University of Cape Town

Multiple scenario analyses forecasting the impacts of sea level rise in Cape Town, South Africa

By

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Declaration of Authorship

I, Sheveenah Sunnassee Taukoor, declare that this thesis titled,
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“*Planet Earth does not need to be rescued. It has survived variations in sea levels ever since the oceans have existed. It's the homo sapiens who are in trouble. They are part of the cause and they are also the victims. Sadly, they also dragged many other species along in this problem."*

Abstract

Sea level rise is highly interdisciplinary and its study entails not only oceanography, but other fields such as geomatics, climatology and geology. In this study we relied on the tools from geomatics to produce sea level rise maps in order to assess the vulnerability of the coastline of Cape Town, South Africa. After generating a DEM of a spatial resolution of 2 m from LiDAR point cloud data, we made use of GIS to design 4 sea level rise scenarios based on the RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 scenarios from the IPCC. Among the findings, it was found that 2.16 – 3.09 km^2 of land would be potentially inundated by 2100. The main receptors which were identified were sandy beaches, rocky shores and built-up land. Permanent inundation would possibly change the appeal and the nature of the beaches and affect the tourism industry. Hence the coastline requires immediate attention as it is one of the most valuable assets in the tourism industry. Tidal effect and storm surge effect were also identified as additional factors which brought temporary changes to the sea level in Cape Town. These impacts were further investigated in 8 coastal suburbs (Tableview, Woodbridge Island, Paarden Eiland, Foreshore, Sea Point, Glencairn, Fish Hoek and Strand.) Suitable adaptation strategies including hard protection measures (e.g groynes, sea walls, barriers) and soft protection measures (e.g beach nourishment) were also proposed for these 8 suburbs.

Acknowledgements

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Dr George Sithole for his support and guidance.

My mum, for basically being my rock, always believing in me and supporting me

My dad, for being my friend and my cheerleader in the hardest times

Dr Neha Awasthi, Watson and Biscuit for letting me a member of our little wolf pack family.

Contents

Dedicated to all those voiceless starving polar bears who struggle daily to survive because of climate change . . .

Abbreviations

ATL	Astronomical Tide level
BTELSS	Barataria Terrebonne Ecological Landscape Spatial Simulation
DEM	Digital Elevation Model
DIVA	Dynamic Interactive Vulnerability Assessment
GIS	Geography Information Systems
HAT	Highest Astronomical Tide
IPCC	Intergovernmental Panel of Climate Change
LIDAR	Light Detection And Ranging
NASA	National Aeronotics Space Administration
PIA	Potential Inundated Area
RCP	Representative Concentration Pathways
RSL	Relative Sea Level
SLAM	Simultaneous Localization and Mapping
SPR	Source Pathway Receptor
SRTM	Shuttle Radar Topography Mission
SSL	Storm Surge Level

Chapter 1: Introduction

1.0 Background

Sea level rise is a natural phenomenon which has been thoroughly studied not only by coastal oceanographers but also by geologists, geophysicists and climatologists during the last century. According to the paleo sea level data, the current global mean sea level is 5m lower than the sea level from 3 million years ago when the average global temperature was 2'C warmer than the current conditions. Variations in the sea level have occurred through every glacial and interglacial phase. However, during the last 5 decades, several studies have shown that anthropogenic factors have become one of the dominant contributors in triggering an increase in the global temperature, hence leading to a rise in the sea level (Warrick and Oerlemans,1990).

We relied on the Sources Pathway Receptor model which acted as a road map to identify the different causes of sea level rise (e.g thermal expansion, melting of glaciers, tides, storm surge) the pathways (e.g inundation, flooding, erosion) and the receptors (e.g beaches, inhabitants, properties, roads). Through this model, we could visualize the link between each component and see a logical picture from the cause to the vulnerable sectors.

In this study, we chose the capital of South Africa, Cape Town as the study area since its coastline is a valuable asset in the tourism and economic industry but it is highly vulnerable to sea level rise.

1.2 Problem statement

The impacts of sea level rise can be highly damaging to the coastline of Cape Town and there is no current means of obtaining reliable prediction of future sea level rise events. Hence long term planning is necessary to allow for preparation of future impacts. It is challenging to forecast which exact location along the coastline would be submerged. Nevertheless, it is still better to have an estimate for future plans of development. Locating the PIAs will differ according to different approaches which are adopted. Henceforth the choice of the methodology is a crucial part in this study. In order to choose an appropriate methodology, we reviewed previous studies and their techniques of identifying PIAs along a coastline.

1.3 Reviewing the literature

Since sea level rise is highly interdisciplinary, it englobes not only coastal oceanography but many other fields including geomatics. Through the literature, coastal oceanographers have borrowed tools from geomatics to delineate the potential inundated regions along the coastline so that they can assess the impacts of sea level rise. There exists a wide range of approaches which have been adopted to create sea level rise maps (Gesch, 2009; Mcleod et al, 2010; Yin et al, 2011). Some studies chose to focus on the accuracy of the maps hence they made use of elevation datasets of high resolution. Other studies emphasized the importance of their choice of simulated heights for their scenarios of sea level rise (Li et al, 2009; Hinkel et al, 2013). The literature was also divided based on the scale of analysis. Some studies involved the investigation of the global impacts of sea level rise while other studies provided detailed assessment of the vulnerability of the coastline at a local level. In the context of Cape Town, there have also been a few studies which have produced sea level rise maps for its coastline.

1.4 Aim

Assess the impacts of future sea level rise on the coastline of Cape Town

1.5 Research question

- Based on a spatial analysis, which areas in Cape Town would be potentially inundated by 2100?
- What are the impacts of the combined effects of future sea level rise and additional temporary flooding on some of the coastal suburbs in Cape Town?

1.6 Research methodology

This study was conducted using quantitative research techniques. The 6 different stages of the study are as follows:

Sea level rise: Firstly it was necessary to have a thorough understanding of sea level rise and the different causes of global and regional sea level rise as well as the different pathways and the major receptors which are at risk.

Study area: Secondly it was important to familiarize with the different systems of the study area, e.g storm surge was identified as one of the sources of local changes in the sea level.

Literature review: The third phase was focussed on an assessment of the previous techniques which have been adopted in previous studies in order to create sea level rise maps.

Methods: From a range of approaches, one of them was adopted and the scenarios of sea level rise were generated.

Results and discussion: In the fifth phase, the results were presented and analysed.

Conclusion: In the last section, a summary of the findings were presented and we explored the different limitations and how this study could be improved.

1.7 Outcome

The principle outcome of this research was aimed at assessing the vulnerability of the coastline of Cape Town and based on a spatial analysis, we calculated the Potential Inundated Areas (PIAs) based on the 4 RCP scenarios from the 5th assessment report of the IPCC, namely the RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5. Moreover, detailed assessments of 8 different suburbs were also conducted in order to investigate the impacts of combined effects of sea level rise and additional temporary flooding.

1.8 Scope of the research

The scope of this study was not to create entirely accurate sea level rise maps, but to identify the different regions which were highly vulnerable to sea level rise. By creating these maps, these results could then act as reliable estimates and contribute in possible adaptation strategies in future coastal development plans at the municipal level. From this study, there is also possibility for expanding this research and assessing the coastal retreat of Cape Town or exploring the impacts on different sectors such as transport and population.

Chapter 2: Sea level rise

In an attempt to meet the objective in our study, i.e to assess how sea level rise would impact the coastline, it is necessary to have a deeper understanding of the sea level. In this chapter, we explored the changes which occurred during the previous glacial phases and looked at the evolution of the different technology used to record the changes. Then we made use of a conceptual model which acted as a roadmap in order to find the connection among the sources, the pathways and the receptors. Firstly we defined the different factors which caused an increase in the sea level. Then we identified the different pathways and the receptors. Finally, in the last section, we examined some sea level models which provide useful estimates for future changes

2.1 Sea level in the past

It is important to note that sea level is a natural phenomenon and it has fluctuated over geologic time by hundreds of metres. Sea level models have reconstructed the past and it was concluded that the current sea level is very similar to the deepest level ever reached (lowest record of sea level during the Permian-Triassic boundary at 250 million years ago).

The planet has been through hundreds of glacial cycles whereby the sea level would undergo drastic changes. Coastal sediment deposits revealed big fluctuations with a later recovery. Some of them included a gradual rise during the Cambrian period, a considerably constant sea level throughout the Ordovician, with a drastic decrease due to the end of a glacial phase and a relatively constant sea level in the Silurian period.

As for the latest ice age (about 20,000 years ago), the models suggested that the sea level of the planet was 125 metres lower than the current one, because of the high evaporation rate of the sea water and the deposit of snow and ice. Eventually, the sea level has increased significantly while much of the ice sheet, more particularly the Laurentide ice sheet in the northern hemisphere has been melting.

2.2 Breakthrough in measurements of sea level

However our understanding of modern sea level has greatly improved during the last century. And this is mostly because of progressive development in the accuracy of the methods of recording sea level. Earlier in the 18th century, it started with the installation of a few tide gauges at some European harbours. Over the years the amount of tide gauges has significantly increased and this contributed to a rich dataset of records of sea level. The satellite altimetry record has also begun in the 1990s. From the launch of TOPEX/Poseidon in 1992, to Jason-2 in 2008, along with satellite imagery from remote sensing, this has allowed us to see a clearer picture of our understanding of the sea level (Willis, 2010).

2.3 Sources – Pathway – Receptors

As mentioned earlier in the introduction, we relied on a conceptual model, the Source – Pathway- Receptors framework in order to visualize a clearer picture among the principle causes of changes in the global and local sea level, the ways through which the ocean can cause the impacts, and the different receptors which are being impacted by sea level rise (Chadwick et al, 2015). In the last 10 years, many system-based approaches to risk assessments were adopted in order to understand the links between the causes and the different components which were being affected (Narayan et al, 2011). However in this study, the SPR model was chosen due as it allows us to visualize an instantaneous representation of the physical inundation process. The SPR model is also known to have been widely used in previous flooding studies and its principle advantage is that it is simple, inherent and flexible in capturing the system linkages in a coastal flood event (Hall et al, 2002). A logic formulation from the identification of the problem of sea level rise to the different impacted sectors is necessary in order to answer the two questions in this study.

Figure 2.1: conceptual model of S-P-R

2.4 Sources for global mean sea level

Looking at the sources for global changes in the ocean volume, the leading contributors during the 20th century are the glacier melting and the thermal expansion of the ocean. Both of these processes are caused by a rise in the global temperature (Rahmstorf, 2007). Oceanographers have developed a growing interest in studying sea level rise during the last few decades ever since anthropogenic forcing was recognized as a major contributor to global warming. Anthropogenic factors accounted for a change of 0.7 ‘C while natural factors only contributed to 0.2 ‘C (Rahmstorf, 2007). Hence emissions of greenhouse gases from humans are partially accountable for a rise in the ocean.

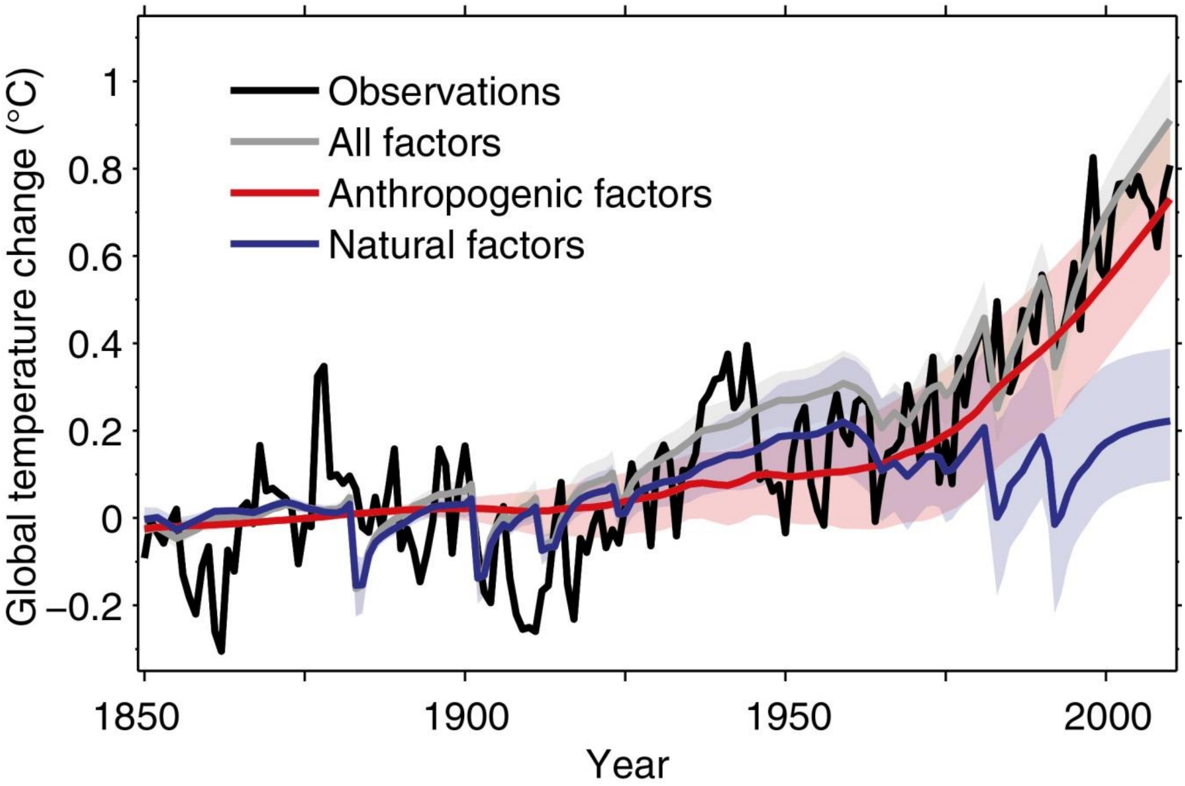
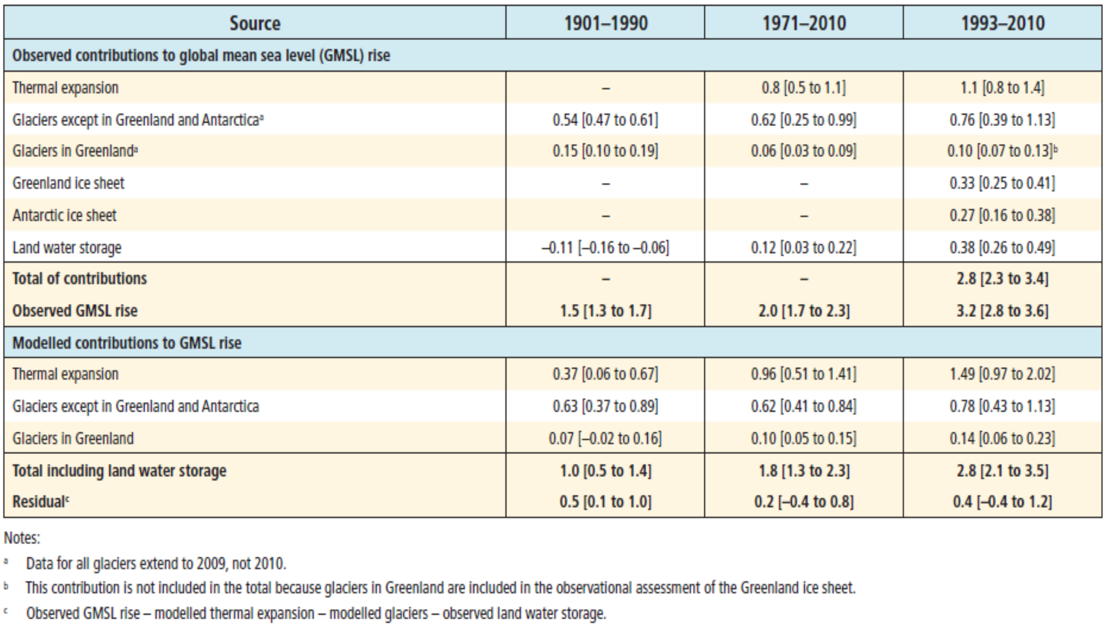


Figure 2.2: Contributors of increase in global mean temperature (Pachauri et al., 2014).

With a rise in temperature due to global warming, this results in the melting of glaciers. As a consequence, this leads to a rise in the ocean. Thermal expansion is also a major contributor as a rise in the global mean temperature translates into the expansion of the seawater molecules, leading to an increase in the volume of the ocean. Based from the historical records, the input of freshwater from glaciers and thermal expansion have accounted for 75% of the global rise from 1993 to 2010 (Pachauri et al., 2014).



Source	1901–1990	1971–2010	1993–2010
Observed contributions to global mean sea level (GMSL) rise			
Thermal expansion	–	0.8 [0.5 to 1.1]	1.1 [0.8 to 1.4]
Glaciers except in Greenland and Antarctica[a]	0.54 [0.47 to 0.61]	0.62 [0.25 to 0.99]	0.76 [0.39 to 1.13]
Glaciers in Greenland[a]	0.15 [0.10 to 0.19]	0.06 [0.03 to 0.09]	0.10 [0.07 to 0.13][b]
Greenland ice sheet	–	–	0.33 [0.25 to 0.41]
Antarctic ice sheet	–	–	0.27 [0.16 to 0.38]
Land water storage	–0.11 [–0.16 to –0.06]	0.12 [0.03 to 0.22]	0.38 [0.26 to 0.49]
Total of contributions	**–**	**–**	**2.8 [2.3 to 3.4]**
Observed GMSL rise	**1.5 [1.3 to 1.7]**	**2.0 [1.7 to 2.3]**	**3.2 [2.8 to 3.6]**
Modelled contributions to GMSL rise			
Thermal expansion	0.37 [0.06 to 0.67]	0.96 [0.51 to 1.41]	1.49 [0.97 to 2.02]
Glaciers except in Greenland and Antarctica	0.63 [0.37 to 0.89]	0.62 [0.41 to 0.84]	0.78 [0.43 to 1.13]
Glaciers in Greenland	0.07 [–0.02 to 0.16]	0.10 [0.05 to 0.15]	0.14 [0.06 to 0.23]
Total including land water storage	**1.0 [0.5 to 1.4]**	**1.8 [1.3 to 2.3]**	**2.8 [2.1 to 3.5]**
Residual[c]	**0.5 [0.1 to 1.0]**	**0.2 [–0.4 to 0.8]**	**0.4 [–0.4 to 1.2]**

Notes:

[a] Data for all glaciers extend to 2009, not 2010.

[b] This contribution is not included in the total because glaciers in Greenland are included in the observational assessment of the Greenland ice sheet.

[c] Observed GMSL rise – modelled thermal expansion – modelled glaciers – observed land water storage.

Figure 2.3 shows the breakdown of the different contributors of sea level rise from observations and models (Pachauri et al., 2014).

2.5 Regional sea level

As for changes in the sea level, the local picture is much more complicated. Fluctuations in the sea level are never uniform and would vary at different sections of the coastline. This has been strongly supported by data from satellites whereby the variations are not constant. The altimetry data from TOPEX/Poseidon and JASON has been analysed in a few studies and it was concluded that there were strong regional variations in the sea level (Willis, 2010). For example there has been an accelerated increase in the sea level in the western Pacific ($3mmyr^{-1}$) (Pachauri et al., 2014). On another note, there has been a drop in the level of the ocean in the eastern Pacific ocean since 1993 (Pachauri et al., 2014). Such variations are often caused by processes such as the El Nino and the Pacific Decadal Oscillation (Pachauri et al., 2014). Through the intensity of surface winds and sea currents, this results in influencing the sea level causing a drop or a rise.

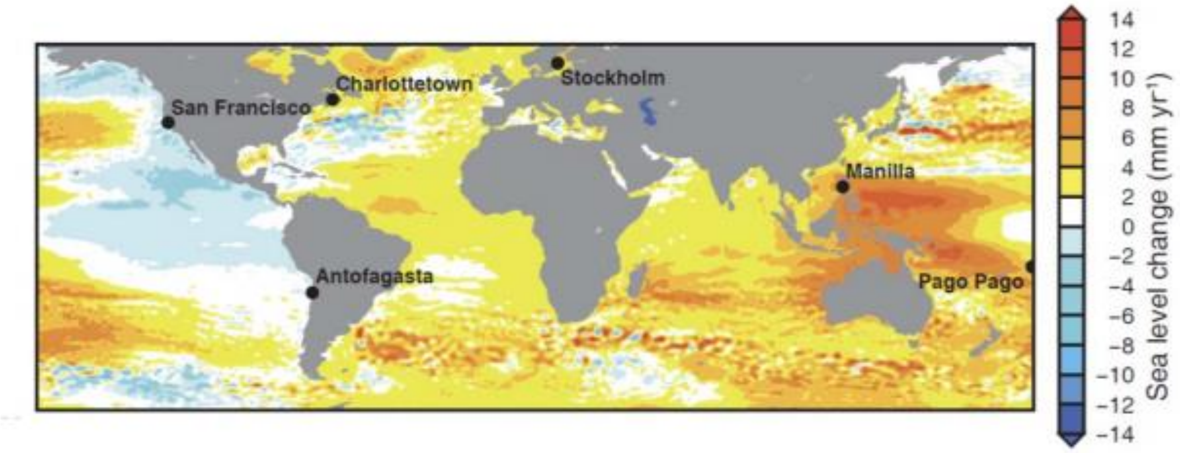


Figure 2.4 regional changes in sea level (Panchauri et al, 2014)

2.6 Sources for local sea level

On the local scale, there are several contributing factors which can lead to variations in the sea level. Some of them include tidal variations, incoming freshwater from estuaries and other water bodies, storm surge and tsunamis.

Tides remain one of the major sources for short term changes in the sea level. Through the gravity exerted by the moon and the sun onto the rotation of the planet, this leads to ongoing rise and drop in the sea level. The impact of tides can vary at different shoreline and is known to affect the shipping and the fishing industry mostly. Local sea level is also affected by the input of water from estuaries, wetlands and lakes. The majority of the rivers end at the shoreline and often this additional volume of water can lead to a flooding event. Storm surge is another source which can disrupt the sea level. Storm surges are normally associated with the low pressure systems (mid latitude cyclones or tropical cyclones). These waves can be highly destructive and cause loss of lives (Munasinghe, 2007).

Figure 2.5: Flooding by storm surge Katrina (courtesy of U.S. Coast Guard)

Other destructive waves include tsunami wave. This type of wave is a seismic sea wave which can also cause extreme wave heights often exceeding 10 metres. Such destructive waves are generally caused by earthquakes, impact of meteorites or volcanoes and are known to trigger the movement of large volume of water towards the shoreline. It is reported that about 230,000 people died due to the Indian Ocean tsunami in 2004 (Munasinghe, 2007).

2.7 Pathways

Pathways are the means through which the changes in sea level can impact receptors. Pathways could also be a result from several sources and could damage a wide range of receptors. In this model, we identified inundation, flooding, erosion and intrusion of the sea as the pathways of action. Inundation occurs from a long term rise in the mean sea level. It is mainly caused by thermal expansion and melting of glaciers and causes permanent changes to the coastline. Flooding is a short-term pathway and occurs mostly at a local scale. Flooding can be triggered from several sources such as storm surge, tides and tsunamis and can be highly detrimental to the shoreline. Other pathways also include erosion and the intrusion of seawater into the water bodies.

2.8 Receptors

The main receptors of sea level rise included beaches, inhabitants, some marine species, reclaimed land, properties, waterfront structures, water pipes, water bodies, stormwater pipes, sewerage pipes, the road network, electricity line, vegetation and some of the protective buffers. Beaches including exposed sandy shorelines, sheltered beaches, rocky shores, bays and estuaries are usually the most vulnerable land cover through the different pathways such as coastal flooding, permanent inundation, seawater intrusion and coastal erosion.

2.9 Projections

Predicting the exact rise in sea level for a particular time period still remains challenging. However models have greatly improved during the last decade in providing more accurate estimates of future sea level based on the rate of increase in temperature. For instance, the 2001 third Assessment report of the IPCC stated that the sea level would rise from 0.2 to 0.7m by 2100. A few years later, the 2007 fourth assessment report has then reported an increase from 0.18 to 0.59m for the same time period. The latest report from the IPCC used 4 scenarios, the RCP scenarios to estimate sea level rise by the year 2100.

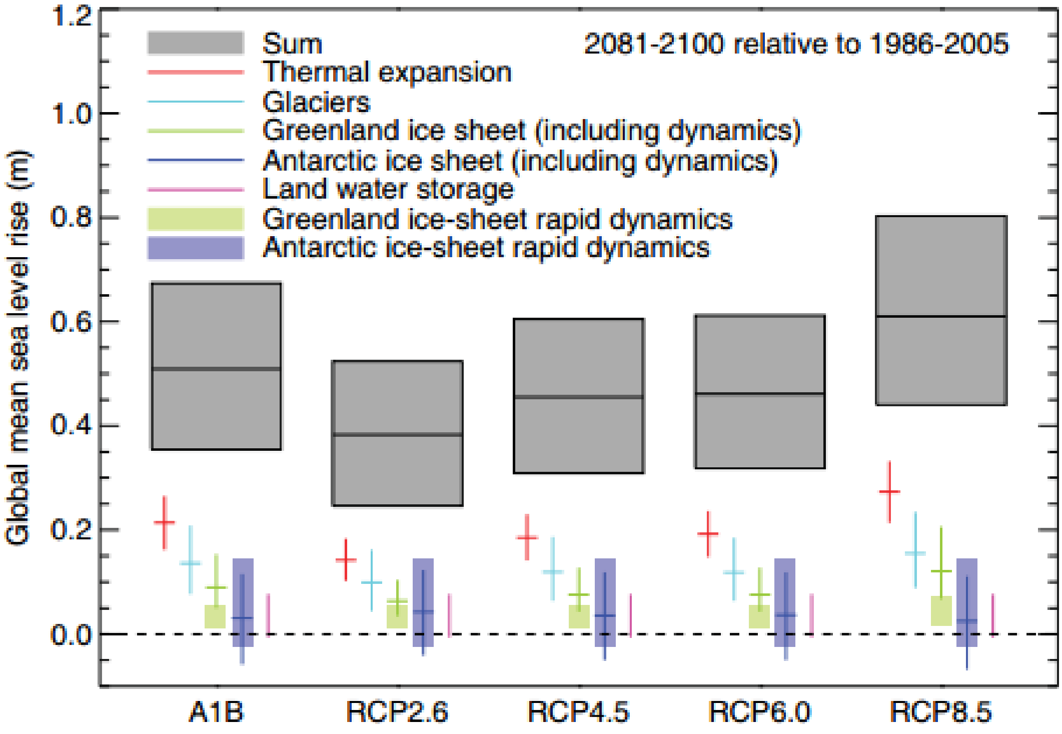


Figure 2.6: Projections of sea level rise based on scenarios from the IPCC (Panchauri et al, 2014)

According to the 5th assessment report of the IPCC, RCP 2.6 is the best case scenario and would cause a rise of 0.40 [0.26 to 0.55] m while the worst case scenario, RCP 8.5 is expected to cause a rise of 0.63 [0.45 to 0.82] m for the period of 2081-2100. RCP4.5 and RCP6.0 are relatively alike towards the end of 2100 and would result in a rise of 0.47 [0.32 to 0.63] m and 0.48 [0.33 to 0.63] m respectively, although RCP4.5 is known to have a higher rate of increase earlier during the century compared to RCP6.0 (Pachauri et al., 2014).

However Rahmstorf et al. (2007) pointed that the rise in sea level from the RCP scenarios should be considered as a conservative value. This is because the models from the IPCC did not consider much contribution from Greenland and Antarctic ice sheets as the scientists strongly believe that Antarctica would be gaining more mass from snowfall. However, it has also been speculated that its melting rate has increased considerably and this would lead to a higher increase in sea level. This debate has led to range of projections of sea level rise for the year 2100.

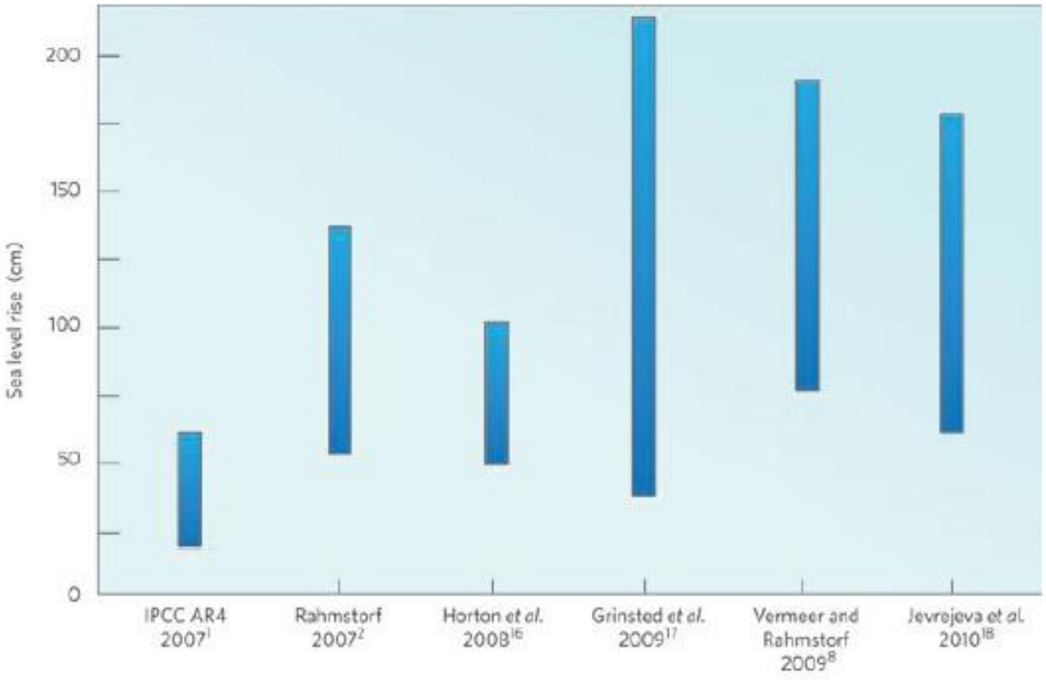


Figure 2.7: A large range of estimates of sea level rise from semi-empirical models compared to the model from IPCC Fourth assessment report.

Chapter 3: Study area

Sea level rise has been recognized as a global risk. However in this study we focused on how it affected one particular study area. In this chapter, we listed some of the previous local sea level rise research which were carried out in that region and based on the Source Pathway Receptor model, we described the main different sources, pathways and receptors for this particular region.

3.1 Chosen city

Figure 3.1: Cape Town, capital of South Africa (Google earth, 2015)

Cape Town, one of the capitals of South Africa was the chosen study area in this study. Much of the 307 km of coastline is a valuable asset in the tourism and economic sector as it provides a wide variety of social and commercial activities. But the coastline is highly vulnerable to considerable changes in the sea level mostly due to its wave climate and extremes in tidal effects. It must also be noted that the level of vulnerability varied at different areas as the coastline consisted of different types of environment, e.g sandy beaches, sheltered bays, rocky shores and reclaimed areas. In 2003, a Coastal Zone Management Strategy was adopted by the City of Cape Town in order to manage and protect the coastline for the present and future generations, and there has been a high emphasis on the need to research the impacts of sea level rise along the city's coastline.

3.2 Sea level rise in Cape Town, South Africa

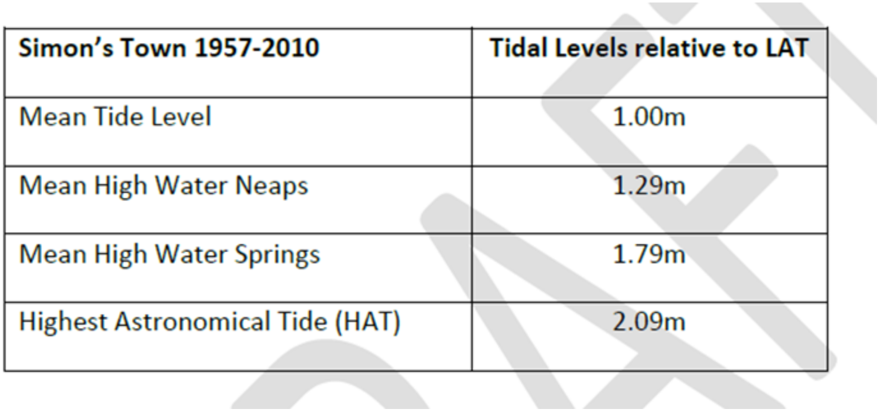
As mentioned in section 2.2, there was not much technology available to study sea level rise (Willis, 2010). Earlier sea level rise studies started gradually in the 1980s whereby Brundrit (1984) conducted a basic assessment of the west coastline of South Africa. Despite an increase in detailed studies conducted in the 1990s, the catalogue for the South African sea level records remained inadequate and the dataset was poor in quality.

During the last decade, there have been some improvements in understanding sea level on the local scale. Mather et al. (2009) worked on a detailed assessment of the entire tide gauge data collected over a span of 50 years across the South African coastline and this assessment showed that the sea level has varied considerably ranging from 0.42 mm per year along the western side of the coast, to 3.55 mm per year at the eastern side of the coast and 1.97mm per year along the southern side.

Following the Source Pathway Receptor model, we identified that changes in sea level could be attributed to two main sources, namely tides and storm surges.

3.3 Sources

Local sea level is often affected by tidal effect on a daily basis as well as fortnightly, seasonally and annually. Tidal variation is usually easily forecasted and the changes are relatively uniform in Cape Town. In False Bay, tidal effect can cause a rise of 0.3 m at a neap tide and 1.9 m at a spring tide (Giljam, 2002). However there have been events in the past where the tidal effect has led to extreme wave conditions.



Simon's Town 1957-2010	Tidal Levels relative to LAT
Mean Tide Level	1.00m
Mean High Water Neaps	1.29m
Mean High Water Springs	1.79m
Highest Astronomical Tide (HAT)	2.09m

Fig 3.2: This table shows some records of some extreme conditions of sea levels at Simon's Town (Theron et al, 2010)

On the contrary, Storm surges are unpredictable. With the presence of synoptic weather systems, this often leads to storm surges to occur and this causes the sea level to increase higher than the average level if there are air masses of low pressure. Such frontal systems normally last for 2-3 days. However sometimes these wave heights can reach their peaks and cause much heavy flooding and are highly detrimental for the coastline.

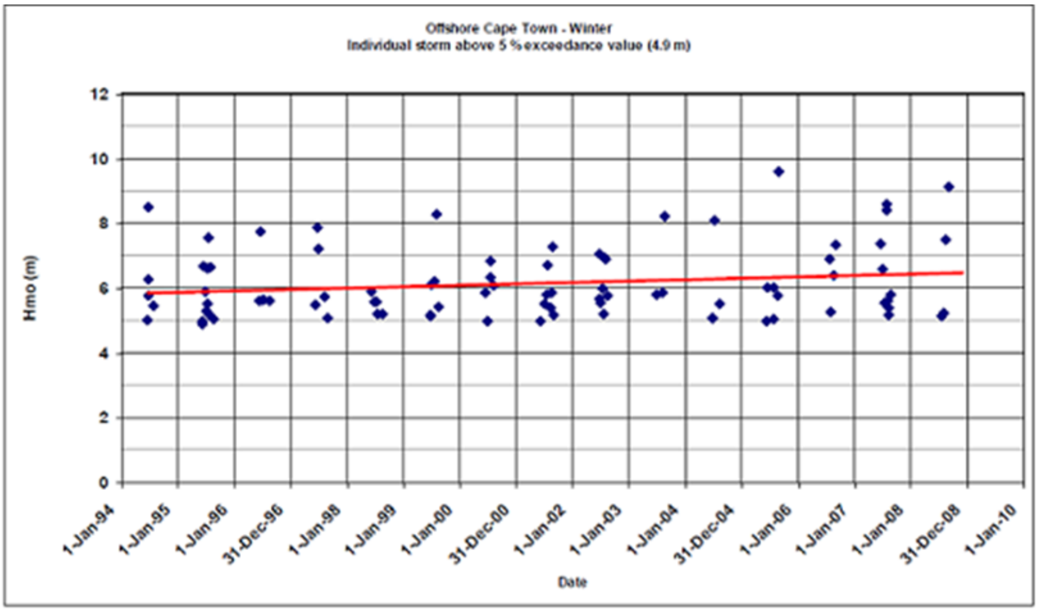


Figure 3.3: extreme wave heights for winter in Cape Town (Theron et al, 2010)

The figure above represents the highest wave heights recorded during storms during winter over a time period of 14 years. These wave heights seem to follow a similar trend, with a gradual increase of 0.5m (Theron et al, 2010) However it was noted that the extreme wave heights tend to follow a decreasing trend in summer (Theron et al, 2010).

3.4 Pathways and receptors in Cape Town

The three main pathways which were identified were inundation, flooding and erosion. And as for the receptors in the city, beaches were identified as the most vulnerable land cover. Other receptors also included the inhabitants, the properties, reclaimed land, the road network, water bodies and electric cables. Changes in sea level have previously proven to be highly detrimental to the properties and roads located within a close proximity to the shoreline. As for reclaimed areas, variations in the sea level would affect regions whereby the land has been previously reclaimed. Waterfront structures are also known to be highly vulnerable to the impacts of sea level rise since they are exposed to the wave action.

Chapter 4: Literature review

4.1 Merging cartography and coastal oceanography

Studying sea level rise entails not only oceanography, but so many other fields such as geology, geomorphology, climatology, and glaciology etc. It is highly interdisciplinary as it is a phenomenon which is caused by different types of events and threatens a range of aspects. As identified earlier in the 2nd and 3rd chapter, we had previously relied on a Source-Pathway-Receptor conceptual model for long term planning as it could display the direct link between each component. However, exploring this conceptual model and identifying the different sources, pathways and receptors for the city of Cape Town would still not allow us to assess the vulnerability of the coastline as such models fail to illustrate the spatial relationships among each component.

For the purpose of this study, we needed to explore other methodologies from other fields which could capture the spatial link between the three sources and allowed us to visualize the impacts of sea level rise spatially. This required the merging of two important fields i.e coastal oceanography and geomatics. Through geomatics, a wealth of different tools has been studied to assist in creating maps (Sutherland, 2012). Coastal oceanographers relied on tools from geoinformatics, remote sensing and photogrammetry and worked on creating sea level rise maps in order to assess the vulnerable areas of a coastal region. Through these maps, the inundated areas could be located and an assessment of the different impacts could be carried out (Gesch, 2009; Mcleod et al, 2010; Yin et al, 2011).

Earlier, the idea of making sea level rise maps was not familiar (Winterbotham, 1934). In fact coastal oceanographers did not actually show much interest in the topic of sea level. Instead, it was mostly geologists and geophysicists who started exploring the previous fluctuations which have been occurring in our oceans during the ice ages. The concept of sea level spread among scientists until it eventually became widely accepted that anthropogenic factors partly contribute to changes in the volume of the ocean.

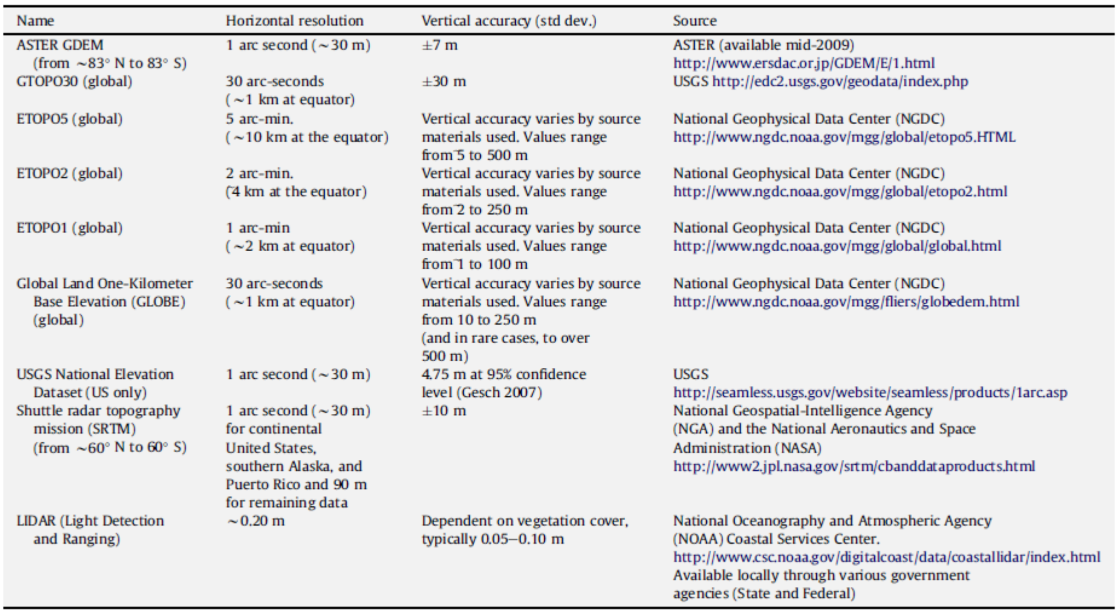
Nowadays, coastal oceanographers make use of different geographic information systems to produce coastal inundation maps with varying resolutions in order to visualize the future changes along the coastline. The current state of the literature is dichotomized by a wide range of approaches. Some of the tools varied in the design phase of the sea level rise scenarios while other studies highlighted the different approaches adopted in the post processing phase in order to generate the quantitative results of the impacts of sea level rise. However most studies shared a common approach: Researchers relied on coastal inundation models and calculated the area which will be flooded based upon a particular scenario of changes in the sea level. There are different types of coastal models and some of them include inundation models using a GIS framework, SLAMM, DIVA, SimCLIM etc. All these models make use of topographic maps to locate the Potential Inundated Areas (PIAs) whereby they are defined as the zones which remain below a set elevation contour. Moreover, the literature also is divided according to the scale of analysis. Some studies were narrowed down to a smaller geographical scale and the focus of the impacts was more specific and detailed while some researchers chose to zoom out and investigated how changes in the sea level would affect the coastline on a global scale.

4.2 Modelling coastal inundation using a GIS framework

In the design phase of the sea level rise scenarios, the majority of researchers made use of a GIS framework and adopted the simple ‘bathtub’ method (also known as the ‘zero-side rule’) whereby if the height value was less than the value of the predicted sea level, the grid cell was assigned to be inundated (Gesch, 2009; Mcleod et al, 2010; Yin et al, 2011). The ‘bathtub’ method also consisted of additional rules which were applied. For instance, the grid cell was inundated only if it was located next to another grid cell which was already inundated or open water. This is why the use of elevation data is highly instrumental in determining the area of possible inundated coastal regions. Looking back at the literature, researchers have shown how coastal elevation datasets in the form of DEMs have proved to be a successful element in the delineation of inundated areas (Gesch, 2009).

4.3 DEM

DEMs are height models of a surface which are obtained through a range of techniques, namely land surveying, photogrammetry, remote sensing and LiDAR. From the literature, it was found that sea level rise studies have been done by using a variety of different types of DEMs (Gesch, 2009, Mcleod et al, 2010).



Name	Horizontal resolution	Vertical accuracy (std dev.)	Source
ASTER GDEM (from ~83° N to 83° S)	1 arc second (~30 m)	±7 m	ASTER (available mid-2009) http://www.ersdac.or.jp/GDEM/E/1.html
GTOPO30 (global)	30 arc-seconds (~1 km at equator)	±30 m	USGS http://edc2.usgs.gov/geodata/index.php
ETOPO5 (global)	5 arc-min. (~10 km at the equator)	Vertical accuracy varies by source materials used. Values range from ~5 to 500 m	National Geophysical Data Center (NGDC) http://www.ngdc.noaa.gov/mgg/global/etopo5.HTML
ETOPO2 (global)	2 arc-min. (~4 km at the equator)	Vertical accuracy varies by source materials used. Values range from ~2 to 250 m	National Geophysical Data Center (NGDC) http://www.ngdc.noaa.gov/mgg/global/etopo2.html
ETOPO1 (global)	1 arc-min (~2 km at equator)	Vertical accuracy varies by source materials used. Values range from ~1 to 100 m	National Geophysical Data Center (NGDC) http://www.ngdc.noaa.gov/mgg/global/global.html
Global Land One-Kilometer Base Elevation (GLOBE) (global)	30 arc-seconds (~1 km at equator)	Vertical accuracy varies by source materials used. Values range from 10 to 250 m (and in rare cases, to over 500 m)	National Geophysical Data Center (NGDC) http://www.ngdc.noaa.gov/mgg/fliers/globedem.html
USGS National Elevation Dataset (US only)	1 arc second (~30 m)	4.75 m at 95% confidence level (Gesch 2007)	USGS http://seamless.usgs.gov/website/seamless/products/1arc.asp
Shuttle radar topography mission (SRTM) (from ~60° N to 60° S)	1 arc second (~30 m) for continental United States, southern Alaska, and Puerto Rico and 90 m for remaining data	±10 m	National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA) http://www2.jpl.nasa.gov/srtm/cbanddataproducts.html
LIDAR (Light Detection and Ranging)	~0.20 m	Dependent on vegetation cover, typically 0.05–0.10 m	National Oceanography and Atmospheric Agency (NOAA) Coastal Services Center. http://www.csc.noaa.gov/digitalcoast/data/coastallidar/index.html Available locally through various government agencies (State and Federal)

Figure 4.1: Variety of DEMs used in sea level rise assessments (Mcleod et al, 2010)

Some DEMs are more appropriate for a larger geographical scale, while some are more suitable for highly accurate maps. Generalized DEMs are usually used at a global scale. Some of these DEMs include the National Elevation Dataset (NED) which was created by the U.S Geological Survey (USGS). Since it is available for free, this dataset has been used in many studies to assess the vulnerability of the shoreline. For instance, Weiss et al. (2011) investigated how a rise of 1-6m would affect the coastline of the U.S at different regions by producing sea level rise scenarios by using this elevation dataset. Despite having a coarse horizontal resolution of 30m, it was suitable for reporting PIAs at a national scale.

Other elevation datasets include the SRTM data which was created by NASA and it remains one of the most accessible elevation datasets. It has a spatial resolution of 30m and covers any region between 60N and 56S latitude. But it is not recommended to be used in a local or regional scale due to its coarse resolution. Onwuteaka (2014) used SRTM datasets to identify the vulnerable areas along the Nigerian coastline. Several scenarios of sea level rise were generated ranging from 1m to 13m and reported that it would cause a loss of dry land ranging from 392 km² to 1154km². In this study, the SRTM was chosen as it was easily accessible. However due to the coarse resolution and the exaggerated rise in sea level, these findings should only serve as a loose estimate of the potential impacts in Nigeria.

Generally these DEMs tend to over or underestimate the PIAs when they are being used in a sea level rise assessment. Shortridge (2006) highlighted that SRTM dataset would overestimate the height constantly with a particular land cover type. Customized DEM have higher spatial resolution and provide better estimates. Ward et al. (2011) conducted a rapid assessment of the coastline of Jakarta and used a DEM of a spatial resolution of 5m to assess the vulnerable areas. This study was useful in highlighting the land subsidence problem of the area. Since they were investigated scenarios ranging from 0.5m to 6m, this DEM was considered appropriate and reliable for this study.

4.4 High resolution elevation datasets

Over the years, accuracy has been recognised as one of the major determining factors in the design of sea level rise scenarios. There has been a high demand for more accurate maps. Hence, coastal oceanographers have opted for a shift in the height models during the last decade. With increasing progress in photogrammetry and remote sensing, researchers are able to design maps of finer resolution by making use of DEMs derived from airborne light detection and ranging (Lidar) remote sensing.

4.5 LiDAR

LiDAR is an application of remote sensing which makes use of laser light to sample the ground surface of a terrain and measures the elevation. It is mostly used in airborne laser mapping applications and is currently being regarded as a more cost-effective option compared to previous surveying methods e.g photogrammetry. Through LiDAR, we obtain point cloud data which can be processed into DEMs.

This particular approach allows users to acquire elevation data for more defined objects such as trees, shrubs and buildings. This section highlighted the major benefits of a fine resolution DEM with its great spatial accuracy through some of the studies listed below and outlined how this technology allowed for significant improvement in modelling inundation from hypothetical increases in the sea level.

As for the Swedish context, Ebert et al.(2016) used LiDAR datasets to create a DEM so that they could assess the impacts of sea level rise on the island of Gotland in Sweden. They chose to produce a DEM of a spatial resolution of 2m due to the average point spacing which was approximately 0.5-1point per m^2. However they generated only one scenario of a rise of 2m in their study and hence, due to the lack of a range of scenarios, these findings should not be regarded as reliable results.

Herberger and al. (2011) investigated a rise of 1.4 m along the Californian coastline in order to calculate the number of people affected by sea level rise and the cost of damage of inundated properties. Unfortunately, Lidar data was not easily accessible. In this case, Herberger and al. (2011) worked with lidar data only for a section of the coastline and had to rely on other DEMs such as the USGS National Elevation dataset and the Interferometric Synthetic Aperture Radar (IfSAR) data to fill in the gaps. Despite using coarser spatial resolution for some areas, this did not entirely affect the results of the study. If the study area is located on a lower elevation, very fine resolution DEM datasets are not compulsory in determining the inundated areas.

Jurado and Zujar (2013) chose the Bay of Cadiz in Spain as the study area and demonstrated how the vertical accuracy of DEMs could make a possible impact for the current conditions of sea level and the predicted high tide for the year 2100. In order to assess their performance, Jurado and Zujar (2013) chose to make use of DEMs which had the same spatial resolution. The first DEM was a traditional DEM derived through aerial photogrammetry while they adjusted the spatial resolution for the second one by filtering a LIDAR-derived DEM. Both DEMs had a spatial resolution of 10 metre but a Root Mean Square Error (RMSE) of 0.68 and 0.205m respectively. They observed an overestimation of the PIA by 72% for the current conditions of sea level and 26% for the changes in sea level in year 2100 from the traditional DEM. Their study clearly showed that LiDAR-derived DEM could provide a better estimation of the location of the inundated areas.

Producing sea level rise maps from LiDAR derived DEMs would portray the results with more confidence due to its fine spatial resolution and high precision of vertical accuracy. During the last decade, due to the growing demand for increased accuracy, coastal oceanographers chose to opt for LiDAR derived DEMs especially when important decisions need to be taken by the government. Unfortunately, as mentioned in a few studies above, Lidar dataset is not always available for every geographic location. Such DEMs also take up more computer memory and need much more processing time, especially if the study area consists of a larger region. Another common drawback is that Lidar dataset is very costly. Nevertheless some studies have demonstrated that sometimes Lidar datasets can be successfully assembled to other lower resolution DEMs in order to obtain a better geographical coverage for the study area and hence providing a more accurate map of coastal inundation while reducing the computational cost.

4.6 Other coastal inundation models

A common benefit of making use of these inundation models is that the computational cost is relatively lower. These models only need a GIS software and an elevation dataset in order to run the sea level rise scenarios (Mcleod et al, 2010). These models are also known to provide fast results as most of them rely on free available DEMs and hence this proves to be very useful in cases whereby there is an urgent demand from decision makers and policy makers regarding setback limits and upcoming construction plans.

Despite the rapid assessment of vulnerability, we need to be careful during the interpretation of the results and we cannot ignore the limitations of these elevation datasets. For instance the wetlands surface is known to keep pace with the changes of the sea level through soil building (Mcleod et al, 2010). But these methods do not account for wetland accretion in such inundation models as they fail to create the link between the dynamic geomorphic processes and the fluctuations in the sea level. Inundation models are also restricted by uncertainties due to predictions of the sea level, elevation datasets, inaccessibility of data on the transport of sediments, and failure of integration of feedbacks among the biological, physical, ecological, geomorphic and social systems. For instance inundation models cannot consider the human-adaptation responses (Mcleod et al, 2010). They produce an overestimation of the actual results when they fail to take the water connectivity into consideration.

There is a variety of other approaches which can be adopted to generate sea level rise scenarios. Researchers can also resort to other coastal inundation models based on the demand of their study. Some of them include the SLAMM model, DIVA model, the BTELSS model, SimCLIM model and a few others.

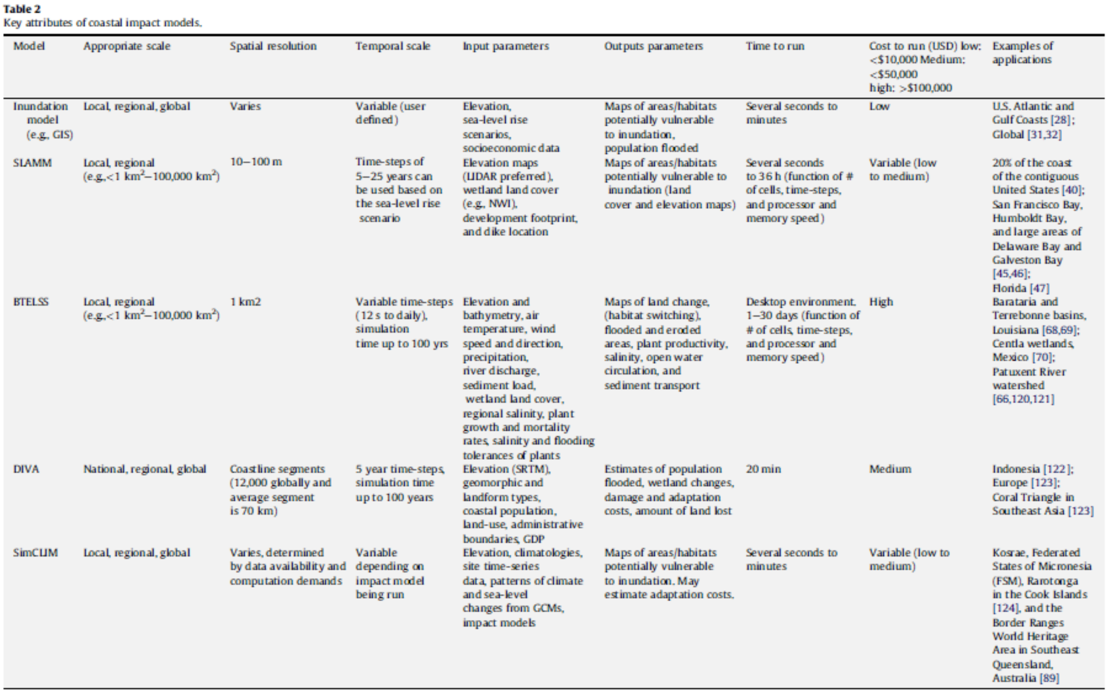


Table 2
Key attributes of coastal impact models.

Model	Appropriate scale	Spatial resolution	Temporal scale	Input parameters	Outputs parameters	Time to run	Cost to run (USD) low: <$10,000 Medium: <$50,000 high: >$100,000	Examples of applications
Inundation model (e.g., GIS)	Local, regional, global	Varies	Variable (user defined)	Elevation, sea-level rise scenarios, socioeconomic data	Maps of areas/habitats potentially vulnerable to inundation, population flooded	Several seconds to minutes	Low	U.S. Atlantic and Gulf Coasts [28]; Global [31,32]
SLAMM	Local, regional (e.g.,<1 km^2–100,000 km^2)	10–100 m	Time-steps of 5–25 years can be used based on the sea-level rise scenario	Elevation maps (LIDAR preferred), wetland land cover (e.g., NWI), development footprint, and dike location	Maps of areas/habitats potentially vulnerable to inundation (land cover and elevation maps)	Several seconds to 36 h (function of # of cells, time-steps, and processor and memory speed)	Variable (low to medium)	20% of the coast of the contiguous United States [40]; San Francisco Bay, Humboldt Bay, and large areas of Delaware Bay and Galveston Bay [45,46]; Florida [47]
BTELSS	Local, regional (e.g.,<1 km^2–100,000 km^2)	1 km2	Variable time-steps (12 s to daily), simulation time up to 100 yrs	Elevation and bathymetry, air temperature, wind speed and direction, precipitation, river discharge, sediment load, wetland land cover, regional salinity, plant growth and mortality rates, salinity and flooding tolerances of plants	Maps of land change, (habitat switching), flooded and eroded areas, plant productivity, salinity, open water circulation, and sediment transport	Desktop environment. 1–30 days (function of # of cells, time-steps, and processor and memory speed)	High	Barataria and Terrebonne basins, Louisiana [68,69]; Centla wetlands, Mexico [70]; Patuxent River watershed [66,120,121]
DIVA	National, regional, global	Coastline segments (12,000 globally and average segment is 70 km)	5 year time-steps, simulation time up to 100 years	Elevation (SRTM), geomorphic and landform types, coastal population, land-use, administrative boundaries, GDP	Estimates of population flooded, wetland changes, damage and adaptation costs, amount of land lost	20 min	Medium	Indonesia [122]; Europe [123]; Coral Triangle in Southeast Asia [123]
SimCLIM	Local, regional, global	Varies, determined by data availability and computation demands	Variable depending on impact model being run	Elevation, climatologies, site time-series data, patterns of climate and sea-level changes from GCMs, impact models	Maps of areas/habitats potentially vulnerable to inundation. May estimate adaptation costs.	Several seconds to minutes	Variable (low to medium)	Kosrae, Federated States of Micronesia (FSM), Rarotonga in the Cook Islands [124], and the Border Ranges World Heritage Area in Southeast Queensland, Australia [89]

Figure 4.2: Different coastal impact model available (Mcleod et al, 2010)

4.61 SLAMM

The SLAMM model is a GIS based model targeted specifically for impacts of sea level rise on varying habitats such as wetland vegetation and tidal marshes. The model makes use of projections of sea level rise, tidal data from NOAA, wetland data, LiDAR and USGS DEMs as elevation datasets and can operate from a local to a regional level. For instance, Craft et al. (2009) used the SLAMM model to investigate how sea level rise would affect tidal marshes along the Georgian coastline in the U.S. They noted that there would be a loss of salt marshes by 20% and based on the mean and maximum projected rise from the IPCC scenario. However the SLAMM model is not able to incorporate feedback mechanisms. A common example would be if salt marshes were inundated, this would possibly lead to a rise in the macrophyte production and eventually it would eventually result into increased vertical accretion.

4.62 DIVA

The DIVA coastal model is another coastal inundation model mainly run by climatic and socioeconomic systems. The DIVA model provides a combination of the sea level rise scenarios with the effect of coastal erosion (direct and indirect), temporary flooding (e.g rivers), fluctuations in wetland habitats and intrusion of salinity into the water bodies (deltas and estuaries). DIVA has been useful in many assessments of sea level rise, for example Hinkel et al. (2012) used DIVA to generate 4 scenarios and reported that 16-27 million of people in 40 African coastal countries would be affected by a rise of 0.64 – 1.26m. This quantitative assessment contributed in estimating the most vulnerable regions despite its coarse spatial resolution.

4.63 BTELSS

BTELSS has also been useful in mapping sea level rise at a regional scale since this model is able to integrate several processes including coastal and estuarine hydrodynamics and wetland habitat changes. Martin et al. (2002) explored the impact of rising seas on the survival of Mississippi Delta marshes through the use of BTELSS model and based on a rise from 1.2 cm/yr to 2.2 cm/yr, the results from the BTELSS model revealed an increasing rate of 89.9% in the loss of tidal marsh in the Baratasin Basin. Martin et al, 2002 explained that delta marshes can hence rejuvenate with the contributions of sediment intake and act as a buffer against the action of waves.

4.64 SimCLIM

SimCLIM is another open framework which can operate at a local level as well as a global level. The size of the study area and the accuracy is defined by the availability of information and the computational demands of the study. SimCLIM can generate scenarios of coastal inundation which include the local components (for instance it takes into account the vertical land movement) and it can locate vulnerable areas through SimCLIM's custom-built GIS tools. Ramachandran et al. (2017) made use of SimCLIM and presented an assessment of the coastline in Tamil Nadu and Puducherry based on the 4 RCP scenarios of the IPCC for 2025, 2050, 2075 and 2100. This study's methodology was relatively new for the Indian coastline and was well accepted by the scientific community.

4.7 Choice of magnitude of rise in sea level

The choice of the inundation model and the choice of the elevation dataset can impact the level of accuracy in the design of sea level rise scenarios. However the main challenge still lies in the establishing of the magnitude of the rise in sea level. Coastal oceanographers ask themselves: how much will the level of the sea increase at a particular year? Unfortunately, there is no correct answer. Planning future sea level rise entails an uncertainty whereby we can only rely on sea level models to estimate the change in the ocean volume. However in the planning phase, the choice of the simulated height is a crucial task. This height will dictate the remaining quantitative results which will be considered highly instrumental at the stage of decision making for upcoming coastal development plans. In many cases, due to uncertainty in the future height of sea level and variations among different models, researchers chose to simply produce hypothetical sea level rise scenarios ranging from 1m to 10m. While in some cases, researchers relied on modelled wave heights and also addressed combined additional temporary effects such as tides and storm surges. In this section, we reviewed the choice of the simulated heights of a few studies and assessed how this choice played an important role in the assessment of the coastline.

Al Buloshi et al. (2014) investigated the impacts of sea level rise on the entire Omani coastal zone by generating 7 different scenarios (0.2m, 0.5m, 1m, 2m, 3m, 4m and 5m) from a DEM of 40m resolution and reported that the PIAs would range from 400 to 900 km^2. However due to the coarse resolution of the elevation dataset, these results could not be entirely reliable. It is also unlikely that the sea level would rise over 2m in the near future, hence these results should only be regarded as a rough estimate.

In the Chinese context, Yin et al. (2009) conducted a study of sea level rise along the coastline of Shanghai. They used high resolution LiDAR DEM to generate not only scenarios of sea level rise but they were also particularly interested in the impact of combined effects of sea level rise and temporary flooding such as tidal effect and storm surge effect. They relied on predicted values of tides and storm surges from models for the year 2030 and 2050 and calculated the impacts from the following equation:

T = RSL + SSL + ATL

where T represents the tidal effect, RSL the relative sea level rise, SSL the storm surge, and ATL the height of the astronomical tide.

This study proved to be particularly useful as it could delineate different land covers which would not be covered by the PIAs in the sea level rise scenarios but they would still be affected by temporary flooding.

Hinkel et al.(2013) also assessed the vulnerability of the coastline at a global level using a DIVA model and generated scenarios of sea level rise based on the scenarios from the fifth assessment report of the IPCC, namely the RCP 2.6, RCP 4.5 and the RCP 8.5. This study was particularly enriching as they generated the scenarios from 2 DEMs (GLOBE and SRTM) and compared the results. However earlier studies have shown reluctance in using the IPCC scenarios of sea level rise as these 4 scenarios vary widely from the minimum to the maximum. It is also suspected that the IPCC projections are an under-estimate of the actual rise in the sea level since they did not include dynamic ice melting processes. (Al-Buloshi et al, 2014)

4.8 Assessment of impacts of sea level rise

In the post-processing phase, much of the literature did not only present sea level rise scenarios but also calculated the impacts of sea level rise on different sectors such as tourism, infrastructure, vegetation, transport etc. Some studies chose to assess the global impacts on population and different land cover while other studies addressed the impacts at national or regional scale and focussed on a specific sector (Nicholls, 2002, Nicholls et al. 1999, Nicholls and Small 2002, Nicholls, 2004, Nicholls and Tol 2006). Each study differs on many levels, and currently there exists a wide range of tools to quantify these impacts.

In an inundation model using a GIS framework, most of the studies adopted a simple approach: the application of spatial overlay (Gesch, 2009). This particular tool proved to be highly instrumental in conducting assessments on different datasets by overlaying vector layers of sea level rise scenarios onto a particular dataset in order to explore how a rise in the sea level would affect this particular dataset. In the next section, some of these previous works are presented. These studies were classified based on their scale of analysis.

4.9 Investigation of global impacts of sea level rise

Firstly looking at the global scale, in the 1990s, there have been a few studies which have ventured out and investigated the global impacts of sea level rise. Nicholls et al, 1995 examined the impact on the global population and reported that an increase of 2 metres would affect 89 million inhabitants. However, this study would only concern a few developing countries due to lack of data. In the coming years, this has encouraged for more sea level rise studies at the global scale. Nicholls (2002), Nicholls et al. (1999),Nicholls and Small (2002), Nicholls (2004) and Nicholls and Tol (2006) relied on global elevation datasets in order to assess the global impacts of sea level rise by performing an overlay analysis. Nevertheless, these studies would still be deemed as unreliable due to a few limitations which were encountered. For instance they used global DEMs of coarse resolution and their studies would be based on the fact that the polygons indicating the countries would have a stable slope and the ones indicating the population would remain constant.

Recently Dasgupta et al. (2009) created sea level rise maps for 84 developing countries. They made use of the DIVA model so that they could explore the impact on the population. They stated that an increase of 1 metre would translate into a displacement of 56 million, while a rise of 5 metres could possibly attain a displacement of 245 inhabitants. The results acted as a good estimate however they were not entirely reliable. It was noted that the population dataset which was used in this research was subject to coarse spatial resolution. Hence this affected the accuracy of the results. Other limitations also included that the DEM could not cover the entire study area and this led to the manual digitising of the PIA for some regions.

Li et al. (2009) also investigated the impacts on population at the global scale. Through an overlay analysis, they stated that an increase in 1 metre would translate into a loss of 1.055km2 of land while it would also cause a displacement 108 million inhabitants. Their study also involved a spatial overlay onto different land covers and they reported that 60% of the forest and grassland would be potentially submerged. However they did not account for the impacts on a high water level and they failed to consider the existence of the current structures which protected the coastline from inundation. Nevertheless, this study still proved to be relatively reliable for using better elevation datasets and providing quantitative results on more than 1 receptor.

The DIVA framework has also been used for addressing global impacts of sea level rise. Nicholls et al. (2011) explored the global impacts of coastal inundation by making use of the DIVA model to compute the number of people displaced and the cost of damage. Their study highlighted an interesting point in their choice of the magnitude of projected change. They reported that they could not rely only on the models from the fourth assessment report projection of the IPCC as it might only be an underestimation when they investigated other projections from other sea level rise models. Hence they set out to calculate the impacts on population based on a rise of 0.5m and 2m and they reported that 53 – 125 million inhabitants would be displaced.

4.10 Regional impacts

As for a smaller study area, there exists a much wider range of assessments which have been conducted during the last two decades. Researchers chose to investigate the impacts of coastal inundation at a regional scale because impacts vary in different ways along different sections of the coastline. Detailed studies can also be conducted more accurately due to the easy availability of data in that particular study area. In this section, we presented the different methods which were adopted by a few regional studies in assessing the impacts on varying sectors such as population, tourism and infrastructure.

Several studies have targeted the impact on population, properties and infrastructure. For instance, Zhang et al. (2011) assessed the quantitative impacts of sea level rise on the population and properties in Florida Keys, United States. They used a LiDAR derived DEM and worked on a range of scenarios ranging from 0.15m to 1.8m. They performed a spatial overlay of the sea level scenarios onto the census blocks of the total population, and they recorded the total number of people for each block which intersected the polygons of the inundated areas. As for the property loss, they used the same approach of a spatial overlay in GIS. Since their study presented a range of scenarios using a high resolution DEM, this provided an accurate perspective of the magnitude of the impacts. However they relied on the population data from the 2000 census block to assess scenarios in the year 2100. Hence the interpretation of these results needs to be done carefully as they did not account for changes in the population value from the year 2000 to 2100. It also remained unknown whether some property parcels were entirely or partially inundated. In this case they added the property value for each property parcel lying in the inundated zones and ignored whether this could be an overestimation of the cost of damage.

Bin et al. (2011) also made use of a similar approach and generated sea level rise scenarios from a LiDAR derived DEM to investigate the value of property loss from four coastal counties in North Carolina, United States. They reported a total loss of $179 million for the year 2030 and $526 million for the year 2080. Similarly, this study explored 6 different scenarios for 2 different years and hence this allowed for a better assessment of the impacts. Nevertheless these results cannot be entirely reliable as this study only considered permanent inundation and did not take temporary coastal flooding into consideration. Storm surges and tidal effect could also potentially damage the residential properties. Another limitation of this study was that these results did not provide an overview for all the properties as Bin et al. (2011) did not take commercial and industrial properties into account.

Again in the American context, Tang et al. (2013) also assessed the impacts of sea level rise along the eastern bank of Delaware Bay in the United States. In fact their study consisted of a multidisciplinary approach whereby they explored how sea level rise will affect the population and the transport infrastructure in 10 and 50 years. However compared to Zhang et al. (2011), they did not rely on the current population data but instead they used an economic-demographic model to obtain the projected values of population. They also conducted a spatial overlay and calculated the length of inundated railroads and inundated roadways. Through the overlay analysis, they also identified bridges and traffic ways which would be potentially submerged. Another highlight of this study was that they incorporated the effect of temporary flooding such as storm surge into the sea level rise scenarios, hence these results turned out to be very reliable.

Some studies also focused on the impact on biodiversity. Fuentes et al. (2010) chose to explore the impacts on the northern Great Barrier Reef green turtle in Australia by looking at how increases in the sea level would disturb the nesting ground for their population. They relied on a GIS inundation model and performed an overlay analysis to calculate the potential nesting area based on three scenarios of the IPCC and a fourth scenario involving the melting of glaciers. Their study also calculated the effect of temporary flooding such as storm surges on these green turtles and reported that it would lead to a rise in egg mortality.

4.11 Sea level rise mapping in the province of Western Cape, South Africa.

In the local context, there have been many attempts of producing maps of coastal inundation along the coastline. Among the earlier studies, researchers produced contour lines with the current maps available. However with the recent breakthrough in remote sensing and photogrammetry, along with the development of high resolution models of sea level rise, they could assess the vulnerability and focus on the calculation of the impacts according to the different scenarios of changes in the sea level.

4.12 Earlier studies of sea level rise maps.

Hughes et al. (1991) developed an interest in mapping the coastline of False Bay and presented a hypothetical scenario whereby the sea level would be increased by 1 metre. Their study showed that it would cause coastal erosion ranging from 50 to 150 metres. This allowed them to conduct an assessment of the vulnerable areas by identifying the properties which would be affected by a 1 metre rise. Hughes and Brundrit (1992) also applied a similar technique to the coastline in Milnerton and predicted the impacts according to a rise of 1 metre. The coastal erosion would range from 60 to 140 metres. They highlighted that it would also affect the biodiversity in the Diep river since the level of salinity would increase. This would in turn affect the groundwater in the region.

Among the earlier studies, there have also been attempts of producing quantitative results of the impacts of sea level rise on the coastline of Cape Town. Hugues and Brundrit (1991) focused on Woodbridge Island to explore the impacts of permanent coastal inundation. From a hypothetical scenario of 50 cm, they performed an overlay analysis and reported that the beaches would undergo extensive erosion. They also added that 350 properties would be submerged.

Following this study, Hughes et al. (1993) designed a methodology for calculating the cost of damage of properties in Woodbridge Island and reported a loss of R131 million. They used the mean value of a property in Milnerton and multiplied it by the total number of potential inundated properties. As for the region of Muizenberg, Hughes (1992) made use of the same technique to calculate the impacts on properties based on a hypothetical scenario of 1 metre. The study concluded that 40 houses formed part of the potential inundated area and the cost arose to R20 million. Such studies are now considered preliminary but at the time, they contributed as a useful estimate for coastal planners.

4.13 Sea level rise maps during the last decade

During the last decade, the need for long term planning for the coastline of Cape Town arose even more after a storm surge event which occurred in Kwazulu Natal during March 2007. Cartwright et al. (2008) conducted a study whereby they mapped the vulnerable areas of Cape Town and calculated the PIA based on 3 different scenarios.

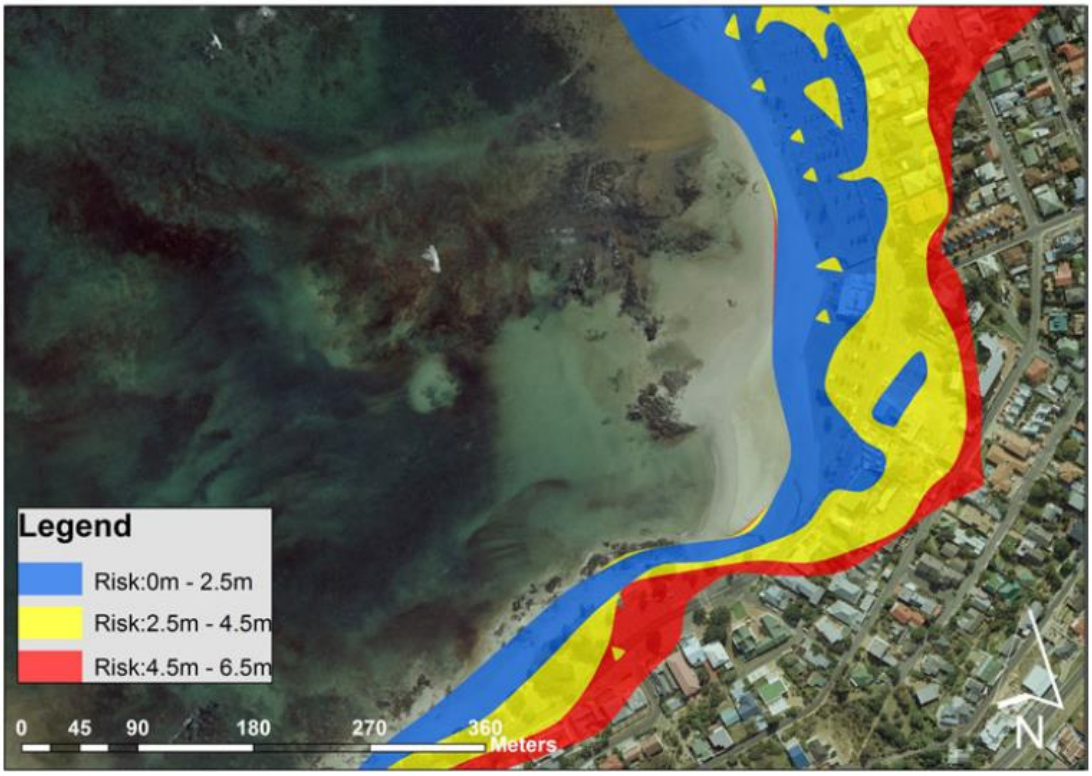
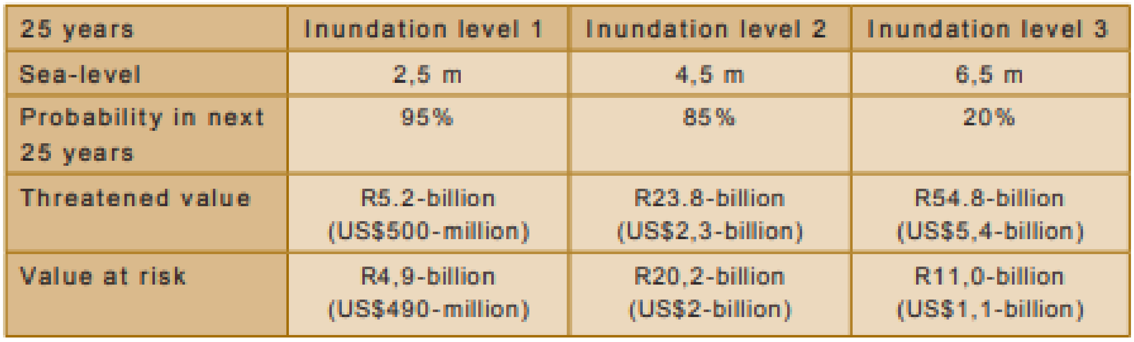


Figure 4.3: Sea level rise flood risk scenario for the coming 25 years (Cartwright et al, 2008)

They reported that the scenario 1 would cover an area of 25.1 km^2 temporarily whereby the first scenario involved a rise of 2.5 metres along a rocky coastline. They also investigated a rise of 4.5 metres in exposed areas (for example sandy beaches) and a rise of 6.5 metres in more vulnerable areas (for example sandy inlets). According to the model, the probability for scenario 1 to occur during the coming 25 years was 95%. As for the second scenario, it covered an area of 60.9 km^2 and the chances for this scenario to happen in the coming 25 years were assumed to be as high as 85%. And lastly, the third scenario was based on the melting of polar ice sheets whereby they calculated a loss of dry land of 95 km^2 in Cape Town.



25 years	Inundation level 1	Inundation level 2	Inundation level 3
Sea-level	2,5 m	4,5 m	6,5 m
Probability in next 25 years	95%	85%	20%
Threatened value	R5.2-billion (US$500-million)	R23.8-billion (US$2,3-billion)	R54.8-billion (US$5,4-billion)
Value at risk	R4,9-billion (US$490-million)	R20,2-billion (US$2-billion)	R11,0-billion (US$1,1-billion)

Figure 4.4: Estimates of the cost of damage for the scenarios (Cartwright et al, 2008)

They also presented the cost of damage of properties, infrastructure, electricity, stormwater and sewerage. Since this study was being conducted for the first time along the coastline of Cape Town, these maps acted as a rough estimate for developments plans for the year 2030 and allowed the coastal planners to have a better understanding of the current infrastructure at risk (Cartwright et al, 2008). Nevertheless, these findings were not reliable as these scenarios were far from the reality and a rise of more than 2 metres seems absurd for permanent inundation. Looking at models from previous studies, it is clearly shown that the global sea level would not happen before 2100. (Pachauri et al, 2014, Rahmstorf et al. 2007). Another source of unreliability was that their method of calculating the cost of damage was loosely based on estimates and probabilities.

Recently Faasen (2014) showed an interest towards the potential inundated properties in Cape Town and discussed the impact of a rise in the sea level in a few selected regions. But the core of the study was focused onto the coastal suburb located in the Atlantic Seaboard, Bakoven. Faasen showed that the properties in Bakoven would be highly threatened in the event of extreme flooding. It was interesting to note that this study included the different adaptation methods to the impacts of coastal inundation. In fact, there was a higher emphasis on the different techniques of adaptation which could be possibly adopted in these selected case studies.

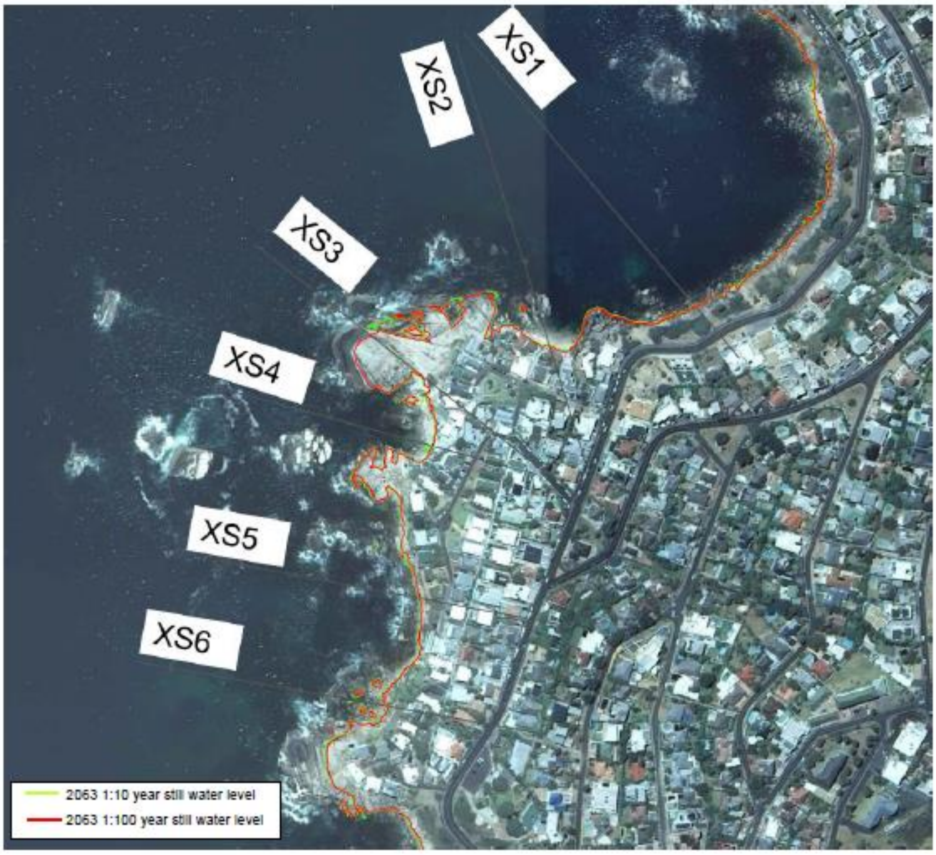


Figure 7-48: Bakoven 2063 Scenario 1:10 (green) and 1:100 year (red) extreme still water levels (National Geo-Spatial Information, 2010)

Figure 4.5: sea level rise scenario applied in Bakoven (Faasen, 2014)

Taukoor (2015) also made an assessment along the coastline of Cape Town and reported that Noordhoek, Muizenberg, Foreshore and Milnerton were among the most vulnerable suburbs with regards to coastal inundation. The main highlight of this study was that an overlay analysis was performed in order to calculate the PIA of the vulnerable properties, water bodies and coastal dunes. However this study was based on scenarios which were higher than 1 metre. The scenarios were also created from an elevation dataset of a spatial resolution of 10 metres. Hence these results were not considered to be entirely reliable due to its low accuracy.

Figure 4.6: Potential inundated properties in Muizenberg (Taukoor, 2015)

4.14 unexplored sectors

Such local studies have contributed greatly to our understanding of the vulnerable areas located along the coastline of Cape Town. However there still exist some aspects which need to be explored. Most studies have chosen to focus on the impact of properties but other sectors were not thoroughly investigated. For instance, the impact on transport in Cape Town was briefly covered by Cartwright et al. (2008). While the names of some of the potentially inundated roads were noted, there was no calculation which was carried out in terms of the length of inundated streets.

Earlier in this chapter, it has also been noted how numerous sea level rise studies have been conducted to estimate the potential number of inhabitants affected. Unfortunately such calculations have also not yet been done for the city of Cape Town. There is also a strong demand to investigate the impacts on beaches, coastal dunes, water bodies and vegetation.

There has been a brief mention of the impacts of these land covers by Cartwright et al. (2008), Taukoor (2015). But due to the lack of high resolution datasets, and the exaggerated rise of permanent inundation, the maps cannot be used as a reliable method. Nevertheless the three scenarios of 2.5m, 4.5m and 6.5m designed in the study conducted by the City of Cape Town have proven to be useful during the last decade by providing a rough estimate for future construction plans in the coastal suburbs.

Chapter 5 Methods

The purpose of this research is to locate PIAs from hypothetical scenarios of changes in the sea level along the coastline of Cape Town so that a risk assessment can be made. The initial section of the research was focused on answering the first research question, i.e identifying all the vulnerable areas based on a permanent increase of global mean sea level. In the second section of this chapter, we plan to explore 8 different coastal suburbs and quantify the indirect impact of changes in sea level on these particular areas. Each section consists of 4 phases, namely, the design phase, the pre-processing phase, the processing phase and the post-processing phase. During the design phase, we discussed the layout of the scenarios and the availability of the datasets. In the pre-processing phase, we focused on the processing of the raw elevation datasets and the refining of the simulated scenarios. The processing phase entailed the presentation of the maps and bar charts so that these results could be analysed. And finally in the post processing phase, we described the approach which was adopted in order to calculate the impacts of sea level rise.

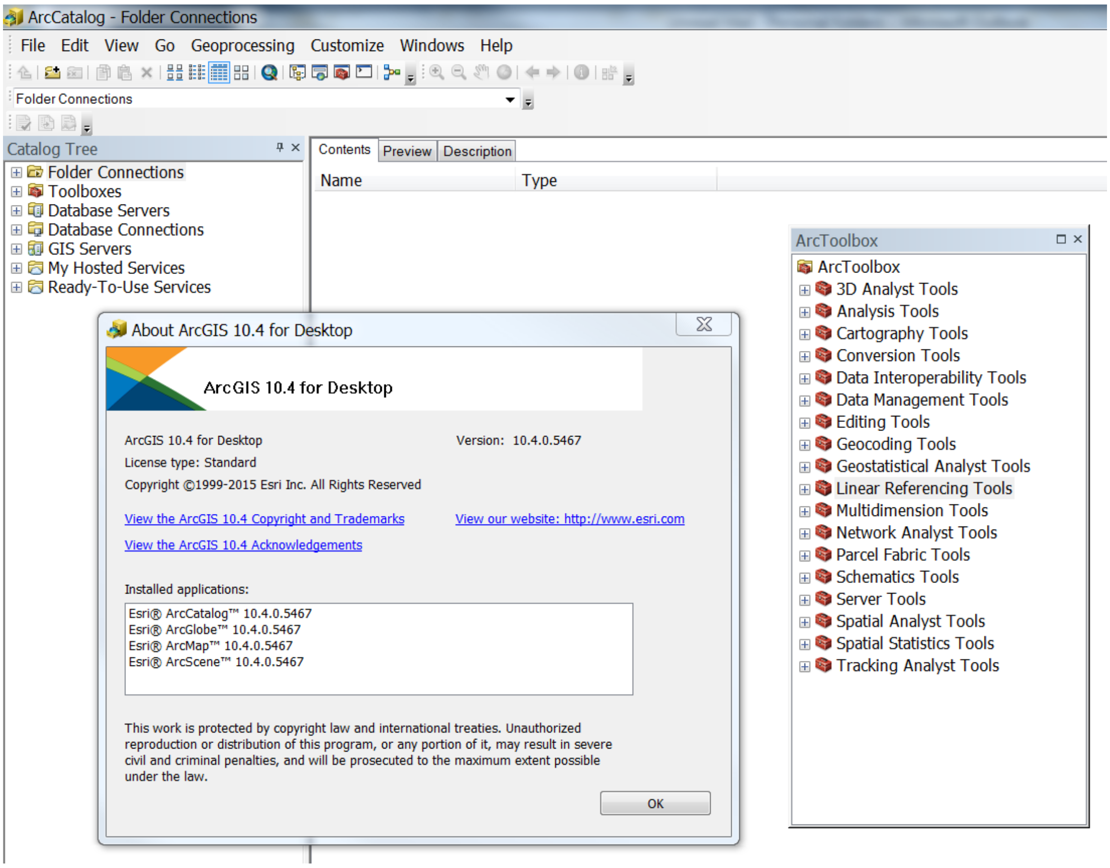
5.1 Design phase

5.11 Choice of the inundation model

As mentioned in the literature review, after having explored the different components in the Source – Pathway – Receptor model, we could capture the spatial relationship between the components through an inundation model and produce a map which would display the PIAs along the coastline. Ideally, we would prefer using a coastal inundation model which could capture all the inter-related dynamic biophysical and socioeconomic processes while it would not require much expertise, computational cost and processing time to operate but it would still produce reliable high resolution maps of sea level rise. Unfortunately, we need to compromise with some trade-offs as such studies are often restricted by financial and human resources and time constraints. For this study, it was more efficient to produce sea level rise maps by using GIS as it required limited human resources and low running costs.

5.12 Choice of software

A variety of software for GIS is available, e.g QGIS, ArcGIS, SAGA GIS, GRASS GIS. ArcGIS is one of the software that is available for users to create maps, manage their database and produce detailed spatial analysis through a range of tools available. In this study ArcGIS 10.4 would be an efficient choice to apply the bathtub method due to its wide selection of tools.



ArcGIS 10.4 for Desktop

Version: 10.4.0.5467

License type: Standard

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Installed applications:

Esri® ArcCatalog™ 10.4.0.5467
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Figure 5.1: Wide range of tools from Arc GIS 10.4

5.13 Choice of elevation dataset

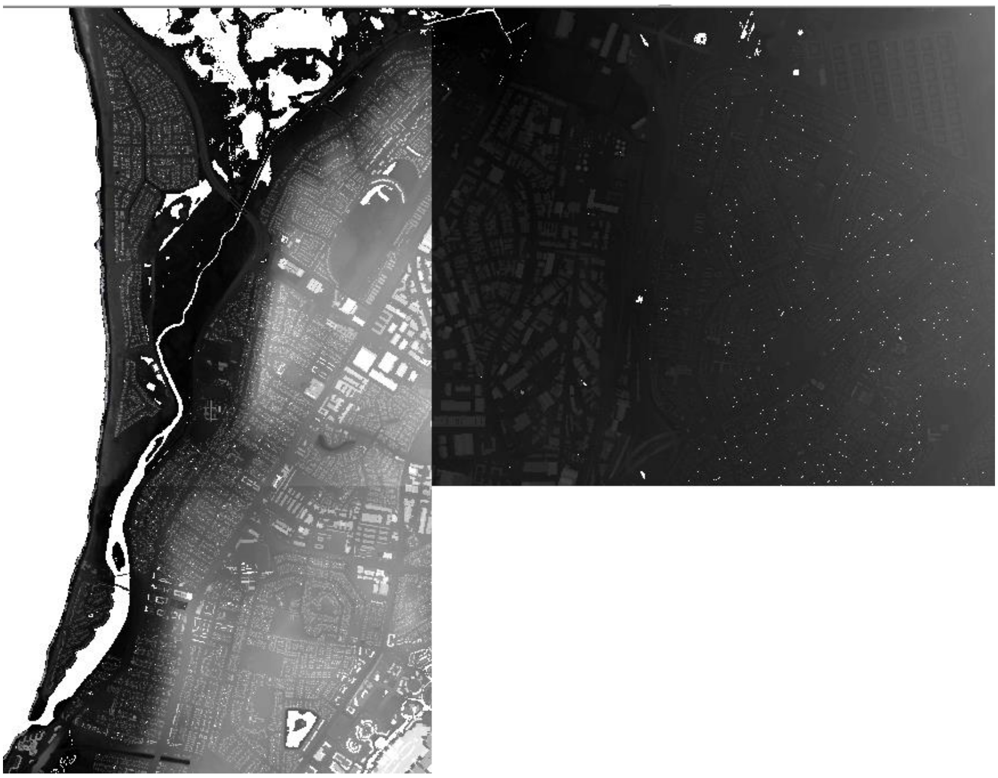


Figure 5.2: screenshot of a DEM

As mentioned in section 4.3, the choice of the elevation dataset is highly instrumental in these models. There are different types of DEMs and the choice is often based according to meeting the objective of the research. Sometimes the focus is on the high resolution of the maps or in some cases, researchers cannot rely on an expensive DEM or sometimes the study area involves a larger geographical cover and hence researchers must ensure that there is an availability of DEMs for their particular study. For the city of Cape Town, the available elevation datasets were the SRTM DEM, a 10m DEM from the City of Cape Town and LiDAR data. However in this study we disregarded the SRTM DEM due its coarse resolution.

5.14 LiDAR derived DEM

The average point spacing and the choice of the post processing software are the main factors which determine the quality of a LiDAR derived DEM. The point cloud data was obtained from the City of Cape Town during the year 2011 and 2014. In this study we made use of the Cloud Compare software to process the point cloud data. Cloud Compare is available for free and offers basic tools which allow the filtering of the raw LiDAR 3D point cloud. Through these tools, we were able to generate a DEM. A spatial resolution of 2 metres was preferred because of the average point spacing of the LiDAR data.

Since we worked with the entire coastline of Cape Town and LiDAR DEM takes up much computer memory, we needed to generate DEMs for different sections of the coastline before merging all the DEMs together into a single DEM.

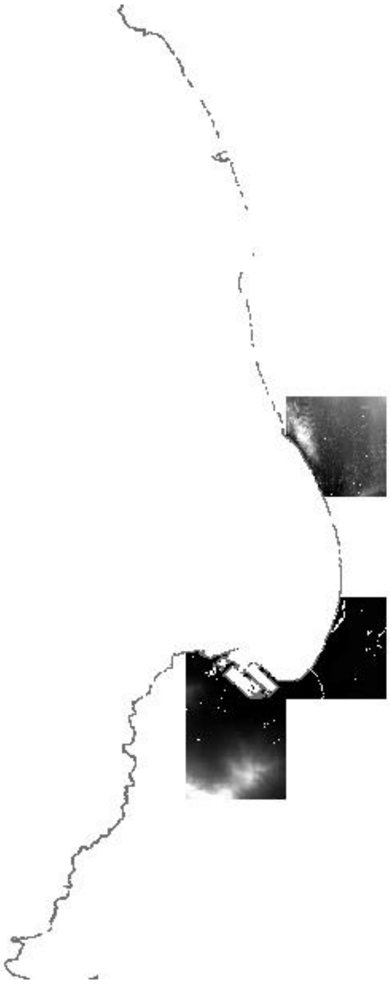
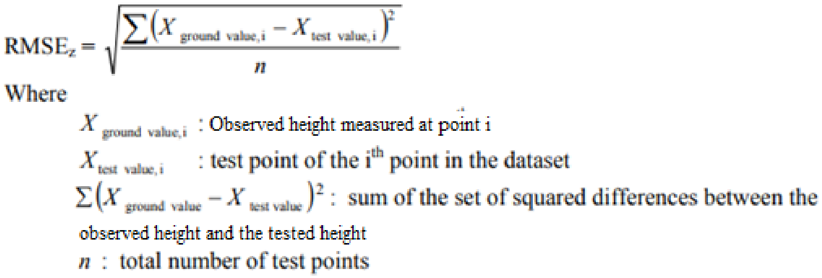


Figure 5.3: Assembling different DEMs together

5.15 Assessing the vertical accuracy of the DEMs

Accuracy was an important determining factor in this study and in order to make the right choice among the elevation datasets of varying spatial resolution it was required to calculate the vertical accuracy of the DEMs in order to measure the uncertainty of the elevation datasets,. The absolute vertical accuracy was assessed by calculating the vertical Root Mean Square Error (RMSE) value for the LiDAR DEM (2m) and the 10m DEM. The RMSE is a common method to express vertical accuracy of DEMs (Gesch, 2009)



$$\mathrm{RMSE}_z = \sqrt{\frac{\sum \left(X_{\text{ground value},i} - X_{\text{test value},i}\right)^2}{n}}$$

Where

$X_{\text{ground value},i}$: Observed height measured at point i

$X_{\text{test value},i}$: test point of the i^{th} point in the dataset

$\sum \left(X_{\text{ground value}} - X_{\text{test value}}\right)^2$: sum of the set of squared differences between the observed height and the tested height

n : total number of test points

We measured the elevation from the sea level at 10 different sites and compared the values from the LiDAR derived DEM and the 10m DEM.

	2m LiDAR DEM	10m DEM
Woodbridge island (beach)	0.3	1.12
Paarden Eiland (pier)	0.37	1.27
Foreshore (pier)	0.25	0.98
Sea Point (beach)	0.25	0.87
Camps Bay (beach)	0.5	1.42
Hout Bay (harbour)	0.4	1.1
Kalk Bay (harbour)	0.15	1.45
Simons Town (harbour)	0.5	1.37
Monwabisi (beach)	0.42	1.35
Strand (beach)	0.18	1.05

Figure 5.4: Elevation difference measured at 10 different sites

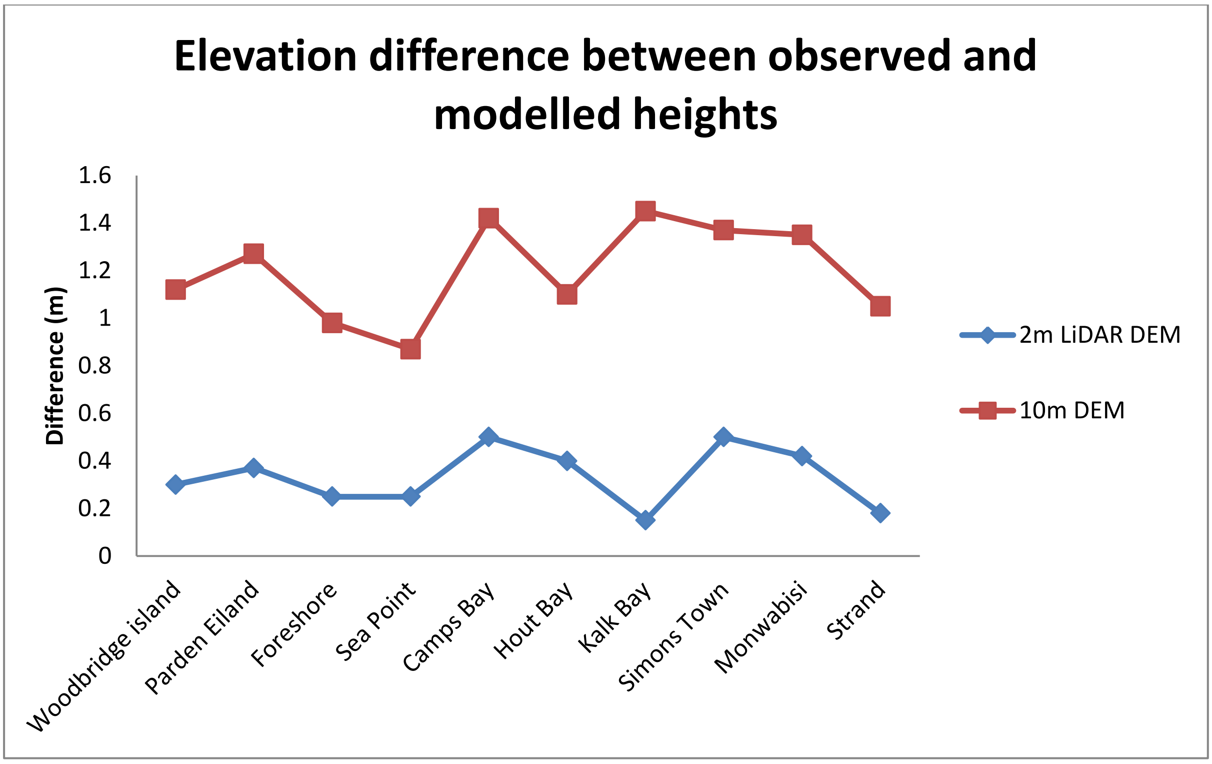


Figure 5.5: Graph of elevation difference between observed and modelled heights for 2m and 10m DEM.

At each site, the elevation difference was much higher for the 10m DEM compared to the LiDAR DEM. Using these elevation differences, we calculated the RMSE values for each DEM and found that the LiDAR DEM had a vertical accuracy of 0.35 m while the 10m DEM had a 1.21m.

Additionally, we also calculated the linear error (L.E) with a 95% confidence level for each DEM. This assessment is the metric adopted by the National Standard for Spatial Data Accuracy (NSSDA) to test the linear error of the DEM by using the following formula:

L.E. at 95% confidence = 1.96 * RMSE

From the calculations, the LiDAR DEM had a L.E. of ±0.69 at a 95% confidence level while the 10M DEM had a L.E. of ±2.38 at a 95% confidence level. Based on these findings, we decided to generate the sea level rise scenarios only from the LiDAR DEM as the results would be relatively more accurate and reliable.

5.16 Using models or historical data

The main challenge in mapping sea level rise scenarios lies in the decision of the increase of sea level. We have noted that some studies chose to use hypothetical values such as 1m, 2m, 5m, and some studies combined coastal flooding along with sea level rise and generated their scenarios. From the literature review, there were also studies that relied on global mean sea level rise projections and adopted these scenarios in their studies. There is a wide range of models available which predict the change in sea level. And in this study we chose to consider the 4 IPCC scenarios for the period 2081 to 2100 as they were considered as the most reliable models by oceanographers. The scenario RCP 2.6 would generate our best case scenario while the scenario RCP 8.5 involved a future whereby no actions have been taken to mitigate or adapt to climate change. RCP 4.5 and RCP 6.0 produced almost similar results at the end of the century. However RCP 4.5 predicted in a higher rate of increase earlier in the century compared to RCP 6.0 (Pachauri et al., 2014). Each IPCC scenario consisted of a minimum, mean and a maximum value. However, the minimum values for 3 of the scenarios were 0.26, 0.32 and 0.3m and the RMSE value for the LiDAR derived DEM was 0.35m. This implied that this DEM would not be reliable for elevations below 0.35m. Hence we opted to focus on the mean and the maximum values only. We were also interested to assess the vulnerability using the 10m DEM, but due to its relatively lower vertical accuracy, we chose to work with the LiDAR DEM only.

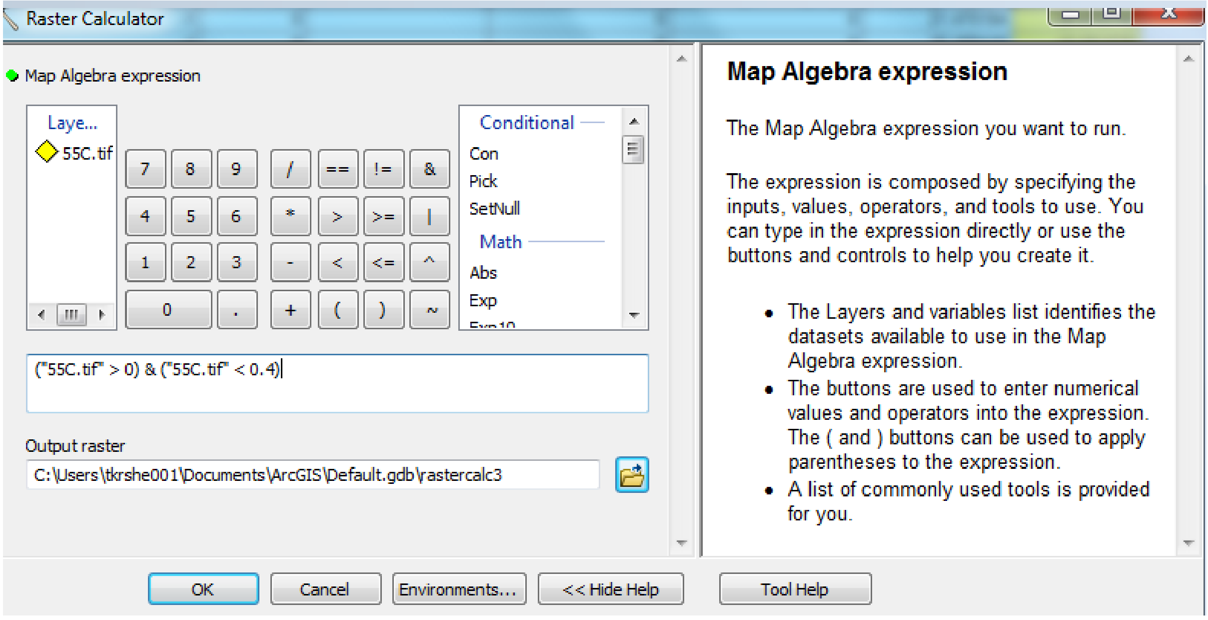
5.17 Availability of data

To address the first question in this study, we generated the scenarios from the LiDAR datasets. However, we also used other data such as the suburb layer for the city of Cape Town to identify the PIAs for each suburb. We also used a satellite image which acted a base map.

5.2 Preprocessing phase

5.21 Bathtub methodology

As mentioned in the literature review, we adopted the bathtub method to delineate the PIAs along the coastline.



("55C.tif" > 0) & ("55C.tif" < 0.4)

Output raster

C:\Users\tkrshe001\Documents\ArcGIS\Default.gdb\rastercalc3

Map Algebra expression

The Map Algebra expression you want to run.

The expression is composed by specifying the inputs, values, operators, and tools to use. You can type in the expression directly or use the buttons and controls to help you create it.

- The Layers and variables list identifies the datasets available to use in the Map Algebra expression.
- The buttons are used to enter numerical values and operators into the expression. The (and) buttons can be used to apply parentheses to the expression.
- A list of commonly used tools is provided for you.

Figure 5.6: Using the raster calculator

Using the raster calculator tool from the spatial analyst toolbox, we could generate a raster layer indicating all the areas at a particular elevation which was required in this study. Since the point cloud data also collected elevation data below sea level (-14.718m), this also needed to be fixed. In the raster calculator, we set the values from 0 to 0.4 so that we could locate all the regions which were below 0.4m (mean value of RCP 2.6). This task was then repeated for the maximum and mean values for all the scenarios.

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 5.7: Refining the scenario by removing disconnected polygons

As all the raster layers were obtained, we could notice some areas which appeared inundated even if they were not connected to the coastline. This implied that these regions were simply existing water bodies or crater located inland which had a lower elevation. These outliers were firstly removed by converting the raster layer into a vector layer so that they could be clipped out. Once they were erased, the vector layers for the scenarios were now ready for further calculations.

5.3 Processing

5.31 Calculation of PIAs

After the pre-processing phase, we could now move to the next step which involved a set of tasks including the identification of the permanently inundated areas, the calculation of the area of any region which would be inundated and the presentation of the final map displaying the location of the PIAs. All these tasks would hence allow us to answer the first research question: Which areas in Cape Town are vulnerable to the IPCC scenarios of sea level rise for the year 2100?

Each scenario could now successfully display the vulnerable areas located along the coastline and hence it was also possible to make calculations of the potential inundated areas. We made use of the Calculate Geometry tool in ArcGIS which allows users to obtain areas of the polygons of a vector layer. For this tool to operate successfully, we must ensure that the coordinate system has the right projection as otherwise this might lead to wrong measurements. Once this has been fixed, the value of the area for each vector layer could now be obtained.

Every model generates some level of uncertainty and in this case, the four models of the IPCC generated a range of values for each scenario. The RCP 2.6 model predicted a rise ranging from 0.26m to 0.55m, with an average value of 0.40m for the year 2081 - 2100. For the purpose of this study, we opted to focus on the impacts based on a rise of the mean value from the model and also included the maximum rise from each model as a limit for the PIAs.

Once these values were calculated, we proceeded to generate a bar chart presenting the results for each model.

The next task in the processing phase was the production of the final maps in ArcGIS. Since it involved 4 different scenarios, the choice of colours was crucial as it would allow the user to make a clear distinction of each scenario and differentiate between the 4 different polygon layers. The scenarios RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 were assigned the colour red, orange, yellow and the green colour respectively. There were other shapefiles which were also in use, such as the vector layer representing the ocean and the base map displaying the city of Cape Town. Other necessary components were also added on the map, such as the data frame, a title, the legend, a scale bar and a North arrow. The font size and the colour of the text displayed on the map should be carefully chosen so that every piece of information being displayed can be clearly read by the user.

5.4 Post processing

After reviewing the literature on regional studies, it was suggested that most of them performed an overlay analysis as a common approach to provide a quantitative assessment of the impacts. In the post processing phase, we focused on a classification of the different land covers and calculated the impacts of sea level rise for each IPCC scenario.

5.41 Investigation of impacts on different land covers

Once the maps had been processed, it was observed that beaches appeared as the most vulnerable land cover. Another land cover which also formed part of the PIAs was the built-up land. Henceforth further investigation was encouraged to calculate the area of potential inundated sandy beaches, rocky shores and built-up land. This task was somehow challenging as it was necessary to digitize a vector layer of polygons covering all the beaches and the built-up land manually along the coastline of Cape Town.

Since Cape Town has a few blue flagged beaches (e.g Fish Hoek, Camps Bay, Clifton 4th), we were also interested to find out how sea level rise affected these popular beaches. Therefore, we added another attribute to identify blue flagged beaches so that we could also calculate the impacts on these beaches. Once we had a vector layer of all the blue flagged beaches, sandy beaches, rocky shores and built-up land, we could now undertake an overlay analysis to obtain the size of the beach which would be submerged. For each IPCC scenario, we carried out an intersection between the sea level rise vector layer and the land cover vector layer. The results were then presented in a bar chart, displaying the range between the mean and the maximum of the inundated beach area for each scenario.

5.42 Investigation of impacts on vulnerable suburbs

Based from an observation of the processed maps, it was also noted that some areas were more vulnerable compared to others and required more attention. We conducted a spatial overlay of all the scenarios onto the suburbs in the city of Cape Town and calculated the PIAs.

5.5 Flowchart

Hence after completing these 4 phases, we could finally assess the vulnerability of the entire coastline based on the IPCC scenarios. A breakdown of all these stages was presented in the flowchart below.

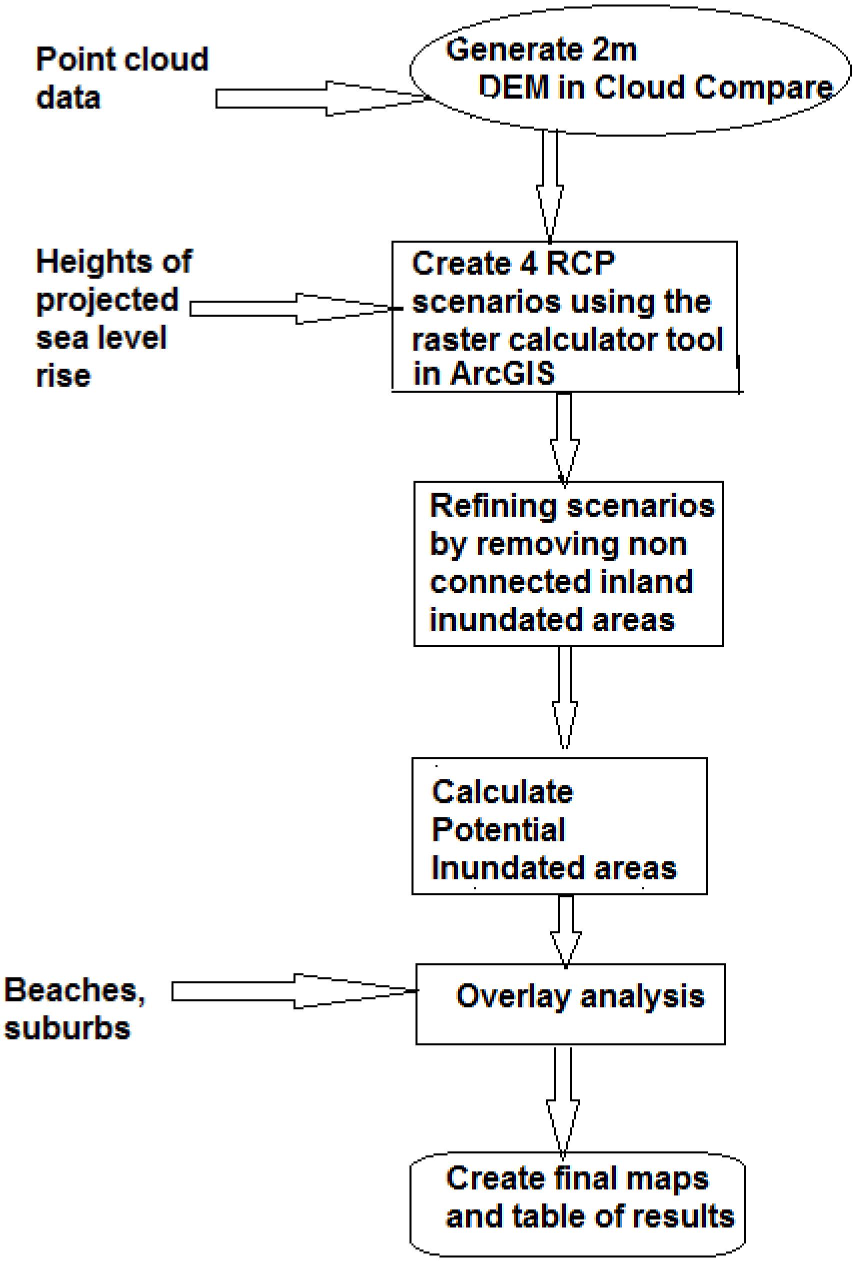


Figure 5.8: Flowchart of the different phases

5.6 Investigation of sea level rise and additional temporary flooding effects on selected coastal areas.

This research was also aimed at quantifying the impact of sea level rise through IPCC forecasted scenarios along with additional temporary effects induced on different land covers in particular areas. Investigating permanent inundation using GIS provides us the clear boundaries between the inundated areas and the protected areas. However we should also take into account that in the year 2100, the sea level will still be affected by other factors such as the tidal effect. This implies that even some of the non-inundated areas would not be entirely protected.

In fact there would still be an indirect impact of sea level rise on these regions. For instance, properties located close to the boundary of the PIAs should not be considered as entirely safe. They would still be indirectly affected by several associated factors. Some common examples include blocked access to specific roads which form part of the PIAs, failure to have access to water due to broken water pumps in the inundation zone and power cut because of damaged power lines located in the inundation zone. Therefore coastal planners must account for such temporary events as well. In this section, we decided to focus on 8 different coastal suburbs based on the availability of data and explored the possible challenges faced by the additional effects of temporary flooding in these regions.

5.7 Design phase

5.71 Mapping the tidal effect on selected coastal suburbs

In chapter 2, it was previously discussed how temporary flooding in Cape Town is often caused by tidal waves and storm surges associated with cold fronts. Therefore in each case study, we focused on the tidal effect and wave run-up heights association with low pressure systems. However, when it comes to mapping, it becomes quite problematic as there are different recorded values of increase in sea level caused by tides.

The effect of tides is constantly causing changes along the shoreline and can often result in extreme heights of waves. It was necessary to map the potential temporary flooded zone for each IPCC scenario and we were particularly interested in the extreme values as this allowed us to estimate the worst case scenario based on a past event of extreme tidal wave. Thus in this research, it was decided to focus on the Highest Astronomical Tide record. In Cape Town, there are only two stations which measure the tidal effects along the coastline, namely Cape Town and Simon’s Town. There has been consistent recording of tidal variations at both stations during the last few decades and this data was thus judged as acceptable and reliable by oceanographers. Once the records for the HAT were obtained for Cape Town, we could now design the scenario by adding the value of the HAT to the mean rise obtained from the modelled IPCC scenarios.

Extreme tidal effect on IPCC scenarios (in metres) = Increase in height from IPCC modelled scenario (in metres) + Increase in height caused by HAT (in metres)

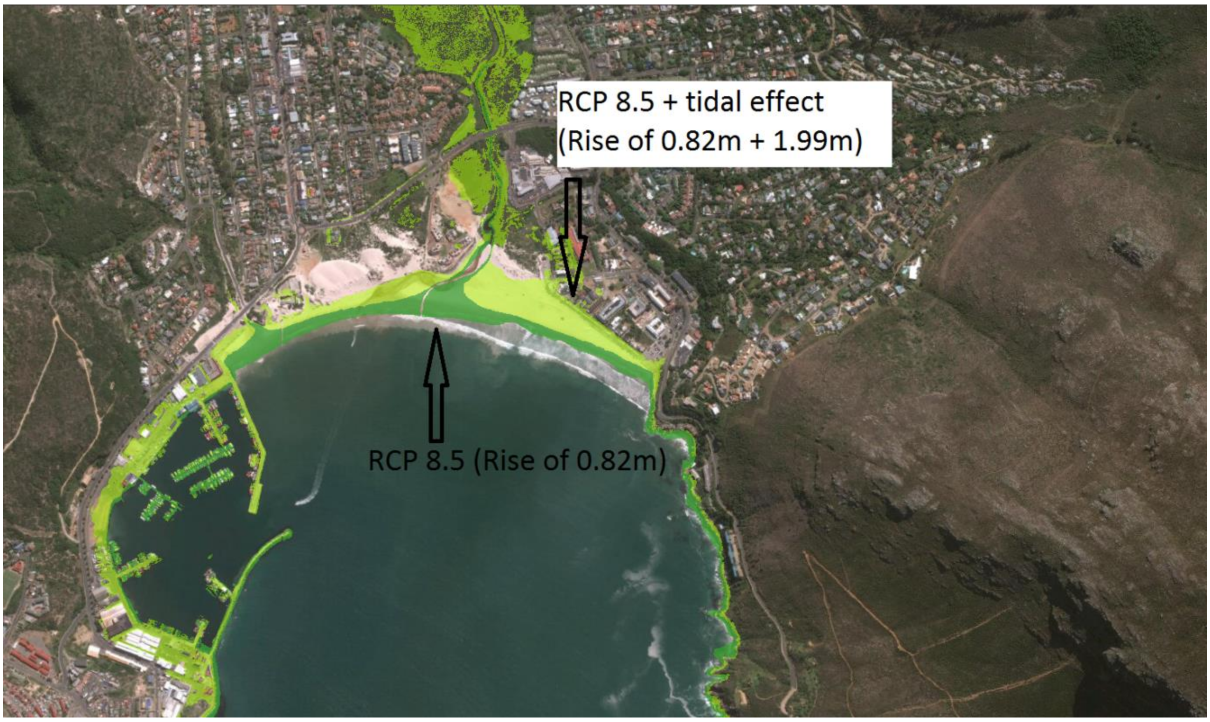
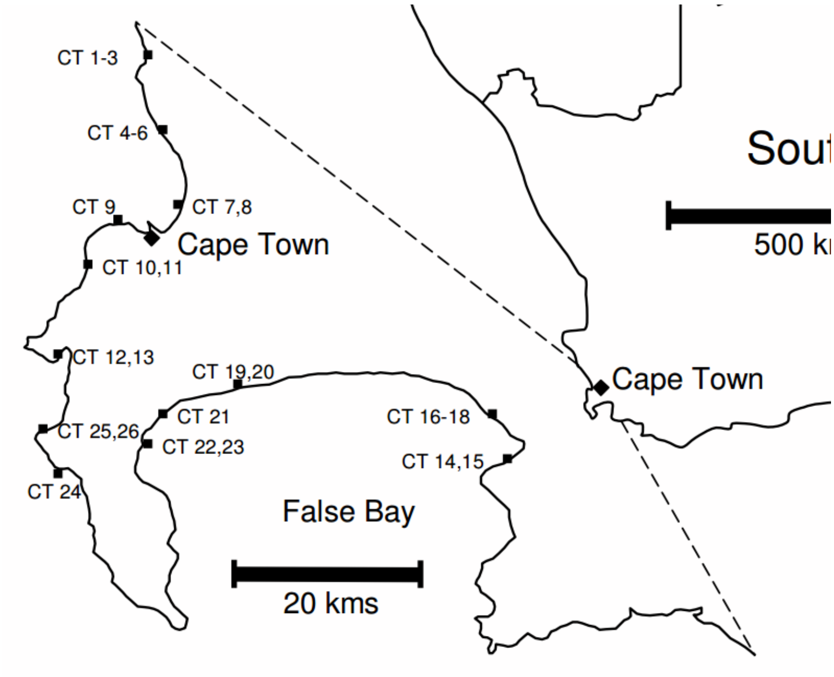


Figure 5.9: combined effects of tides and sea level rise

5.72 Mapping the wave run-up heights on selected coastal suburbs

After designing the tidal effect for each case study, we now chose to investigate the indirect impact of temporary flooding caused by storm surges linked with low pressure systems. Again, the main challenge was to decide which height of the measured storm surges would be mapped. Similarly, we were particularly interested in planning the worst case scenario by making use of extreme values.

Hence, based on the availability of data, we focused on a previous cold front event which occurred in September 2008 and which was known for having caused serious damage to the shoreline, the harbour, the infrastructure, the transport system and the biodiversity. During this event, the extreme wave run-up heights were recorded across 17 beaches in Cape Town and the maximum recorded wave height during this storm was as high as 10.7 m.



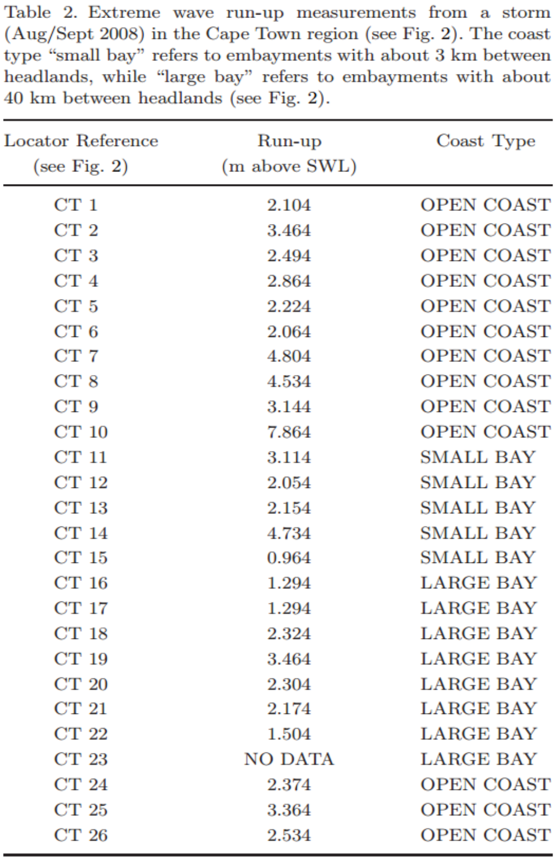


Table 2. Extreme wave run-up measurements from a storm (Aug/Sept 2008) in the Cape Town region (see Fig. 2). The coast type “small bay” refers to embayments with about 3 km between headlands, while “large bay” refers to embayments with about 40 km between headlands (see Fig. 2).

Locator Reference (see Fig. 2)	Run-up (m above SWL)	Coast Type
CT 1	2.104	OPEN COAST
CT 2	3.464	OPEN COAST
CT 3	2.494	OPEN COAST
CT 4	2.864	OPEN COAST
CT 5	2.224	OPEN COAST
CT 6	2.064	OPEN COAST
CT 7	4.804	OPEN COAST
CT 8	4.534	OPEN COAST
CT 9	3.144	OPEN COAST
CT 10	7.864	OPEN COAST
CT 11	3.114	SMALL BAY
CT 12	2.054	SMALL BAY
CT 13	2.154	SMALL BAY
CT 14	4.734	SMALL BAY
CT 15	0.964	SMALL BAY
CT 16	1.294	LARGE BAY
CT 17	1.294	LARGE BAY
CT 18	2.324	LARGE BAY
CT 19	3.464	LARGE BAY
CT 20	2.304	LARGE BAY
CT 21	2.174	LARGE BAY
CT 22	1.504	LARGE BAY
CT 23	NO DATA	LARGE BAY
CT 24	2.374	OPEN COAST
CT 25	3.364	OPEN COAST
CT 26	2.534	OPEN COAST

Figure 5.10: wave run up heights from previous storm surge (Sept 2008) (Mather et al, 2011)

In this study, we added the extreme wave run up height to the mean rise from the IPCC scenario to generate our scenario for the combined effects of sea level rise and storm surge.

Extreme storm surge effect on IPCC scenarios (in metres) = Increase in height from IPCC modelled scenario (in metres) + Increase in height caused by maximum wave run up height

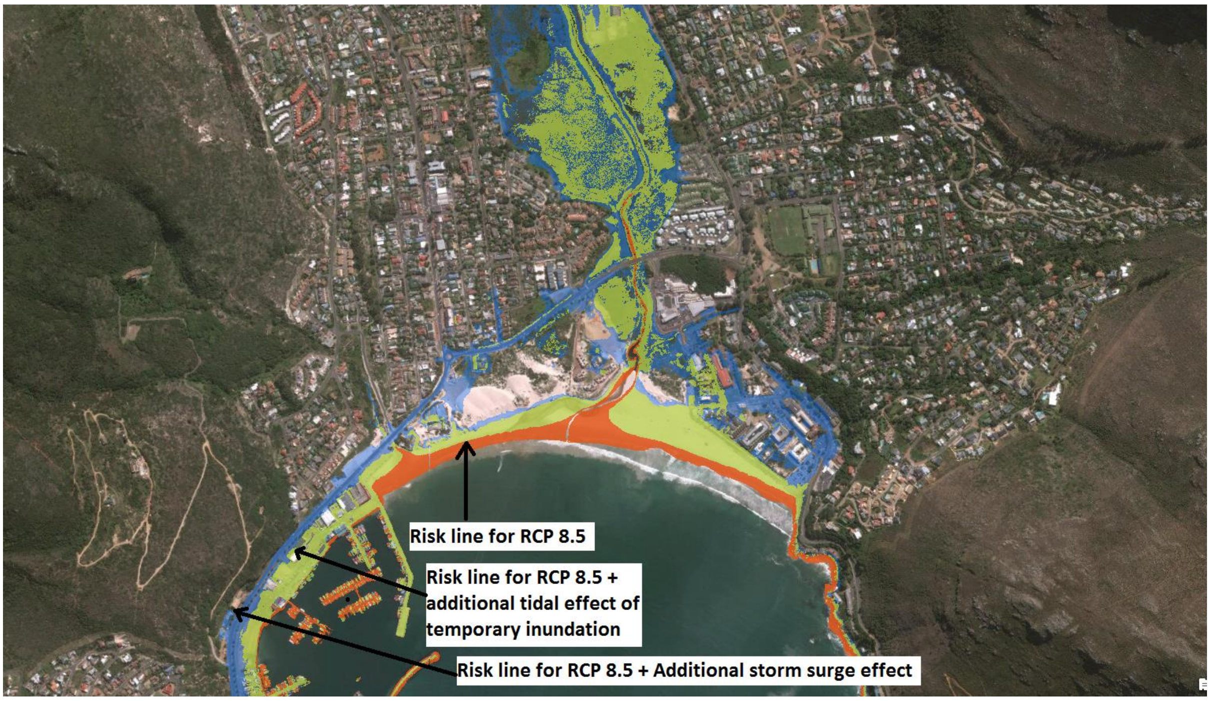
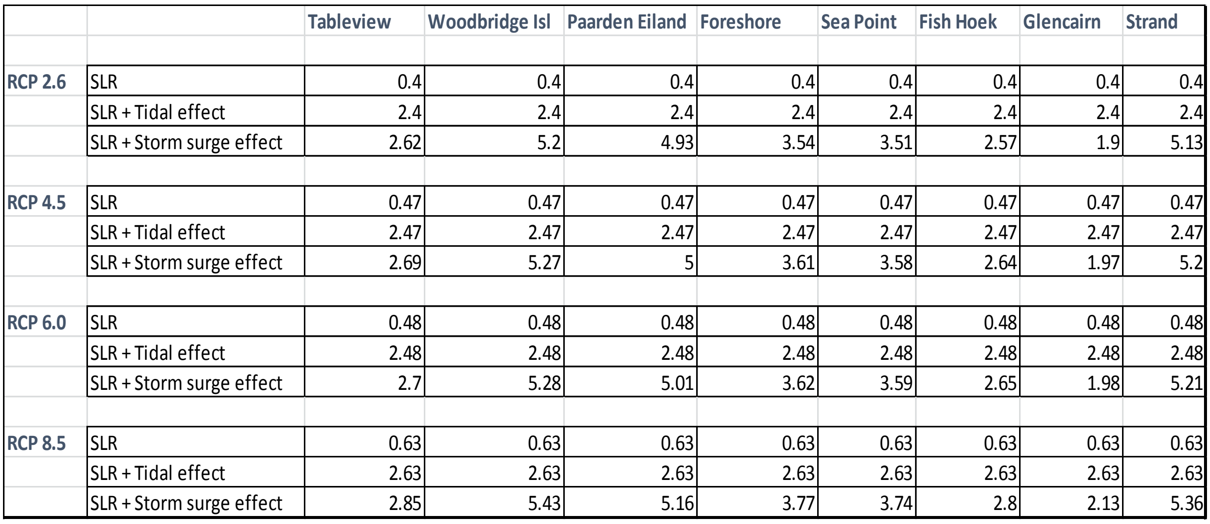


Figure 5.11: Combined effects of storm surge and sea level rise for Hout Bay

The table below showed the different increases in the sea level which was investigated based from the IPCC scenarios, wave run up heights and tidal data for each suburb.



		Tableview	Woodbridge Isl	Paarden Eiland	Foreshore	Sea Point	Fish Hoek	Glencairn	Strand
RCP 2.6	SLR	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	SLR + Tidal effect	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
	SLR + Storm surge effect	2.62	5.2	4.93	3.54	3.51	2.57	1.9	5.13
RCP 4.5	SLR	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
	SLR + Tidal effect	2.47	2.47	2.47	2.47	2.47	2.47	2.47	2.47
	SLR + Storm surge effect	2.69	5.27	5	3.61	3.58	2.64	1.97	5.2
RCP 6.0	SLR	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
	SLR + Tidal effect	2.48	2.48	2.48	2.48	2.48	2.48	2.48	2.48
	SLR + Storm surge effect	2.7	5.28	5.01	3.62	3.59	2.65	1.98	5.21
RCP 8.5	SLR	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
	SLR + Tidal effect	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63
	SLR + Storm surge effect	2.85	5.43	5.16	3.77	3.74	2.8	2.13	5.36

Figure 5.12: Estimated rise in sea level from RCP scenarios, HAT value and historical data of extreme wave heights.

5.73 Availability of data

In this section, we selected 8 different suburbs, namely Tableview, Woodbridge Island, Paarden Eiland, Foreshore, Sea point, Fish Hoek, Glencairn and Strand. These suburbs were chosen randomly from a list of coastal suburbs exposed to the impacts of sea level rise. We explored the combined effects of sea level rise and temporary flooding for each suburb.

As pointed out in the literature review, there have also been many studies which calculated the impacts on population. However in this study, we chose to avoid making such predictions as it would be unfair to use the population data from the census. Due to data restrictions, we chose to focus only on these three land covers. However if we had access to the valuation of properties, we could have also calculated the cost of damage. But prediction of the cost of properties for the year 2100 is somehow problematic as it is unknown whether there would be inflation or deflation rates.

We made use of the same Lidar dataset to generate a DEM for each suburb.

5.8 Preprocessing phase

5.81 Case study of 8 different coastal suburbs affected by sea level rise

After having chosen the magnitude of elevation for the tidal effect and the storm surge effect, we could now proceed to the calculation of the PIAs in these particular areas. The raster calculator tool was once again useful in designing the scenarios of indirect impacts by following the 2 equations stated above. Hence for each selected suburb, we could now produce 4 different IPCC scenarios of permanent inundation (RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5) , as well as 4 scenarios displaying the additional temporary tidal effects and 4 scenarios mapping the temporary effects from storm surges.

The scenarios were then refined by deleting any polygon which was not connected to the coastline.

5.9 Processing phase

Once all the scenarios have been refined, we could now prepare the maps for each suburb and present the final results, showing the calculated area for the PIAs.

5.10 Flowchart

All these phases in this section led to the findings which addressed the second research question, i.e the quantifying of the impacts of combined effects of sea level rise and tidal and storm surge effects on 8 selected suburbs. The flowchart below represents a breakdown of all the processes which were carried out.

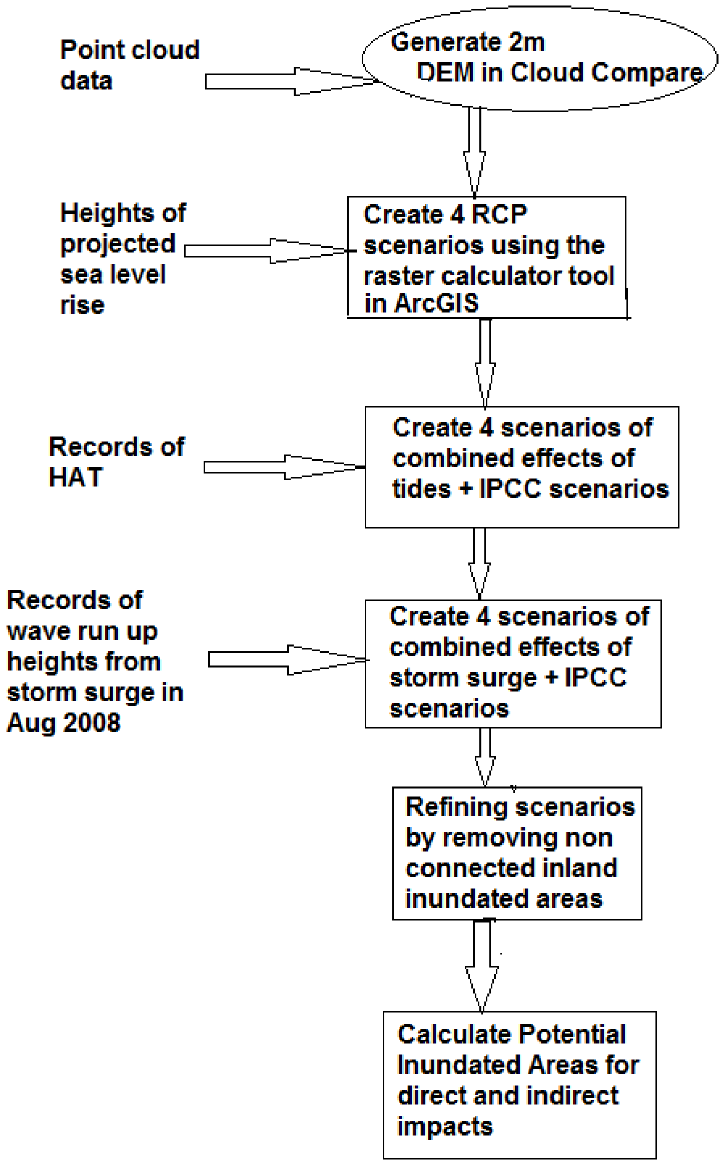
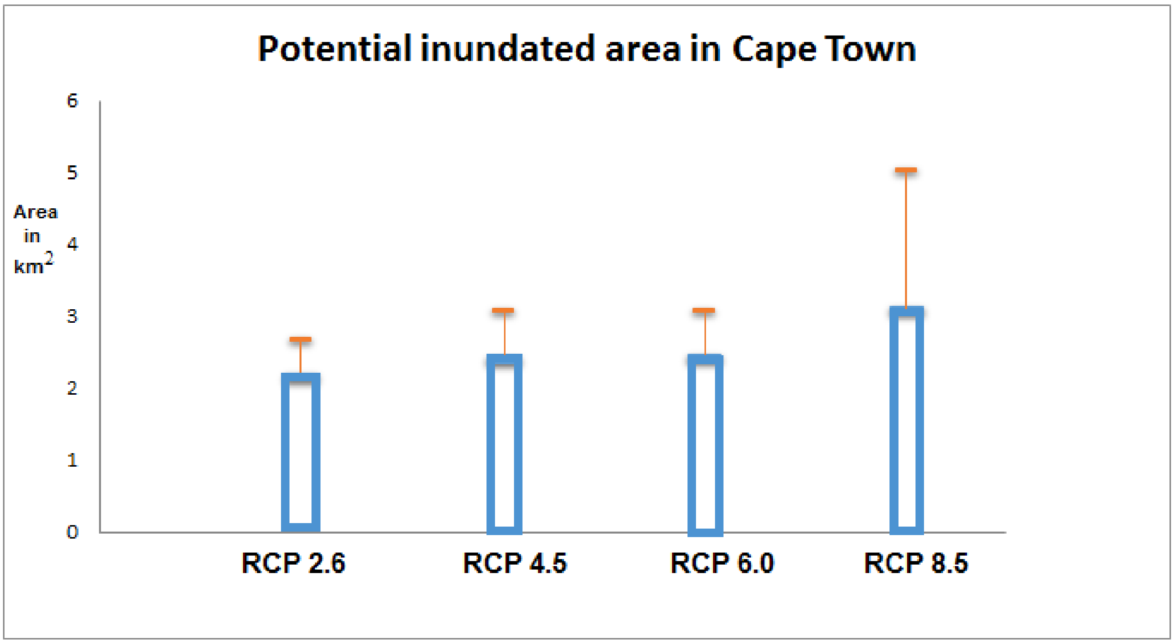


Figure 5.13: Flowchart of the different stages to generate scenarios of combined effects of temporary flooding and sea level rise

Chapter 6: Results and discussion

6.1 Assessment of sea level rise scenarios along the coastline of Cape Town.



	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Mean	2.16	2.43	2.43	3.09
Maximum	2.69	3.09	3.09	5.04

Figure 6.1: Potential inundated areas based from the 4 RCP scenarios measured in km^2

Considering the mean values for the PIAs, the RCP scenarios had a relatively smaller variation range (2.16-3.09 km^2) On the contrary, there was a wider range observed in the PIAs from the maximum values whereby the maximum for RCP 8.5, (5.04 km^2) was almost twice the value for the maximum of the RCP 2.6 (2.69km^2). The PIAs from the scenario RCP 2.6 did not seem to pose much threat to the infrastructure. They covered some sections of the beaches but such damage could be avoided if the necessary actions were taken now. Scenario RCP 4.5 and scenario RCP 6.0 were very similar in terms of impacts of sea level rise along the coastline. The PIAs from these 2 scenarios included beaches and showed some damage to the infrastructure at a few places along the coastline. These damages could still be managed and avoided if there are appropriate measures taken. The scenario RCP 8.5 however revealed much more damage along the coastline. Based on the maps, it is observed that a major section of the PIA were beaches. The remaining PIAs also consisted of built-up land around the coastline, some sections of the harbour structures, road network and the railway line. Much of the coastline would require immediate attention if such changes would occur in the sea level as it would be highly detrimental for the beaches, the waterfront structures, the harbours, surrounding properties and road network.

6.2 Assumptions

Before analysing the results, it is important to consider the following points. First of all, this was only a simulation of hypothetical scenarios of potential changes in the sea level. We relied on models to visualize the potential impacts which may happen in the future. However, these values could be an underestimate or an overestimate of the rise in sea level. In reality, there is always a constant variation of the sea level. For the purpose of this research, we focused only on 4 different scenarios of fixed increases in sea level. It was also assumed that the rise is uniform across every part of the shoreline.

But careful consideration needs to be done when applying a global mean sea level rise scenario to a local region. The coastline consists of different types of environment, for instance sandy beaches, rocky shores, estuaries, high cliffs and reclaimed land and in a real situation. The current existing conditions such as the bathymetry and the climate will also influence greatly on its resistance to changes in sea level. As for the LiDAR DEM, the water base mark depended on the particular day onto which the LiDAR data was collected. Hence, it also included some land parcels which may not officially form part within the boundary of the city. However in this research, it was assumed that these regions were merged along with the legal boundary of the city. Most of these areas were beaches or rocky shores and in general, no development can be done in these regions.

Another important point which was assumed in the design is that these maps only represented a visualization of the impacts for permanent inundation and the scenarios did not consider any additional temporary effect such as tides, storm surges or tsunamis. In a real situation, there are variations which occur daily and hence these scenarios would fail to reflect the exact situation. Although if such events would take place in Cape Town, the water level would eventually reach back its original point within a few hours.

6.3 How well do the findings address the question in this study?

It must be noted that these IPCC scenarios would still not allow for a clearer picture of the impacts which need to be addressed. Since the IPCC scenarios entailed a high level of uncertainty in their prediction of sea level rise, this wide range of values is problematic for the assessment of the impacts and the adaptive response of the city. For instance, the RCP 2.6, which is defined by the IPCC as the best case scenario, displayed a mean rise of 0.4m and would cause a loss of land of 2.16 km^2. This change did not cause much damage to the beaches, properties and infrastructure. This particular scenario could easily be handled in the future, and only minor changes need to be implemented to prepare the city for the future risk in 2100. In contrast, the maximum rise for the RCP 8.5, the worst case scenario of the IPCC, consisted of a PIA of 5.04 km^2. Consequently preparation for such a disastrous scenario would involve several changes which might require more costly civil engineering projects such as construction of sea walls, groynes and barriers.

Another valid critique of this methodology is that we are only presented with the potential impacts of future of sea level rise in Cape Town. Such geomatics-based sea level rise assessment do not account for solutions and adaptation strategies. Nevertheless, these maps would still be a requirement for further analysis and could provide the basis for the City of Cape Town to begin discussions of appropriate adaptation strategies for the coastline.

6.4 Observations from the maps

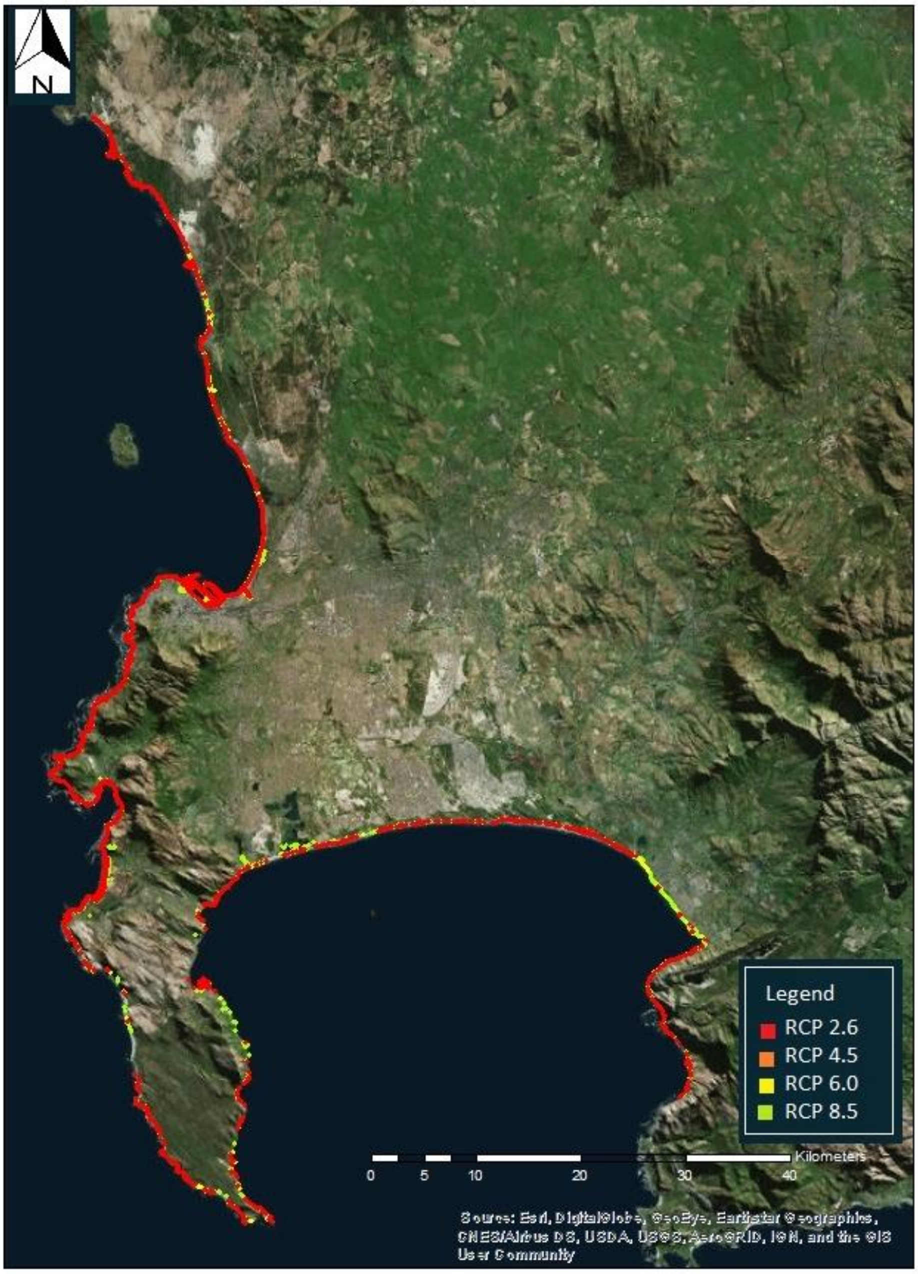


Figure 6.2: Sea level rise map showing all 4 RCP scenarios

Based from the findings, it was observed that the southern Cape Peninsula is relatively less vulnerable compared to other regions such as Hout bay and Fish Hoek. The most threatened PIAs were the exposed sandy beaches. In fact at several regions such as Muizenberg and Milnerton, the PIA extended through the water bodies which are connected to the ocean. Other vulnerable regions also included reclaimed land such as Paarden Eiland

and the Foreshore and it would become problematic with an increasing sea level as the coastline has already been fixed. In the next section, a more detailed assessment was carried out for different sections along the coastline.

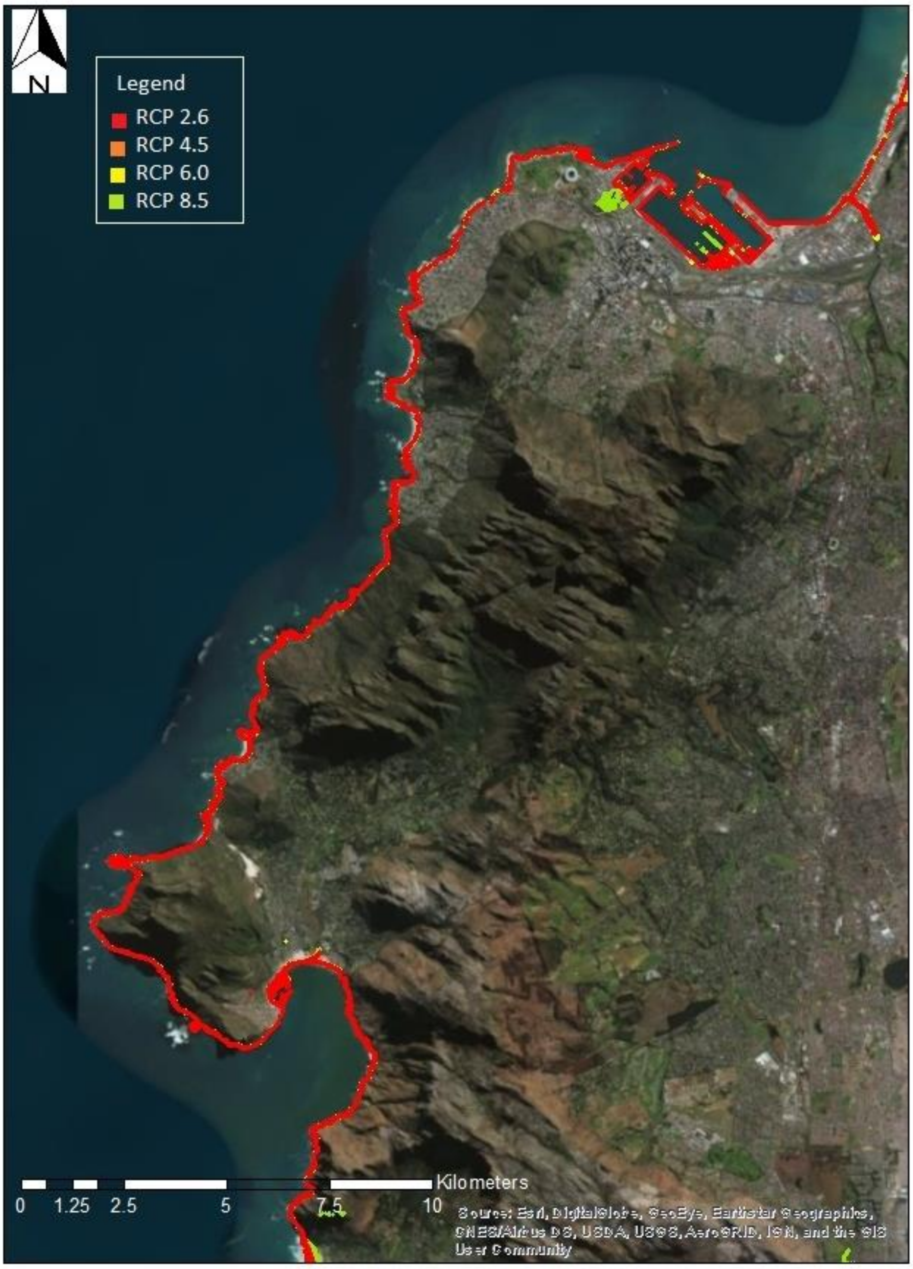
6.41 From Silwerstroom strand to Milnerton.

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 6.3: Sea level rise scenarios from Silwerstroom strand to Milnerton

Zooming closer on the maps, it was observed from the DEM that the section from Silwerstroom strand to Milnerton consists of relatively lower elevation, and hence much coastal retreat is expected to occur by 2100. However the Robben Island acts as a barrier against big waves and brings a reduction in the intensity of the waves. Nevertheless, all the 4 RCP scenarios identified the beaches as the main receptors. In the case of additional temporary coastal flooding, receptors would also include dunes, electric cables, stormwater pipes, sewerage pipes, properties, roads, the Potsdam Waste and the Caltex Oil refinery. In the past, the sandy zones have migrated both landward and seaward. The dunes were highly vulnerable, and hence they may not act as a buffer against big waves anymore due to their instability. Most of these zones which were regarded as semi-protected would now be exposed to the waves.

6.42 From Foreshore to Llandudno



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 6.4: Sea level rise scenarios from Foreshore to Llandudno

Looking at the areas from Foreshore to Llandudno, this section is not well protected due to its bathymetry and topography. Much of it consists of reclaimed land, and some beaches. Coastal erosion is already noticeable (for instance there is a gradual coastal retreat at the sandy beach of Llandudno.) Since the beaches are highly relevant to the tourism sector, there is much more concern regarding the erosion at Camps Bay and Clifton. It has also been noted that several properties and new buildings have underground parking which would be potentially inundated. Sea level rise would also have an indirect impact on other receptors such as industrial properties and roads in Paarden Eiland, waterfront structures in the Foreshore, sewerage and stormwater pipes in Mouille Point, Bantry Bay, Camps Bay, Clifton and Llandudno.

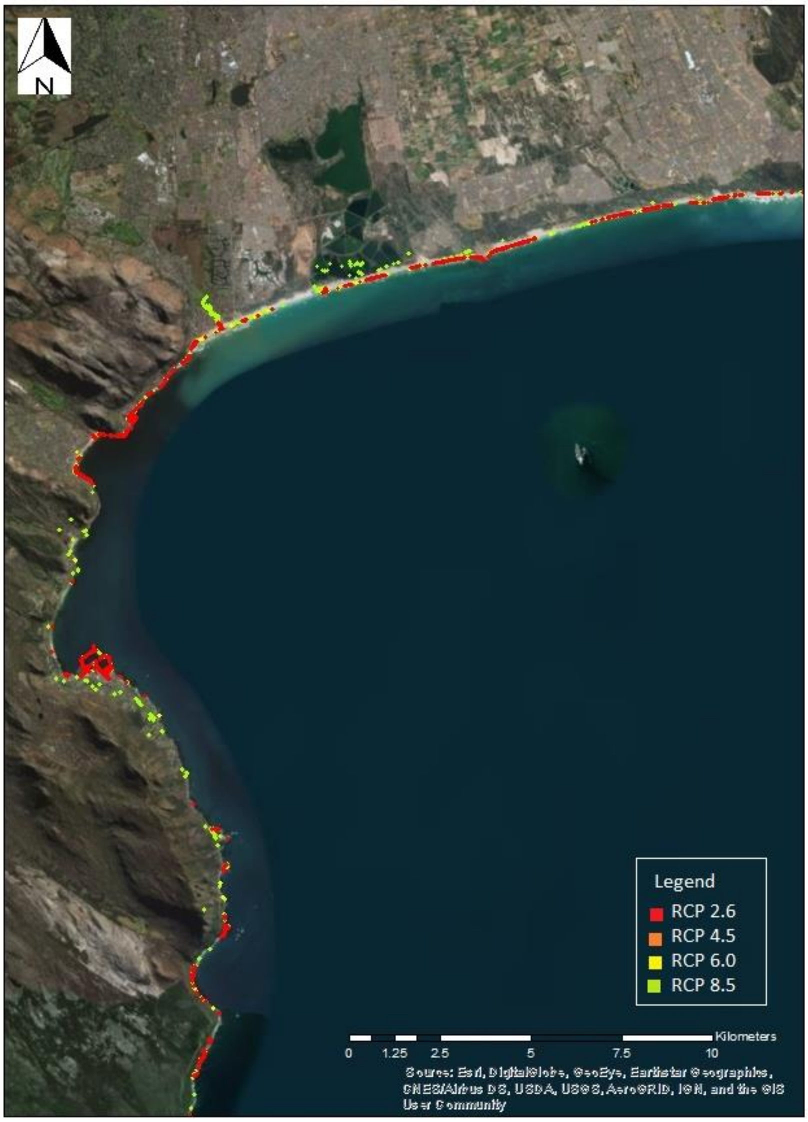
6.43 From Hout Bay to Scarborough

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 6.5: Sea level rise scenarios from Hout Bay to Scarborough

The coastline from Hout Bay to Scarborough consists of several sandy beaches and some rocky shores. Most of the shoreline is exposed to the big swells except for Hout Bay which is relatively sheltered from the waves. But since Hout Bay is located at a lower elevation, there could be considerable damage to the harbour infrastructure. Residential properties, the transport system, the electric cables and the water services would also be indirectly impacted in this section if additional temporary flooding occurs.

6.44 From Millers Point to Strandfontein



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 6.6: Sea level rise scenarios from Millers Point to Strandfontein

False Bay is generally much more sheltered from big waves compared to the remaining areas along the coastline of Cape Town. On the west side of the shoreline, the coastline consists mostly of rocky shores, some sandy bays and pocket beaches. The best case scenario did not cover much along the coastline, while the worst case scenario showed that the sandy beaches, the rocky shores and some sections of the built-up land were highly vulnerable. Most of the properties are located on a higher elevation. However the railway line and the roads in Glencairn and Fish Hoek would be highly threatened in the event of big waves due to the lack of hard coastal structures

6.45 From Monwabisi to Gordon's bay

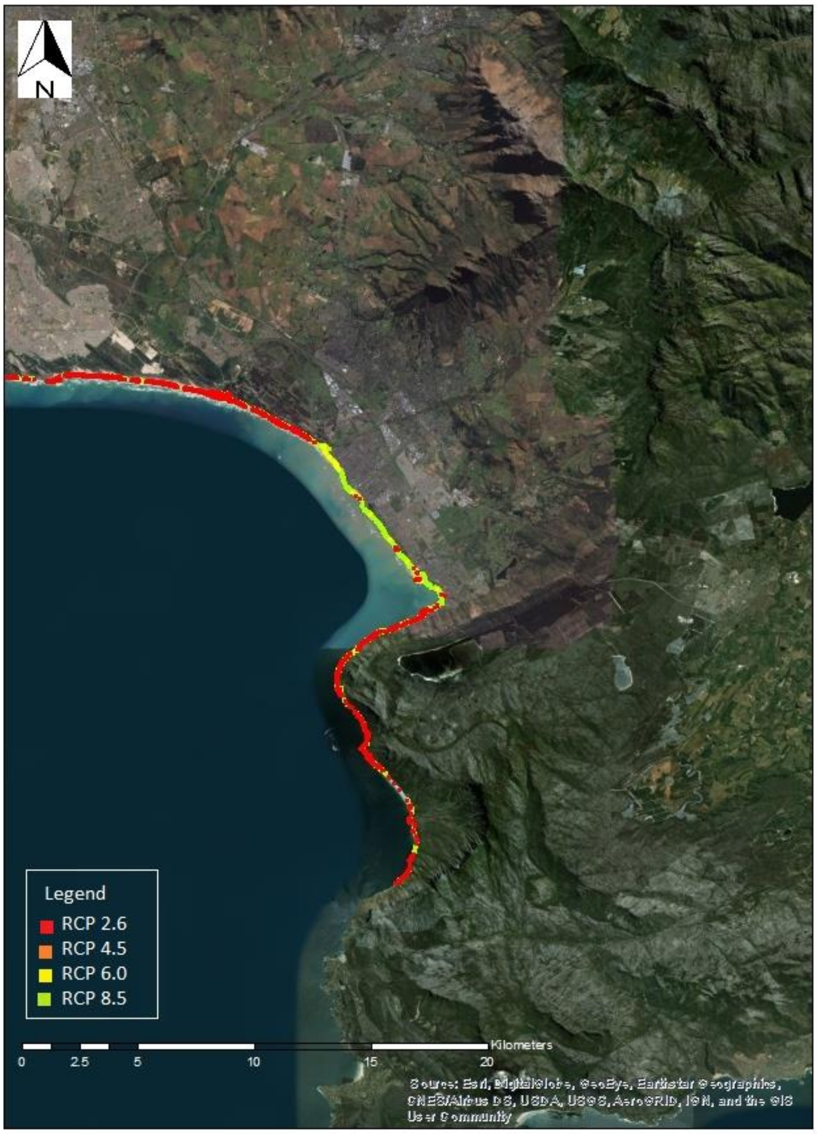


Figure 6.7: Sea level rise scenarios from Monwabisi to Gordons Bay

Compared to the western side, the northern and the eastern side of False Bay is more exposed to big waves. The maps show that the PIA affected mostly Strand and Gordons Bay as much of this area is located at a lower elevation. There is a sea wall in Gordons bay to keep it sheltered from the impact of big waves and to reduce erosion. Other receptors which are indirectly impacted by sea level rise are properties, storm water pipes, sewerage pipes, electric cables and some sections of a few roads in Monwabisi, Strand, Gordons Bay and Macassar.

6.5 Impact of sea level rise on coastal suburbs

As observed from the maps, the impacts of sea level rise varied differently at different sections of the coastline. Some regions required more immediate attention while in a few suburbs, there would not be much damage. Below is a breakdown of the PIA in some of the main coastal suburbs.

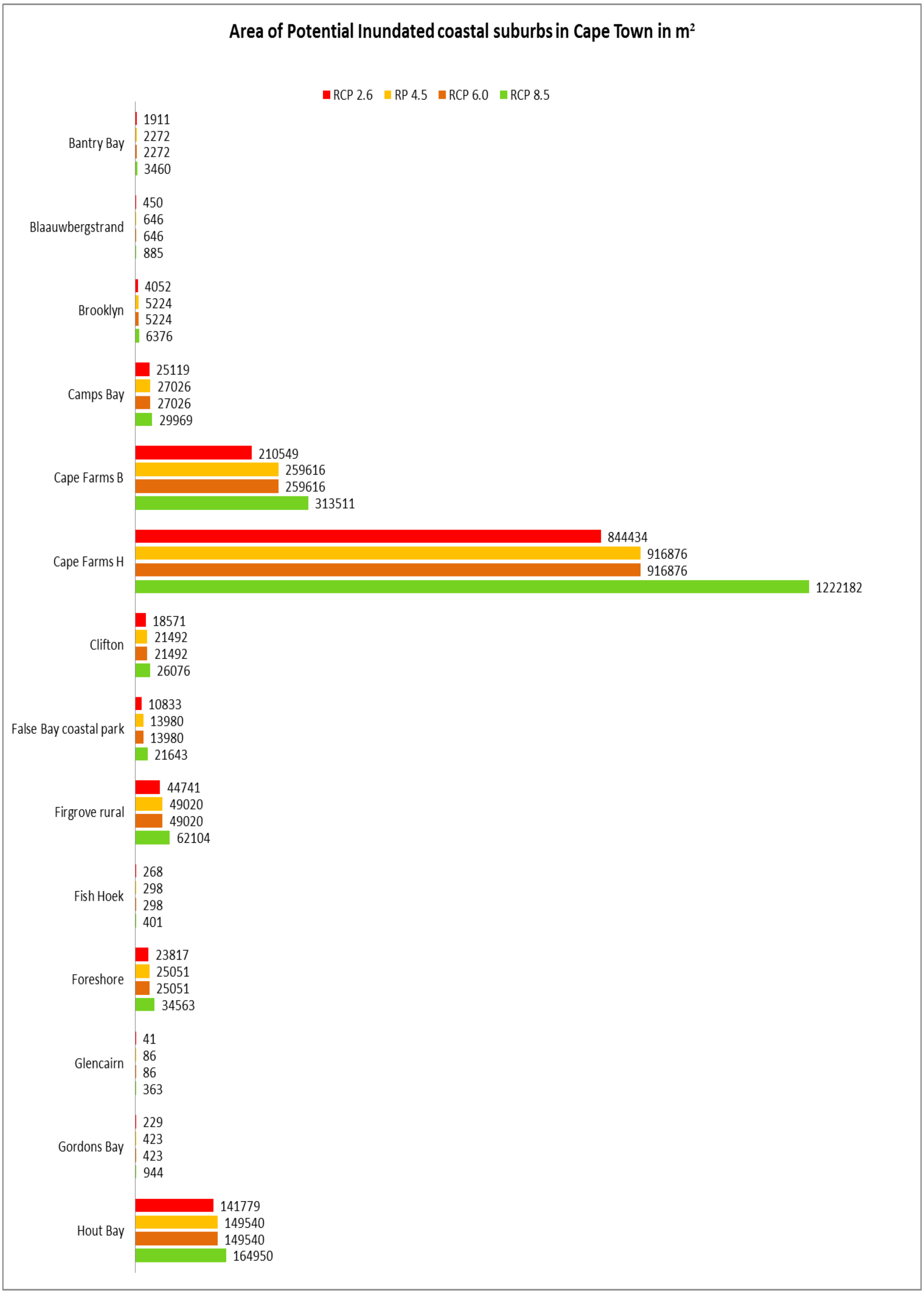


Figure 6.8: PIAs of coastal suburbs in Cape Town (Continued)

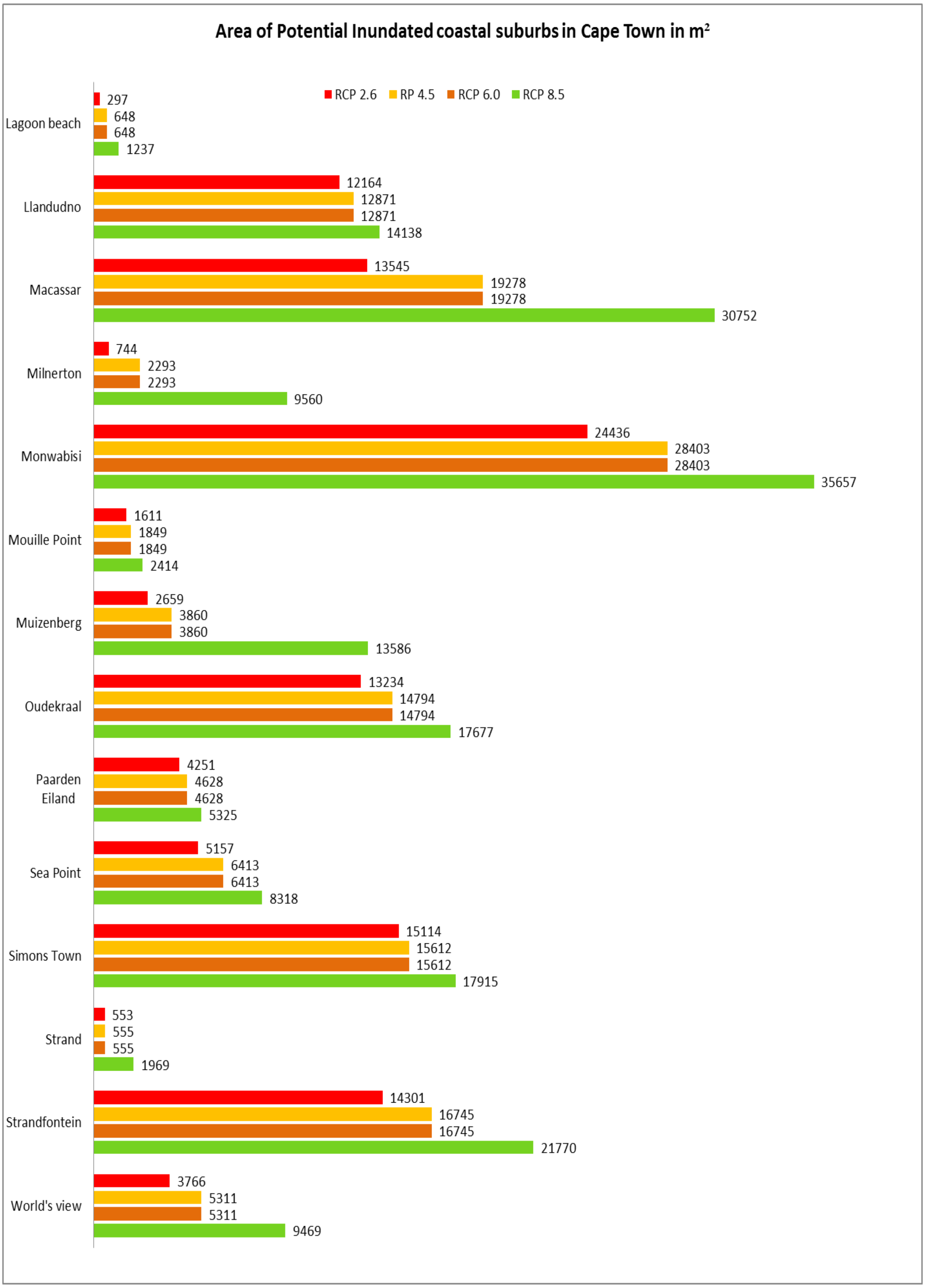
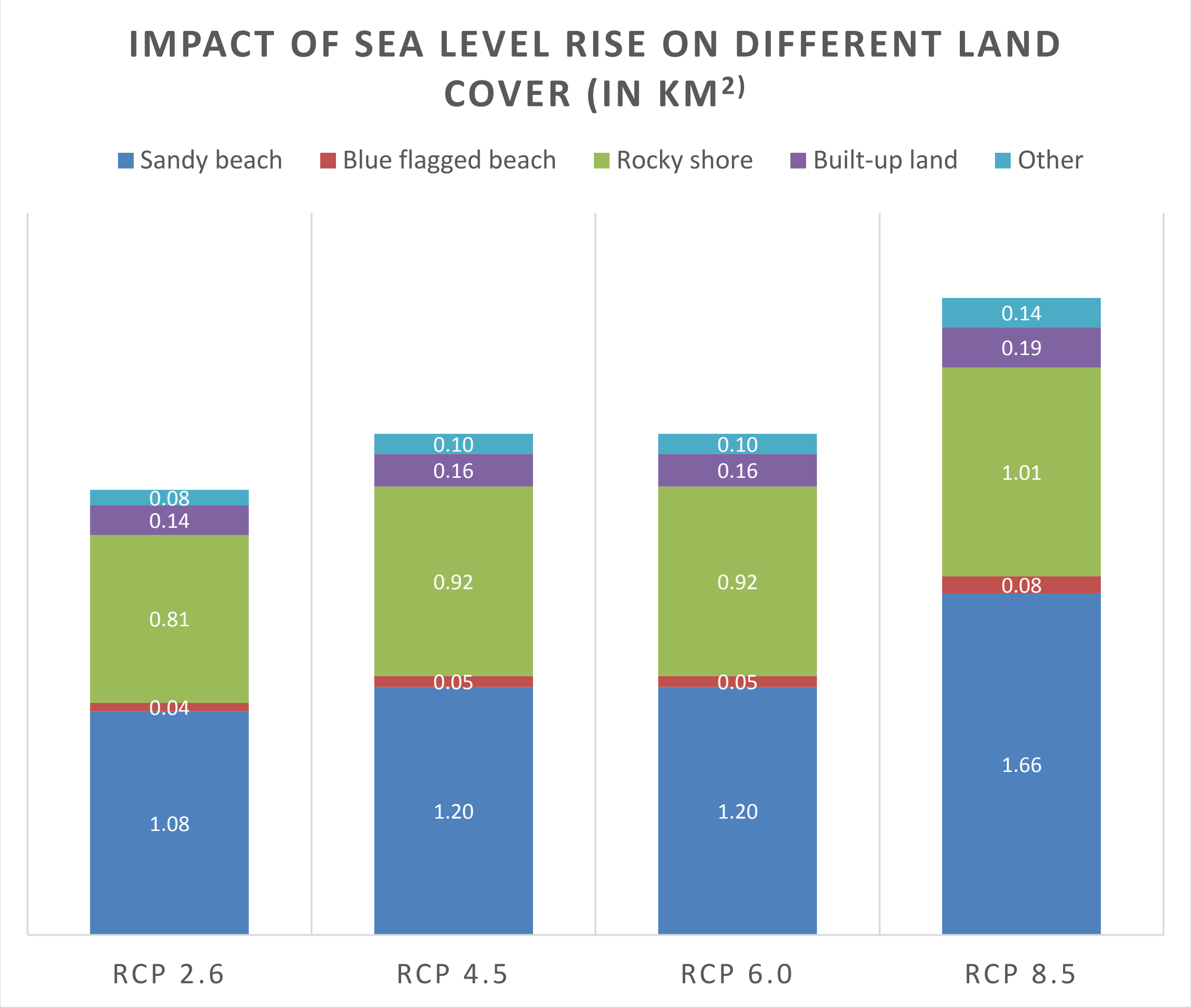


Figure 6.9: PIAs of coastal suburbs in Cape Town

From these findings, Cape Farms H, Cape Farms B and Hout Bay would appear as the some of the most vulnerable suburbs. However these suburbs consist of a longer coastline compared to the other suburbs hence they had relatively higher values for its PIAs. Coastal suburbs vary in size and we must take into consideration that the recorded values of the PIAs for each suburb cannot exactly determine whether this suburb is entirely vulnerable. For instance Foreshore is smaller in size; hence it had a smaller value for the PIA even though a major section of the suburb would be inundated. However, it is still a good estimate to have an overview of the different vulnerable suburbs so that the City of Cape Town can address their attention towards particular vulnerable suburbs.

6.6 Receptors of impacts



	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Sandy beach	1.08	1.20	1.20	1.66
Blue flagged beach	0.04	0.05	0.05	0.08
Rocky shore	0.81	0.92	0.92	1.01
Built-up land	0.14	0.16	0.16	0.19
Other	0.08	0.10	0.10	0.14

Figure 6.10: PIA of different land covers in Cape Town measured in km^2

Such land loss implied that it would affect many different receptors. From the findings, we calculated the impact on different land cover based from the 4 RCP scenarios, and the most threatened land cover was the beaches. This land cover included blue flagged beaches, sandy beaches and rocky shore. Other receptors also included the built-up land, and some vegetation and minor sections of dunes and wetlands.

6.7 Impact of sea level rise on beaches

There are different types of beaches along the coastline of Cape Town and each type of beach reacts differently to temporary changes in sea level. In general sandy beaches such as Llandudno, Camps Bay and Clifton are mostly exposed to big waves while rocky shores such as Sea point and Bakoven are relatively sheltered. Even though the design of the scenarios of sea level rise did not take this fact into account, the findings would still provide a close estimate of the quantitative impacts. The RCP scenarios revealed that 0.04-0.08 km^2 of blue flagged beaches would be potentially inundated, 1.08-1.66 km^2 of sandy beaches would be potentially submerged and 0.81-1.01 km^2 of rocky shore would be potentially submerged by 2100.

Over the years it has been proved to be necessary to assess the impacts of sea level rise on beaches in Cape Town as they are one the main assets of the South African’s tourism industry. In fact, from a survey conducted among international tourists, the city was linked to the terms “beautiful, white, sandy beaches.” Although only around 20% of international tourists visit the city, one third of the profit from the entire tourism industry is contributed by Cape Town, implying that some tourists travelling to Johannesburg include Cape Town in their vacation plans. In 2015 it was reported that an amount of R24.9 billion was collected from the expenditure on day trips from tourists in Cape Town and the most preferred accommodation was the coastal suburbs. Hence calculation of the potential inundated beaches will allow coastal planners to take appropriate decisions regarding the planning of the city in order to mitigate the negative impacts on the tourism sector in Cape Town.

Sea level rise along with temporary increases in sea level also cause a direct and an indirect impact on beaches and the tourism sector. Permanent inundation can result in a change of the appeal and the nature of the shoreline through erosion, causing a drop in public interest to visit these beaches. Temporary flooding of sea water can block access to particular roads which lead to the beach, hence limiting access to the public. In the case of narrow beaches e.g Boulders and Seaforth beach, the coastal retreat may be aggravated during a spring tide or in the event of a storm surge. As for beaches at the Melkbos and Tableview, the sandy shoreline along with the dunes is not only a valuable asset in the tourism industry but they also act as a natural defence against the impact of big waves. However with ongoing increases in the sea level, this would lead to the instability of the dunes and result in accelerated erosion. Other beaches such as Hout Bay and Sandy beach may also be expected to change into a rocky shore due to the coastal erosion from the wave action.

In the case of scenario RCP 2.6, this scenario could be easily handled and would not require expensive adaptation strategies. However according to RCP 8.5, we would need to invest further. Nicholls et al. (2011) pointed that although a rise of 1-2 m would translate into the submersion of infrastructure and beaches, some of the damage may be prevented through different adaptation strategies, e.g beach nourishment. It consists of adding sand to the eroded beach in order to replace the previous loss from coastal erosion.

This type of large scale solution could prove to be an appropriate approach to tackle the impacts on the beaches. It would act as a buffer zone against big waves and slow down the process of erosion. Beach nourishment is an effective method except that it is very expensive. During the 1980s, the city of Miami considered the option of beach nourishment and invested $65 million. This turned out to delay the beach erosion as well as boost the local economy by attracting more tourists. Although this is regarded as a softer adaptation measure, it could be implemented along with other projects such as vegetation and dune rehabilitation plan to reinforce the protection of the beaches against the changes in sea level.

Other adaptation strategies include the construction of hard structures such as groynes, sea walls, barriers, rock revetments and gabion mattress. However, such costly civil engineering projects are not much encouraged in the tourism industry as they cause obstruction to the views of the sea and make the beach inaccessible to the visitors. For such reasons, it may be more appropriate to consider the setting up of an artificial beach which is shielded by a sea wall. In this case, visitors can still have access to the beach while the shoreline remains protected from the impact of big waves.

Figure 6.11: Structural protection to keep the artificial beach sheltered (Scott et al, 2012)

6.8 Impact of sea level rise on built-up land in Cape Town

From the findings, the built-up land was also identified to be a highly threatened land cover whereby if the RCP scenarios were to occur, a surface area of 0.14-0.19 km² would be potentially submerged. In this study, the built-up land included mostly harbour structures, and a small portion of roads, buildings, electric cables, water pipes, storm water pipes and sewerage pipes. There was not much difference among the four RCP scenarios. All the RCP scenarios showed that sea level rise would be detrimental to the built-up land and considerable damage would be expected to occur on the piers, breakwaters and marinas. Most of this land cover is located on reclaimed land and most of these structures would get eroded slowly with the rise in the occurrence and intensity of storms. The impact of big waves would also prevent access to ships at harbours and affect the berthing, loading and storage facilities for oil and gas.

The shoreline would not be expected to shift landward at a constant rate and there should be enough space for the retreat. Normally natural undeveloped buffer zones located in front of the infrastructures provide adequate space for a retreat. But in some areas such as Simons Town, Kalk Bay and the Foreshore, the coastline has already been fixed and these regions would be highly vulnerable to sea level rise. Hence there is an immediate need to manage the infrastructures at risk. More importantly, further development in these vulnerable areas should be simply avoided.

Possible solutions would be the construction of barriers, sea walls and groynes to protect the built-up land and to avoid further erosion. These engineering solutions are costly but could prove to be effective. A sea wall for instance would keep the existing infrastructure protected from sea level rise. It would mostly be appropriate at the base of cliffs. A barrier would also be another means to protect the built-up land, especially at some sections at the waterfront.

6.9 Impact on population and properties

Another receptor identified in this study was the inhabitants residing in the coastal suburbs. Currently, the concern is the alarming increasing rate of population growth of Cape Town. From the last census data, the rate of the population growth has been rising at 2.6% from 2001 to 2011. The current population of Cape Town in 2018 is estimated to be 3,776,000. According to the UN, the estimated population for 2030 is 4,322,000 (Nations, 2014).

With an increasing population, this results in the pressure and demand for more residential, commercial and industrial properties. Residential and commercial properties have increased at 200% from 1980 to 2007 and there has been an increase in the number of properties on the prime real estate adjacent to the coast. Even though the PIAs did not cover properties, sea level rise would still cause an indirect impact on the properties which are located close to the PIAs. Some of these vulnerable properties are situated within a close distance to the high water mark while others are located on reclaimed land. Earlier it was assumed that sea level in the future would not be a threat and appropriate engineering solutions would keep the regions sheltered from any rise in the sea level. However, during the last three decades, such studies are currently highly encouraged as it is now necessary to find immediate solutions to adapt to the risks of sea level rise.

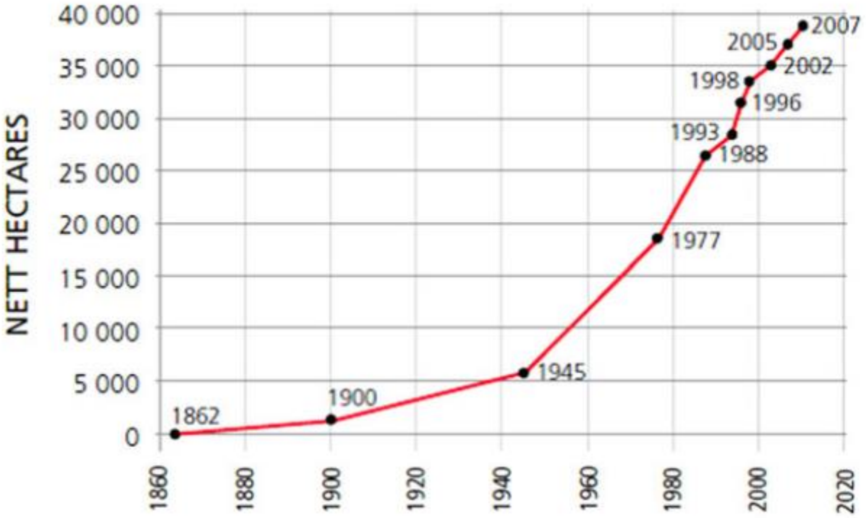


Figure 6.12: Cape Town property growth from 1860 to 2007 (Colebrander et al, 2015)

In this study we chose to not produce any quantitative results for the impacts on population. It is not ideal to predict the potential number of people affected by coastal inundation, as inhabitants cannot be accurately defined as stationary points geographically. However, many previous studies (e.g Tang et al, 2013, Zhang et al, 2011) have calculated the impacts on the population by using the current population density or an estimate of the projected population density to calculate the number of people for every 1 km^2 of loss of land. But the projected value for the population for the year 2100 is dependent on many unknown factors and it is unfair to rely on historical population values for an assessment in the future.

We also avoided calculating the cost of damage of properties, as it is difficult to estimate the appreciated/depreciated value of the properties for the year 2100. Moreover, it is not suitable to assume that the cost of damage equals the exact value of the property, especially if the property is only being inundated partially.

However such damage could be avoided if appropriate measures are taken to cope with the impacts of sea level rise. For instance further land should not be reclaimed for additional development on the coastline. Relocation of people and infrastructure could be considered as an option. However it becomes problematic to know the exact distance of the retreat. We could also resort to engineering solutions such as barriers and sea walls even though if these structures require high maintenance.

6.10 Impact on transport

Although these findings did not cover major roads, sea level rise would still have an indirect impact on the transport system in Cape Town. Roads and bridges can generally only last for about 50 – 100 years. One of the major concerns is that roads and bridges in Cape Town are relatively “old” and the tidal and storm surge effect would cause further degradation to the road network. Temporary flooding would also possibly affect the main road in Fish Hoek and disrupt the railway lines in Glencairn and Fish Hoek. Other vulnerable roads include the Marine Drive in Paarden Eiland and the Otto du Plessis drive in Tableview.

Lack of adaptation strategies would only lead to the disruption of services and traffic congestion. Raising the infrastructure could be an appropriate measure for the roads. However this approach would only work for the road network but not for bridges, as it would be too costly. Other approaches involve the proposal of a faster bus system from Tableview to the Foreshore through the older Paarden Eiland railway line. There are plans of constructing a road adjacent to Table Bay Boulevard dedicated only for public transport. The reconstruction of the Table Bay Boulevard is high likely to occur in the future and this would contribute in raising the road infrastructure by 300mm. Unfortunately, the sea level is expected to rise much higher, and this approach would not be effective in coping with the risk of permanent inundation.

6.11 Combined effects of sea level rise and additional temporary flooding

The 4 RCP scenarios from the IPCC were useful in providing us an estimate of the PIAs along the entire coastline of Cape Town and allowed us to address the first question in the study. However, a second question addressed in this study was to investigate the impacts of the combined effects of temporary flooding and permanent inundation. We conducted a detailed analysis on these following 8 coastal suburbs to quantify the direct and indirect impacts of sea level rise. Similarly, for each suburb, the range of scenarios which were presented provided a range of possible outcomes which may occur by 2100 and hence before interpreting the results, we must ensure that we have a clear understanding of each scenario.

Before analysing the findings, it is also important to note the different assumptions which were made in the design of the scenarios. Firstly, the chosen values for the increases in coastal flooding were based on the maximum values of wave heights from previous storm surge events and maximum tidal heights. However we must take into account that such values only represent the extreme cases of coastal flooding and would not generally occur on a daily basis. After a coastal flood, the water level would eventually retreat back to its original point.

6.111Case study: Impact of sea level rise on Tableview

Tableview is a large coastal suburb which consists of a beach, residential and commercial properties and some dunes. The beach follows a steep slope and goes rapidly into deeper water. Hence this influences the shorebreak to be very strong as well as intense dumping waves which do not allow for safe swimming. As a measure for the coastal erosion, there has also been a dune rehabilitation project which has been set up and visitors are advised to avoid the dunes.

Due to its bathymetry, Tableview is not well protected from big waves. In fact it is highly vulnerable to sea level rise as the waves follow a north east direction and hit the coastline of Tableview.

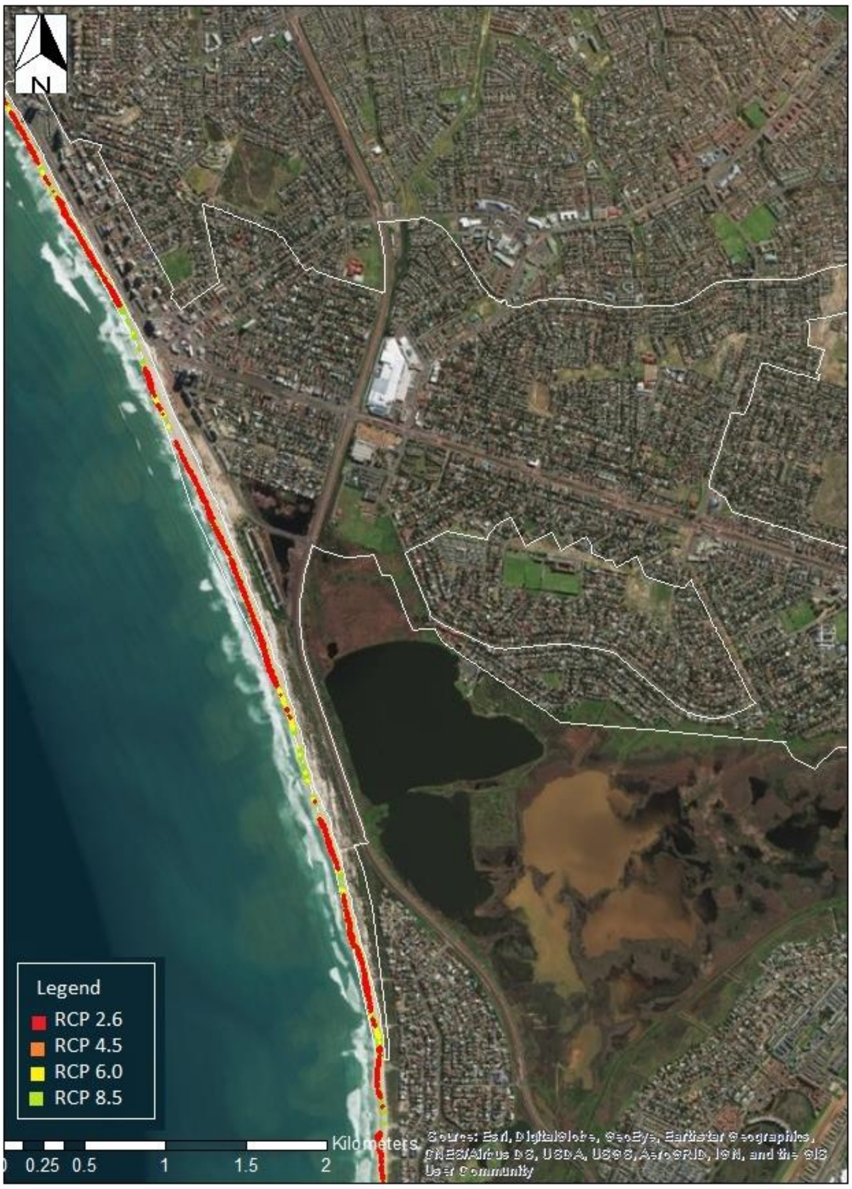


Figure 6.13: Sea level rise scenarios in Tableview

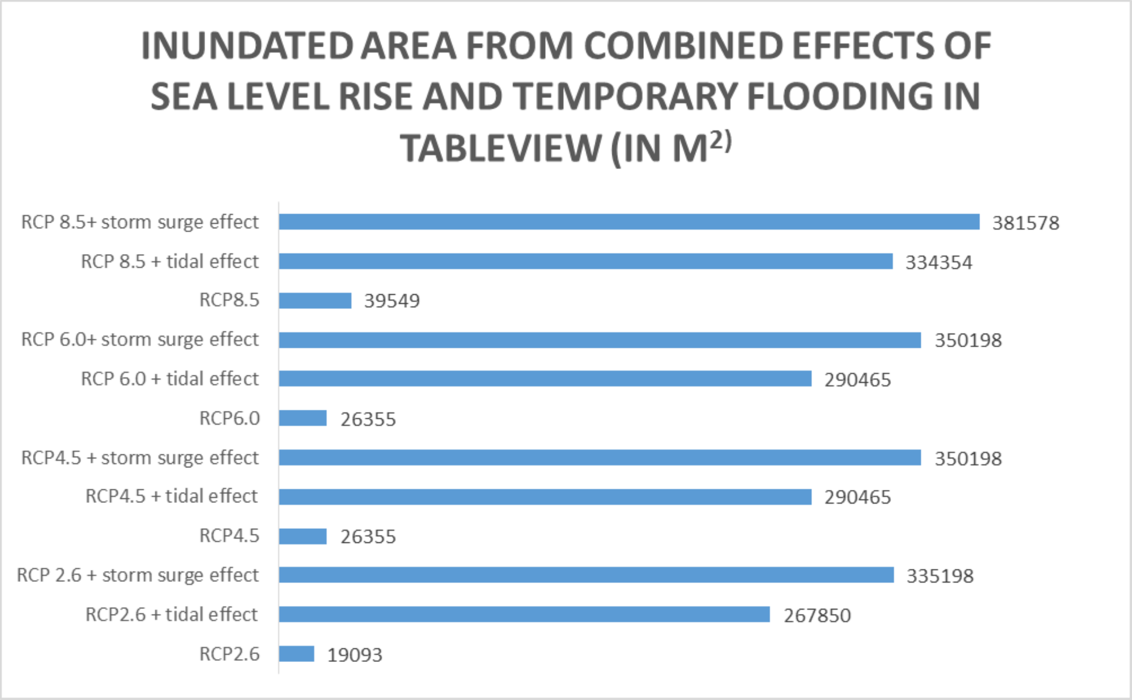


Figure 6.14: Loss of dry land from combined effects of sea level rise and temporary flooding in Tableview

From the findings, the RCP scenarios showed a submersion of land ranging from 19093m^2 to 39549m^2. All the 4 RCP scenarios would affect mostly the beach and cause erosion along the shoreline. Considering only sea level rise, RCP 2.6 would cause minimal damage which could be easily managed. On the contrary, the PIA value for RCP 8.5 was twice the PIA measured for RCP 2.6 and it would require serious damage to the shoreline.

Considering the event of a high tide or a storm surge, the potential flooded areas ranged from 0.268 km^2 to 0.382 km^2. all the 4 scenarios showed that serious damage would occur and it would affect many other receptors including the properties, roads, water bodies and the dunes. The existing Otto du Plessis Road, one of the major roads in the road network of Cape Town would also be partially flooded. As for the dunes, they would need further attention since they generally act as a buffer against the impact of big waves but their erosion is bound to increase at an accelerated rate.

Previously Hughes et al (1993) have conducted an analysis of the impact on erosion and they reported that an increase in 1 metre would lead to a landward retreat by 60m based on the Bruun rule. However this value should be viewed as a conservative one as this study was conducted 25 years ago.

Eventually, if no action is taken, the shoreline is expected to retreat landward due to the permanent inundation. But according to Bruun (1962) and Dean (1977) it would still manage to keep a balanced profile of the shoreline. As a way to adapt to the rising sea level in Tableview, hard protection measures could be considered to protect this suburb. For instance, a sandbag revetment could be built up in order to avoid further coastal erosion and to allow the dunes rehabilitation programme to be successful. Another protection measure would be the building of groyne structures in order to protect the coastline as well as to allow for a build-up of sediment. As for the Otto du Plessis drive, we could consider building a revetment buried inside the dunes as a method of adaptation to keep the road protected from the erosion.

6.112 Case study: Impact of sea level rise on Woodbridge Island

Woodbridge Island is a residential suburb located on the west side of the Diep river in Milnerton. The estuary of Diep river merges with the lagoon at Milnerton Lagoon beach. The beach is frequently visited by locals and tourists and is famous for long walks. However the sandy beach is gradually being eroded due to the impact of big waves, causing a steep dune cordon. A closer look onto the bathymetry and the wave climate shows that Woodbridge Island is greatly exposed to storm surges and high tides.

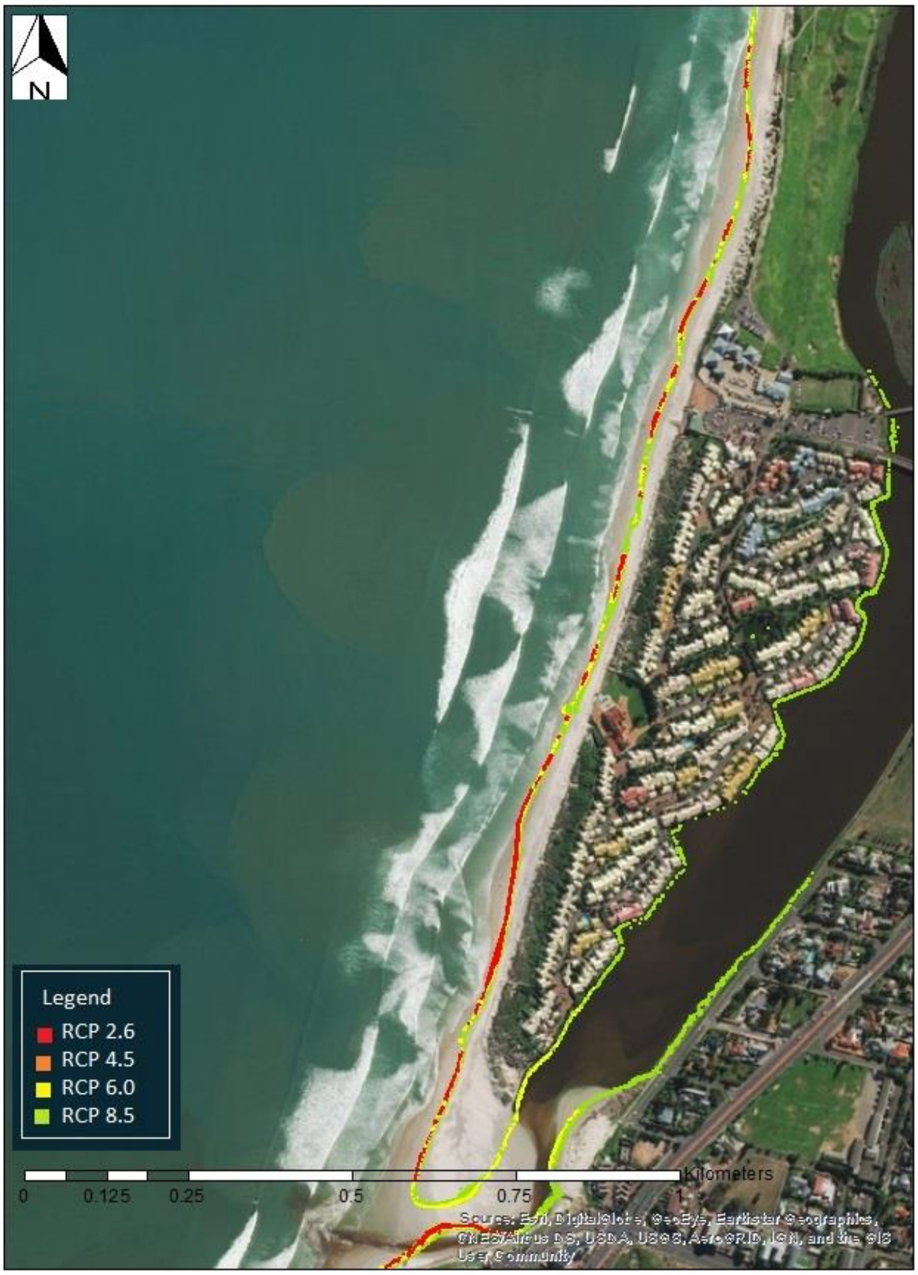


Figure 6.15: Sea level rise scenarios in Woodbridge Island

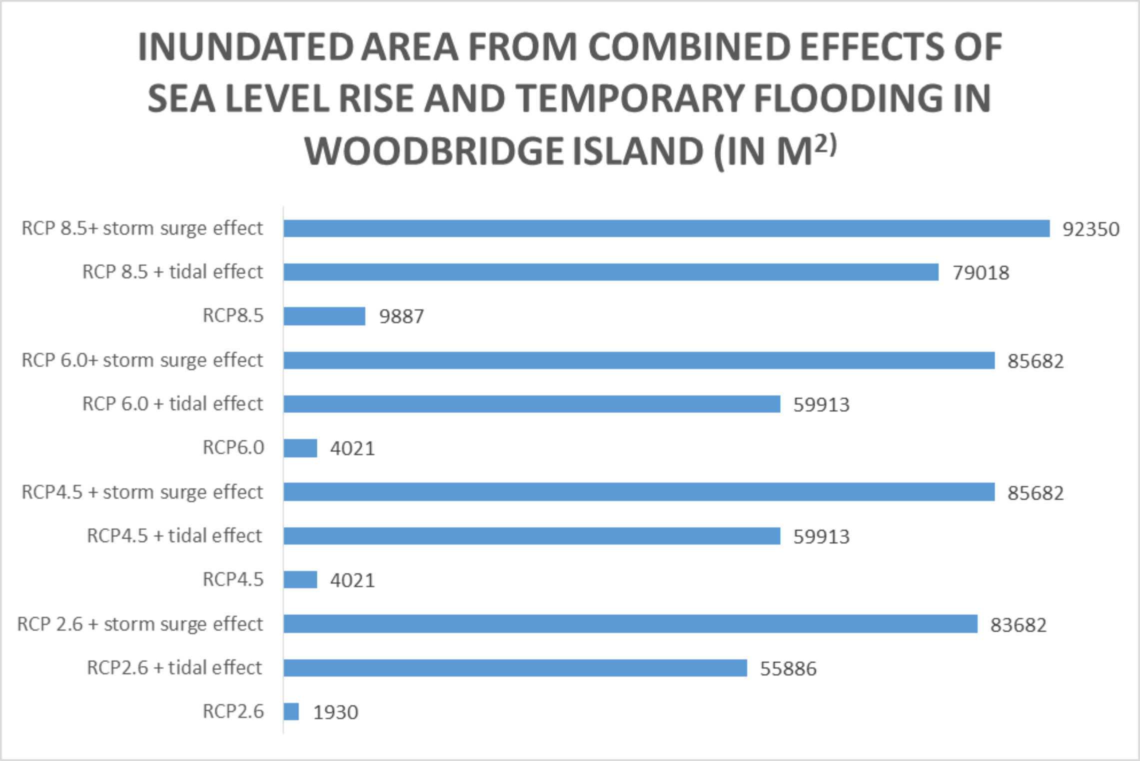


Figure 6.16: Loss of dry land from combined effects of sea level rise and temporary flooding in Woodbridge Island

All 4 RCP scenarios demonstrated that the beach is highly at risk of coastal erosion. A wide range of impacts was observed from the calculated PIA for the sea level rise scenarios. For instance RCP 2.6 would cause a loss of dry land of 1930 m^2 while RCP 8.5 revealed that 9887 m^2 of dry land would be potentially inundated. As for the combined effects of the RCP scenarios along with other temporary flooding effects the potential flooded areas ranged from 0.0559 km^2. to 0.0923km^2. The most vulnerable infrastructure included the Milnerton Golf clubhouse, the beachfront restaurants, Milnerton Lifesaving Club building, some beachfront properties and parking lots. A storm surge could lead to further penetration into the lagoon and the vlei. Moreover, if there is an additional effect of rainfall, this would lead to the surrounding water bodies causing flooding as there would be no space for the water to dissipate.

Earlier Hughes (1993) assessed the coastal retreat in Woodbridge Island and reported that a rise of 1 metre would lead to a shift of 80m landward. This could also cause the river bank to be breached and this could give birth to a river mouth at the Milnerton Golf clubhouse. Such results must however be regarded as conservative over-estimates.

It is important to emphasize that property developers should not engage in removing the remaining dunes despite the strong motivation of the construction of properties with better views of the ocean. Currently the dunes act as a natural buffer and shelter the beach from the impact of big waves. Hence, as a matter of safety for Woodbridge Island, the unstable dunes must not be removed.

Possible methods of adaptation would include the building of a rock or sandbag revetment to prevent further erosion. A crown wall structure should also be considered for the revetment so that it does not allow any overtopping. Buried revetments could also act as a shield for the existing dunes.

6.113 Case study: Impact of sea level on Paarden Eiland

Paarden Eiland has been established as an industrial suburb and comprises mainly of the harbour, industrial properties and the Salt river. Looking at a closer look at the bathymetry and wave climate, Paarden Eiland is listed among the sheltered regions due to its geographical location. It lies in the shadow zone and hence is not frequently visited by big waves.

There have been major transformations in the Paarden Eiland during the last two centuries. The harbour constructed extended to this zone whereby property developers have reclaimed most of the land. Since it consists mostly of reclaimed land, Paarden Eiland is highly vulnerable to the impacts of sea level rise. Reclaimed lands are usually subject to erosion and cannot easily endure storms due to the impact of big waves.

Figure 6.17: Sea level rise scenarios in Paarden Eiland

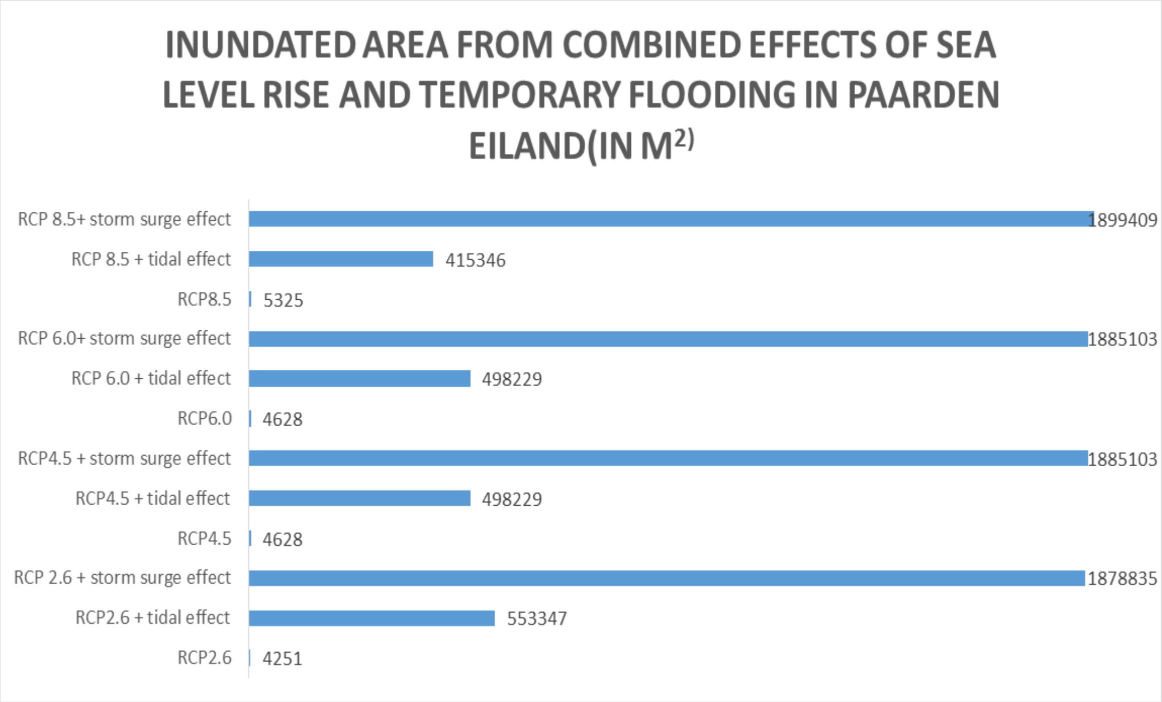


Figure 6.18: Loss of dry land from combined effects of sea level rise and temporary flooding in Paarden Eiland

The PIA values for the 4 RCP scenarios did not have a wide range (4251-5325 m^2) and would be expected to cause damage to the piers, breakwaters and marinas. Sea level rise would also have an impact on the Salt river and cause an intrusion of sea water which could prove to be detrimental to the aquatic life. The picture was more complicated in the case of additional effects of temporary flooding. Since Paarden Eiland is a small suburb, most of the suburb (1.88-1.90km^2) would be potentially flooded according to the 4 scenarios of additional storm surge effect and sea level rise. This would affect the shipping industry as it would restrict access to ships and disrupt berthing, loading and storage facilities for oil and gas. This would also involve the flooding of major roads in the road network including some sections of the Marine drive.

Taukoor (2015) previously explored the impact of sea level rise on the industrial properties in the suburb and presented a cost of damage based on the value of the potential inundated properties according to the scenarios. Although these figures did not include the current inflation rate, they allowed us to obtain a simple estimate of the loss of property area in this region.

As a coastal protection measure, a ‘dolosse’ acts as an armour and protects the coastline of Paarden Eiland. A ‘dolosse’ is a hard structure that has been specifically designed to dissipate the wave energy. Another adaptation strategy which should be considered is raising the level of the road in Paarden Eiland. This would protect the infrastructure from the overtopping by the sea. However this approach is highly costly and is also problematic as we should ensure that we know the appropriate value before raising the infrastructure.

6.114 Case study: Impact of sea level rise on Foreshore

Most of the Foreshore was built up on reclaimed land. The foreshore is an important part of the city as it consists mainly of the harbour and most of the major commercial properties. The Foreshore is situated in the shadow region whereby it is sheltered from big waves. Due to the diffraction, Green Point protects most of the northern coastline, including the Foreshore region.

Figure 6.19: Sea level rise scenarios in Foreshore

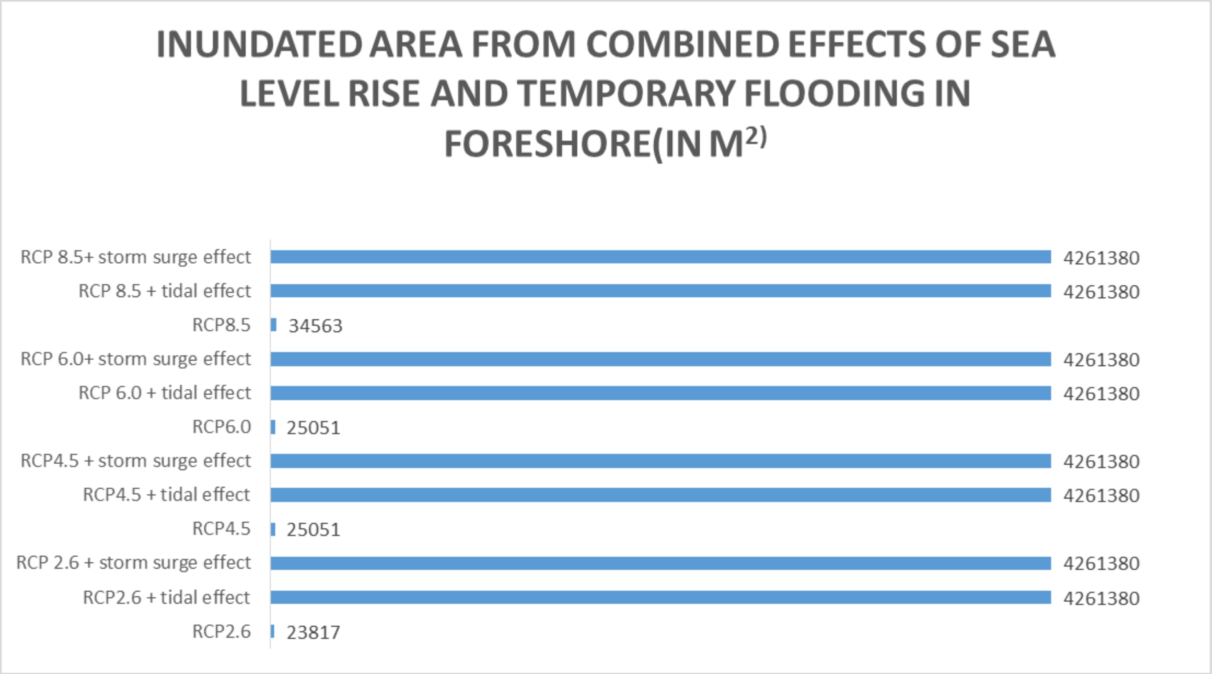


Figure 6.20: Loss of dry land from combined effects of sea level rise and temporary flooding in Foreshore

According to the IPCC scenarios, sea level rise would cause permanent inundation in some crucial areas in the suburb. RCP 2.6, RCP 4.5 and RCP 6.0 would cause a permanent inundation of 23817-25051 m^2. This would damage mostly some sections of the waterfront and harbour structures. As for the worst case scenario, the measured PIA was 34563 m^2 and extended to some of the properties and roads. The port is currently protected by breakwaters which aid in reducing erosion and the dolosse keeps the Port and the harbour pier sheltered from wave action. Foreshore has also proven to be capable of coping with discharge of large volumes of water and the roads have been designed to allow for emergency drainage.

However, these measures would not be adequate in the future and other adaptation strategies need to be considered. In the event of a storm surge or if the wave height reached the HAT value, the entire suburb would be flooded due to its lack of unreliable coastal defences against the impacts of big waves, and the fact that the reclaimed land is less stable compared to the land which rests on its parent material. This would be problematic as it would affect the entire city, including the inhabitants, the shipping industry, the properties, the road infrastructure and the water services.

Based from the findings, Foreshore would be classified as a highly vulnerable suburb which would require urgent attention. Firstly, reclamation of further land should be highly discouraged and fixing the coastline would not contribute in making it resistant to wave action. If the current coastal defences are not properly maintained, this would lead to further flooding and cause major disruption in many sectors. Regular maintenance of the stormwater system would also be necessary to ensure that the drains and the stormwater systems would not block any flow of flood water.

Other adaptation solutions include relocation. Unfortunately in the case of the Foreshore, relocation is not a solution. One example would be the Cape Town docks. Alternately, the raising of infrastructure could be more appropriate to prevent further flooding even if it requires much financial investment. Construction of solid sea walls and barriers would also keep the suburb protected only if there would be regular maintenance so that leaks could be avoided.

6.115 Case study: Impact of sea level rise on Sea Point

Much of Sea Point consists of reclaimed area as well as a few beaches along the coastline from Mouille Point to Bantry Bay. Most of these beaches are either small bays or strips of sand forming across the rocky coastline. It has also been reported that visitors tend to avoid these beaches for recreational use due to a high pollution level. For the majority of this suburb, the sea wall has been constructed along the coastline and it attracts a huge number of locals who prefer walking along the promenade.

Sea Point is generally well exposed to breaking waves but does include some areas which are protected due to the presence of offshore reefs. The rocky coastline is located on an unprotected wave cut platform rising above the ocean. At the Big Bay for instance, there are rock outcrops which shelter the bay from the wave action.

Figure 6.21: Sea level rise scenarios in Sea Point

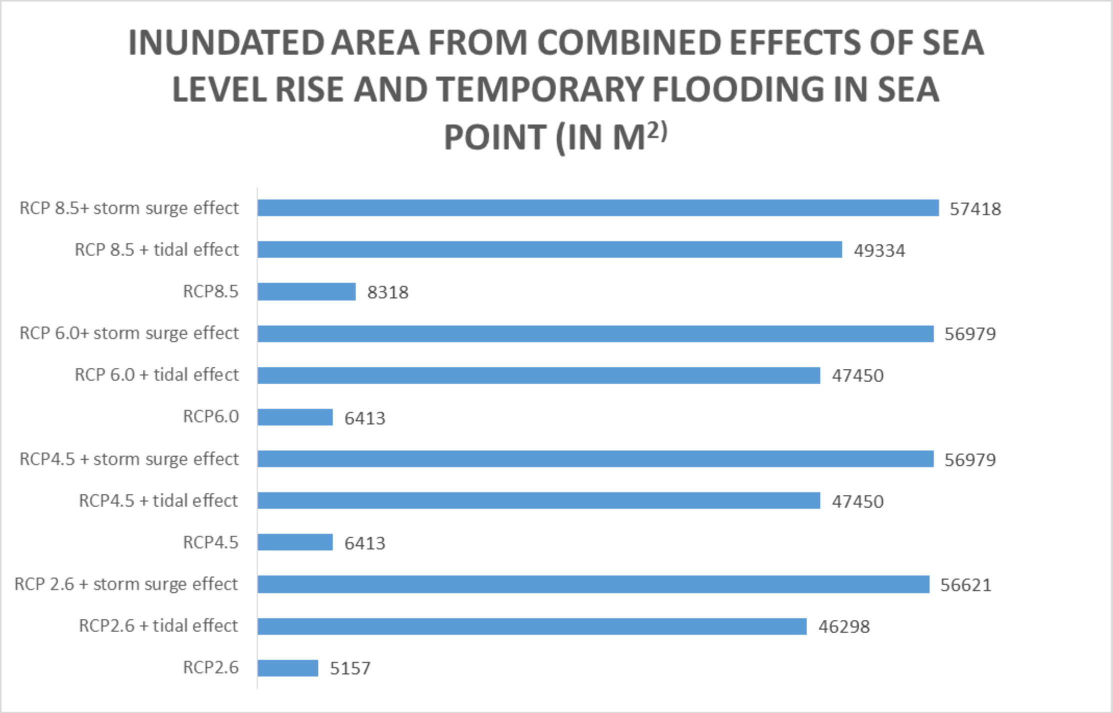


Figure 6.22 Loss of dry land from combined effects of sea level rise and temporary flooding in Sea Point

The RCP scenarios showed a considerable rate of increase in the PIAs ranging from 5157 m^2 to 8318 m^2. According to the 4 RCP scenarios, the promenade would not be highly threatened. Sea level rise would only have an impact on the sandy beaches and rocky shores of Sea Point. Although with additional temporary flooding, it might lead to overtopping events which would flood a potential surface area of 46298-57418 m^2. This would damage the promenade, parking lots and several beachfront properties. This could also lead to partial flooding of the Beach road. As an adaptation method, we should think of the installation of draining facilities along the road e.g stormwater retention ponds to cope with future coastal flooding.

Much of Sea Point is part of being reclaimed area; this implied that the coastline had already been fixed. And hence the only remaining protection measure against sea level rise is the sea wall. It is necessary to ensure that the sea wall undergoes regular maintenance. In fact sea walls constantly need repairs as they are often not well designed and hence fail to dissipate the wave energy. There is a possibility that the impact of big waves eventually leads to the steepening of the littoral zone and hence threatens the foundations of the fixed hard structures such as the sea wall and the embankment. In fact, there are cases whereby the sea wall can worsen the impacts of sea level rise by allowing the waves to concentrate all their energy and flow towards the end of the wall and causing an accelerated rate of erosion at adjacent coastal areas. In case of failure of the sea wall from extreme waves, this would cause much damage to the infrastructure, the properties and could even cause loss of life.

The installation of flood sensors would also be useful and could aid in early forecasting systems of coastal floods. This would in turn allow for better planning, and the Beach road could be temporarily closed off during such events. In addition, there should be new legislation to reinforce no further development seaward of Beach road.

6.116 Case study: Impact of sea level on Glencairn

Glencairn is a small coastal residential suburb which consists of a sandy beach. The mouth of the Else River is located at the side of the beach. The presence of the railway tracks has greatly modified the Else River's hydrology. Over the years, the plantation of the marram grass has contributed in maintaining the stability of the sand. Wind regularly blows the sand onto the railway tracks, and this extends to the vlei area. Earlier there has been an alien invasion of the Acacia shrubs in the valley, but they were eventually removed and this led to the formation of artificial ponds.

Looking at the wave climate of the west side of False Bay, the coastline which starts from Muizenberg extending towards the southern cape peninsula, is generally protected from waves entering the bay. This is because there is a diffraction of the waves in the shadow area and eventually they travel to the coast after getting refracted by the bathymetry.

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 6.23: Sea level rise scenarios in Glencairn

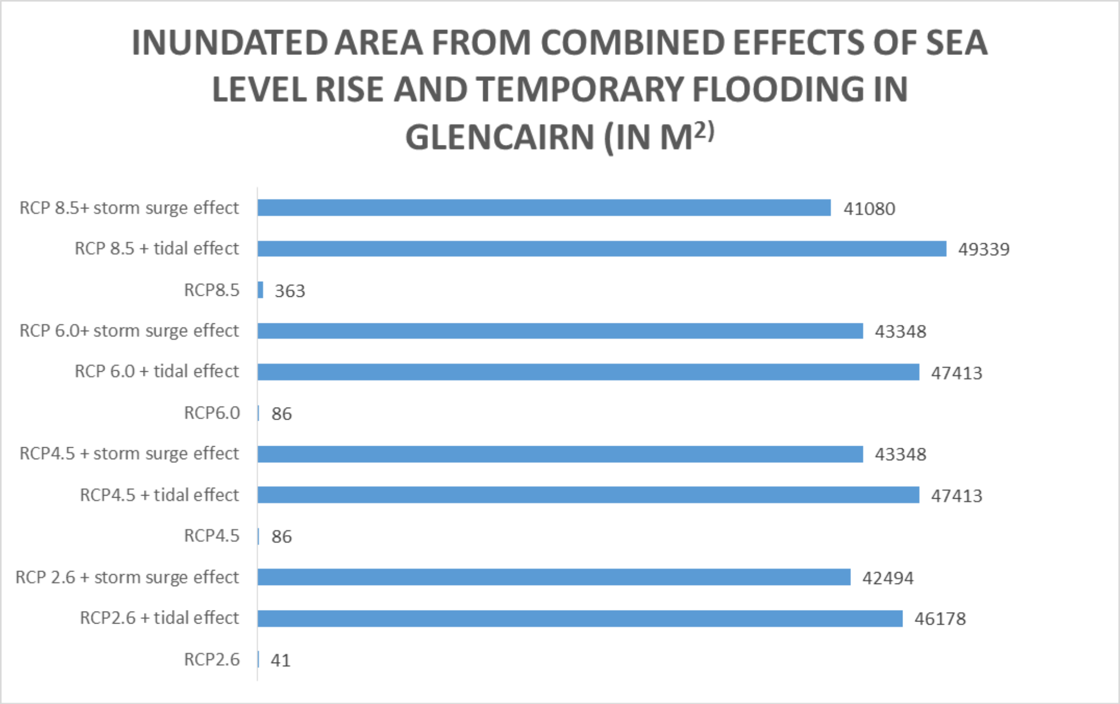


Figure 6.24: Loss of dry land from combined effects of sea level rise and temporary flooding in Glencairn

Based on the findings, the RCP 2.6, RCP 4.5 and RCP 6.0 did not show much damage to the shoreline (41-86 m^2) while RCP 8.5 showed a loss of dry land of 363 m^2. However the 4 RCP scenarios along with additional temporary effects revealed that Glencairn's coastline would be highly affected by the impacts of sea level rise due to its lower elevation coastal zone. In this case, tidal effects have been known to exceed the impacts of the effects from a storm surge and an area of 46178-49339 m^2 would be potentially flooded. The main receptors included the beach, the road infrastructure and the railway line.

Glencairn is mostly vulnerable due to the variations in the occurrence and strength of storm surges and other natural processes which included the migration of dunes and coastal erosion. (City of Cape Town, 2005; Cartwright, 2008; Cartwright et al, 2008). During the summer months, the south-easterly winds cause much coastal erosion along the beaches in the southern peninsula and during the winter months, the beaches experience a phase of accretion due to the westerly winds accompanying the storms. (Colenbrander et al, 2012). Hence major erosion incidents would be expected to occur during summer, although there have also been reports of erosion due to storm surges accompanied by cold fronts during the winter.

It is high likely that the sea level rise will cause the sandy coastline to retreat towards the land while keeping a balance. However, this shift may be restricted by the existing revetment.

One of the main vulnerable infrastructure of Glencairn is the railway track. There is urgent attention required for the railway tracks to ensure that the railway line can still operate properly and avoid any accidents. In this small coastal suburb, the railway plays an important role in the tourism sector as well as it contributes to a sustainable local economy.

A few local studies have previously outlined the threat of sea level rise on the railway tracks. Hughes (1993) worked on the mapping of the coastal erosion in Glencairn and suggested that a 1 metre rise would cause a coastline recession of 48 metres. According to that study, Hughes also reported that the contourline of 1 metre would include much of the railway line. Faasen (2014) investigated a rise of 1m in Glencairn and based from this assessment, it was concluded that the railway line was situated at an elevation of 4 metres above sea level and would be highly vulnerable in the event of a high tide. Taukoor (2015) also proposed 3 scenarios for Glencairn and pointed out that the most vulnerable railway line was located in the Glencairn and Simons Town sites. She suggested that this particular region required more attention in terms of maintenance and repair to prevent further damage.

Previously there have been many occasions whereby the railway tracks could not be operational due to a rise in the sea level and they needed to be repaired. However such disruption was in turn causing a major disruption in the transport system. It was affecting the tourism sector and other local activities which relied entirely on the operation of the railway. For instance, during summer 2011, a major erosion event happened in the area. There were records of waves which could then reach within 50 cm of the railway tracks. Hence immediate decisions were taken and the railway line was closed down temporarily.

Similarly for Fish Hoek, several adaptation strategies could be done. For instance raising of the infrastructure would keep the railway line along with the roads protected. Other hard structures such as groynes, barriers and sea walls could also be considered. However such coastal protection measures would not allow easy access to the beach.

6.117 Case study: Impact of sea level on Fish Hoek

Fish Hoek is a coastal suburb located along the Cape peninsula. This residential suburb has an exposed sandy beach. Fish Hoek beach has recently been granted the status of a blue flagged beach and has been attracting many visitors. At Clovelly, there is a river which flows into the ocean during the winter months while the lagoon remains stagnant during summer. Most visitors make use of the beach for recreational activities. However at a springtide, it has been reported that the waves reach the wall of the beachfront promenade and this does not allow for much space on the beach. Some locals also visit the beach for fishing activities. Although since 2006, new changes were implemented with regards to long term fishing rights, and this has led to a decrease in the number of permit holders.

Due to its location along the western side of the False Bay, Fish Hoek formed part of the list of areas which are sheltered from big waves. However in the event of a uniform increase in sea level, Fish Hoek would be very vulnerable.

Figure 6.25: Sea level rise scenarios in Fish Hoek

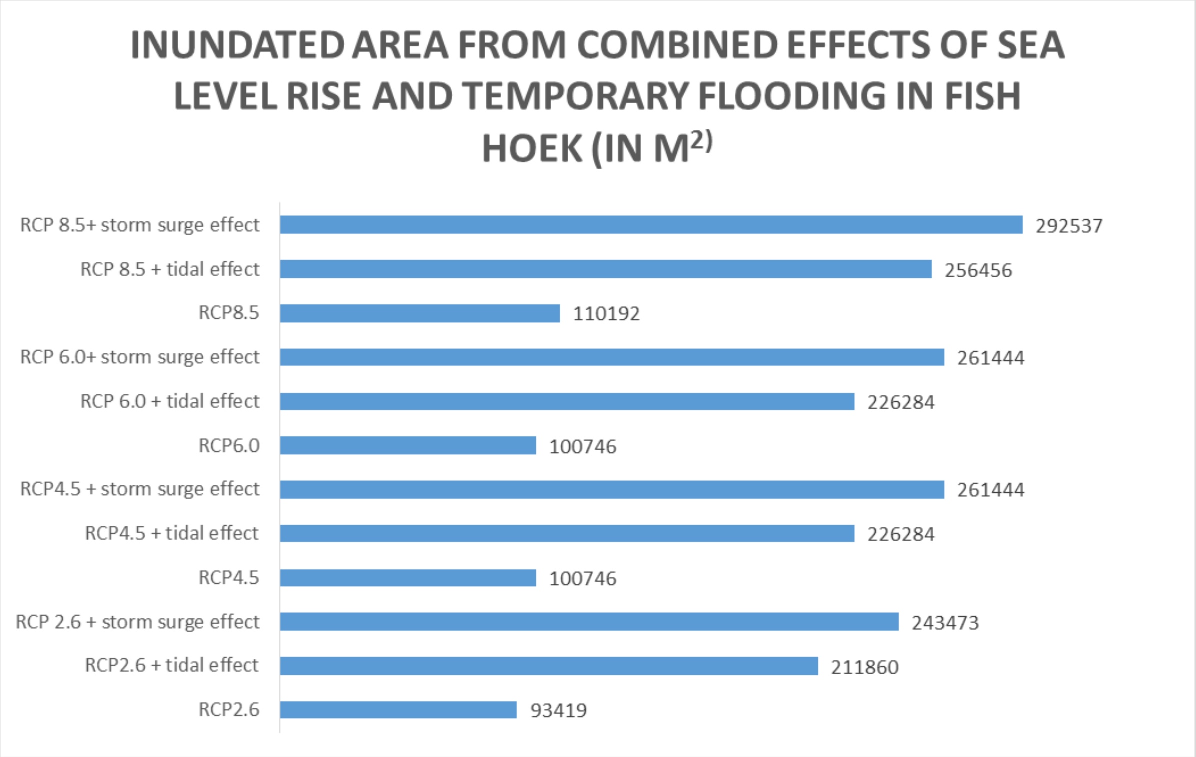


Figure 6.26: Loss of dry land from combined effects of sea level rise and temporary flooding in Fish Hoek

Looking at the scenarios, the RCP scenarios showed potential submersion of 93419 – 110192 m^2 of dry land. The most threatened zones of Fish Hoek were the beach, some beachfront properties, car park, and the yacht club. Currently there are sand bags which are being used to reduce the impact of waves. As for the combined effects of temporary flooding, the PIAs showed that 211860 – 292537 m^2 of dry land would be potentially flooded. Some of the receptors of the indirect impacts include the railway tracks and the camping zone as they lie at an elevation of 3 metres above sea level.

Faassen (2014) conducted a preliminary assessment of sea level rise in Fish Hoek and explored the impacts of a rise of 1 m. The study showed that this would cause the HAT for Fish Hoek to reach a new value of 2.247m. The study highlighted that this rise would prove to be highly concerning for the beachfront properties as these properties are located at an elevation of 2.5 m above sea level.

If no action is taken place, the coastline will probably get eroded gradually as the level of the ocean keeps increasing. In fact, earlier, Hughes (1993) investigated the impact of sea level rise on coastal erosion and pointed out that the beach could possibly recede to 70 m based on the Bruun rule. This would imply that the shoreline would be within 25 metres from the railway tracks. It is also argued that the recession could also be reduced due to the current infrastructure such as revetments.

There are several ways which could be considered to address the impacts of sea level rise in Fish Hoek. One of the suggestions is the setting up of an embankment whereby it would be shielded by a revetment and a crown wall. The fixed hard structures could be made from sand bags, rock or concrete units and this in turn would greatly reduce coastal flooding.
As for the vulnerable beachfront properties, smaller but hard structures such as groynes could be constructed to protect them against the impact of big waves. Raising the infrastructure would also be one of the solutions as an attempt to adapt to the changes of the sea level. However the main challenge lies in the decision of the elevation to which the infrastructure should be raised. The cost of raising the properties could also be very high. Hence if such measures cannot be taken, then it might be best to relocate them to a safer zone since the cost of maintenance for these properties would be too high.
In the case of adaptation measures for the railway line, it could be raised onto another layer of bridge structure. Another important suggestion would be to install flood sensors and provide early warnings to inform passengers when it is not safe anymore to travel to Fish Hoek by train.
As for the beach of Fish Hoek, as mentioned earlier, since it is a blue flagged beach, it might be necessary to consider beach nourishment to preserve this valuable asset for the local tourism sector. Despite being an expensive adaptation strategy, this would not only protect the beach against erosion, but as well as the local infrastructure and the railway line.

6.118 Case study: Impact of sea level rise on Strand

Strand is a coastal suburb which consists of 2 sections, namely Melkbaai and Mostertsbaai. The most vulnerable receptors in Strand are the beaches, the Beach road and some beachfront restaurants and shops. At Melkbaai, visitors mostly use this beach for swimming and as for Mostertsbaai, it consists of a rocky shore whereby visitors would often go fishing.

Strand is located on the eastern side of False bay and is moderately exposed to big waves due to the north east direction of the waves coming from the south. The bathymetry is moderately sloping. The rocky banks are situated offshore and it is believed that they decrease the wave intensity since the waves break further offshore.

Figure 6.27: Sea level rise scenarios in Strand

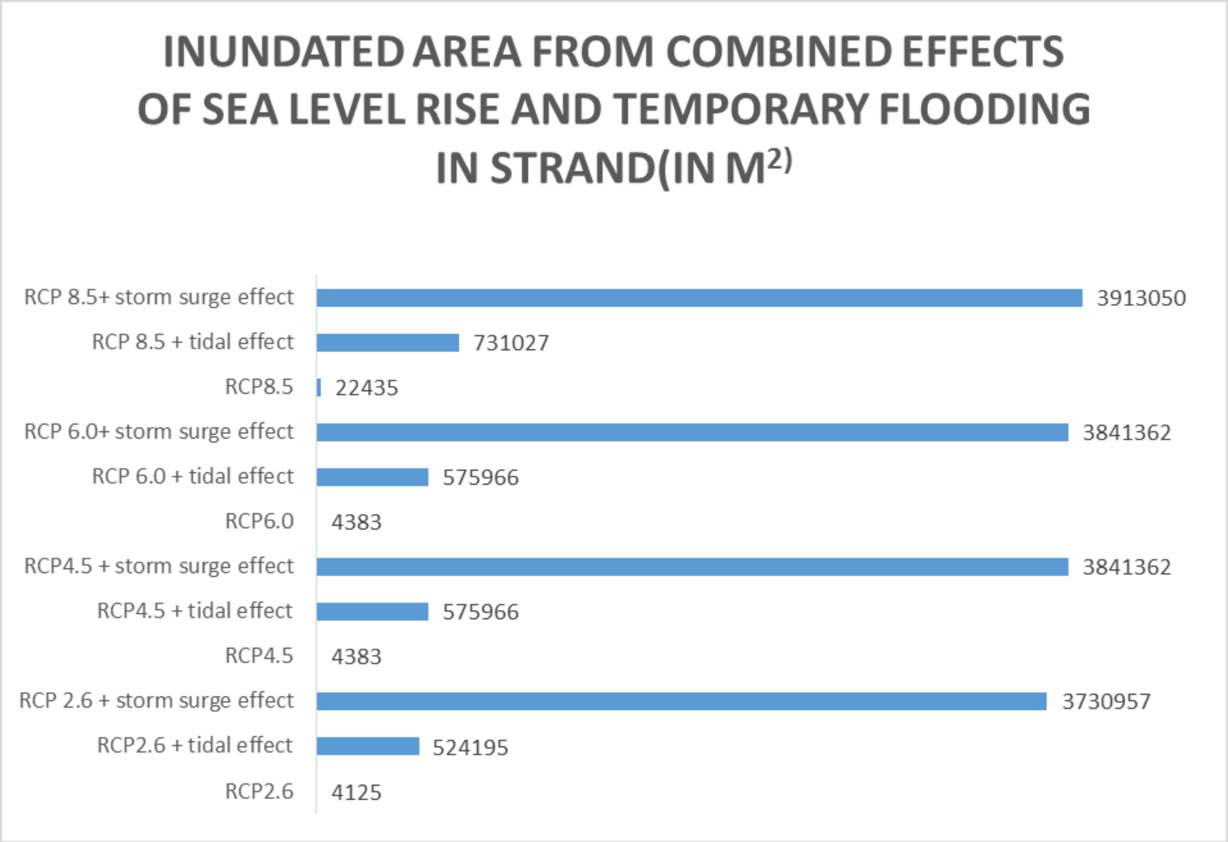


Figure 6.28: Loss of dry land from combined effects of sea level rise and temporary flooding in Strand

Applying the IPCC scenarios of sea level rise to Strand, RCP 8.5 had a relatively higher PIA (22435 m^2) compared to the remaining RCP scenarios which ranged from 4125m^2 to 4383m^2. The additional tidal effect would cause some damage ranging from 524195 m^2 to 731027 m^2, but the scenarios for the additional storm surge effect would be disastrous for the suburb. All the scenarios identified the beach of Strand as a highly vulnerable land cover. It was also observed that the parking lots, streets and beachfront properties would be affected as a consequence of overtopping and temporary flooding. Despite the presence of rock revetment, Strand is not entirely sheltered from storm surges and tidal variations. The rock revetment can aggravate the impacts of coastal flooding by instead converging all the wave energy towards the areas which are adjacent to the revetment.

Due to a poorly developed coastline within the coastal active region, sea level rise has impacted adversely on the infrastructure in the Strand area. Despite no evidence of significant recession of the coastline, extensive development

This is strongly supported by other local studies such as Hughes (1993) and Faasen (2014). Hughes (1993) demonstrated a rise in 1 metre would cause the coastline to retreat by 150 metres. However, this study was based on the assumption that the entire shoreline comprised of a substrate which could be eroded and the design of the scenario also ignored the rocky reefs located offshore as well as the sea wall. Hence this value is considered as an over-estimate. Faasen (2014) assessed the impacts based from a rise of 1 metre and added an effect of an extreme tide value. From a rise of 2.247 metres, the sea level was now 40 cm away from the upper end of the sea wall and it was reported that any temporary increase in sea level is high likely to lead to coastal floods.

In the case of Strand, beach nourishment or sandbag revetment would be a suitable solution to keep the shoreline stabilised instead of investing in hard protection measures such as groynes or rock revetments.

Chapter 7: Conclusion

7.1 Summary

This study highlighted the impacts of sea level rise along the coastline of Cape Town based from the 4 scenarios of the 5th Assessment report of the IPCC. After processing LiDAR data and creating a DEM of a spatial resolution of 2 metres, we were able to generate the mean and the maximum rise for the RCP scenarios. RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 would cause a loss of dry land of 2.16 km², 2.43 km², 2.43 km² and 3.09 km² respectively. Looking at a breakdown of the PIAs, it was observed that the major receptors were beaches including blue flagged beaches (0.04-0.08 km²), sandy beaches (1.08-1.66 km²) and rocky shores (0.81-1.01 km²) and built-up land (0.14-0.19 km²)

The scenarios for sea level rise were also applied on 8 different coastal suburbs, namely Tableview, Woodbridge Island, Paarden Eiland, Foreshore, Sea Point, Fish Hoek, Glencairn and Strand. The effects of additional temporary flooding from tidal effect and storm surge effect were also explored and the loss of dry land was calculated. Through this assessment, different adaptation strategies were discussed, for instance, beach nourishment was suggested in the case study of Fish Hoek beach, while the raising of infrastructure may be an appropriate solution in Tableview.

7.2 Limitations and improvements

However this research was restricted by some limitations. The 2 metre grid cell from the LiDAR derived DEM would still include some uncertainty. However an increase in the spatial resolution would only lead to an interpolation of the point cloud data due to the average point spacing. Hence it was preferable to work with a spatial resolution of 2 metres. However if the average point spacing was lesser, we could have generated a DEM of higher resolution. This study also included some level of uncertainty. Since many processes were done manually, the results were bound to include some minor human errors. For instance, during the pre-processing phase, the removal of the inundated polygons which were not connected to the coastline had been done manually. Another source of error lied in the manual digitisation of the beaches and the data capture for the shapefile of coastal suburbs. Unfortunately, it would be difficult to fix these errors at this stage.

Another limitation which was identified was that we did not have access to valuation datasets. We also did not explore the different techniques and tools to assess the cost of damage using an inundation model. This in turn prevented us to assess the cost of damage based from the RCP scenarios. This study was also restricted by errors which could have occurred during the refining of the DEM by deleting the polygons which are not connected to the coastline. This could have been improved through the use of an algorithm to delineate only the pia which are connected to the coastline. This study could have also been improved by providing the PIA results from more scenarios, e.g the RCP scenarios for another time period could have been calculated and an assessment of the comparison could have been done.

Lastly these scenarios did not take into account other dynamic processes. For instance different sections of the shoreline react differently to a rise in the sea level. This study also did not account for the impact on water bodies whereby precipitation could also bring changes to the local sea level from the inland water bodies. However such systems are complex and the model would require a more complex methodology. This model could not also take into account the different flood walls along the coastline. Hence the results could possibly be an overestimate for some areas.

7.3 Future research

Following this study, it was found that sea level rise would cause much coastal erosion along the sandy beaches. However we are unsure by how many metres would the shoreline shift landward. This research could be expanded by investigating the quantitative impact of coastal erosion on the sandy beaches. Previous studies have used the Bruun model to calculate the coastal retreat from the bathymetry and the magnitude of the rise in the sea level. We would have a better understanding of the vulnerability of the shoreline of Cape Town if we assessed the distance of the coastal retreat based from the RCP scenarios of the sea level.

Another way of expanding this research would be to investigate the impacts of sea level rise and additional temporary flooding effects on a range of sectors such as population, properties, the transport system, water bodies (including the wetlands, lakes, estuaries and groundwater), dunes, vegetation and the electric cables. The cost of damage of properties and other services could also be calculated based on the RCP scenarios. Through these impacts, we would be able to determine better adaptation strategies for these receptors.

These maps could also be designed to be interactive and could be uploaded online on a website so that more awareness could be raised on the risks of sea level rise. Through this website, we could offer a range of different tools whereby the users could have access to a user-friendly interface and learn about the different areas and land covers which would be affected by sea level rise. Lastly this study could also be expanded by exploring the socio-economic aspect. The vulnerability could be measured through different socio-economic index and this study could help in determining the most appropriate coastal adaptation policies.

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