future development or adaptations such as seawalls or beach nourishment projects. Furthermore, due to the "concave up" profile of the coastal zone, inadequate benchmarks and insufficient vertical resolution, elevation grids may also overestimate land elevations and therefore underestimate the susceptibility of coastal areas to sea level rise (Titus and Richman 2000, cited in Cooper et al., 2008). Moreover, land-use maps are not a true representation of the existing land cover of Chittagong City Corporation. A generalised grouping yields incomprehensive understanding of the impact of SLR changes.

### 3. Results and Discussion

#### 3.1 Relative sea level change

RSLC at Chittagong coast has been estimated as minimum 0.73 -1.58 meters. Moreover, under the H++ scenario which considers the unpredictable rate of ice melting, the rate of RSLC may be as high as 2.73 – 3.58 m. The details are in the following Table 3.1.

Sea level components		Estimation in meter	IPCC, AR5, 2014 (Meter)	Considering the uncertainties ties of ice melting An H++ Scenarios added (Nicholls et al 2011)
Global sea level change (SL <sub>G</sub> )		-	0.28 - 0.98	2.28 - 2.98
Relative sea level change	a. Thermal expansion (SL <sub>RM</sub> )	0.05	0.33 – 1.03	2.33 – 3.03
	b. Gravity effect (SL <sub>RG</sub> )	80-100% increase	0.26 – 1.03	2.26 – 3.03
	c. Vertical land movement (SL <sub>VLM</sub> )	0.05	0.31 – 1.08	2.31 – 3.08
	c.i. Human action (VLM <sub>H</sub> )	0.36	0.67 - 1.44	2.67 - 3.44
	d. Change in storm surges (10%)		0.73 – 1.58	2.73 – 3.58
Relative Sea level Change (Total)		-	0.73 – 1.58	2.73 – 3.58
e. Strom Surge		9 m	9.73 – 10.58	11.73 – 12.58

**Table 1.2: Construction of relative sea level change using two ranges**

## 3.2 Key results from other studies

Due to the unavailability of literature on RSL changes in the context of Chittagong city, it was not possible to compare our results with others. However, the work so far undertaken by several national and international organisations have been reviewed in this context (Table 3.2) in order to attain the local level estimate from global scenarios. Unlike global sea-level change, our estimation shows that Chittagong city would experience a much higher sea level rise. The minimum range of relative change has been estimated at 0.73m, which is higher than any other global estimation.

Organisation	Source	Year	Global Sea Level (Meter)	Regional Sea Level (Meter)	Relative sea level change (Meter)
UNEP	1989	2030	1.5		
IPCC	AR1, 1990	2100	0.66	-	
IPCC	AR2, 1995	2100	0.95	-	
IPCC	TAR, 2001	2100	0.9 and 0.88	-	
IPCC	AR4, 2007	2090	0.18 and 0.59	-	
IPCC	AR5, 2014	2100	0.53–0.98 (RCP 8.5)	0.50	
			0.28–0.61 (RCP2.6)		
<b>Arafat, 2015</b>		<b>2100</b>	-		<b>0.73 – 1.58</b>

Table 1.3: Result of different studies

### 3.2.1 Land cover change

More than 50% of the land in this city lies below 9 m elevation and 30% are below at about 4 m (Figure 3.1). Given the estimation of RSL changes, an inundation map was developed. As the estimation was in range value and the capacity of the software was limited, we created maps with three levels of inundations viz., 1m, 3m and 12 m. According to the inundation map, Chittagong city is not susceptible to coastal flooding by 1 m rise in the sea level which may cause permanent inundation of a total of 2.5 km<sup>2</sup> land. But a 3m rise in sea level will submerge approximately 10.26 km<sup>2</sup> of land, which is 6% of the city's land.



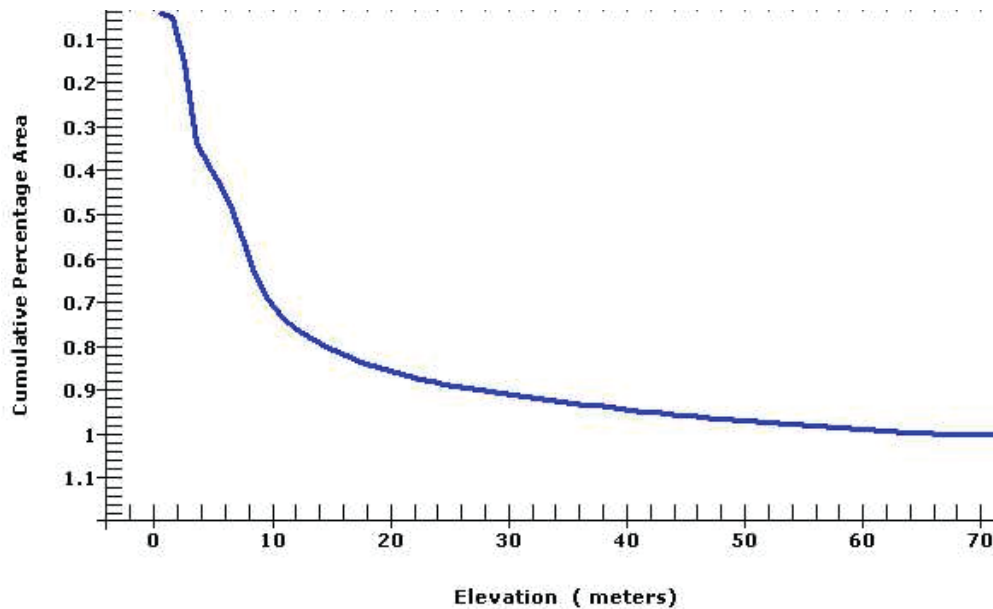


Figure 1.2: Distribution of land in the study area (%) into different elevation groups

Chittagong City Corporation is largely dominated by settlements and open space (Figure 3.2). The additional water from the Bay of Bengal would grasp lands permanently and episodically depending on the scenarios. Whatever scenarios we do apply, land cover types will not be equally affected. Among the land cover types, forest, road and railway will be minimally affected by the sea-level changes. In contrast, settlement and water bodies will be largely affected by the episodic flooding (Figure 3.2).

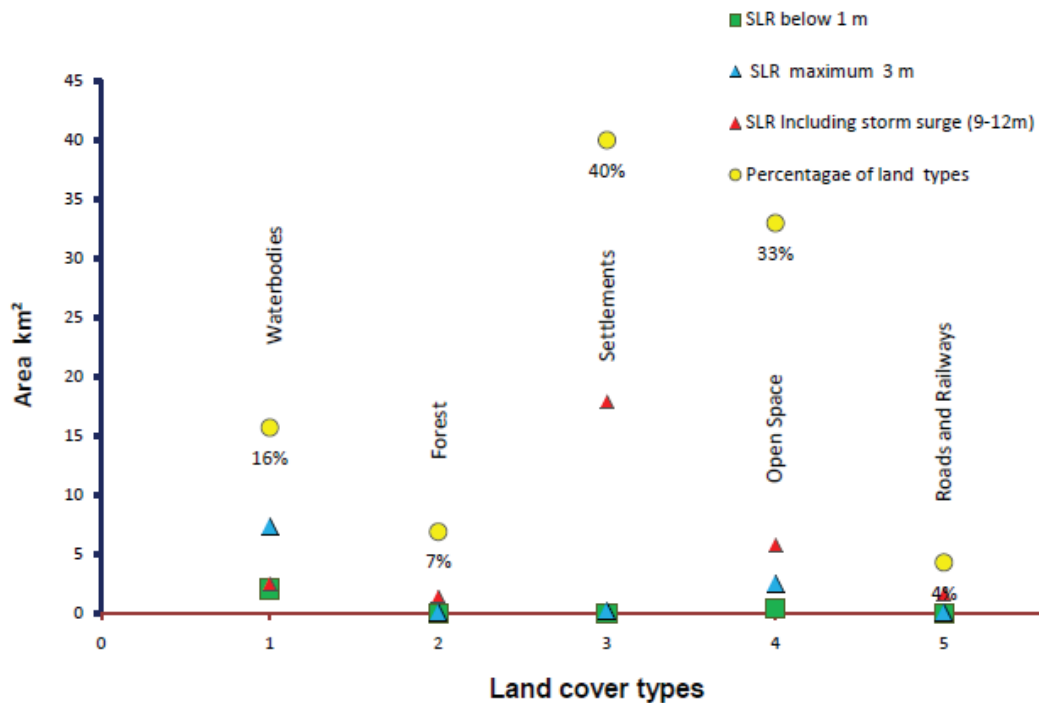
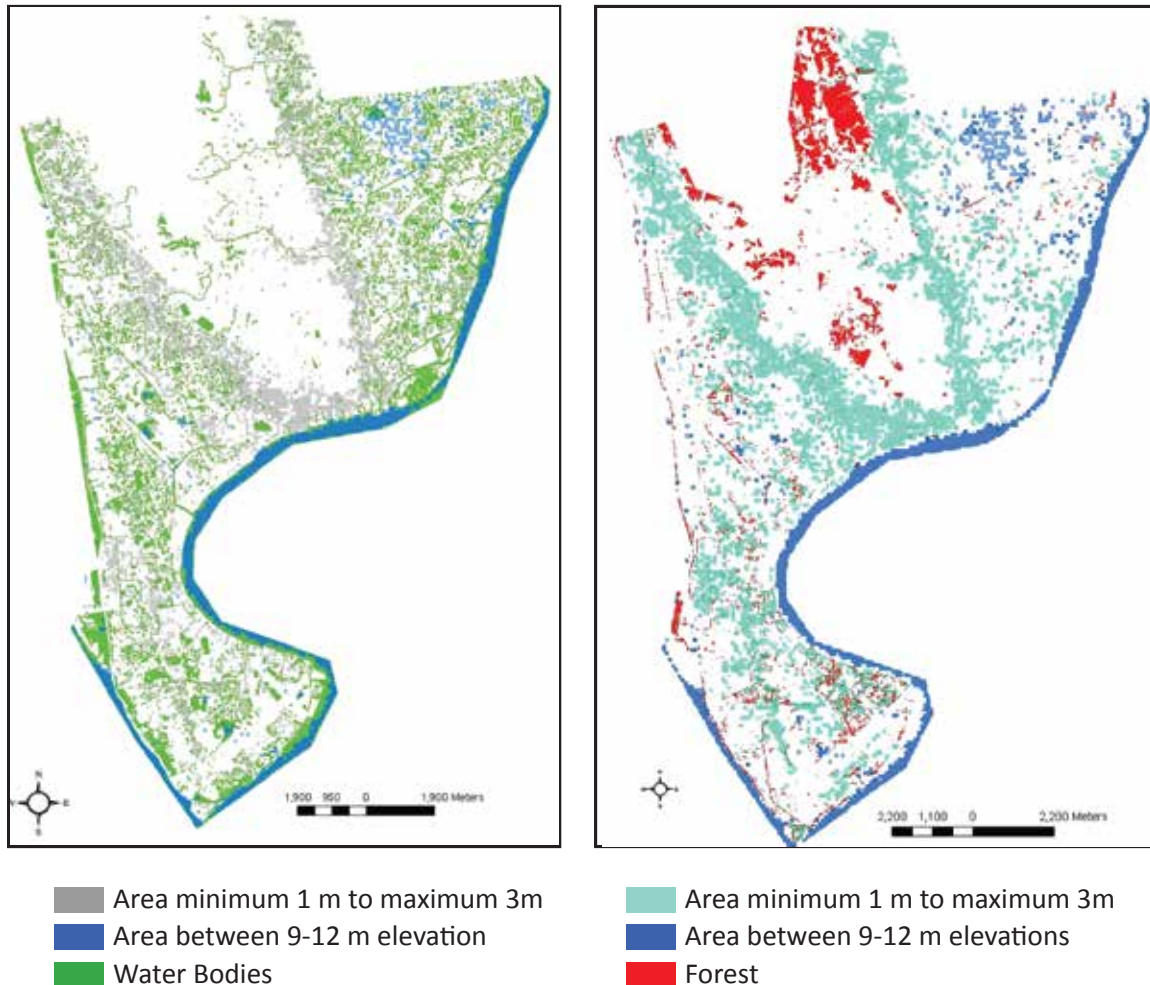


Figure: 1.3: The estimation of potential land cover change based on the various scenarios constructed. The graph also shows the percentage of land types occupied by different types of land.

### 3.2.2 Water bodies and forest cover

Natural and manmade water bodies are dispersedly distributed in Chittagong city. Approximately 4500 man-made water bodies are recorded by Chittagong Development Authority (Daily Star 2011). Most of the water bodies will remain unaffected by 1 m rise in SLR, but more than 9 km<sup>2</sup> area will go under water for a 3 m rise in sea level. An additional 2.5 km<sup>2</sup> area will be flooded seasonally by saline water if we consider a 9 m storm surge (Figure 3.3).

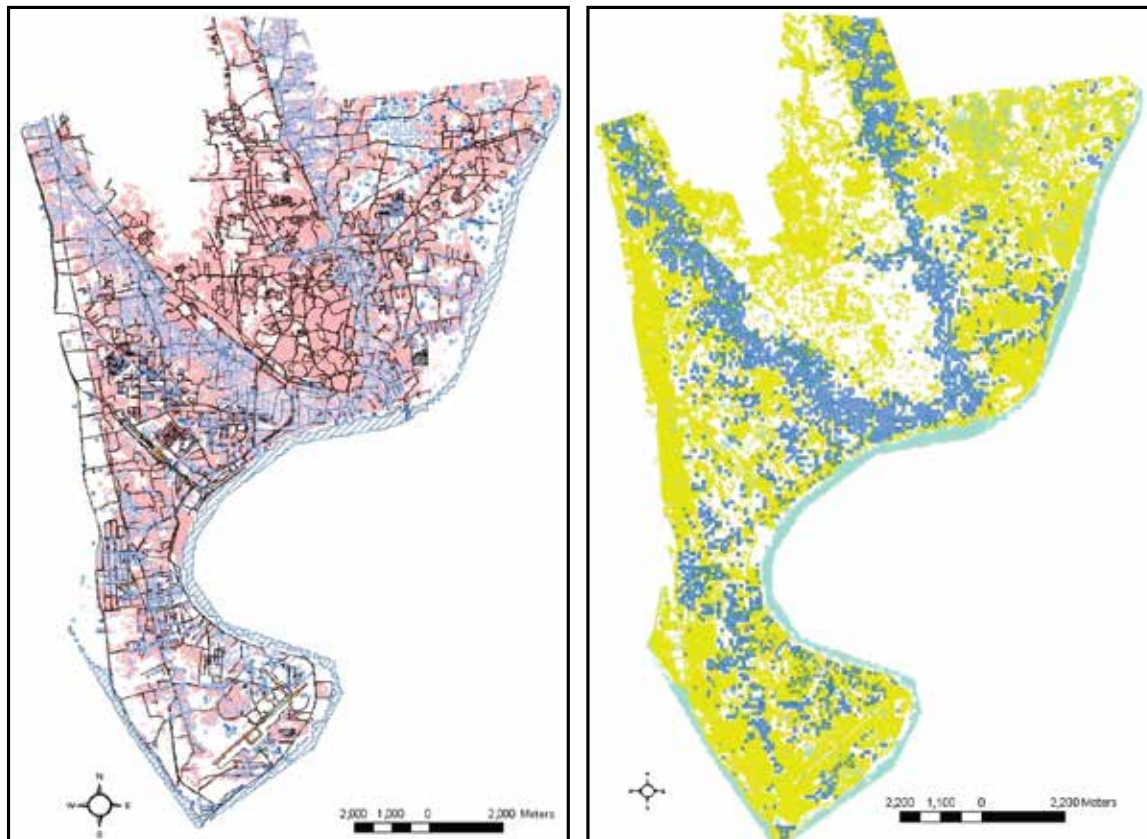







**Figure 1.4: Chittagong city's land area susceptible to direct inundation under 1 m to 3m rise in the sea level and storm surges of 12 m height. The right panel shows forest cover and the left panel shows water bodies which are susceptible to storm surge.**

Forest cover, in contrast, will not change even a square mile by 3 m rise in sea level. Only less than 1.5 km<sup>2</sup> areas under forest cover may be affected by storm surges. Forest land will be less affected because most of the forests occupy the upper hill of the city corporation (black circle) especially Leubagan, Batali Hill, Baizid bostami and the Foy's lake areas.

### 3.2.3 Settlement, rail and roadways

Settlement and road networks in Chittagong City Corporation are not susceptible to the minimum sea level rise of 1m. Only 0.2 km<sup>2</sup> of settlement areas may be transformed to water bodies. Under the 3 m RSL rise scenario - the settlement areas and road networks will not have any mentionable impact. In fact settlements, roads and railways are above 3 m of existing sea level. An episodic flood with 12 m storm surge may have dramatic impact on settlement areas. It may submerge about 18 km<sup>2</sup> of settlement area with saline water. Road networks, on the other hand, are not susceptible to 1 m rise in sea level, but some roads will be inundated if we consider the 3 m scenario (Figure 3.4). The highest storm surge including the maximum sea level rise may drown 1.6 km<sup>2</sup> of roads. The railway is not susceptible to permanent and episodic flooding. Open space, however will have negligible impact by minimum rise in sea-level (Figure 3.4). About 2.5 km<sup>2</sup> will be permanently inundated under the 3 m RSL rise scenario. A further 5.8 km<sup>2</sup> of open space would face episodic inundation by storm surges.



- |   |  |
|---|--|
|  .Area minimum 1 m to maximum 3m |  Area minimum 1 m to maximum 3m |
|  .Area between 9-12 m elevation  |  Area between 9-12 m elevations |
|  Road/Railway                    |  Open Space                     |
|  Settlement                      |  |

#### 4. Conclusion and Recommendation

This study constructed scenarios of relative sea-level change for 2100. We found the highest possible RSL rise is 0.99 m under normal conditions which may be as high as 2.99 meter if we consider the H++ scenario. The estimation has been in agreement with other national studies though it slightly differed from the global estimation. An inundation map was developed based on the scenarios constructed which helped to identify the lands under different land uses susceptible to permanent or episodic inundation under RSL rise. The city has many valuable infrastructures and densely populated settlements. Different land uses will suffer differently under different RSL rise scenarios. In all, the water bodies are the most susceptible land cover type followed by settlements. Our study, with its limitations, can still undoubtedly be a guiding document for the decision and policy makers. The results of this type of studies lack precision but they are crucial in availing a sense as to what extent the city is vulnerable in the face of 1 m to 3 m RSL rise and 12 m storm surge.

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## Annex

**Annex 2.1: Thermal expansion ( $SL_{RM}$ ) (Meteo-oceanographical effects):** Application of the pattern-scaling method to sea level, developed by SimCLIM, which produces scaled scenarios for regional sea-level rises (Nicholls et al, 2011). According to the diagram for thermostatic and ocean dynamic changes, Chittagong will have 0.05 m of additional sea level rise from this mechanism (figure 1). We estimated the entire range of sea-level rises which is 0.2 m and 2 m, based on both IPCC and Nicholls guideline. Thus the estimation stood at  $(0.28+0.05$  to  $0.98+0.05) = 0.33$  m to 1.03 m by the year 2100.

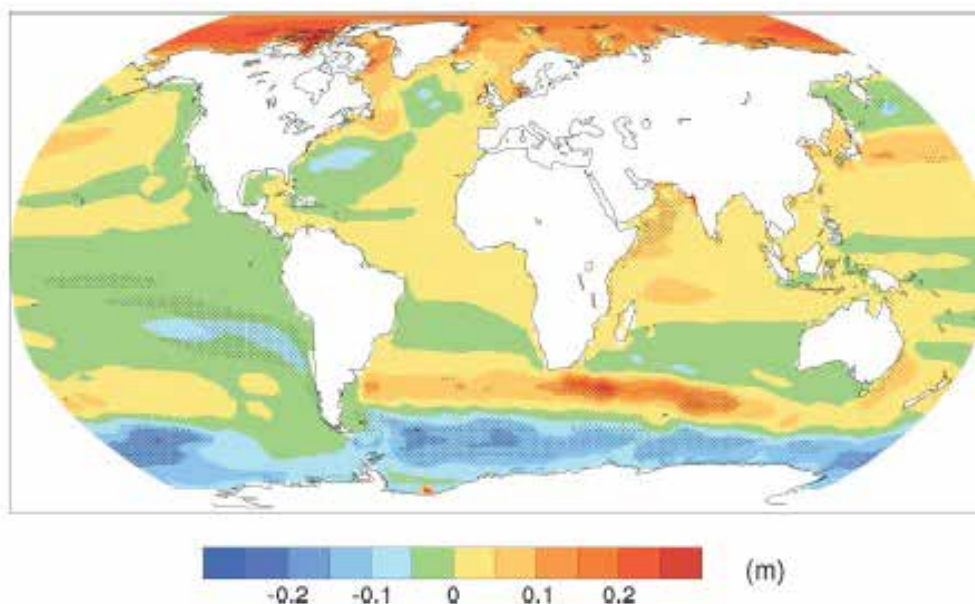


Figure 1: Variations in local sea-level changes (m) from the global average (i.e., positive values indicate greater local sea level change than global) during the 21st century with the SRES A1B scenario. Variation is due to ocean density and circulation and is calculated as the difference between averages for 2080 to 2099. (Source: After MEEHL et al., 2007).

**Annex 2.2: Gravitational effects ( $SL_{RG}$ ):** Glacier melting in Antarctica or in mountain ranges will not only pour water to the sea but also change the global eustatic in an irregularly distributed manner. For example, if Antarctica loses its ice then the sea level will increase and the mass balance between the places will be change (Figure 2). Considering the gravity field, Mitrovica et al, 2001 developed a model which shows the sea-level changes in relation to the water melting from Greenland ice sheet, Antarctic ice sheet, small glaciers, water storage on land etc. It is a tough to estimate the gravitational effect because the gravity correction depends on where the melted water is coming from; Antarctica, Greenland or mountain ice caps. For Chittagong coastal area, we considered 80 to 100 percent of gravitational effects. Thus the calculation stood at  $(0.33*0.8 - 1.03*1)$  0.26 to 1.03 meter.



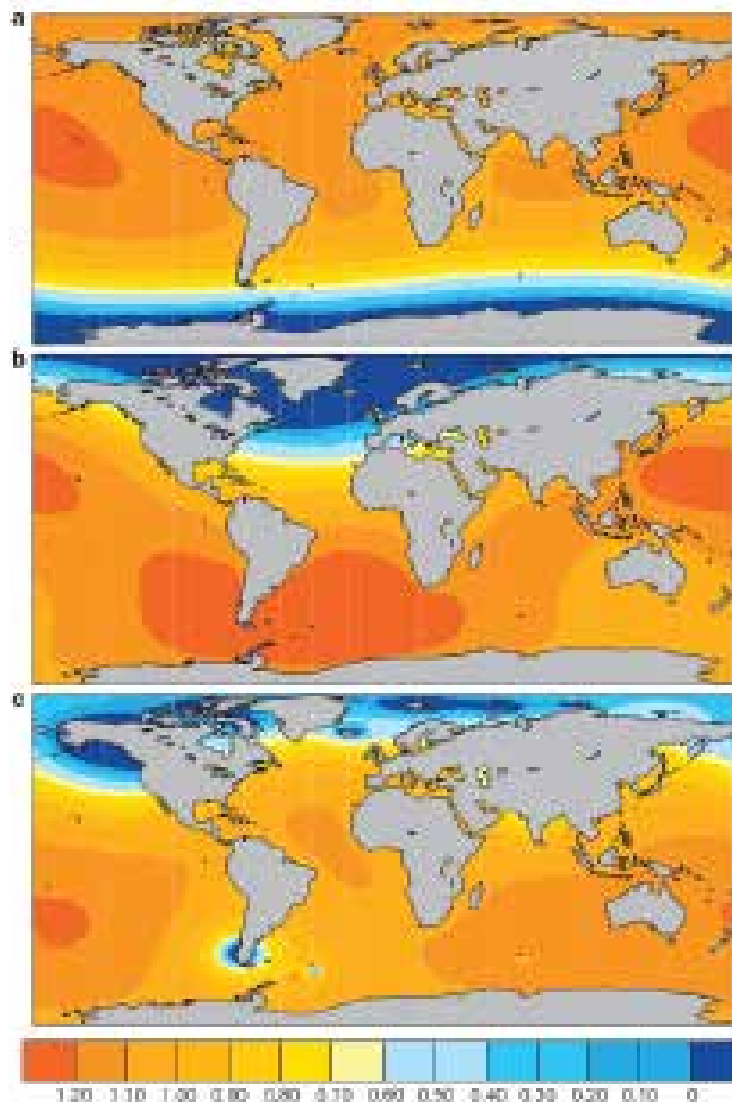


Figure 2: Gravitoanl effects from different melt scenarios, expressed as fraction of total eustatic sea-level rise a) Antrartica b) Greenland, c) Small mountain glaciers and ice caps (Source: MITROVICA et al., 2001).

**Annex 2.3: Natural Vertical Land movement ( $L_{VLM}$ ):** Following the GIA model (Peltier , 2011), the record shows a  $-0.62$  mm fall per year in Charchanga tide gauge point. Thus, the number for sea level rise for the year 2100 will stand at  $85 * (-0.62)$  mm =  $-55$ mm =  $-0.05$ m. the range stood at  $0.31$  m to  $1.08$  m for the year 2100.

**Annex 2.4: Human Induced Land Movements ( $LM_H$ ):** Changes in RSL can be understood from the tide gauge records by comparing them with the global mean. Global mean sea-level rise is estimated as  $1.8 \pm 0.05$  m (Church, 2010). For Chittagong city, Charchanga tide gauge point in Table 1 shows a  $4.22$  mm faster rise in regional sea-level than that of global mean. Charchanga is among three tide gauge points, and was selected for this study as it has records for a longer time period.

It is assumed that this trend will continue and will add an additional relative sea level rise of  $(4.22 \times 85 = 0.36 \text{ m})$  by the next century. According to this estimation the minimum sea level rise will stand at  $(0.31 + 0.36 = 0.67 \text{ m})$  and maximum to  $(1.08 + 0.36) = 1.44 \text{ m}$ .

Tide Gauge point	Time Period	Trend PSMSL	Trends SMRC	GIA Value
Char change (Eastern)	1978-2005	6.01 mm/y	6.0 mm/y	-0.62 mm/y
Coxs bazaar (Central)	1978-2000	1.45	7.8	-0.57
Hiron point (Western)	1983-2003	3.54	4.0	-0.56

(Source: Permanent Service for Mean Sea Level - [www.psmsl.org](http://www.psmsl.org))  
 SMRC :(SAARC Meteorological Research Centre ([www.SMRC.com](http://www.SMRC.com)))

**Table 1.4: Showing tide gauge points with different trends.**

To construct the current sea level change, tide gauge data at Charchanga (1978- 2005) tide gauge point was used from Permanent service for mean sea-level change ([www.psml.com](http://www.psml.com)). Three tide gauge stations from three geographical locations are presented in Table.2. Charchanga tidal point estimation seems in good agreement with the secondary data cited in Alam, 2003. The station is also the nearest one to the study area - the Chittagong coast. The other two tide gauges varied significantly in terms of datum and trend. However, all the tidal stations had less than 25 years of records which were less than the 36 years of the lunar cycle. There was another problem with the trends in that they were not smooth but rather unstable.

**Annex 2.5: Changes in storm surges:** According to MEEHL et al. (2007 an increase in storm surge height needs to be included wherever possible ), for coastal cities and ports. Data used for the global assessment of exposure to climate change for port cities in the 2070s suggested that sea-level change due to storm surge may increase by 10% in appropriate locations. In this study, for Chittagong city, a 10% increment was considered. Accordingly, the future changes in storm surge ranged between  $(0.67+0.06 = 0.73 \text{ m})$  to  $(1.44+ 0.14= 1.58 \text{ m})$ .

**Annex 2.6: Storm surge elevation:** In Bangladesh western coast, the maximum height of storm surge is recorded as (Banglapedia, 2011). In Chittagong, the highest elevation of storm surge was recorded 7m (Brammer, 2004) and 9 m high (Flather et al, 1997). The additional height of sea-level by the 2100 will increase the storm surges. Thus, including extreme storm surge events the estimation stood at  $(0.73+9.00) = 9.73$  to  $(1.58+9.00) = 10.58 \text{ m}$  for this study. As far as Chittagong city's adaptation and planning concern, the entire range of 0.73 to 1.58 meter, including storm surges 9.73m to 10.58 meter, has been constructed and accepted.

**Annex 2.7: Uncertainty with data source and estimating land cover change:** There are two major sources of uncertainties in this study. The estimation of relative sea level changes includes both primary and secondary data which were collected from various sources. In the development of RSL change tide gauge data (Figure 3) which we used in the estimation was not mature. Charchanga tide gauge point is only 25 years old and a sudden jump in the tide gauge record shows the evidence of an El Nina in southern Pacific Ocean which occurred in 1997-98 (www.noaa.com). In addition, various models that were used in modelling thermal expansion in oceans and for understanding potential ice melting that contributes to the RSL changes possess inherent uncertainties.

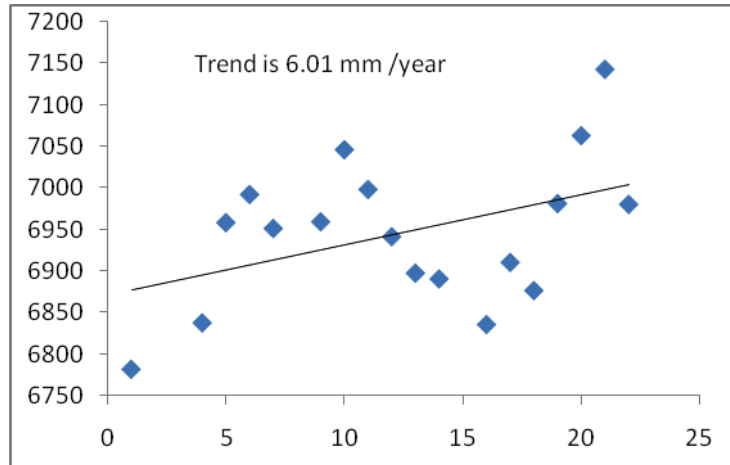


Figure 3: The variations in tide gauge records at Charchanga point between 1979 to 2000. Source: (www.psml.com, 10/07/2011)

**Annex 2.8: Selecting software for inundation modelling:** We used MICRODEM that includes scientific applications and incorporates significant new functional capabilities, runs on higher resolution monitors and allows all Digital Elevation Models (DEM) to consider the topography and slope. The underlying algorithm of the method takes a Z value and divides it by a horizontal distance.

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