ASIA-PACIFIC NETWORK FOR
GLOBAL CHANGE RESEARCH

Project Reference Number: ARCP2013-08CMY-DeCosta

A Study on Loss of Land Surface and Changes to Water Resources, resulting from Sea Level Rise and Climate Change

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A Study on Loss of Land Surface and Changes to Water Resources, resulting from Sea Level Rise and Climate Change

Final Report Submitted to APN

Part One: Overview of Project Work and Outcomes

Non Technical Summary

Since seawater level rise due to climate change has the potential to significantly impact on coastal zones through changes and loos of adjacent land and changes to water resources this research focused on this area in order to develop management strategies to mitigate adverse effects of such change.

Hence, initially GCM analyses in conjunction with historical data were used to derive possible sea level rise and then in conjunction with digital elevation maps and GIS information changes to land surface / loss of land has been investigated. Further changes to water resources such as changes to ground water table, salinity intrusion to aquifers, impact on low lying areas etc., have been investigated. Thereby management strategies to cope with the impact of these changes have been developed.

The study also investigated and developed a model to forecast the impact of sea level rise in situations and locations when the required data or the detail of the required data is unavailable. In addition to the detail modelling and the resultant findings the study developed a simplified / composite model to forecast loss of land surface and changes to water resources in coastal zones that could be easily globally adoptable. And thereby lists of management strategies to manage such changes globally have been proposed.

Keywords: Climate change, loss of land, groundwater

Objectives

Seawater level variation in the Asia pacific region caused due to global / climate change to be analysed and in conjunction with digital elevation maps and GIS information loss of land surface in coastal zones to be predicted. The forecasted sea water level is also to be used to predict salinity intrusion and resulting changes to water tables. In addition, changes to water bodies in coastal zones are to be investigated. Thereafter a composite model is to be developed to forecast loss of land surface and changes to water bodies. This is then to be used to develop management strategies to manage such changes.

Amount Received and Number of Years Supported

The Grant awarded to this project was:
US$ 40,816 for Year 1:
US$ 31,150 for Year 2:

Activity Undertaken

- Literature review and data collection
  As stated in the proposal, as well as in the time line of the proposal we conducted an extensive literature review.

- Establishing links / inputs with policy makers –
  Initially preliminary meetings with all collaborators, some stakeholders and policy makers were held. Thereafter regionally meetings / seminars / workshops with local collaborators, stakeholders and policy makers were held.

  - Meeting with Indonesian collaborators and stake holders were held between the 5th and 7th of July 2013 in Yogyakarta Gadjah Mada University as well as in Jakarta. We had 18 participants at the seminar on day two. While on day one and three the focus was with the research collaborators. At these meetings assessment of sea level rise and associated problems in the coastal region of Semarang city including land subsidence was discussed. Tidal and flood management methods were discussed as well. We were able to identify and communicate the approximate rate of land subsidence and that sea level position in the Semarang tidal station follows a linear pattern in with specific parameters were found. The collaborators will now be working on forecasting the loss of land and changes to water resources and developing management strategies to better manage these changes.
  - The meetings with Japanese collaborators were held at Kyoto University, Japan, both at the DPRI centre as well as at its main campus, between 10th and 17th of July 2013. The number of participants was 12. The average sea level rise in different locations of the Asia Pacific was discussed and communicated. The methodology adopted was discussed as well.
  - Meetings with the Indian collaborators and stakeholders were held between 6th and 10th January 2014 at IIT Bombay. The number of participants was 8. The meetings resulted in discussing and communicating regional climate change down scaling techniques for climate change impact assessment.
  - Meetings with the Sri Lankan collaborators were held at the Open University of Sri Lanka as well as the University of Moratuwa. These resulted in the communication of assessing the risk of sea level rise and the importance of Geo Information in relation to Sri Lanka.
  - The joint workshop was held on the 20th of January at the Open University of Sri Lanka, there were 21 participants. This workshop occurred at the end of year one and was a Joint workshop. Collaborators from Japan, India, New Zealand and Sri Lanka participated. The Indonesian collaborator could not eventually come. In addition there were 21 participants from the Sri Lanka who were policy makers, scientist, engineers or researchers. Findings of the project were presented and climate change impacts, sea level rise, and its impact on water resources and land surface was discussed. In addition to the knowledge exchange, and development of a strategy for researching forward in terms of research thrust and methods, as a result of the workshop it was decided to formulate a climate

change impact forum in Sri Lanka where research, findings and updates could be regularly provided and discussed.

— Meetings with stake holders and collaborators were regularly held in Wellington and in Auckland, and the impact of sea level rise with respect to, land surface loss has been established. In addition the changes to water resources resulting from sea level rise and climate change for the Wellington area Waiwhetu aquifer has been analysed.

- A preliminary paper on, Techniques to exclude of seawater from low-lying areas in relation to sea level rise was presented at an International conference. (i.e. Proceedings of the 17th Congress of the IAHR APD)

- Another paper entitled "Assessing the risk of sea level rise and wave climate of Sri Lanka" was publication in proceedings at the 19th congress of the IAHR APD, 2014. And this was presented at the Congress in September 2014.

- Two other papers are in the Proceedings of the 35th Congress of the IAHR 2015 and they were presented. The papers are entitled, Changes to water resources resulting from sea level rise and climate change and loss of land resulting from sea level rise and climate change – Case of the Whaiwetu aquifer Wellington

- In January 2015 the Indian collaborators came together and held a seminar on the 9th of January. There were 17 participants. Impact of sea level rise of land and water resources as well as management strategies were presented and discussed.

- In April / May 2015, the Japanese collaborators came together in the week from April 23rd. The 1st regional workshop was held at Kyoto University on the 28th of April. There was a much discussion on the impacts of sea level rise on the environment and ground water as well as land and also the methods adopted. There were 15 participants.

Itemised activity list

1) Assessment and forecast of sea water level in key Asia Pacific sites –
2) Forecasting changes to water resources – (Ground water table, effect on low-lying areas)
3) Forecasting land surface loss in coastal zones due to seawater rise. -
4) Establishing a composite model to forecast changes in land & water resources due to seawater level change. Particularly when data is scarce.
5) Development of technical as well as human dimension management strategy
6) Increasing the profile and awareness of global change, its effect, mitigation and management
7) Establishing links & networks with policy makers & information disseminated to them
8) Conference papers as well research paper in recognized international journal.

While policy makers have been participating in collaborator countries at workshops for better information flow as well as disseminate the findings from the data analysed so far, in

Proponent country the findings of the analysed data have been published in the Mass Media as well.

The following web addresses detail articles that appeared,

- On the 1st page of the Dominion Post of Wellington (The leading Daily Newspaper in Wellington).
- http://www.stuff.co.nz/national/health/9964219/Rising-sea-threatens-citys-tap- water (It mentions project leader's name – Gregory De Costa)
- Advance a research magazine going out to most of the industries in New Zealand. http://www.unitec.ac.nz/toolbox_items/advance_apr_2014.pdf (Pages 14 – 17. Detail the ongoing research). APN has been mentioned as well in this article.

Results

a. Assessment and forecast of sea level rise
b. Sea level rise and its impact on water resources have been investigated. (Ground water table, salinity intrusion and effect on low-lying areas)
c. Sea level rise and its impact on land have been investigated.
d. In addition to the above simplified model is developed to forecast climate change / sea level rise impacts in situations where data is sparse.
e. Management strategies have been analysed.
f. International and local collaborative teams have been established.
g. Findings have been and are being presented at many forums.
h. Workshops have been conducted
i. Three papers have been published and presentation at an International Conferences and one is in publication in an International Journal.
j. Awareness of impact of global climate change has been raised.

Relevance to the APN Goals, Science Agenda and to Policy Processes

This research, by investigating the changes in sea level and its effect on land surface and ground water, and providing policy makers with tools, endeavours in addition to improving scientific understanding of global change and its implication in the region, establishes scientific basis for policy making which is a core strategy defined by 2SP 2010-2015. It includes all elements as defined by the goals in this plan. The potential for application of the developed methodology is global in nature, although the specific applications to be illustrated are limited to localized areas. Further, loss of surface area in coastal zones, gradual degradation of water quality and the resulting changes on the catchments agro - socio economic characteristics if unchecked would result in an extremely detrimental global change.

Science agenda - This research envisaged and accomplished to establish linkages between changes to climate (global change) changes to catchment characteristics and changes surface and ground water bodies in selected areas of the Asia Pacific. Global change & its effects have been highlighted in participating Asia Pacific countries, as well as management strategies & guidelines disseminated to policy makers. The project while it mainly relates to

Theme 3 of APN Science agenda as it deals with changes in Marine domains, it also directly relates to Theme-1, Climate change as it is about sea water level prediction due to climate change and more relates to Theme 2 Ecosystems and land use as well, as it is about loss of land surface and changes to the water environment.

Policy Agenda -This proposal envisaged and accomplished scientists and engineers from 5 countries to work together. Further the workshops not only provided scientific input for policy and decision making strengthening ties between scientist, policymakers and wider professional stake holder base regionally as well as globally. Policymaking should be influenced by scientific manifestations of the, environment, the people, the interaction between the people and the environment, and, the future impacts and effects on the people by the environment and vice versa. Dissemination of frontier scientific results, not only influenced policy makers in making new policy and taking relevant decisions, it also enlightens policy makers the importance and on the reliance and usage of scientific results. This gives rise to strengthening linkages between science and policy. Interaction and discussion also always improves linkage between the two sides. As the study developed management model so that policy and decision makers would be better equipped to make decisions, the relevance to policy makers are high as well.

Institutional Agenda -This project involves collaborators from 5 APN member countries. Further inputs from other member countries also have been sought increasing the participation of countries in the Asia Pacific Region. This research endeavoured to reduce the financial burden to APN by leveraging in kind resources such as office space, equipment, proponent and collaborator research time etc.

Potential for further work

It is evident that further research is required in the area of forecasting land loss as well as changes to water resources due to climate change impacts in situations where data is sparse, which is the case in most of the coastal areas round the world and particularly in the smaller islands of the Asia Pacific area.

Publications

1. Bamunawala, R. M., Hettiarachchi, S., Samarawickrema, G., & De Costa, G. S. (2014). Assessing the risk of sea level rise and the wave climate of Sri Lanka. In Proceedings of the 19th Congress of the IAHR APD. Hanoi, Viet Nam.
2. Tutulic, M. R., Shamseldin, A., & De Costa, G. S. (2015). Changes to water resources resulting from sea level rise and climate change. In E-proceedings of the 36th IAHR World Congress. The Hague, Netherlands.
3. Tutulic, M. R., Shamseldin, A., Liefting, R., & De Costa, G. S. (2015). Loss of land resulting from the sea level rise and climate change. In E-proceedings of the 36th IAHR World Congress. The Hague, Netherlands.

4. Li, J., De Costa, G. S., & Philips, D. (2016). Simplified method forecasting changes to groundwater table and land lost due to sea level rise. In Proceedings of the 20th Congress of the IAHR APD. Colombo, Sri Lanka.
5. De Costa, G. S., & Dassanayake, W. (2016). Estimation of impact of sea level rise on land and water resources when data is sparse - Case of Colombo. Environment and Ecology Research, 4(5), 244–250.

Acknowledgments

The authors express their heartfelt gratitude and appreciation to the Asia Pacific Network (APN) for funding this project over the last few years, for without it none of this would have been possible. The authors wish to express their gratitude to all the collaborating organizations for their kind support in many ways. In addition the authors thank the many other local organizations that supported this research by providing data and in many ways not detailed here in.

Preface

Seawater level variation in the Asia pacific region caused due to global / climate change has been analysed and thereby sea water levels at numerous locations have been predicted. The results of which have been then used in conjunction with digital elevation maps, GIS information to predict loss of land surface in coastal zones in the Asia Pacific Region. The forecasted sea water levels were used to predict salinity intrusion and resulting changes to surface and ground water bodies. Thereafter a composite model to forecast loss of land surface and changes to water resources in coastal zones where data is sparse has been developed. Thereby management strategies to manage such changes have been proposed.

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1. Introduction

Climate change could be said to be significant change in elements that converge to represent climate and lasting for a long period of time, it encompasses changes in temperature and rainfall. (Change, 2007). The Intergovernmental Panel on Climate Change (IPCC), the major international authority on climate change also defines climate as the average weather in terms of the mean and its variability over a certain time-span and a certain area (Kumar, C.P., 2012). They have concluded not only that the world is indeed getting warmer, but also that there is evidence that most of the warming observed over the last 50 years may be attributed to human activities (Gluckman, J. & Boyle, C., 2009).

The science of climate change is a controversial one with various theories and claims however this study while it investigates climate change, acknowledges this controversy and investigates impacts of such change if they were to occur and suggest mitigatory measures. This effect on the climate system from the concentration of greenhouse gases such as carbon dioxide and methane in the atmosphere has resulted in most of the observed increase in globally averaged temperatures since the mid-20th century (Change, 2007).

Average sea level is expected to rise due to thermal expansion of the oceans and melting of glaciers and ice-sheets resulting from the climate change phenomenon. There are currently over 1.2 billion coastal residents around the world i.e. people living within 100 km of the coast and less than 100 m above sea level, apparently the broad area that will be affected by global rising sea levels (Small and Nicholls, 2003). As the planet gets warmer due to climate change, sea levels will continue to rise due to oceanic thermal expansion, which is where warm water takes up more room than cold water. Melting glaciers also compound the problem by dumping even more fresh water into the oceans and rising seas tend to inundate low-lying areas and islands, loss of land in coastal areas, threatening dense coastal populations, eroding shorelines, changing ground water table and destroying ecosystems.

Sea level change and be modelled by GCM modelling and its impact on land loss and groundwater table can be analysed using sophisticated modelling software such as. ArcGIS, FEFLOW etc. The following chapters (i.e. Chapters 2, 3 and 4) detail such investigations. However, the specific conditions for the use of such cutting edge research increases the difficulty for its global application. Therefore in this research, chapter 5 details simplified composite model development with conceptual and a mathematical approach for ease of applicability particularly when data is sparse and resources are limited. Chapters 6 and 7 deal with down scaling of hydrological factors that are used to predict climate change and assessing uncertainty in climate change simulation. Chapter 8, 9 and 10 look at cases studies of climate change impacts in India, Indonesia and Sri Lanka. Chapter 11 details climate change impact on estuaries and Chapter 12 deals with climate change impact on small islands, the case of Vanuatu. Finally in Chapter 13 the work done here in and its findings have been summarised.

2. Sea Level Rise

As the sea level is naturally fluctuating it is important to find the mean sea level, which then could be said to be the average sea level of a given location. And then thereafter it is possible to analyse any variation to tis over the long term.

The following summary for this section on sea level rise (the next 4 pages) is largely based on and written from excerpts of the research publication in the Elsevier Journal of Ocean Engineering entitled Multi model climate projections of ocean surface variables under different climate scenarios Volume 71, pages 122- 129, 2013, authored by Nobihito Mori and Tomohiro Yasuda Tomoyo Shimura and Hajime Mase,, two of whom supported and collaborated with our research.

Past research indicate that between 1870 and 2004, the sea level rose at an average rate of 1.7 mm±0.3 mm/year, with a significant increase in the rate during the last 10 years (Church and White, 2006 and Church et al., 2011).

Past research indicate that, another factor affecting the sea level is barometer effects. Therefore, the mean future change in SLP (ΔSLP) has been computed in past work as shown in the next figure. ΔSLPΔSLP is small, with a magnitude of ±3hPa at the maximum. The ensemble mean ΔSLPΔSLP shows a clear latitudinal pattern in both the Northern and the Southern Hemisphere, and a pole ward shift in pressure distribution observed in the future climate. As a result, the mean SLP is expected to decrease at higher latitudes and a related SLP increase is expected immediately below this change. If the barometer effect is taken as 1 h Pa = 1 cm, the future change in SLP due to the barometer effect is 3 cm at the maximum. This effect is included in the previous analysis of SLR.

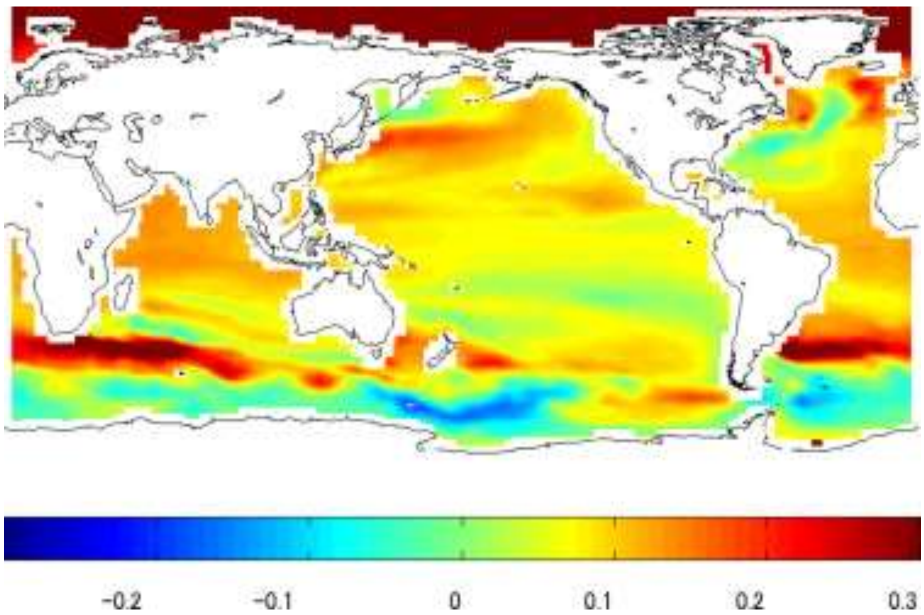

Figure 1 Projected SLR at year 2100 (SRES A1B; unit:meter)

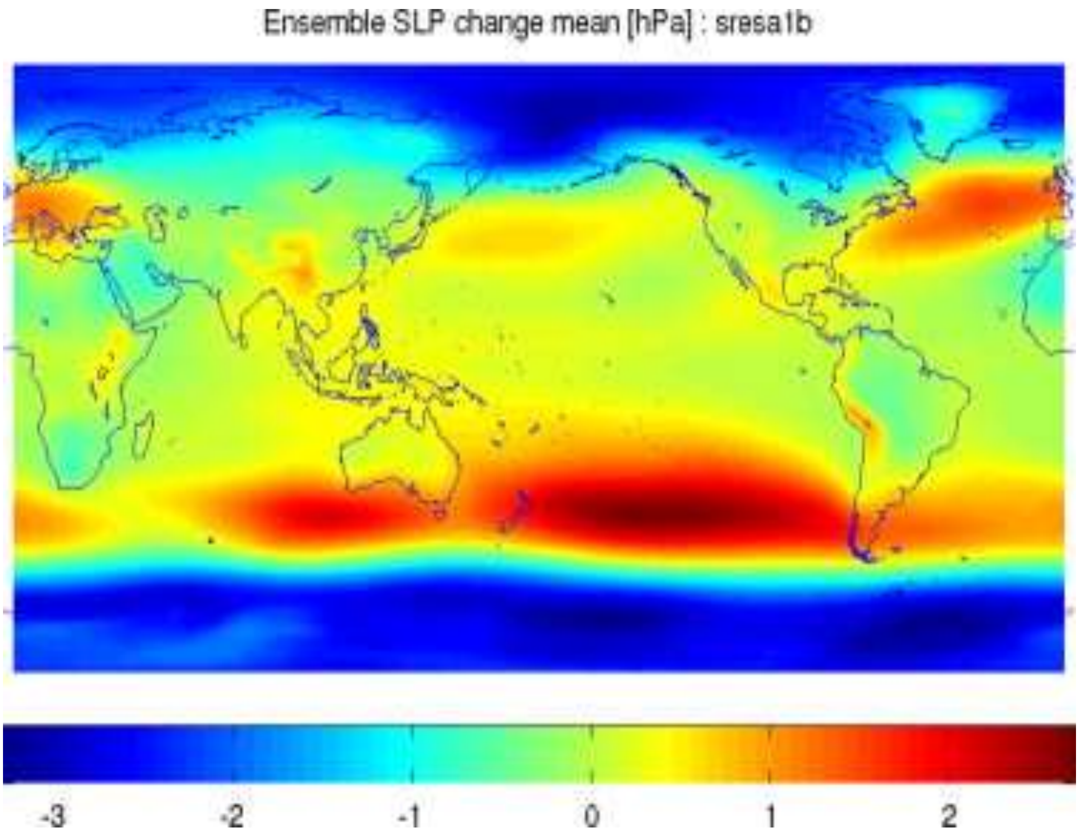

Figure 2 Future changes in SLP for the period between 2000 and 2100

Following figures from past research shows the time history of the spatial average of SLR for the period between years 2000 and 2100 both on a global scale and for the East Asia region. The ensemble mean has been applied for global scale and the East Asia region (10°N–40°N, 120°E–150°E). The regional projection computed spatial averaging of corresponding grid points. The thin, thick solid and thick dashed lines in the figure indicate individual GCM results, ensemble mean and ensemble mean ±± standard deviation, respectively. The 36-month moving averaging procedure was applied in the analysis, and 1–3 years of inter-annual oscillations are excluded from the projection

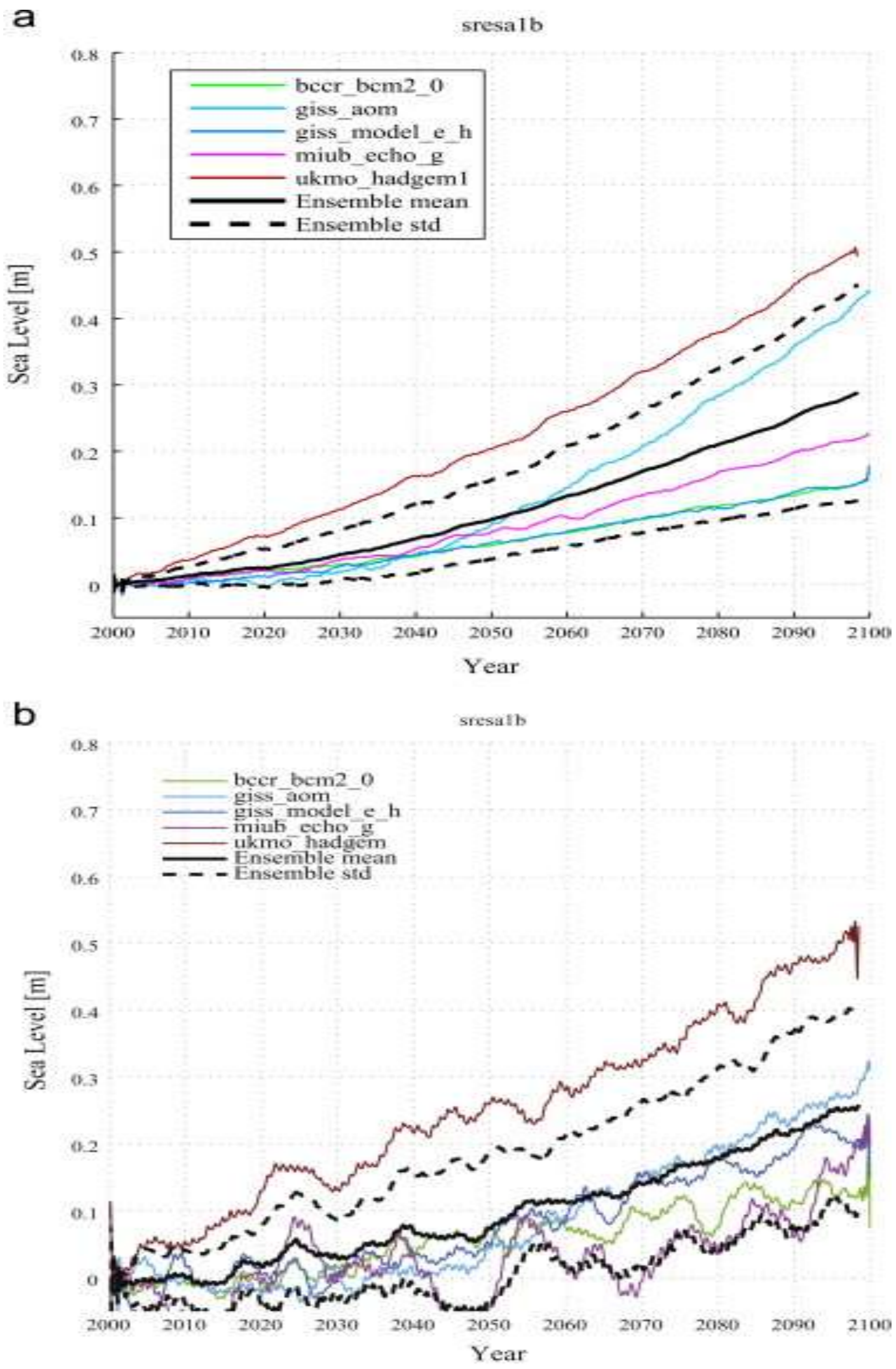

Figure 3 Annual changes in SLR for the period between 2000 and 2100: SRES A1B (thin lines: individual GCMs, thick solid line: ensemble mean, thick dashed line: standard deviation). (a) Global and (b) East Asia.

The analysis from these past research yields a future change in SLR of 0.27 m on a global scale and slightly lower in East Asia. Although there is no substantial difference between the global scale result and that for East Asia, the standard deviation for the East Asia region is much larger than that of the global scale results. Uncertainty in model projection becomes notable at the regional scale and should be considered carefully in impact assessment.

This study investigates loss of land and changes to ground water table (Chapters 3 and 4). In addition two simplified composite models are developed (Chapter 5) for use in regions where data, resources and expertise is limited to identify the possible sea level rise and its impacts. Further other impacts of sea level rise have also been investigated.

3. Impact on Water Table

a. Introduction

Increase in groundwater table levels in coastal aquifers caused by sea level rise due to climate change is a very important and growing issue around the world. Rising sea levels increases the hydraulic pressure exerted on the interface of fresh water bodies adjacent to coastal zones. This then alters the ground water table resulting in some cases of ease in flooding or in some cases of salinity intrusion.

This research highlights investigation and the impacts of the changes in groundwater table caused by sea level rise due to climate change with particular reference to the Whaiwhetu Aquifer, Lower Hutt, and New Zealand. The Whaiwhetu aquifer is very productive and it supplies around 40% of Greater Wellington’s annual water demand.

In the past 100 years sea level rose on average 0.2m in Wellington region and it is predicted that by the 2090 sea level will increase by 0.8 m and by 2115 almost 1m. Therefore an investigation has been carried out by developing a three-dimensional hydrodynamic numerical model. Numerical model was developed using comprehensive groundwater modelling package FEFLOW 6.1. Once the model was developed and calibrated, four “what if” scenarios regardless of the time period were investigated. Scenario 1 assumed the increase of 0.5 m of the mean seawater level (MSL). Scenario 2, Scenario 3 and Scenario 4 assumed an increase of 1.0 m, 1.5 m and 2.0 m MSL respectively. The changes were compared in nine observation bores and the results are discussed as follows.

b. Greater Wellington

Within Greater Wellington Region there are three major ground water zones. Those zones are: the Lower Hutt Valley, Kapiti Coast and the Wairarapa Valley (Jones, 2005). Lower Hutt Groundwater Zone (LHGZ) is a system composed of a number of alternating confined and unconfined aquifers. One of them is Whaiwhetu aquifer, known also as Whaiwhetu Artesian Aquifer and Whaiwhetu Gravel Aquifer. The Whaiwhetu aquifer is located within almost completely urbanised area of the Lower Hutt and it is located on north of Wellington City This is very productive aquifer that accommodates around 40 % of Greater Wellington's annual water demand (GWRC, 2013).

In the past 100 years sea level raised on average 0.2 m in Wellington region (Bell and Hannah, 2012). The authors Bell and Hannah (2012) have also predicted that by the 2090 sea level will increase by 0.8 m and by 2115 almost 1 m. The purpose of this study is to present investigation on changes in groundwater table due to sea level rise. In order to do such investigation numerical (computer) model was developed. The numerical model was developed using a comprehensive groundwater modelling software package FEFLOW 6.1 (DHI-WASY, 2012). It has capabilities for pre and post data processing, and very powerful simulation engine.

The groundwater modelling reported on here is fundamental part of the investigation on changes to groundwater table due to sea level rise. The model is built to fit the purpose and that is to estimate change of groundwater level due to sea level rise.

Lower Hutt Groundwater Zone (LHGZ) is bounded by Wellington fault in the east, on the west by the Eastern Hutt Hills and Taita Gorge in the north. Southern boundary is not well defined and it is assumed that it lies between Somes Island and entrance to Wellington Harbour (Reynolds, 1993; WRC, 1995 and Reynolds, 1993).

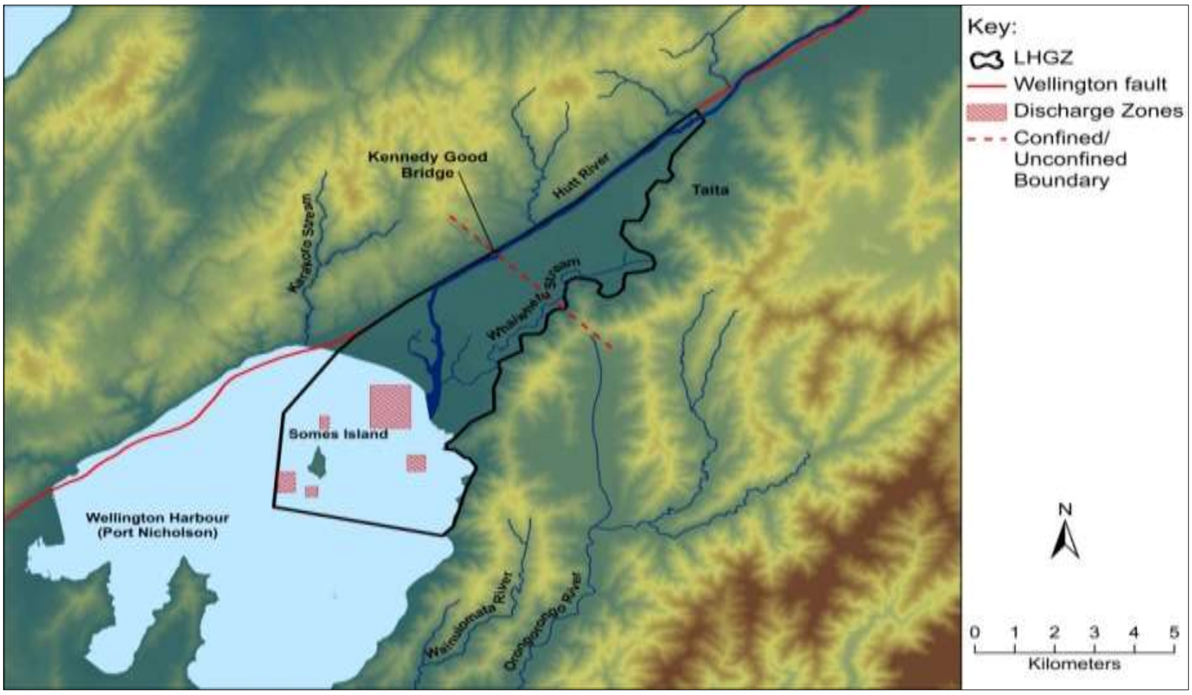

Figure 4 Model boundary, boundary between confined and unconfined aquifer and discharge zones in the Lower Hutt Groundwater Zone (LHGZ)

Whaiwhetu Aquifer is situated in the Hutt Valley and it is build-up of "water-holding sand, gravel and boulders" (GWRC, 2013). It lies within highly urbanised area and it is one of the sources for the water supply for the Greater Wellington Region. The thickness of the Whaiwhetu Aquifer varies form 20 m at the south-eastern boundary (harbour) up to 70 m at the western boundary-Wellington fault. From Taita Gorge southward to Kennedy Good

Bridge (Melling suburb) Whaiwhetu Aquifer is unconfined and this zone is recharge zone of the Whaiwhetu aquifer (Stevens, 1956 and WRC, 1995). The aquifer becomes confined (artesian) in the zone of the Kennedy Good Bridge and it stays pressurised all the way towards to the southern boundary that lies in the Wellington Harbour. Aquifer discharges into the Wellington harbour via submarine springs on the sea floor (Harding, 2000) due to the pressure in the aquifer. Although, discharge zones for the whole Wellington Harbour were identified by Harding (Harding, 2000).

The main recharge source of the Whaiwhetu Aquifer is the Hutt River. Water leakage from the riverbed in the upper part of the Hutt River (recharge zone) replenishes the groundwater resources of the Whaiwhetu Aquifer and it takes up to a year (GWRC, 2013) for water to reach the aquifer.

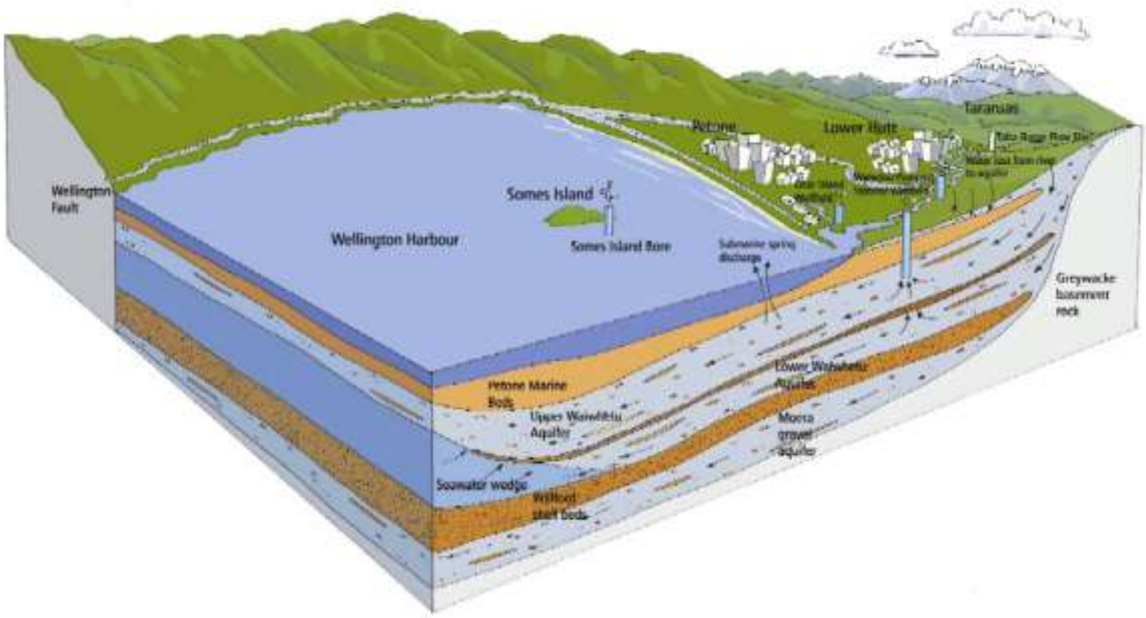

Figure 5 Conceptual model of the Lower Hutt Groundwater Zone (GWRC, 2013)

Greater Wellington Regional Council (GWRC) is in charge of Whaiwhetu Aquifer and it is closely monitoring groundwater levels, so the aquifer stays under the pressure and in that way prevents the saltwater intrusion via spring into the Whaiwhetu Aquifer (GWRC, 2013). Fresh water from the Whaiwhetu Aquifer covers 40% of the overall annual water supply in the Wellington Area (GWRC, 2013).

c. Geological Context

The Lower Hutt basin has been very well investigated and described by many authors. One of the first authors that have defined stratigraphy of the Hutt Valley is Stevens (Stevens, 1956 a and Stevens, 1956 b). The groundwater system in the Lower Hutt Zone consists of six stratigraphic units. Those units are (from top to the bottom): Taita Alluvium, Melling Peat and Petone Marine Beds, Whaiwhetu Artesian Gravels (upper and lower), Wilford Shell Bed, Moera Gravels and Deeper Glacial/Interglacial deposits. The list of stratigraphic units & their characteristics are given in **Table 1** below.

Table 1 Hydrostratigraphic units of the Lower Hutt Groundwater Zone (Stevens, 1956 a)

Stratigraphic Unit	Hydrogeological Unit
Taita Alluvium	Unconfined and semi-confined aquifers
Melling Peat and Petone Marine Beds	Aquitard
Whaiwhetu Artesian Gravels (upper and lower)	Confined aquifers separated by interstadial aquitard. Unconfined in the north and harbour entrance
Wilford Shell Beds	Aquitard
Moera Gravels	Unconfined, semi-confined in the north
Deeper Glacial/Interglacial deposits	Confined aquifers/aquitard sequence

First subzone is unconfined and it lies between Taita Gorge (northern boundary) and Kennedy Good Bridge. In this zone Waiwhetu Gravels and overlaying Taita Alluvium are hydraulically connected with the ground surface. Both aquifers consist of grey-brown gravels with spatial variable amounts of sand, silt and clay. The Lower Hutt Groundwater Zone can be divided in to two hydrological contrasting sub zones

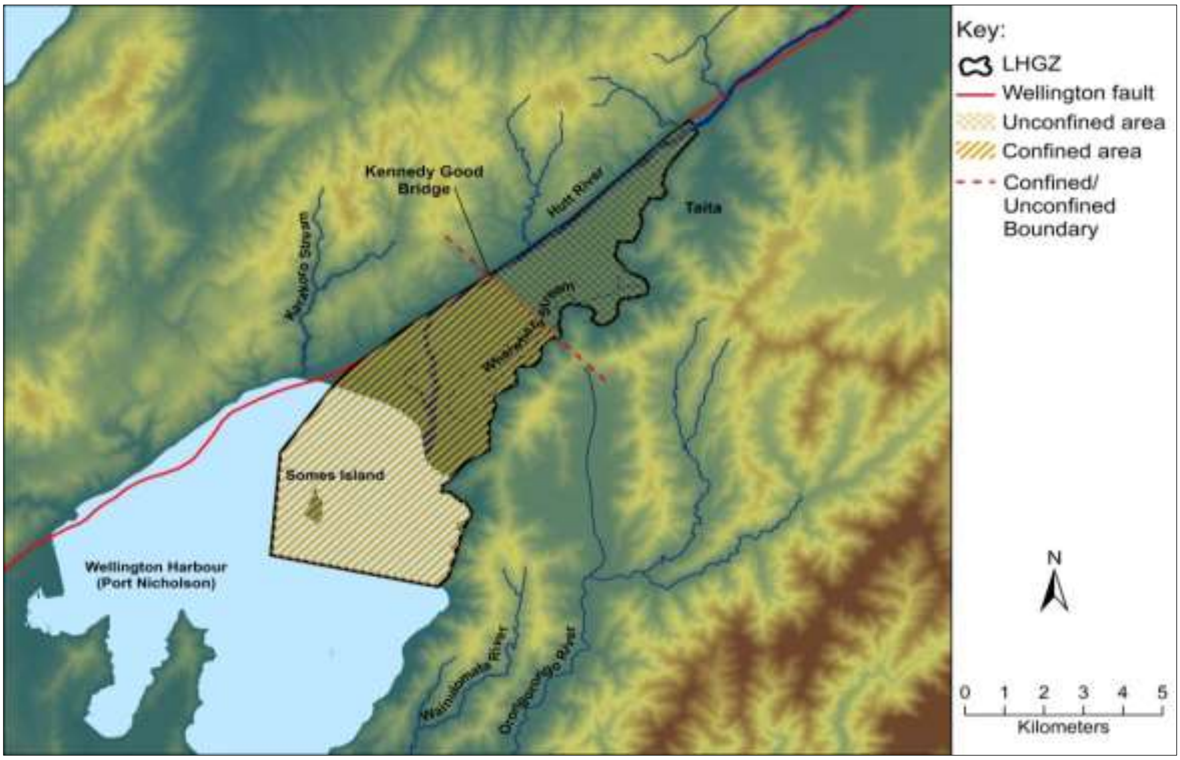

Figure 6 Unconfined and confined subzone of the Lower Hutt Groundwater Zone (LHGZ)

From Kennedy Good Bridge all the way to southern boundary aquifer is confined. In this subzone fine confining sediments of Melling Peat and Petone Marine Beds are found on the top over the Waiwhetu Gravels.

Taita Alluvium

The top layer of the Hutt Valley, Taita Alluvium, extends from foreshore towards the northern catchment boundary forming unconfined aquifer. From foreshore to artesian boundary it overlies the Melling Peat and Petone Marine Beds (aquitard). Northwards from the artesian boundary it overlies Whaiwhetu Artesian Gravels. It is a thin layer, with thickness varying from 0- 16 m, with average thickens of 4.5 m (Reynolds, 1993). Taita Alluvium is formed in recent times from deposits of the Hutt River.

Melling Peat and Petone Marine Beds

Melling Peat and Petone Marine Beds are forming confining layer for the Whaiwhetu Artesian Gravels. The top of the aquitard is located at the depth no less than 10 m from the ground surface. They form main aquitard that extends form the artesian boundary to the southern boundary. The thickness ranges from 10-12 m (offshore area) up to 30 m (below the harbour) (Phreatos, 2003 and Reynolds, 1993).

The Melling Peat and Petone Marine Beds consist of fine grained materials that have significantly less hydraulic conductivity than Whaiwhetu Artesian Gravels, such as clays, silts and sands with addition of shells and wood (peat).

Whaiwhetu Artesian Gravels

The Waiwhetu Artesian Gravels (upper and lower) are forming the main water bearing aquifer in the Lower Hutt Zone. The aquifer extends across the whole Lower Hutt Zone and under the Wellington harbour most likely all the way to the Harbour entrance (WRC, 1995 and Phreatos, 2003). This unit is formed from high preamble coarse gravels that are interbeded with lenses of fine silt and clay. The thickness of the Whaiwhetu Gravels in the Hutt Valley ranges from 47 m to 56 m. Below the harbour it ranges from 20 m at the east and south of the harbour and getting thicker towards north and west reaching the thickness of 70 m along the Wellington fault (WRC, 1995 and Phreatos, 2003).

The interspatial layer arises at depths between 40 to 70.0 m dividing Whaiwhetu gravels into upper and lower. The unit forms an aquitard and it consists of sand, silt and clay intrbedded with carbonaceous material.

Wilford Shell Bed

Unit that lies beneath Waiwhetu Artesian Gravels is Wilford Shell Bed with thickness ranging from 17 m to 22 m (Phreatos, 2003, Reynolds, 1993 and WRC, 1995). It consists mainly of low permeable silty sand with addition of shells, forming an aquitard. The thickness of the unit is decreasing from Petone towards the north of the Hutt Valley.

Moera Gravels

Unit that underlies the Wilford Shell Bed is Moera Gravels forming artesian aquifer. These gravels are the oldest gravels that are found in the Lower Hutt Valley. The thickness of the unit is 25 m and it is assumed that it consists of two aquifers, upper fresh water and deeper saltwater (Reynolds, 1993). Recharge zone for the Moera Gravels is north of the Lower Hutt Valley North. In that zone Moera Gravels became hydraulically conceded with Whaiwhetu Artesian Gravels and Taita Alluvium, since the Wilford Shell Bed diminishes in that zone.

Deeper Glacial/Interglacial deposits

These deep deposits lay underneath the Moera Gravels, thickening towards south from Taiata Gorge. The deposits lie on Greywacke basement that has very low permeability.

d. Recharge

The aquifers in the Lower Hutt Groundwater (LHGW) zone are recharged by losses from the Hutt River, as a primary source and rainfall, as secondary source. The recharge occurs in the upper part of the catchment north from the artesian boundary (Error! Reference source not found.). This zone is also known as recharge zone and it lies in the area between Taita Gorge and Kennedy Good Bridge (suburb Melling). In this zone Taita Alluvium and Whaiwhetu Artesian Gravels become hydraulically connected and Upper Waiwhetu Artesian Gravels gain water from the Hutt River via Taiata Alluvium by vertical infiltration. Lower Waiwhetu Artesian Gravels and Moera Gravels gain less recharge due to lower permeability and hydraulic gradients.

Recharge from the rainfall also occurs to unconfined Tatita Alluvium aquifer. Since this aquifer is mainly urbanized it is estimated that only 40% of the rainfall is available for the re charge (Reynolds, 1993).

River recharge

Primary recharge sources in LHGZ the Hutt River. Losses from the Hutt River contribute to recharge in the unconfined zone of the LHGZ, north of artesian boundary Error! Reference source not found.. In this area all aquifers, Taita Alluvium, Whaiwhetu Gravel and Moera Gravel, are connected hydraulically due to non-existence of low permeability watertight strata. South of artesian boundary, in the confined zone of deeper aquifers (Lower Whaiwhetu Gravel and Moera Gravel) recharge from the river loss occurs only to Taita Alluvium Aquifer and there is no recharge to deeper aquifers, since overlaying confining layer of Melling Peat and Petone Marine Beds is preventing recharge.

Due to lack of river flow data estimated values for recharge from the river losses are adopted from (Reynolds, 1993) and (Phreatos, 2003). The authors have developed the relationship between concurrent flow gauging at Taita Gorge (29809), Kennedy Good Bridge (29824) and Boulcott (29811) on the Hutt River.

The relationship developed by Reynolds (1993) was based on records made between 1970 and 1993, at Taita Gorge (29809) and Boulcott (29811): The measurements were taken mostly under low flow conditions varying between 2.3 and 5.7 m3/s:

Equation 1.

Boulcott flow = -595 + (0.975 x Taita Gorge flow) l/s (Reynolds, 1993)

During 1995 pumping test was carried out under the normal flows that are ranging between 11 and 30 m3/s (Phreatos, 2003). Regression analysis of the data for the period 1970 -and 1993 and 1995 gave the mathematical relationship for the flow at Taita Gorge (29809) and Kennedy Good Bridge (29824):

Equation 2.

Kennedy-Good Bridge = 0.974(Taita Gorge) – 912 L/sec (Phreatos, 2003)

This equation is similar to the equation that was using only low flow data for the period from 1970 to 1993 developed by (Reynolds, 1993). Therefore losses between Taita Gorge (29809) and Kennedy Good Bridge (29824) are assumed to range between 100,000 to 160,000 m3/day for average river flow conditions and for the flows less than 6 m3/sec (low flows) no less than 80,000 – 85,000 m3/day.

Rainfall recharge

Simple model for the estimate of daily rainfall recharge for deeper aquifers (Lower Whaiwhetu Gravel and Moera Gravel) was developed by (Reynolds, 1993):

Equation 3.

Recharge = Rainfall-Actual Evapotranspiration -Soil Moisture Deficit (Reynolds, 1993)

If annual rainfall was greater than 1000 mm, then the annual recharge was calculated using the following equation:

Equation 4.

Annual Recharge (mm) = [0.97 x Annual Rainfall (mm)] - 500 (Reynolds, 1993)

Where data used in Equation 4 is data accumulated on annual basis from the Equation 3.

The estimate minimum, mean and maximum recharge values are shown in **Table 2** below.

Table 2 Estimated potential rainfall recharge (mm) to LHGZ (Reynolds, 1993)

Month	Minimum (mm)	Mean (mm)	Maximum (mm)
January	0	18	119
February	0	8	62
March	0	38	133
April	0	58	172
May	17	117	261
June	18	135	242
July	43	138	278
August	19	108	190
September	10	73	224
October	21	72	177
November	0	41	165
December	0	45	306
Annual mean	476	833	1352

LHGZ is highly urbanised area with lot of impermeable surface, so it is estimated that only 40% of the catchment is available for the rainfall recharge.

e. Groundwater levels

Time series of ground-water levels were obtained from the GWRC for nine bores that are within LHGWZ

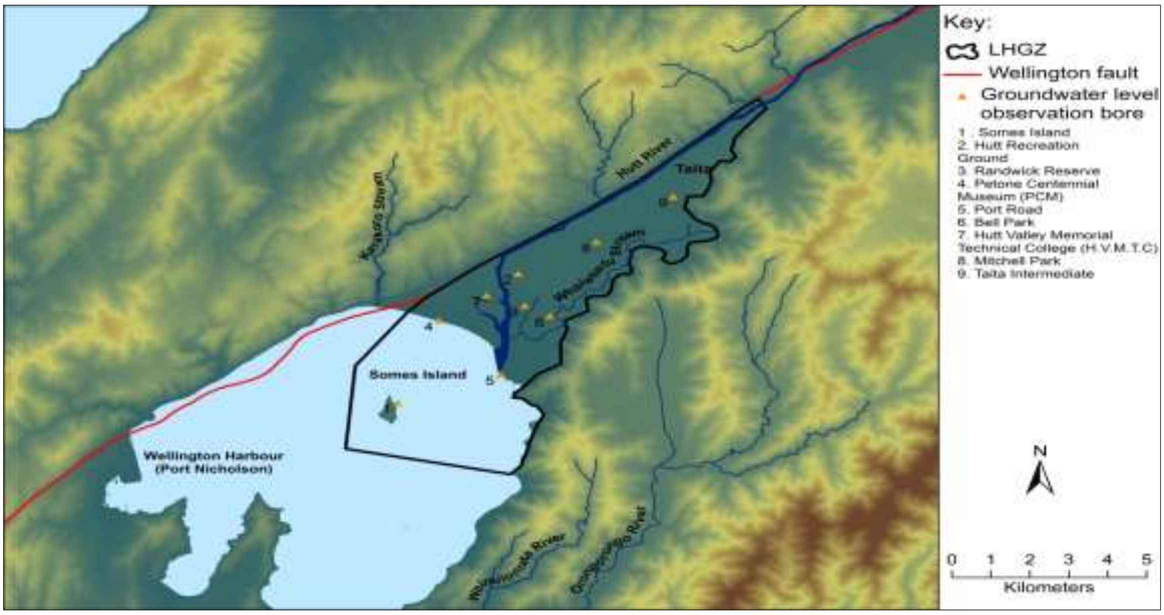

Figure 7 Location map of groundwater level monitoring sites in the Lower Hutt Groundwater Zone (LHGZ)

Most of the sites take a reading every 15 minutes (J. Marks, pers. comm.), but for the purposes of this study monthly averages were obtained. The summary of all obtained data for the groundwater monitoring sites is given in **Table 3** below.

Table 3 Summary of available time series of groundwater levels in the Lower Hutt Groundwater Zone

Site Name	Well number	Aquifer	Bore Depth (m)	Available Record period
Somes Island	R27/1171	Upper Waiwhetu	21.2	1968-present
Hutt Recreation Ground	R27/1115	Upper Waiwhetu	23.5	1968-1979; 1987- present
Randwick Reserve	R27/1122	Upper Waiwhetu	24.4	1975-1977; 1979-1984 1987- present
Petone Centennial Museum (PCM)	R27/0121	Upper Waiwhetu	26.2	1968-1996
Port Road	R27/1118	Upper Waiwhetu	28.7	1970-1994
Bell Park	R27/1123	Upper Waiwhetu	23.2	1975-1979; 1987-1994

Hutt Valley Memorial Technical College (H.V.M.T.C)	R27/0120	Upper Waiwhetu	29.6	1968-2009
Mitchell Park	R27/1116	Upper Waiwhetu	51.8	1968- present
Taita Intermediate	R27/1117	Upper Waiwhetu	14.6	1968- present

f. Groundwater Abstraction

The groundwater in LHGZ is fully allocated. The Waterloo and Gear Island well fields are abstracting 87 % of the allocated volume for the public water (Jones, 2005). The abstraction rates from the Whaiwhetu Aquifer were set according to groundwater permits for the Lower Hutt Zone. The abstractions rates were obtained from GWRC and the values are given in **Table 4** below.

Table 4 Groundwater permits in the Lower Hutt Aquifer System

Consent No.	Name	Volume per day (m^3)	Volume per year (m^3)	Water meter ID no.
WGN000020	Hutt Valley Health	2160	786,240	R27/1076
WGN030126	Teri Puketapu	43.2	15,725	R27/6390
WGN040360	Petone Pure Water Company Ltd	50	18,200	R27/6441
WGN070154	NZTS Services Limited	142.7	51,936	R27/4003
WGN070183	Shandon Golf Club	560	63,000	R27/1235
WGN070184	Feltex Carpets Ltd	542.9	197,601	R27/1141
WGN070189	Imperial Tobacco New Zealand	65	23,660	R27/1234
WGN070193	Unilever NZ Trading Ltd	2542.9	925,600	R27/6354
WGN080198	Manor Park Golf Club	680	116,000	R27/4089
WGN080208	Boulcott's Farm Heritage Golf Club Inc.	400	80,000	R27/1089
WGN080397	Hutt City Council	1530	17,075	R27/6333

Consent No.	Name	Volume per day (m^3)	Volume per year (m^3)	Water meter ID no.
WGN080402	Boulcott's Farm Heritage Golf Club Inc.	995	199,000	R27/1104
WGN080433	Woolyarns Ltd	285.7	104,000	R27/6025
WGN090243	Hutt City Council	30	10,920	R27/1238
WGN090282	Department of Conservation	24	8,736	R27/6146
WGN120019	Avalon Studios	2419.2	880,589	R27/1183
WGN970036	Wellington Regional Council (Utility Services Division)	83115	30,253,860	R27/1168

g. Conceptual Model

The conceptual model, based on the model described in Phreatos (2003), consists of seven geological layers. These geological layers have been described in section 0 and the summary is given in the figure below.

The model domain corresponds to the boundary of the Lower Hutt Groundwater Zone. The northern boundary is at Taita Gorge where gravels thin out. Western boundary of the model domain coincides with Wellington fault. Eastern model boundary is defined by Eastern Hutt Hills. Southern boundary lies within the Wellington Harbour, between Somes Island and entrance to Wellington Harbour.

The upper boundary of the conceptual model is defined by the elevations of the land surface. This was obtained from the University of Otago - National School of Surveying 15 m digital elevation model. The lower boundary was set as bottom Moera Gravel Layer.

The thicknesses of the layers were determined from the bore logs given in the Revision of the numerical model for the Lower Hutt groundwater zone (Phreatos, 2003) (Appendix A). The inflow in the model is the recharge from the rainfall in the onshore zone of the model domain and from the river in the unconfined zone of the LHGZ. Discharge is assumed to be into the Wellington harbour via submarine springs on the sea floor Error! Reference source not found. (Harding, 2000).

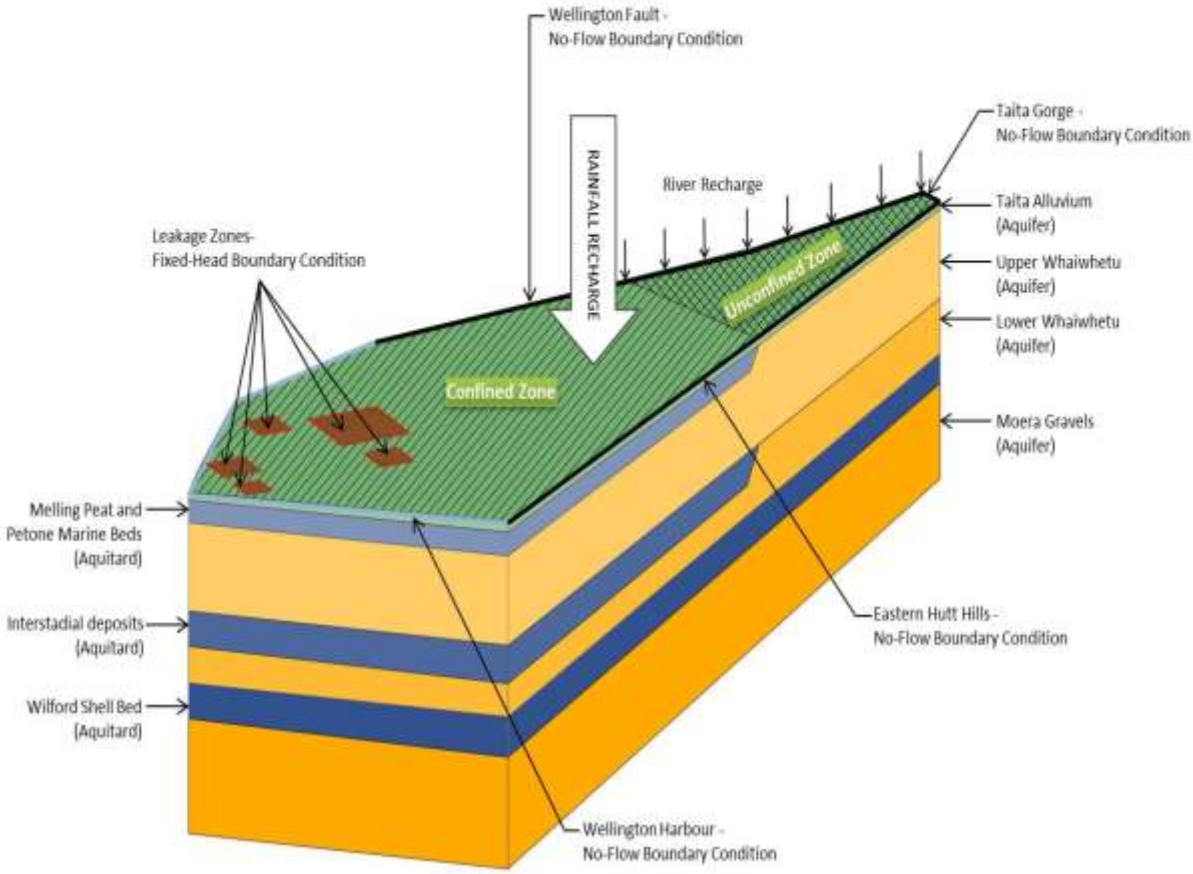

Figure 8 Conceptual model of the Lower Hutt Groundwater Zone

h. Modelling Software - FEFLOW 6.1

The modelling software FEFLOW 6.1 (DHI-WASY, 2012) was chosen for building the model. FEFLOW 6.1 is the existing version of software that was first developed in Germany in 1979. It is at a high level of development and refinement and has wide global use by universities, consultants, and government and private research organizations. FEFLOW 6.1 is a three-dimensional finite-element software package for modelling subsurface water flow and contaminant transport. It can be used to build two- or three-dimensional models with steady state or transient conditions, and includes graphical user interfaces for model building, model input, and post-processing of model output (DHI-WASY, 2012).

i. Finite-Element Mesh Generation and 3D Discretization

The outer boundary of the framework, called the "super mesh" in FEFLOW, is defined by model domain (Error! Reference source not found.). The model domain was drawn using ArcGIS (DHI-WASY, 2012). The two-dimensional finite element mesh was generated using the Gridbuilder mesh generation algorithm in FEFLOW. The nominal number of elements was specified as 3000, giving an actual number of elements of 4478 (Error! Reference source not found.). The model was then expanded in to 3D, by setting the number of layers to 7, and resulting mesh was applied to each of the slices in the model (ground surface, surfaces between each layer of the model, and lower surface of the Moera Gravel aquifer), giving a total of 31346 elements.

To define the elevations of the slices, the node positions (x and y coordinates) were exported from FEFLOW as an ESRI point shape file, and imported into ArcGIS. The Slice 1 elevations (ground surface level, above mean sea level) at the nodes were obtained using bilinear interpolation between the elevations at the centres of the cells of the 15 m digital elevation model (Otago, 2011). To estimate elevations for all other slices, a first-order polynomial (planar), linear-regression trend of depth values for each stratigraphic unit from the bore logs of 29 bores (Phreatos, 2003) within the LHGZ. Values of this trend surface were determined at the node positions using bilinear interpolation, and the values were subtracted from the previously estimated Slice 1 elevations to give elevations for the all of the remaining slices. Values of all node elevations for each slice were combined into an eight ESRI shape files (one shape file correspond to one slice) containing the node number, x and y coordinates, node elevation, and slice number. These files were imported into FEFLOW, and the node elevations were assigned using the FEFLOW data assignment tool.

Once the layers have been defined the layer type needed to be defined. The summary of the layer type for each modelled layer is given the Table.

Table 5 Model Layer

Layer	FEFLOW Layer Type
Layer 1 - Tatita Alluvium	Free
Layer 2 - Melling Peat and Petone Marine	Dependent
Layer 3 - Upper Whaiwhetu Artesian Gravels	Confined
Layer 4 – Interstadial deposits	Confined
Layer 5 - Lower Whaiwhetu Artesian Gravels	Confined
Layer 6 - Wilford Shell Beds	Confined
Layer 7 - Moera Gravels	Confined

The "Free surface" option in FEFLOW was chosen for modelling the characteristics of the Layer 1 (Tatita Alluvium) for the model runs. For Layer 2 (Melling Peat and Petone Marine Bed) the option dependent was chosen, which means that the layer above defines current layer. This means that the Layer 2 property will depend on Layer 1. All the rest layers were set up as confined at all times.

j. Boundary Conditions

For the LHGZ model, boundaries were defined as follows (Figure 9):

- Eastern, southern, western and northern boundary: assumed to be no flow boundaries
- Leakage zones: fixed head, set at a value of 0.0 m above sea level;

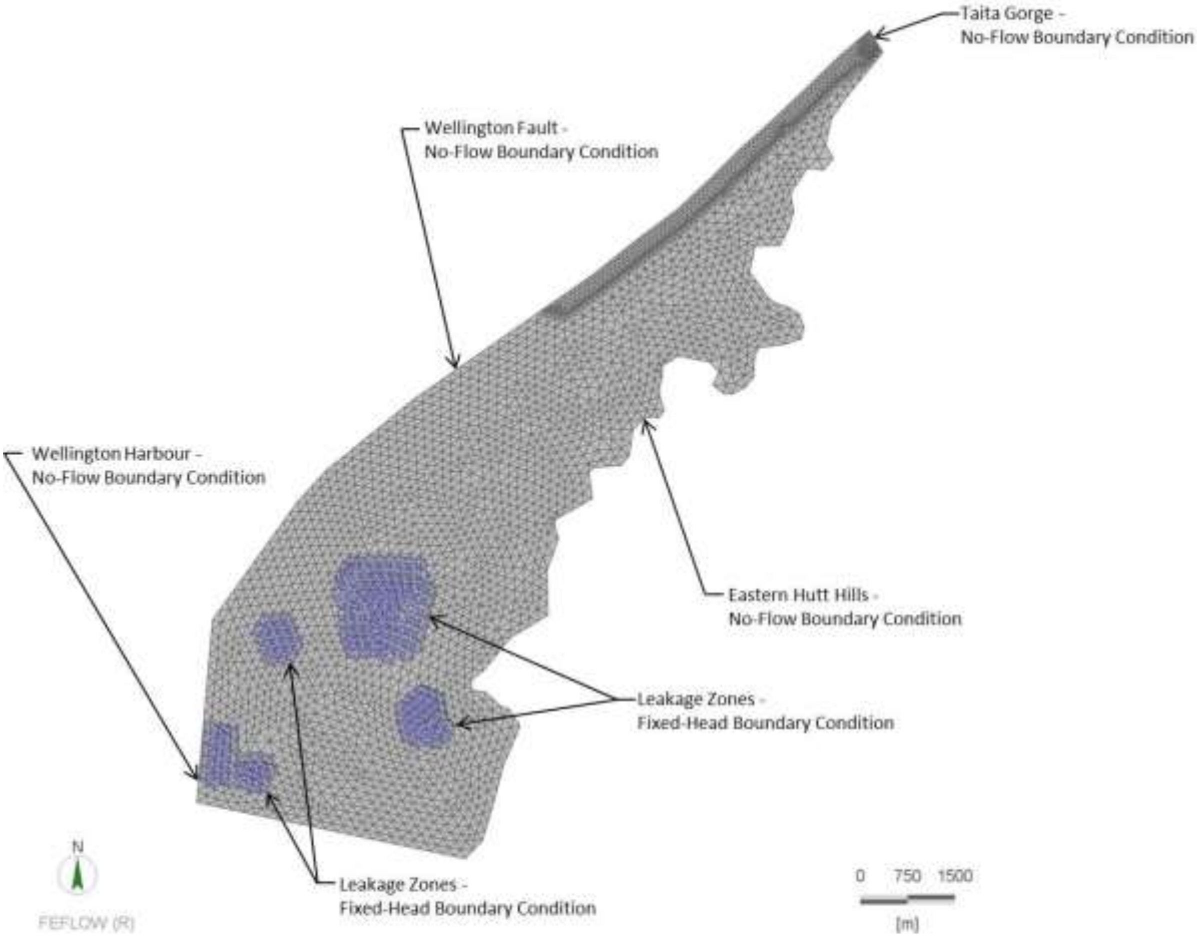

Figure 9 Boundary Conditions

k. Parameter Values

The parameters required for the FEFLOW input are, for each layer:

- Conductivity values in all directions, Kx, Ky and Kz. It was assumed that all layers of the model are isotropic in the horizontal plane (i.e., Kx = Ky, hence Kxy)
- Drainable / fillable porosity (specific yield).

The a priori conductivity values were set up to be the same as calibrated steady state values in model presented Revision of the numerical model for the Lower Hutt groundwater zone Table (Phreatos, 2003).

Drainable / fillable porosity or specific yield values for all the layers were also available in Revision of the numerical model for the Lower Hutt groundwater zone in Table (Phreatos, 2003).

I. Model Calibration

Due to insufficient data regarding river flows in the Hutt River and lack of series of rainfall data, calibration was done only for steady state conditions. Calibration was based on comparison of the simulated and observed water levels in nine observation bores. Many runs were performed in order to match the simulated levels with observed ones and for each model run the Nash-Sutcliffe efficiency coefficient (Nash and Sutcliffe 1970) was also calculated.

The model was accepted as suitable for further use when there was the same number of overestimated and underestimated water levels in observation bores, and when the Nash-Sutcliffe coefficient was a maximum and close to 1.

The best fits were obtained with K values close to the a priori values, with little change in vertical conductivity values for first three layers (Tatita Alluvium; Melling Peat and Petone Marine Beds; Upper Whaiwhetu Artesian Gravels). The calibrated conductivity values are presented in Table 6.

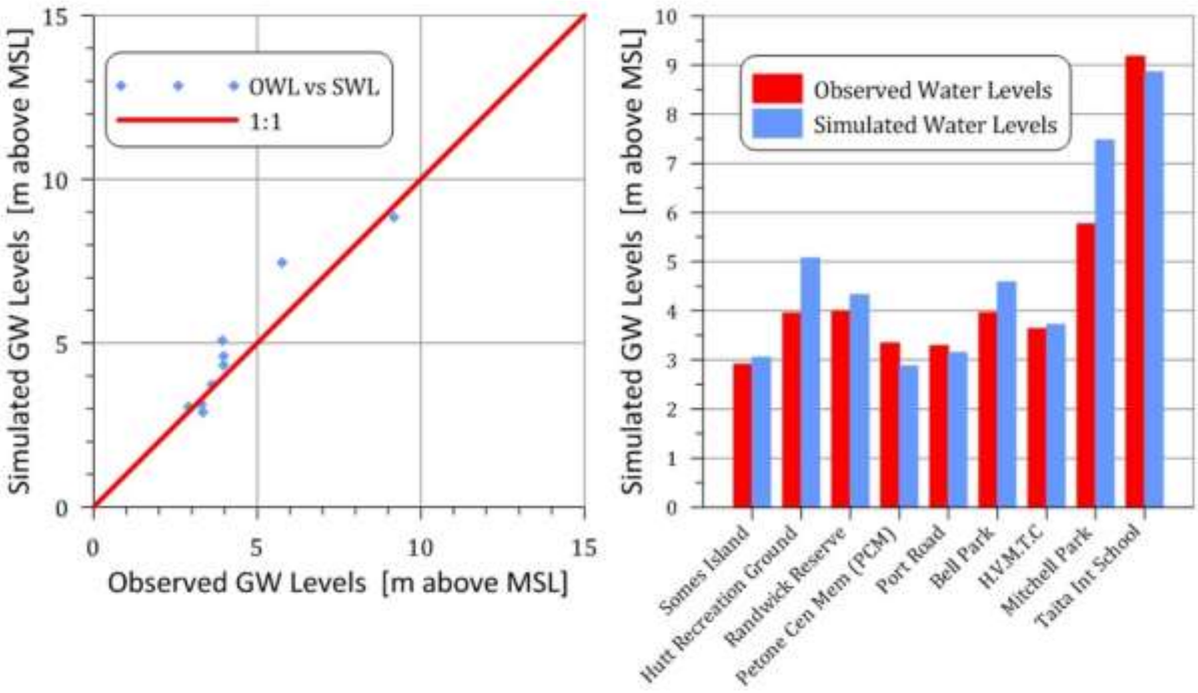

Figure 10 Comparison of simulated and observed groundwater levels

Table 6 Calibrated conductivity values

Layer	Confined Zone k_{XY} m/day	Confined Zone k_Z	Unconfined Zone k_{XY}	Unconfined Zone k_Z
Layer 1 - Tatita Alluvium	2600	3	2600	0.3
Layer 2 - Melling Peat and Petone Marine Beds	0.1	0.02	1300	3
Layer 3 - Upper Whaiwhetu Artesian Gravels	1120	3	1300	3
Layer 4 – Interstadial deposits	0.1	0.002	1300	3
Layer 5 - Lower Whaiwhetu Artesian Gravels	600	0.5	600	0.5
Layer 6 - Wilford Shell Beds	0.1	0.002	80	0.1
Layer 7 - Moera Gravels	80	0.1	80	0.1

The pattern of simulated groundwater contours is presented in Error! Reference source not found.. It matches very well with the patterns of the groundwater contours simulated in previous modelling (Phreatos, 2003 and Reynolds, 1993). In the southwestern part of the model due to high abstraction rates the local depression is visible in Figure 11.

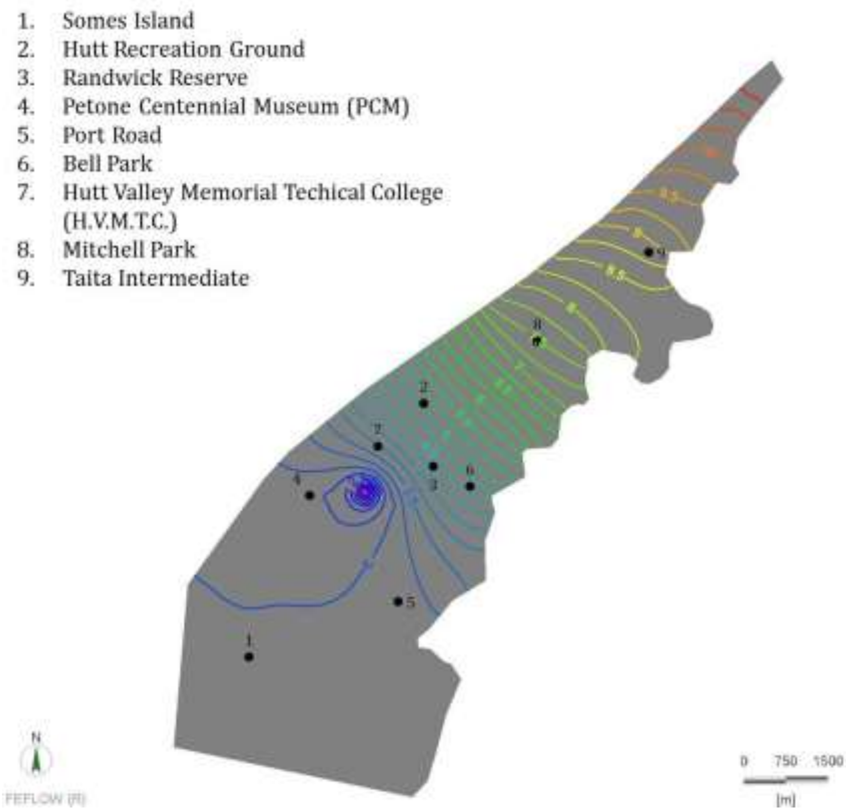

Figure 11 Pattern of the simulated groundwater levels

m. Investigation of changes to groundwater table due to sea level rise

Four scenarios were used for investigation of the changes of the water table due to sea level rise. Scenario 1 assumes increase of 0.5 m of the mean seawater level (MSL), Scenario 2 assumes increase of 1.0 m and Scenarios 3 and Scenarios 4 1.5 m and 2.0 m respectively.

This increase of the mean sea level in the model was represented by changing fixed head boundary condition at the leakage zones for each scenario. Therefore there were four model runs for each scenario.

In Scenario 1 that assumes increase of 0.5 m the average increase of the groundwater levels in the Upper Whaiwhetu Aquifer is 0.07 m. The significant increase is noticeable in the part of the aquifer which lies in the harbour area if the model and in the coastal zone of the LGHZ (Error! Reference source not found.). The change can be observed in bores Somes Island, Petone Centennial Museum (PCM) and Port Road that are 0.17 m, 0.11 m and 0.13 m respectively. North of the bores H.V.T.M.C., Randwick Reserve and Bell Park there is no change to the water table due to increase 0.5 m in the mean sea level.

Scenario 2 investigates influence of the increase of 1.0 m in the mean sea level. The results of this scenario show that increase in the ground water level will vary from 0.39 m to 0.61 m. The rise in elevation decreases from the south towards the northern part of the aquifer.

The increase of the 1.5 m of the mean sea level will cause on average the change of 0.86 m in water table elevations. This change was investigated in Scenario 3. The change in elevations varies from 0.76 m to 0.98 m.

Last scenario, Scenario 4 investigated the change caused by the increase of 2.0 m in the mean sea level. Minimum increase for this case is 1.15 m in the northern part of the aquifer and maximum is 1.39 m in the southern part of the aquifer that lies in the harbour. On average elevations of the ground water table will rise 1.25 m. The results of all four scenarios are presented in Table 7.

Table 7 Summary of the investigation results

Site Name	Scenario			
	1	2	3	4
	Increase (m)			
	0.5	1.0	1.5	2.0
	Change in water table (m)			
Somes Island	0.17	0.61	0.98	1.39

Hutt Recreation Ground	0.05	0.48	0.85	1.23
Randwick Reserve	0.11	0.54	0.91	1.31
Petone Centennial Museum (PCM)	0.13	0.56	0.94	1.34
Port Road	0.06	0.48	0.85	1.24
Bell Park	0.07	0.49	0.86	1.25
Hutt Valley Memorial Technical College (H.V.M.T.C)	0.04	0.47	0.83	1.22
Mitchell Park	0.00	0.42	0.78	1.17
Taita Intermediate	0.00	0.39	0.76	1.15

Four scenarios were investigated for the increase of 0.5 m, 1.0 m, 1.5 m and 2.0 m. The average increase in groundwater levels in Whaiwhetu Artesian Aquifer is 0.07 m, 0.49 m, 0.86 m and 1.25 m respectively. The land loss due to se level rise was also calculated for all four scenarios and it varies from 0.84 km2 to 1.7 km2

n. Conclusion

A numerical model has been developed in order to analyse the influence of the sea level rise on the Whaiwhetu Artesian Aquifer. The Whaiwhetu Artesian Aquifer is the main source for the water supply in the Greater Wellington region, and therefore any significant change to the water table can influence the supply, as well the quality of the groundwater. In order to develop such model firstly available stratigraphy data was analysed. The available data was obtained from 29 bore-logs given in the Revision of the numerical model for the Lower Hutt groundwater zone (Phreatos, 2003). Data was analysed and then imported into ArcGIS where shape files for each model slice of the numerical model was created. The Lower Hutt Groundwater Zone is mainly recharged from the losses in upper part of the Hutt River that lies in unconfined part of the LHGZ. Losses from the river range from 80.000m3/day to 160000 m3/day. The potential annual recharge from the rainfall is estimated to be between 476 mm and 1352 mm per annum, with mean value of 833 mm. Since the LHGZ is mainly urbanised it is estimated that only 40% of the estimated rainfall is available for the recharge to the groundwater (Phreatos, 2003). Recharge rates both from the river losses and rainfall was acquired from reports done by (Phreatos, 2003 and Reynolds, 1993) on numerical modelling in Lower Hutt Groundwater Zone. Abstractions rates and series of monitored groundwater levels in 9 observation bores were obtained from Greater Wellington Regional Council. All available data then was used for the development of the conceptual model of the LHGZ.

Once the conceptual model was developed, the numerical model was developed and calibrated by using FEFLOW. The model was accepted as calibrated once the number of overestimated and underestimated levels in observation bores were similar and when the Nash-Sutcliffe coefficient was a maximum. Calibrated model was then used for investigation of the changes to groundwater table in Whaiwhetu Artesian Aquifer. Four scenarios were investigated for the increase of 0.5 m, 1.0 m, 1.5 m and 2.0 m. The average increase in groundwater levels in Whaiwhetu Artesian Aquifer is 0.07 m, 0.49 m, 0.86 m and 1.25 m respectively.

The model presented in this report fits the purpose and that is analysing the changes in water table in Upper Whaiwhetu Aquifer. It is strongly recommended that further improvement of the model should be done so it can be used for other investigations such as saltwater intrusion and interaction between the Hutt River and the LHGZ. Such improvement can be achieved in obtaining detailed data regarding the river flow, cross sections of the river and riverbed conductance of the Hutt River.

4. Impact on lands adjacent to coastal areas

a. Introduction

The modelling work considered the impact of sea level rise on land and groundwater.

The case of Wellington Lower Hutt was investigated in detail. The output of the modelling and mapping work provide information regarding the horizontal extent of loss of land due to sea level rise scenarios, which could inform boundary conditions for surface and groundwater models as well as providing preliminary information for an assessment of the economic damage of sea level rise.

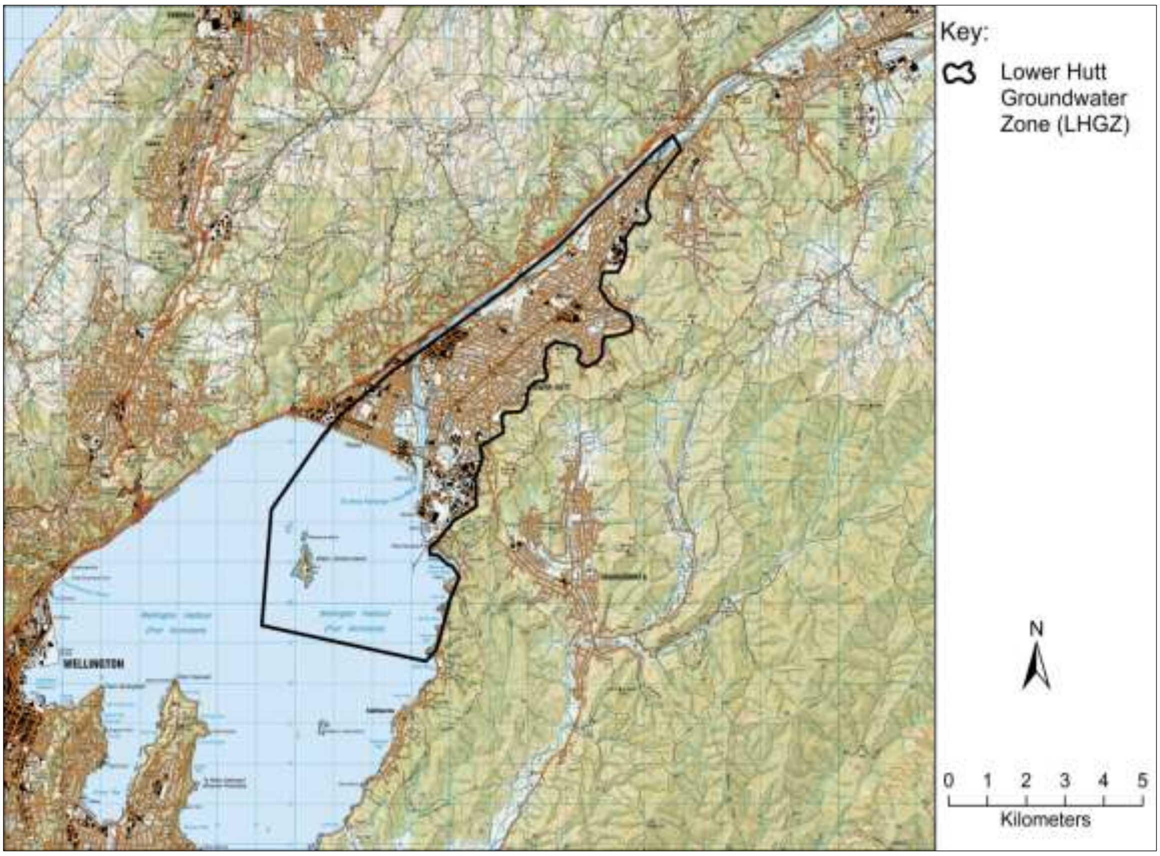

Figure 12 Lower Hutt area of Wellington

The information required for the inundation modelling study can be delineated into the following three aspects:

a. Sea level rise predictions
b. Storm induced sea level
c. Elevation data

It must be noted here that land loss due to sea level rise is caused due to the wave surging in, however it must be noted that at the time the ground water level or the surface water situation will also play a role the impact sea level rise will have on adjacent land.

Hence here in this case, the average rainfall, and ground water table situation has also been presented.

Table 8 ***Potential rainfall recharge (mm) to LHGZ (Reynolds, 1993)***

Month	Minimum (mm)	Mean (mm)	Maximum (mm)
January	0	18	119
February	0	8	62
March	0	38	133
April	0	58	172
May	17	117	261
June	18	135	242
July	43	138	278
August	19	108	190
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Table 9 ***Summary of available time series of groundwater levels in the Lower Hutt Groundwater Zone***

Site Name	Well number	Aquifer	Bore Depth (m)	Available Record period
Somes Island	R27/1171	Upper Waiwhetu	21.2	1968-present
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Hutt Valley Memorial Technical College (H.V.M.T.C)	R27/0120	Upper Waiwhetu	29.6	1968-2009
Mitchell Park	R27/1116	Upper Waiwhetu	51.8	1968- present
Taita Intermediate	R27/1117	Upper Waiwhetu	14.6	1968- present

Table 10 *Groundwater permits in the Lower Hutt Aquifer System*

Consent No.	Name	Volume per day (m^3)	Volume per year (m^3)	Water meter ID no.
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WGN070183	Shandon Golf Club	560	63,000	R27/1235
WGN070184	Feltex Carpets Ltd	542.9	197,601	R27/1141
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WGN080397	Hutt City Council	1530	17,075	R27/6333
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WGN120019	Avalon Studios	2419.2	880,589	R27/1183
WGN970036	Wellington Regional Council (Utility Services Division)	83115	30,253,860	R27/1168

Sea level rise projections for the next 100 years are based on the outputs of global emissions models using a range of emissions scenarios. The loss of the land in the LHGZ due to sea level rise was estimated by using ArcGIS (ESRI, 2012). The affected area by the sea level is defined by the corresponding contour, 0.5 m, 1.0 m, 1.5 m and 2.0 m, and the coast line which corresponds to 0 m contour and the sea level at present day. The modelling software FEEFLOW 6.1 was chosen to investigate the impact on ground water. The Ministry of Environment (MfE, 2008) identifies that sea level is predicted to raise due to the effects of climate change. Figure below shows four possible scenarios of sea level rise and historical mean sea level recorded in Wellington. An increased rate of sea level rise for the future is likely to increase coastal erosion and coastal inundation risk.

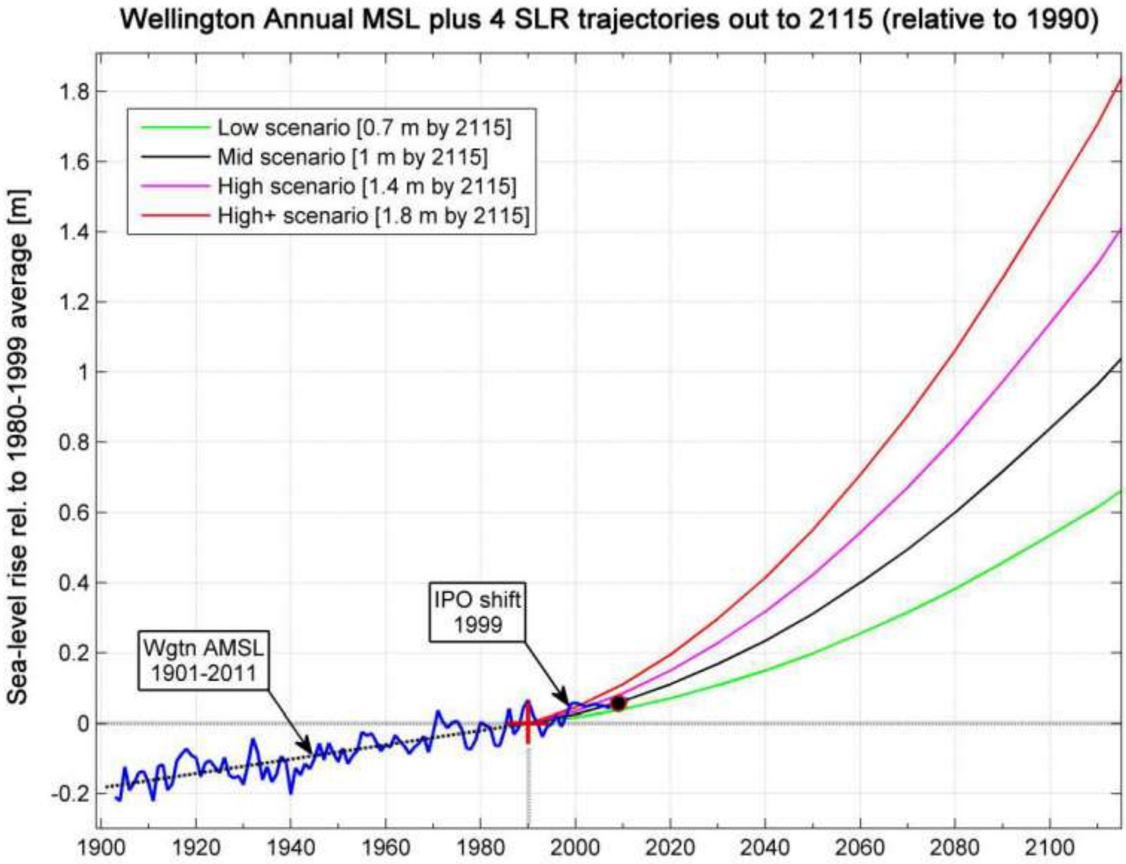


Figure 13 ***Showing historical mean sea level (MSL) for Wellington and 4 Sea Level Rise (SLR) scenarios. The black dot indicates the 6 year average sea level from 2006 to 2011, centred on 2009 Source: Bell and Hannah 2012.***

The MfE 2008 guideline recommends a base value sea level rise of 0.5 m by 2100 (relative to the 1980-1999 average). Furthermore, the guidelines suggest assessing the potential consequences from a range of possible higher sea level rises, with, at the very least, consideration of the consequences of mean sea-level rise of at least 0.8 m and an additional sea level rise of 10 mm per year beyond 2100. Table 3.1 below shows the recommendations as set out by MfE.

Table 11 Extract from MfE 2008 showing baseline sea level rise recommendations for different future timeframes

Baseline sea-level rise recommendations for different future timeframes

Timeframe	Base sea-level rise allowance (m relative to 1980–1999 average)	Also consider the consequences of sea-level rise of at least: (m relative to 1980–1999 average)
2030–2039	0.15	0.20
2040–2049	0.20	0.27
2050–2059	0.25	0.36
2060–2069	0.31	0.45
2070–2079	0.37	0.55
2080–2089	0.44	0.66
2090–2099	0.50	0.80
Beyond 2100	10 mm/year	

The planning timeframes used for this study is 2115 (i.e. approximately 100 years from present). The resulting sea level rise for the 2115 timeframe is 1.0 m (rounded) (i.e. 0.8 m plus an additional 10 mm/year).

Due to the potential uncertainty with the current sea level rise predictions a sensitivity test is also undertaken by comparing elevation 0.5 m above and below the 1.0 m SLR scenario.

b. Storm effects

An assessment of actual wave effects along the shoreline has been undertaken by NIWA and has been recently released. The results of this recent NIWA analysis have not been considered in this study due to its parallel timescales.

Two storm components are included in this analysis;

A. *Storm surge* is the temporary increase in sea level above that expected by tidal variation caused by extreme meteorological conditions such as low pressure system and/or strong winds
B. *Wave setup* is the super-elevation in water level across the surf zone caused by energy expended by breaking waves. This occurs even in calm conditions, but is exacerbated during storm events.

The Figure illustrates how these components interact. Highest astronomical tides were not specifically included but differ from the standard tidal variation by 0.07m and as such are considered to be represented within the accuracy of the modelling undertaken.

Note that wave setup is localised along the coast. Wave setup is unlikely to propagate significantly land ward from the coast up watercourses. However, the super elevated water at the coast may cause up stream effects due to the increased water level.

Wave run-up is the ultimate height reached by waves after running up the beach and coastal barrier. Wave effects can vary significantly along the coast due to variations in offshore bathymetry and onshore topography and was not used in this assessment due to lack of data.

Available data were used (Gorman et al., 2006 and Stephens, et al. 2011) relating to the wave climate affecting the Wellington Harbour during a 1% Annual Exceedance Probability (AEP) event. This is a storm event that has a 1% chance of happening in any given year.

For the harbour shoreline, wave set up was derived from empirical methods with waves resulting from a 30 m/s wind over the maximum 10 km fetch across the harbour. Storm surge within the harbour was derived from Stephens et al. 2009. The total inundation level derived for the harbour using these methods compared very well with observed and predicted inundation levels contained within the 2009 report.

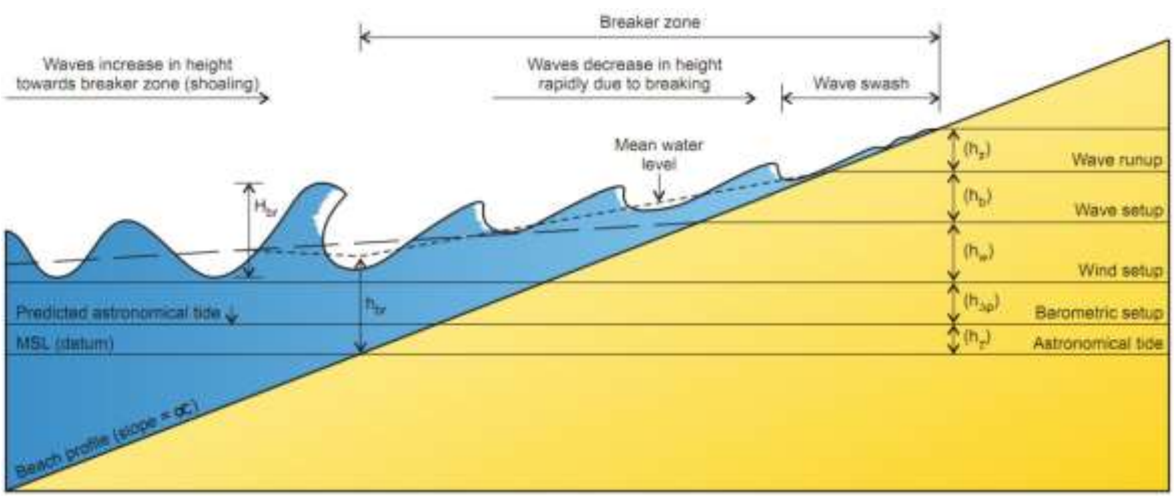


Figure 14 ***Storm components (Source: Shand et al 2011)***

The derived 1%AEP storm effect elevations are considered to provide a conservative upper bound of water levels in addition to the sea level rise component.

There are a number of factors that can influence future storm events that are not considered by this analysis. These include:

a. Increased sea level resulting in greater water depths, possibly longer fetches and different shoaling patterns, leading to a different wave climates
b. Increased 'storminess' resulting in higher winds
c. A change in the prevailing weather, resulting in changing wave climates
d. Propagation of wave setup into the major inlets (i.e. Hutt River and Sea view Marina)

c. Sea level rise components

Scenario	Source	Sea level rise (m)	MHWS (m RL)	Sea level variability (m)	Storm effects (m)	Total no storm effects (m RL)	Total with storm effects (m RL)
1	Ministry of Environment (MfE) (2008)	**1.0**	0.83	0.25	1.1	2.1	3.2
2	Min. of Env. (MfE) (2008)	**0.5**	0.83	0.25	1.1	1.6	2.7

Scenario	Source	Sea level rise (m)	MHWS (m RL)	Sea level variability (m)	Storm effects (m)	Total no storm effects (m RL)	Total with storm effects (m RL)
	minus 0.5						
3	Min. of Env. (MfE) (2008) plus 0.5	**1.5**	0.83	0.25	1.1	2.6	3.7

An upper bound value for sea level variation of 0.25m (MfE, 2008) was included to account for seasonal and longer-term climate cycle variances in water level. The sea level rise and sea level variation components were added to Mean High Water Spring (MHWS) relative to Wellington Vertical Datum 1953 (WVD) incorporating Mean Level of the Sea (MLOS) for 2012.

It could be seen that a 0.5m sea level rise could yield a 2.7m total storm effect on a bad day.

The 'building block' additive approach used for this study is considered sufficiently conservative that these processes are likely to be encapsulated within the levels considered. Whilst the storm tide effects are only specifically included in the SLR scenario the datasets provided will enable the user to consider the effect of a storm event combined with any 0.1 m sea level rise increment.

d. Digital Elevation Model (DEM) creation

The LiDAR derived DEM supplied was a 2 m x 2m grid. The DEM was modified to ensure hydraulic connectivity through artefacts of the LiDAR capture. Features such as bridges for example were included in the original DEM and formed a barrier over water courses. To allow connectivity through these areas the DEM was 'burned' to allow connectivity.

e. Inundation modelling

Inundation typically refers to an area permanently submerged, but is also sometimes used in relation to temporary inundation during storm events. Inundation modelling was undertaken using GIS. A "bathtub" concept was applied, where a uniform depth of water is applied to the existing land surface. This model is widely used in studies of this type, for example in the work of the NOAA Coastal Services Centre in the United States, and is considered appropriate for the purposes of this study.

The GIS model was based on the 'cost-distance' technique which allows modelling of inundation from the coast to where there is a physical 'flow' through the DEM surface. For instance the model would not inundate areas, such as landward of a stop bank, even if the land was below the specific inundation elevation.

There are limitations to this approach particularly that it does not consider any dynamic or changing coastal processes, which could change areas of inundation and its duration. However, it is suitable to provide high level extents of inundation hazard and is commonly applied as a first order assessment (AGDCC, 2009).

Inundation zones at 0.1 m intervals from 1.7 m to 5.2 m above WVD have been created based on the modified DEM.

No storm effect

With storm effect

Figure 15 Modified DEM used in the inundation modelling

f. Coastal Watershed

While no modelling of wave overtopping has been undertaken, an estimate of possible extent is provided by identifying the coastal watershed. The coastal watershed, is the area that is likely to drain to the coast as opposed to draining land ward and to a water course. Note that the watershed is derived from the LiDAR topography only and does not include influence of storm water infrastructure. The inundation due to the 3 scenarios of Sea level rise are shown in the following Figures (No storm effects and with storm effects. Table below shows the area affected by the inundation.

The inundation due to the 3 scenarios of Sea level rise are shown in Figure. (No storm effects and with storm effects). Table below shows the area affected by the inundation.

Table 12 Inundation area

Scenario	**Area – no storm effects (ha)**	**Area – with storm effects (ha)**
1 – SLR 1.0 m	418	903
2 – SLR 0.5 m	141	737
3 – SLR 1.5 m	695	1016

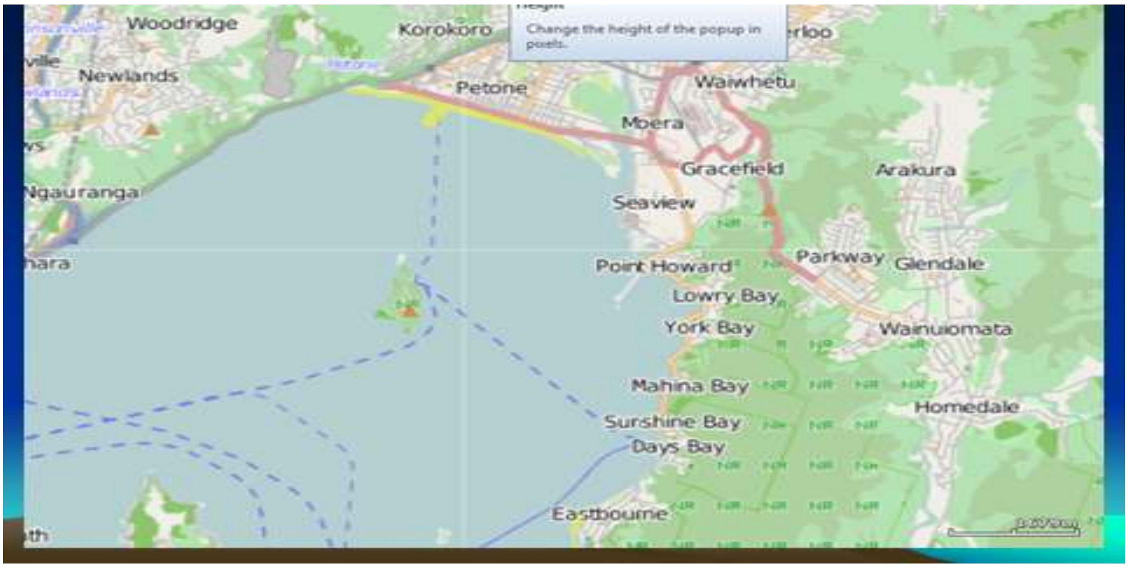
g. Loss of the land due to sea level rise

Estimated land loss of the land varies from 0.84 km^2 for 0.5m increases up to 1.70 km^2 for the increase of 2.0 m. The area of inland part of the LHGZ is 26.2 km^2, therefore the loss of the land expressed in percentage is varying from 3.23% to 6.51%. The results are presented below.

Sea level increase (m)	***Loss of the land (km^2)***	***Percent of inland of the LHGZ lost due to sea level rise (%)***
0.5	0.84	3.23
1.0	1.17	4.49
1.5	1.45	5.54
2.0	1.70	6.51

Inundation pattern as sea level rises is given sequentially in the following diagrams.

Yellow colour indicating inundation area as sea level rises.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Korokoro
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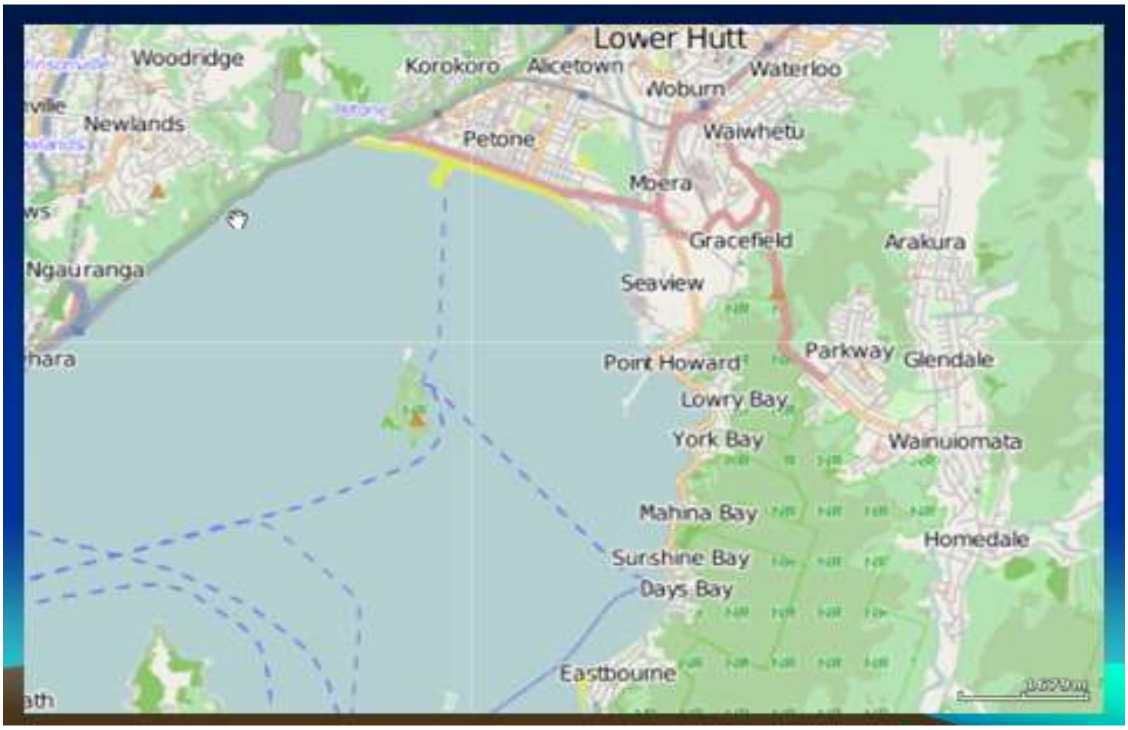
Newlands
Petone
Waiwhetu
Moera
Gracefield
Arakura
Ngauranga
Seaview
Point Howard
Parkway
Glendale
Lowry Bay
York Bay
Wainuiomata
Mahina Bay
Homedale
Sunshine Bay
Days Bay
Eastbourne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Woburn
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Moera
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Sunshine Bay
Days Bay
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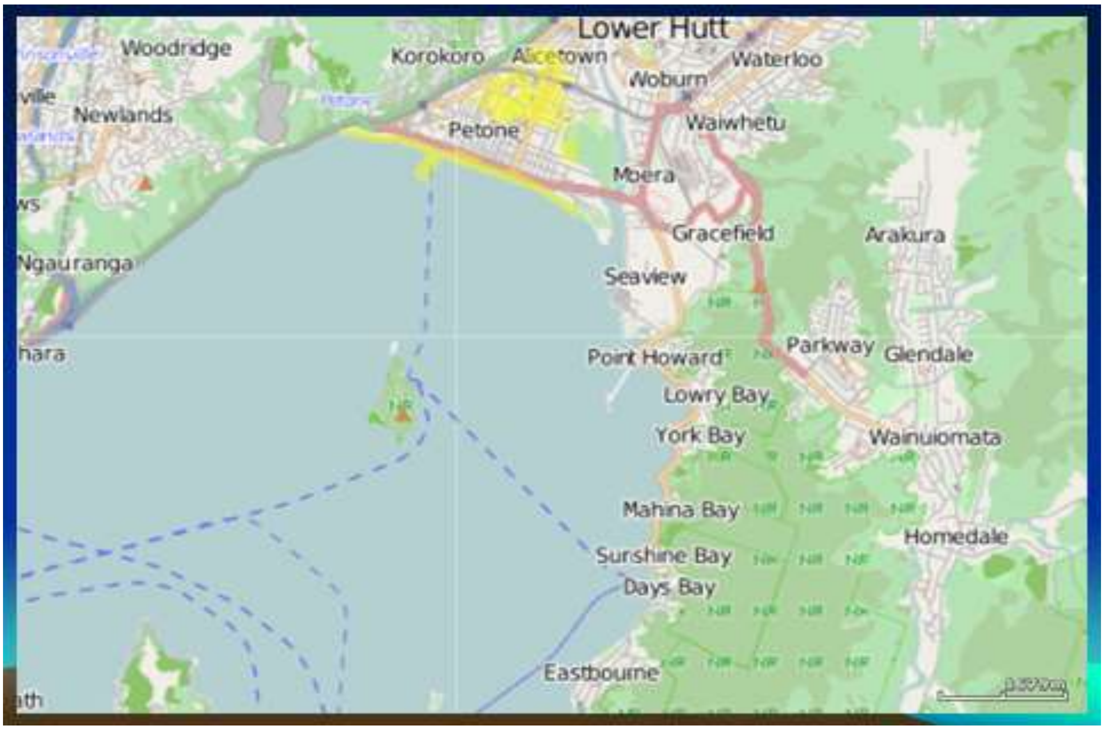
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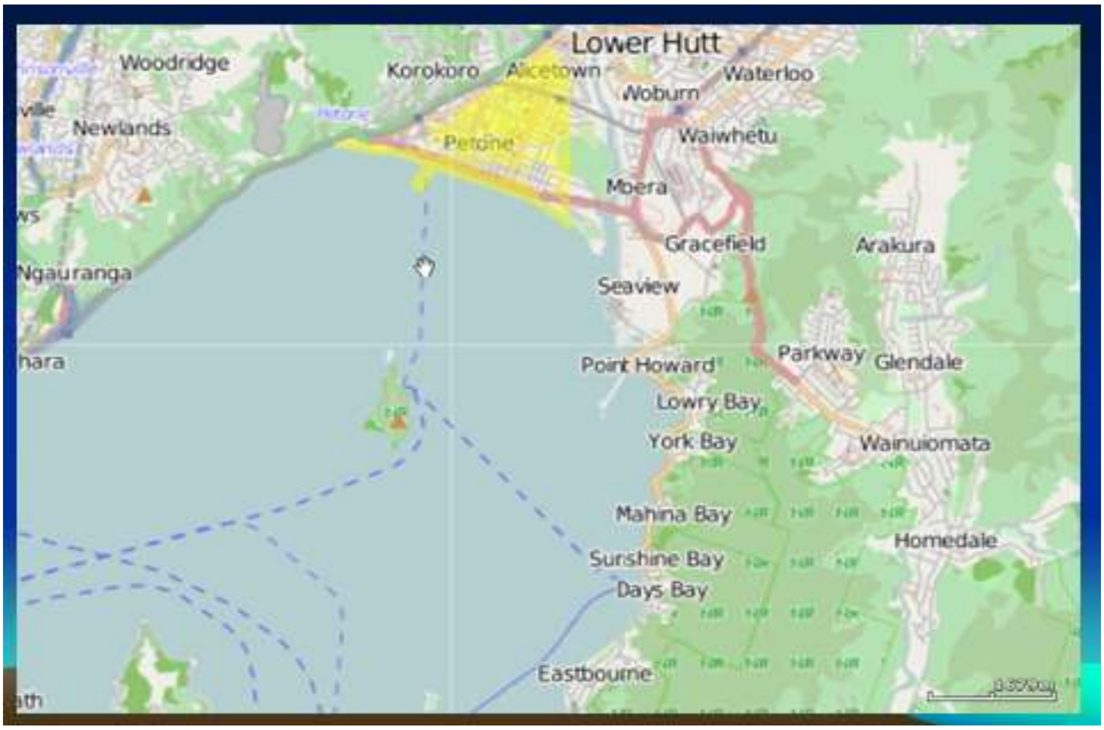
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h. Conclusion

Sea level rise scenarios with and without storm effects have been modelled using GIS. The range of SLR levels with and without storm effects shows the relative extents of land inundation. The GIS modelling is a simplistic approach to identifying possible risk areas and effects of infrastructure. The extents can be used to priorities areas for further inundation assessments. We recommend that further work is undertaken to provide better understanding of the extents and effects.

It has been estimated that as the sea level increases from 0.5m to 2 m the loss of land increases from 0.8 Km^2 to 1.7km^2 or the percentage of inland ground water zone lost varies from 3 to 6%.

5. Simplified Composite model

a. Introduction

It is evident that climate change and sea level change is occurring globally and that this threatens coastal habitats round the world. While in some instances resources such as finance, knowledge, data and skill is available, in most instances we lack one or many of these elements a vital criteria for accurate forecast and prediction of sea level change and its impact on water resources as well as land surface. The previous chapters dealt with use of cutting edge knowledge for the application, simulation and prediction of sea level change and its impact on land surface as well as ground water table. The situation at Wellington was analysed and its impact assessed. However as there are many instances and locations where either data, software or skill is unavailable and in such instances as it is yet required to simulate, forecast and predict in order mitigate and manage coastal zones subject to sea level change impacts a simplified composite model is needed.

The simplified model developed in this project will provide information on loss of land, effect on water table and rivers especially where data is scarce or unavailable. Its development adopts two approaches; one being a conceptual approach while the other is a mathematical approach.

The conceptual approach consists of parameters chosen at random to create a hierarchy of events within the climate system. It will provide estimates of how much land will be lost and how much effect climate change and sea-level rise will have on the water table using scenarios of 0.5m, 1.0m, and 1.5m sea level rise. The model achieved satisfactory results in comparison tests carried out, although it is based on only a few parameters and some assumptions, it hopes to shed some more light into the climate change phenomenon and help in the decision making process of choosing well suited adaptation methods even in situations when data is sparse.

The mathematical approach method proposed to estimate the changes occurring in these areas, initially sea level changes using linear regression method. Changes to land and water table in Wellington New Zealand were simulated, modelled and a simple model was developed thereafter using this data to estimate changes. The model was validated using a different data set series. This model could now be used to easily estimate the changes to ground water and land loss in other coastal zones, particularly where data is sparse and technical knowhow on modelling is limited, which is generally the case in most areas.

b. The Conceptual approach Model design

For the purpose of this work, some climate change elements have been highlighted for consideration and figure below provides a visual of these components. Changes in these elements or parameters have an important part to play in the cycle of events resulting in sea-level rise and the apparent loss of land.

Variations in these parameters will determine the effect of climate change and sea-level rise on the water table, rivers, land and ultimately describe the relationship between climate change and sea-level rise for a particular area.

The pyramid in figure also shows the series of events that occur with climate change residing at the top. As described in literature, climate change results in temperature increase while also increasing oceanic temperature causing thermal expansion and altering rainfall patterns to bring about sea-level rise.

Sea-level rise on the other hand affected by local parameters such as local topography, hydrological patterns, storm patterns, localized global average temperature effects and tectonic movements or subsidence will result in effect on water table, loss of land and effect on rivers.

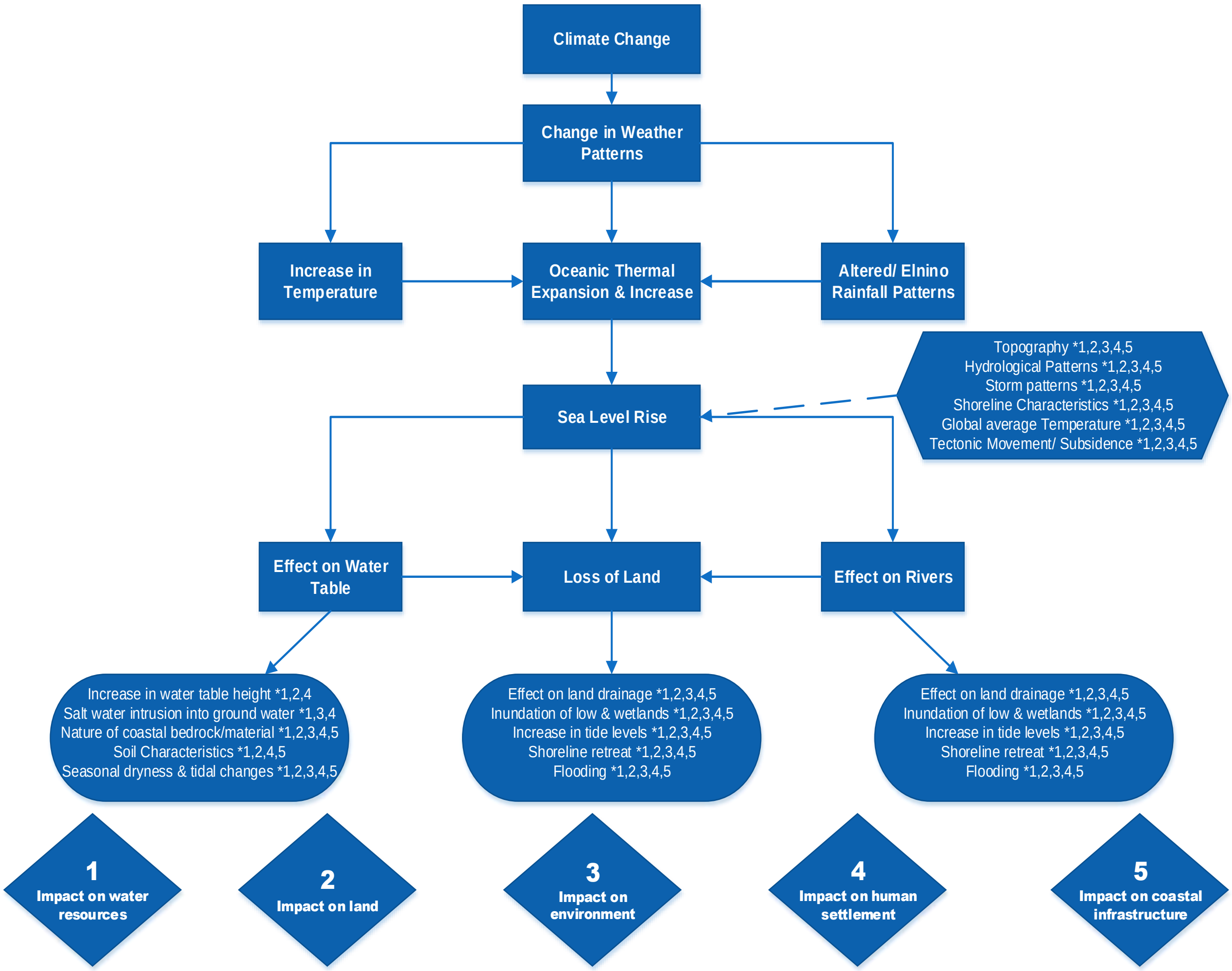


Figure 16 Simplified model showing some components of climate change and sea level rise

Effect on water table

Sea-level rise will affect the local water table by increasing its height, by causing an intrusion of salt water into groundwater and the intensity of these effect will depend on factors such as the nature of the coastal bedrock material, seasonal dryness and tidal changes, hydrological and soil characteristics, and as shown in figure, numbers have been assigned to these factors from 1 to 5 based on respective impacts.

Effect on Loss of land

Sea-level rise will result in loss of land and amount of land lost will also depend on local parameters such as local topography, hydrological patterns and storm patterns with loss of land in relation to the pyramid in figure 4.1, ultimately caused by secondary factors such as flooding, shoreline retreat, increase in tide levels, inundation of low and wetlands, and effect on land drainage. Numbers have also been assigned to these factors in figure, from 1 to 5 based on respective impacts.

Effect on rivers

Sea-level rise affects rivers by causing an intrusion of salt water into river networks disrupting river ecosystems and flow patterns. As shown in figure, this is also as a result of secondary factors such as flooding, shoreline retreat, inundation of low and wetlands, and effect on land drainage. Numbers have also been assigned to these factors in figure, from 1 to 5 based on respective impacts.

Parameterization of Conceptual model

One of the objectives of this project is to obtain an estimate of the effect of sea level rise on land and water resources. For the purpose of this model, the following assumptions have been made:

- 90% conversion for all parameters.
- Values are assigned to parameters from a rating scale of 0 -100 or 0-1000 as listed in table below.

Table 13 Parameters rating scale

Level	Parameter	Rating
1	Climate Change	0-100
2	Change in Weather Patterns	0-100
3	Increase in Temperature	0-100
3	Oceanic thermal expansion & increase	0-100
3	Altered/Elnino Rainfall Patterns	0-100
4	Sea Level Rise	0-1000
5	Effect on water table	0-1000
5	Loss of land	0-1000
5	Effect on Rivers	0-1000

As shown in table above, each parameter has been assigned a level relative to their position in the pyramid earlier described in figure. As the cycle of events occurs down the pyramid from one level to the other, there is a conversion rate of 90% and in levels where there are two or more parameters such as in levels 3 and 4, the conversion factor is split evenly among the residing parameters.

Conversion table

Numerical estimates of resulting effects have been obtained using a conversion table, which provides equivalents for each parameter and their respective units of measure. Figure below provides a side-by-side view of the pyramid and a sample conversion table showing relevant parameters.

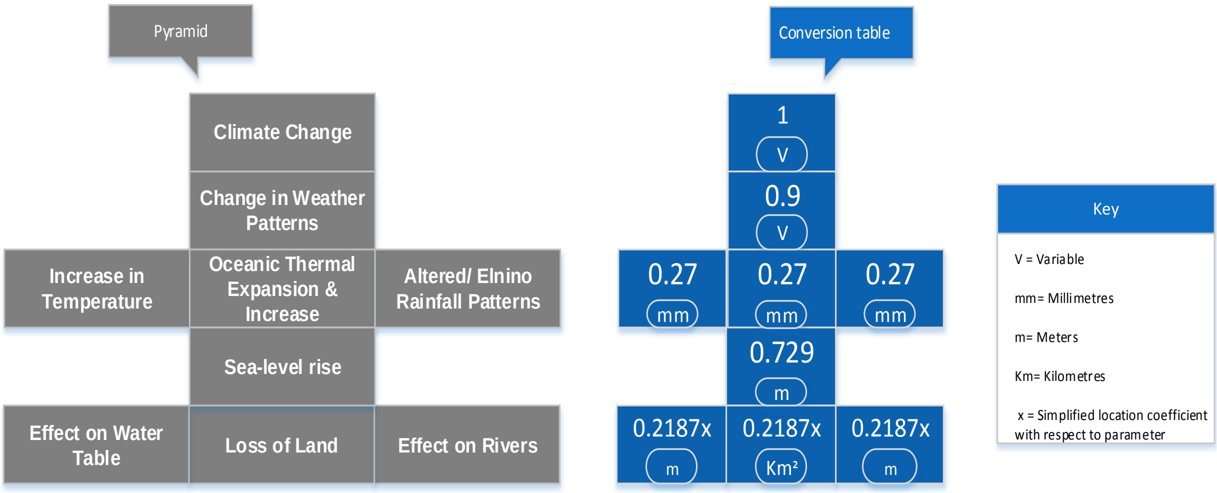


Figure 17 Climate change pyramid and sample conversion table showing relevant parameters

From the conversion table (see figure below), a climate change effect rating of 1 (one) on a scale of 1-100 will result in an equivalent land loss of approximately 200cm. At level 1, climate change will produce a 'change in weather patterns' effect of 0.9 at level 2, which also then converts at 90% to 0.81 split equally among the level 3 parameters (Increase in temperature, oceanic thermal expansion & increase, and altered/el-nino rainfall patterns) at 0.27 each.

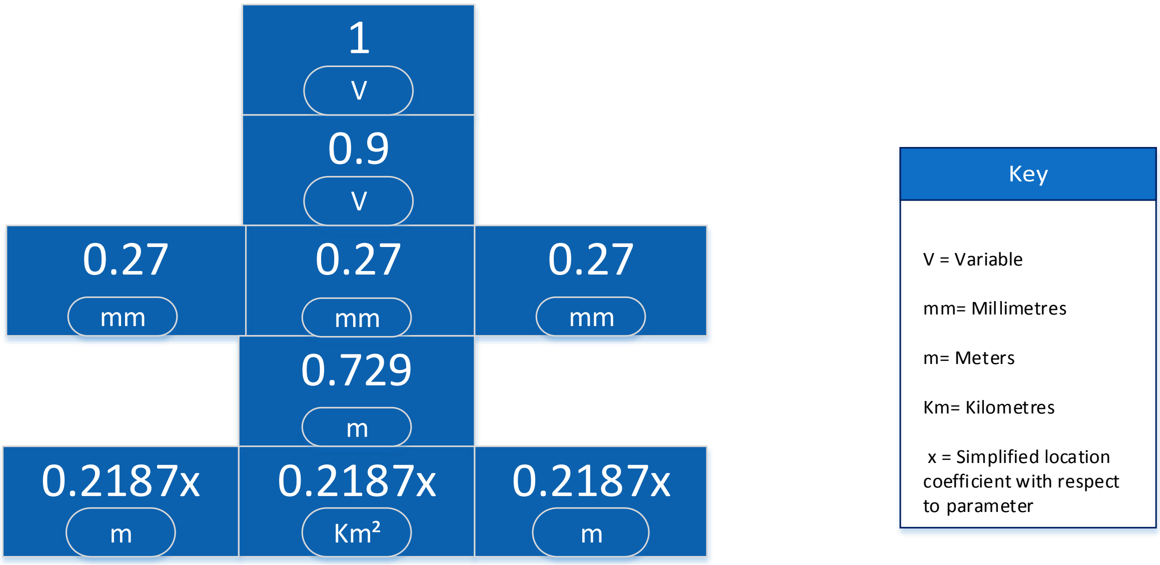


Figure 18 A conversion table showing values obtained from a climate change effect rating of 1.

The sum of estimates obtained for level 3 parameters (0.81) is then converted at 90% to produce a sea-level rise of 0.729, which also converts at 90% to cause the effects at level 5. The intensity or scale of the parameters at level 5 (effect on water table, loss of land & effect on rivers) will be subsequently determined by a multiple of x, which is the location coefficient with respect to the parameter.

Model testing & Results

Using data from Wellington & considering scenarios 1, 2 & 3 of 0.5m, 1.0m & 1.5m sea-level rise with no storm effects, land loss in Km² was calculated for all 3 (three) scenarios as shown in figure below.

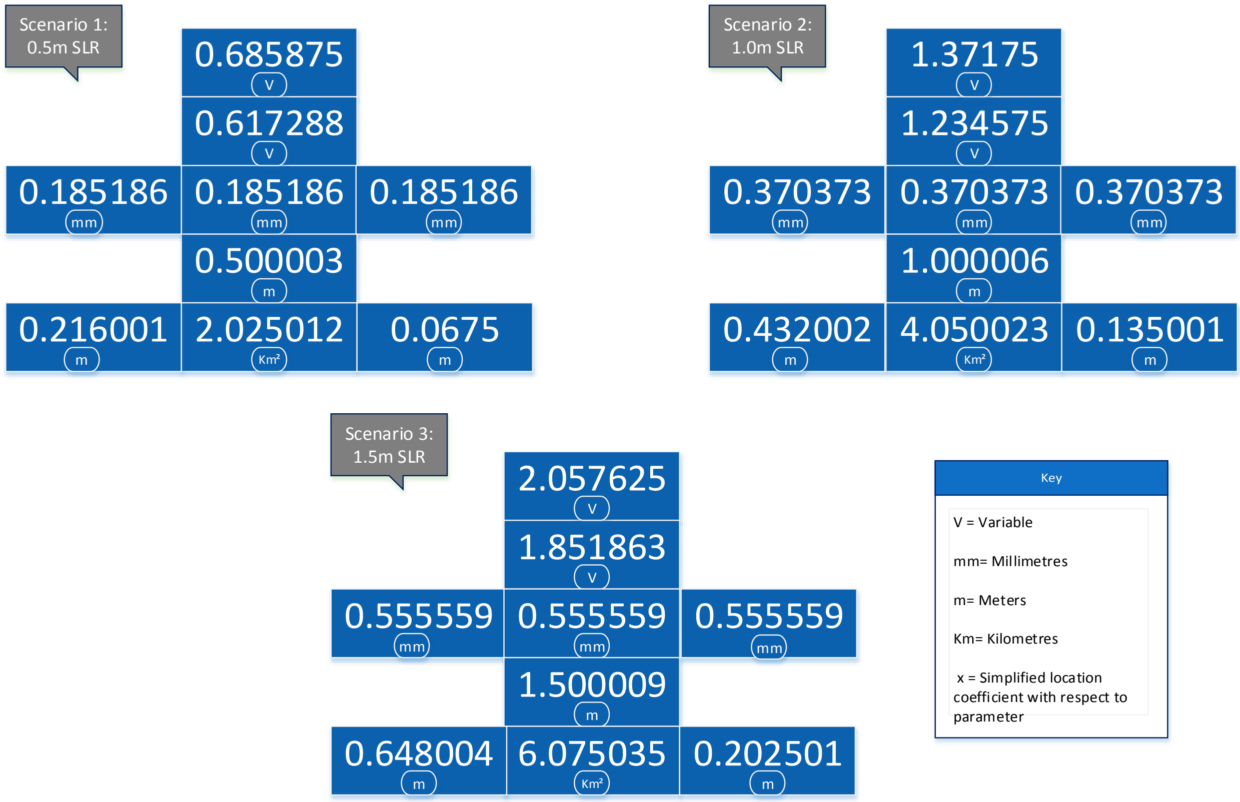


Figure 19 Conversion tables showing results obtained from scenarios 1, 2 & 3 of 0.5m, 1.0m, & 1.5m SLR.

Considering scenario 1 of 0.5m sea-level rises, climate change occurred at a rate of 0.68 on a scale of 0-100, resulting in an equivalent land loss of 2.02km². Scenario 2 of 1.0m sea-level rise resulted from climate change at a rate of 1.37 on a scale of 0-100, affecting 4.05km² of land while scenario 3 of 1.5m sea-level rise occurred due to climate change at a rate of 2.05 on a scale of 0-100 thereby causing a land loss of 6.07km².

Table 14 Comparison of Wellington & Model data

Scenario	SLR (m)		Wellington	Model
1	0.5	Loss of land (Km^2)	1.14	2.02
2	1.0		4.18	4.05
3	1.5		6.95	6.07
1	0.5	Effect on water table	0.00 - 0.17	0.21
2	1.0		0.39 - 0.61	0.43
3	1.5		0.76 - 0.98	0.65

Table above provides shows a comparison chart for values obtained from Wellington and those obtained from the model. With a close look at the values for loss of land, we can tell that model values seem within reasonable tolerance of the estimated values for Wellington. Although model estimate (loss of land) for scenario 1 (2.02Km^2) is somewhat higher than its equivalent Wellington value (1.14Km^2), adaptation measures provided against the model value will definitely address both estimates but maybe at a slightly higher cost.

Effect on water table (in meters) was also calculated using Wellington values for scenarios 1, 2 & 3 of 0.5m, 1.0m & 1.5m sea-level rise and the results (see table 3.2) also show model values to be within reasonable tolerance of the estimated values for Wellington. Model values obtained for scenarios 1, 2 & 3 of 0.5m, 1.0m & 1.5m sea-level rise were: 0.21m, 0.43m and 0.65m respectively.

Discussion

The simplified model designed, described the theory of climate change resulting in an increase in global temperature thereby giving rise to an increase in sea level. It also shows how sea level rise coupled with a few other parameters cause loss of land in coastal areas as well as effect on rivers and water table.

A conversion table was also developed to calculate the how much land is lost due to climate change and sea-level rise. The model was tested with values obtained from the Wellington region for scenarios 1, 2 and 3 of 0.5m, 1.0m and 1.5m sea-level rise and these provided satisfactory results in comparison with the Wellington data.

Estimates were obtained for loss of land but a few key points of note during model development were the assumptions made such as conversion at 90%, and the assignment of units to parameters. These may in some way affect the reliability or integrity of the model as there were also limitations with regards to parameters, especially when only a few were considered. As stated by Nicholls & Casenave (2010), thermal expansion accounted for about 25% of the observed SLR since 1960 and about 50% from 1993 to 2003. However with this model, thermal expansion was a major player accounting for sea-level rise to a large extent. Other dynamic factors or changing coastal processes like changes in inundation area and duration were also not taken into account.

Effect on water table (in meters) was also calculated using Wellington values for scenarios 1, 2 & 3 of 0.5m, 1.0m & 1.5m sea-level rise and the results (see table 3.2) also show model values to be within reasonable tolerance of the estimated values for Wellington. Model values obtained for scenarios 1, 2 & 3 of 0.5m, 1.0m & 1.5m sea-level rise were: 0.21m, 0.43m and 0.65m respectively.

Predicting sea-level rise impacts as a result of climate change is complex, and simple models are mostly of limited use. However, the simplified conceptual model designed in this project produced satisfactory results in comparison with available data and will help in the decision making process of what adaptation methods to employ or implement in certain coastal areas. Although models like these are based on assumptions of the impact of climate change and a few parameters, they shed some light into the climate change phenomenon, bringing it to the forefront and encouraging coastal authorities to take necessary action.

c. The Mathematical approach model design

Previous chapters dealt with research studies of land loss and changes to groundwater table in Lower Hutt region for sea level rise using sophisticated model simulation. Here a mathematical approach simplified composite model is developed by using linear regression method. Simplified model of sea level increase is developed based on sea level prediction.

It has been shown that Global sea level is rising at a steady rate with 3.1mm each year and which will continue for at least decade (Climate Institute, 2010). Another research states that between AD 1500 – AD 1900, sea level accelerated by 0.3 +- 0.3 mm every year in New Zealand. (Roland Geherls, W., Hayward, B., Newnham, R., Southall, K., 2008). Global average sea level rise's has accelerated since 1880 and has been about 0.009 +- 0.003 mm per year^2, noticed that this figure increased since 1970 as 0.09 mm/year^2 till 0.12mm/year^2 in 1990. (Church, J. & White, N., 2011)

<u>Sea level rise prediction</u>

Relationship between number of year since 1990 and sea level rise express as:

$$X = V_s N + A_s (N^2 - N) / 2$$

Where

N = Number of year since 1990 (N = current year – 1990, e.g. current year is 2015 then,

N = 2015 – 1990 = 25)

X = Sea level rise since 1990 (mm)

V_s = steady rate of sea level rise, 3.1mm/year

A_s = Acceleration of sea level rise, 0.085mm/year

Hence,

$$X = 3.1N + 0.085(N^2 – N) / 2$$
$$= 0.0425N^2 – 3.0575N$$

This formula is based on chart shows in the following Figure 20 of mid-scenario.

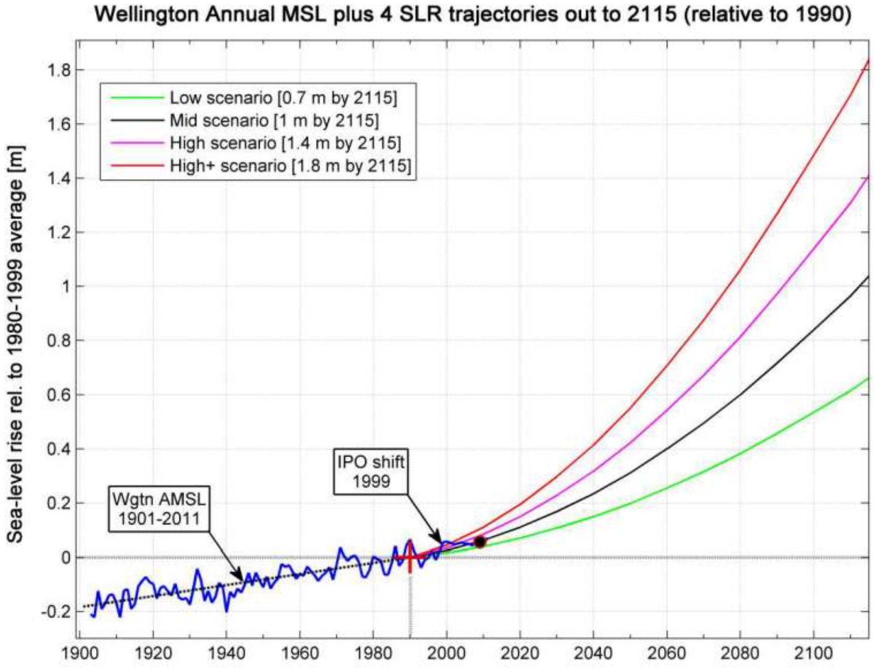


Figure 20 Mid-scenario

By having this formula, a full table was found indicating sea level increasing since 1990 up to 2115. Figure below depicts the trend of sea level increase projected according to the above calculation.

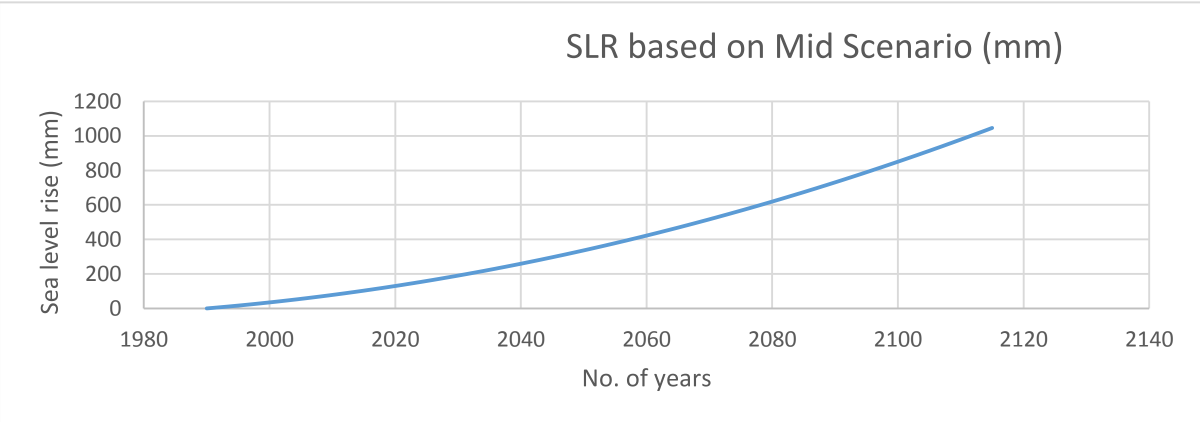


Figure 21 SLR model based on mid scenario

Following figure indicates the accuracy between the collected data from the above figure and the application of the simplified formula above.

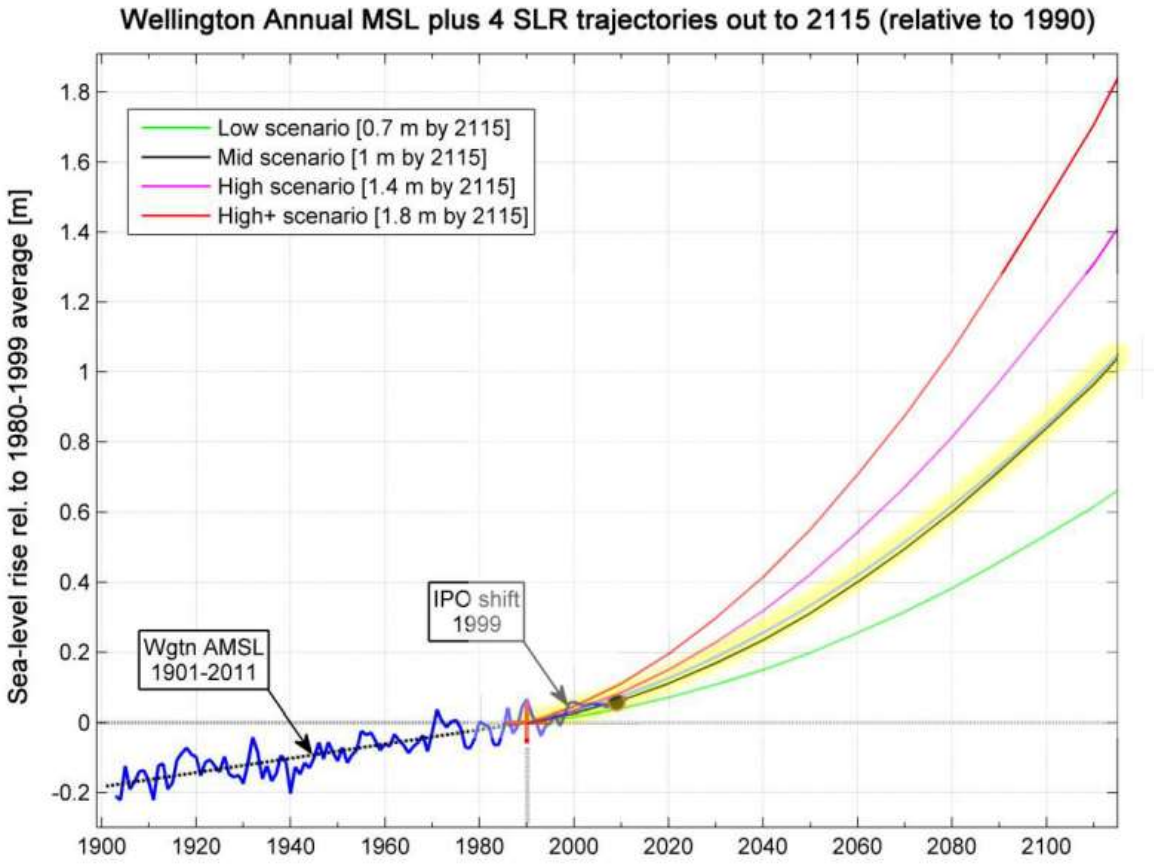


Figure 22 Comparison between original data and model result (light blue)

Table 15 Sea level rise prediction

Year	SLR (mm)
1990	0
1991	3.1
1992	6.285
1993	9.555
1994	12.91
1995	16.35
1996	19.875
1997	23.485
1998	27.18
1999	30.96

2000	34.825
2001	38.775
2002	42.81
2003	46.93
2004	51.135
2005	55.425
2006	59.8
2007	64.26
2008	68.805
2009	73.435
2010	78.15
2011	82.95
2012	87.835
2013	92.805
2014	97.86
2015	103
2016	108.225
2017	113.535
2018	118.93
2019	124.41
2020	129.975
2021	135.625
2022	141.36
2023	147.18
2024	153.085
2025	159.075
2026	165.15
2027	171.31
2028	177.555
2029	183.885
2030	190.3
2031	196.8
2032	203.385

2033	210.055
2034	216.81
2035	223.65
2036	230.575
2037	237.585
2038	244.68
2039	251.86
2040	259.125
2041	266.475
2042	273.91
2043	281.43
2044	289.035
2045	296.725
2046	304.5
2047	312.36
2048	320.305
2049	328.335
2050	336.45
2051	344.65
2052	352.935
2053	361.305
2054	369.76
2055	378.3
2056	386.925
2057	395.635
2058	404.43
2059	413.31
2060	422.275
2061	431.325
2062	440.46
2063	449.68
2064	458.985
2065	468.375

2066	477.85
2067	487.41
2068	497.055
2069	506.785
2070	516.6
2071	526.5
2072	536.485
2073	546.555
2074	556.71
2075	566.95
2076	577.275
2077	587.685
2078	598.18
2079	608.76
2080	619.425
2081	630.175
2082	641.01
2083	651.93
2084	662.935
2085	674.025
2086	685.2
2087	696.46
2088	707.805
2089	719.235
2090	730.75
2091	742.35
2092	754.035
2093	765.805
2094	777.66
2095	789.6
2096	801.625
2097	813.735
2098	825.93

2099	838.21
2100	850.575
2101	863.025
2102	875.56
2103	888.18
2104	900.885
2105	913.675
2106	926.55
2107	939.51
2108	952.555
2109	965.685
2110	978.9
2111	992.2
2112	1005.585
2113	1019.055
2114	1032.61
2115	1046.25

Land loss predictions

Land loss model due to sea level rise also has been divided into two parts, area effected by SLR and area effected only by storm. Analysis accordingly the result for Lower Hutt are as indicated in the following tables.

Scenario	Source	Sea level rise (m)	MHWS (m RL)	Sea level variability (m)	Storm effects (m)	Total no storm effects (m RL)	Total with storm effects (m RL)
1	Ministry of Environment (MfE 2008)	**1.0**	0.83	0.25	1.1	2.1	3.2
2	Min. of Env (MfE 2008) minus 0.5	**0.5**	0.83	0.25	1.1	1.6	2.7

Scenario	**Source**	**Sea level rise (m)**	**MHWS (m RL)**	**Sea level variability (m)**	**Storm effects (m)**	**Total no storm effects (m RL)**	**Total with storm effects (m RL)**
3	Min. of Env. (MfE2008) plus 0.5	**1.5**	0.83	0.25	1.1	2.6	3.7

Scenario	**Area – no storm effects (ha)**	**Area – with storm effects (ha)**
1 – SLR 1.0 m	418	903
2 – SLR 0.5 m	141	737
3 – SLR 1.5 m	695	1016

Scenario	SLR (m)	MHWS (m RL)		Sea level variability (m)	Storm Effect (m)	Total **no** storm effect (m RL)	Area - **no** storm effect (ha)	Delta of effect Area (ha)	Total **with** storm effect (m RL)	Area - **with** storm effects (ha)	Delta of effect Area (ha)	Area - storm effect (ha)
0	0	0.83		0.25	1.1	0	0		1.1			
2	0.5	0.83		0.25	1.1	1.6	141		2.7	737		596
								277			166	
1	1	0.83		0.25	1.1	2.1	418		3.2	903		485
								277			113	
3	1.5	0.83		0.25	1.1	2.6	695		3.7	1016		321

Loss of land area without storm effect climbs up in a certain rate (shows in chart as linear line), because of this, a linear model formula was developed as:

Where

Z = Land lost area (with no storm effect) (ha)

X = Sea level rise since 1990 (m)

Hence,

$$Z = (X-0.5) \times 554 + 141$$

$$= 554X - 136$$

The initial point of linear line states as:

Set Z as zero (0)

$$0 = 554X - 136$$

$$554X = 136$$

$$X = 136/554$$

$$= 0.245$$

Dash line in following graph shows the tendency of land loss area before sea level rise reach 0.5m, Inundation starts occurring in coastal area when sea level rise reach 0.245m (leaving out storm effect).

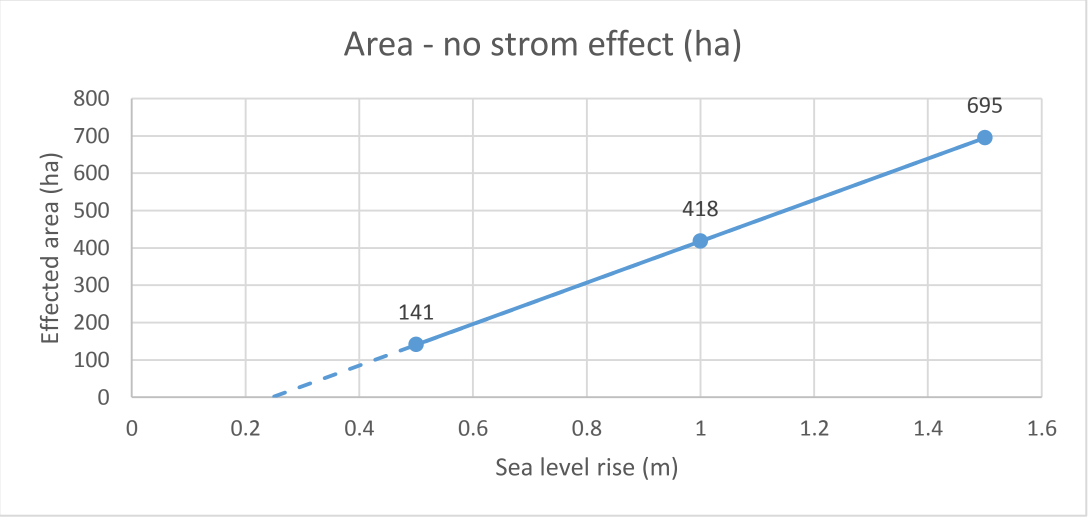


Figure 23 Effected area due to sea level rise with no storm

Land loss area effected by storm hinge on sea level, as mentioned, storm event is considered as additional 1.1 metres above mean sea level, loss of land impacted by storm effect states decrease whilst sea level climb up.

Dashed line represents collected data from Lower Hutt research, while orange solid line illustrates the trend based on original data. From figure below, until sea level rise up to approximately 2.2 metres, when sea level rise up to approximately 2.2 metres, storm effect on land lost will be ignored.

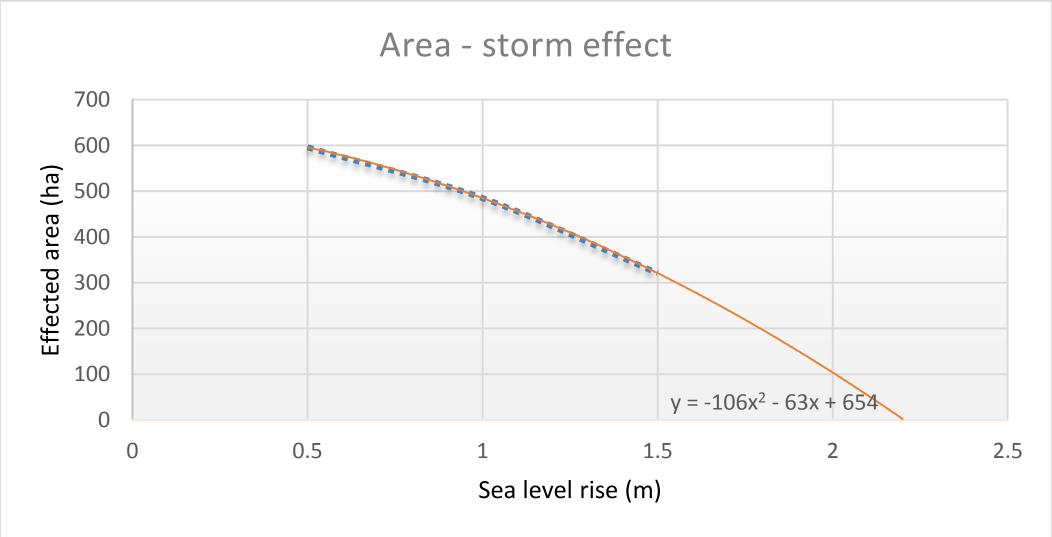


Figure 24 Effected area due to storm effect

Total land lost model can be explain by the following formula: Land lost = Area affected by SLR + Area affected by Storm. From results determined above, land lost area affected by SLR can be calculated as:

Where

X = Sea level rise (mm)

Z = Land lost area (with no storm effect) (ha)

Y = Land lost area (with storm effect only) (ha)

L = Total land lost area (ha)

Combine following two sections:

$Z = 554X - 136$

$Y = -106X^2 - 63X + 654$

Hence

$L = Z + Y$

$= (554X - 136) + (-106X^2 - 63X + 654)$

$= -106X^2 + 491X + 518$

According to expression above, relation between land loss and sea level rise is given in the following tables and illustrated in the graph below, when sea level reach about 2.3 metres, area of land lost begin to drop which is not acceptable, hence this expression only valid before sea level rise climb over 2.3 metres, which can still be used for approximately 250 years from now

Table 16 Land lost impaction due to SLR

SLR (m)	Land lost (ha)
0.5	737
0.6	774.44
0.7	809.76
0.8	842.96
0.9	874.04
1	903
1.1	929.84
1.2	954.56
1.3	977.16
1.4	997.64
1.5	1016
1.6	1032.24
1.7	1046.36
1.8	1058.36
1.9	1068.24
2	1076
2.1	1081.64
2.2	1085.16

2.3	1086.56
2.4	1085.84
2.5	1083
2.6	1078.04
2.7	1070.96
2.8	1061.76
2.9	1050.44
3	1037

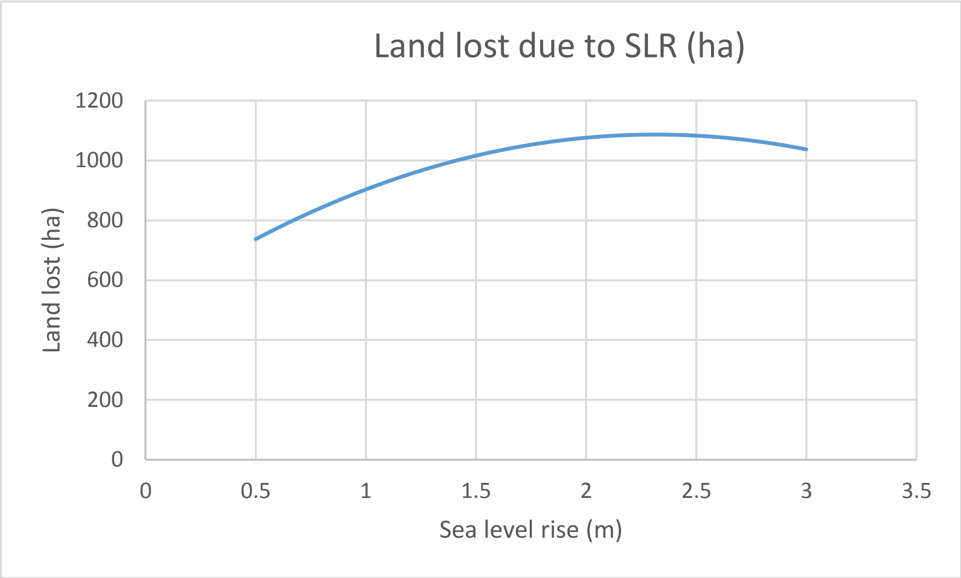


Figure 25 Total land loss due to SLR

Predictions for ground water table changes

Investigation of changes to groundwater table due to sea level rise simulated by FEFLOW 6.1, is as in the following table. 9 monitoring sites are chose in investigation, based on geographical different situation.

Table 17 Changes in water table due to SLR

Site Name	Scenario			
	1	2	3	4
	Increase (m)			
	0.5	1.0	1.5	2.0
	Change in water table (m)			
Somes Island	0.17	0.61	0.98	1.39
Hutt Recreation Ground	0.05	0.48	0.85	1.23
Randwick Reserve	0.11	0.54	0.91	1.31
Petone Centennial Museum (PCM)	0.13	0.56	0.94	1.34
Port Road	0.06	0.48	0.85	1.24
Bell Park	0.07	0.49	0.86	1.25
Hutt Valley Memorial Technical College (H.V.M.T.C)	0.04	0.47	0.833	1.22
Mitchell Park	0.00	0.42	0.78	1.17
Taita Intermediate	0.00	0.39	0.76	1.15

According to the main objective in this part, is to deliver a model which can be used to obtain idea of groundwater table rise in general costal area, couple of monitoring sites are out of investigation. Site number 5, 6 and 7 is excluded from analysis, according to their geographic location and simulated result from FEFLOW, a great amount of increased groundwater from sea level rise discharge via neighbouring river, simulated data looks irregular compare to others. Similarly, Site number 1 is out of consideration referring to its geographic location and analogic information.

Data of remaining 5 monitoring bore holes list in the following table analysed indicate a relatively parallel linear trend illustrated trend in table below. The main factor manipulates start point and end point is current groundwater level. Simulated groundwater level in LHGZ illustrates in the figure.

Table 18 Analysis table for changes to groundwater table due to SLR

	SLR Scenarios					
Site name	0.5	1	1.5	2	Gradient	GWL
1 - Somes Island	0.17	0.61	0.98	1.39		
4 - Petone Centennial	0.13	0.56	0.94	1.34	0.802	2.9
3 - Randwick Reserve	0.11	0.54	0.91	1.31	0.794	4.3
2 - Hutt Recreation Ground	0.05	0.48	0.85	1.23	0.782	5.3
8 - Mitchell Park	0	0.42	0.78	1.17	0.75	7.5
9 - Taita Intermediate	0	0.39	0.76	1.15	0.76	8.8
5 - Port Road	0.06	0.48	0.85	1.24		
6 - Bell Park	0.07	0.49	0.86	1.25		
7 - Hutt Valley Memorial Technical College	0.04	0.47	0.833	1.22		

Note: Yellow fill = excluded from analysis

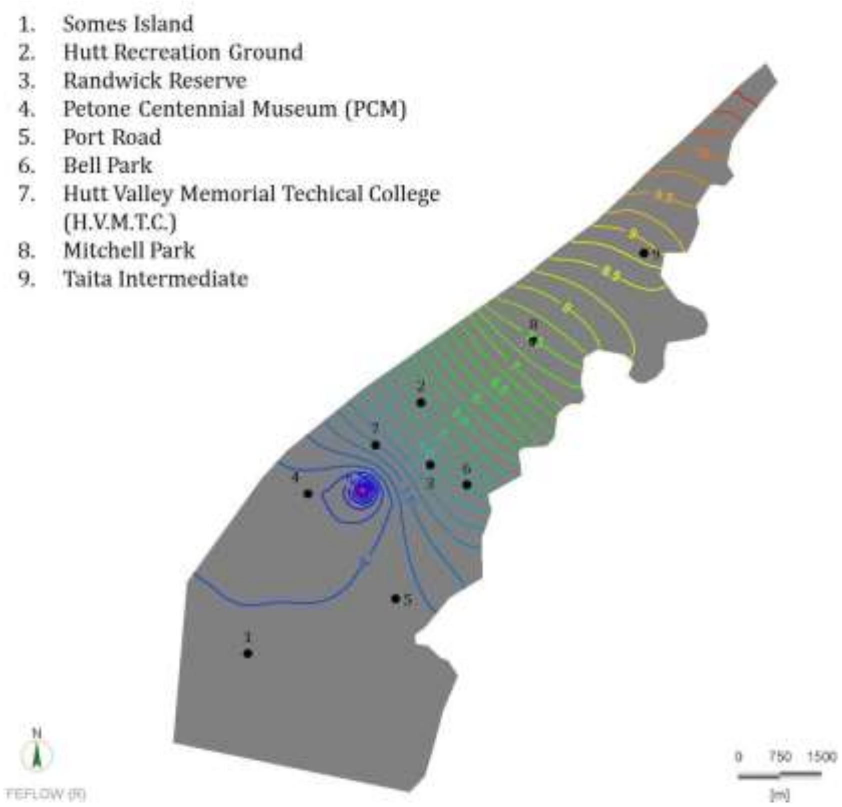
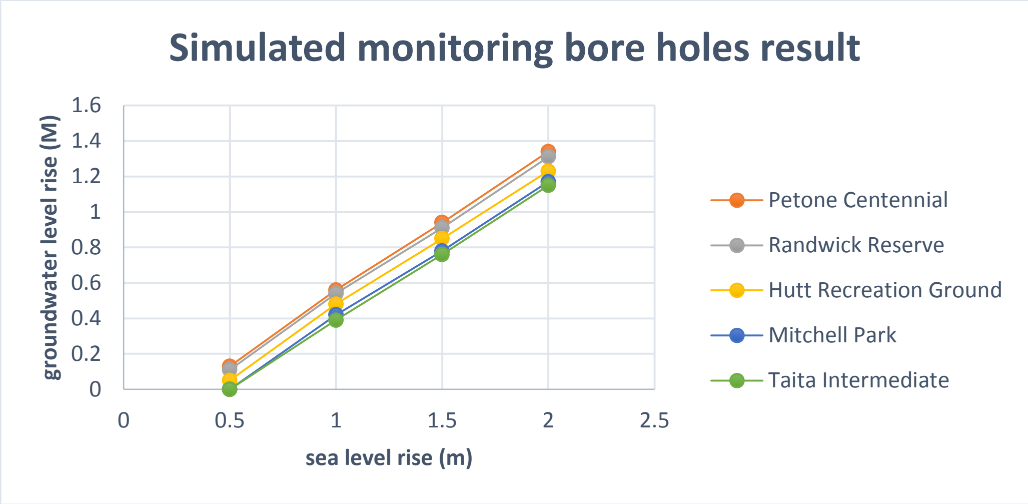


Figure 26 Pattern of simulated monitoring bore hole - groundwater level



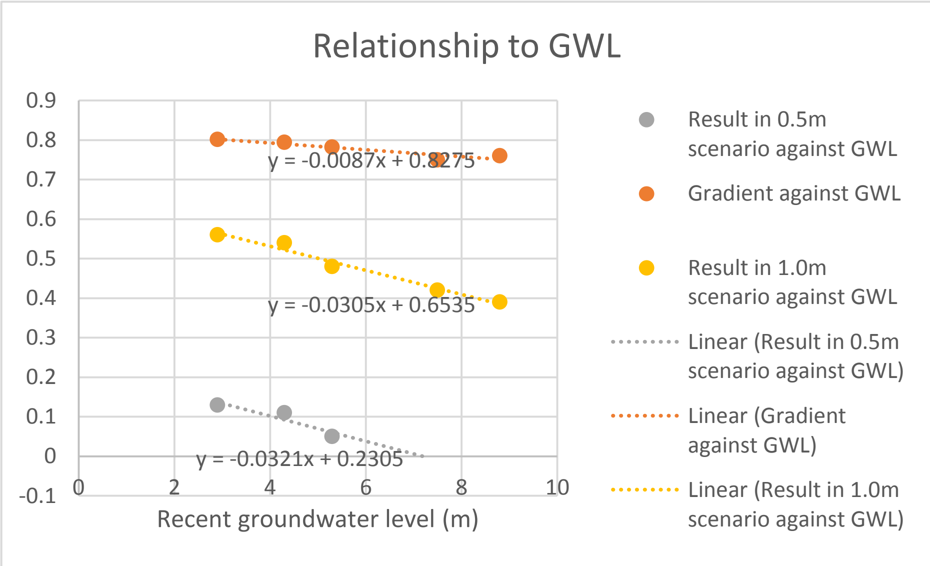


Figure 27 Relationship sea level rise scenarios, 0.5, 1.0m trend gradient and original groundwater level

GC = aX + b

Where:

GC = Groundwater elevation changes (m)

X = Sea level rise (m)

a = -0.0087GWL + 0.8275

GWL = Current groundwater level (m)

Assume:

Sea level rise = 0.5 m

-0.0321GWL + 0.2305 = 0.5 x (-0.0087GWL + 0.8275) +b

Then:

b = -0.02775Z – 0.18325

Hence:

GC = (-0.0087GWL + 0.8275) X – (0.2775GWL + 0.18325)

Change unit of GC from metre to millimetre:

GC = (-8.7GWL + 827.5) X – (27.75GWL + 183.25)

Comparison with other sites

The mathematical model to calculate land loss and groundwater table changes are compared with some other simulated situations, investigated in some others place of world.

Land loss

Study taken by Yale school (Wei-shiuen Ng & Robert Mendelsohn, 2005), estimate the vulnerability of Singapore under the fact of sea level rise in the future. Sea level rise scenarios had been adopted from IPCC 2001, figure shows below (Church et al., 2001). High scenario of 0.86m by 2100 is used in simulation of area of land lost in selected 10 coastal area including: CBD, Loyang, Marine Parade, Sentosa, Pulau Bukom, Keppel Harbor, Jurong, Tuas, Kranji, and Woodlands.

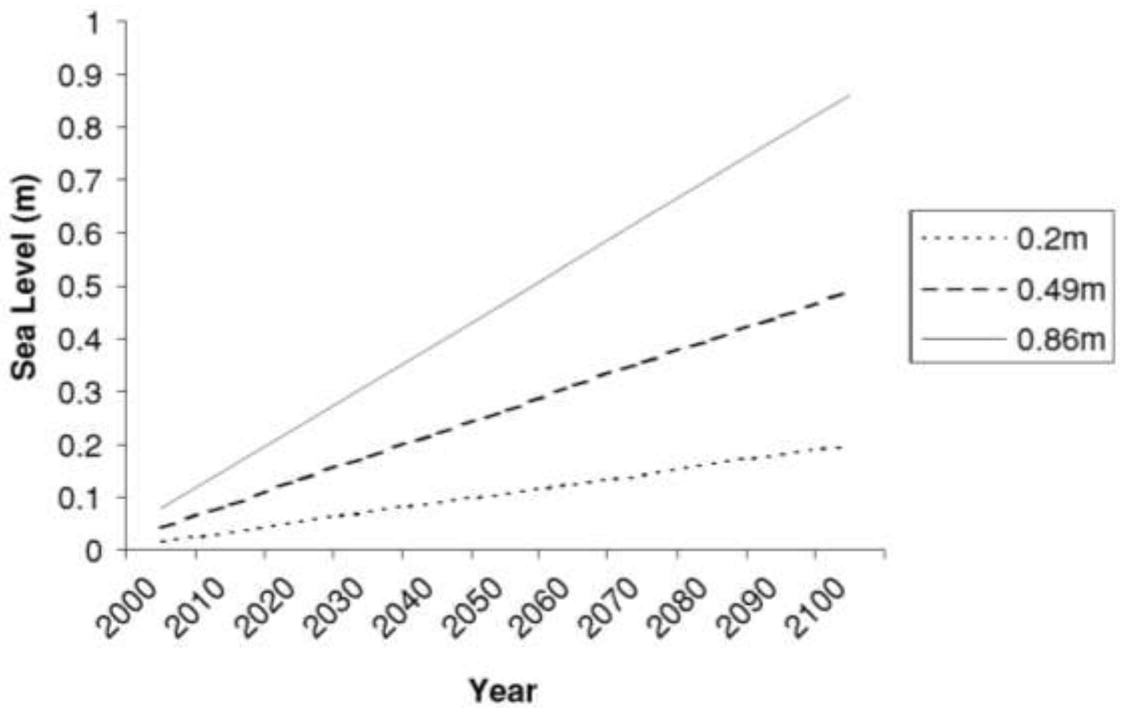


Figure 28 Three scenarios adopted in Singapore sea level rise impaction study

Table of inundation area in ten coastal sites are as shown below (Wei-shiuen Ng & Robert Mendelsohn, 2005).

Table 19 Ten coastal inundation area in Singapore (0.86m scenario)

Year	Sentosa	Keppel Harbor	Loyang	Wood lands	Kranji	Marine Parade	Tuas	Jurong	Pulau Bukom	CBD
2000	0.01	0.02	0.05	0.05	0.07	0.09	0.1	0.11	0.2	0.2
2010	0.02	0.05	0.1	0.11	0.14	0.18	0.2	0.22	0.39	0.4
2020	0.03	0.07	0.14	0.16	0.21	0.27	0.3	0.33	0.59	0.6
2030	0.04	0.09	0.19	0.21	0.28	0.36	0.4	0.44	0.78	0.8
2040	0.05	0.12	0.24	0.26	0.35	0.45	0.5	0.55	0.98	1
2050	0.06	0.14	0.29	0.32	0.42	0.54	0.6	0.66	1.17	1.2
2060	0.07	0.16	0.34	0.37	0.49	0.63	0.7	0.77	1.37	1.4
2070	0.08	0.18	0.39	0.42	0.56	0.72	0.8	0.88	1.56	1.6
2080	0.09	0.21	0.43	0.47	0.63	0.81	0.89	0.99	1.76	1.8
2090	0.1	0.23	0.48	0.53	0.7	0.9	0.99	1.1	1.95	2
2100	0.11	0.25	0.53	0.58	0.78	0.99	1.09	1.24	2.15	2.19

Storm effect is not included in the simulation. Area of land lost is increase steadily with interval of every 10 years. Comparing of ten series of data into same chart against timeline, it shows 10 linear line growing with different gradient. Main reason responsible to diversity is site elevation.

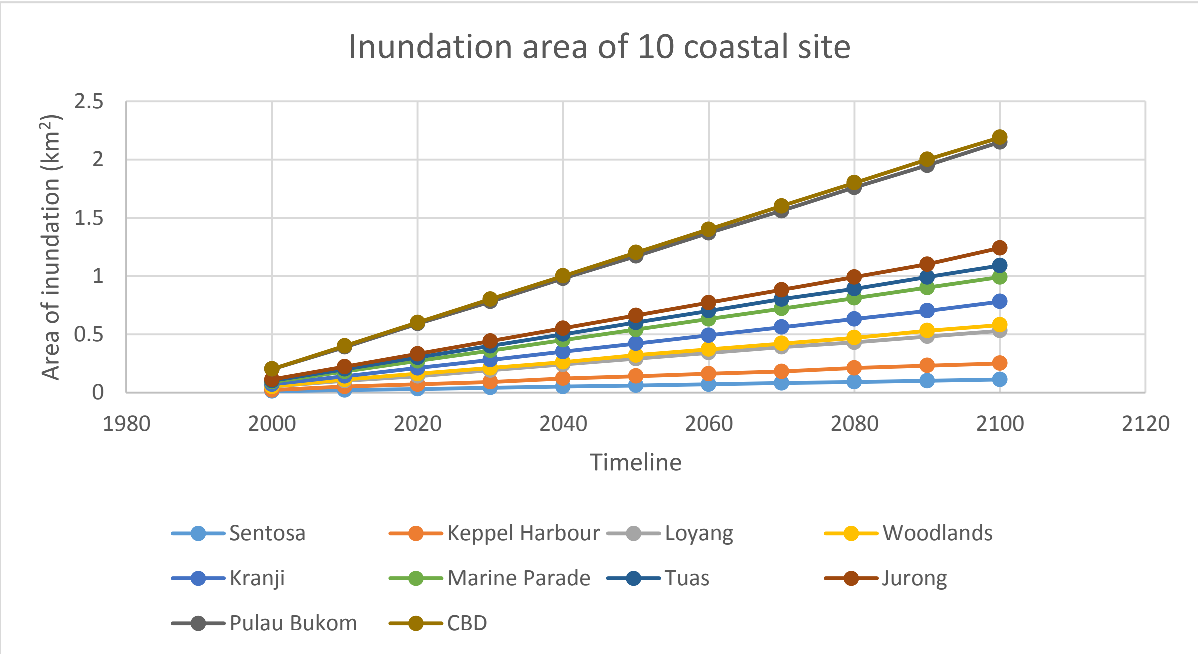


Figure 29 Inundation area of 10 coastal site

Singapore CBD is selected in comparison with the simplified model regarding to two reasons:

1. Plan view of Lower Hutt and Singapore CBD see as below, both of two have river cross through the whole area, which open a channel to have more area to be inundated while sea level rise.
2. Average elevation of Singapore CBD has the least average elevation compare to other 9 coastal sites, and also it is the closest to the average elevation of Lower Hutt town centre.

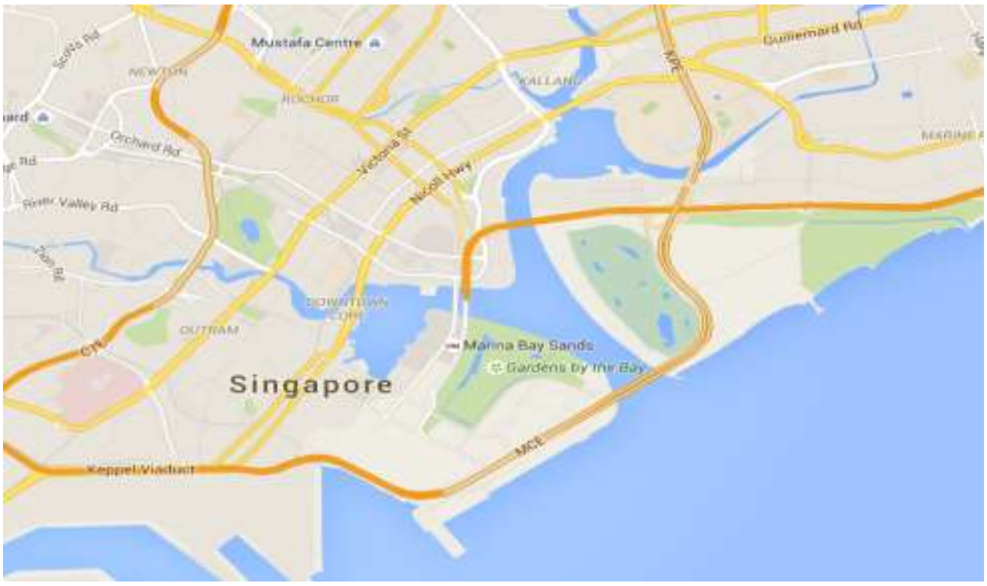


Figure 30 Overlook of Singapore CBD

Figure 31Overlook of Lower Hutt region

Following graph illustrates the comparison between inundation area calculated by land lost model (blue) and Singapore CBD assumption (yellow). Referring to current sea level, erosion hasn't occurred in any coastal area, a conservative model has been updated from original land lost model, by adding a constant number C at the end of the formula (green). New conservative model express as below:

$Z^* = Z + C$

$= 554X – 136 + C$

Where:

Z^* = Conservative model to adapt Singapore assumption (ha)

Z = Land lost area (ha)

X = Sea level rise (m)

C = Constant figure in order to allow original land lost model start counting lost land from 2015, take as 0.4736 km2 or 47.36 hectares

Hence:

$Z^* = 554X – 136 + 47.36$

$= 554X – 88.64$

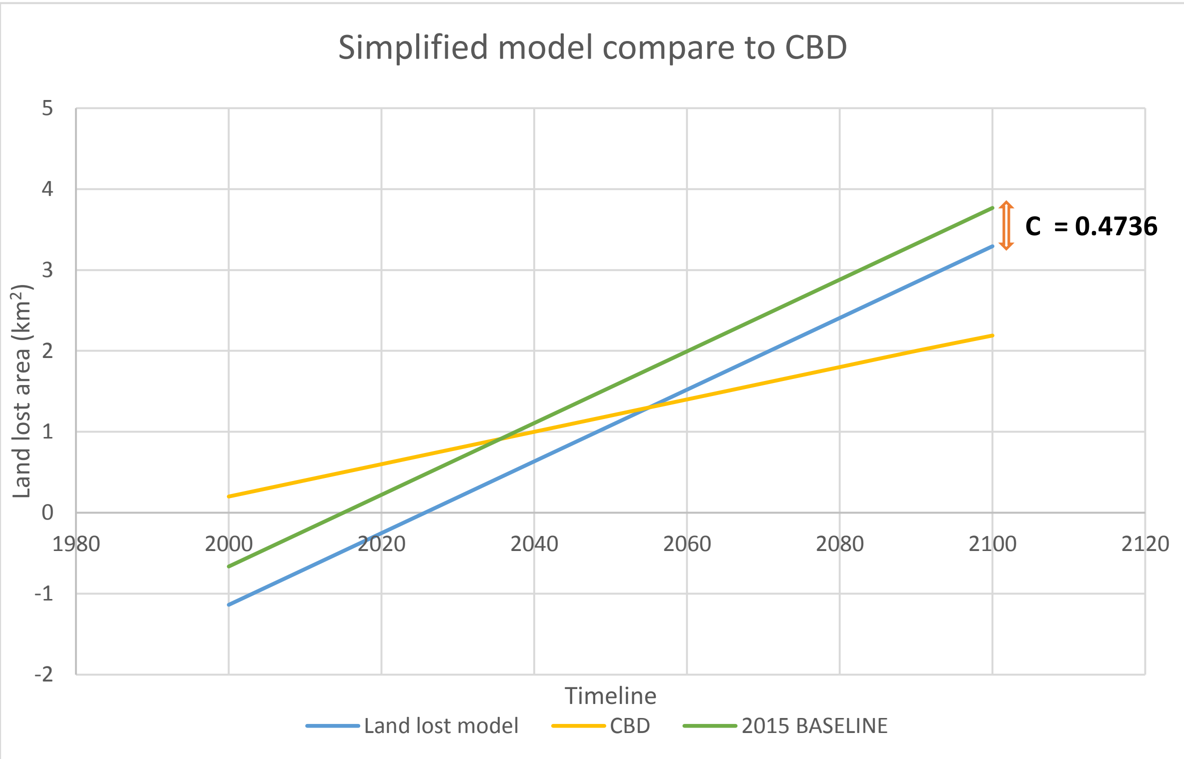


Figure 32 Comparison between land loss model, CBD assumption and conservative model based on identical sea level rise assumption

Primary factor triggers the different gradient between land lost conservative model (green) and Singapore CBD assumption showing on the chart, is disparity of average elevation. Lower Hutt region has average elevation of 4 metres whereas Singapore CBD built on the ground with elevation of 6 metres higher. In terms of topography, Lower Hutt centre city is in the middle of basin, with one side opening towards ocean, where raising sea water is more easily flood into. Nevertheless, the foundation of Singapore CBD described as combination of brae (with elevation of over 25 metres) and plain (with elevation of lower than 10 metres), which play a pivotal role in resisting excess sea water. Moreover, Lower Hutt region contains more space of 95 km^2 than Singapore CBD, latter only possess 40 km^2. With same percentage of land lost, Lower Hutt region actually suffers greater threat.

Groundwater table changes

Research emphasis on global warming and sea level rise effect on groundwater, investigation took place in Southern Finland, undertaken by Geological Survey of Finland (Samrit Luoma & Jarkko Okkonen, 2014). Likewise, two scenario bases of sea level rise have been applied in the study, in terms of different time period (between 2021 to 2050 and 2071 to 2100) and recognised (high and medium), shows in following table. Modelling software MODFLOW -2005 is used in this study, in order to simulate the influence of sea level rise on groundwater table in coastal area.

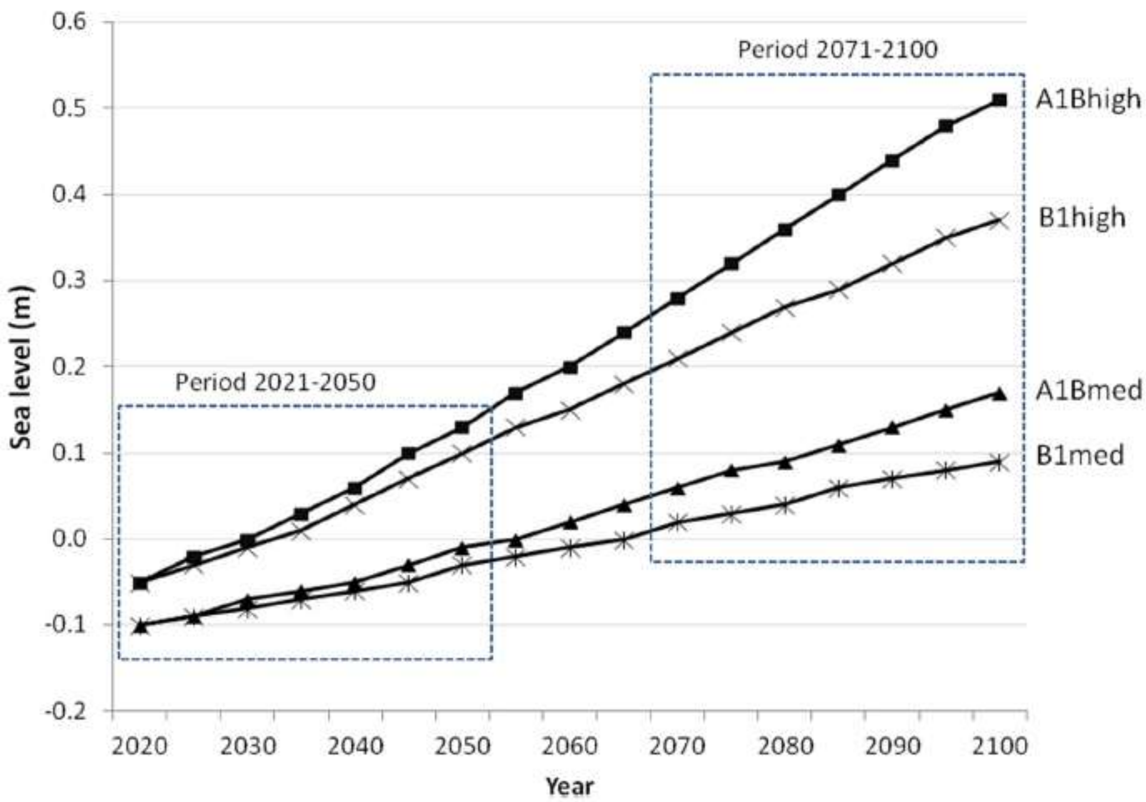


Figure 33 Sea level rise scenarios adapted by Southern Finland investigation (Samrit Luoma & Jarkko Okkonen, 2014)

The following table (Samrit Luoma & Jarkko Okkonen, 2014) list all eight of simulation results under MODFLOW calculation.

Table 20 Simulation result of sea level rise effect on groundwater table changes in Southern Finland

Scenario	SLR (m)	Groundwater change (m)
B1med2050	-0.01	-0.23
A1Bmed2050	0.01	0.13
B1med2100	0.11	0.18
B1high2050	0.12	-0.16
A1Bhigh2050	0.15	0.2
A1Bmed2100	0.18	0.19
B1high2100	0.39	0.33
A1Bhigh2100	0.53	0.39

Contrast between Southern Finland investigation (orange) and simplified model (blue) against equal sea level rise scenario is shown.in the following table. Every dot represents a scenario base. An arresting dot counting the 4th from left pointed by green arrow, is not following the orderliness as rest, this could happened by mistake from data recorder or while inputting information into software, therefore this dot can be neglected.

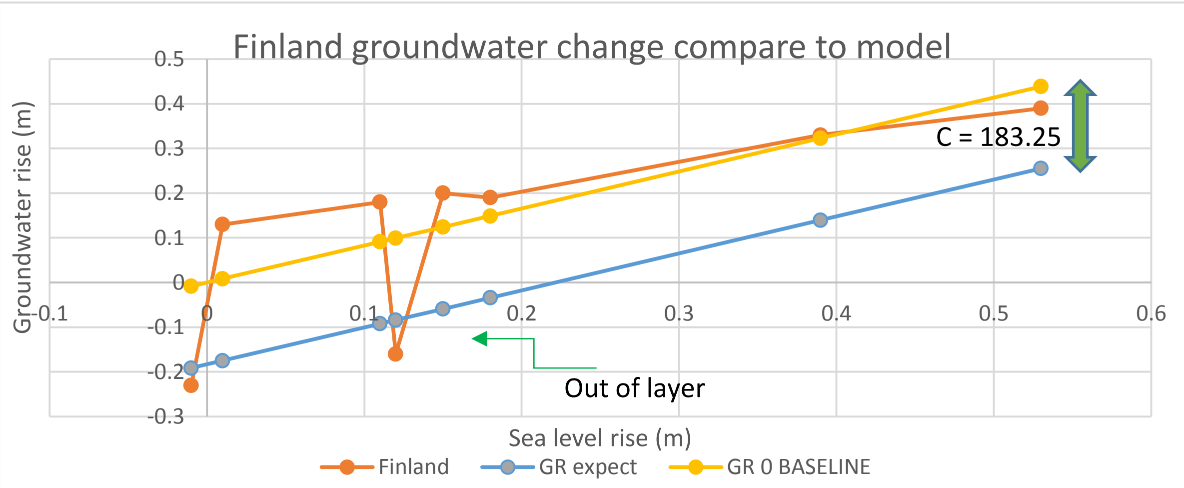


Figure 34 Comparison between Southern Finland investigation and groundwater model

In Finland investigation, groundwater changes has considered precipitation, temperature and surface leakage, while Lower Hutt research included one more, i.e. groundwater abstraction, which explained the disparity between the orange and the blue regarding to the chart. Conservative model is developed based on assumption of groundwater abstraction in Southern Finland by adding constant number C at the end of model.

$$GC^* = GC + C$$

$$= (-8.7GWL + 827.5)\,X - (27.75GWL + 183.25) + C$$

Where:

GC* = Conservative model adapting to Southern Finland investigation

GC = Groundwater table changes (mm)

GWL = Original groundwater level (m)

X = Sea level rise (m)

C = Constant number in order to develop conservative model, take as 183.25 (mm)

Discussion

Sea level rise can be estimated from year 1990 baseline by "$X = 0.0425N^2 - 3.0575N$" where N is number of year since 1990 and X is sea level rise (m).

Land loss area due to sea level rise (without storm event) can be formulated by "$Z = 554X - 136$" whereas loss of land triggered by storm expressed as "$Y = -106X^2 - 63X + 654$". Therefore, total land loss area is forecasting as "$L = Z + Y = -106X^2 + 491X + 518$".

Meanwhile, simplified model estimating changes to groundwater table caused by sea level rise define as "$GC = (-8.7GWL + 827.5)\,X - (27.75GWL + 183.25)$" where GC denotes Groundwater level changes (mm), GWL represents Current Groundwater level (m).

The advantage of simplified composite model serves general public to obtain approximate values of sea level rise, land loss area and changes to groundwater table, particularly when data is sparse.

d. Summary and Conclusion

The simplified composite model designed, described the theory of climate change resulting in an increase in global temperature thereby giving rise to an increase in sea level. It also shows how much sea-level rise coupled with a few other parameters cause loss of land in coastal areas as well as effect on rivers and water table.

Conceptually, a conversion table was developed to calculate the how much land is lost due to climate change and sea-level rise. The model was tested with values obtained from the Wellington region for scenarios 1, 2 and 3 of 0.5m, 1.0m and 1.5m sea-level rise and these provided satisfactory results in comparison with the Wellington data.

Estimates were obtained for loss of land but a few key points of note during model development were the assumptions made such as conversion at 90%, and the assignment of units to parameters. These may in some way affect the reliability or integrity of the model as there were also limitations with regards to parameters, especially when only a few were considered. As stated by Nicholls & Casenave (2010), thermal expansion accounted for about 25% of the observed SLR since 1960 and about 50% from 1993 to 2003. However with this model, thermal expansion was a major player accounting for sea-level rise to a large extent. Other dynamic factors or changing coastal processes like changes in inundation area and duration were also not taken into account.

Effect on water table (in meters) was also calculated using Wellington values for scenarios 1, 2 & 3 of 0.5m, 1.0m & 1.5m sea-level rise and the results (see table 3.2) also show model values to be within reasonable tolerance of the estimated values for Wellington. Model values obtained for scenarios 1, 2 & 3 of 0.5m, 1.0m & 1.5m sea-level rise were: 0.21m, 0.43m and 0.65m respectively.

Mathematically, simply

Sea level rise can be estimated from year 1990 baseline by

"$\mathbf{X = 0.0425N^2 – 3.0575N}$" where N is number of year since 1990 and X is sea level rise (m).

Land loss area due to sea level rise (without storm event) can be formulated by

"$\mathbf{Z = 554X – 136}$" whereas,

Loss of land triggered by storm expressed as "$\mathbf{Y = -106X^2 – 63X + 654}$".

Therefore, total land loss area is forecasting as "$\mathbf{L = Z + Y = -106X^2 + 491X + 518}$".

Meanwhile, simplified model estimating changes to groundwater table caused by sea level rise define as

"$\mathbf{GC = (-8.7GWL + 827.5) X– (27.75GWL + 183.25)}$"

where GC denotes Groundwater level changes (mm), GWL represents Current Groundwater level (m).

The advantage of simplified composite model serves general public to obtain approximate values of sea level rise, land loss area and changes to groundwater table, particularly when data is sparse.

Predicting sea-level rise impacts as a result of climate change is complex, and simple models are mostly of limited use. However, the simplified conceptual model designed in this project or the simplified mathematical model developed in tis research produced satisfactory results in comparison with available data and will help in the decision making process of what adaptation methods to employ or implement in certain coastal areas. Although models like these are based on assumptions of the impact of climate change and a few parameters, they shed good light into the climate change phenomenon, the sea level rise, the loss of coastal land due to it, the changes to ground water table due to it and bringing it to the forefront and encouraging coastal authorities to take necessary mitigatory action.

6. Down scaling of hydrological factors to predict climate change.

a. Introduction

Climate encompasses the statistics of temperature, humidity, atmospheric pressure, wind, rainfall, atmospheric particle count and other meteorological elemental measurements in a given region over long periods of time. Climate can be contrasted to weather, which is the present condition of these same elements and their variations over shorter time periods. The climate of a location is affected by its latitude, terrain, and altitude, as well as nearby water bodies and their currents. Climates can be classified according to the average and the typical ranges of different variables, most commonly temperature and precipitation.

The Intergovernmental Panel on Climate Change (IPCC) is a scientific intergovernmental body tasked with reviewing and assessing the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change. It provides the world with a clear scientific view on the current state of climate change and its potential environmental and socio-economic consequences, notably the risk of climate change caused by human activity.

According to IPCC, Climate in a narrow sense is usually defined as the "average weather," or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organization (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate change in general refers to any systematic change in long-term statistics of climate elements (such as temperature, pressure, or winds) sustained over several decades or longer time periods (American Meteorological Society, http://amsglossary:allenpress:com/glossary). One of the major causes of global warming is the increased emission of greenhouse gases due to anthropogenic activities [Intergovernmental Panel on Climate Change (IPCC), 2001]. The consequences of global warming are reflected in global as well as regional climate in terms of changes in key climatic variables such as precipitation and atmospheric moisture, snow cover, extent of land and sea ice, sea level and patterns in atmospheric and ocean circulation. The following figure depicts the variation of the global temperature over a period of 140 years. The plot also shows the average increase of 0.6º C in recent years. Therefore, study of climate change is necessary to understand its impact on hydrological processes. Water resources are inextricably linked with climate. The global climatic change has serious implications for water resources and regional development (IPCC, 2001). It is mentioned in the IPCC report (IPCC, 2001) that increased evaporation (resulting from higher temperatures), combined with regional changes in precipitation characteristics (e.g., total amount, variability, and frequency of extremes), has the potential to affect mean runoff, frequency and intensity of floods and droughts, soil moisture, and water supplies for irrigation and hydroelectric generation. Therefore, assessing the impact of climate change on hydrology involves a) projections of climatic variables (e.g., temperature, humidity, mean sea level pressure etc.) at a global scale b) downscaling of global scale climatic variables into local scale hydrologic variables and c) computations of risk of hydrologic extremes in future for water resources planning and management.

Climate change impacts assessment involves downscaling of coarse-resolution climate variables simulated by general circulation models (GCMs) using dynamic (physics-based) or statistical (data-driven) approaches. Here we use a statistical downscaling technique for projections of all-India monsoon rainfall at a resolution of 0.5_ in latitude/longitude. The present statistical downscaling model utilizes classification and regression tree, and kernel regression and develops a statistical relationship between large-scale climate variables from reanalysis data and fine-resolution observed rainfall, and then applies the relationship to coarse-resolution GCM outputs.

A GCM developed by the Canadian Centre for Climate Modeling and Analysis is employed for this study with its five ensemble runs for capturing intramodel uncertainty. The model appears to effectively capture individual station means, the spatial patterns of the standard deviations, and the cross correlation between station rainfalls. Computationally expensive dynamic downscaling models have been applied for India. However, our study is the first to attempt statistical downscaling for the entire country at a resolution of 0.5_. The downscaling model seems to capture the orographic effect on rainfall in mountainous areas of the Western Ghats and northeast India. The model also reveals spatially nonuniform changes in rainfall, with a possible increase for the western coastline and northeastern India (rainfall surplus areas) and a decrease in northern India, western India (rainfall deficit areas), and on the southeastern coastline, highlighting the need for a detailed hydrologic study that includes future projections regarding water availability which may be useful for water resource policy decisions.

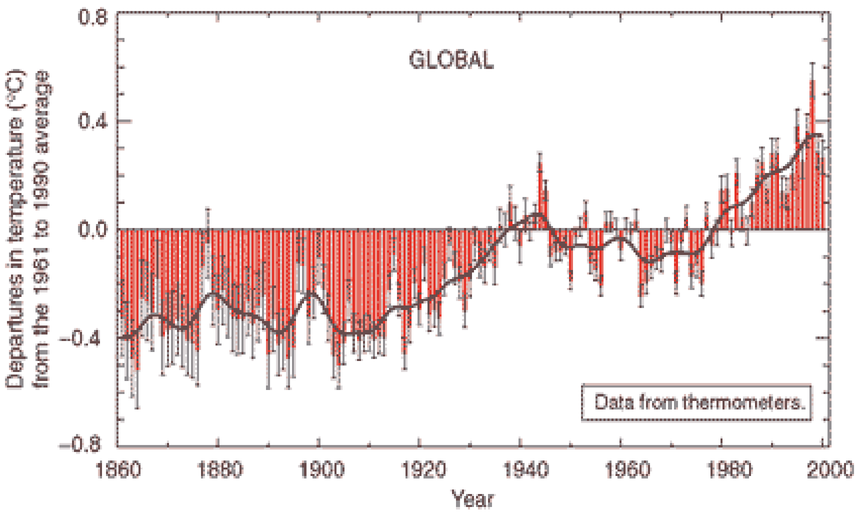


Figure 35 Variation of the Earth's surface temperature for the past 140 years (IPCC 2007)

'Climate change' is actually a response to the stimulus of change in the global energy balance. The solar energy which is distributed around the globe by wind, ocean currents and other mechanisms actually affect the climate in that region. The factors which actually shape the climate are called as 'Climate forcing mechanisms'. Such mechanisms are classified into

(1) Internal forcing and (2) External forcing. Natural changes in the components of earth's climate system and their interactions are the cause of internal climate variability, or "Internal forcing". Ocean variability is a key component of internal forcing. Short-term fluctuations (years to a few decades) such as the El Niño-Southern Oscillation, the Pacific decadal oscillation, the North Atlantic oscillation, and the Arctic oscillation, represent climate variability rather than climate change. On longer time scales, alterations to ocean processes such as 'thermohaline' circulation play a key role in redistributing heat by carrying out a very slow and extremely deep movement of water, and the long-term redistribution of heat in the world's oceans.

General Circulation Models (GCM) are tools designed to simulate time series of climate variables globally, accounting for effects of greenhouse gases in the atmosphere. They attempt to represent the physical processes in the atmosphere, ocean, cryosphere and land surface. They are currently the most credible tools available for simulating the response of the global climate system to increasing greenhouse gas concentrations, and to provide estimates of climate variables (e.g. air temperature, rainfall, wind speed, pressure etc.) on a global scale. GCMs demonstrate a significant skill at the continental and hemispheric spatial scales and incorporate a large proportion of the complexity of the global system; they are however, inherently unable to represent local sub-grid scale features and dynamics (Wigley et al., 1990). The spatial scale on which a GCM can operate for Coupled Global Climate Model (CGCM2)) is very coarse compared to that of the hydrological process (e.g. rainfall in a region, stream flow in a river etc.) to be modelled in the climate change impact assessment studies. GCM accuracy decreases from climate related variables, such as wind, temperature, humidity and air pressure to hydrologic variables such as rainfall, evapo-transpiration, runoff and soil moisture which are also simulated by the GCMs. The scientists working in the field of impact assessment require the point level data. Hence we need to downscale the data at finer scale. Downscaling is a method for obtaining high-resolution climate or climate change information from relatively coarse-resolution GCMs. Typically, GCMs have a resolution of 150-300 km by 150-300 km. The finer scale data can be obtained in two ways. Dynamic downscaling uses a limited-area, high-resolution model (a regional climate model or RCM) driven by boundary conditions from a GCM to derive smaller-scale information. The RCM is physics based model which is formulated incorporating local parameters and solved numerically using the boundary conditions simulated by GCMs. RCMs generally have a domain area of 106 to 107 km^2 and a resolution of 20 to 60 km. The statistical downscaling is another approach to achieve high resolution data. It produces future scenarios based on statistical relationships between large scale climate features and hydrologic variables. The main shortcomings of the dynamic downscaling are that RCMs still require considerable computing resources and are as expensive to run as global GCMs themselves; these models still cannot meet the needs of spatially explicit models of ecosystems or hydrological systems and that there will remain the need to downscale the results from such dynamic downscaling models to individual sites or localities for impact studies. Moreover, dynamic downscaling is inflexible in the sense that expanding the region or moving to a slightly different region requires redoing the entire experiment. The 'Statistical Downscaling' techniques are not heavily computational and at par with 'Dynamic Downscaling' techniques when it comes to accuracy. The following is the flowchart illustrating one of the 'Statistical Downscaling' techniques used for future rainfall projections. The subsequent sections give detailed description of each components and mathematical operations performed on the data.

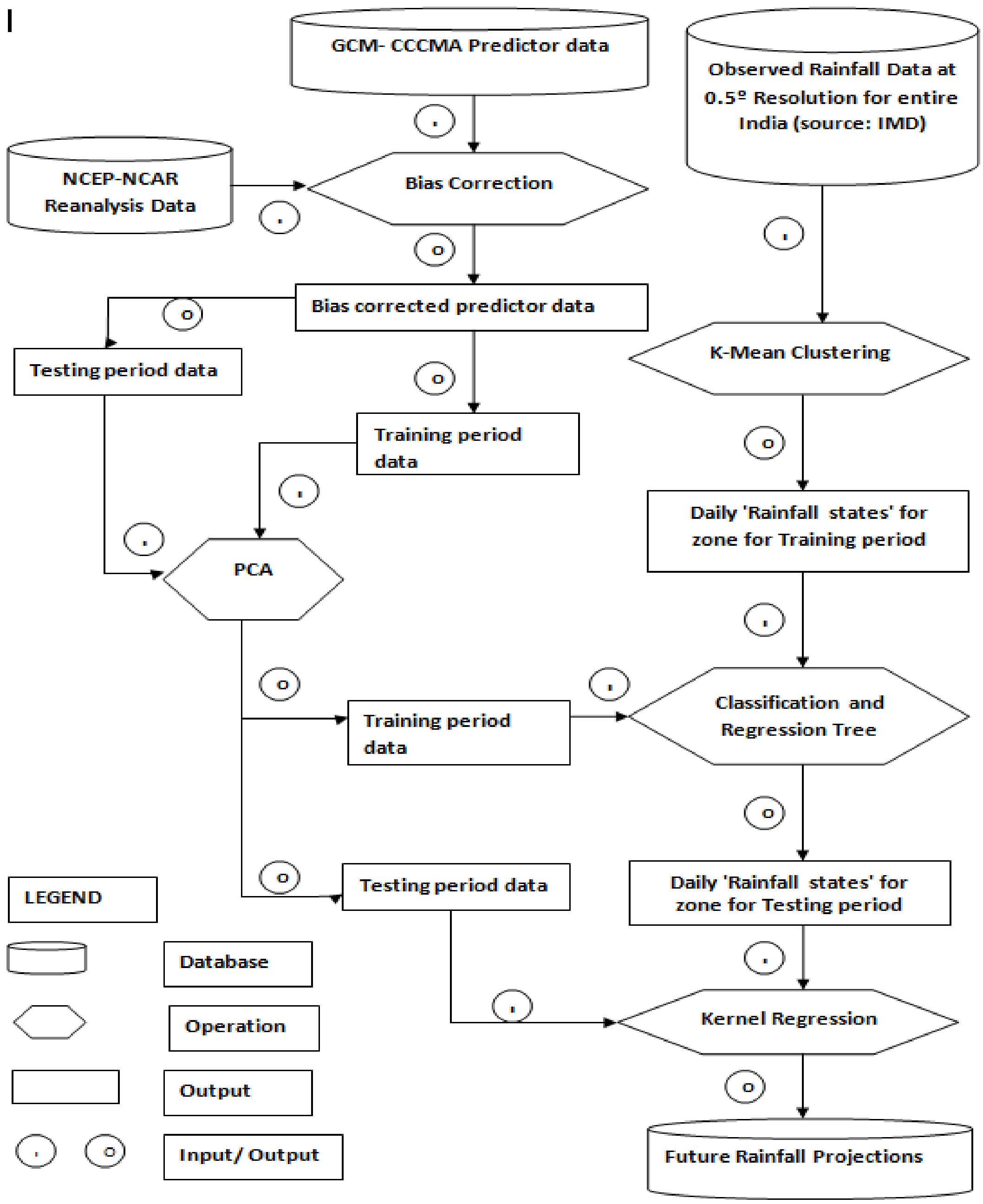


Figure 36 Flowchart for Multisite Statistical Downscaling Model

b. Climatic variables influencing rainfall

Precipitation is one of the most important meteorological variables and there are several theories established in regards to the growth of raindrop. Raindrops grow in size primarily because water exists in all three phases in the atmosphere and because the air is supersaturated at times (especially with respect to ice) because of adiabatic expansion and radiation cooling. This means that ice crystals coexist with liquid water droplets in the same cloud. The difference in the vapour pressure between the water droplets and the ice crystals causes water droplets to evaporate and then to sublimate directly onto the ice crystals. Sublimation is the process whereby water vapour changes into ice without passing through the liquid stage. Condensation alone does not cause droplets of water to grow in size. The turbulence in cloud permits and aids this droplet growth processes. After the droplets become larger, they start to descend and are tossed up again in turbulent updrafts within the cloud. The repetition of this causes the ice crystals to grow larger (by water vapour sublimating onto the ice crystals) until finally they are heavy enough to fall out of the cloud as some form of precipitation. It is believed that most precipitation in the mid-latitudes starts as ice crystals and that most liquid precipitation results from melting during descent through a stratum of warmer air. It is generally believed that most rain in the tropics forms without going through the ice phase. In addition to the above process of droplet growth, simple accretion is important. In this process, the collision of ice crystals with super-cooled water droplets causes the droplets to freeze on contact with the ice crystals. As the droplets freeze on the ice crystals, more layers accumulate. This process is especially effective in the formation of hail. For statistical downscaling, it is necessary to find out other climatic variables which show some correlation with the precipitation. Using these variables, a statistical relationship is established which is utilised to project rainfall. Following are the climatic variables which are used in the current study.

Temperature

The 'Sun' is the source of radiation which is responsible for the heating of land masses, water bodies and atmospheric gases. This results in rise in temperature which occurs more close to land surface. The temperature variation with the altitude is shown in the following figure.

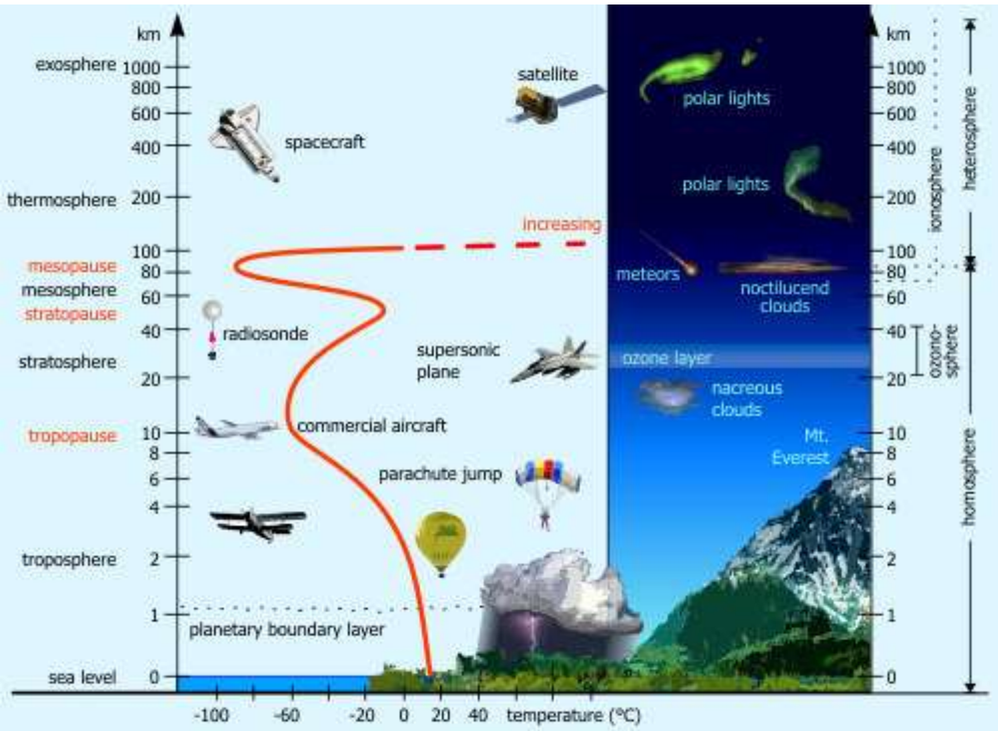


Figure 37 Temperature variation with altitude (courtesy: http://www.aerospaceweb.org/question/atmosphere/q0112.shtml)

The temperature gradient actually causes the air mass to undergo continuous churning. It also affects the other climatic parameters plays an important role in deciding moisture carrying capacity of the air.

Humidity

Humidity in general terms is the amount of water vapour present in air. It can be subdivided into absolute humidity, relative humidity and specific humidity. *Absolute humidity* on a volume basis is the quantity of water in a particular volume of air. If we actually condense the amount of water vapour present in one cubic meter of air in a container, then the mass of the water vapour condensed is absolute humidity. Relative humidity is defined as the ratio of the partial pressure of water vapour (in a gaseous mixture of air and water vapour) to the saturated vapour pressure of water at a given temperature. In other words, relative humidity is the amount of water vapour in the air at a specific temperature compared to the maximum water vapour that the air is able to hold without it condensing, at that given temperature. Specific humidity is the ratio of water vapour to dry air in a particular mass, and is sometimes referred to as absolute humidity or humidity ratio. While humidity, itself, is a climate variable, it also interacts strongly with other climate variables.

Wind

Wind is the flow of gases on a large scale. In meteorology, winds are often referred to according to their strength, and the direction from which the wind is blowing. Short bursts of high speed wind are termed gusts. Strong winds of intermediate duration (around one minute) are termed squalls. Long-duration winds have various names associated with their average strength, such as breeze, gale, storm, hurricane, and typhoon. Wind occurs on a range of scales, from thunderstorm flows lasting tens of minutes, to local breezes generated by heating of land surfaces and lasting a few hours, to global winds resulting from the difference in absorption of solar energy between the climate zones on Earth. The two main causes of large scale atmospheric circulation are the differential heating between the equator and the poles, and the rotation of the planet (Coriolis Effect). Within the tropics, thermal low circulations over terrain and high plateaus can drive monsoon circulations. In coastal areas the sea breeze/land breeze cycle can define local winds; in areas that have variable terrain, mountain and valley breezes can dominate local winds. The wind approximations are broken into its two horizontal components. The "U" component represents the east-west component of the wind while the "V" component represents the north-south component. The following fig. illustrates the variation of wind velocity with altitude. The winds at the height 850 HPa are of real significance. This is mainly because the boundary layer effect due to earth's surface is up to 1 km in the atmosphere. So the winds flowing above that level do not have any surface influence and the directions are purely based on the atmospheric interactions. In the current study the difference between wind velocities at 850 HPa and 200 Hpa, named as 'Wind shear' is used as predictor just for comparison.

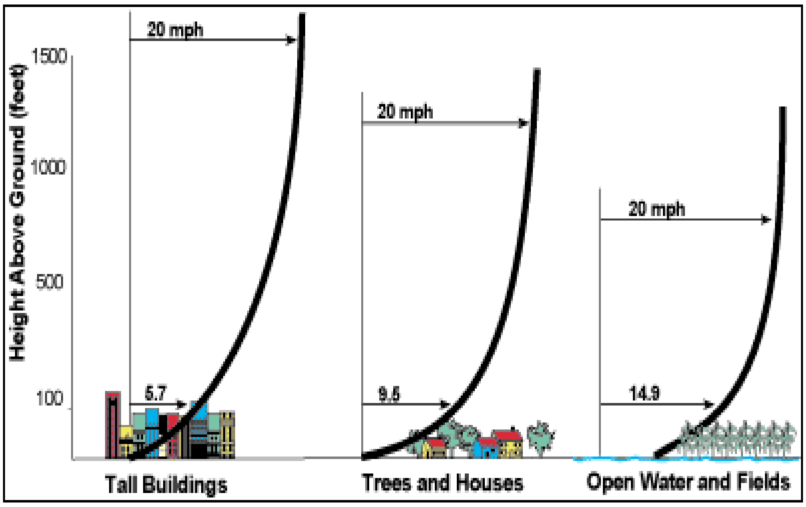


Figure 38 Variation of wind velocity with altitude (Courtesy: http://launchloop.com/wind)

Sea level pressure

Atmospheric pressure is the force per unit area exerted against a surface by the weight of air above that surface in the Earth's atmosphere. In most circumstances atmospheric pressure is closely approximated by the hydrostatic pressure caused by the weight of air above the measurement point. Low pressure areas have less atmospheric mass above their location, whereas high pressure areas have more atmospheric mass above their location. Similarly, as elevation increases there is less overlying atmospheric mass, so that pressure decreases with increasing elevation. Mean sea level pressure (MSLP) is the pressure at sea level. Pressure variation is one of the key inputs to precipitation.

c. Data

Being a data driven approach, the accuracy and reliability of the data which will be used for downscaling are important aspects. The flowchart displaying the steps for downscaling show three types of data bases (shown by cylinders). The GCM simulates all the climatic variables are used as predictors. Using NCEP-NCAR reanalysis data, they get bias corrected and observed gridded rainfall, along with predictors, serves as inputs for future projections. The details about the data used for the current study are as follows.

d. GCM simulated predictors

The choice of the predictor variables is of utmost importance. As mentioned in the review of literature, Hewitson and Crane (1996) demonstrated how the down-scaled projection of future change in mean precipitation and extreme events may alter significantly depending on whether or not humidity is included as a predictor. The downscaled results can also depend on whether absolute or relative humidity is used as a predictor (Charles et al., 1999b). The implication here is that while a predictor may or may not appear as the most significant when developing the downscaling function under present climates, the changes in that predictor under a future climate may be critical for determining the climate change. Some estimation procedures, for example stepwise regression, are not able to recognise this and exclude variables that may be vital for climate change. Hence, the selection of the predictors should be dependent on (1) Data for that particular predictor should be available for desired period (2) The selected GCM should be able to simulate that variable well and (3) The predictor should show a good correlation with the predictand. For the current study, the climatic variables mentioned in Kannan et. al. 2010 are used as predictors viz. Temperature, Pressure, Specific humidity, u-wind and v-wind at surface level. 'CCCma' (Canadian Centre for Climate Modelling and Analysis) is a division of the Climate Research Branch of the Meteorological Service of Canada of Environment Canada based out of the University of Victoria, Victoria, British Columbia. Its purpose is to contribute to research in climate modelling and climate change. For the rainfall projections in the current study, 'CCCma' is chosen as GCM. The reason for choosing this model is availability of data for predictors. This GCM provides the data for all the selected predictors for all the scenarios mentioned in the table. But the most important reason behind choosing this model is availability of runs. This model possesses five simulations for each scenario with slightly modified initial and boundary conditions. Hence intra-model uncertainty can be taken care of. The data is not masked even for higher altitude u-wind and v-wind.. The GCM data is at 3.75º resolution. The high resolution data is also available with this GCM but it is for less number of time period and hence avoided.

e. NCEP-NCAR reanalysis data

Reanalysis data is surrogate for observed data for any predictor variable. As the numerically solved fundamental equations in case of GCMs result in systematic errors known as bias, it is necessary to correct them. This correction is done based on the observed data. The observed data for a predictor is obtained from gauge stations. But these stations are not available at every location in the world. Also in many cases, the projections are done for grids at a particular resolution. To achieve this task, we need observed data in gridded format. For such cases, reanalysis data can serve the purpose. The NCEP-NCAR Reanalysis data set is a continually updating gridded data set representing the state of the Earth's atmosphere, incorporating observations and numerical weather prediction (NWP) model output dating back to 1948. It is a joint product from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). For the current projections, the reanalysis data was downloaded. The resolution is 2.5º lat × 2.5º long. The higher resolution data is also available.

f. Observed Rainfall data

The daily data for India (Latitude: 6.5 to 38.5, Longitude: 66.5:100.5) at 0.5° resolution was provided by Indian Meteorological Department (IMD) (Rajivan and Bhate, 2008). This is actually the data in the gridded format which is derived from the station level data by applying some interpolation technique. IMD is a governmental body mainly responsible for collection and analysis of climatic data. The rain gauge stations are established all over India and data is collected. In the Himalayan part of India, less number of rain gauge stations are established for obvious reasons. Hence there is less confidence in the gridded data which is generated using station level data in this zone. Also the data is provided for the land mass only and the ocean part is masked.

g. Methodology

As mentioned before, the statistical downscaling is a way of establishing statistical relationships between coarse resolution climate variables acting as predictors to the predictand at fine resolution. The data downloaded for the downscaling purpose has to undergo three mathematical transformations so as to project future. In the flowchart, these operations are shown by 'Hexagons'. Each of these is discussed in details. The methodology adopted for the current study is proposed by Kannan and Ghosh [2012].

Bias correction

Bias is a systematic error in the GCM simulation mainly due to incomplete knowledge of physical processes and influence of numerical schemes for solving differential equations. It is necessary to remove it. For this, the methodology by Li et al. (2010) i.e. quartile based mapping method is applied on cumulative distribution functions of observed, training and testing data. This methodology is already discussed in details in section 3.3. Here the NCEP-NCAR data is used as observed data and since it is at 2.5º resolution, the GCM data was brought down to 2.5º resolution from 3.75º using 'Bilinear interpolation' and then bias correction is done in exactly the same manner. The table depicts the classification of the data based on scenarios for training and testing period. For future scenarios, three time slices of thirty years are considered.

Table 21 Training and Testing period details for Bias correction

Scenario	Training Period	Application Period
20C3M	1971-1985	1986-2000
SRESA1B	nil	2010-2039
SRESA2		2040-2069
SRESB1		2070-2099

Principle component analysis

Principal component analysis (PCA) is a mathematical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of uncorrelated variables called principal components. The number of principal components is less than or equal to the number of original variables. This transformation is defined in such a way that the first principal component has as high a variance as possible (that is, accounts for as much of the variability in the data as possible), and each succeeding component in turn has the highest variance possible under the constraint that it be orthogonal to (uncorrelated with) the preceding components. This is a very important analysis to be carried out in downscaling. For the current study, the Indian landmass is divided into seven zones and for each zone the predictors are fixed. IMD has divided India into seven zones based on rainfall homogeneity.

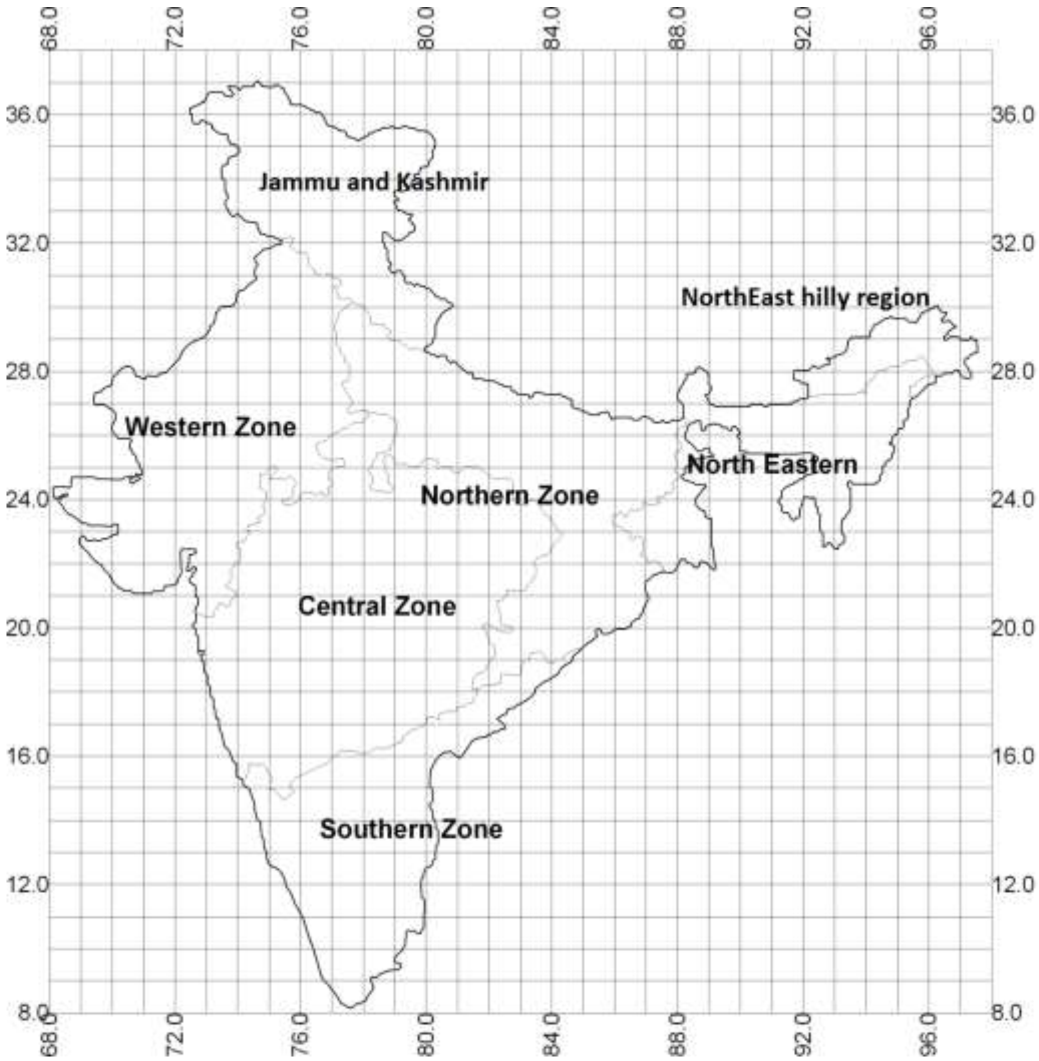


Figure 39Zones of India based on Rainfall Homogeneity (Source: IMD)

All the future rainfall projections are done considering each zone as independent unit and finding out the predictors and passing them through the principle component analysis test. Table below shows the region encompassing each zone which is assumed to be the region of predictors for the corresponding zone. Here is it assumed that the rainfall, being a spacial phenomenon, is influenced by the climatic variables surrounding that area.

Table 22 Rainfall Zones and their Predictors

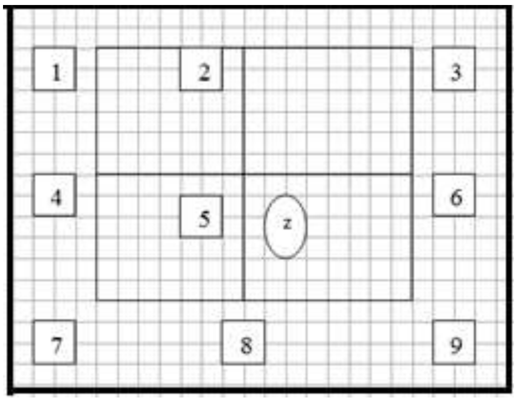
Sl. No.	Zone	Latitude		Longitude	
		From	To	From	To
1	Southern	5	22.5	70	90
2	Central	12.5	30	70	87.5

Sl. No.	Zone	Latitude		Longitude	
		From	To	From	To
3	Western	17.5	35	65	80
4	Northern	15	32.5	72.5	92.5
5	North East	20	32.5	85	100
6	JK*	27.5	40	70	82.5
7	NEH**	25	32.5	90	100

: Jammu and Kashmir

*****: North Eastern hills***

Explanation on PCA: Refer following figure,. Let's assume that we need to downscale rainfall at location 'Z' and the rectangular grid around 'Z' is the grid at which the GCM is simulating the predictors. In all we are considering nine nodes from where we will be getting data for predictors and we will establish the statistical relationship between these predictors at 9 nodes and predict and at 'Z'.



Explanation on PCA

As discussed previously, we have in all five predictors viz. Temperature, pressure, humidity, u-wind and v-wind. Hence at each node we have five variables which imply that we have in all 9×5 = 45 variables. So from here onwards if we directly go for downscaling we need to deal with 45 variables. This is where PCA plays its role. As the resolution at which predictors are brought after the bias correction step is 2.5º, we simply cannot assume that all the 45 predictors are independent and they do not have any kind of correlation among them. It is quite possible that temperature at node numbers 1 and 2 may show a very high correlation. Also node number 1 is at larger distance from 'Z' as compared to other nodes and variables at this node may not have any significant influence on rainfall at 'Z'. So here is the need to find out the status of correlation among these 45 variables and also which of the predictors explain the variability of rainfall at 'Z' the most. Here we apply PCA and find out exactly what are the predictors required to downscale the rainfall at 'Z' effectively. The similar approach is adopted to get the PCA for each zone in India which are utilised to establish the relationship between rainfall state and variables.

K-Mean Clustering

k-means clustering is a method of cluster analysis which aims to partition n observations into k clusters in which each observation belongs to the cluster with the nearest mean. It is one of the data mining techniques. In the current study, it is used to deal with the 'Spacial variation' of the rainfall in a particular zone. Consider fig. 3.6 displaying the 'Central zone' of India as per IMD divisions. At 0.5º resolution, we have around 300 gridded points at which rainfall is to be projected.

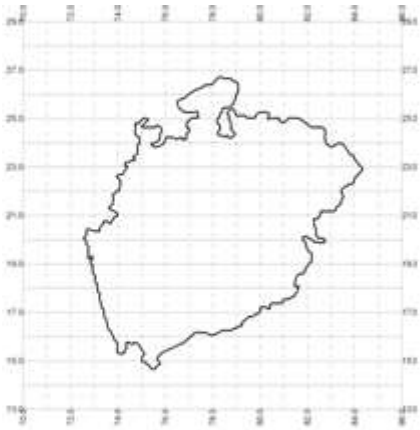


Figure 40 Central Zone of India (By IMD)

Even though the India is zoned based on homogeneity of rainfall, we do not receive equal amount of rainfall in entire central zone consisting of about 300 grid points. We encounter spacial variation in the rainfall amount. In order to deal with this problem, the k-mean clustering technique is adopted which reads the observed rainfall values at one particular day for all 300 nodes, clusters it and gives back one representative value which is called as the 'State' for that day. Here we have gone for the formation of three clusters i.e. for each day, based on rainfall at all nodes, central zone will be assigned one of the three state values (1, 2, 3). The number of clusters was decided as '3' after finding out Dunn's index and Silhouette index for all the cluster numbers varying from 2 to 11. The highest indices values were for two numbers of clusters. But two clusters implies dry and wet kind of classification and hence the second best value of clusters were selected i.e. The following figure shows the graph of number of clusters v/s Dunn's index.

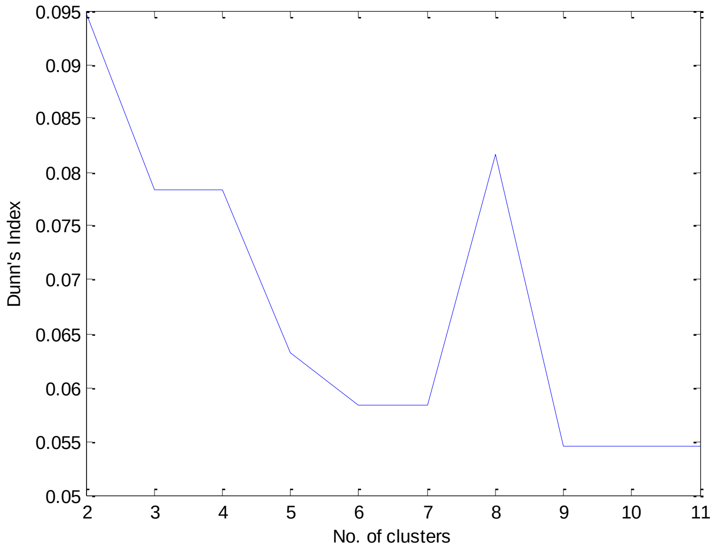


Figure 41 Variation of Dunn's index with number of clusters

The algorithm for K-mean clustering is as follows (Kannan et. al. 2010)

Let x_i denote the i^{th} feature vector in the n-dimensional attribute space

$$\{\boldsymbol{x_i} = [\boldsymbol{x_{i1}}, \boldsymbol{x_{i2}}, \dots \dots \boldsymbol{x_{ij}} \dots \boldsymbol{x_{in}}] \in \boldsymbol{R}\} \qquad \textbf{.......(1)}$$

The K-means algorithm is an iterative procedure in which the feature vectors move from one cluster to another to minimize the objective function, F, defined as:

$$\boldsymbol{F} = \sum_{k=1}^{K} \sum_{j=1}^{n} \sum_{i=1}^{N_k} \boldsymbol{d^2(x_{i,j}^k, x_j^k)} \qquad \textbf{.........(2)}$$

Where $d^2(x_{i,j}^k, x_j^k)$ is the squared Euclidian distance between feature vectors, K is the number of clusters, N_k is the number of feature vectors in cluster k, x_{ij}^k is the value of attribute j in the feature vector i assigned to cluster k, and x_j^k is the mean value of attribute j for cluster k, computed as

$$\boldsymbol{x_j^k} = \sum_{i=1}^{n} \frac{\boldsymbol{x_{i,j}^k}}{\boldsymbol{N_k}} \qquad \textbf{.........(3)}$$

By minimizing F in Eq. 2, the distance of each feature vector from the centre of the cluster to which it belongs is minimized. The computational steps involved in programming K-means algorithm to obtain clusters for a given value of K are as follows:

- Set 'current iteration number t = 0 and maximum number of iterations to t_{max}.
- (2) Initialize K cluster centres to random values in the multi-dimensional feature vector space.

- (3) Initialize the 'current feature vector number' i to 1.
- (4) Determine Euclidean distance of i^{th} feature vector xi from centres of each of the K clusters, and assign it to the cluster whose centre is nearest to it.
- (5) If $i < N$, increment i to $i + 1$ and go to step (4) else continue with step (6).
- (6) Update the centroid of each cluster by computing the average of the feature vectors assigned to it. Then compute F for the current iteration t using Eq. 2. If $t = 0$, increase t to $t + 1$ and go to step (3). If $t > 0$, compute the difference in the values of F for iterations t and $t - 1$. Terminate the algorithm if the change in the value of F between two successive iterations is insignificant, else continue with step (7).
- (7) If $t < t_{max}$, update t to $t + 1$ and go to step (3), else terminate the algorithm.

The optimal value attained by F depends on the assumed number of clusters (K) and initialized values of their centres.

CART Analysis

Supervised classification is a machine learning technique for learning a function from training data. The training data consist of pairs of input objects (typically vectors) and desired outputs. The output of the function can be a continuous value or can predict a class label of the input object. The task of the supervised learner is to predict the value of the function for any valid input object after having seen a number of training examples (i.e. pairs of input and target output). The CART model builds classification and regression trees for predicting continuous dependent variables (regression) and categorical predictor variables (classification). In most general terms, the purpose of the analysis via tree-building algorithms is to determine a set of if-then logical (split) conditions that permit accurate prediction or classification of cases. The tree is built through a process known as binary recursive partitioning algorithm. This is an iterative process of splitting the data into partitions, and then splitting it up further on each of the branches. The steps involved in building CART are as follows:

- Initially, place all observations in the training set (the pre-classified records that are used to determine the structure of the tree) at the root node. This node is considered impure or heterogeneous, since it contains all observations. The goal is to devise a rule that initially breaks up these observations and creates groups or binary nodes that are internally more homogeneous than the root node.
- Starting with the first variable split a variable at all of its possible split points (at all of the values the variable assumes in the sample). At each possible split point of the variable, the sample splits into two binary or child nodes.
- Apply goodness-of-split criteria to each split point and evaluate the reduction in impurity or heterogeneity due to the split.
- Select the best split on the variable as that split for which reduction in impurity is the highest.
- Repeat steps (2)–(4) for each of the remaining variable at the root node and rank all of the 'best' splits on each variable according to the reduction in impurity achieved by each split.
- Select the variable and its best split point that reduces most of the impurity of the root or parent node.
- Assign classes to these nodes according to a rule that minimizes misclassification cost.

- Repeatedly apply steps (2)–(7) to each non-terminal child node at each of the successive stages.
- Continue the splitting process and build a larger tree. The largest tree can be achieved if the splitting process continues until every observation constitutes a terminal node.
- Prune the results using cross-validation and create a sequence of nested tree, and select the optimal tree based on minimum cross-validation error rate.

The advantages of using the CART model are:

- It makes no distributional assumption of any kind, either on dependent or on independent variables. No predictor variable in CART is assumed to follow any kind of statistical distribution;
- The predictor variables in CART can be a mixture of categorical, interval, and continuous;
- CART is not affected by outliers, colinearities, heteroscedasticity or distributional error structure that affect parametric procedures;
- CART has the ability to detect and reveal interactions in the dataset;
- CART is invariant under monotonic transformation of independent variables; and
- CART effectively deals with higher-dimensional data.

In the current study, the CART Analysis is used to (1) Obtain the relationship between the PCA processed predictors mentioned in the section 3.5.2 and rainfall states mentioned in the section 3.5.3 for training period (2) Generate future rainfall states using the developed relationship and PCA processed predictors for testing period (simulated by GCM) with as assumption that the relationship developed for training period holds good for future as well. Once the future states are simulated, using Kernel regression the future rainfall is projected.

Kernel Regression

The kernel regression is a non-parametric technique in statistics to estimate the conditional expectation of a random variable. The objective is to find a non-linear relation between a pair of random variables X and Y. The relationship between the rainfall and other climatic variables acting as predictors is always non linear. Hence using parametric linear regression will simulate erroneous results. Mathematically, kernel regression is written as follows.

$$\boldsymbol{m_h(x)} = \frac{\widehat{\sum_{i=1}^{n}} K_h(x - X_i)\, Y_i}{\sum_{i=1}^{n} K_h\,(x - X_i)} \qquad \textbf{.......(4)}$$

Where $m_h(x)$: value of function at $X_i = x$

K_h: Kernel with bandwidth h.

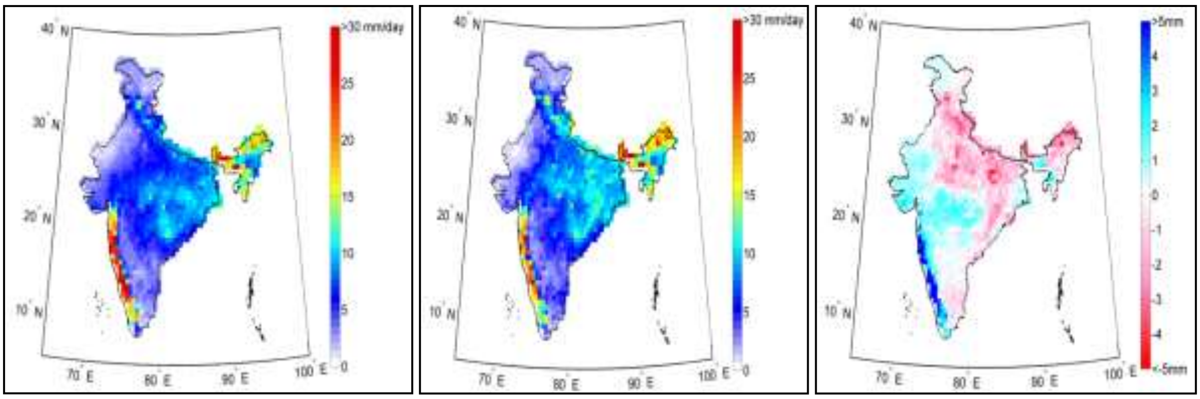
For the current study, three different kernels were used based on the projected state of rainfall as mentioned in section 3.5.3. e.g. if the state for day 1 (testing period) is 2, then the rainfall values for all those days in training period having state as 2 will be used in the kernel to generate the day 1 rainfall. The kernel used here is an exponential function which assigns the probabilistic weights based on the difference between predictor vector for testing period (day 1) and training period predictor vectors. The advantage of using exponential function is that if the difference is small (i.e. Day 1 predictors for testing period resemble very well with a particular day predictor vector in training period) very high weight is assigned. As the distance increase, a very low weight is assigned to that day in training period.

h. Results and Discussion

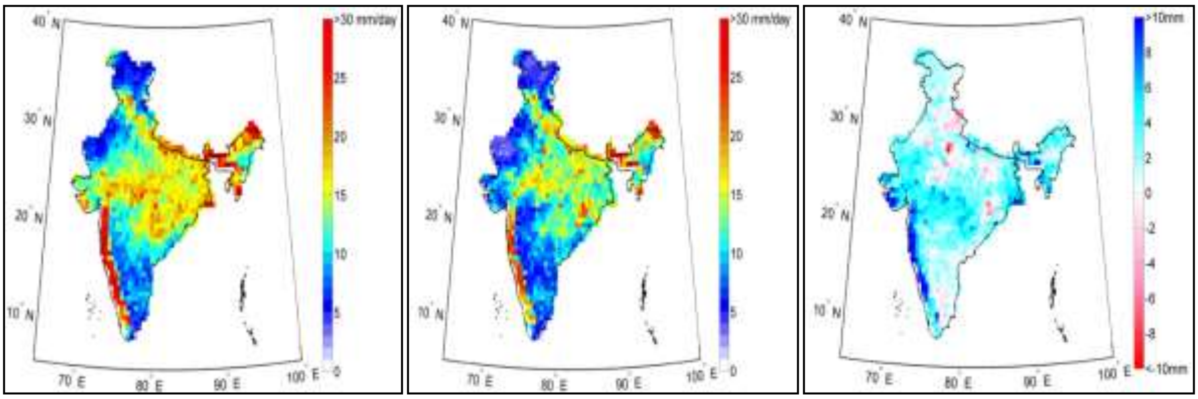
The high resolution rainfall projection for 20C2M as well as other future scenarios was achieved through the statistical downscaling techniques. The comparison of the mean and standard deviation for observed data and projected data (20C3M) for testing period was made to ensure whether both the data have their statistical properties in sync. But for the future scenarios, the comparison is restricted to the mean rainfall only. The following section is a compiled version of all the projections obtained.

20C3M

The following plots show the comparison between observed data and projected data for testing period (1986-2000) using five predictors viz. Specific humidity, temperature, pressure, u-wind and v-wind all at the surface level . This comparison is made based on the fifteen year daily ensemble mean values and ensemble standard deviation values. The fig. (a) and (b) are the mean plots of observed data and projected data respectively and fig. 3.8(c) is the error plot obtained by subtracting projected mean from observed mean. The error plot show a major chunk of white colour indicating very less difference between projected and observed mean. It is clear from the plots 3.8 (d) (e) and (f) that the observed standard deviation and projected standard deviation is not matching to the level of mean data.



(a) (b) (c)



(d) (e) (f)

Figure 42 Comparison of observed mean and standard deviation with projected mean and standard deviation (1986-2000)

(a) Daily ensemble mean of observed rainfall data 1986-2000;

(b) Daily ensemble mean of projected rainfall data 1986-2000;

(c) Error plot: Difference between projected mean and observed mean.

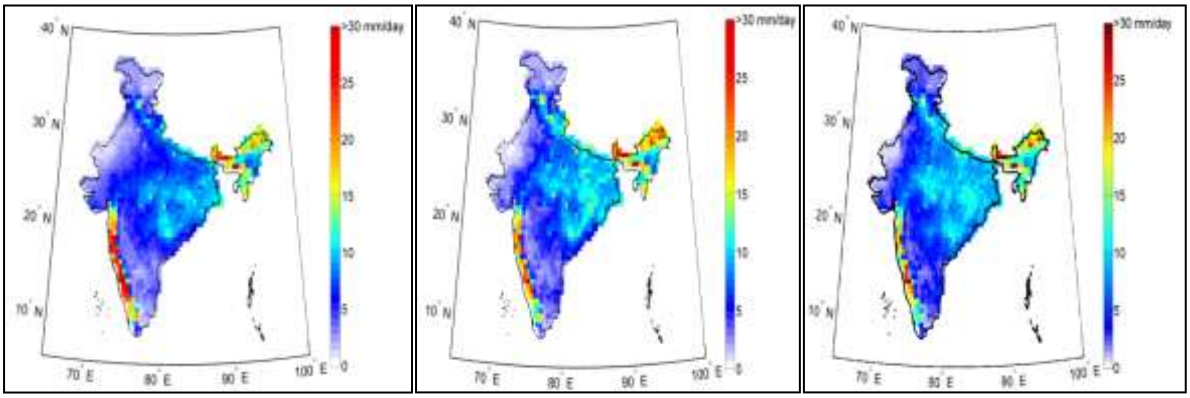
(d) Standard deviation of observed rainfall data 1986-2000;

(e) Standard deviation of projected rainfall data 1986-2000;

(f) Error plot: Difference between standard deviations of projected data and observed data.

This indicates that the standard deviation is not well captured as that of mean in this methodology. In the plot 3.8(c), it is observed that for northern part of India i.e. Himalayan region and north east part of India do not show white colour. This implies that the daily mean projections are not so good when compared with observed data for these regions.

[Dobler and Ahrens, 2011] have used u-wind and v-wind at higher altitudes as predictors in the form of wind shear. Wind shear is basically the difference between the wind velocities are 850 HPa and 200 HPa. We have also incorporated these wind shear values as predictors and verified the extent of improvement in the 20C3M projections. Following are the plots (the following fig. (a), (b) and (c)) show the comparison of mean projected rainfall for testing period (1986-2000). The plot (c) is generated using seven predictors viz. Specific humidity, temperature, pressure, u-wind, v-wind at surface level and u-wind shear and v-wind shear ($V_{850HPa} – V_{200HPa}$).



(a) (b) (c)

Figure 43 Comparison of daily observed mean, projected mean with five predictors, projected mean with seven predictors (1986-2000)

(a) Daily ensemble mean of observed rainfall data 1986-2000;

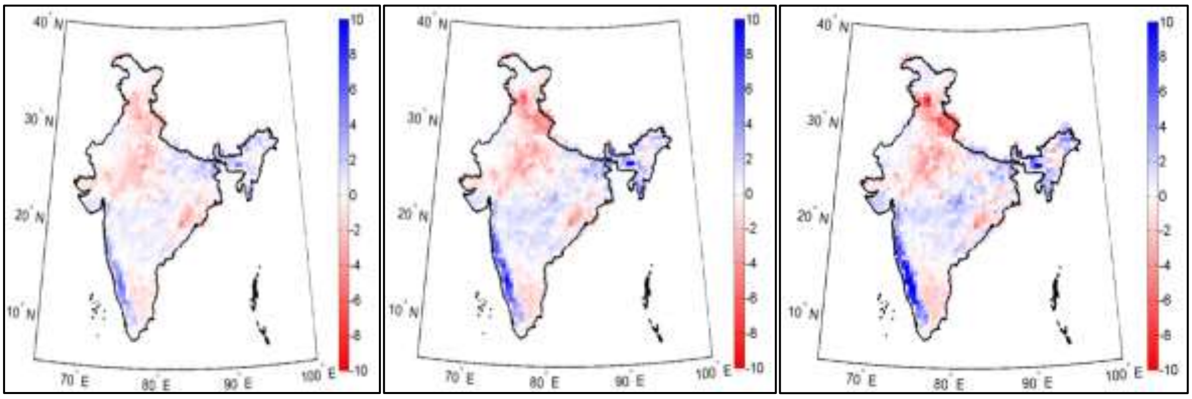
(b) Daily ensemble mean of projected rainfall data 1986-2000 using **five** predictors;

(c) Daily mean of projected rainfall data 1986-2000 using **seven** predictors

Comparison between plots (b) and (c) shows that there is no significant improvement in the projections when compared to observed plot (a). But while running PCA, considerable reduction was achieved in the number of principle components which will explain 98% of variability even though the number of predictors was increased from five to seven at each node.

SRESA1B

SRESA1B is the scenario in which the CO_2 concentration is assumed to reach 720 ppm in 2100. Following plots (fig. (a), (b), (c)) are the future ensemble projections for A1B scenario keeping



(a) (b) (c)

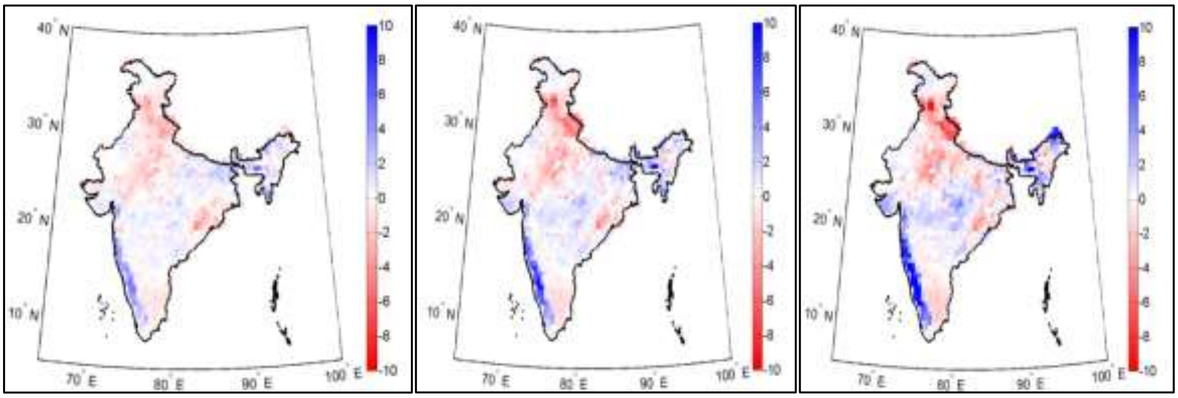
Figure 44 Difference between AIMR projections for scenario A1B and 20C3M

(a): AIMR Projections for the period 2010-2039; (b): AIMR Projections for the period 2040-2069; (c): AIMR Projections for the period 2070-2099.

20C3M scenario projections are the baseline. These are actually the rainfall projections showing deviation from 20C3M. These plots show that at some nodes there is increase in the mean rainfall (shown by blue colour) and at some points there is decrease in the mean rainfall (shown by red colour). The west coast, central India and northeast India show increase in mean rainfall as compared to 20C3M mean rainfall. North India and southeast coast of India show decrease in the mean rainfall.

SRESA2

SRESA2 is the scenario in which the CO_2 concentration is assumed to reach 850 ppm in 2100. A2 is the most stringent scenario when compared with A1B and B2. This is evident even from the temperature projections in previous chapter. Following plots (fig. (a), (b), (c)) are the future ensemble projections for A1B scenario keeping 20C3M scenario projections are the baseline as above.



(a) (b) (c)

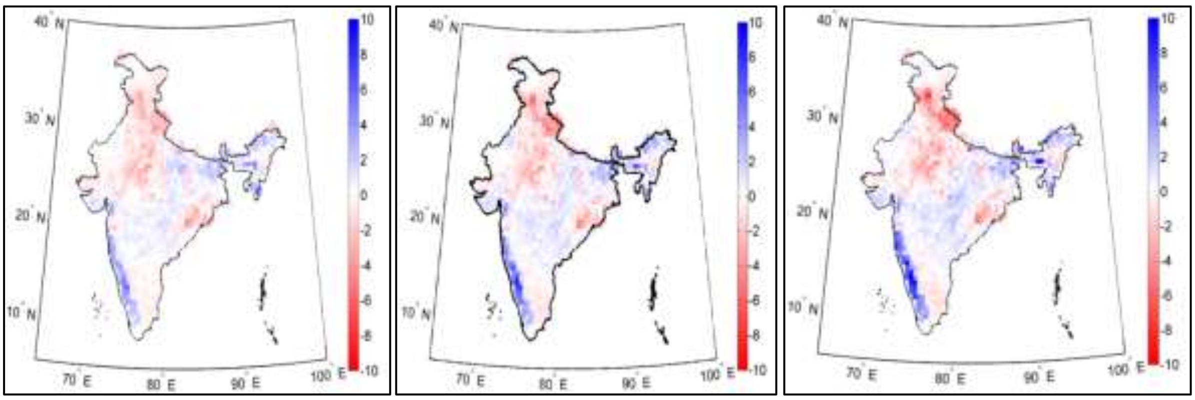
Figure 45 Difference between AIMR projections for scenario A2 and 20C3M

(a): AIMR Projections for the period 2010-2039; (b): AIMR Projections for the period 2040-2069; (c): AIMR Projections for the period 2070-2099.

The projection trends (i.e. rise in mean rainfall or fall in mean rainfall) for A2 scenario looks similar to that of A1B scenario. But the key difference is in the above fig (a) and this fig. (a) which is showing a completely different shade in northeast part of India. A2 Shows rise in the mean rainfall value. The other observations regarding north end of Himalayan region and about west coast line are the same in both the scenarios. The comparison of fig. (a) and (c) shows that in the Rajasthan region, the number of nodes with decrease in the mean rainfall are increasing. This is evident from the extended area shaded with magenta colour.

SRESB1

SRESB1 is the scenario in which the CO_2 concentration is assumed to reach 550 ppm in 2100 but the key point is 'High land use change'. This scenario will actually show the effect of land use change as compared to the greenhouse gas emissions. Following plots (fig. (a), (b), (c)) are the future ensemble projections for A1B scenario keeping 20C3M scenario projections are the baseline as above.



(a) (b) (c)

Figure 46 Difference between AIMR projections for scenario B1 and 20C3M

(a): AIMR Projections for the period 2010-2039; (b): AIMR Projections for the period 2040-2069; (c): AIMR Projections for the period 2070-2099.

Again the overall pattern of increase or decrease in mean rainfall looks similar to that of other two scenarios. But the changes (positive or negative) are compared keeping the magnitude of change as bottom line, this scenario show less variations from 20C3M projections are compared to other two.

7. Uncertainty Assessment in climate change simulation – Case of the Ganges Basin

a. Introduction

Various hydrological models are coupled with climate models in the recent past to study the hydrological responses to the climate change at river basin scale as it is very important for planning and management of water resources. However, these models have uncertainties due to the model parametrisation, choice of GCM and downscaling techniques, inaccurate data for calibration and validation. The calibration of the parameters is the major challenge in hydrological modelling as it demands very accurate observed data. The runoff data which is generally used for model calibration are controlled data due to the presence of dams, reservoirs and irrigation practices and are hence not reliable. Therefore it is very important to identify the major source of uncertainty so that the level of accuracy required in the model calibration can be studied. The objective of this study is to identify and compare the different sources of uncertainty in climate change simulations of Ganges basin. The Variable Infiltration Capacity (VIC) model used in this study is a semi distributed macroscale model. The Monte Carlo simulation (MCS) method is carried out for the four calibration parameters and vegetation parameters in VIC and the model is run with observed and reanalysis data for years 2000-2009. The results obtained are evaluated using observed soil moisture and evapotranspiration. The hydrological simulations are carried out for years 1979-2005 and 2011-2037 for different GCMs and downscaling methods. The spatial distribution of changes in soil moisture, evapotranspiration and water yield are plotted to obtain uncertainty band for each of the datasets. From the study it is demonstrated that the uncertainty due to choice in GCM is higher compared to the hydrological parameter uncertainty.

The effect of change in climate on various hydrological processes can be studied using the hydrological models that are developed in the recent past. The implications from the hydrological modelling can be useful for proper planning and management of water resources. (Raje and Krishnan 2012). Some of the model parameters are not well defined and hence has to be calibrated which demands observed data with high accuracy(Yapo et al. 1996). Generally the hydrological models are calibrated using runoff data which are controlled because of the presence of dams in the river basin.(Degu et al. 2011; Haddeland et al. 2006a; b; c) The parameters estimated for small basins may not hold good for large basins.(Leavesley 1994). GCMs used for the climate change studies work well at continental scales but fails to demonstrate the local processes accurately. (Chong-yu XU et al, 2005).The downscaling techniques that are adopted also involves assumptions which can lead to uncertainties. Hence the major sources of uncertainty are parameter uncertainty, GCM uncertainty and downscaling uncertainty. The uncertainties associated with hydrological models are given less attention in climate change impact assessment. Hydroclimatic ensembles with different data and models were constructed to assess the uncertainty in the study conducted by Velázquez et al. 2013.Another technique is the Bayesian approach implemented using the Markov Chain Monte Carlo (MCMC) methods(Raje and Krishnan 2012). The quantification can be also done using the technique of optimisation. Multi-objective calibration approach can be used to find the structural uncertainty in hydrological modelling(Ruelland et al. 2015).

The data availability for the calibration is one of the major challenges in the uncertainty assessment. Mostly runoff is used to calibrate the model, which is always a controlled flow due to the construction of dams and reservoirs. Therefore the approach used in this study for uncertainty modelling is Monte Carlo simulation and analysis. In this method a probability distribution is assumed for the calibration parameters and a set of random number is generated for each of the parameters. The model used in this study is the VIC model, which is semi distributed macro scale hydrological model. Then using different GCMs and downscaling methods the meteorological forcing files are prepared. The model is run with these input parameters and meteorological files. The spatial distribution in changes between future and past for the outputs is plotted resulting in the uncertainty band. The uncertainty bands for each set of meteorological files can be compared for the uncertainty assessment.

The following section describes the data and methodology followed in the present study.

7.2 Study area and data description

There has been considerable environmental changes in the Indian subcontinent. There has been increase in population, agricultural demands, irrigation, and land use changes in the past few decades. The Ganga river basin is the most populated and intensively cultivated areas in the world.(Tsarouchi et al. 2014) The Ganga basin lies between 73^{0}30’E to 89^{0}0’Ein east and 22^{0}30’N to 31^{0}30’N. It extends over India, Nepal and Bangladesh and covers an area of 1086000 sq. km. In India it extends over an area of 861404 sq. km and contributes to 43% of population and 26% of landmass. The average rainfall is 110cm and varies from 39 to 200cm. The monsoon months are from June to September(NRCD Moef 2009).

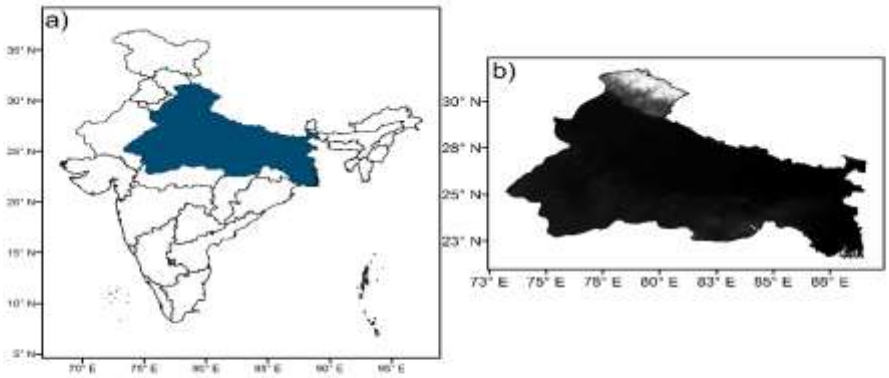


Figure 47 (a) Location map of study area in India (b) DEM of Ganga Basin

The grid resolution for VIC model chosen in this study is 0.5º and requires topographic, soil, hydro-meteorological and land use data for running. The observed precipitation data at 0.5º resolution was obtained from IMD (Indian Meteorological Department). The 1º maximum and minimum temperature from IMD was interpolated to 0.5º and the wind data was obtained from CFSR (Climate Forecast System Reanalysis). The soil data was directly taken from the higher resolution update of the 2-degree global parameters developed by (Nijssen et al. 2001a; b). The land use land cover data at 1km resolution was taken from the AVHRR (Advanced Very High Resolution Radiometer) available at the website of University of Maryland. The digital elevation map at 1km resolution was obtained from USGS (U.S. Geological Survey) HYDRO1k dataset. The period selected for evaluation of the model was 2000-2010 and the ESACCI (European Space Agency Climate Change Initiative) soil moisture and MODIS 16 ET (Evapotranspiration) were used. The GCMs considered were IPSL (Institut Pierre Simon Laplace) and EC-EARTH and the corresponding CORDEX (Coordinated Regional Climate Downscaling Experiment) data was obtained from IITM (Indian Institute of Tropical Meteorology) Pune website. The statistical downscaled data developed by Salvi et al. 2013 was used.

b. Hydrological model and methodology

Variable Infiltration Capacity (VIC) model is a semi-distributed macroscale hydrological model in which the water and surface energy budgets are balanced within the grid cell and the sub-grid variability is captured statistically(Liang et al. 1994, 1996). The variability of vegetation classes, soil moisture storage capacity and topography is considered sub grid wise and the baseflow is represented as a non-linear recession. It has a separate routing model based on linear transfer function to simulate the streamflow(Lohmann et al. 1996; Lohmann et al. 1998a; b) The model has a snow module, frozen soil and permafrost algorithm and blowing snow algorithm for cold land processes. Some of the applications of VIC model are future forecast of streamflow and other hydrological variables, drought monitoring and water management. The model can be run in water balance or energy balance mode and at a daily or sub-daily time step.

In VIC model, the variables that rely on model calibration include:

(a) Dsmax – it represents the maximum baseflow that can occur from the lowest soil layer (in mm/day). It can vary from 0 to 30 depending on the hydraulic conductivity.

(b) Ds -This represents the fraction of Dsmax at which the non-linear (rapidly increasing) baseflow begins. With a higher value of Ds, the baseflow is higher at lower water content in lowest soil layer. The range of Ds can be restricted to lie between 0 and 1.

(c) Ws -This correspond to the fraction of the maximum soil moisture in the lowest soil layer where non-linear baseflow occurs and is analogous to Ds. A higher value of Ws will raise the water content required for rapidly increasing, non-linear baseflow, which will tend to delay runoff peaks. The value of Ws is typically restricted between 0 and 1.

(d) binf - This parameter defines the shape of the Variable Infiltration Capacity curve. It describes the amount of available infiltration capacity as a function of relative saturated grid cell area. A higher value of binf gives lower infiltration and yields higher surface runoff. It can vary from 0 to 0.4.

(e) Soil Depth (of each layer)- many model variables are affected by soil depth. If the thickness of the soil layer is high, the peak flows are slowed down and loss due to evaporation will be higher.(http://www.hydro.washington.edu)

The study region comprises of mountainous area with snowfall. The snow module with energy balance is made use in those grids. Snow band files are prepared and sub daily time step is selected. The remaining grids are run in water balance mode. A triangular distribution is assumed for the soil calibration parameters with mean from Nijssen et al. 2001a; b and limits as defined previously and 1000 random numbers are generated resulting 1000 soil parameters files. Some of the vegetation parameters like LAI (Leaf Area Index), rooting depth, vegetation roughness length and vegetation displacement height are varied randomly assuming uniform distribution and 1000 vegetation parameter files are created. First the model is run for observed period of 2000-2009 and evaluated using ESACCI observed soil moisture and MODIS ET. The meteorological files for different GCMs and downscaling i.e. IPSL CORDEX, IPSL statistically downscaled, EC-EORDEX and EC-EARTH statistically downscaled are prepared and the model is run for 1979-2005 and 2011-2037. The spatial distribution of changes in soil moisture, evapotranspiration and water yield are plotted resulting in uncertainty bands for each of the meteorological datasets.

c. Results and discussion

The correlation coefficient between the observed soil moisture and the ensemble mean of VIC simulated soil moisture was calculated for each of the grids for pre-monsoon, monsoon, post-monsoon and winter (Figure below (a)-(d)). The mathematical formula for correlation coefficient is given by:

$$\mathbf{r} = \frac{N\sum_{i=1}^{N} S_i O_i - \sum_{i=1}^{N} S_i \sum_{i=1}^{N} O_i}{\sqrt{\left[N\sum_{i=1}^{N} S_i^2 - \left(\sum_{i=1}^{N} S_i\right)^2\right] - \left[N\sum_{i=1}^{N} O_i^2 - \left(\sum_{i=1}^{N} O_i\right)^2\right]}}$$

Where, r= correlation coefficient, N=total number of months, Si=simulated soil moisture, Oi=observed soil moisture, $\overline{O}$ =mean observed soil moisture. A good correlation was observed in monsoon and post monsoon. Possible reason for average correlation for few grids in summer and winter could be that VIC does not take into account irrigation. The MODIS ET is compared with the ensemble mean of VIC simulated ET in Figure below (e)-(l). It was observed that the spatial plots show similarity in pre-monsoon and post monsoon.

When the climatology of ET for VIC simulated, MODIS, ERA-INTERIM and MERRA were compared, MODIS ET was observed to be under-estimated in monsoon.

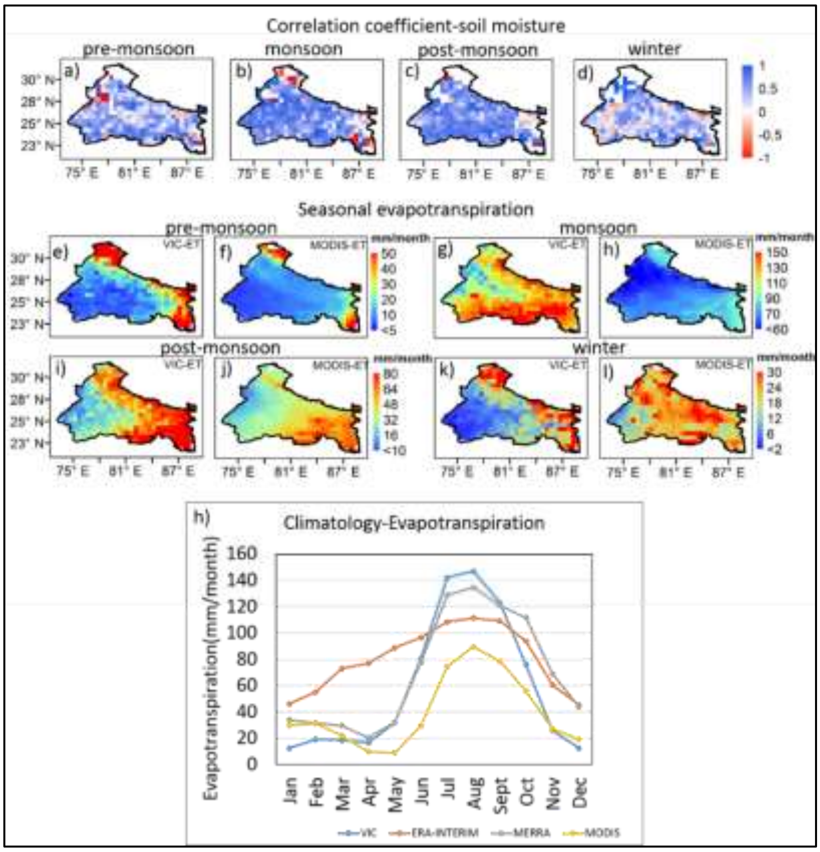


Figure 48 Evaluation of VIC model. (a)-(d) shows the correlation coefficient between observed soil moisture and ensemble mean of simulated soil moisture for the four seasons.(e)-(l) shows the spatial comparison of MODIS ET and ensemble mean of VIC simulated ET and (h) represents the climatology of various ET products.

The spatial distribution of changes in soil moisture and evapotranspiration is presented in Figure below. The spatial probability density function for seasonal average of changes in evapotranspiration and soil moisture between 2011-2037 and 1979-2005 is shown in Figure. The band corresponds to the probability density obtained for the 1000 different set of input files. It can be observed that the width of the uncertainty band is less compared to the difference in the bands for the 4 meteorological datasets. The box plots for water yield in Figure 4 also depicts the same result that the hydrological uncertainty is less compared to the GCM and downscaling uncertainty.

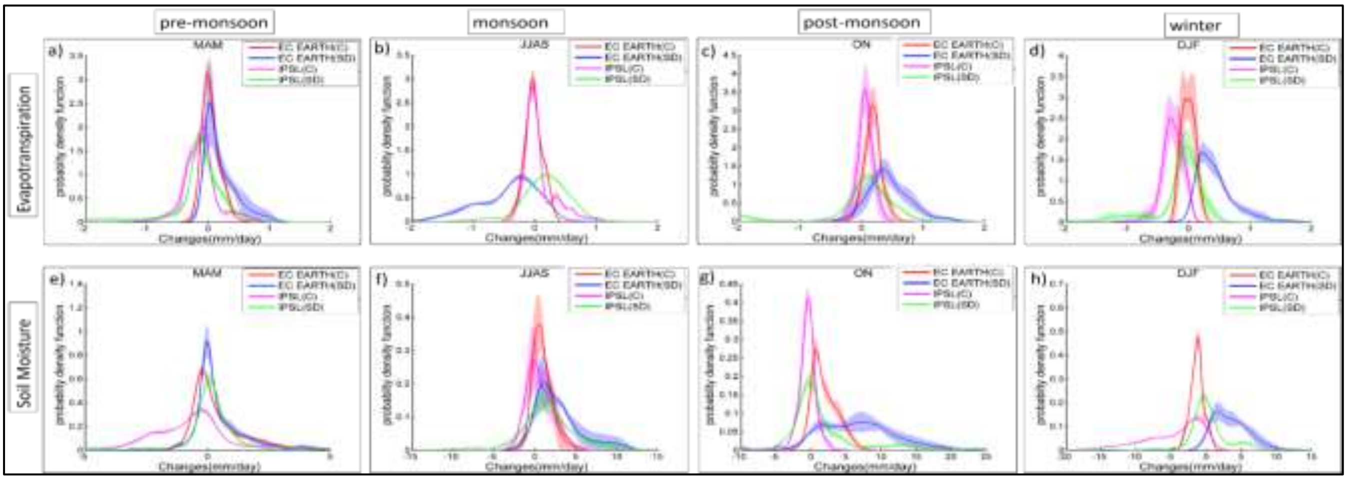


Figure 49Spatial probability density function for changes in evapotranspiration (a-d) and soil moisture (e-h) for different seasons

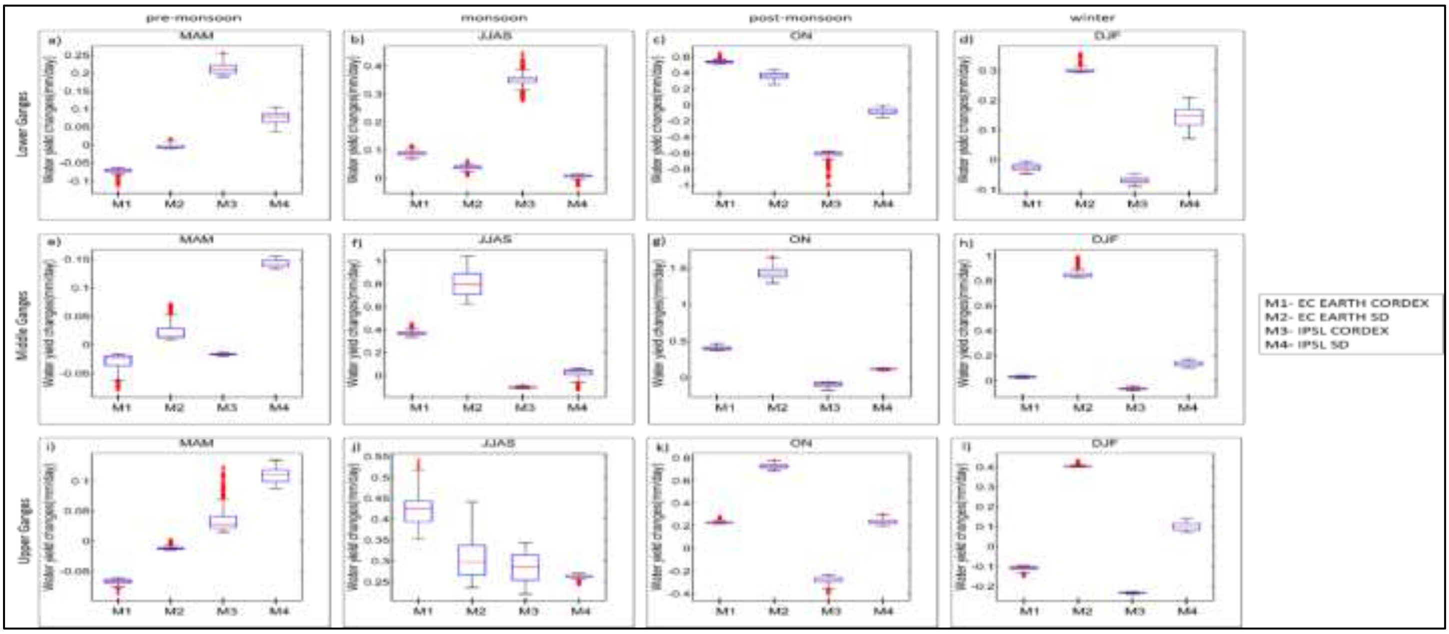


Figure 50 Box plots for changes water yield for different seasons

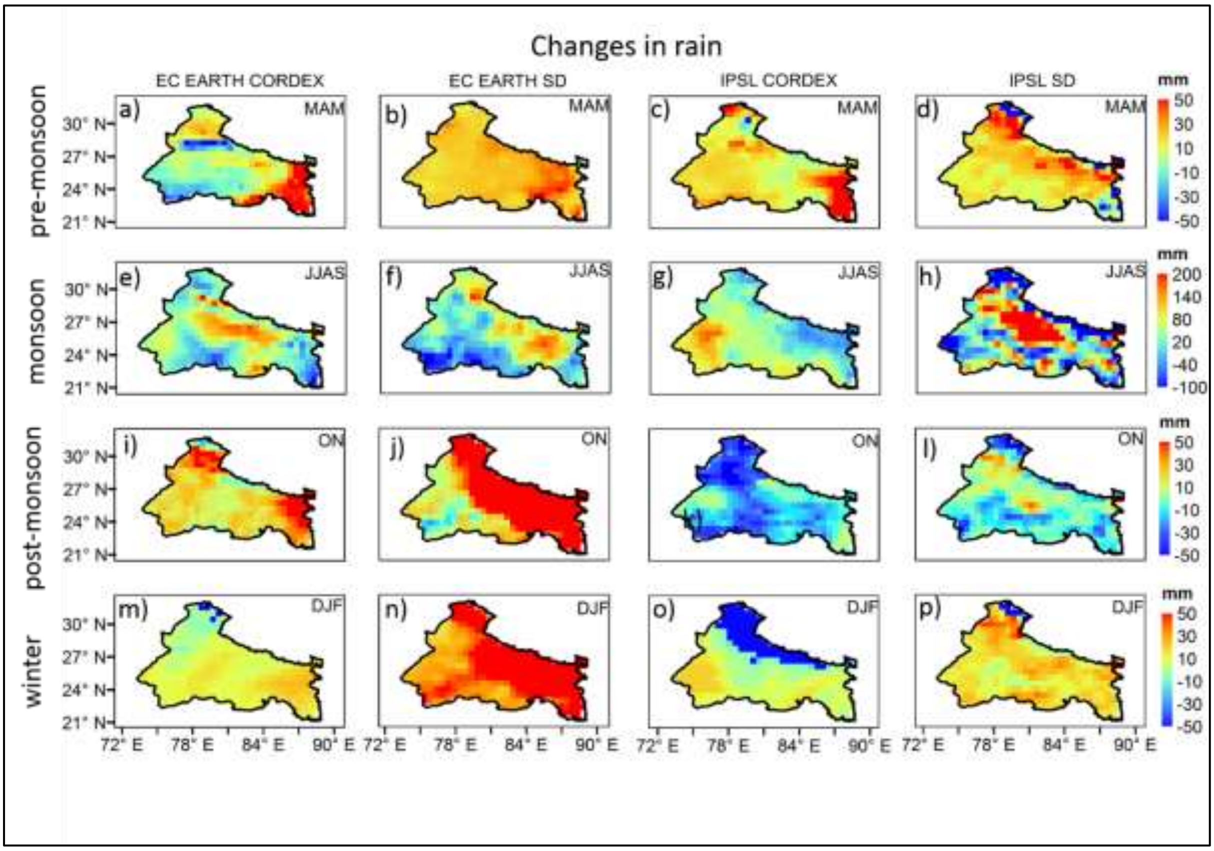


Figure 51 Seasonal average in changes in rain between 2011-2037 and 1979-2005 for EC-EARTH CORDEX, EC-EARTH statistically downscaled, IPSL CORDEX, IPSL statistically downscaled data.

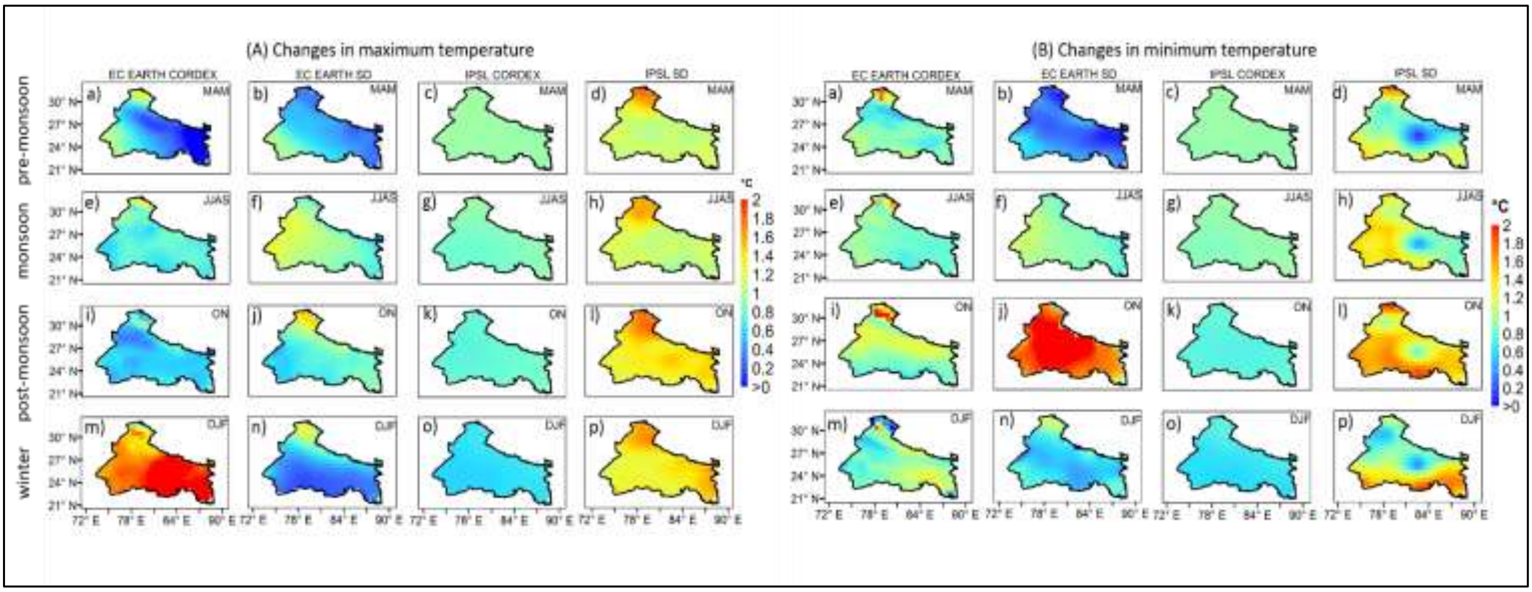


Figure 52Seasonal average in changes in (A) maximum temperature (B) minimum temperature between 2011-2037 and 1979-2005 for EC-EARTH CORDEX, EC-EARTH statistically downscaled, IPSL CORDEX, IPSL statistically downscaled data.

The seasonal average of changes in rain, maximum temperature and minimum temperature for IPSL CORDEX, IPSL statistically downscaled, EC-EARTH CORDEX and EC-EARTH statistically downscaled were plotted as in Figure 4 and 5. The changes in rain shows high deviation among the 4 datasets whereas maximum and minimum temperature do not show much of deviation. Hence it can be inferred that the within the meteorological datasets, precipitation contributes to uncertainty more when compared to the maximum and minimum temperature.

d. Summary and conclusion

The hydrological modelling is always associated with uncertainty which may include parameter uncertainty, GCM uncertainty and downscaling uncertainty. The calibration of the model demands very accurate observed data. Generally runoff data is used for model calibration are controlled data due to the presence of dams, reservoirs and irrigation practices. The future projections are not accurate since these data are not reliable.

The uncertainty assessment was carried out for hydro-climatic simulations of Ganga river basin using Monte Carlo simulations for different GCMs and downscaling methods. It was found that the hydrological is very less when compared to the different GCMs and downscaling methods used. In the spatial probability distribution plotted for difference between future and past in ET, soil moisture and water yield, the uncertainty band for a particular meteorological input file was less compared to the difference in the distribution for one meteorological file with the other. Hence it can be concluded that the hydrological uncertainty is much less compared to GCM and downscaling uncertainty. Therefore, improvement in GCMs and downscaling methods should be given more importance than the calibration of the hydrological model.

8. Climate Change Impacts - Case from India

a. Introduction

Flooding due to Sea Level Rise and Increase in Salt water intrusion to rivers are two direct impacts of Climate change on Costal/Estuarian areas. Cochin estuary situated on the west coast of India and is 80 km long extending from Munambam (North most) to Vembanad Lake (South Most). The estuary has two openings to sea and home to six rivers. On the south the estuary is known as Vembanad lake which is surrounded by low lying paddy fields(Kuttanad region) which is called the Rice bowl of the state of Kerala. A barrage is constructed to check sea water intrusion to the low lying cultivate areas of Kuttanad region

The barrage is already affecting the ecology of the area and need for an agriculture calendar for minimizing the closing of bund is already proposed in state budget of 2009-10. The barrage has reduced the salinity intrusion and resulted in reduction in catch of fish consequently fisherman are opposing the closing of the barrage. Future projected Sea level rise challenges the agriculture system of the area due to flooding and saltwater intrusion and the role of bund need to be analyzed. Hence projecting seasonal water level variation and extend of inundation for future is essential for assessing the impact of climate change on agriculture. A numerical model is setup using Delft3D to study effect of Sea level Flooding and Salt water intrusion.

Figure 53 Cochin Estuary

b. Numerical Modelling of Tidal Hydrodynamics and Salinity Transport for Cochin Estuary

Cochin Estuary is a 80 k.m. long backwater body running along the wester coast of the state of Kerala. The Estuary has two openings to Sea and home to 5 river outlets. The city of Kochi and its industrial areas as well as Kuttanad (the rice bowl of Kerala) shares the estuary. The estuary is already challenged by 2004 Tsunami, Floods and Salt Water Intrusion into rivers. A bund/barrage is constructed to check salt water intrusion to Paddy fields during non-monsoon season. The present study is to assess the salinity levels in the estuary and impact of climate change induce sea level rise on the same . A tide model was setup and validated with observed water levels at 7 locations. The Salinity model was then validated with observed salinity levels at 10 along the length of the estuary.

c. Model Setup

The model domain of Cochin estuary is a network of four channels with two open boundaries. The entire backwater is divided into two halves i.e., from Munambam (inlet 1) to Cochin (inlet 2) as northern channel and from Cochin (inlet 2) to Alleppy as southern channel. Area of study covers from Munambam in the northern channel till Thannermukkam Barriage extends up to Vembanad Lake in the southern channel. Tidal observations are taken from different stations which are set along the length of domain.

The estuary is supplied with river discharge from six rivers. River run-off points were set at four different points: for Periyar at mid of northern channel, Muvattupuzha and Meenachil at the point where they joins the backwater and the other three rivers at end of southern channel.

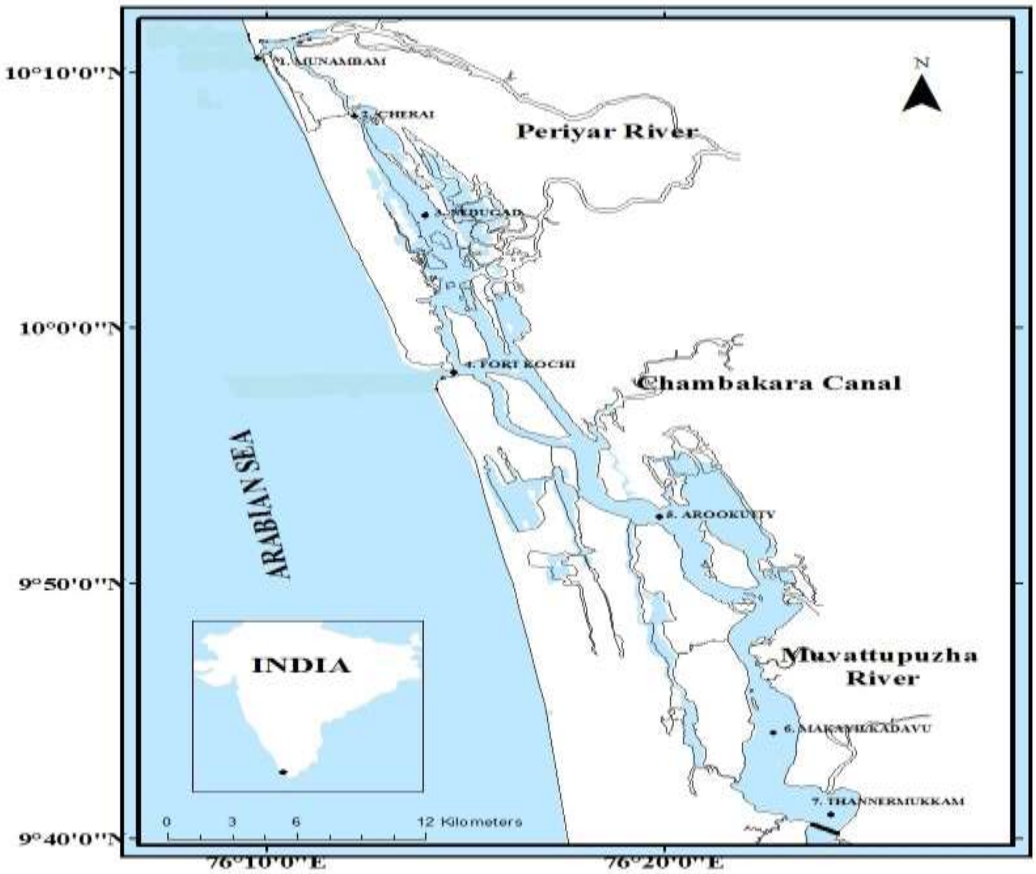


Figure 54 Observation stations for Tide model

d. Model Configuration

The study area is restricted within the estuary and initiated with tidal constituents at offshore boundary approximately located along 20m depth contour. The offshore boundary (approximately 30km offshore from the Cochin inlet) was simulated as an open water level boundary. Each boundary was divided into segments of 10 cells and tidal constituents for each segments was used as the boundary conditions. The red boundary in Fig indicates the tidal boundary.

A variable grid size scheme was used in order to reduce the number of computation points as well as the computation time. The size of the grid is increased progressively from the estuarine area to the boundaries. The model with a rectilinear grid reasonably represents the observed patterns and it was decided little would be gained by using a curvilinear grid for this application. The grid was set up as follows, The grid was refined in the inlet and narrow region of estuary with cells: 30 x 80 m, the rest of estuary had cells: 80 x 100 m., coarsest to the offshore region, with cells: 80 x 200m.

Bathymetry data of the Cochin estuary were obtained from recently developed bathymetry charts of The Inland Waterways Authority of India: IWAI NW-3 Planning charts-3Nos, IWAI NW-3 Subcharts-8Nos) and Admiralty Chart No: INT 7356 . It was digitized using 3D Analysis tools in ArcGIS software. The approach channel data was verified with the data taken from a port survey of June 2005. The bathymetry keeps varying in each channel, but along a particular channel it varies linearly. A constant depth of 13m is maintained along the approach channel. The bathymetric plot is given in figure.

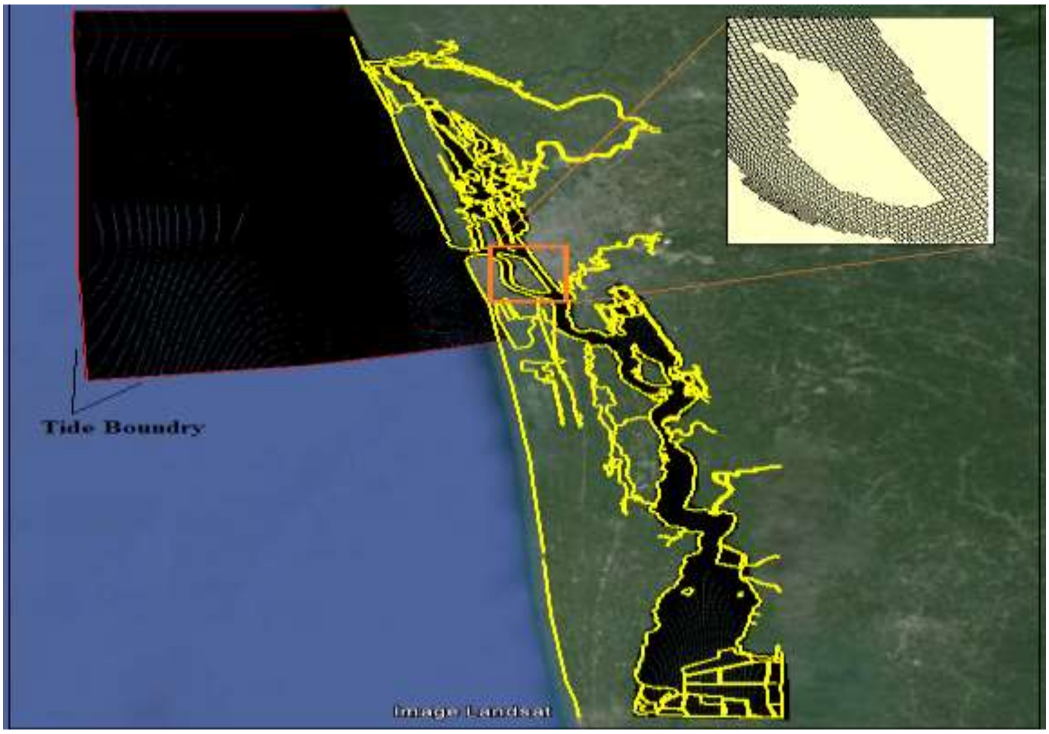


Figure 55 Grid used for Delft-3D model

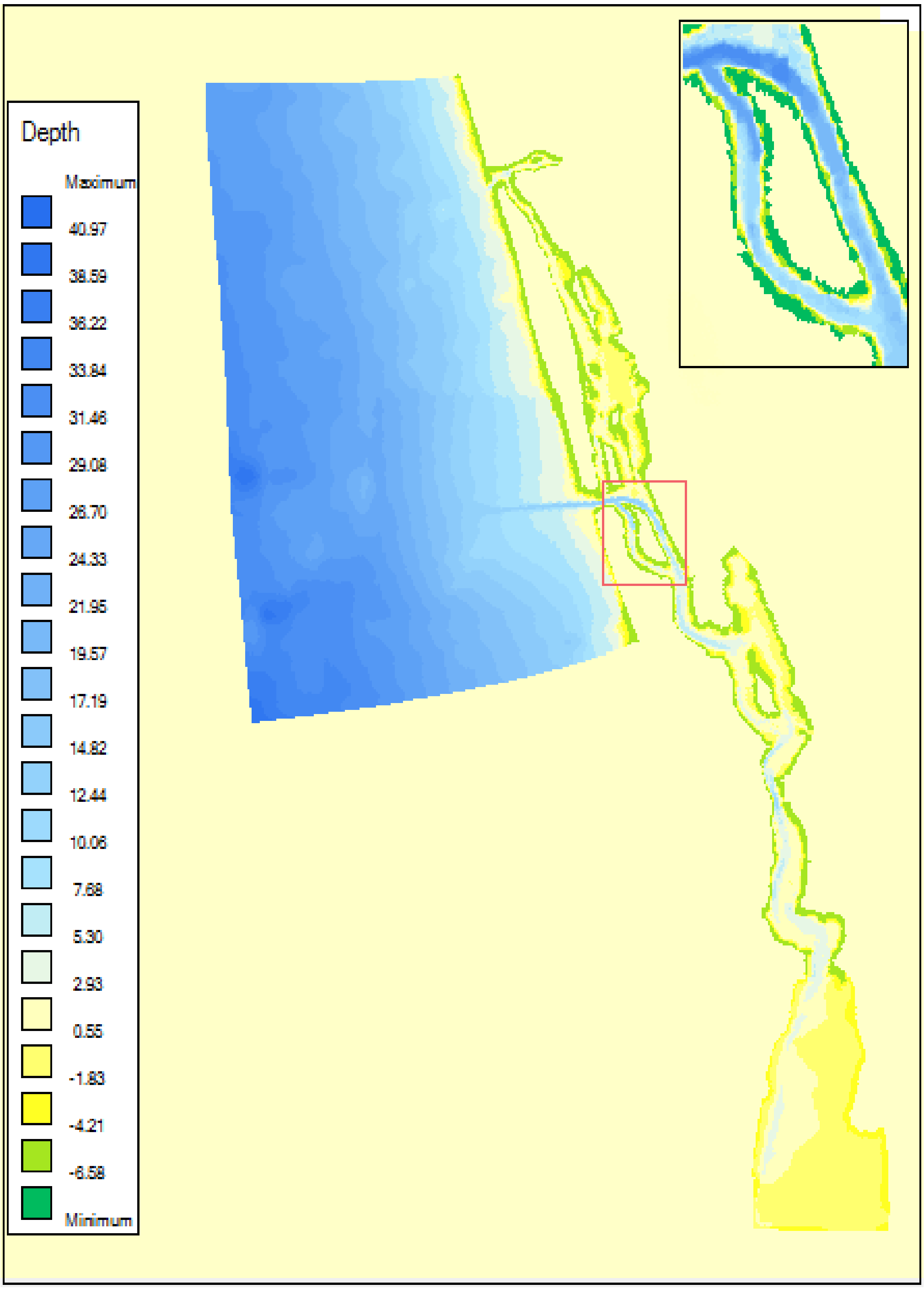


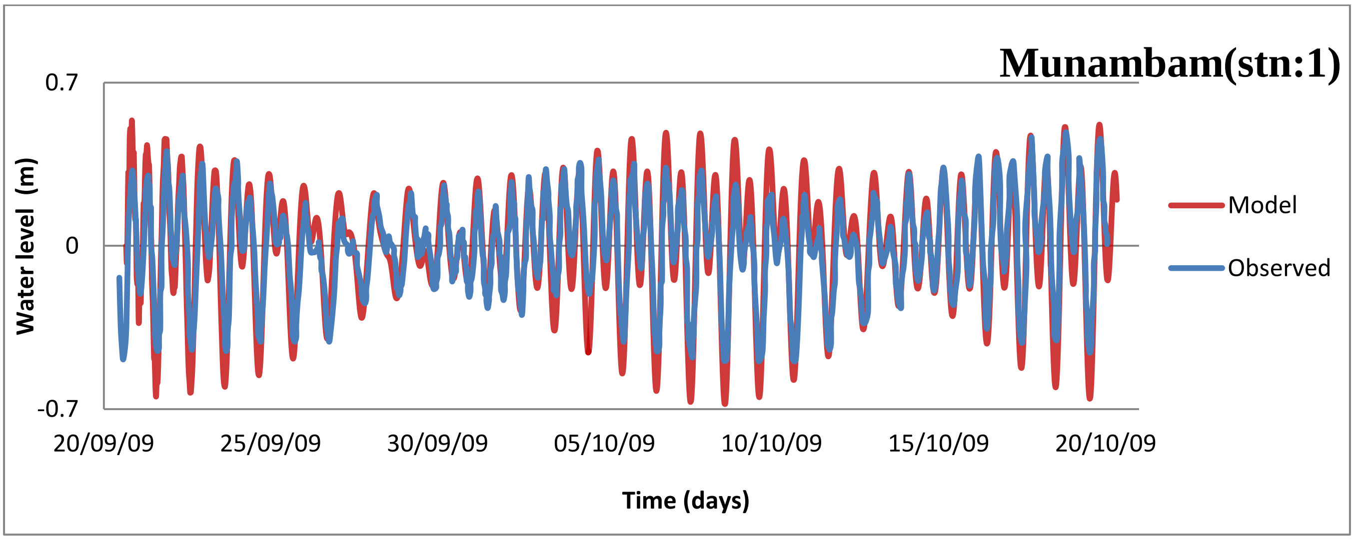
Figure 56 Bathymetry of Cochin Estuary generated in Delft-3D (depth in meters)

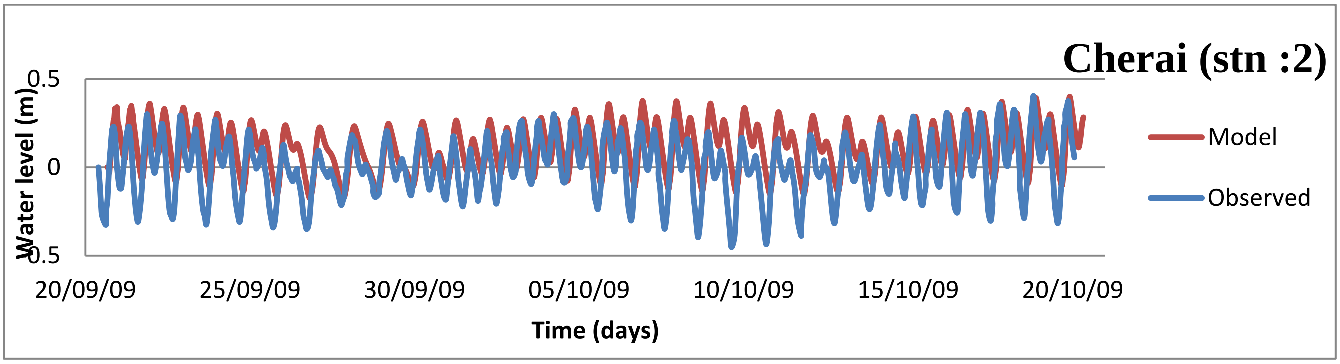
e. Validation of the Model for two cases

The model is validated for two cases, one high run off case and low run off case. In high run off case the river discharges are high and the Thannermukkom barrage at southern side is kept open. In low runoff case the river discharges are minimum and the barrage at Southern part is kept closed.

Case 1: Simulation of tides during high run-off

The tidal constituents extracted from TMD is used at the open boundaries and are forced for a time frame of high runoff (September-October 2009). The river runoff computed is introduced to the respective locations of the rivers outlets in the system. Daily river runoff data for Periyar, Muvattupuzha, Meenachil and other three rivers are supplied at middle of the northern arm, middle of the southern arm, below the Thannermukkam bund and end of southern arm respectively. The Manning's coefficient used in this scenario is 0.02 and horizontal eddy viscosity is taken as $1m^2/s$. Observed tides were of mixed semidiurnal nature with decaying amplitude towards upstream. Tide is at its maximum amplitudes in the inlets (Stn1&4). The simulation shows that the model has captured the observed results (Fig. a & b) at 1, 4 and 5 stations. The simulated tides lag behind the observed at station 2, 3 and slightly overestimates at stations 6 and 7 during the neap phases. The tidal amplitudes decay more toward the upstream regions of the southern arm. Whereas in the northern arm, tides from the two inlets do not decay much until the middle of the northern arm. There is no region in the southern and northern arms where tidal effects can be neglected due to high runoff. The model results also show that the mean water level rises in both the arms during the high runoff.





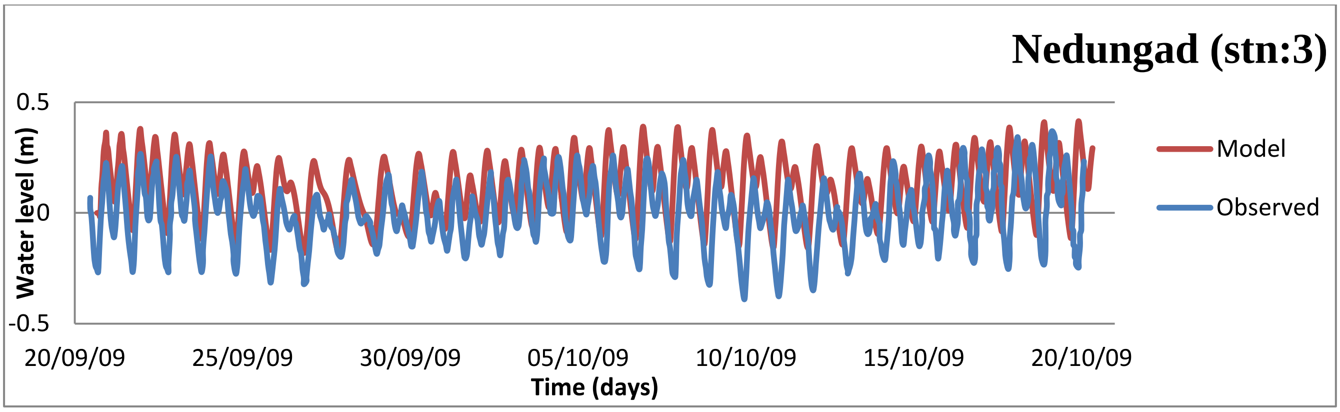
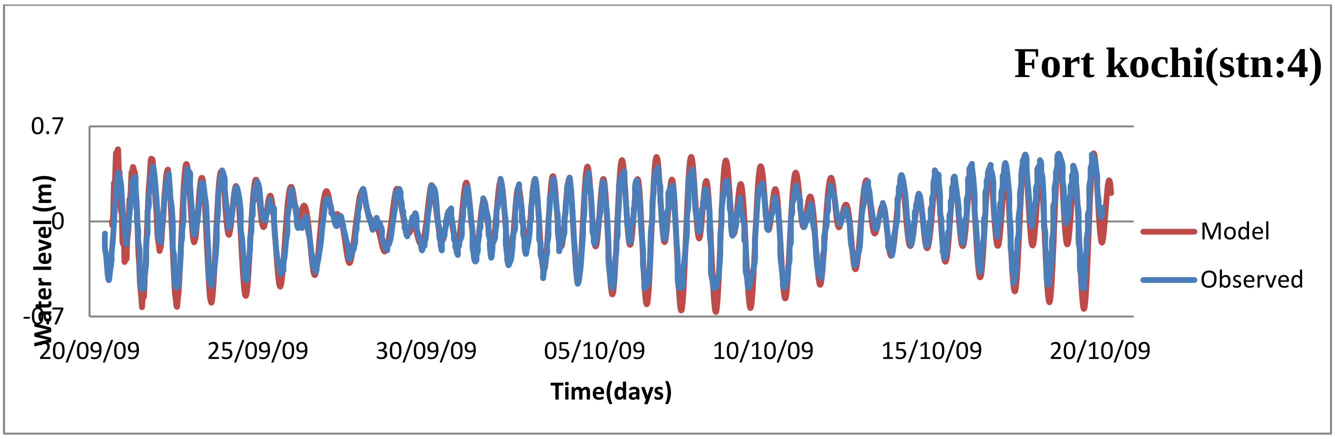
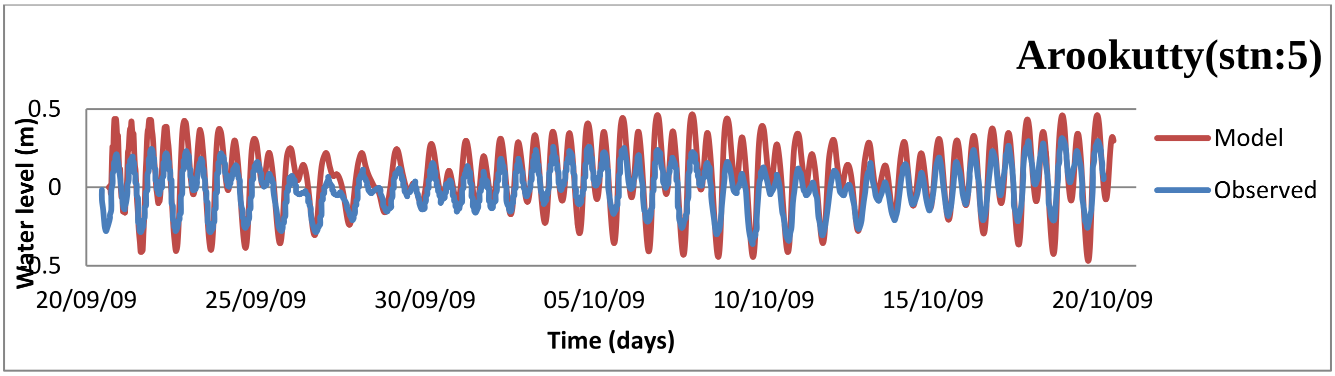
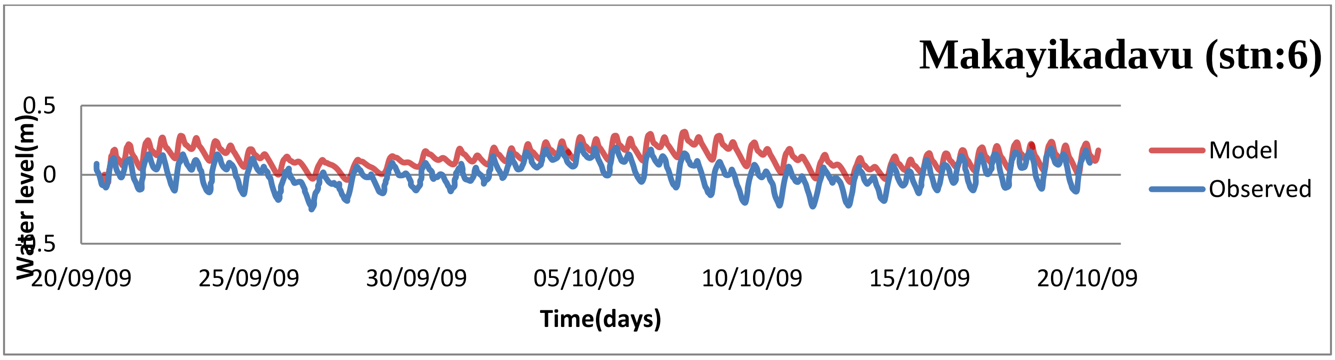


Figure 57 Observed and simulated tides during high runoff (20/09/2009 16:00hrs to 20/10/2009 8:00hrs)







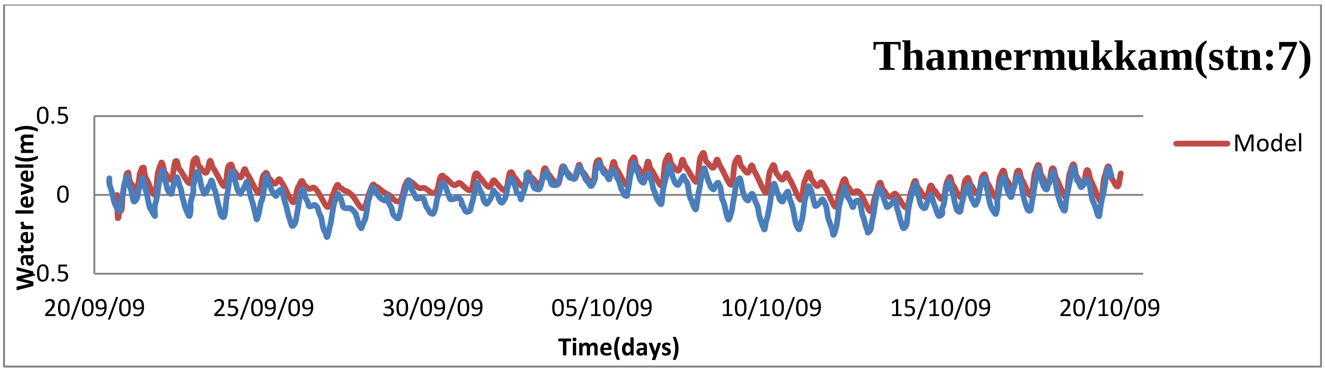


Figure 58 Observed and simulated tides during high runoff (20/09/2009 16:00hrs to 20/10/2009 8:00hrs)

Simulated results for high runoff shows the stations near the inlets (1&4) is having a tidal range from +/-0.7. Station 2 and 3 being shallower and narrow part, the progressive waves slows down and so the amplitude increases. In stations 6 and 7, the tides have reduced considerably as it is the widest and shallow area of the estuary. Figure shows the velocity variations for ebb and flood tide.

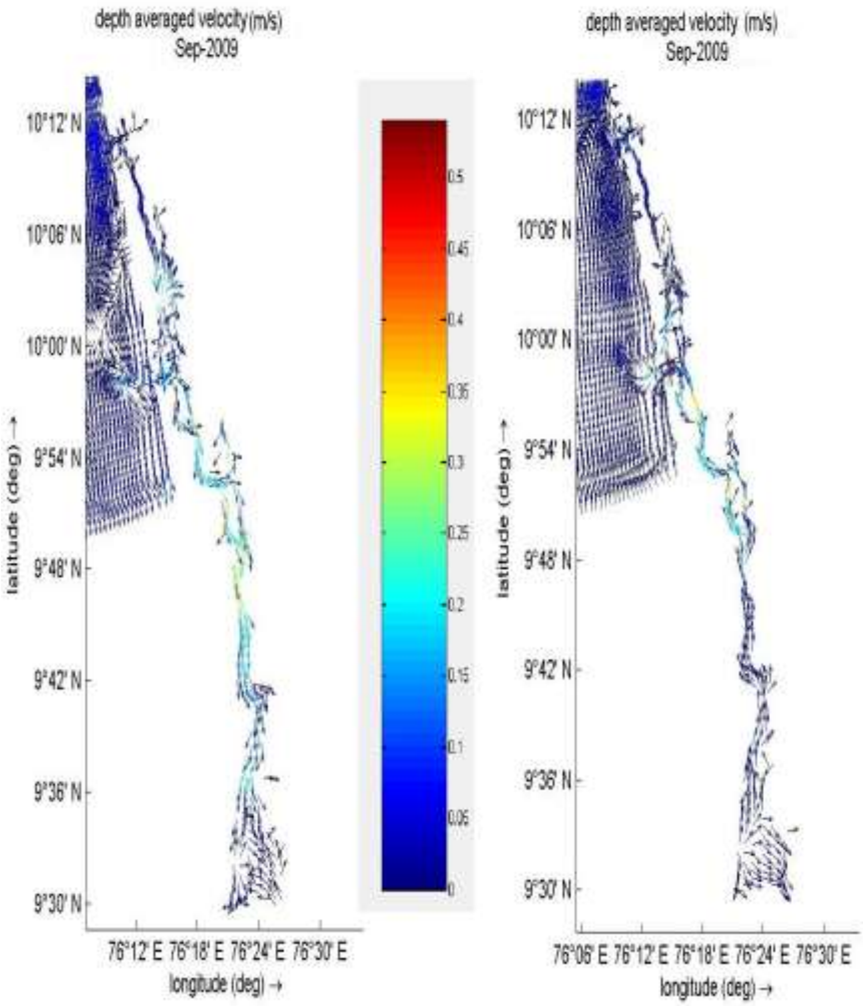


Figure 59 Velocity vector of ebb and flood tide at Cochin estuary (September 2009).

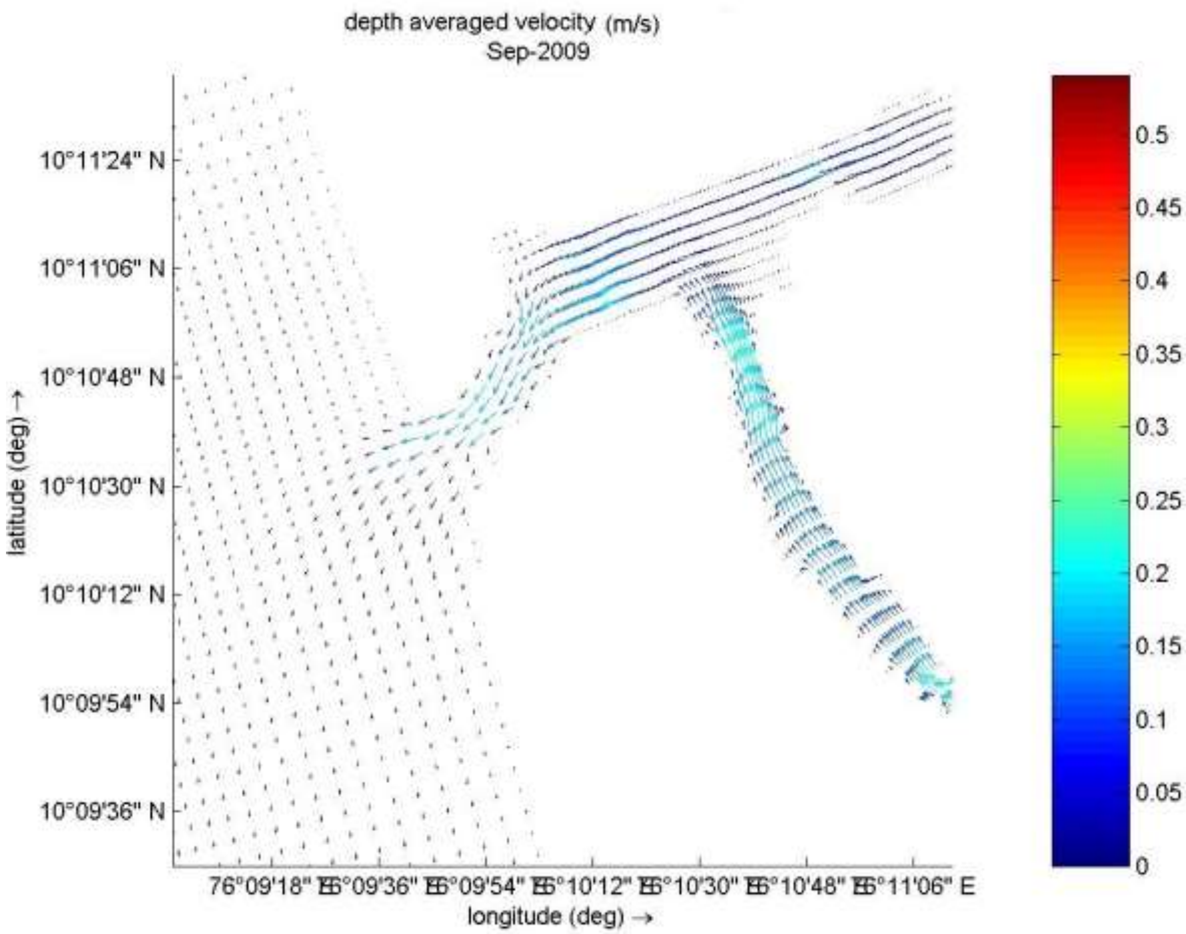


Figure 60 Velocity vector at Munambam (Inlet 1) (September 2009).

The velocity vector plots shows velocity of ebb and flood tide for high discharge condition. Fig 1.8 and 1.9 show the velocities at Munambam and Cochin Inlet respectively. The velocities increases at the mouth and decreases gradually to the interior.

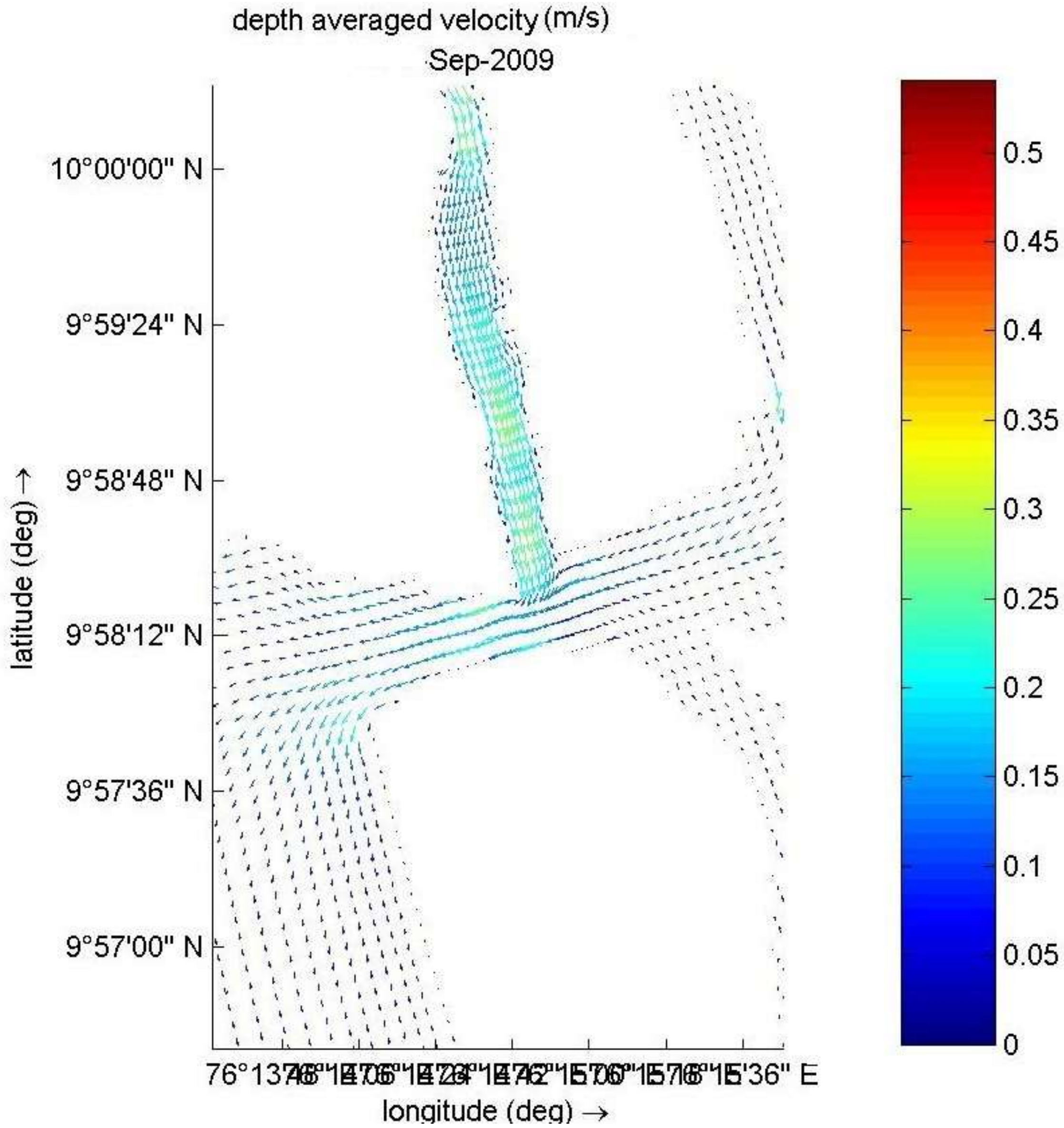
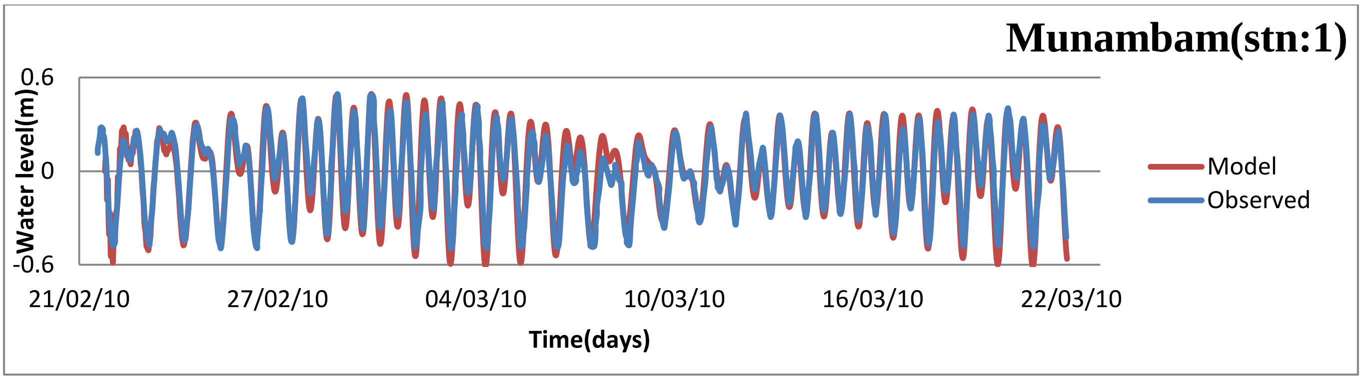
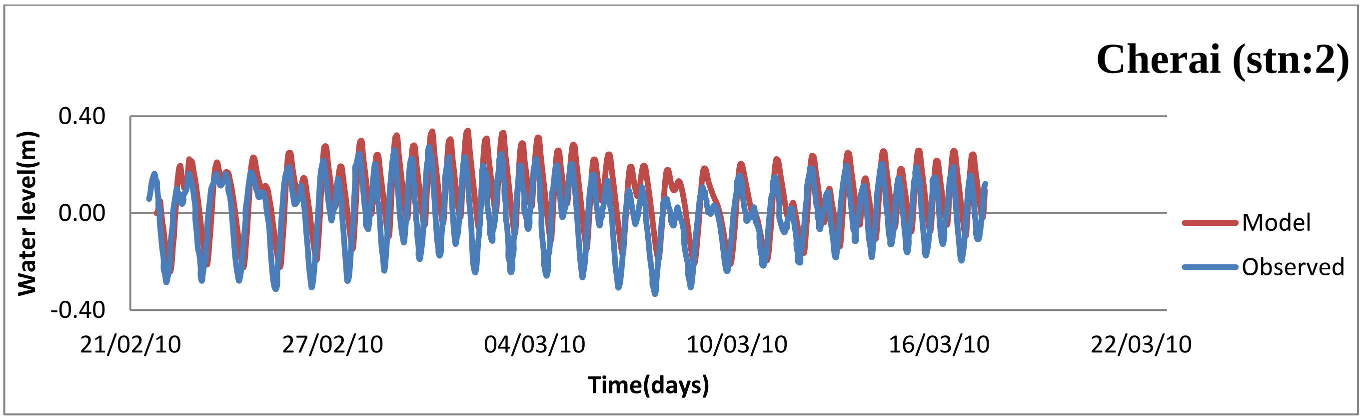


Figure 61 Velocity vector at Cochin (Inlet 2) (September 2009).

Case 2: Simulation of tides during low run-off

The barrage is closed for Low run off case and hence the daily river runoff south of the barrage is introduced at Thanneermukkam barrage at south of the estuary. The Manning's coefficient used in this scenario is 0.02. The observed data for few days are missing at Cherai and Thannermukkam. In this case, the model simulates the observed signals accurately at all the stations (Fig. 1.9va and 1.9 b). During this period the Thaneermukam Barrage remains closed. Station 2 and 3 slightly overestimates at the neap phase. In station 6 and 7 the there is rise in water height comparing to that of high runoff result. This can mark the influence of barrage and runoff on tidal propagation.





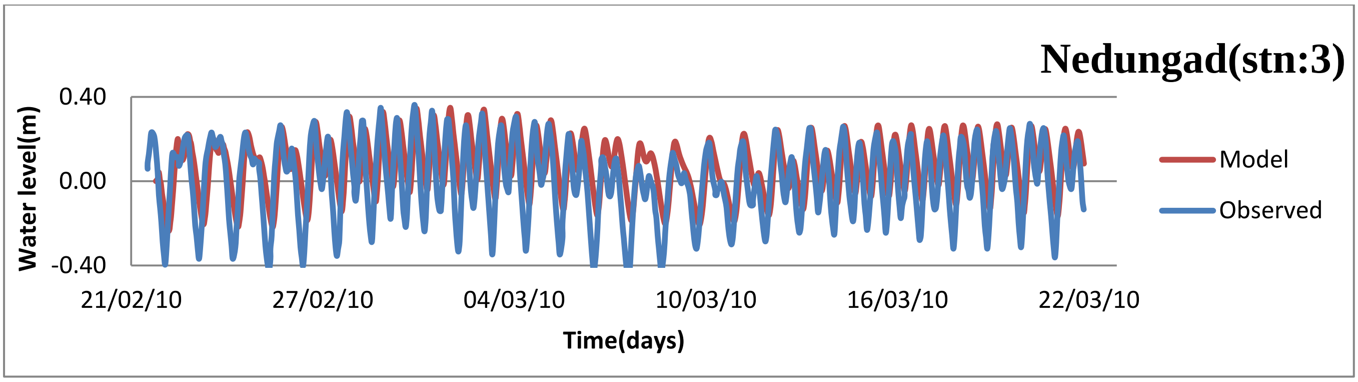
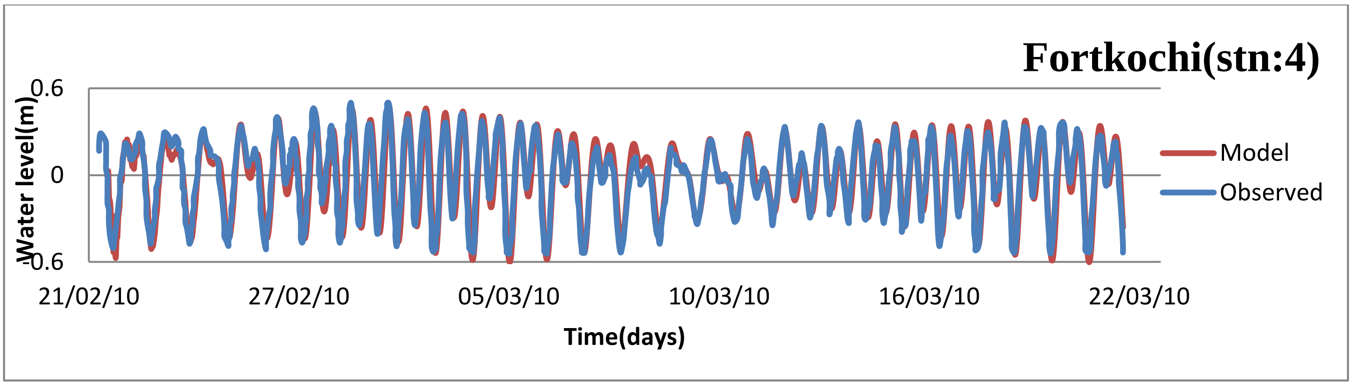


Figure 62 Observed and simulated Tide during Low runoff (22/2/2010 00:00hrs to 22/3/2010 08:00hrs).



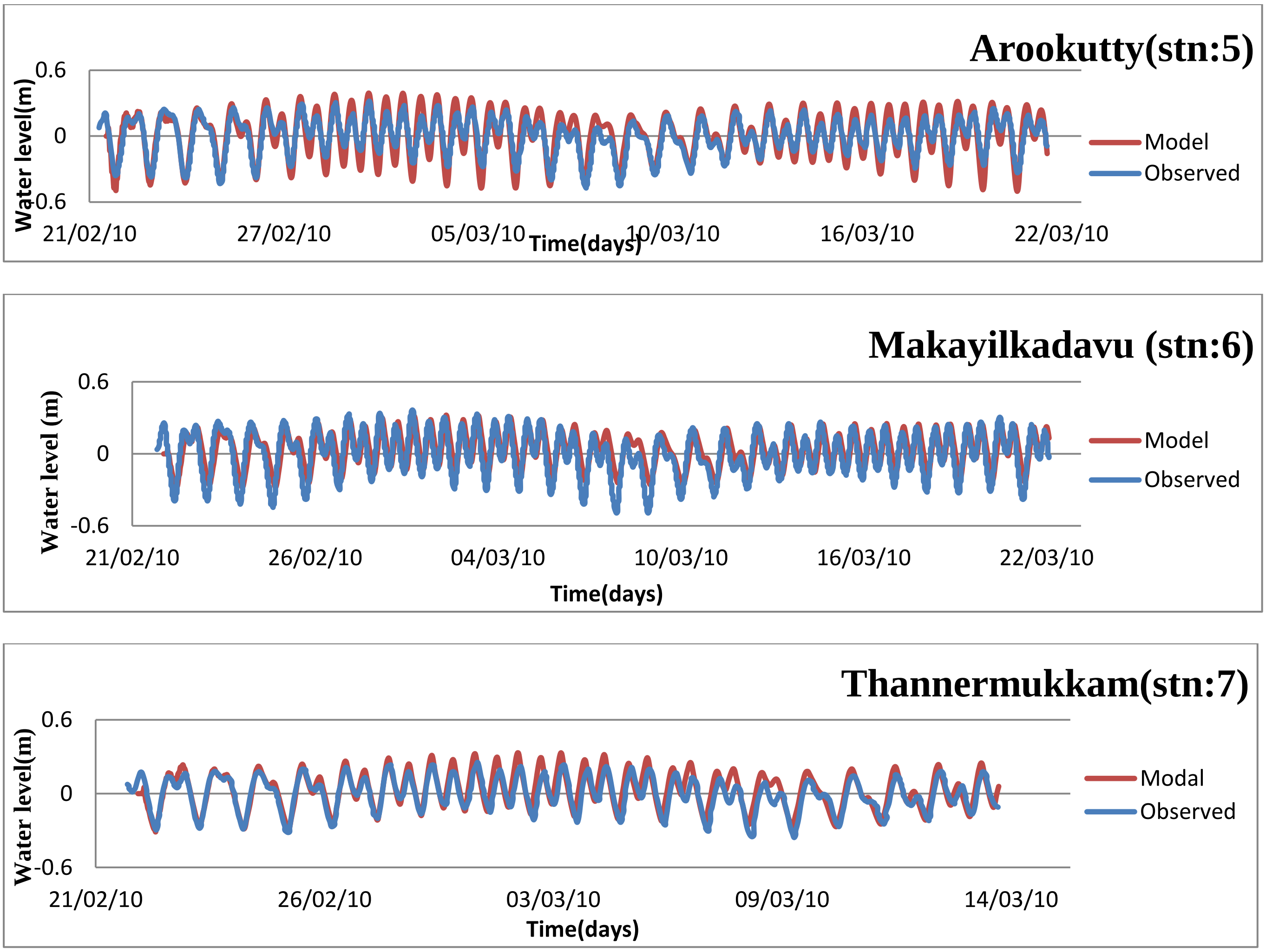
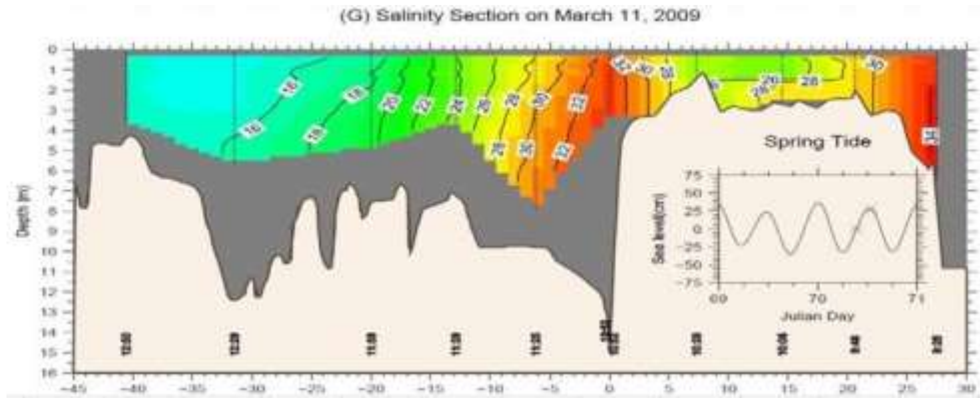


Figure 63 Observed and simulated Tide during Low runoff (22/2/2010 00:00hrs to 22/3/2010 08:00hrs).

f. Salinity Transport Model

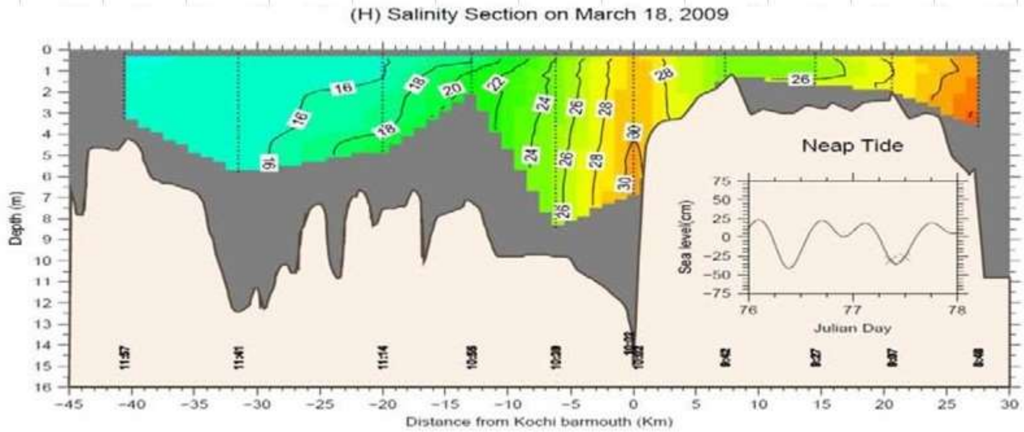
A salinity model is setup using the validated tide model. The time step is reduced from 1 minute to 0.4 minutes. The horizontal eddy diffusivity found for a reasonable model is found to be 5 meter square/sec. The salinity readings of observed at 10 stations along the estuary is compared with the modelled salinity levels in the following plots. The readings are compared for two cases a neap tide case and a spring tide case separated by 7 days time. It shows good agreement with the observed reading. The model represents the salinity transport in the estuary reasonable well despite adopting temperature variations and 3D modelling A constant density of 1026 kg/m3 is adopted throughout the estuary but river water discharge.

The model is used to find the critical river discharge for keeping saline water out of the agriculture area. As there are 6 rivers and each discharge to the estuary, to work on 6 scenarios to find critical discharge for each river is inconvenient. Hence the daily average river discharges are compared to combined daily average discharges of river Meenachil, Manimala, Pampa and Achancoil and the combined discharge is kept as a standard discharge. Hence the discharges of all the rivers can be worked out based on discharge of the combined daily average discharge. As the river discharges are somewhat comparable and follows somewhat similar trends multiplication factors for each river w.r.t to standard river discharge is computed. The model is now used to arrive at critical river discharges to keep salt water intrusion to paddy fields.



	Stat-10	Stat-9		Stat-8	Stat-7	Stat-6	Stat-5	Stat-4	Stat-3	Stat-2	Stat-1
	15.0779	17.1061		20.1126	26.0353	30.0094	33.3245	27.9982	27.9499	34.1416	34.9387

Figure 64 Observed and modelled Salinity profiles during Spring tide at 10 stations (marked by vertical dotted lines). The coloured plot represents observed salinity levels (ppt) and the modelled salinity levels (ppt) at each stations are listed below the stations.



	Stat-10	Stat-9		Stat-8	Stat-7	Stat-6	Stat-5	Stat-4	Stat-3	Stat-2	Stat-1
	15.1995	16.9442		19.2269	24.4523	28.8591	32.5677	28.6469	31.7033	34.7432	34.9634

Figure 65 Observed and modelled Salinity profiles during Neap tide(bottom) at 10 stations(marked by vertical dotted lines). The coloured plot represents observed salinity levels (ppt) and the modelled salinity levels (ppt) at each stations are listed below the stations.

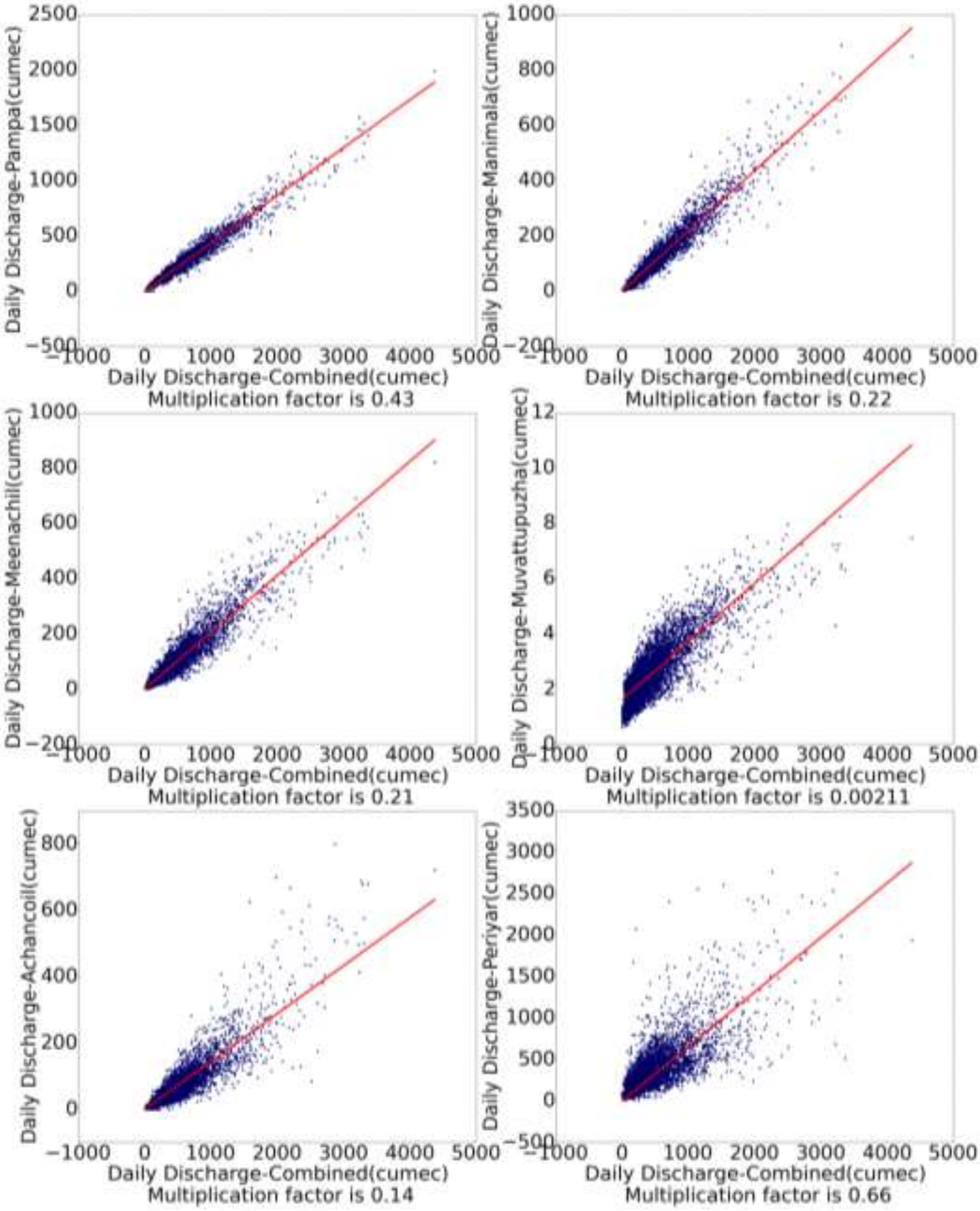


Figure 66 Comparison of Daily Average River discharge with Combined Daily average River discharge (Combined discharges of Meenachil, Manimala, Pampa and Achancoil Rivers)

The minimum river discharge needed to keep the Kuttanad region from salt water intrusion is arrived for various sea level rise(0.5m, 1m and 2m). Recommended salinity levels for irrigation water is less than 0.450 ppt. The combined river discharge in multiples of 10 cumecs is checked for safe salinity levels for different sea level rise mentioned. The simulations were initialled with nearly 15ppt salinity at the TMB region and zero salinity upstream of bund and the equilibrium salinity levels attained along the estuary are checked. The minimum discharge arrived is provided in the table below.

Table 23 Minimum Combined River Discharge for safe salinity levels

Sea Level Rise (meters)	Minimum Combined discharge required(Cumecs)
0	60
0.5	70
1.0	90
2.0	120

g. Sea Level Rise Projections

Climate model outputs were used to project the future Sea Levels. Two approaches were taken for the same. In first approach the Sea Level rise is been worked out for Kochi area from 2000 to 2100 for RCP 8.5 scenario as it is the worst case scenario. The SLR from 200 to 2055 and 2056 to 2100 were calculated separately and GIA correction for the area i.e. 0.44mm is added to the GCM projections. The maximum Sea Level rise computed in this approach 0.25 meters for year 2100. The average sea level rise computed for year 2100 is around 0.080 meters. The projections are shown in table below.

Table 24 Projected Sea Level Rise

GCM Models	GIA correction (mm/yr), Unnikrishnan et al(2007)	GCM projected SLR for year (2010-55) mm/yr	GCM projected SLR for year (2056-2100) mm/yr	SLR for year 2055 (mm)	SLR for year 2055 (mm)
CanESM	-0.440	0.471	0.846	50.114	107.983
inmcm4	-0.440	0.067	-0.201	27.900	38.655
IPSL-C	-0.440	-0.029	-0.578	22.583	16.359
MIROC	-0.440	2.896	1.164	183.470	255.643
MIROC5	-0.440	-0.759	-0.004	-17.539	2.095
MRI-ES	-0.440	0.367	0.040	44.375	65.954

In the second approach the Climate models historical run is compared to the observed Sea Level Rise from Tide Gauge data available from the year 1970 to 2005. The difference between observed sea level rise and GCM projected Sea level rise is treated as an anomaly and the same is corrected for future projections. The approach is really crude and the effectiveness of the method can be questioned especially when the anomaly is much higher than projected Sea Level Rise. However even with the above uncertainties this method is also used to project Sea Level Rise and is shown in the table below. The maximum Sea Level rise computed in this approach 0.52 meters for year 2100. The average sea level rise computed for year 2100 is around 0.33 meters. The projections are shown in table below.

Table 25 Projected Sea Level Rise

GCM Modals	Tide Gauge SLR (mm/yr)	GIA correction (mm/yr), Unnikrishnan et al(2007)	Resulting SLR (mm/yr)	SLR projected by GCM historical run (mm/yr)	Anomaly in SLR (mm/yr)	GCM projected SLR for year (2010-55) mm/yr	GCM projected SLR for year (2056-2100) mm/yr	corrected SLR for year (2010-55) mm/yr	corrected SLR for year (2056-2100) mm/yr	SLR for year 2055 (mm)	SLR for year 2055 (mm)
CanESM	1.281	-0.440	1.721	-0.421	2.142	0.471	0.846	3.053	3.428	167.914	322.166
inmcm4	1.281	-0.440	1.721	0.191	1.530	0.067	-0.201	2.037	1.769	112.052	191.659
IPSL-C	1.281	-0.440	1.721	-3.335	5.056	-0.029	-0.578	5.467	4.918	300.662	521.958
MIROC-	1.281	-0.440	1.721	-0.597	2.319	2.896	1.164	5.654	3.923	310.996	487.509
MIROC5	1.281	-0.440	1.721	-0.586	2.307	-0.759	-0.004	1.989	2.744	109.373	232.845
MRI-ES	1.281	-0.440	1.721	-0.263	1.985	0.367	0.040	2.791	2.464	153.531	264.418

As the projected maximum Sea Level rise is around 0.25 to 0.5m the loss of land due to the same would be negligible. However the flooding the climate extremes like high river discharges can cause severe flooding.

h. River Discharges

The combined river discharges for the rivers Meenachil, Manimala, Pampa and Achancoil from the year 1986 to 2011 is analysed to check the lowest and most probable discharges. A histogram of the annual river discharges is shown in figure below.

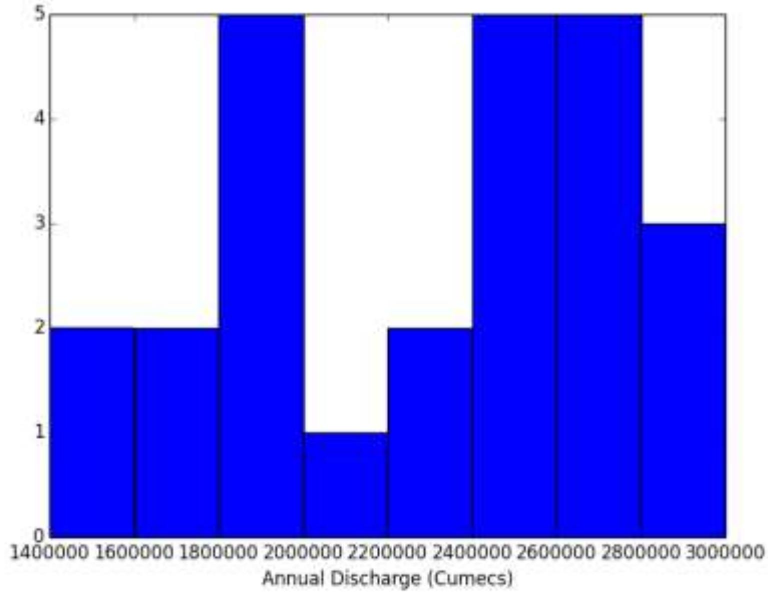


Figure 67 Histogram-Annual river discharges (combined)

It can be observed that a higher value of 26lakh cumecs discharge is found to be the most probable discharge and a lower value of 17lakh cumecs discharge is probable lower discharge. The river discharges for year 1993, 2000 and 2003 are selected as they represent the probable high river discharges, probable low river discharges and lowest recorded river discharges respectively. The daily river discharges are also plotted for the above mentioned years.

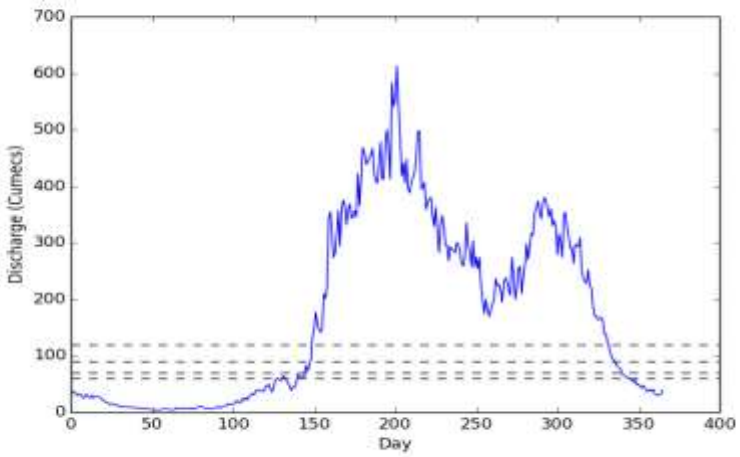


Figure 68 Combined Daily River Discharges, Probable High discharge scenario. The dotted lines marks the minimum discharge computed for lower salinity levels (60, 70, 90 and 120 cumecs)

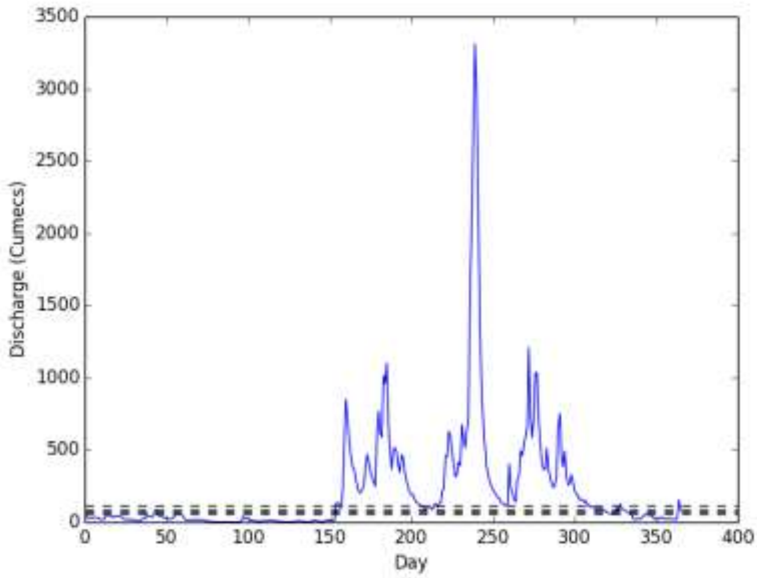


Figure 69 Combined Daily River Discharges, Probable Low discharge scenario. The dotted lines marks the minimum discharge computed for lower salinity levels (60, 70, 90 and 120 cumecs)

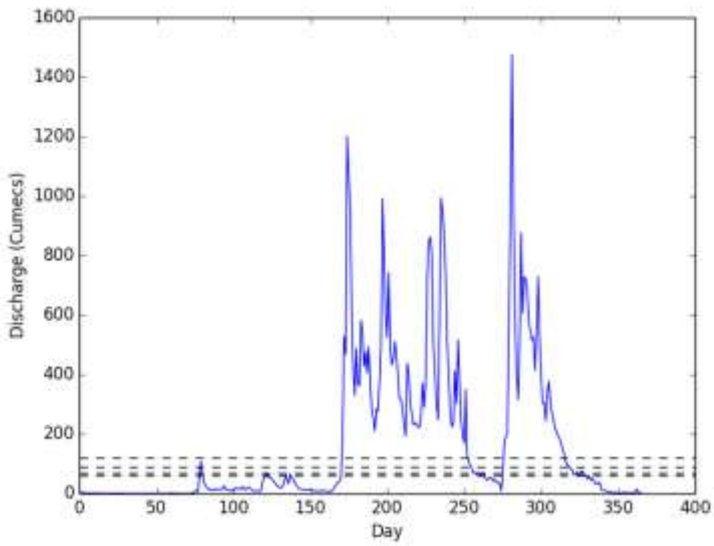


Figure 70 Combined Daily River Discharges, Lowest discharge recorded. The dotted lines marks the minimum discharge computed for lower salinity levels (60, 70, 90 and 120 cumecs)

The number of days the barrage can be opened for these three scenarios with different sea level rise is checked and is given in table below.

Table 26 Number of days the barrage can be kept opened for different river discharge and Sea level rise scenarios

River Discharge	0.0m SLR, minimum Discharge 60cumecs	0.5m SLR, minimum Discharge 60cumecs	1.0m SLR, minimum Discharge 60cumecs	2.0m SLR, minimum Discharge 60cumecs
High	209	196	189	184
Low	169	168	165	151
Recorded Lowest	154	151	149	146

i. Conclusion

The maximum Sea level Rise projected for the area is around 0.25m to 0.5m and therefore low land loss can be negligible. However the possibility of extreme floods due to climate change should be evaluated. The effect on sea level rise of Salt water intrusion rate is found to be profound. As the river discharges are mainly monsoon dominated the river discharges during monsoon time is higher than the minimum river discharge required to keep the areas safe from salt water intrusion for different sea level rise scenarios. The difference in the number of days the barrage can be kept opened for no sea level rise and sea level rise of 2.0m is found to be 8 to 25days.

9. Sea level rise land subsidence and flooding – Case from Indonesia

a. Introduction

Many cities are located in coastal zones where the altitude is less than 10 meters above sea level. When faced with subsidence and high tide could easily be subject to flooding. Hence general adaptation measures are required to mitigate such situations. The city of Semarang, in Indonesia and many other cities around the world are in the similar case. When it comes to land subsidence, high water tide, sea level rise, in many cases, inadequate structural measures play important roles in the coastal inundations.

This chapter focusses on two objectives: identifying the causes and impacts of land subsidence, sea level rise and flooding, in order to deal with the negative effects of the coastal hazards and assessing the adaptive capacity in dealing with the increasing coastal hazards. The findings of the study indicate that the issues affect the social, economic and environmental problems of the inhabitants. In summary, adaptation is needed to cope with the effects of such situations which are further exacerbated and need to take local community's response into consideration.

This research investigates and proposes recommendations to improve the adaptive capacity of the city to cope with the present and increasing tidal flood & land subsidence and worsening sea level rise.

Similar to Venice, Shanghai, Las Vegas and La Paz, the Indonesia city – Semarang joins the 'sinking cities'', as reported by local media – the Jakarta Post (2012). But the case of Semarang might be slightly different with that of other developed cities, because Semarang is facing the dilemma between urbanization development and survival or saving from the coastal environment hazards. Some cities, who can afford the cost of adaptation solutions, are investing in such as, new sea walls, dykes and polders, or high-tide gates – like London's Thames Barrier – to hold back high waters, while In poorer places, people have no choice, but simply endure the problem until they have to abandon their homes (Vince, 2013).

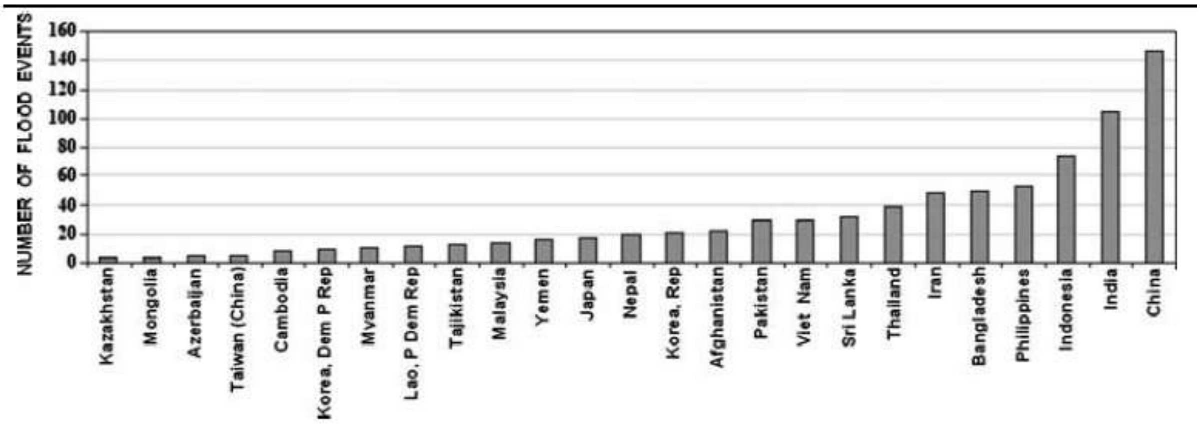


Figure 71 Vulnerable countries due to flood hazard in Asia (Source: Dewi, 2007)

It is clear to see from Figure that Indonesia is the third most vulnerable countries in Asia. (Dewi, 2007). The city of Semarang, the capital of Central Java province is located on the north Coast of Java Sea. It is reported that Semarang urban coastal area has been significantly vulnerable to coastal envrionment problems, caused by the rapid urbanization and high population density (Sutanta 2002; Kobayashi 2003) According to the record of the Devlopment Planning Board [DPB] (2002), the population of Semarang is 1.5 million with a growth rate at around 2% annually.

Generally, there are two broad aspects leading to the severe coastal problem in Semarang. Although human activities play a critical role in the coastal problems, the effect of Semarang's special topographical and geographic conditions also cannot be ignored. On the other hand, the vunerable geological conditions provide hotbed for the coastal disaster issues. For example, Sukhyar (2003) pointed out that volcanic rock, sedimentary rock, and alluvial deposits are made up of lithologies of Semarang. Compared with the southern part, the northern part of the city is lying across on the plain coast with higher population density as well as more industrial and commercial zones. By contast, the southern part is on the hilly side (Sukhyar, 2003). And some researches (e.g. by Marfai et.al. 2005) also indicate that the shoreline moves toward to the sea at approximate speed of 8m per year. The record of the Devlopment Planning Board [DPB] (2002) implies that the humidity is about 62-84% and annual rainfall is around 2,65-2460 mm. However, around 90 percent of the rainfall becomes the runoff or discharge instead of groundwater recharge (Galot et al., 2001). Last but not the least, Semarang has six major rivers, which could play a key role in coastal flooding (Mafai, 2003). In recent years, Semarang suffering from coastal flooding, land subsidence, high water tide, which has drawn more and more attention from government, local communities and researchers, etc.

Java has an area of only 6% of total land extent of Indonesia which is the most populated island in Indonesia. As summarized by Bird and Marfai and King (2008), northern coast of Java, especially Central Java, is dominated by erosion and sedimentation process. Since they are the most dynamic process occurring in coastal area, dynamic shoreline change is expectantly found in the study area in which Tegal, Semarang, and Demak experience the most dynamic change (Marfai and King, 2008)

Abidin et al. (2012) completed a comprehensive research regarding the land subsidence in city of Semarang, from three aspects: characteristics, impact and causes. They found that land subsidence is not a one-time or short-term phenomenon, but an on-going one in Semarang. Meanwhile, Abidin et al. (2012) estimate and observed that the rate of land subsidence was up to around 19 cm per year from 1999 to 2011.Lubis et al. (2010) also provide a good insight into land subsidence in Semarang via analysing the results of ALOS-PALSAR satellite SAR interferometry. Marfai & King (2007a) discusses digital elevation model (DEM) and benchmark data from GIS to predict the rate of subsidence in the coming years. Notably, they predict that an area of 27.5 ha will be below sea level at 1.5-2.0 meters (Marfai & King, 2007a).

Marfai & King (2008) generated the coastal inundation due to sea level rise in the Semarang coastal zone model employing GIS-Technology and considered it as a useful tool to assess the impact of the coastal hazard and the corresponding economic losses. In 2014, Marfai (2014) expanded his study area to the northern part of Java Island, Indonesia, including Semarang. He investigates and compares the impacts of sea level rise on coastal ecology in Jakarta, Pekalongan, Semarang and Demark, thus attaining a convincing primary data and analysis (Marfai, 2014)

While not that much literature delivers an insight into the change of the local community adaptation features from the perspective of time, Marfai and Hizbaron (2011) conducted a deep research by descriptive manner questionnaire to attain hands-on data of local community's response and perception to the various level tidal flood. The community side is independent but important to figure out the solution plan to coastal risk management, since the physical adaption, which the community adopts, has been significantly affected by the perception to this issue (Marfai & Hizbaron, 2011). In addition, Dewi (2007) completed a comprehensive case-study on "community-based" adaptive capacity, which investigates more factors and aspects of coping mechanism based on the previous research by Marfai and other researchers. The study area – Semarang- is so unique that people here have homogenous adaptive capacity due to sharing the same tradition, occupation and being relatives (Dewi, 2007). Their findings contribute to make more effective solutions, taking the local community's response, which was neglected by decision-makers, into consideration.

The coastal area is a region highly vulnerable to environmental pressures both from land and from the sea. One pressure threatening the sustainability of coastal areas around the world is the sea level rise.In general, sea level rise is the impact of global warming that occur across this hemisphere. Based on IPCC, global temperature on average increase by 0.3-

0.6oC. From 19 century to 2100, the temperature will increase up to 1,4 - 5,80C (Dahuri, 2002 and Bratasida, 2002). Rising in global surface temperatures cause melting of ice at the north and south poles of the earth so that there was Sea Level Rise. Estimated from the upcoming 1999-2100 year sea level rise approximately 1.4 to 5.8 m (Dahuri, 2002).

Semarang city as a metropolitan city has a coastal areas in the north to the shoreline along the 13 km that clearly affected by the sea level rise. Presence of sea level rise is also compounded by the occurrence of land subsidence in Semarang where according Sarbidi (2002) land subsidence in Semarang coastal area reaches 2-20 cm / year. The land subsidence caused by consolidation events (compression) and taking excessive groundwater (Sarbidi, 2002 and BAPPEDA Semarang, 2000).

Sea level rise and land subsidence that occured in Semarang coastal area is often flooded during high tides within ± 25 years. The tidal flood inundated areas is lower than sea level at high tide (HWL). According Sarbidi (2002) due to the tidal flood water depth can reach 20-60 cm with extensive inundation is expected to reach 32.6 km2. Sea-level rise is thought to be one cause of the tidal flood in Semarang is a very difficult problem to solve. Until now, the exact figure of the sea level rise in Semarang is still unclear because of some studies apparently show different results. According Wirakusumah and Lubis (2002) from 1950 to 2003 is expected to take place sea level rise of 39 cm in Semarang due to global warming. This means that sea level rise in Semarang reached 7.36 mm / year. According to the ITB Research Team (1990) in Abdurachim (2002) sea level rise in Semarang reached 9.27 mm per year. Then according Manurutng et al. (2002) sea level rise in Semarang at 6 mm / year. Suripin (2002) in a research report stating that the sea level rise in Semarang reached 5.01 cm / year. While based on research Adhitya (2003) from the beginning in 1991 to 1997 sea level the average annual increase in Semarang ranged from 1.5 to 6.7 cm, but in the following years until 2000 the sea level actually fell by 1.31 to 39.9 cm.

The existence of those different results, presumably because the tidal time series data are used to determine sea level rise in the Semarang in just a short period of time that is <18.6 years. Besides, because of the decline in soil that has not been taken into account in the calculation of sea level rise. Therefore, in this study, the problem of sea level rise that occurred in Semarang will be discussed in depth whether caused by global warming and the decline of soil in tidal stations so that the results of this study are expected to be the basis of the response of tidal flood (rob).

The purpose of this study is to examine the component and tidal type, analyze the development of tidal and sea-level position in Semarang in the last 20 years, to assess the value of sea level rise due to global warming and analyze the value of land subsidence in tidal station.

The data examined in this study include tidal data in Semarang for 20 years and the data of land subsidence in the Port of Tanjung Emas.

The main data collected in this study are:

1. tidal data / sea level data in Semarang.

2. land subsidence in tidal station.

The tidal data include:

1. daily tidal data in October, November and December (2004), January, February and March (2005) were obtained from PT Pelabuhan Indonesia. Data were analyzed by using the Admiralty method that can be used to analyze MSL, LLW, HHW and tidal type

2. Monthly tidal data for the last 20 years

According to the calculations that based on tidal data in September 2004-March 2005, it can be seen that type of tidal tend mixed and average value of tidal at Semarang was 1.1 (Table 1). The result is supported by the results of the study of Adhitya (2003) and DARMONO (2003). This means that in the waters of Semarang happened twice high tide and twice low tide in a day but different in height and time.

b. Sea-level development in Semarang

Trend of sea level rise in Semarang follow a linear pattern with the equation Y = 4.8967 X - 9645.9 (R2 =0.9636) and the tidal increase in the average value per year is 5.43 cm (Figure 1 Table 2), but sea level rise is meant here is the total sea level rise that is affected by land subsidence in the vicinity of the station and rising tide global sea level. So the linear function Y = 4.8967 X - 9645.9 (R2 = 0.9636) which is a function of sea level rise in Semarang, the coming years may be subject to change depending on changes in global sea level rise and changes in the value of land subsidence in the vicinity of tidal observation stations. Therefore, to ensure the presence or absence of these changes need to be made to the leveling activities BM tidal station continuously.

In this study, the data tidal for more than 22 years the years 1983-2005, but it is unfortunate for the data years 1998-2005 can not be used to examine the development of sea-level position in Semarang. This is due to very sharp fluctuations in the data. In 1998-1999 sea level on average decreased by 32.83 cm, then in 2001-2002 increased by 75.01 cm, plainly in 2002-2003 decreased again by 66.41 cm (Figure 2). When compared with the data tidal at Jepara, the area closest to the tidal station Semarang, Jepara tidal is apparently not encountered any sharp fluctuations in the rise or fall in sea level.

Therefore the inconsistency tidal data in Semarang were allegedly caused by tide gauges have undergone correction, namely the raising tide buoy position because the tidal buoy sinking due to rising sea levels. It also may be caused by damage to the tide gauges. So the tide of data that is used to observe the development of the position of sea level is the data for 1983 - 1997 or the measurement data for 14 years.

c. Land subsidence at tidal station

According Wirasatriya (2005) BM elevation 1 SPP II-1 in November 2004 was 3,165 m + MSL. After the measurement of the height difference between the BM 1 SPP II-1 with BM tidal station in May 2005 obtained the BM elevation tidal station at 1,166 m + MSL (Figure 3). In May 1985 the height of BM tidal station is 2,199 m + MSL. So since the 1985-2005 BM tidal stations has decreased by 1,033 m. According to IPC III branch Tanjung Emas (2000) subsidence events generally follow the hyperbolic function, but based on the report of the Queen Sriboga Kingdom (2004) who has conducted measurements on a regular basis (every month) since 1998 of land subsidence at some point in the area of the plant, obtained that land subsidence occurred following a linear pattern, although there are variations in the magnitude of the decline in each point, depending on the severity of the burden that was on it and the depth of the building foundation. Therefore, the assumption that decline occurred in BM tidal station also follows a linear function, it can be expected to decline in BM sinking tide station at 5,165 cm / year, but this figure only applies to locations tidal station alone, while for other locations is highly dependent on soil degradation that occurred at that location.

From the data are known that MSL in 1985 amounted to 81.2 cm and a height of tidal station BM 2,199 m + MSL. So when the water has reached a height of 301.1 cm (= 81.2 cm + 219.9 cm), the sea water has reached BM tidal stations. If the figure is 301.1 cm we enter the formula Y = 4.8967 X - 9645.9 (R2 = 0.9636) in the year 2032 it is predicted tidal stations have been flooded by sea water.

The sea level rise due to global warming effect is the difference between the value of total sea level rise with the value of land subsidence on tidal station locations, namely:

5.43 cm/year - 5.165 cm/year = 0.265 cm/year = 2.65 mm/year. Sea level rise that occurred in Semarang is inseparable from tidal station is at 1,033 m within 20 years. Level rise is 0.05165 m / year = 5,165 cm / year.

Today the method of measurement that is used to observe the development of the global sea level is by using satellite altimetry data because this method has advantages in terms of the density of the data obtained and able to cover the entire surface of the earth (Miller, 2005). Satellite TOPEX / Poseidon and Jason-1 altimetry data recording has been since 1992 and shows sea level rise of 2.4 mm / year (Miller, 2005). European satellites ERS 1 altimeter data record has also since April 1992 - March 1995. From the data obtained values of global sea level rise of 2.0 + 1.9 mm / year, (Anzenhofer et al., 2005).

Besides TOPEX, ERS-1 and Jason-1 satellites actually there are still some altimeter capable of recording data, including ERS 2, GFO and Envisat. Nowadays researchers often use a combination of data from multiple satellite altimetry is to get more accurate results. According to Miller (2005) to make estimates of global sea level rise at the end of a decade ago and makes predictions for the future would be better if all the data using a combination of satellite altimeter. By using a combination of satellite altimeter data is obtained global sea level rise of 2.4 mm / year. While the results of this study found that the value of sea level rise due to global warming in Semarang is equal to 2.65 mm / year, where the figure is obtained by correcting the total sea level rise of data recorded on AWLR at Tanjung Emas tidal station with the data reduction on the ground the AWLR location. It turns out the results of this study approached the value of global sea level rise derived from satellite data altimetry is 2.4 mm / year. So it can be concluded that the rise in sea water to expand into mainland causing tidal flooding in several areas in Semarang, an increase of 2.65 mm / year donated by global sea level rise.

Type in the tidal of Semarang is a semidiurnal meaning that occurs twice high tide and twice low tides in a day but different in height and time.

Development of sea-level position in waters listed in Semarang tidal station follows the linier pattern with the equation Y = 4.8967 X - 9645.9 (R2 = 0.9636) and the rate of increase of 5.43 cm / year.

The rate of land subsidence occurred in Semarang tidal Station at 5,165 cm / year.

Global sea level rise is not a dominant factor in sea level rise that occurred in Semarang because only resulted in an increase of 2.65 mm / year

Table 27 Tidal at Semarang September 2004-Maret 2005 using Admiralty Method 29 days

Month	So	M2	S2	N2	K2	K1	O1	P1	M4	MS4	F	Zo	LLW	HHW
Sept '04	83	7.6	12	2.4	2.7	15	9.5	4.9	0.4	0.5	1.3	54	29	134
Okt '04	78	12	13	3.3	3	15	7.5	5.1	0.3	0.8	0.9	60	18	134
Nov '04	79	13	12	3.7	2.7	19	6.5	6.3	0.3	1.7	1	65	14	138
Des '04	74	13	8.2	4.6	1.9	21	4.1	7.1	0.7	1	1.2	62	11	130
Jan '05	75	12	3.4	4.5	0.8	21	4.7	6.8	0.8	0.3	1.7	54	22	123
Feb '05	70	11	8	3.9	1.8	16	6	5.4	0.7	0.5	1.2	54	16	118
Mar '05	67	12	12	3.3	2.9	12	6	3.9	0.5	0.8	0.7	54	13	116
Average	**75**	**12**	**9.8**	**3.7**	**2.2**	**17**	**6.3**	**5.6**	**0.5**	**0.8**	**1.1**	**58**	**11**	**138**

Note:

if F:- < 0,25 : tidal semi diurnal)

- 0,26- 1,50 : mixed type tend to semi diurnal
- 1,50-3,00 : mixed type tend to diurnal
- >3,00 : diurnal

Table 28 MSL yearly at Semarang in 1983-2004

Year	MSL	Year	MSL
1983	58.90	1995	124.00
1984	72.70	1996	135.50
1985	81.20	1997	134.93
1986	81.70	1998	110.25
1987	80.60	1999	77.42
1988	88.60	2000	79.82
1989	95.40	2001	79.73
1990	97.50	2002	154.74
1991	98.30	2003	88.33

1992	106.00	2004	78.41
1993	109.00		
1994	113.00		

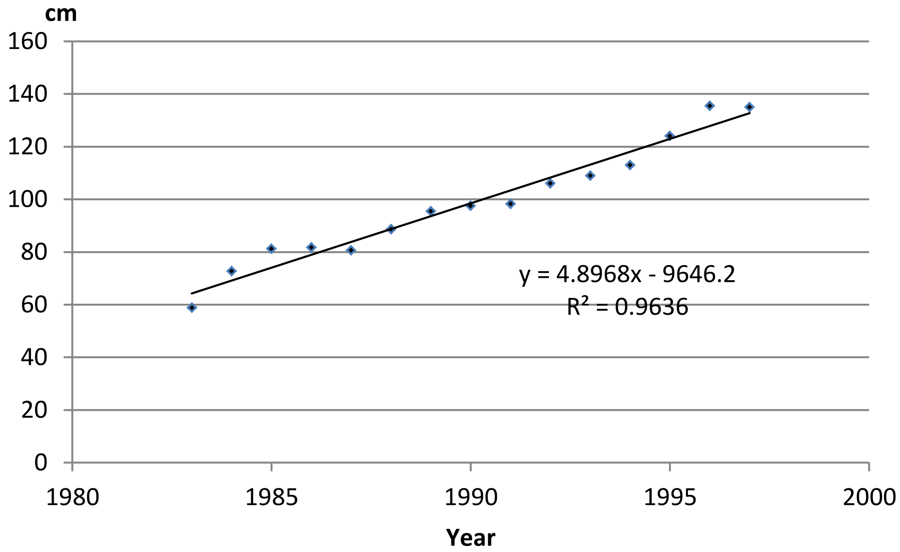


Figure 72 Yearly MSL at Semarang 1983-1997

d. Semarang data and its analysis

The data analysis in this paper is based on secondary data, which is collected from previous literatures and reports by government agencies or some leading researchers. They are providing significant input and a good insight of the dynamic change on the coastal zone in Semarang during the past few years. In order to keep the consistency of the analysis on the related topic, not all the data is shown in this section, meanwhile some information will be displayed throughout the main body of this report. In that case, the analysis can be more consistent.

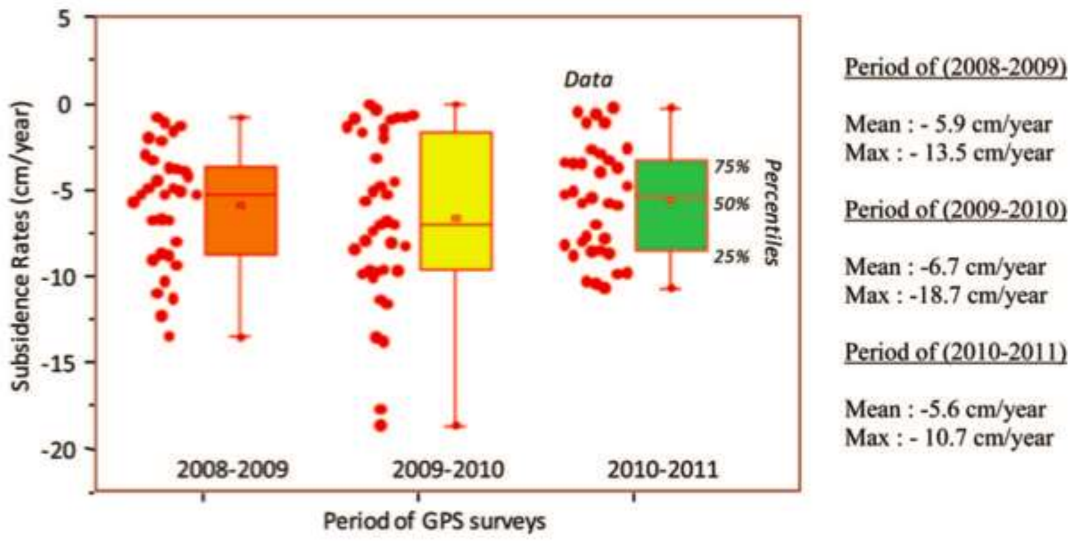


Figure 73 Box and whisker plot of GPS derived subsidence rates in Samarang (Source: Abidin et al 2012)

GPS stations	Subsidence in cm (2008–2009)		Subsidence in cm (2009–2010)		Subsidence in cm (2010–2011)	
	Δdh_{12}	$\sigma(\Delta dh_{12})$	Δdh_{23}	$\sigma(\Delta dh_{23})$	Δdh_{34}	$\sigma(\Delta dh_{34})$
259	−1.00	0.10	−1.64	0.11	−2.92	0.09
1106	−6.20	0.20	−2.21	0.19	−2.67	0.11
1114	−4.80	0.20	−0.44	0.16	−0.60	0.08
1124	−3.40	0.20	−5.23	0.17	−8.51	0.08
1125	−4.10	0.10	−5.60	0.09	−4.02	0.06
1303	−0.80	0.10	No subsidence		−1.12	0.09
AY15	−2.00	0.10	−1.01	0.08	−1.09	0.06
BM01	−12.40	0.20	−10.49	0.16	−10.45	0.11
BM05	−4.50	0.60	−7.67	0.12	−5.44	0.08
BM11	−3.50	0.10	−10.66	0.09	−3.30	0.06
BM16	−9.40	0.20	−3.48	0.17	−3.50	0.09
BM30	−1.50	0.20	No subsidence		No observation data	
BTBR	−8.00	0.10	−8.79	0.12	−8.58	0.05
CTRM	−6.10	0.10	−20.37	0.07	−7.00	0.05
ISLA	−11.30	0.10	−10.56	0.08	−5.76	0.12
JOHR	−4.40	0.10	−19.29	0.08	−8.70	0.06
K371	−3.00	0.30	No subsidence		No subsidence	
KO16	−1.80	0.20	−0.89	0.17	No subsidence	
MP69	−4.70	0.20	−1.82	0.16	−0.47	0.08
MSJD	−7.90	0.10	−8.07	0.11	−5.77	0.08
MTIM	−8.60	0.10	−10.54	0.09	−5.92	0.05
PMAS	−4.90	0.10	−12.39	0.09	−7.67	0.06
PRPP	−8.30	0.10	−15.02	0.09	−10.30	0.04
SD01	−7.30	0.20	−5.76	0.15	−7.83	0.06
SD02	−3.90	0.10	No subsidence		No subsidence	
SFCP	−3.60	0.10	−7.46	0.11	−3.69	0.08
SMG2	−1.20	0.10	No subsidence		−8.04	0.06
SMG3	−10.10	0.10	−10.80	0.11	−9.90	0.06
SMG5	−5.20	0.10	−14.80	0.08	−8.81	0.06
SMPN	−4.80	0.10	−8.65	0.09	−5.09	0.08
SP05	−10.40	0.30	−6.14	0.24	−4.80	0.06
T447	−2.80	0.10	−0.86	0.13	No subsidence	
VTRN	−6.20	0.20	−0.93	0.15	−0.27	0.07
SMKN	No observation data		−8.99	0.09	No observation data	
T374	No observation data		No subsidence		No subsidence	
CPMR	No observation data		−9.25	0.04	−3.50	0.05
RMPA	No observation data		−11.02	0.06	−9.80	0.06
DRI1	No observation data		−4.95	0.00	−5.28	0.04
K370	No observation data		−12.70	0.13	−8.20	0.09
KOP8	No observation data		−7.67	0.13	−10.69	0.10
PAMU	No observation data		−0.73	0.09	No subsidence	
PBR1	No observation data		No subsidence		−2.58	0.87
QBLT	No observation data		−1.49	0.04	−3.42	0.06

Table 29 GPS-derived subsidence results in Semarang, based on GPS surveys (2008–2011). (Source: Abidin et al., 2012)

The monitoring results are shown in Table, which indicates that land subsidence has spatial and temporal variations. Referring to the Figure 4, the average rate of subsidence in Semarang is around 6 ~ 7 cm per year, but it may go up to 14-19 cm per year at some locations (Abidin et al., 2012) Further, the results also indicate that subsidence is an on-going phenomenon in Semarang and the rates of the northern region are relatively higher than that of the southern region, especially the rates results observed around the industrial area (Abidin et al., 2012). Table xx below suggests that the area of land subsidence will increase in future. As the urbanization and population increase rapidly, if no action is taken against this problem, parts of the coastline will be inundated permanently (Marfai & King, 2007b).

Table 30 Expected Area 0 – 2 M below Sea Level in Semarang (Source: Marfai & King, 2007a)

Elevation (m) below sea level	2010		2015		2020	
	Number of pixels	Area (m^2)	Number of pixels	Area (m^2)	Number of pixels	Area (m^2)
1.5–2.0	–	–	14	35,000	110	275,000
1.0–1.5	8	20,000	101	252,500	511	1,277,500
0.5–1.0	126	315,000	748	1,870,000	2,427	6,067,500
0.0–0.5	1,314	3,285,000	4,648	11,620,000	5,858	14,645,000

At this stage, although studies about tidal flooding have drawn attention, there exist few available studies and little literature on the impact of flood hazard on local community. Besides, it is helpful to understand the response of community and people to tidal flooding, which is essential to tackle issues in coastal hazard management. (Marfai et al, 2008)

According to Abidin (2007), global postitioning system (GPS) is an ideal method to monitor the characteristcs of land subsidence, since it is a passive, all-weather and satellite-based navigation system. A recent 3-year (from 2008 to 2011) survey for studying land subsidence in Semarang has implemented at forty-four GPS points as shown in Figure in yearly basis. Abidin et al. (2012) pointed out that dual-frequency carrier phase data process with stringent measurement and processing tactics are key to achieve the positioning accuracy at the mm level.

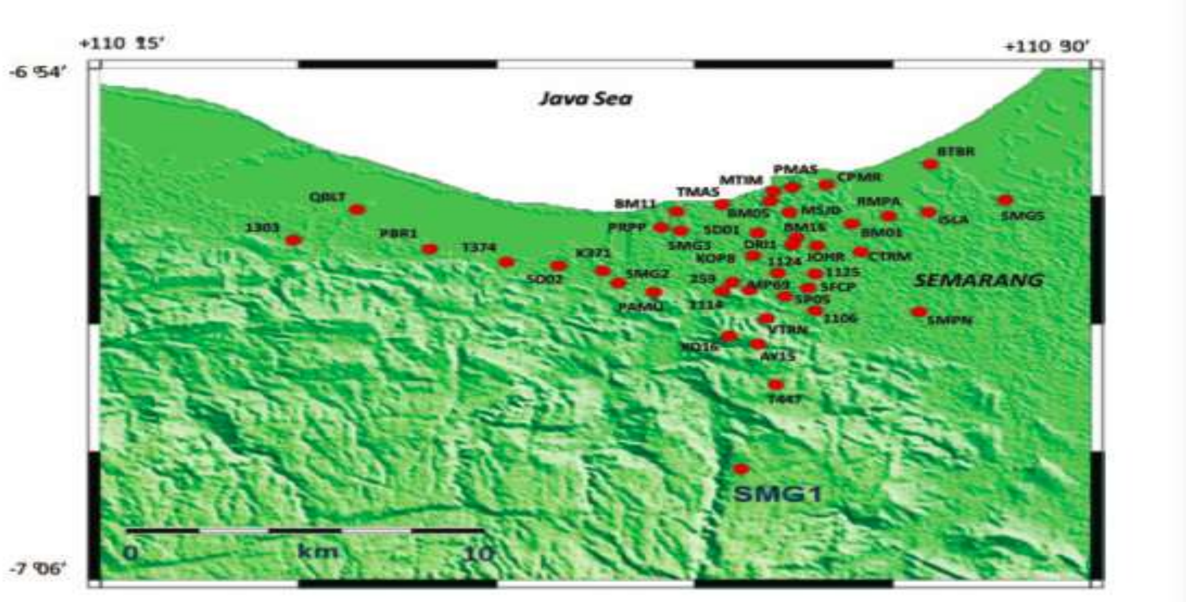


Figure 74 Distribution of GPS stations for studying land subsidence in Semarang. (Source: Abidin et al., 2012)

According to Marfai and King (2007b), the following six villages on the coast of Semarang (i.e. Tambakharijo, Tawangsari, Panggungor, Bandarharjo, Tanjun Mas, and Terboyo Kulon) are exposed most under the tidal flooding problems (See Fig. 6 below). In the developing countries, village level is the proper sample size, since people living there are sharing the same culture, tradition and even kidship, thus the same undertanding of the coastal hazards (Details can be found in the survey regarding the response of local community to the different level of coastal hazards).

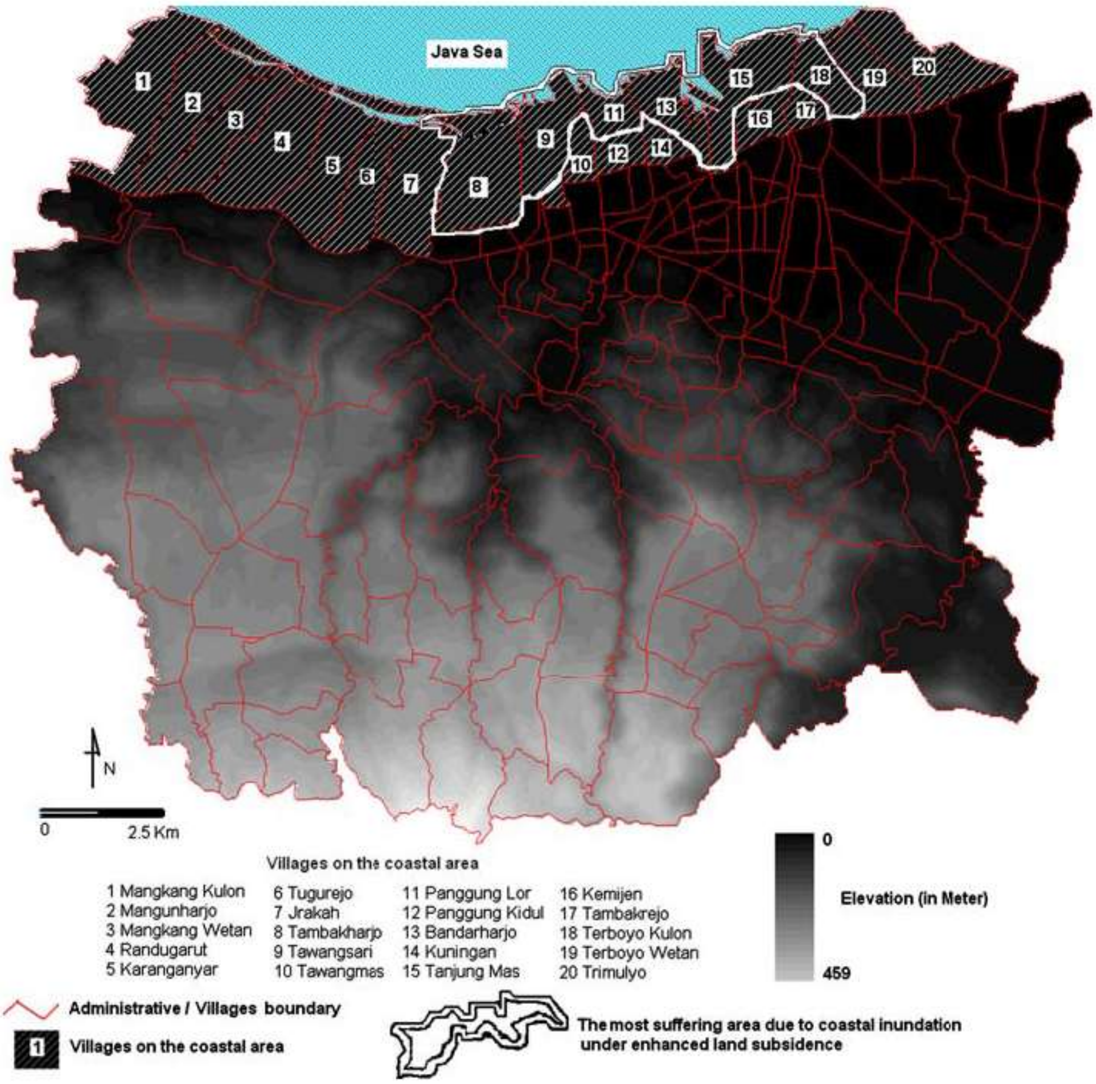


Figure 75 Villages on the coast of Semarang (Marfai and King, 2007b)

The bar chart below illustrates that coastal inundation, caused by sea level rise, has the most impact on fishpond area, under both Scenario of 120 cm and Scenario of 180 cm. It is not hard to infer that the fish prodction of Semarang would be affected most as well, which is the pillar industry in Semarang. Thus, it may cause the chain effect, the details will be discussed in latter section.

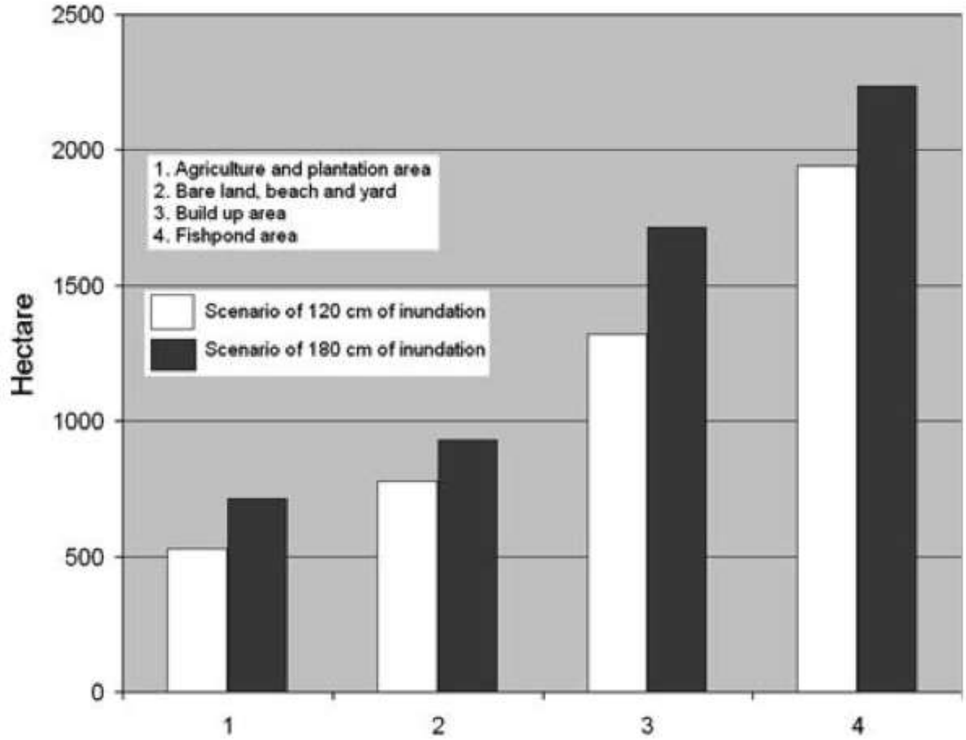


Figure 76 Land Use Affected by Coastal Inundation (Source: Marfai & King, 2008)

Table 31Social-economic Characteristics of the Study Area (Marfai et al, 2008)

Characteristic	Tanjung Mas	Bandarharjo
Number of households	5,705	4,174
Number of employed people		
Farmer/fisherman	1,048	569
Industry laborer	8,817	3,975
Driver	211	512
Government employer	569	401
Other jobs	1,067	3,399
Number of people according to education level:		
Non-educated	783	598
Passed from primary school	6,784	441
Passed from secondary school	7,217	4,713
Passed from high school	7,153	4,624
Passed from university	1,144	957
Utilization/Function of coast	Tanjung Mas: harbor, packaging area, industrial estate, warehousing, office complex, retaining basin for drainage	Supporting area of harbor, warehousing, squatter settlements, trading area, service area, polder for drainage, educational, and house of workshop facilities
Number of industry:		
Big, medium and small Industries	64	160
Household-industries	3	108

According to the table, the majority of respondents work as the industry labourer or a farmer/fisherman. The minor are working as other jobs, for example, government employer.

Over half of respondents are graduated from secondary school, and almost one third are graduated from higher school.

It is obvious that people is the key factor in taking mitigation action to address the issues of tidal flooding, while the mitigation action concerning tidal flooding threat may be various depending on their socio-economic characteristics. Therefore, the respondents sample was carefully selected based on social-economic features of local community, such as employment status, education level, utilization of coast and industry. The research conducted by Marfai et al (2008) involved 230 structured household interviews and almost 10,000 households. The questionnaire adopted took the impact of the tidal inundation on local communities as well as the adaptation response of local community and government to tidal flooding threats into consideration, except for social-economic characteristics mentioned above.

Flooding

Coastal flooding is a common problem especially Semarang is a waterfront city and development take place nearby shoreline. Basically, poverty and shortage of relevant technology as well as knowledge on tidal flood management make the flooding situation in some regions in Indonesia problematic.(Marfai et al, 2008) Dewi (2007) pointed out that a large amount of local people who are living in the coast in Semarang, have been experiencing the threat of tidal flooding rather than that from river / flash floods. Tidal flooding brings negative effect on: firstly, people's daily activities, including working and domestic activities (for instance, cooking or washing); secondly, health condition (for example, fever and malaria have become more prevalent in inundation area; lastly, the building deterioration (However, the effort, which has been made in this coastal risky area, seems to be in vain.) (Marfai et al, 2008) The seawater tidal flooding occurs most daily when sea level rises to a critical height exceeding the coastal lands. Also, it should be noted that in the coastal areas of Semarang, the combined effects of land subsidence and sea level rise will worsen the tidal flooding phenomena every year, already experienced by Semarang during the high tide periods. (Marfai et al, 2008)

It can be seen from Figure 77 which is an illustration of typical coastal profile of the study area by Marfai & King, 2008) , that the coastal residential settlement zones are most vulnerable to inundation, as they are directly nearby the shoreline with limited protection or even no protection.

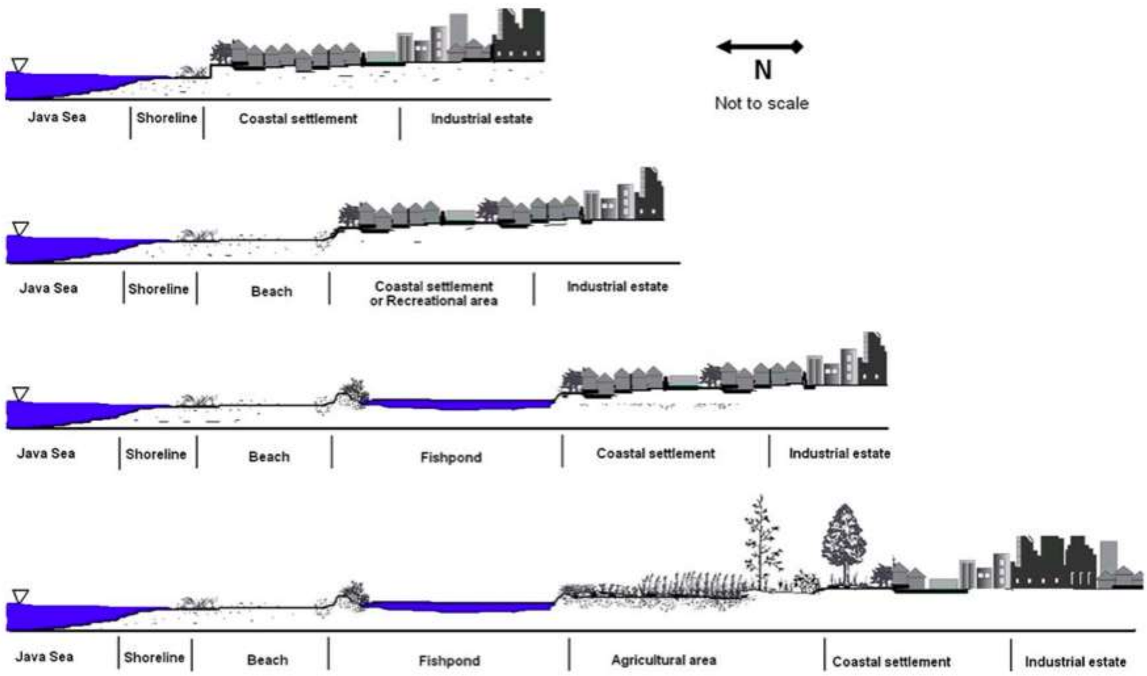


Figure 77 Typical Coastal Profiles on The Study Area (Source: Marfai & King, 2008)

Additionally, six major rivers (i.e. Blorong River, Beringin River, Silandak River, West floodway/Garang River, East floodway River, and Babon River) result in increasing risk in coastal flooding, since rivers can carry large amount of sediment leading to river mouth clogging (Sudaryatno, 2000). Furthermore, Kobayshi (2003) found that the runoff from the upper part of Semarang – the Southern part – dramatically increased, since the land use has changed from agricultural purpose to building purpose. Another two factors assumed to cause flooding are garbage disposal and informal settlement. The local people have no positive habit to dispose that household garbage wisely. Besides, the informal settlement, particularly those built along the river bank, not only produces pollution, but more importantly, hinders rivers from cleaning up and even the implementation of mitigation action on the name of economic excuses. (Dewi, 2007)

Figure 78 Inundation on the Coastal Area; Inundation on the Road (a) and in the Residential Areas (b), (c) (Source: Dewi, 2007)

Sea level rise

Semarang contains low-lying area, with the altitude of only 5 meters above sea level and hilly areas, with the altitude of 348 meters. Since the lowland area are bearing the main settlement, the main road connection, all the transportation system centres, the most severe hazards from climate change for this area is sea level rise.(Susilowardhani, 2014). Current ground elevation is affected by land subsidence and therefore needs the Digital Elevation Model (DEM) to be continually adjusted and improved. DEM data was used as input for the inundation model when researchers investigate the potential result of inundation under the scenoria of sea level rise. (Marfai et al., 2005)

Table 32 Predicted Impact of Sea Level Rise to Ecosystems in Study Area

Major impacts of sea level rise towards ecosystem	Location			
	Jakarta	Pekalongan	Semarang	Demak
Increasing coastal erosion		√	√	√
Increasing coastal flooding	√		√	
Damages on mangrove ecosystem		√		√
Damages on fishpond/aquaculture		√		√
Damages on agriculture		√		
Damages on urban settlement and infrastructure	√		√	
Increasing environmental sanitation problem	√		√	
Increasing vector-borne disease and health problem	√		√	

From the above table, which is the comparision among some cities of North Java about several specific problems related with sea level rise issue, we can see that the predicted main impacts on ecosystem of Semarang are: (1) increasing coastal erosion & flooding; (2) increasing environmental sanitation problem, thus further increasing health problem; (3) damages and losses on urban infrastructure. (Marfai, 2014)

Table 33 Diseases Suffered by Local Community in Semarang due to Sea Level Rise (Source: Syahrani, 2011)

Illness	Malaria	Dengue fever	Labtoferosis	Others	Total
Kuningan	10	8	0	8	26
Bandarharjo	4	5	0	2	11
Dadapsari	12	10	0	16	38
Tanjung Mas	22	19	1	17	59
Total	48	42	1	43	134
Frequency (%)	36	31	1	32	100

Land subsidence

Land subsidence is actually not a new phenomenon but a serious problem in Semarang coastal areas, since Semarang has experienced it for over one hundred years. It's greatly reported that the impact of land subsidence has been seen in people's daily life.

Undoubtedly, it has brought enormous economic losses to Semarang. Namely, lots of buildings and infrastructures are suffering from land subsidence and its subsidiary coastal flooding disasters. The living conditions are severely affected since the government and communities need to devote more funds to maintenance and repair houses, transportation (e.g. railways station, airport and even harbour) and public utilities. More importantly, land subsidence will further contribute to inundation and flodding except for these direct economic losses, which we will discuss in next section.

Basically, Public Works Department of Semarang [PWD] (2000) disclosed that there are three main causes of land subsidence – groundwater exploitation, natural consolidation process of alluvium soil as well as subsidence caused by the heavy load constructions.

From the point view of geography, there are three kinds of lithologies in Semarang, that is, volcanic rock, sedimentary rock and alluvial deposits. Especially, the major composition of lithologies in Semarang is fairly young alluvium, which is highly compressed. As shown in Figure, various types of deposits are made up of the alluvial deposits found in coastal area, such as beach, floodplain, tidal and near-shore deposits, etc (Barry, 2001).

Table 34 Land Subsidence Velocity in Semarang city (Source: Merdeka, 2004)

Rate of land subsidence (cm/year)	Location in Semarang city
6–8	Surrounding of Tawang Station
4–6	Johar and Genuk
1–4	Simpanglima, Tanah Mas, and Marina

Most of parts of the large cities in north coast of Java are located in areas with altitude of less than 10 meters above sea level. Table 34 shows the land subsidence ranging from 2 to 10 cm per year (Merdeka, 2004), causing damage in infrastructure and inundated in some parts of coastal areas. Details of land subsidence rate in Semarang are shown in Figure 79.

Figure 79 Land subsidence in the coastal area of Semarang city

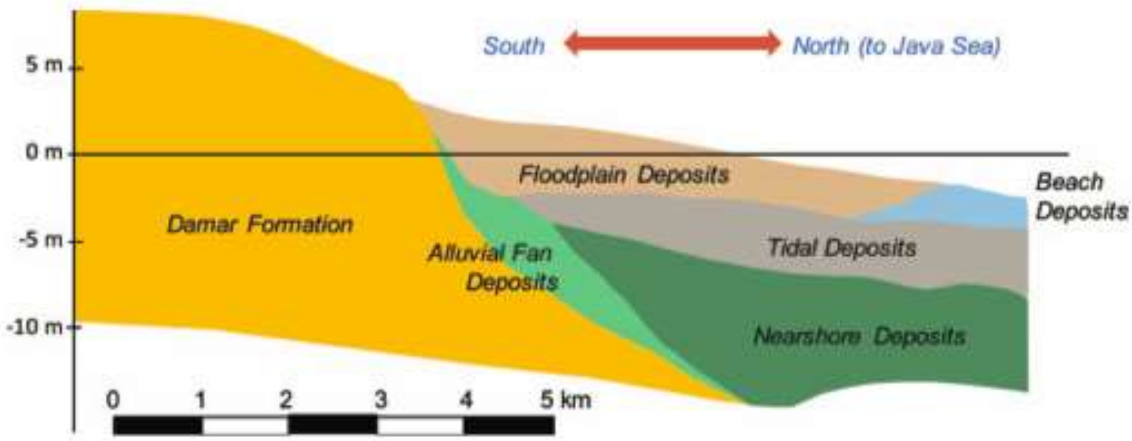


Figure 80 Quaternary geological sections east of Kaliwungu, Semarang, after GRDC (1996)

Excessive groundwater withdrawal may be another main factor causing land subsidence in Semarang. Marsudi (2001) stressed that the ground water level decrease at rate of 1.2-2.2 meter per year between 1980 and 1996, which causes land subsidence on the surface. From the Figure, we can see that groundwater has been excessively extracted since 1990 with the rapid growth of population. During the 1990s, the numbers of registered groundwater extraction wells had increased from 300 (in 1990) to 1050 wells (in 2000), and the volume also boosted from 23 million m^3 to 38 million m^3 (Merdeka, 2004). These figures above all prove that how serious the overuse of groundwater issue is. Not to mention, there might be many unregistered extracting wells, which worsen the current problem. Though Semarang seems to have potency of groundwater, over-extraction of it will compact the aquitards, thus leading to permanent land subsidence (Lubis et al, 2011).

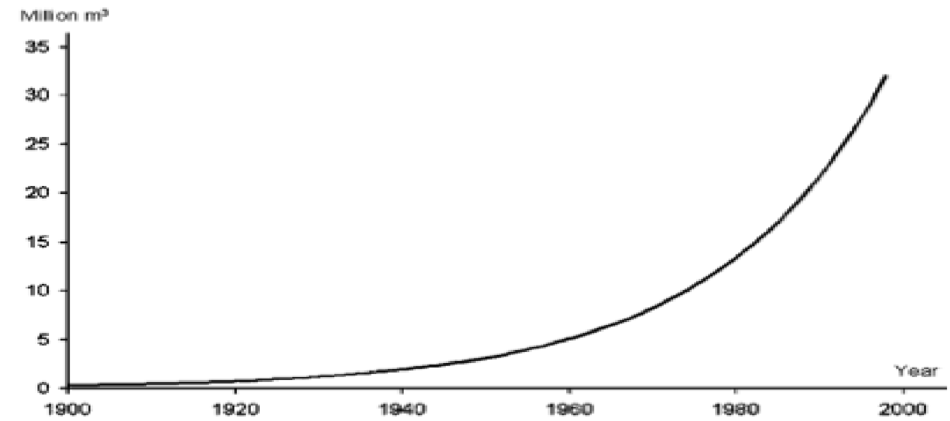


Figure 20:

Figure 81Groundwater withdrawal in million m^3/year (Source: Marfai & King, 2007a)

Changes in land use pattern, caused by the rapid urban residential growth, industrial expansion and agriculture boost, have become uncontrollable (Marfai & King, 2007a). In the northern part of Semarang, which is the lower area, ground subsidence become worse resulting from the increasing load of buildings, in order to meet the demand of urban population growth (Lubis et al, 2011). Based on the analysis of distribution of land subsidence in Semarang, it can be concluded that the growth of population (consuming lots of groundwater) and changing of land use (high-density industrial and residential settlements) especially in coastal area, result in groundwater exploitation and land compaction [To be precise, when the soil compressibility is high, that is, Holocene clay & sand with a thickness of over eighty meters, the subsidence caused by the load of construction could aggravate. (Lubis et al, 2011; Marfai and King, 2007a) .

Fortunately, by contrast, the southern part of Semarang, which is surrounded by valley and hill area, do not show any remarkable signs of surface subsidence and hence are treated as stable area at this stage (Lubis et al, 2011).

e. Coastal Food management

The fundamental objective of the coastal flooding management is to establish an integrated conceptual and theoritical framework to alleviate future coastal flooding and damages. Therefore, it is essential to take the three respects in to consideration, namely: "firstly, hazard information and assessment; secondly, policy and regulations; lastly, planning and construction" Marfai & King, 2008, P1516).

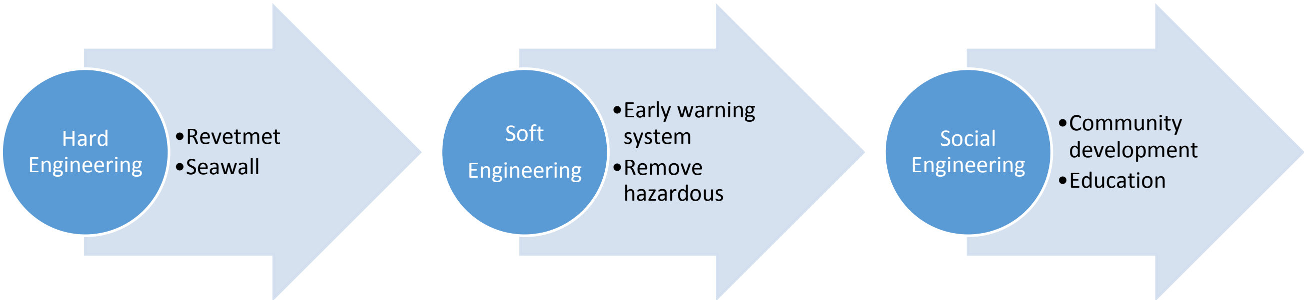


Figure 82 Model for coastal zone management

Hard engineering strategies

These tend to be expensive and short-term options. They may also have a high impact on the landscape or environment.

Sea wall

The highest protection in the short term, it can be constructed from any type of material (sand-filled bags to reinforce concrete structures). It has about 50 year's lifespan but they are very expensive to build. And it may cause significant erosion of the land on either side of the structure. (Maimunah et al., 2011) It will be a good adaptation and mitigation as the structure of Semarang city itself is a low land accompanied with frequently floods.

Obviously, the construction will involve many parties, such as local government, local community and technicians. Therefore, the issue which face to the city is, where can we find the funds.

Revetments

This is the most within budget and situated away from the coastline and attempt to reduce the energy of the waves before they reach the coastline. However, revetments do need to be replaced quite often and can be regarded as ugly structure. On the other hand, this is the one of the useful ways to mitigate flooding. It can direct water supply, hydroelectricity, controlling water courses, flow balancing and recreation. (Maimunah et al., 2011) In order to implement this plan, we have to get the different stakeholders involved to achieve the objective. Source the funds from central and local government or loan from the foreign government. Tendering to select suitable main contractors to ensure the quality of the project.

Soft engineering strategies

Soft engineering options are generally less expensive than hard engineering options. They are generally more long-term and sustainable, with less impact on the environment.

Early warning system

According to the data collection and research analysis, flooding is the mostly disaster from coastal area in Semarang city. Thus, integrated flood early warning system needs to implement to reduce negative impact from coastal flooding. The system can provide high resolution by using the simulation and prediction combined satellite monitoring. However, it does not work well in Jakarta City, as the poor education on the local community. (Maimunah et al., 2011)

There are many stakeholders involved, such as government, local community and private sector. To establish this integrated system, the application and sharing networks have to create some functions and target among the multi stakeholders. Before the system can be easily understand by the local community, the government should make interpretations based on observation data to simulate a prediction for alerting the flood. Susilowardhani, A., (2014)

Furthermore, the sharing networks should be not only supported by central government, but also to the local community, as it quickly bringing brainstormed knowledge and information for easy understanding and visualization before disasters.

Remove from Hazardous area

To solve the problems, we need to provide the on-going training and socialization for local community. Thus, they can easy to understand the plan and co-operate it. Garang River, West Floodway and Simongan Weir are the main rivers in the Semarang City. According to

FOE Japan's report on December 2008, there are 264 houses and 498 shops have to relocate to another place. Local government has some programs called LARAP. It gives compensation to the people that need to move from the river areas. However, it is not successful yet, as the selected places are not suitable for the economic living and the riverside people are poor. (Maimunah et al., 2011)

From my point of view, the local government should convince the people and provide some alternative jobs to support the local community.

10. Sea level rise and its impact in Sri Lanka

a. Introduction

Sri Lanka is an island in the Indian Ocean. It is located south of the Indian subcontinent (65,610 km^2 in area), surrounded by coastal lowlands. Nearly 75% of the land is flat or undulating.

Study Area

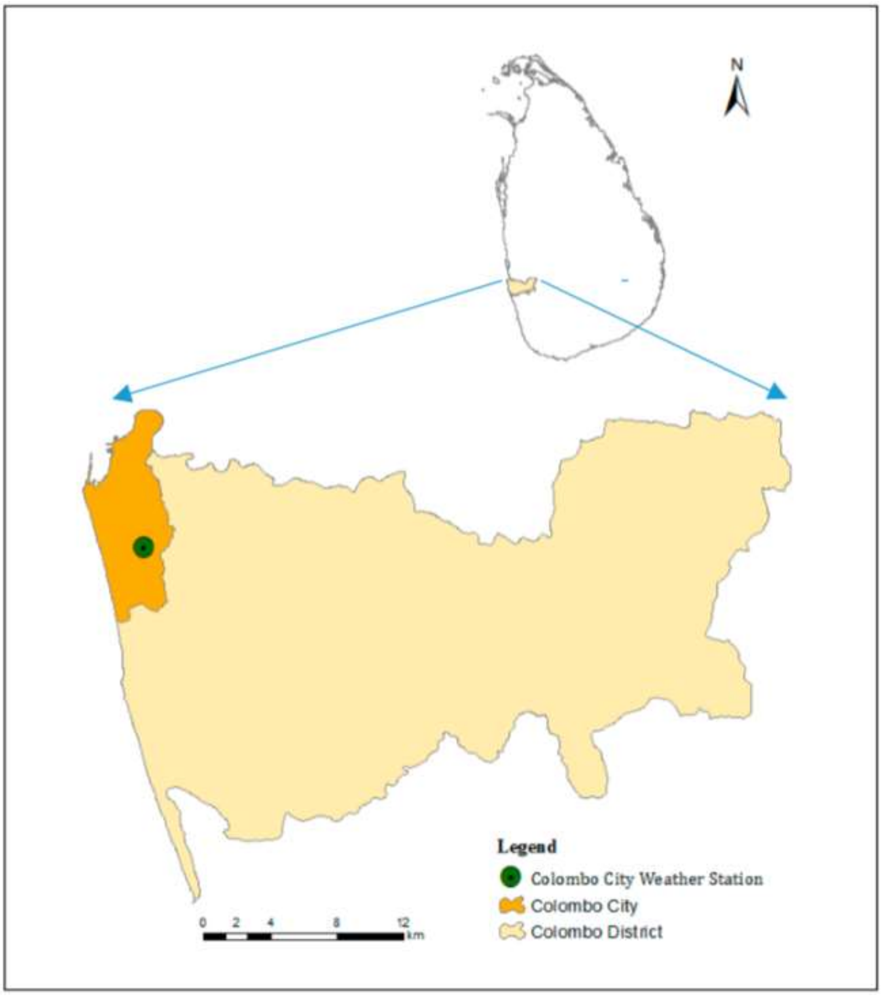


Figure 83 Location map of Colombo City and the Kelani ganga catchment area

The seasonally varying monsoon system govern the rainfall pattern and climate of Sri Lanka. Two principal monsoon rainfall seasons and two transitional periods, called inter-monsoon seasons, can be identified in Sri Lanka. Colombo City is in the Wet Zone

One of the major rivers of Sri Lanka the Kalani Ganga flows in the northern border of Colombo City, The main potable source of water is from the surface water from Kalani Ganga River at Ambatale and the two impounding reservoirs, namely Kalatuwawa and Labugama. Nowadays, the temperature is increasing and it may result rainfall increasing and evapotranspiration increasing, meanwhile, the number of population is rising. These problems are becoming severe.

b. Data Sources

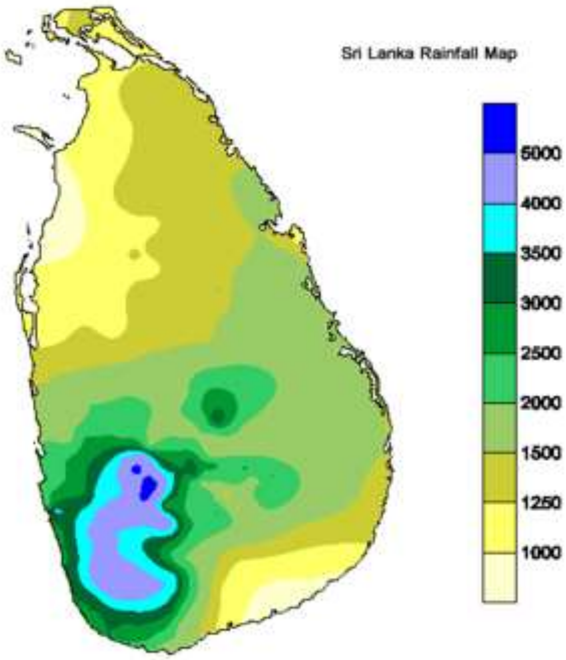


Figure 84 Rainfall data in Colombo region

In this study, we used the past 30 years' daily rainfall data of Colombo city area.

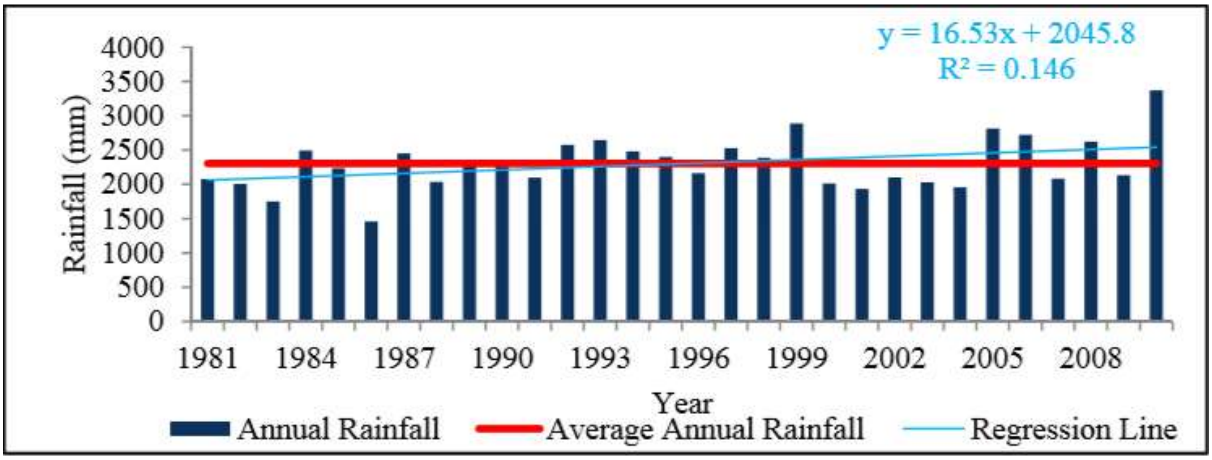


Figure 85 Average annual rainfall in the Colombo city area from 1981 to 2010.

From the bar chart, it easy to find out that the average annual rainfall for Colombo City is 2302 mm. The long-term trend of this annual rainfall records shows that there is a slight increase

According to the bar chart, the equation we have found is Y = 16.53X + 2045.8 and R2 = 0.146 (R2 is the goodness of fit which is between 0 to 1. If it is close to 1, it indicates the regression line is accurate.)

Table 35 Basic data for the annual rainfall data at the Colombo study site (1981–2010).

Parameters	Values
Time period (years)	30
Mean (mm)	2,301.98
Median (mm)	2,249.05
Maximum (mm)	3,369.90
Minimum (mm)	1,456.60
Standard deviation	374.45
Average annual wet days	171.84
Average annual dry days	193.41
Wet/total ratio	0.47
Dry/total ratio	0.53

The average annual wet days are 171.84 and dry days are 193.41. There are more dry days than wet days in Colombo City. It demonstrates I need to consider about what kind of system we should use while the Colombo region is in dry period.

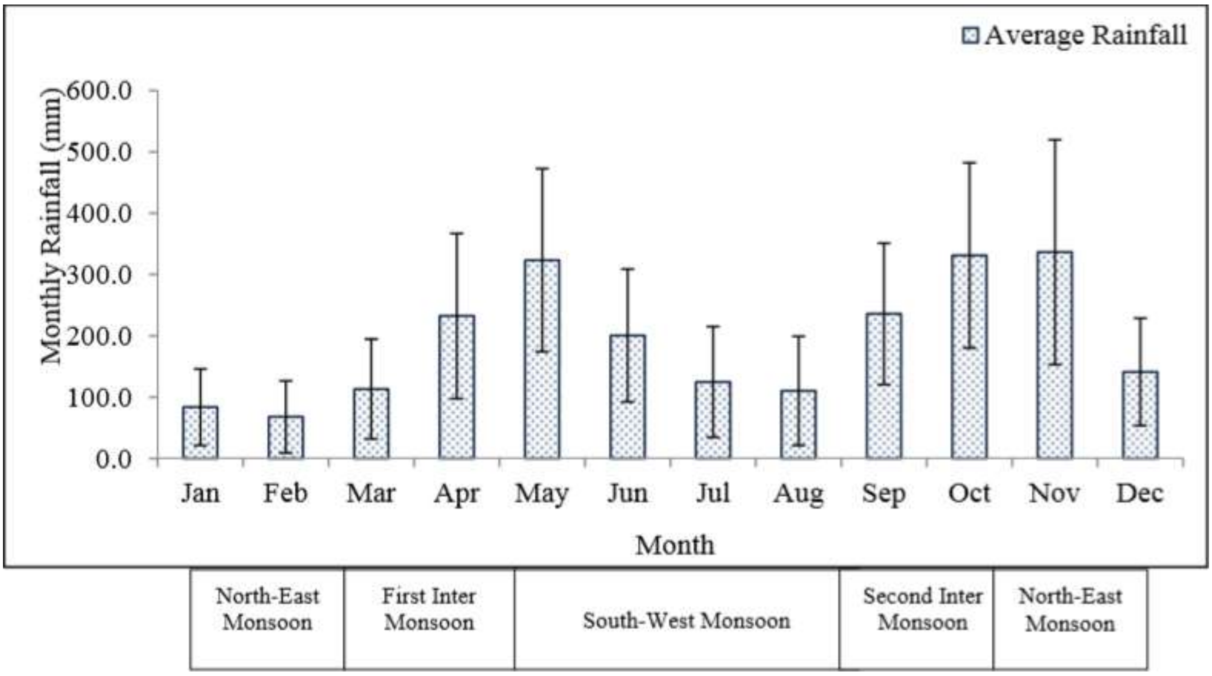


Figure 86 Monthly rainfall variation at the Colombo Weather station (1981–2010) (whiskers on this histogram shows one standard deviation above and below the mean value).

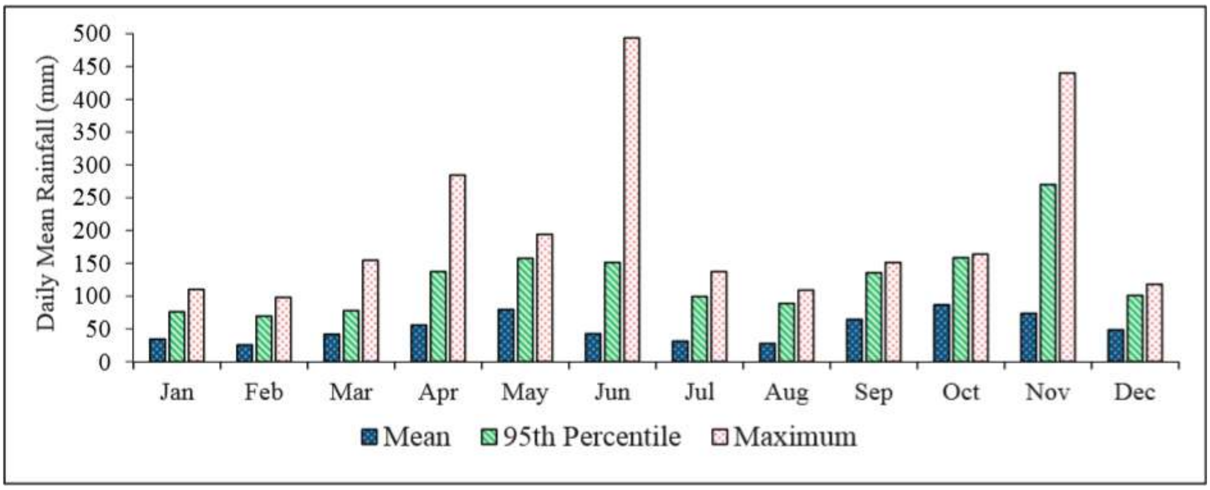


Figure 87 Variation of the daily rainfall maximum records at the Colombo weather station (1981–2010).

c. The trend of rainfall in the future

There will be rainfall increases in the later months towards the end of the century, There is also a slight decrease in the northeast monsoon (January–February). These results, therefore, suggest that towards the end of the coming century, Colombo will be faced with heavy rainfall and potential floods. Results further reveal that several extreme weather events with very heavy rainfall may occur in the future. However, the frequency of these big events may not occur too often.

d. Population data in Colombo region

The impacts of population on the quantitative water needs of a locality are related to population density and to the rate of increase or decrease in population growth. Because population changes affect such variables as the economy, the environment, natural resources, they also affect the availability and quality of the water sources that can be drawn upon for use. Population growth is a major contributor to water scarcity. Growth in populations means increasing demand and competition for water for domestic, industrial, and municipal uses. Water is also needed for agriculture and industrial use, and for the evacuation of waste materials. The most water scarce or stressed areas are typically those with few water resources, but high population densities, and high population growth rates.

Demographics

According to the first census of population in 1871, Colombo had a population of 98,847 people. This figure became slightly more than doubled by the 1911. The current city population according to the 2001 population census was 642,163 people. The unique feature of population growth in Colombo has been its slow growth. The annual population growth rate has been varying between 0.5 and 3.7 in the recent past (Department of Census and Statistics, 2001).

Table 36The Area, Population Density & Growth Rate of Colombo (1870-2001)

Census	Extent (Ha)	Population	Density (P/Ha)	Growth Rate
1871	2448.6	98,847	40	-
1881	2448.6	110,509	45	1.18
1891	2448.6	126,825	52	.8
1901	2720.6	154,691	56	2.201
1911	3091.1	211,274	68	3.66
1921	3350.3	224,163	73	0.61
1931	3368.4	284,155	84	2.67
1946	3438.4	362,074	105	1.83
1953	3593.9	425,081	118	2.48
1963	3710.4	511,639	138	2.04
1971	3711.0	562,430	152	1.24
1981	3711.0	587,647	158	0.45
2001	3729.0	642,163	172	0.45

Source: Centenary Volume, CMC, 1963 and Urban Development Authority, 1996

The trend of population

The population data is from 1870 to 2001. It shows the population is increasing annually. From 1931 to 2001 this period, the population is increasing rapidly. The rate reaches highest point in 1931 by 2.67. And in 1981 and 2001 the rates dropped to 0.45. For the population density the values is increasing.

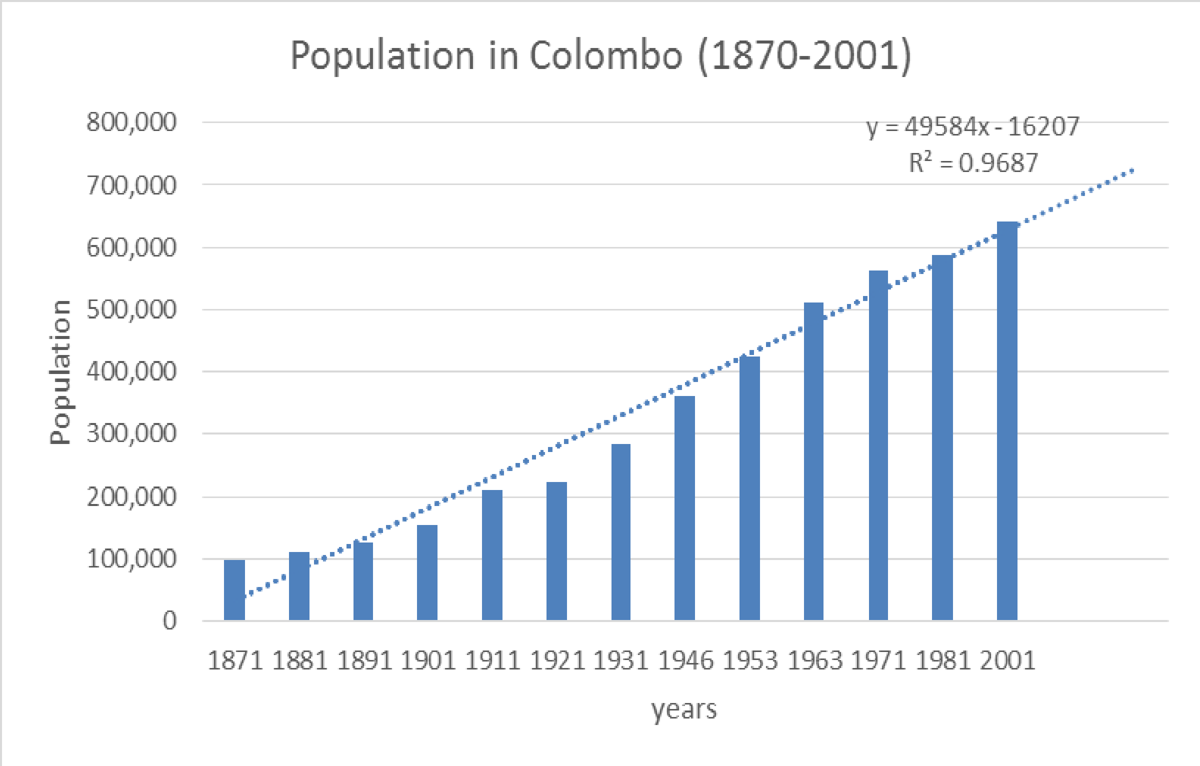


Figure 88 The trend of population in Colombo region from 1870 to 2001

This is a bar chart of population from 1871 to 2001. During this 130 years, the number of population in Colombo region is increasing annually. The equation of the bar chart is Y = 49584X - 16207 and R2 is 0.9687. This means the regression line is very accurate for this chart.

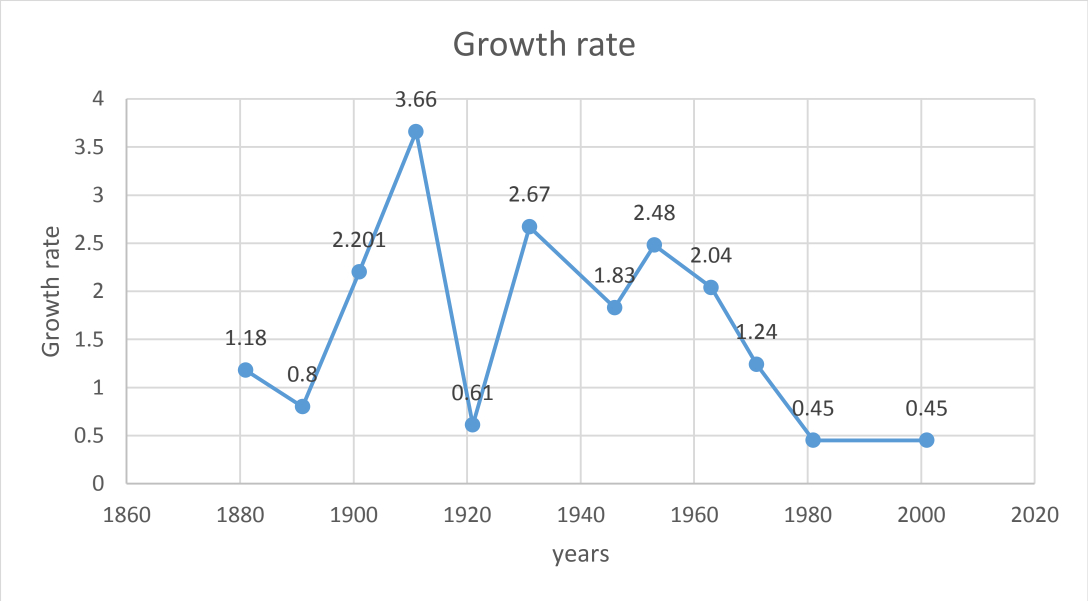


Figure 89 The growth rate in Colombo region (1871-2001)

It is easy to see the growth rate of Colombo region becomes stable in recent years which is 0.45 for 1981 year and 2001 year. According to the current development trend the growth rate is decreasing. Also, growth rate is a significant factor when we predict future population. Colombo has 0.45 growth rate, this rate is not high and also indicates that the population will not increase rapidly.

By combining both figure we can predict the future population, but this is based on the used two datum which may be different from the reality.

Predicting the future population in Colombo region

As I used the equation Y = 49584X – 16207, I found the population until 2051 year will be:

Table 37Population predicting from 2011 to 2051

Census	Population
2011	677,976
2021	727,560
2031	777,145
2041	826,729
2051	876,314

There is also a main factor which affect the water resource is population density.

Table 38 The density in Colombo region (1871-2001)

Census	Density (P/Ha)
1871	40
1881	45
1891	52
1901	56
1911	68
1921	73
1931	84
1946	105
1953	118
1963	138
1971	152
1981	158
2001	172

e. Temperature data (Sourced from the internet)

According to our previous analysis of population in Colombo region, the trend is increasing every year. From the research, the highest population density is in Colombo Northern which is 974 people per hectare and the low-density distributes in Colombo southern.

In the theory, the greenhouse effect results global average temperature increase. In my following parts, I will analyse the temperature data and trend in Colombo region.

The trend of temperature

As I collected the temperature data from academic website and there are several graphs of temperature trends which is from January to November, based in Colombo region.

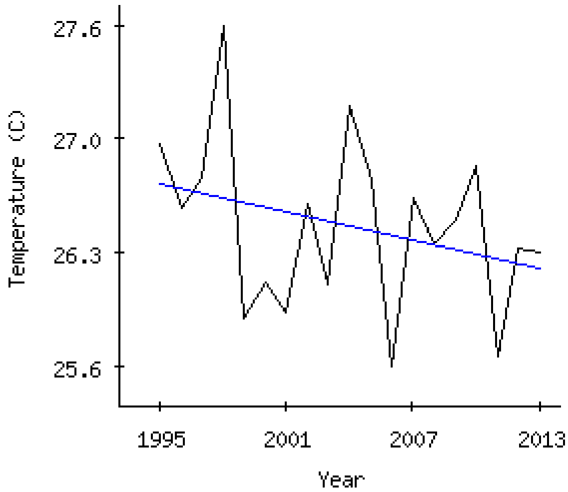


Figure 90 January temperature changes -0.28°C per year. The true change will be between -0.73°C and 0.17°C with 95% likelihood.

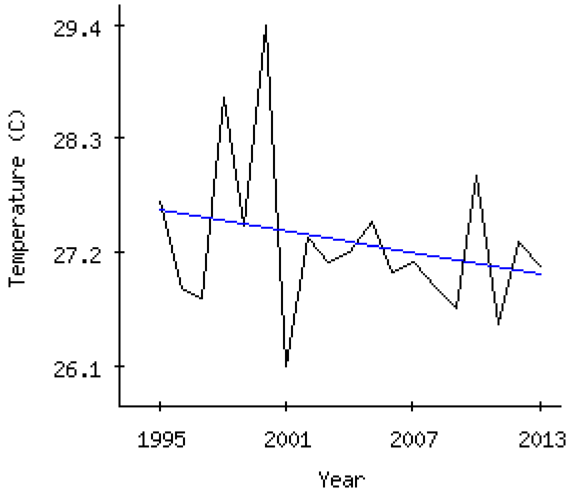


Figure 91 February temperature changes -0.35°C per year. The true change will be between -1.01°C and 0.32°C with 95% likelihood.

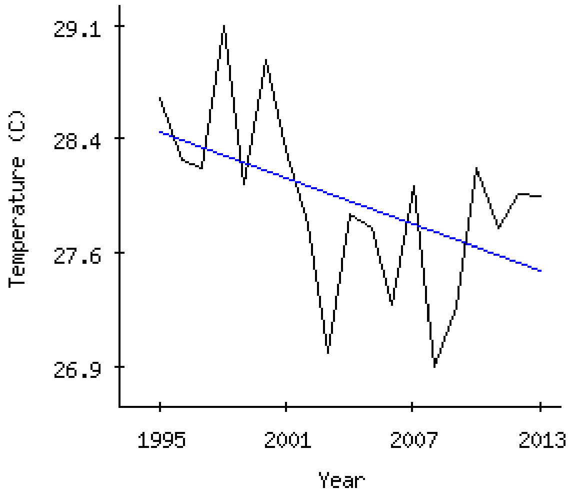


Figure 92 March temperature changes -0.50°C per year. The true change will be between -0.95°C and -0.05°C with 95% likelihood.

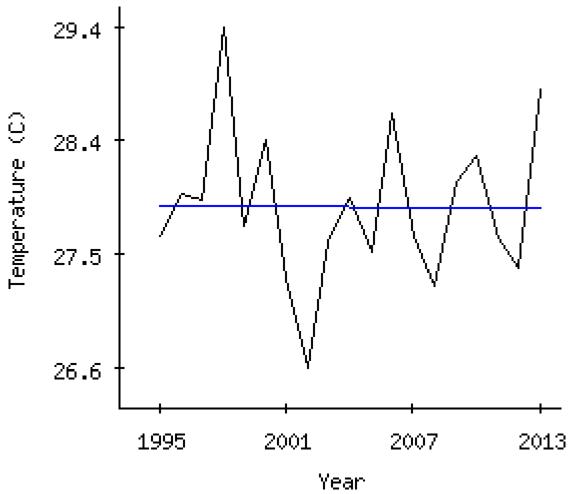


Figure 93 April temperature changes -0.00°C per year. The true change will be between -0.58°C and 0.57°C with 95% likelihood.

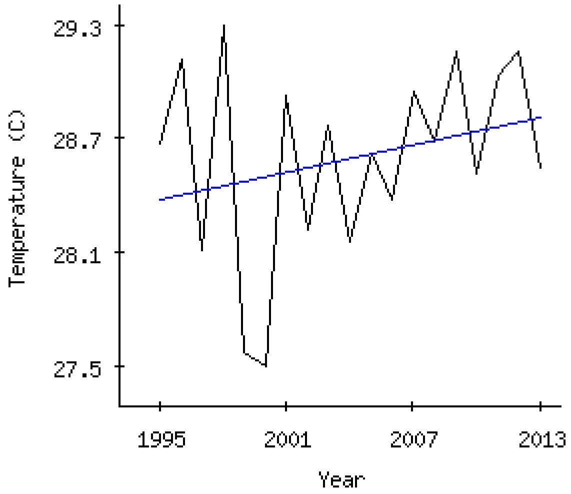


Figure 94 May temperature changes 0.24°C per year. The true change will be between -0.20°C and 0.68°C with 95% likelihood.

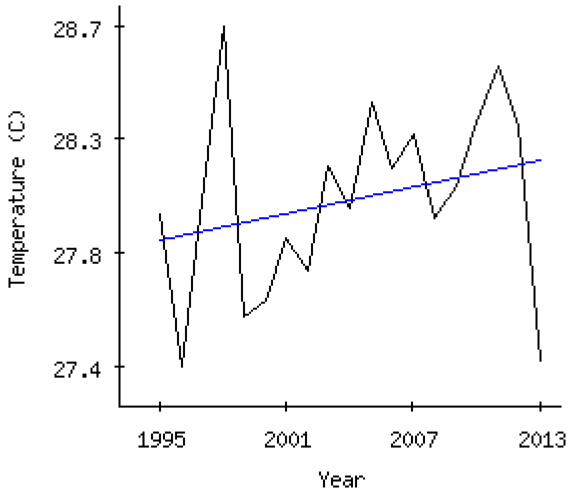


Figure 95 June temperature changes 0.16°C per year. The true change will be between -0.14°C and 0.46°C with 95% likelihood.

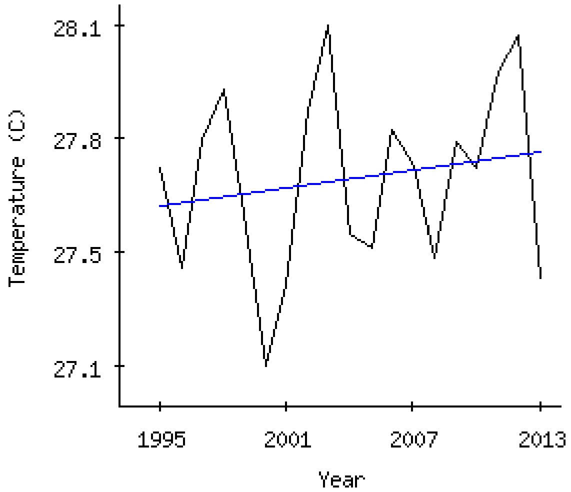


Figure 96 July temperature changes 0.09°C per year. The true change will be between -0.15°C and 0.33°C with 95% likelihood.

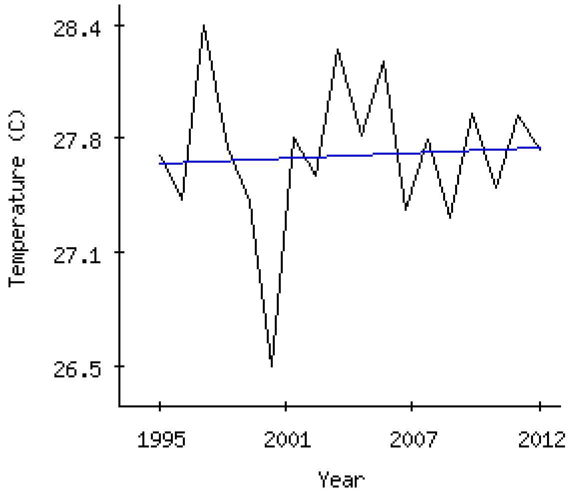


Figure 97 August temperature changes 0.06°C per year. The true change will be between -0.37°C and 0.48°C with 95% likelihood.

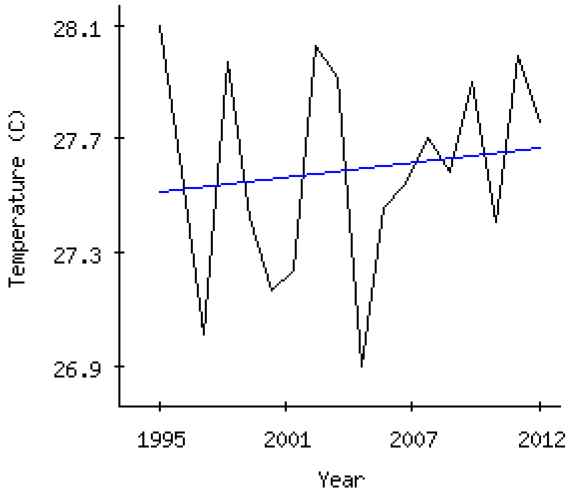


Figure 98 September temperature changes 0.09°C per year. The true change will be between -0.26°C and 0.44°C with 95% likelihood.

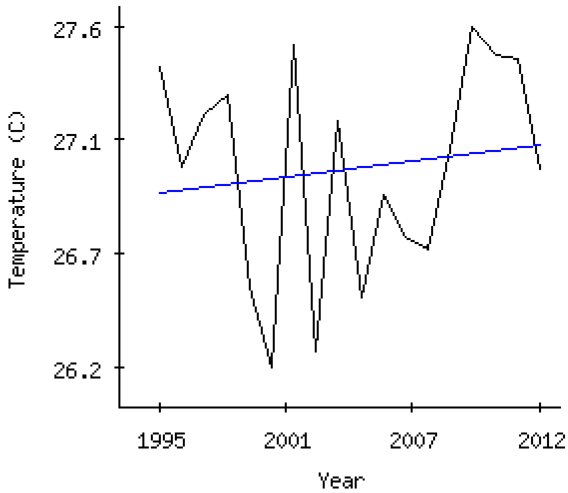


Figure 99 October temperature changes 0.12°C per year. The true change will be between -0.31°C and 0.55°C with 95% likelihood.

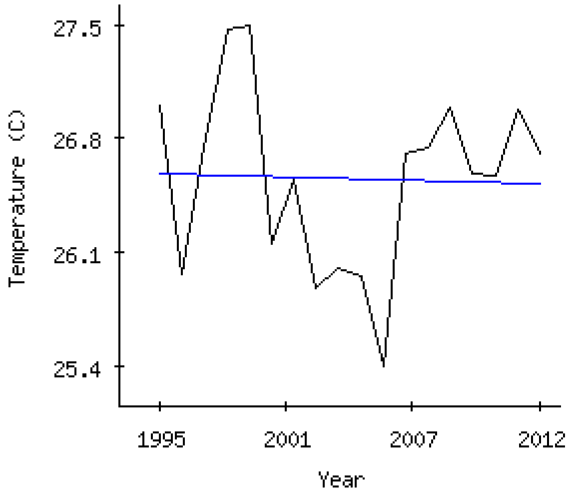


Figure 100 November temperature changes -0.03°C per year. The true change will be between -0.56°C and 0.50°C with 95% likelihood.

Totally, combining the every individual month temperature, the trend is increasing slightly.

In addition, we have collected the air temperature data. The trend has 0.0164 ^{0}C/year slope and R^2 = 0.67.

The equation we calculated is: Y = 0.0261X + 25.176

In the future, the temperature will become higher than this moment, I find out some ways to manage this behaviour.

Discussion

With rising temperature, planting is a very good way to manage this problem. Vegetation can play an important role in the climate of cities. Besides providing a conducive environment for social activity, promotion of mental, the introduction of greenery is a useful mitigation strategy in rising temperature due to climate change. For high-density urban environments, greenery can help to cool the air and provide shade. It can also lower a building's energy consumption by providing better outdoor boundary conditions.

We also find out the feasibility of greenery strategy. Figure shows the temperature change curves from 8.00 hrs to 18.00hrs in green and low greenery environments in Colombo. In the morning hours low greenery environment curve shows nearly 2^{o}C increases than greenery atmosphere. Following the increases in heavy traffic congestion and industrial activities in midday, the city temperatures rise gradually and maintain less than 0.5^{o}C intervals between both environments. Subsequently the temperature of the greenery area goes down while the temperature of the low greenery environment increases up to the 15th hour as shown in the graph. At the end of the day temperature of both the environments comes down to almost the same level. This decrease of temperature in the greenery area of the urban city provides a more comfortable residential atmosphere than the low greenery environment.

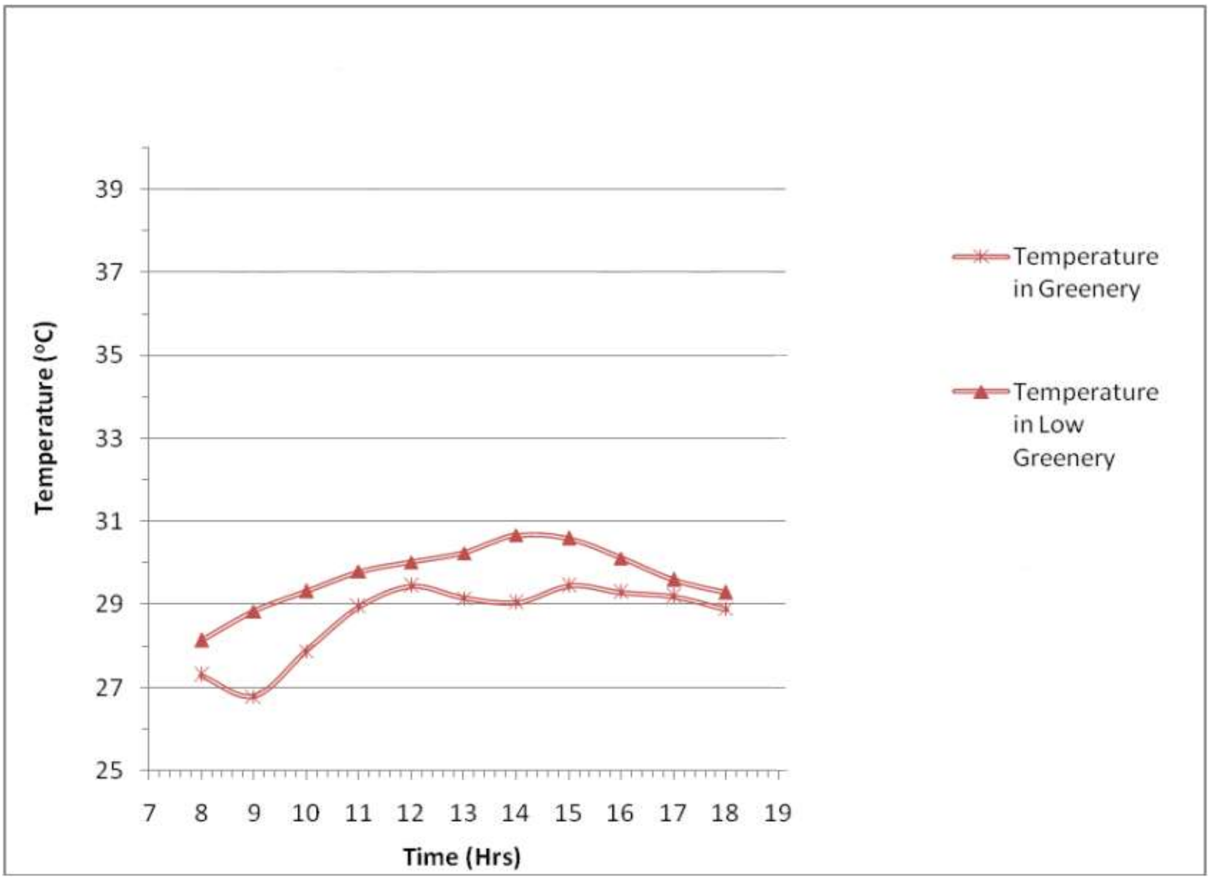


Figure 101 Temperature variation in Colombo in greenery and low greenery environment

Strategic planting on valuable free space, such as roofs and walls in our cities, is set to transform the urban environments of the future.

f. Evapotranspiration Data

Evapotranspiration varies regionally and seasonally. A larger volume of water flow through the air all around us in two invisible paths: evaporation and transpiration, 61% of all terrestrial precipitation and together are referred to as evapotranspiration. Increasing evaporation will increase demand for irrigated water for agricultural, further contributing to scarcity of water. Rising potential evapotranspiration rates and declining rainfalls conspire to increase the severity, frequency and duration of droughts. Surface water will impact on droughts in the Dry Zone areas could lead to greater evapotranspiration.

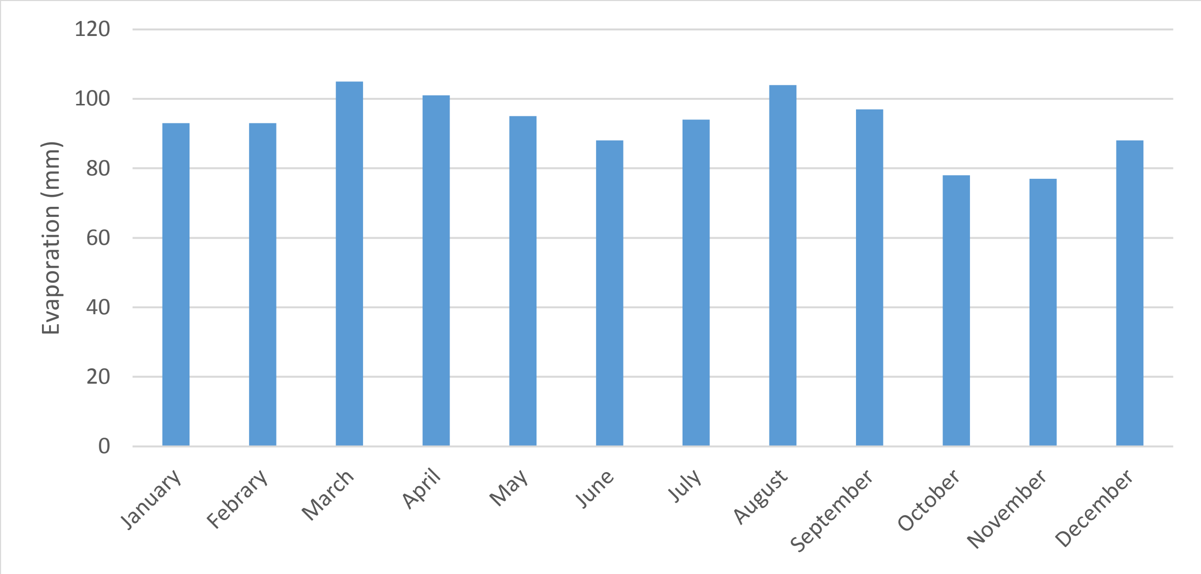


Figure 102 Monthly Evaporation at the Colombo station

We have collected the data from the irrigation department of Sri Lanka. The bar chart vertical axe indicates the evaporation in mm and horizontal axe indicates the months. From the bar chart, the average evaporation is not very high in Colombo region. Totally, the trend of evaporation is characterized by a bimodal distribution with peaks around March and August. In March and August, the evaporation reaches approximate 100mm.

In addition, we found the average day evaporation data for Colombo region in 12 Months.

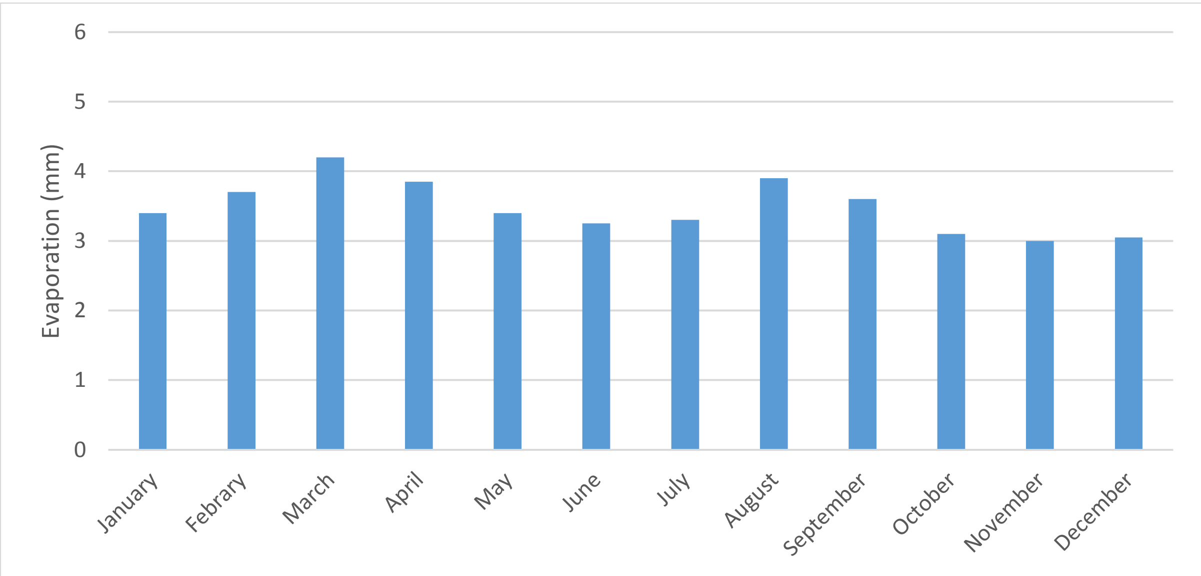


Figure 103 Average day evaporation of each months in Colombo region

According to the average temperature in April and August is higher than other months, the evaporation in those months are higher than the rest. Also, increasing evaporation affects the precipitation.

g. Flood runoff

Due to climate change results the trend of rainfall in Colombo region is increasing and in the future the extreme weather event with heavy rainfall will become more frequently, the flash floods may be occur more frequently than the present.

In Sri Lanka there are several types of floods:

Bank-full discharge – most important in terms of incidence and impact. This type of flood occurs when surface run-off entering the river exceeds the discharge capacity of the river channel

Flash Floods: Sudden accumulation of water on low-lying areas leads to flash floods. (Common occurrence in urban areas)

Breaching of reservoirs and channel bunds: mostly seen in the dry zone

Tsunami: along coastal areas

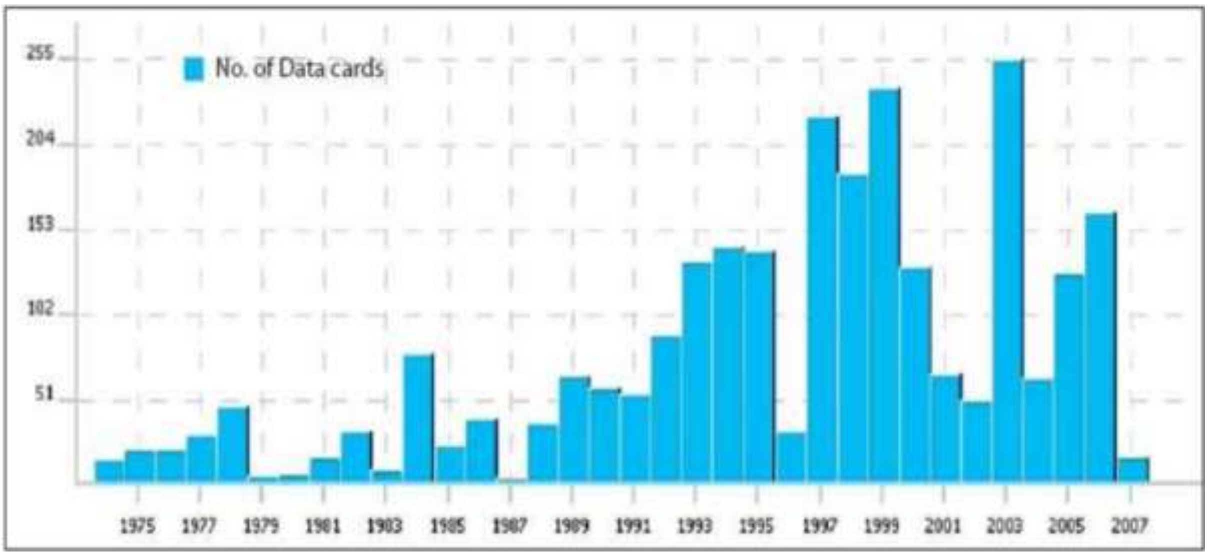


Figure 104 Floods general trend of occurrence from 1974 to 2007

According to this chart, the trend of floods occurrence is increasing. Especially in the recent years, due to extreme weather event with heavy rainfall happens frequently, floods occurrence may become more frequently.

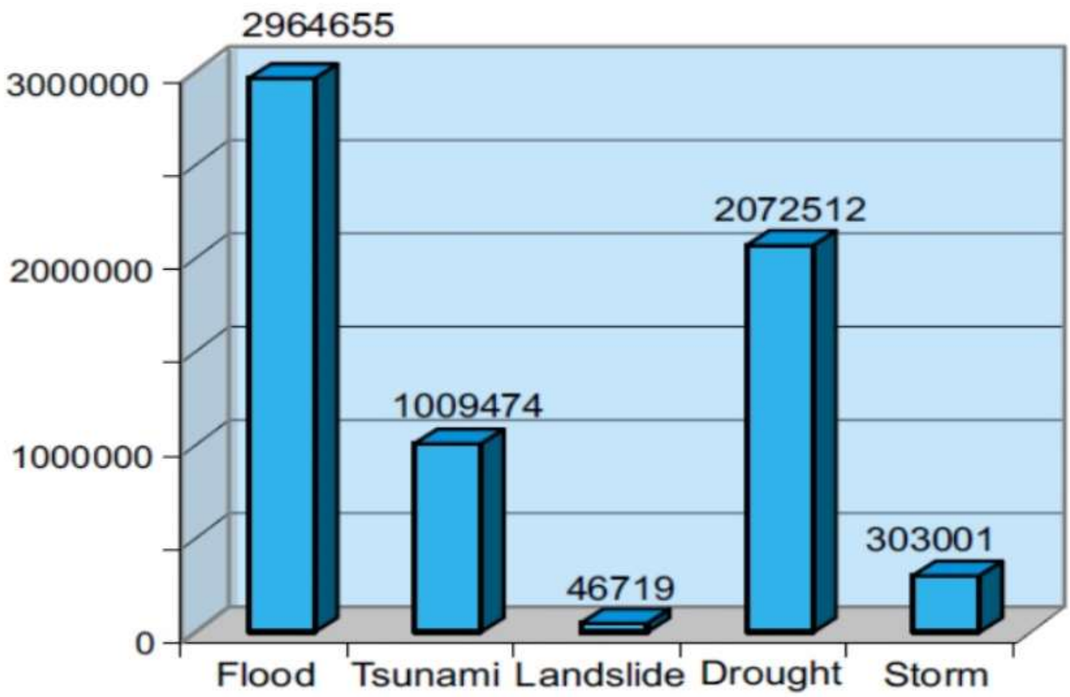


Figure 105 People affected by different disasters in Sri Lanka from 1974 to 2004

Totally, the number of people affected by floods is 2964655 which is the most number among these disasters.

h. Kelani River

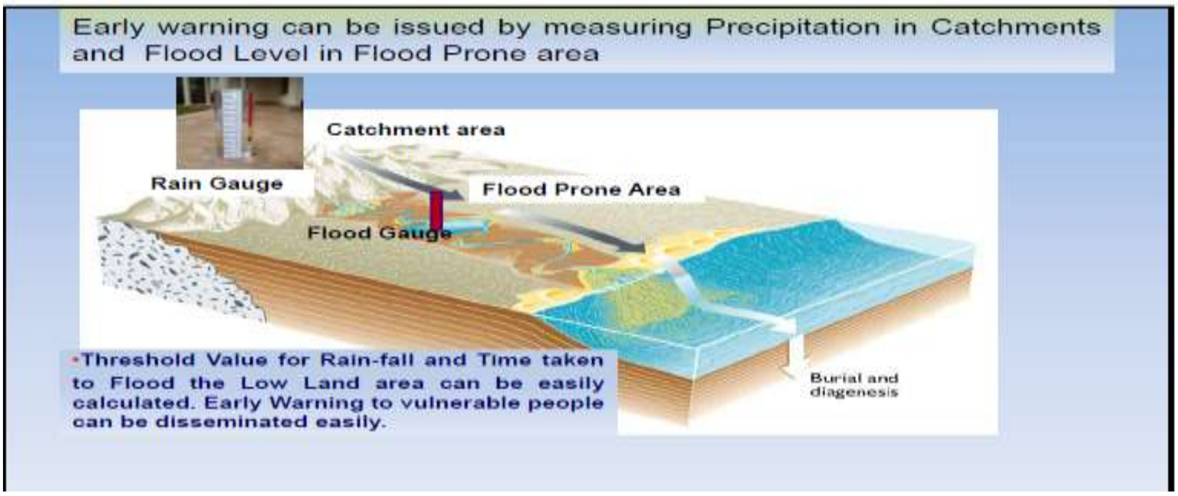
Because, floods in Kelani River are important due to its outfall being near the capital city of Colombo, and my research of flood is based on low part of Kelani River. According to Seenipellage Chaminda Sugeeswara, the Kelani River is a 145 km (90 miles) long river with a catchment area of 2292km^2. It is ranked as the fourth longest river in Sri Lanka. The River flow variation during rainy seasons (monsoons) is from 800m^3/s to 1500 m^3/s generally (Ministry of Irrigation and Water Resources, 2009). The river starts from Sri Pada Mountain situated in central hills. It flows through steep slopes from the start up to around 90km (close to Awissawella area) and then change to flow through a mild slope until it reaches the river mouth at the commercial capital Colombo.

Floods are generally severe in lower reaches starting from Hanwella (situated around 27kms from the river mouth) to most downstream, the Colombo city. Kelani River floods receive highest attention as it causes floods in densely populated (highly urbanized) city Colombo.

Impacts of flood

Agricultural loss, loss of human life, damage to property, destruction of crops, loss of livestock, and deterioration of health conditions owing to water borne diseases.

Recommendation and management:



This graph shows one of the method, by measuring the rain gauge and flood gauge to give people early warning of flood then evacuate people before flood coming. This is the way to mitigate the condition but cannot really solve it.

Also, deforestation in catchments has drastically reduced water retention capacity and has increased the silt in downstream area, construction should not block the flood prone area. These are the problems should be solved. From this, I recommend information on rainfall data and water level data should collect regularly and flood early warning systems need to be further improved. Trees need to be plant around prone area and prohibit deforestation, especially in catchments area.

i. Model development

We have three equation which represents rainfall trend, population trend, and temperature trend.

$Y_1 = 16.53X + 2045.8$……………………………………………………..…….Rainfall

$Y_2 = 49584X – 16207$……………..……………………………………….…… Population

$Y_3 = 0.0261X + 25.176$……………………………………………………… temperature

In these equations, y_1 represents the rainfall in mm, y_2 represents the number of population, and y_3 represents the temperature in oc. X represents year.

By combining them together, I obtain the equation: $X = aY_3 + bY_2 + cY_1$

As an assumption, a represents land, b represents evaporation, c represents water.

In the future, three factors are all increasing. Therefore, increasing the land space can mitigate the urbanization, also controlling the population density. Water and evaporation affects rainfall and temperature. Increasing the usage of water, reduces the water of water then mitigating the evaporation, meanwhile, affect the rainfall.

Summary

In Colombo region, the long-term trend of rainfall is rising. According to analysis, the dry days are more than wet days. We need to consider about the demand of fresh water and how people could live through this period. Also, the large standard deviation is occurred annually. From predicting, in the southwest monsoon and the second inter-monsoon season, we should focus on these period due to large rainfall occurs during that time, meanwhile, the several extreme weather events also occurs in that time. This phenomenon can cause flash flood and drainage system may not able to work. The population in Colombo region is rising every year. Due to the high population density in the north of Colombo, the water scarcity may become a big problem even though the rainfall in Colombo is sufficient. In addition, the demand of fresh water and water quality should all be considered about. The urbanization becomes more severe for Colombo City. In addition, large population density in city means more buildings should be built, this result the micro climate formed in city. Temperature may increase. The trend of temperature is increasing with 0.0164^{o}C/year slope and the $R^2 = 0.67$. According to the average temperature in April and August is higher than other months, the evaporation in those months are higher than the rest. Also, increasing evaporation affects the precipitation. The flood in lower part of Kelani River is becoming more frequently. Meanwhile, humans' behaviour can also cause the flood occurrence.

Totally, the impact of climate change can cause the extreme event weather with heavy rainfall becomes frequently. Rainfall is increasing which will cause flood. Temperature increases.

j. Calculation of loss of and changes to groundwater table

Sri Lanka is an island off the southeast coast of Indian Ocean directly affected by the sea level rise. The deforestation, global warming, overpopulation, depletion of freshwater aquifers, beach erosion aggravate the submergence issues, thus, a special attention must be focused on the policy making in coastal management. Our endeavour in this pilot study is to approximately predict the likely loss of land as a result of the sea level rise in the coastal area of Colombo. The major limitation of this estimation process is the sourcing of precise data for Colombo. Thus, we adopt a simplistic statistical approach to estimate the confidence intervals of the loss of land (km^2) based on the New Zealand results obtained by Tutulic et al. (2015).

Confidence intervals consist of a range of values that act as appropriate estimates of the unknown population parameter/s, however, in seldom, none of these values may represent the value of the parameter/s. The level of confidence of the confidence interval would indicate the probability that the confidence range captures this true population parameter given a distribution of samples. We adopt the following equation in our estimation process.

$$\bar{X} \pm Z \, \sigma / \sqrt{n}$$

In this statistical estimation we assumed that all the variables except the rainfall variation used in the estimation of Wellington remain the same. We understand that this approach is an over simplification, but data limitations force us to adopt this strategy to highlight the potential impact of sea level rise on the coastal areas in Colombo. Thus, our estimation must be examined cautiously as there may have been unrecognized variations in temperature, humidity, soil permeability, natural and human causes of coastal erosion in Colombo compared to Wellington.

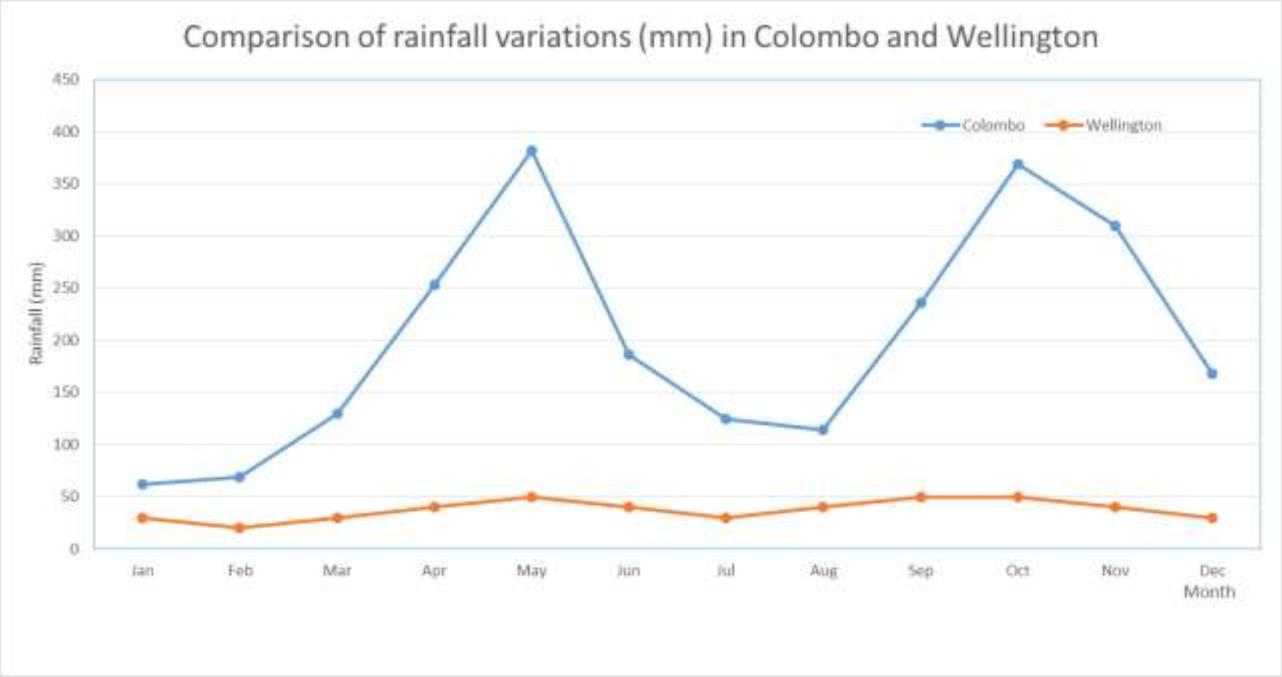


Figure 106 Comparison of rainfall variation in Colombo and Wellington

The tables below provides the 95 percent confidence limits for the land area affected by sea level rise in the Colombo Groundwater Zone (CGZ) at 0.5 m sea level rise, 1 m sea level rise, 1.5 m sea level rise and 2 m sea level rise.

Table 39 Land area affected by sea level rise in the Colombo Groundwater Zone (CGZ)

Sea level increase (m)	**Loss of the land (km^2) [at 95% confidence]**		***Percent of inland of the CGZ lost due to sea level rise (%) [at 95% confidence]***	
	Lower Limit	**Upper limit**	**Lower Limit**	**Upper limit**
0.5	0.78	0.90	3.17	3.29
1	1.11	1.23	4.43	4.55
1.5	1.39	1.51	5.48	5.60
2	1.64	1.76	6.45	6.57

Similarly the change in groundwater table has been estimated to be as follows.

Table 40 Change in groundwater table

Site Name	**Scenario**							
	1		**2**		**3**		**4**	
	Increase (m)							
	0.5		**1**		**1.5**		**2**	
	Change in water table (m) [at 95% confidence]							
	Lower Limit	**Upper limit**	**Lower Limit**	**Upper limit**	**Lower Limit**	**Upper limit**	**Lower Limit**	**Upper limit**
Elevation level 1	0.11	0.23	0.55	0.67	0.92	1.04	1.33	1.45
Elevation level 2	-0.01	0.11	0.42	0.54	0.79	0.91	1.17	1.29
Elevation level 3	0.05	0.17	0.48	0.60	0.85	0.97	1.25	1.37
Elevation level 4	0.07	0.19	0.50	0.62	0.88	1.00	1.28	1.40
Elevation level 5	0.00	0.12	0.42	0.54	0.79	0.91	1.18	1.30
Elevation level 6	0.01	0.13	0.43	0.55	0.80	0.92	1.19	1.31
Elevation level 7	-0.02	0.10	0.41	0.53	0.77	0.89	1.16	1.28
Elevation level 8	-0.06	0.06	0.36	0.48	0.72	0.84	1.11	1.23
Elevation level 9	-0.06	0.06	0.33	0.45	0.70	0.82	1.09	1.21

Elevation 1 to 9 refers to distances in 500 m interval starting from the coast.

Summary

Sea level rise scenarios have been analysed and modelled using GIS for Wellington. These values have then been translated to estimate the loss of land in Colombo for sea level rise scenarios. It has been found that the percentage loss of land could be varying from 3 to 6.5% for the Colombo coastal zone. The GIS modelling is a simplistic approach to identifying possible risk areas and effects of infrastructure. Nevertheless, the extents can be used to priorities areas for further inundation assessments.

Similarly a numerical model was developed and calibrated by using FEFLOW. The model was accepted as calibrated once the number of overestimated and underestimated levels in observation bores were similar and when the Nash-Sutcliffe coefficient was a maximum. Calibrated model was then used for investigation of the changes to groundwater table. Again four scenarios were investigated for the increase of 0.5 m, 1.0 m, 1.5 m and 2.0 m. The average increase in groundwater levels in Wellington was found to be 0.07 m, 0.49 m, 0.86 m and 1.25 m respectively while in Colombo it is estimated to be varying from 0 to 1.45m.

k. Assessing the Risk of Sea Level Rise

Climate change will have significant impacts on the oceans and on the coastal zone on a global scale. It will introduce new hazards and increase existing hazard potential, both with respect to magnitude and frequency of occurrence, in coastal regions. The hazards would be both chronic (e.g. sea level rise) and episodic (e.g. storm events). Sea level rise is one of the more certain responses to global warming and presents a major challenge in the administration and management of coastal zones including that of Sri Lanka. A large percentage of the population of Sri Lanka is located in coastal regions and these regions play a vital role of the economic growth of the country.

Sri Lanka is one of the few countries, which have a fully operative, national Coastal Zone Management Plan **(1).** The Coast Conservation Department has the full responsibility for the implementation of the plan. It is therefore necessary that the impacts of sea level rise are addressed via the Coastal Zone Management Plan.

In Sri Lanka, the Coast Conservation Act has defined the coastal zone on geo-physical considerations using linear dimension. This narrow and geographically defined coastal zone does not recognize the interconnections within coastal ecosystems its resources and the human interactions. This limitation in the definition of the coastal zone could become a critical constraint when implementing action plans to respond to sea level rise.

Impacts of sea level rise

Sea level rise is a progressive chronic hazard that is affecting most of the world's coasts. While recognizing issues of global scale, including global sea level rise due to melting of land-based ice and thermal expansion of upper layers of the ocean arising from global warming, other causes of sea level rise on a regional and a local scale are very important when investigating impacts on specific coastal regions. In this respect it is essential to identify and understand the connectivity of inter-related issues, all emerging as a result of global warming. Global, regional and local scales of impacts have all to be considered, as it would be the resultant that would finally affect a given environment.

Investigations conducted in Sri Lanka have revealed that climate change will result in changes to critical forcing parameters of the coastal zone, which would affect the physical condition of the shoreline. They are raising sea levels, change in wave patterns arising from changes in wind pattern and water depth, increased rainfall and the occurrence of extreme events more frequently.

Sea level rise on its own would lead to

1. Inundation and displacement of low lying coastal areas and wetlands
2. Coastal erosion and degradation of shorelines
3. Salinization of estuaries and freshwater aquifers
4. Changes to and migration of coastal eco-systems and habitats

Impacts on the coastal zone of Sri Lanka

Preliminary investigative studies have revealed the following specific impacts for the coastal zone of Sri Lanka.

Inundation

The most direct impact of the rise in sea level is the inundation of areas that have been located just above the water level prior to sea level rise. Low lying coastal settlements and coastal wetlands belong to this category.

Coastal Erosion

A rise in sea level and changes in wave pattern due to changes in wind patterns would increase the present rates of erosion, thereby resulting in the loss of land and increasing the vulnerability of coastal communities. The country has been experiencing an erosion rate of the order of 0.30–0.35 m per year for nearly 50% of its coastline. The Coast Conservation Department has been able to implement strategic coast protection measures for coast conservation. Any acceleration of erosion due to sea level rise will contribute to an increased loss of land, thereby affecting communities and economic activities.

Flooding and Storm damage

A rise in sea level could affect flooding and storm damage in coastal areas due to two main reasons. Firstly, higher water levels would provide storm surges with a higher base to build upon. Secondly, higher water levels would decrease natural and artificial drainage; this could also lead to pollution of water bodies. It is also recognized that change in climate due to global warming could contribute to increase frequency of storms and floods, thus increasing the frequency of extreme events.

Quality of Surface and Groundwater

Rise in sea level increases the salinity of an estuary by altering the balance between fresh water and salt-water hydraulic regimes. The impact would be widely felt during dry weather conditions with greater penetration of salt water. Sea level rise will cause the penetration of salt water into cultivated areas, increase of saline water in aquifers, transforming fresh water habitats, migration of fresh water fish and impacts on other habitats causing a breakage in the food chain of certain species. It will also impact fresh water intakes located at critical positions nearer to urban coastal centres.

Marine Eco-systems and Habitats

Sea level rise will affect coastal wetlands in many ways. Overall climate change would also exert impacts on marine eco-systems and habitats including coastal wetlands, reef systems and fisheries.

Sea defense structures, Near shore infrastructure and Land reclamation

Climate change and sea level rise will impose considerable pressure on existing coast and estuary protection and port structures such as revetments, sea walls and breakwaters. The pressures include, overtopping due to rising sea levels, increase in the frequency and intensity of extreme events such as storm attacks and flooding increase in the hydraulic force regime, beach loss in front of protection works, change in erosion and accretion trends arising from variations in drift and weakening of toe support leading to the undermining of structures.

Assessing risk for sea level rise in the coastal zone

In order to develop a strategic approach towards planning and management of impacts of sea level rise, it is necessary to conduct a detailed risk assessment. This assessment should be done within a broad framework for multi-hazard coastal risk assessment framework.

The risk assessment will comprise hazard, vulnerability and capacity assessments. The superimposition of these components will lead to risk assessment.

Hazard Assessment

For this component the impact on the coastal zone for three credible scenarios should be assessed. The said scenarios will cover low, medium and high states of sea level rise which can be developed giving due consideration to existing seal level data along the coast and global predictions for the region. The primary impacts to be assessed are inundation and forecasts on increase in coastal erosion.

In the longer term an assessment should also be done on the impact of global climate change on the wind patterns and the resulting impact on coastal erosion. The analysis could also accommodate the projected seal level rise. This assessment has to be achieved by use of numerical models

Vulnerability Assessment

Vulnerability represents the proneness of society, infrastructure and natural resources to the impact of hazards. Critical parameters to be incorporated are identified under the six broad categories of human, physical, environment, socio-economic, functional and administrative. In this context it is necessary to prepare a Vulnerability Database for the coastal zone. This will enable an assessment of vulnerability to sea level rise along the coastal area of the country and estimate the economic cost for different scenarios.

Capacity Assessment

Capacity assessment is carried out to assess the ability of society to respond to the impacts of sea level and also to assess the whether critical infrastructure would be able to withstand potential impacts. The ability of those engaged in low-lying agriculture to move into other types of agriculture or trade if their land cannot be protected is typical example. The relocation of fresh water intakes of heavily populated urban cities that are highly vulnerable to sea level rise is another example.

Risk Assessment

Risk assessment can be achieved by superimposition of hazard, vulnerability and capacity assessments. This could be achieved by using a number of methods. Scenario based approaches for hazards are frequently used together with weighted methods for vulnerability. Such methods must be developed in consultation with a full stakeholder forum.

Modeling and Geo-information

The success of assessing risk will depend heavily on the use of reliable mathematical models for simulating the physical processes and the availability of geo-information. Good quality bathymetric and topographical data are essential for successful implementation of a risk assessment study.

Topographical data for hazard, vulnerability and risk assessment can be obtained by advanced methods incorporating LIDAR Surveys or less expensive methods such as Aerial Video Assisted Vulnerability Analysis.

Aftermath of the Indian Ocean Tsunami, LIDAR Surveys supported with satellite images were carried out on the west, south and eastern coasts of Sri Lanka. The project that was funded by the Italian Government provided a valuable database covering a distance from the mean water level up to 2 to 2.5 km inland. This database provides valuable information for inundation modeling and the preparation of a vulnerability database. The availability of LIDAR Surveys is certainly a great advantage for both vulnerability analysis and modeling of hazards. This information together with the use of an appropriate land loss model permits the estimation of physical impacts for different sea-level rise scenarios.

In the absence of LIDAR Surveys it is possible to adopt rapid and low cost reconnaissance technique such ‘Aerial video assisted vulnerability analysis (AVA)’ developed by Leatherman et al.

Development of a Vulnerability Database requires an assessment of index of terrain and relief changes, types of coastal environments, land use practices, status of infrastructure and population in the coastal zone. The results from this type of exercise provide national assessment of vulnerability to sea level rise and focuses attention on areas at risk. Critical parameters relating human, physical, socio-economic and environment should be considered. The information to be acquired for this type of analysis should be incorporated within a coastal zone management of framework for wider usage. This approach is very relevant in the Sri Lankan context.

Proposed actions and investigation for the coastal zone

Based on risk assessment it is possible to identify a series of measures to mitigate the impact of risk sea level rise. Arising from preliminary investigative studies undertaken along the coastal zone of Sri Lanka some of the actions identified are listed below. These actions will be refined after the completion of risk assessment studies.

<u>Inundation</u>

- Incorporate climate change concerns in town and country planning and wetland conservation programmes

<u>Salt-water intrusion</u>

- Assess the increase in salt-water intrusion in important water bodies.
- Evaluate engineering interventions needed to counter threat based on the potential impact on agriculture

<u>Fresh water intakes</u>

- Review the performance of existing intakes taking sea level rise into account
- Design new water intakes giving due consideration to climate change impacts

<u>Groundwater</u>

- Prepare groundwater extraction regulation policy
- Introduce monitoring systems for groundwater extraction and water quality assessment in vulnerable areas

<u>Irrigation and Low-lying Agriculture</u>

- Study impact on existing irrigation structures
- Introduce salinity tolerant varieties of crops, alternative land use or engineering interventions to maintain the existing regime

<u>Fishery Industry</u>

- Conduct sectorial assessment on climate change impacts on fishery development including fishery harbours, fishery settlements and sustainable use of fishery resource as a basis for long term planning

<u>Sea defense structure, near shore infrastructure and land reclamation</u>

- Assess vulnerability and prepare plans for improvement as well as plans emergency response/contingency.
- Accommodate sea level rise in the design of new coastal structures
- Screen near shore reclamation against sea level rise impact

Incorporating Sea Level Rise and Coastal Zone Management

Coastal zone management involves management and decision-making regarding activities of the coastal zone including physical measures for coastal and flood protection and development works. It has been identified that the three principal objectives of coastal zone management related to sea level rise are to:

1. Avoid development in areas that are vulnerable to inundation
2. Ensure the continued function of critical natural systems
3. Protect human lives, essential properties, and economic activities against the adverse impacts of the sea

In this respect the following recommendations are made with respect to the management of the coastal zone

- Prepare set back limits to take account of sea level rise
- Delineate critical areas and prepare special area management plans
- Formulate coastal database incorporating information on hazards and vulnerability for implementing integrated coastal area management
- Incorporate greater consideration of climate change impacts in the next revision of the Coastal Zone Management Plan (CZMP)

Almost all the possible responses to sea level rise are best addressed within a broader context of coastal zone planning and management. Responses to climate change must be seen as a part of a broader coastal management policy, which incorporates non-climatic issues. If considered in isolation the effectiveness of such responses would be reduced mainly due to incompatible policies and/or actions taken by other coastal sectors. Many responses to sea level rise are very similar to those required to address existing coastal zone management problems, thus identifying a clear demand for the planning of sea level rise to be integrated with coastal zone management practices.

Adaptive responses for sea level rise

The Intergovernmental Panel on Climate Change (IPCC) classified the responses to sea level rise to two categories namely

- Mitigation/ Limitation
- Adaptation

Sri Lanka's response strategy to anticipated climate change includes the implementation of both mitigation and adaptation measures. The country's contribution to the emission of green house gases is considered negligible. Even so, every effort is to be made to maximize the country's potential towards controlling the amount of gases being emitted to the atmosphere however small it may be. The proposed actions for the coastal zone consist essentially of adaptation responses required to address the potential impacts of climate change.

Due to the relatively broad range of predictions of sea level rise, those of the IPCC represent reasonable estimates on average sea level rise. The corresponding sea level rise projections from IPCC 1990 for the BAU scenario where the average global sea level rise is estimated at 31 cm to 110 cm by the year 2100 with a best estimate of 66 cm. A recent increase in the rate of sea-level rise has been observed by satellite altimeters, which have also provided new insight into the complex geographical patterns of sea-level change. The rate of rise computed from these data (1993-2003) is indicated to be 3.1 +/- 0.7 mm per year. By 2090 the global sea level rise is expected to be 22 cm–44 cm above the 1990 level and to be increasing by about 4 mm per year (IPCC SRES scenario A1B).

Although there exists an uncertainty in the magnitude of future sea level rise predictions, knowing the order of magnitude of the likely increase and the fact that it will rise in response to global warming will certainly assist in planning response strategies.

The IPCC Reports highlight the adaptive response strategy classified under three categories namely,

1. Retreat
2. Accommodation
3. Protection

The appropriate adaptation mechanism for implementation depends on a number of considerations. For examples assuming that land for settlement is available, retreat can be implemented through anticipatory land use regulations, building codes and other forms of restriction which an be adopted as an integral part of a coastal zone management plan. Accommodation may evolve with or without governmental action but could be assisted by strengthening flood protection and flood insurance programmes. Protection measures have to be implemented by the authorities responsible for the conservation and protection of coastal areas.

In the engineering context it is possible to provide full protection to coastal areas from inundation and to adjust the water management systems in such a way that the major functions of the coastal areas can be maintained. However, economic considerations and environmental impacts will often make such protection strategies non-feasible and unacceptable. Therefore there is a need to develop a protection strategy consisting of different phases, each phase offering a specific level of protection and having its own level of risk with respect to failure. The economic and environmental costs of each phase should also be evaluated. Obviously a 'higher level' protection strategy will be more costly in economic terms but would offer a greater degree of protection with a lower level of risk of failure. This would enable the decision makers to reach sound judgment based not only on the level of protection and socio-economic considerations but also on environmental impact assessment and on risk of failure. The risk of failure can be judged by developing performance standards for the strategies adopted. This approach thus enables the decision makers to be fully aware of the associated risks of the preferred solution as well as on the need for monitoring the post project implementation period.

This paper has highlighted important areas relating to climate change, sea level rise and its impact on the Sri Lankan coastal regions. The paper has presented an approach for the assessment of risk arising from sea level rise focusing on the importance of availability and use of geo-information. A series of further studies have also been recommended for the assessment of impacts arising from sea level rise. Important issues relating to the implementation of adaptive responses have also been presented.

I. Summary and conclusion

In Colombo – Kalani ganga catchmet region, the long-term trend of rainfall is rising. According to analysis, the dry days are more than wet days. Large standard deviation is occurred annually. From predicting, in the southwest monsoon and the second inter-monsoon season, we should focus on these period due to large rainfall occurs during that time, The trend of temperature is increasing with 0.0164^{o}C/year slope and the R^2 = 0.67. According to the average temperature in April and August is higher than other months, the evaporation in those months are higher than the rest. Also, increasing evaporation affects the precipitation. The flood in lower part of Kelani River is becoming more frequently. The impact of climate change can cause the extreme event weather with heavy rainfall becomes frequently. Rainfall is increasing which will cause flood. Temperature increases.

Estimate the loss of land in Colombo – Kelani ganga for sea level rise scenarios has been found that the percentage loss of land could be varying from 3 to 6.5%. The GIS modelling and its translation t Kelani ganga is a simplistic approach to identifying possible risk areas and effects of infrastructure. Nevertheless, the extents can be used to priorities areas for further inundation assessments. Similarly numerical modelled data was used to mathematically translate to identify the ground water changes in Colombo – Kelani Ganga area. It is estimated that ground water table changes will occur from 0 to 1.45m in the Kelani Ganga area depending on sea level rise. A risk assessment of sea level rise and its impacts are also presented here in.

11. Climate change impacts on Estuary systems

a. Introduction

An estuary is a partly enclosed body of water where fresh water coming down the rivers mixes with salt water from the sea. Any changes to this system will result in major changes to eco systems in bays, lagoon, harbours, sounds, fiords and sounds. Past research indicate the following issues.

b. Problems and possible solutions

problem	Possible action
Sea level rise	*Reduce C02 emissions and prevent global warming.* *Dig more reservoirs and man-made lakes.* *Increase use of fresh water from lake/river.*
Drop in tidal wetlands	*Create more tidal wetland. Move further away from wetlands.*

Damage to submerge aquatic vegetation	*Create more vegetation where possible.*
Loss of barrier Islands	*Top up threatened islands or Create artificial Islands.*
Effects on Fresh water resources	*Stock rain water. Recycle/reuse fresh water.*
Life and death of estuaries	*Dig more reservoirs and man-made lakes.*
Accelerated aging	*Reduce C02 emissions, prevent global warming.*
Saltwater intrusion	*Reduce C02 emissions, prevent global warming.*
Damage to Estuary elements ○ *Food webs* ○ *Detritus producers* ○ *Detritus feeders* ○ *Habitat providers* ○ *Harsh habitat* ○ *Seagrass* ○ *Mangroves* ○ *Salt marsh plants* ○ *Salt meadows* ○ *Cordgrass* ○ *Mud worms* ○ *Crabs* ○ *Cockles* ○ *Fish* ○ *Migrating Fish* ○ *Birds* ○ *Migrating Birds*	○ *Create more reserves to protect from excessive human caused damages.* ○ *Monitoring estuary systems to identify damages and taking immediate actions to protect them.* ○ *Implementing environmental rules more strictly.* ○ *Restoring estuary elements as much as possible. eg. Planting in estuary, cultivating effected parties etc* ○ *Less dependency on estuaries for livelihood.*

c. Effects in Lake and River system (Sourced from the internet)

Lake Ogawara

Location -

- Aomori Prefecture, Japan.
- 40:47N, 141:20E; 0.0 m above sea level.

Lake Ogawara is a brackish water lake and is the eleventh largest lake in Japan The lake was formed from a marine bay some 3,000 years ago by the recession of the sea and the formation of sand bar at its mouth, and has thereafter been gradually transformed into the present configuration.

Surface area [km2]	62
Volume [km3]	0.714
Maximum depth [m]	25.0
Mean depth [m]	11.2
Water level	Unregulated
Normal range of annual water level fluctuation [m]	0.7
Length of shoreline [km]	67.4
Residence time [yr]	0.8
Catchment area [km2]	800

Ishikawa et. al. (2001) indicate that the Ogawara lake located in the north of Japan's main island Honshu has suffered intermittent salinity intrusion during particular periods. The Ogawara river case shows that there can be positive aspects of salinity intrusion. In this case the breeding of clams in the high salinity areas is taking advantage of this natural phenomenon. It also indicates that numerous complexities that exist in salinity intrusion.

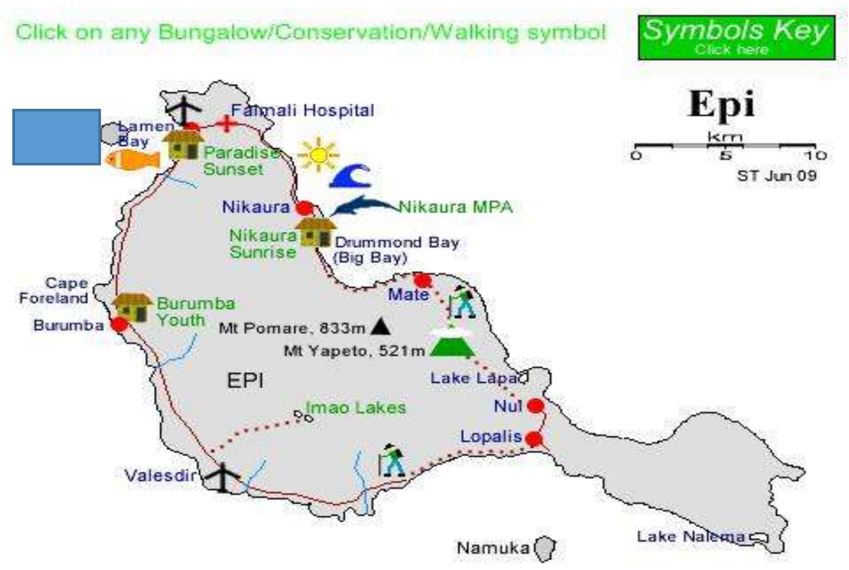
d. Summary and Conclusion

Estuaries and wetlands are areas that face gradual impacts of sea level rise and will be subject to change. Its change will be gradual, and finally will result in irreversible damage if not managed. The Ogawara case has been analysed. Numerous recommendations have been proposed to manage Estuary systems subject to climate change impacts.

12. Climate change impact and mitigation – small islands, case of Vanuatu

a. Introduction

Climate change has been a big threat to all pacific island nations this past couple of years and will continue to affect the islands. Studies revealed that although islanders have contributed very little to global greenhouse gas which leads to climate change, compared to bigger countries, they are the ones affected most. In most pacific islands, climate changes have affected the communities in a number of ways. The impact is experienced in the infrastructure, costal and forest ecosystem, fisheries, agriculture, human health and water supply.



This research is based on the island of Epi in Vanuatu, as shown in figure 1 above, particularly on Lamen bay (shaded area).The discussion of coastal erosion, as the effect to climate change will be covered in detail in the coming sections and also the changes in the weather patterns where regular longer heavy rain falls is now experienced in the area. This research is based on raw local data to map the effects of climate change. A few elderly locals were also spoken to about how climate change has altered their areas. Some confirmed that their ground water wells along the coastal area turned to have a salty taste during high tides which they believed due to the rising of sea water. Most have confirm that in the past the sea level used to be way out in the ocean but the erosion has allowed the ocean to move inland.

This has caused people to move their homes inland as an alternative to avoid salty water in their wells and get away from the rising of sea levels. Figure 1.2 shows a clear example of the affected area where part of the airport runway has eroded as a result of the rising sea level. This project will also cover the issues surrounding of the amount of water available in the area by using the rainfall data collected. The research will discuss in detail with calculations how the availability of water can improve their current water system which can lessen the current issue of high water demand. Therefore it is the sole purpose for this project to highlight some options and design systems to help tackle these changes which have come as a result of climate change.

Tiny pacific islands, for instance, on Epi Isand, on the area of Lamen Bay, Vanuatu, are experiencing the worst effects of climate change. The main effects are the changes in the weather patterns and the rising of sea levels.

The rising of the sea level can be confirmed through other research and studies that were done in other regions. A comparison with an article from (Keener,W.V;PIRCA, 2012) supports that the tiny islands are experience the worst effects of climate change. The effects are basically on sea levels rising and changes in weather patterns. This produces extreme bad weathers like cyclones, and the alteration of rainfall patterns. Some regions experience long rainfall compared to the others, while some areas in another places are struggling to get fresh water. Communities in the affected areas find all measures to adjust to the changes, like collecting and storing rain water since salt intrudes with ground water as the sea level rises. (Ingraun,P.I, “Effect of Climate Change on the pacific Islands”, web.01/10/15)

As climate change direct impact on coastal areas by waves, tides, and storms. This causes people living along coastal areas have to migrate inland away from this situation (McLeman, 2011). In worse case scenarios where land or beaches become eroded damaging the natural scene of the area. To protect the coastal areas from these impacts, seawalls are constructed to minimise damages on areas where the evidence of erosion is worse. Most seawalls are constructed from materials that are not cheap depending on the design. Although to account for this, the materials suggested for the seawalls are available locally on Lamen Bay therefore, minimising the cost. Seawalsl are constructed to protect the coast line from erosion ("Geotechnical Aspects of Seawall Stability with Climate Change".web.1/09/15).

According to research there are some areas where there is plenty of rainfall as the weather pattern changes. However most of these areas do not have sufficient funds to build or maintain their existing water system to meet the demand for their community. During longer periods of dry season fresh water shortage becomes an issue. According to an article, ("water safety plan for mele rural area": mele rural water supply Port Vila Vanuatu, web 01/10/15) the existing water supply in Mele, Port Villa, Vanuatu was first constructed in 1986 and it was later modified ten years later but since 1996 nothing has been done to upgrade the existing water system. This is an indication that rural communities need financial help, training and knowledge on how to manage their existing water systems. Upgrading these water supplies need to be established through the help of governments or Non-Government Organisation (NGO).

A sufficient supply of clean, fresh water is a key vital for humans to survive, according to (Horvath.B & Delsalle.J, 2012). This supports the idea that any sources of water cater for a community should be of high quality. Any existing water supply system should be fully maintain or demolished if needed and new ones built. Constructing new water systems and reservoirs also depends on the water demand and the population for certain areas. This along with rainfall and existing water sources can therefore cater to the demands of population ("Household Water Supplies", 2014).

Theoretical studies of climate change have proven that humans have contributed heaps to the releasing of green-house gas into the air. Therefore one could argue that there is no other way to stop climate change but to adapt to these changes (SPM,"Climate Change", 2013). Also rural communities have a higher expose rate to climate change effects compared to the urban centres. This is due to their very little availabilityof human and institutional resources and smaller or less diversified economies (Catto.N, 2010). Therefore the proposed adaption strategy should be taken seriously to allow the changes to happen fitting the settings for the community.

b. Effects of Climate Change on land

Erosion

Erosion can happen either inland or along the coastal area where soil are been washed away. For centuries tiny pacific islands or atolls are experiencing the coastal erosion where the islands are slowly going under water due to the rising of the sea level which leaves no choice for their respective governments to negotiate with some other bigger pacific countries to help them. This rising of the sea level has eventually caught up with this island on the area where I am doing my research which later in this section I will compare how the water mark has risen and analyse it with the present and future scenario. These findings are done by asking locals on what they have seen and observe this is because in the rural areas in the islands no data is recorded so all the findings can be collected or recorded by interviewing the locals.

To have a good range of information about the water mark on the area, at least five different people with a variation of over 70 year olds have been ask for their estimation about the sea level horizontal distance. Their estimations is based on what they have seen in the past and comparing it with the current situation.

Below table shows the respective age group of different people with their estimated sea level at a horizontal distance. The estimate distance is based on a stationary mark on the affected area which will be later shown in the figure 107.

Table 41 The estimate sea level at horizontal distance.

Year	Age difference	Horizontal distance(m)
1955	60	15
1975	40	6
1995	20	4
2005	10	2
2010	5	1

Figure 107 object used as stationary point – Sea Level

Stationary mark

1955 – 2015 = 60 years

Analysing the water mark level for future scenario

Below is the analysis of the sea level based on the estimated figure from table 1. This accessing of water mark will illustrate where the water mark level has been 50 years ago and 50 years into future.

Below is how calculation is done.

Horizontal rate of sea level distance = total distance in 60 year/number of years

$$= \frac{13m}{60} = 0.2\text{m/year}$$

Future analysis, 50 years

0.2 x 50 = 11 metres

50 years from now the water mark level will recede 11 metres inland an average rate of 0.2m every year.

Google map snap shot of Laman bay airport runway which clearly indicates that in 50 years' time, the 11 metre horizontal distance in land will cause part of the runway to be under water if nothing is to be done to slow down the rate of erosion.

Problems caused by erosion

The erosion discuss in this project is based on coastal erosion since the selected study area at current is heavily experiencing coastal erosion. This is similarly to other places in the pacific region experiencing the same problem, and it is a bigger threat to the coastal vegetation. Coastal vegetation holds the soil intact along the coastal area which slows down the rate of erosion. Once the coastal vegetation is gone, the rate of soil eroding will escalate furiously and any plants or trees including the native coastal trees will sadly becoming extinct. There is a need to slow down the rate of coastal erosion on the worst affected areas while educating the people on affected areas on how to adapt to these changes. For example, giving out awareness and reasons why people need to stop digging up sand beaches on the coastal areas. This is because if nothing is done sooner enough then there will be more complicated problems related to erosion to deal with.

For this study, the main focus is the fearing of losing the island airport runway due to coastal erosion. The other fear is the high water mark level during extreme high tides of been to high closer to homes of the locals along the coastal area. However the airport runway is the big concern here since it is one of the very few means of linkage for the island to the outside world. Therefore it is best to come up with options to do something to slow down the rate of erosion while consider another alternative for the locals living to close to the water mark. It has been a practise for them for century to live close to the coast line and for some it is hard to accept the fact that living along the coastal area is not an option anymore with the current high rate of coastal erosion. The only option to help the locals is to give awareness on how to adapt to climate changes and build a seawall to protect the airport runway before most of the runway is wash away.


The airport runway is slowly eroded away settlements along the coast

Available sea wall options

Constructing sea wall is the only option to slow down the soil erosion along the airport runway but in order to do the construction there are few things to take into consideration. Money is the priority subject that controls everything in any construction so in order to get a good reasonable budget it is best to choose the best type of sea wall that may suit the resources available within the community to reduce on cost.

Below are some type of sea wall construction that could be taken into account considered the case study area settings and its resources. This type of sea wall options are taken from the link listed below; http://www.ehow.com/list_6323989_types-seawall-construction.html http://www.coastalconference.com/2012/papers2012/Lex%20Nielsen%20Full%20Paper.pdf

- Riprap seawall
- Concrete seawall
- Cobble boulder seawall
- Bulkhead walls

Riprap seawall

Riprap can be of any kind of stones mixture to even sand bags that can be used to protect shoreline or even river banks. In the figure below it shows the riprap wall constructed from stones and sandbags. The spaces between the stones can allow plants to grow as well as it stops the force of the waves before it can reach the soil and sand behind the riprap walls


source: http://www.ehow.com/list_6323989_types-seawall-construction.html

Concrete seawall

Concrete seawall is another option, a seawall that is reinforced with steel bars and sometimes is a large and very expansive structure design to protect shoreline from heavy forces that can be produces from the waves. It is obviously an expensive option for the case study area as it is in a rural community setting, however it can last for many years if design and construct to the standards.

Source:http://www.ehow.com/list_6323989_types-seawall-construction.html

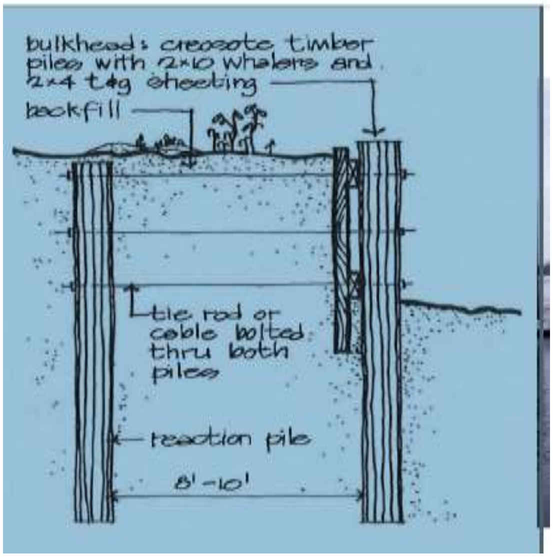
Cobble Boulder seawall

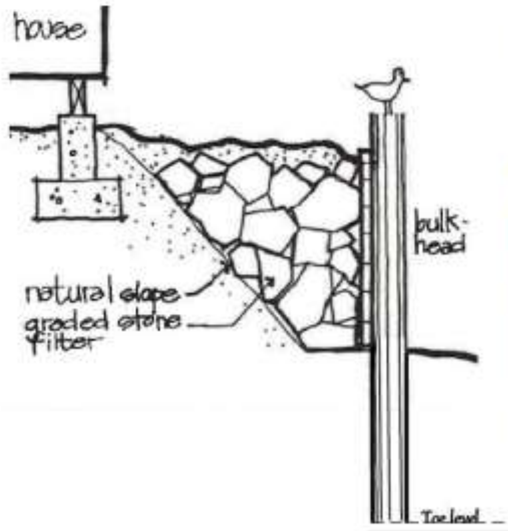
Cobble boulder seawall can be made out from large rocks stacked over a mound of small stones which kind of similar to the riprap pattern but the only difference is the bonding between the small rocks and the large ones can sometimes join together with mortar.

Source: http://www.ehow.com/list_6323989_types-seawall-construction.html

Bulkhead seawall

This seawall structure can be built using treated timber for a quality resistance against soil erosion especially along the coastal area. According to Roger.H.C & Christian.P.D bulkhead seawall is a “low cost sea-wall and bulkheads can be made of treated timber, sometimes combined with steel H-ties, though this raises prices” (212). The backfill materials can be either of sand, soil or rocks. Huge consideration must be taken to make sure that there is no leakage of backfill if the backfill are of sand or soil materials but not much to worry about if rocks are used as the backfill materials.





Source:
http://www.coastalconference.com/2012/papers2012/Lex%20Nielsen%20Full%20Paper.pdf\\

Recommended Options

Considering the given options discussed above, it looks like the riprap, cobble boulder seawall and bulkhead seawall could be the best suitable option for the community. Any of the three options can be chosen depending of the materials available or can be provided by the community. However another possible option is to mix these three options together a one product of seawall. This will help to reduce the cost of constructing if materials are to be pre order.

Riprap seawall & Bulkhead wall

- Rocks
- Sandbag

Bulkhead wall & cobble boulder seawall

- rocks & smaller stones

Scanning the community area for resources, from observation, the community can provide sand for sandbag riprap seawall as well as large rocks and stones as cobble boulder. To reduce the over using of resources, it is best to combine more than the two type of seawall together to get an effective result.

Below are figures showing the materials that can be provided by the community.

sand beach

stones & Rocks

c. Effect of climate change on Ground water

Well Water

It has been a normal practise for local village people to dig underground well closer to the coastal area, because its logic that site does not matter as long as it's closer to the coast line there will still be fresh water underground. However despite the western influence on changing the building style for well water, majority of the community people goes for the underground well water due to difficulty in financing western (concrete, steel and poly-well) type wells. The biggest problem to underground well water is the rising of the sea water level which turns the fresh water salty. Moving further inland to dig underground well becomes more and more challenging in terms of depth and the exact site to reach the water level easily. Therefore choosing the underground well water site requires a skill person, normal an elder person who is experience and have learn the techniques and skills passed on from generation.

An example of an existing inland ground well is shown in Figure 16 below

Water Depth

As mention earlier, the water depth varies depending on the site. Site closer to the coast line may have a depth of 1.5 – 2.5 metres but site further inland from the coast may have a deeper range from 3 – 6 metres. Therefore it is harder and requires a lot of time and energy to get to the water level further inland, while lesser effort for ground wells closer to the coast line. But for most locals in the community they prefer sticking to underground well closer to the coast line which does not require much effort to reach the water level.

Water Quality

The water quality depends on the depth of the well, deeper the well better the water however for the underground well are closer to the coast line , it has the higher change that the water may taste salty or may contain lots of sand in it when fetching for use. Another factor that may contribute to contamination of the ground water well is the building material. Some building material corrode very quickly when in contact with salt but are cheaper and affordable for the locals and so it is the only cheaper option for the locals to have water for the community. Most of the locals in the community live off their land and it is very hard for them to purchase quality materials to have better ground water wells.

Problems to well water cause by Climate Change

As it has been mention earlier, when the sea water level rises, water wells that are close to the shores are either damage or bury by the high tides. This is worse during extreme weather like tropical cyclones. Another problem is that, water wells close to the sea shores turn salty when the sea level rise which stops the community from using it. Also cheaper materials that are used for constructing the ground water well close to the sea may contaminate the fresh water when eroded and that may lead to health issue when using the water. Another factor that may add problem to the well water is the fact that dirt may get into the water well since all the existing water well are expose to contamination from the surroundings for not been fully shelter.

Below are the figures showing the different existing water wells around the community.

Recommended Well Water Option

Analysing the detail discussion above about underground Well Water, the best option for the underground well water will be the Well Water that is not close to the coast like shown in Figure 21 above. However this option needs some modification to provide clean water for the community. This modification may include putting a wall or build a semi- permanent building for the ground wells to reduce any dirt that may get in and contaminate the water. Additional features, if it is affordable, may added on to the building over the Well Water which may include a solar panel on top on the roof to power a simple water pump. This water pump may then pump water to a simple reservoir which then can supply a tap so people instead of using the olden way to fetch water, can fetch water from a tap.

d. Population growth impact on climate change and its adaptation

To control the population impact on climate change, people need to be educated on how to adapt to the changes happening around them. As mention earlier, these people in this case study area are mostly people living in the rural with less connections to the outside world and their way of living has been practise in the past for generation. Little did they know that their way of living been describe in the previous section have big impact to climate change. Speaking to some about climate change, only a few have some idea on what is happening but still confess they cannot do anything about it due to lack of information. For instance, controlling the birth rate in the community by advising women to take contraception is not an effective option, since most local men oppose this idea according to their custom beliefs which has been a great challenge for the health workers for years. There should be other ways to consider for an effective control of the population which may requires the help from the government, NGO and the community leaders to work together to get this across the locals.

Best Option; More detail Awareness

Observing this situation, from my point of view, I think the government, NGO (Non-Government Organization) and the Community should work together to educate the community on the issues with the increase of population.

- Government:
  - Introduce syllabus into schools to educate students about the issue on Climate Changes and population.
  - Educate students on different effective methods to control the rapid increase of population
  - Work closely with all health centres in the rural areas to educate people about the effects on population increase and the best method to decrease the rate of population
  - A follow up plan to check on this propose options to get feedback and do changes.

- NGO's:
  - Work closely with the government on any awareness to be conducted in the rural areas
  - Individual planning to visit and educate rural communities on how to adapt to these changes if necessary when approve by the government. i.e how to reduce the rate of the soil erosion along the coastal area
  - Report back to the government on any issues that need amended.

- Community:
  - Community leaders should be educated by the government or NGO on the issues of population increase and let them govern their own communities by making laws that does not affects the
  - To make sure that every senior community members understand how the increase in population contributes to climate change and abide by any laws set by their leaders. i.e cutting down and replanting the same number of trees

the same day or stopping people from digging up sand beach where the erosion is worst.

- People listen to their leaders in the community so any control options set in place will come into effect eventually.

e. Summary and Conclusion

Loss of land and changes to ground water is prevalent and evident in island countries in the pacific caused due to sea level rise. Here sea level rise and its impact in Vanuatu has been investigated and possible solutions have been suggested to suit the location, and resource availability.

13. Summary and Conclusion

It is evident that climate change and sea level changes are occurring round the globe. These changes impact on, coastal zones in terms of land adjacent to the ocean being susceptible to loss, changes to ground water table where the water table is hydraulically connected to the ocean, salinity intrusion where aquifers are hydraulically connected to the ocean and on the sustainability of estuary systems. This study investigated these aspects using modern day sophisticated software and up to date accurate data, identifies the impact and proposes management methods.

In addition it is clear that most populations in coastal zones are experiencing these changes. However, they do not possess sufficient resources namely, past data, technical expertise or modern technology and software to accurately predict the impact of climate change and sea level rise. Hence there is a need for a simplified easy to apply composites models and methods in order to identify the impact and develop management strategies. This study details this aspect conceptually, mathematically and practically.

It is found that sea level has been rising at an average of 3mm / year and the acceleration of the rise will increase.

A numerical model has been developed in order to analyse the influence of the sea level rise on the Whaiwhetu Artesian Aquifer in Wellington. The available data was obtained from 29 bore-logs, was analysed and then imported into ArcGIS where shape files for each model slice of the numerical model was created. Rainfall data, evaporation data, recharge data etc., were initially used for the development of the conceptual model of the LHGZ. Once the conceptual model was developed, the numerical model was developed and calibrated by using FEFLOW. Four scenarios were investigated for the increase of 0.5 m, 1.0 m, 1.5 m and 2.0 m. The average increase in groundwater levels in Whaiwhetu Artesian Aquifer is 0.07 m, 0.49 m, 0.86 m and 1.25 m respectively. The land loss due to se level rise was also calculated for all four scenarios and it varies from 0.84 km^2 to 1.7 km^2

Sea level rise scenarios with and without storm effects have been modelled using GIS. The range of SLR levels with and without storm effects shows the relative extents of land inundation. The GIS modelling is a simplistic approach to identifying possible risk areas and effects of infrastructure. The extents can be used to priorities areas for further inundation assessments. We recommend that further work is undertaken to provide better understanding of the extents and effects.

It has been estimated that as the sea level increases from 0.5m to 2 m the loss of land increases from 0.8 Km^2 to 1.7km^2 or the percentage of inland ground water zone lost varies from 3 to 6%.

The simplified composite model designed, described the theory of climate change resulting in an increase in global temperature thereby giving rise to an increase in sea level. It also shows how much sea-level rise coupled with a few other parameters cause loss of land in coastal areas as well as effect on rivers and water table.

Conceptually, a conversion table was developed to calculate the how much land is lost due to climate change and sea-level rise. The model was tested with values obtained from the Wellington region for scenarios 1, 2 and 3 of 0.5m, 1.0m and 1.5m sea-level rise and these provided satisfactory results in comparison with the Wellington data.

Estimates were obtained for loss of land but a few key points of note during model development were the assumptions made such as conversion at 90%, and the assignment of units to parameters. These may in some way affect the reliability or integrity of the model as there were also limitations with regards to parameters, especially when only a few were considered. Effect on water table (in meters) was also calculated using Wellington values for scenarios 1, 2 & 3 of 0.5m, 1.0m & 1.5m sea-level rise and the results (see table 3.2) also show model values to be within reasonable tolerance of the estimated values for Wellington. Model values obtained for scenarios 1, 2 & 3 of 0.5m, 1.0m & 1.5m sea-level rise were: 0.21m, 0.43m and 0.65m respectively.

Mathematically, simply

Sea level rise can be estimated from year 1990 baseline by

"$\mathbf{X = 0.0425N^2 - 3.0575N}$" where N is number of year since 1990 and X is sea level rise (m).

Land loss area due to sea level rise (without storm event) can be formulated by

"$\mathbf{Z = 554X - 136}$" whereas,

Loss of land triggered by storm expressed as "$\mathbf{Y = -106X^2 - 63X + 654}$".

Therefore, total land loss area is forecasting as "$\mathbf{L = Z + Y = -106X^2 + 491X + 518}$".

Meanwhile, simplified model estimating changes to groundwater table caused by sea level rise define as

"$\mathbf{GC = (-8.7GWL + 827.5) X - (27.75GWL + 183.25)}$"

where GC denotes Groundwater level changes (mm), GWL represents Current Groundwater level (m).

The advantage of simplified composite model serves general public to obtain approximate values of sea level rise, land loss area and changes to groundwater table, particularly when data is sparse.

Predicting sea-level rise impacts as a result of climate change is complex, and simple models are mostly of limited use. However, the simplified conceptual model designed in this project or the simplified mathematical model developed in this research produced satisfactory results in comparison with available data and will help in the decision making process of what adaptation methods to employ or implement in certain coastal areas. Although models like these are based on assumptions of the impact of climate change and a few parameters, they shed good light into the climate change phenomenon, the sea level rise, the loss of coastal land due to it, the changes to ground water table due to it and bringing it to the forefront and encouraging coastal authorities to take necessary mitigatory action.

Even when accurate forecasting with advanced methods, still downscaling of hydrological factors would be required to predict climate change. This study presents an investigation in this area. In addition The hydrological modelling is always associated with uncertainty which may include parameter uncertainty, GCM uncertainty and downscaling uncertainty. The calibration of the model demands very accurate observed data. Generally runoff data is used for model calibration are controlled data due to the presence of dams, reservoirs and irrigation practices. The future projections are not accurate since these data are not reliable. Hence an uncertainty assessment was carried out for hydro climatic simulation of Ganga river basin and it is concluded that the hydrological uncertainty is much less compared to GCM and downscaling uncertainty. Therefore, improvement in GCMs and downscaling methods should be given more importance than the calibration of the hydrological model. A study on climate change impact and management strategies for a case in India is presented.

The maximum Sea level Rise projected for the area is around 0.25m to 0.5m and therefore low land loss can be negligible. However the possibility of extreme floods due to climate change should be evaluated. The effect on sea level rise of Salt water intrusion rate is found to be profound. As the river discharges are mainly monsoon dominated the river discharges during monsoon time is higher than the minimum river discharge required to keep the areas safe from salt water intrusion for different sea level rise scenarios. The difference in the number of days the barrage can be kept opened for no sea level rise and sea level rise of 2.0m is found to be 8 to 25days.

From the investigation done on the Samarang basin in Indonesia it is found that sea level rise is exacerbated due to land subsidence as well. Hence, the sea level rise due to global warming effect is the difference between the value of total sea level rise with the value of land subsidence and it si noted that in Samarang land subsidence is a significant cause of flooding in the area. While hard engineering startegies sucha s construction of sea walls, revetments are proposed soft engineering startegies such as moving from hazardos are as and early warning systems are proposed.

From the Colombo – Kalani ganga catchmet region investigation, the long-term trend of rainfall is rising. According to analysis, the dry days are more than wet days. Large standard deviation is occurred annually. From predicting, in the southwest monsoon and the second inter-monsoon season, we should focus on these period due to large rainfall occurs during that time, The trend of temperature is increasing with 0.0164^{o}C/year slope and the R^2 = 0.67. According to the average temperature in April and August is higher than other months, the evaporation in those months are higher than the rest. Also, increasing evaporation affects the precipitation. The flood in lower part of Kelani River is becoming more frequently. The impact of climate change can cause the extreme event weather with heavy rainfall becomes frequently. Rainfall is increasing which will cause flood. Temperature increases.

Estimate the loss of land in Colombo – Kelani ganga for sea level rise scenarios has been found that the percentage loss of land could be varying from 3 to 6.5%. The GIS modelling and its translation t Kelani ganga is a simplistic approach to identifying possible risk areas and effects of infrastructure. Nevertheless, the extents can be used to priorities areas for further inundation assessments. Similarly numerical modelled data was used to mathematically translate to identify the ground water changes in Colombo – Kelani ganga area. It is estimated that ground water table changes will occur from 0 to 1.45m in the Kelani Ganga area depending on sea level rise. A risk assessment of sea level rise and its impacts are also presented here in.

Estuaries and wetlands are areas that face gradual impacts of sea level rise and will be subject to change. Its change will be gradual, and finally will result in irreversible damage if not managed. Numerous recommendations have been proposed to manage Estuary systems subject to climate change impacts. In addition, loss of land and changes to ground water is prevalent and evident in island countries in the pacific caused due to sea level rise. Here due the lack of data, impact of sea level rise in Vanuatu has been investigated using the knowledge of the inhabitants and possible solutions have been suggested to suit location, and resource availability. As a rule of thumb given the analysis above it is clear that 500 meters from sea line should be delimeated as coastal reerves or parks devoid of infrastructure and human habitation while abstration wells should be six km's away from the sealine to minimize potentail of salinity intrusion, and changes to graound water table.

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