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The Effects of Climate Induced Sea Level Rise on the Coastal Areas in the Hambantota District, Sri Lanka

A geographical study of Hambantota and an identification of vulnerable ecosystems and land use along the coast

Hanna Frykman & Per-Olof Seiron

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Physical Geography and Ecosystems Analysis
Lund University
Sölvegatan 12
S-223 62 Lund
Sweden

The Effects of Climate Induced Sea Level Rise on the Coastal Areas in the Hambantota District, Sri Lanka

A geographical study of vulnerable ecosystems and land use along the coast

Hanna Frykman and Per-Olof Seiron
Master's thesis in Physical Geography and Ecosystem Analysis

Supervisors: Petter Pilesjö and Jonas Åkerman
Department of Physical Geography and Ecosystem Analysis
Lunds University, 2009

Abstract

For about two centuries the atmospheric concentrations of greenhouse gases has been increasing as a result of human activities. This has lead to what is now commonly knows as the greenhouse effect. The need to predict and to understand the affects that elevated concentration of greenhouse gases has on Earths systems is important. One effect that is predicted to occur is the rise of global sea levels due to the increase in global mean temperatures.

The Intergovernmental Panel on Climate Change (IPCC) predicts a sea level rise (SLR) of 18-59 cm by the end of the 21st century. In a worst case scenario, the sea level could rise with as much as 5 to 6 meters. With an ever increasing number of people living around the world's coasts and with all the vulnerable ecosystems that habitat these areas, makes this an important issue to study. The challenges of facing these threats will be greater on countries in the developing world.

Therefore the focus of this study will be on sea level rise and its effects on the Sri Lankan coastal district of Hambantota. The Hambantota coastal area host's a number of unique ecosystems that are sensitive to change. The district is also dependant on the economical value of the coastal area for its salt, fishing and tourism industry. The impact of a potential SLR on the coastal areas of Hambantota would most likely affect the whole district.

Two models were applied in this study: Digital Elevation Model (DEM) and the Bruun Rule. The SLR scenarios used in this study were: 0.18, 0.59, 1, 2 and 6 meters. The DEM modelled flooding scenarios with the different SLR predictions and the Bruun rule applied the same SLR predictions to model shoreline retreat. Both models were applied, analysed and evaluated using GIS software.

The results suggest that the coastal areas of Hambantota district will be affected by a potential SLR. According to the DEM flooding scenarios, 5.9 square kilometres will be flooded using the 0.18 meter scenario and 44.6 square kilometres for the 6 meter scenario. For the Bruun rule the shoreline retreat for the 0.18 scenario will average 2.2 meters and for the 6 meter scenario the retreat will average 74.3 meters. The total affected land area for the Bruun 0.18 m and 6 m scenarios will be approximately 82000 m^2 and 2760000 m^2 respectively.

Keywords:
Physical geography, Sea level rise, GIS, DEM, Bruun Rule, Sri Lanka

Sammanfattning

I nästan två århundraden har koncentrationerna av växthusgaser i atmosfären ökat som ett resultat av mänskliga aktiviteter. Detta har lett till vad som nu är känt som växthuseffekten. Behovet av att kunna förstå och förutsäga effekterna som förhöjda koncentrationer av växthusgaser har på jorden är viktigt. En diskuterad effekt är en global höjning av havsnivåerna tillföljd av höjd global medeltemperaturer.

Intergovernmental Panel on Climate Change (IPCC) förutspår en havsnivå höjning på 18-59 cm innan slutet på århundradet. I värsta tänkbara scenario kan havsnivån höjas med så mycket som 5-6 meter. Det evigt ökande antal människor som bor längs världens kuster och de känsliga ekosystem som finns lokaliserade här, gör detta till ett viktigt problem att studera. De utmaningar som krävs för att möta dessa hot kommer att bli större i länder i utvecklingsvärlden.

Fokus för denna studie ligger på stigande havsnivåer och dess effekter på kust området i regionen Hambantota, Sri Lanka. Hambantotas kustområden är hem till ett antal unika ekosystem som är känsliga för förändring. Regionen är också beroende av det ekonomiska bidragen från dessa kustområdena för dess salt-, fiske- och turistindustri. Effekterna av en potentiell havsnivå höjning i Hambantota skulle med största säkerhet påverka hela distriktet.

Två olika modeller användes i denna studien: Digital höjdmodell (DEM) och en matematisk erosionsmodell; Bruun Rule. De olika scenariona för höjd havsnivå som användes i denna studien var: 0.18, 0.59, 1, 2 och 6 meter. I DEMen modellerades översvämningsscenarier och Bruun använde samma gränsvärden för att modellera kustlinjens tillbakadragande. Båda modellerna applicerades, analyserades och utvärderades medhjälp av GIS mjukvara.

Resultaten antyder att kustområdena i Hambantota kommer att bli påverkade av en potentiell havsnivå höjning. Enligt DEMens översvämningsscenarion kommer ca 6 km^2 översvämmas vid 0.18 m scenariot och ca 45 km^2 vid 6 m scenariot. För Bruun kommer kustlinjen att flyttas i genomsnitt 2.2 m för 0.18 m scenariot och 74 för 6 m scenariot. Den total påverkade markarean för 0.18 m och 6 m scenariona kommer att bli 82000 m^2 och 2760000 m^2 respektive.

Nyckelord:
Naturgeografi, Havsnivåhöjning, GIS, DEM, Bruun Rule, Sri Lanka

Handledare: **Petter Pilesjö** och **Jonas Åkerman**
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1. Introduction

Scientific evidence suggests that emissions of greenhouse gases originating from anthropogenic sources significantly affect the earth's climate primarily by an increase of the global mean temperature (Houghton et al., 1996 in IPCC 2007). The warming of the earth's climate system is predicted to have extensive effects on the global climate and these climatic effects are predicted to intensify in the 21st century. One such intensified effect is an increasing rate of the global sea level rise (SLR) (Warrick et al., 1996 in IPCC 2007). Between the years 1961 and 2003 the global sea level rose at an average rate of 1.8 mm per year and between the years 1993 and 2003 this rate was higher, averaging approximately 3.1 mm per year (IPCC 2007). An increase of the global mean temperature will lead to accelerated glacial melting (eustatic change) which combined with thermal expansion (steric change) of ocean water will raise global sea levels (Komar, 1998). According to IPCC's SRES scenarios, sea levels will rise by between 18 and 59 cm by the end of the 21st century (IPCC 2007). In the worst case scenario, which would be a collapse of the West Antarctic Ice Sheet (WAIS), the sea level might rise with as much as 5 to 6 m over a period of 100 years (Nicholls et al, 2005). Due to the time scales involved in climate processes, the anthropogenic warming of the global climate and SLR will continue for centuries, regardless of whether a stabilization of greenhouse gas concentrations were to take place or not (IPCC 2007).

There are heated arguments regarding whether or not climatic changes and increased global temperatures are anthropogenic. It is also debated what the reasons for climate changes are and what the effects of them will be. However, these arguments will not be covered by this study which focuses on the actual fact that there is a change in temperature and that the rise of sea levels is evident and irreversible within the near future (IPCC 2007).

The size of the ice caps has fluctuated greatly over time and the sea level has been both higher and lower than at present. The big difference now, though, is that the world is much more densely populated than ever before and millions of people would therefore be affected if sea levels were to rise (Nicholls et al. 2005).

The predicted bio- geophysical effects of SLR on coastal areas include an inundation of low lying lands, an erosion of coastlines, intensified storm flooding and the increasing salinity of freshwater aquifers and estuaries. These effects will endanger both sensitive coastal ecosystems and human activity such as industries and settlements (IPCC, 2007 WG II). With an ever increasing number of people choosing to live along the coasts of the world, an SLR is becoming a serious threat. Trying to predict the effects of SLR constitutes an important measure both economically and ecologically (Nicholls & Klein, 2000) and it is important to find methods for identifying endangered areas. Although SLR is a global problem, adapting to rising seas is a greater challenge for the developing world than it is for the developed world. This is basically due to a lack of means and experience with regard to tackling this specific problem in developing countries (IPCC, 2007 WG II).

1.1 Project background

This study is the result of a field study made in early 2008 as part of a "minor field study" for a Master's degree. The study area is the coastal zone in the Hambantota district, located in southern Sri Lanka. Hambantota's 140 km coastline is an important part of the region's economy which relies heavily on tourism, salt production and fishing. Within this coastal zone some of the most valuable and productive ecosystems in the world can be found, and it includes lagoons, river deltas and estuaries, coastal wetlands and sand dunes (HICZMP 4, 2005). The effects of an SLR could potentially jeopardize these ecosystems and industries.

The potential threats can be identified by the use of existing erosion and inundation models. Digital Elevation Models (DEM) in combination with GIS software are commonly used in coastal modelling. DEMs are becoming more and more available to the public with an ever increasing accessibility of data and software. Low resolution DEMs (standard of around 50m) can be produced quickly and at low costs. They can easily identify coastal areas that are at risk of an increasing in mean sea level rise. Thus, this is one of the modelling approaches used in this study.
Mathematical models are also regular features in costal modelling and the Bruun Rule, which is a 2- dimensional mathematical model and often used in coastal studies such as DuBois (1975, 1976, 1992), is also employed in this study. The simplicity of the model makes it easy to use and interpret and it proposes a trustworthy method by which to calculate expected changes in the beach profile that are caused by SLR.

A geographical information system (ArcGIS) is used as the main analysing tool for this study. By combining publicly available data, i.e. data you can access or purchase through different governmental departments and authorities or research institutes, with personally collected field data, it is possible to make an estimation of potential risk areas.

1.2 Aim of the study

This study examines the potential impact of sea level rise (SLR) focusing on inundation of low-lying lands and erosion of coastlines in the Hambantota district, Sri Lanka. A geographical study is conducted in order to become familiar with the physical conditions of the area studied and thereby to facilitate examination and analysis of the results.

The primary aim of this study is to investigate and test methodologies for coastal modelling using Digital Elevation Models (DEM) and the Bruun Rule in combination with GIS on the Hambantota coastline, Sri Lanka. The secondary aim is to identify potentially endangered ecosystems and land use classes by applying the above mentioned models.

1.3. Specific objectives

The rather wide scope of the two aims mentioned above can be separated into more specific objectives. The research questions of the primary aim are:

1. Is the use of our DEM an accurate method for coastal modelling of SLR impacts?
2. Is the use of the mathematical Bruun model a trustworthy method for coastal modelling of potential SLR impacts?

The research questions of the secondary aim are:

i. Based on predictions of rising sea levels over the next hundred years, where will a possible future coastline be situated if calculated on the two modelling methods in this study?
ii. What land use classes and how much of each class is potentially threatened by the sea level rise?
iii. Is the methodology in general suitable for the area based on the data available?

2. Background

The background chapter consists of six sections: a presentation of the study area and some of its unique physical and biological features, a layout of the environmental sensitive areas in Hambantota, an outline on the SLR issue and the scenarios used in this study, an SLR impact description, a summation on the potential impacts of SLR and finally a short background on the choice of models.

2.1. Study area presentation

The Hambantota district is situated in Sri Lanka's Southern Province and is the largest district in the Southern Province with an approximately 140 kilometre long coastline (figure 1). During the British Empire its jungles became well-known as popular hunting grounds for the colonisers. Today, Hambantota is well-known for its salt flats and for its intensely hot arid zone climate. It is possible to identify three different climates in the area: a dry zone, an intermediate zone and a wet zone.

The Hambantota economy is predominately rural and along the coastal areas fishing is the most important business. The beaches also play an important economic role as tourism is an important industry in the area. Many hotels in the Hambantota district are situated along the beaches and therefore the success of the tourist industry is highly dependant on the quality and the state of the beaches.

The beaches and sand dunes in Hambantota are important for other reasons too; they provide protection for people and property and low-lying coastal areas inland. The sand dunes are predominantly high and steep serving as protection against damages from storms, which often sweep in during the monsoon periods. The sand dunes also play an important role for the fishing industry, mainly serving as areas for net mending, as boat landings for smaller fishing boats and for dry fish processing. These activities are extremely important to many people living along the coasts in Hambantota as their livelihood totally depends on their ability to carry out fishing.

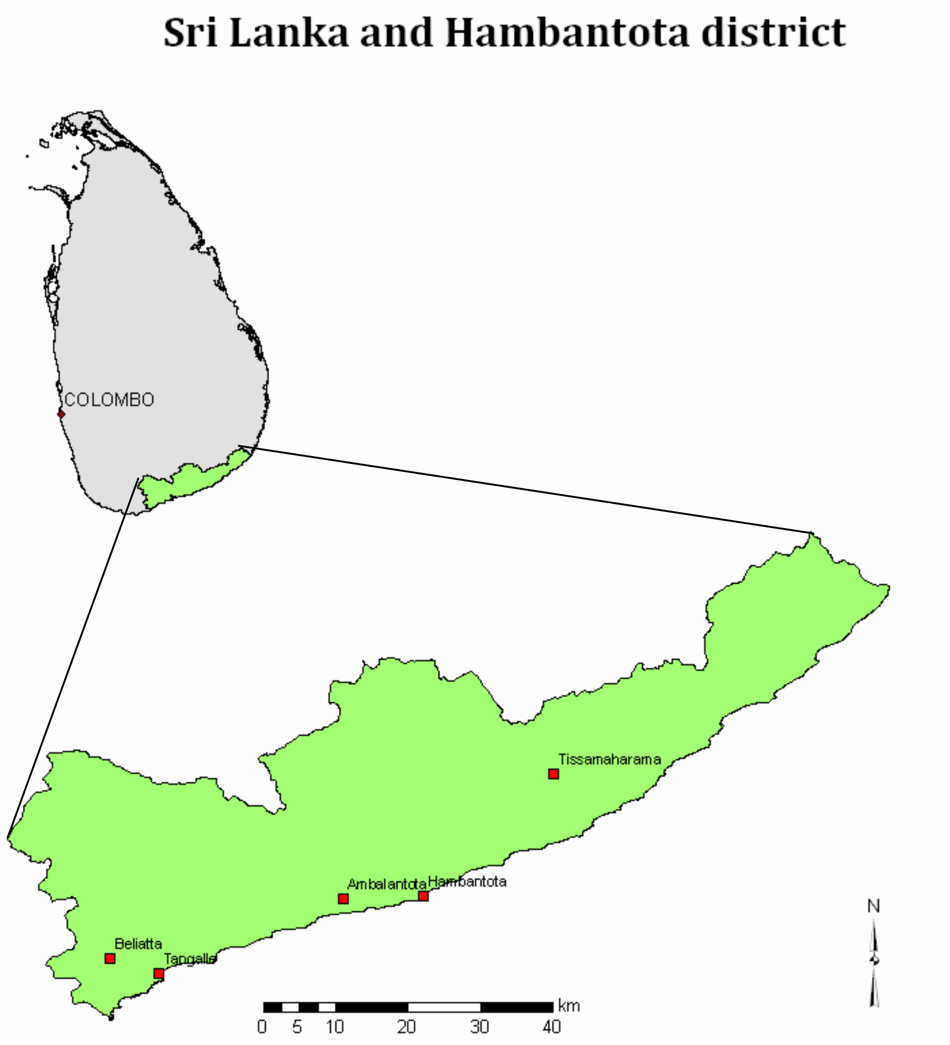


Figure 1. The map illustrates the location of the Hambantota district in Sri Lanka and the major settlements within the district. (Source: data material from Sri Lanka Survey Department)

Our study area does not cover the full Hambantota district. The Yala National Park and another area of land just before the park, which together cover approximately two fifths of the district, have been left out. The reasons for excluding these parts have to do with time limitations and safety, as these areas were not safe to visit because of the political instability at the time. Furthermore, the investigation focuses on the coastal area and approximately 2 km inland, leaving the rest of Hambantota further inland out of the study. The study relies on basic data which was obtained from the Sri Lanka Survey Department and at the time it was not possible to access data for the full area. Hence, the two parts of which this study consists, the DEM and Bruun models, accounted for below, have different area sizes. The basic data with land use classification and elevation has a smaller scope than the satellite images in which sand beaches are identified and where the on- site studies are visualised (figure 2). As mentioned above, the concentrated research area is restricted to the coast and is shown below in fig 2. From here on this is referred to as ***the restricted research area*** within on which the different models are applied.

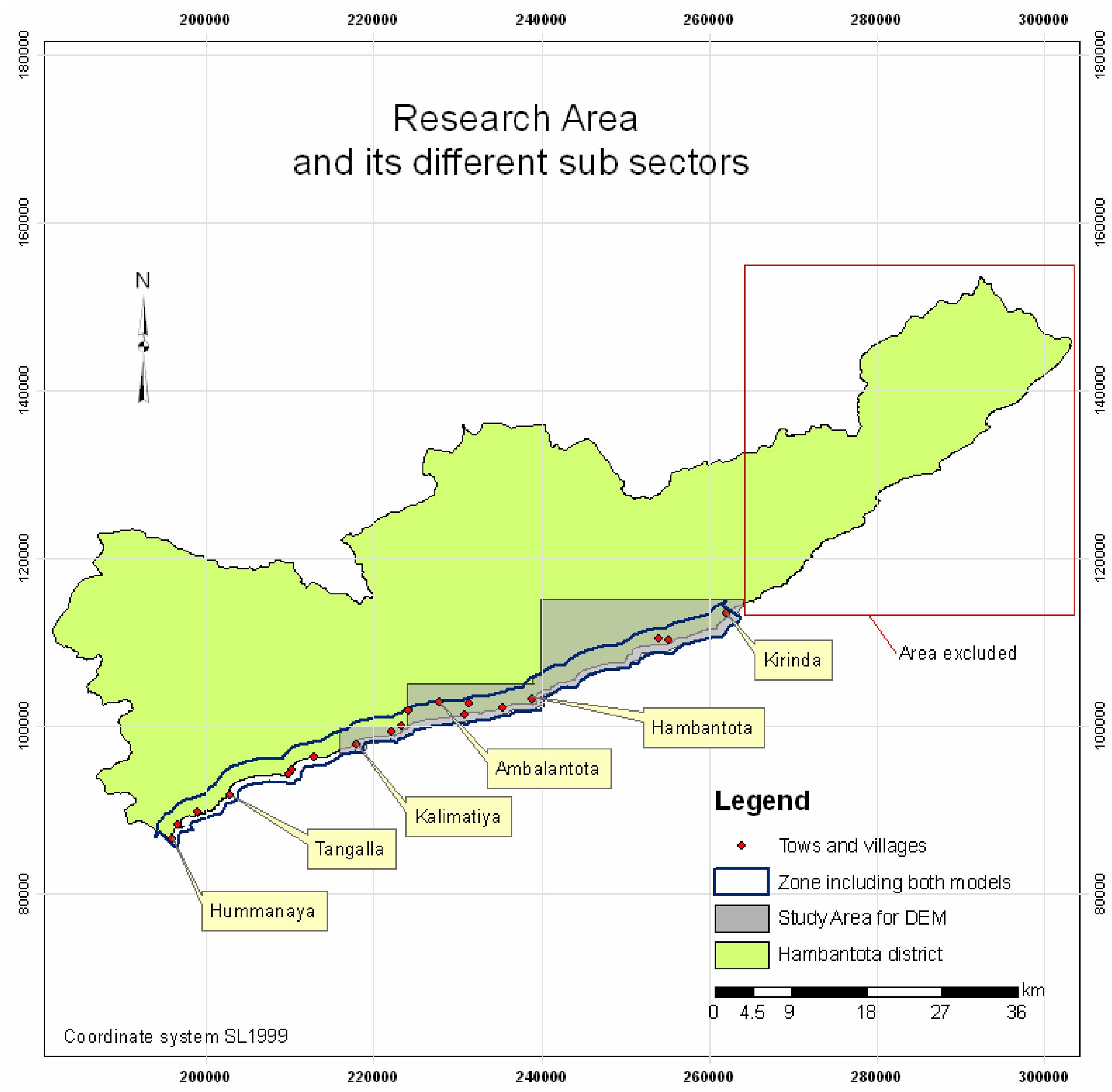


Figure 2. The map illustrates the study area and the different sectors for the two applied models. The blue line shows what is referred to as ***the restricted research area*** on which both models are applied in their different parts. (Source: data material from Sri Lanka Survey Department)

The grey parts of the map show the areas for which detailed data have been gathered from various departments in Sri Lanka. For further information on these data see Chapter 4. The DEM modelling approach for inundation has been employed within the grey area alone. The Bruun modelling approach has been applied on every suitable sand beaches in the whole of the restricted research area (fig 2). Satellite images cover most of the restricted research area at different resolutions for different tiles. For more information on this see Chapter 4.

2.1.1 Selection of study area

There are several reasons for selecting Hambantota as a study area: the area is accessible, there is available data from the area and it is an area of vulnerable coasts. These coasts host a large biodiversity and they contain many scenic and recreational areas as well as cultural,

religious, archaeological and historically significant areas. Also the fact that an SLR study, like this one, has not been done for this area, makes it interesting and useful to carry out.
The beaches of Hambantota are long-stretched and to be able to view the results in detailed maps the study area has been divided into seven smaller maps, fig 3.

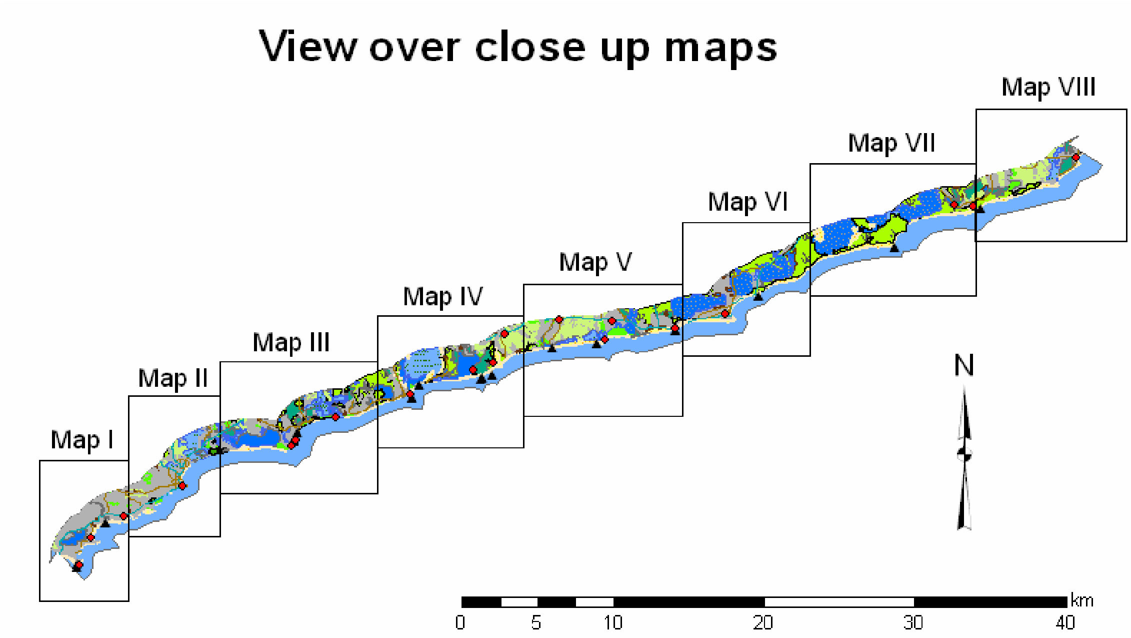


Figure 3. A map showing the seven small close-up maps covering the full stretch of the research area. A cut out from map 2 of the buffer zone, which constitutes the research area 2km inland from the coast. (Source: data material from Sri Lanka Survey Department)

2.1.2 Climate

As mentioned above there is a variety of climate zones in the Hambantota district but since our study resides predominately along the coasts, the climate does not change to the same extent as it does further inland. However, there is a variation in rainfall patterns from the east to the west with moderate wet (approx 1270mm annually) in the west to arid (less than 1000mm annually) in the east. The isohyets for 1250mm rainfall cross the area close to Tangalla, the next isohyets for 1000mm cross the area through Lunama Lagoon. The rainfall distribution has determined different Agro- Ecological Zones where the area to the west of Rekawa is classified as the Intermediate zone. The area between Rekawa and Lunama is classified as Dry zone and the area east of Lunama is even drier (Land Use Division, DA made in 1979) (figure 4).

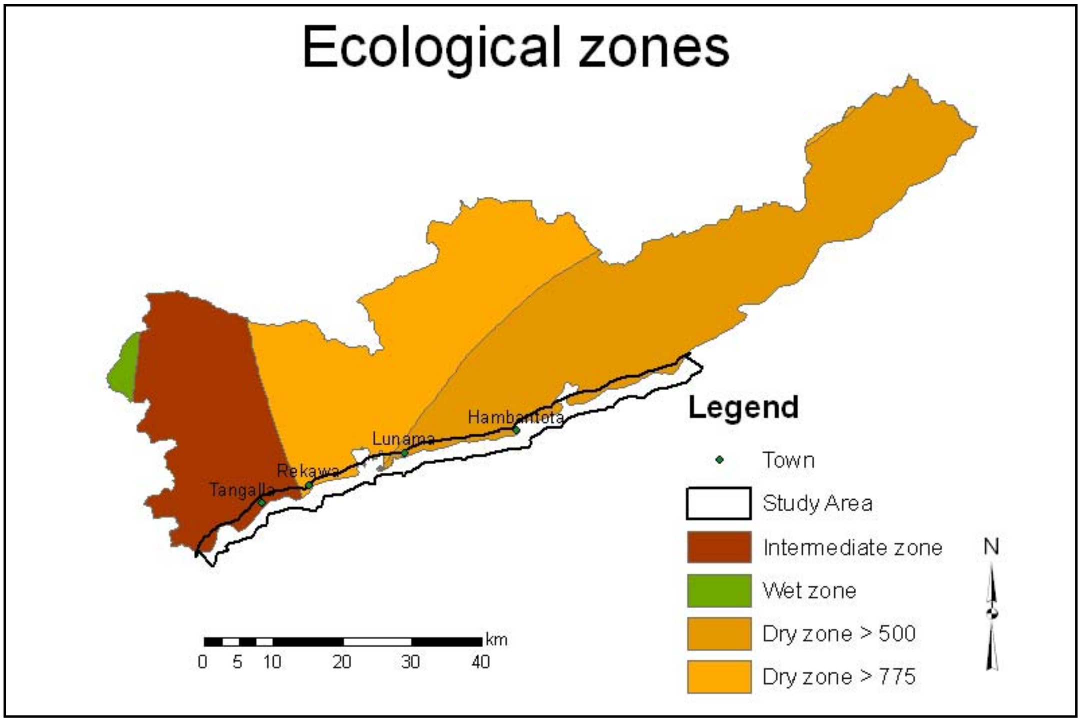


Figure 4. The map illustrates the ecological zones in the Hambantota district. These zones correspond to the precipitation zones. (Source: data material from Sri Lanka Survey Department)

There are strong seasonal differences in rainfall distribution during the year with more than half of the annual precipitation between October and December/January. This is called the Maha season. The rainfall in this season has many different sources such as: convectional, monsoon and cyclonic rains. The Yala rain season is shorter, from March to mid-May, but still delivers a large amount of rain. From May through to September there is a long dry period (HICZMP 1a, 2000). The temperature profile is stable without much annual or diurnal change with an average temperature of 27.1 C (Peiris G H, 2006).

The wind pattern shows stronger winds on the coastal fronts from May to September and from January to February, with velocities around 20 to 23km/hr. The highest wind velocity has been noted between Hambantota to Palatupana and is caused by the relief of the land behind the coast which is low and has a low vegetation cover. To the west of Hambantota the relief of the land is higher and east of Palatupana the vegetation cover is higher than between the towns.

The wind pattern during the year:
February to March: the north-eastern monsoon wind fades
April: mixed winds from SW, W, S and North with the SW winds dominating
May to August: A south-western wind, with decreasing intensity from west to east
September-October: The inter-monsoonal period without regional winds
November-February: The north-eastern monsoon winds dominate

2.1.3 Hydrology

Within the Hambantota district there are large differences in water availability. Due to the distribution of rainfall, to the natural hydrology and to irrigation facilities there are areas which are relatively water sufficient and areas where water is scarce. The Rekawa headland consists of regolith aquifers that are good sources of ground water and in the coastal plains there are isolated places with good groundwater supplies. To the east of Tangalla there is an abundance of lagoons. Some of them are used for salt production (Lewayas) while others serve as national parks or recreational areas. In some lagoon systems the hydrology has been altered by man allowing the intrusion of salt water.

The main estuaries are found east of Tangalla where the largest estuaries form large deltas, like the Godawaya delta of Welawe Ganga. The estuaries are highly dynamic in nature because of the interaction between the ocean and the river. The complex processes cause the landforms in these areas to constantly change (HICZMP 1a, 2000).

2.1.4 Geology, geomorphology and soils

The landscape in the area can be described as two different types, presented in the HICZMP (Hambantota Integrated Coastal Zone Management Project 1a, 2000) report as:

(1) Lowest Peneplain, which has resulted from millions of years of surface weathering of an ancient landmass of folded crystalline rocks.

(2) Coastal plain of flat-lying sedimentary deposits of more recent age lying on basement of Lowest Peneplain of crystalline rocks or on flat Miocene limestone.

The landscape types presented above generally run parallel to the coastline and the landscape has two quite distinct divisions from the west to the east. West of Tangalla the coastline has a clear abundance of headlands and rocky beaches, the exposed rock on the cliffs representing the rock underlying the peneplain. The small gaps between the rocky headlands are open to the sea as bays. The peneplain derived residual soil is deep and well drained. The beaches between the headlands to the west of Tangalla are gradually getting smaller and the sand on these beaches, which tend to be less steep, is finer. East of Tangalla the coasts consist more of the flat-laying sedimentary deposits from the coastal plain with fewer rocky headland features. The landscape falls into three different patterns that are described in the HICZMP 1a 2000 report:

(a) From Tangalla to Ambalantota, the shoreline consists of prominent headlands separated by longberm/low sand dune. Marsh/lagoon/flood plain occurs behind the berm/low sand dune eg Medillamarsh, Rekawa lagoon, Walawe flood plain. Mangrove creeks are common. Further inland is either flood plain eg. Tangalu Wela, or upland ridge/hill eg Bata Ata hill, Ussangoda plateau, which belong to the lowest peneplain.

(b) Between Ambalantota and Dorawa point (close to Kirinda) long high dunes occur between the prominent headlands. Behind the dunes are lagoons or flood plain, and further inland the flood plain continues or upland landscapes commence. Mangrove creeks are present in the lagoon or flood plain.

Of these two zones east of Tangalla the first has low sand dunes or long berms between the headlines and the second stretch is filled with high dunes between its headlines.

Figure 5. The image shows rocky headlands near Tangalla. Photo: P. Seiron

Close to Kudawella, in the most western part of the study area, blowholes can be found. The geomorphology of the low-lying parts of the coastal plain depends to a great extent on fluvial influences (HICZMP 1a, 2000). The mineralogy of the sand on the Hambantota beach is further described in the same report. This shows an abundance of sand with larger grain size. Winds arrange the sand during dune formations and lighter sand is lifted further away from the dry beach whereas heavier sand settles earlier. Hence the dunes appear to contain more heavy sands than in the inland where the sand is lighter.

East of Tangalle the coastal plane is distinct and prominent and runs along the full stretch of the coast with the exception of some intrusions of headland tops consisting of Red Latosols as well as some interruptions of the Lowest Peneplain. The coastal plain itself mainly consists of Regosols on Resent Beach and Dune Sands. Directly inland from this Regosols and Red Latosols the soils are Reddish Brown Earths and have a high amount of gravel in the subsoil. The undulations in the landscape have a higher amount of gavel on the crest of the undulations and on the slope elements, making these areas highly suitable for Chena farming (slash and burn cultivation for grain and vegetables, i.e. primary level cultivation). The bottom of the undulations contains Low Humic Glay soils, which are more suitable for Paddy cultivation.

The transition continues into the peneplain, which dominates the inland area with its Reddish Brown Earths and a decreasing amount of gravel in the subsoil. Also the mixture of the Low Humic Glay soils makes this area more suitable for cropping vegetation in general (fig 6). In some areas Solodized Solonetz soils appear which are even more suitable for paddy cropping.

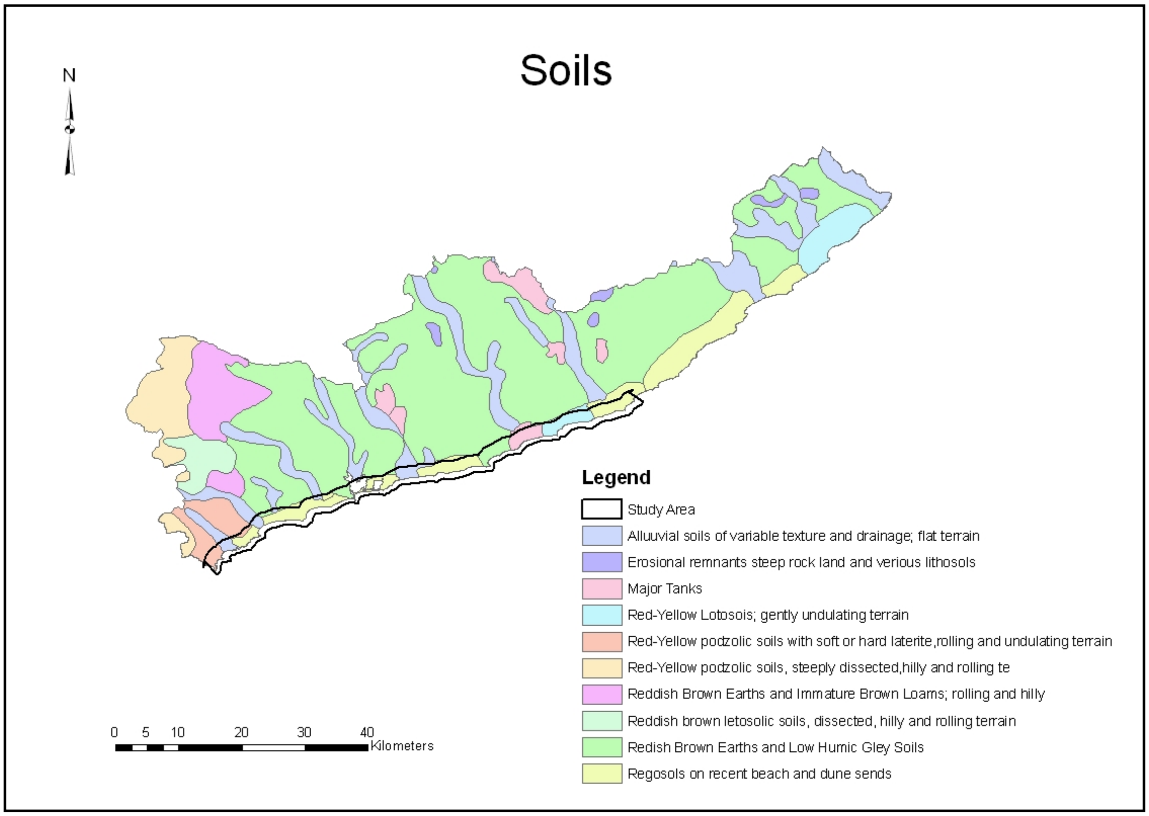


Figure 6. The map is illustrating the different soil types in Hambantota district and our study area. (Source: data material from Sri Lanka Survey Department)

Flood plains and river banks filled with river alluvia emerge in cross sections over the coastal plain and lowest peneplain. They are suitable for vegetation and cropping since the soil on the river banks is sandy and has a combination of being well drained as well as having ground water. In the actual flood plains the suitability for cropping varies as the drainage can be good or bad in different areas (HICZMP 1a, 2000).

2.1.5 Sand dunes

In the HICZMP report 1a, 2000 the conditions for the creation of sand dunes and the process behind are described as follows:

> *"For sand dune formation to be possible there are many requirements. The weather must be dry enough to desiccate the beach sand for the wind to be able to dislodge and lift the sand particles. The land behind the dune that is being formed must be low lying so that the wind is not weakened by additional resistance. With increasing duration of dry weather and increasing velocity of wind, the width and height of the sand dunes tend to increase as evident from Ambalantota to Dorawa".*

The location of sand dunes follows the direction of the littoral drift and of wind, from the southwest to the northeast. The formation of the primary sand dunes begins at the windward side, growing backwards and as long as there is open space and the wind is blowing at sea level there will not be much sand added to the dune. As the wind hits the leeward side of a headland the sand dunes cease to grow. Secondary sand dunes, behind the primary dunes, are frequent in most beaches. The secondary dune has an acute angle to the primary dune and is created from sand that is deposited from wind which carries sand coming through an occurring wind gap in the primary dune.

When sand dunes are formed the wind arranges the sand so that lighter sand is lifted from the beach. The lighter sand moves further inland and the heavier sand settles earlier. This is the reason why dunes appear to contain heavier, coloured sands than in the inland where the sand is lighter and whiter. The sand on the Hambantota beach shows an abundance of heavy sand and therefore the dunes appear to be darkly coloured. "The stable sand dunes seem to owe their stability to their geometry (WCP 1993), surface hugging creeper vegetation on them on the sea/windward side and the concentration of heavy sand".

Figure 7 and 8. The images show the typical appearance of the sand dunes of Hambantota. The image to the left is taken in the western parts of the study area. The vegetation clearly indicates a wetter climate. The image to the right is taken in the dry eastern parts. One can clearly see the darkly coloured sand. Photo: P. Seiron.

2.1.6 The sea and the coast

The near shore currents are weak along the coast of Hambantota with little influence on the coast and the tidal range is also low (below 50cm) in Sri Lanka (JICA 1989). These factors imply that water waves significantly influence coastal processes in the district. The waves, which are generated by storms in the Indian Ocean, are called southern swells. They are reinforced by south-western winds in the period between April and August which means that they become more erosive during this season. Since the swell is countered by north-eastern winds in November to February/March, the waves are less erosive during this period. The erosion on the coast by the southern swell also decreases from west to east resulting in a net erosion to the west of Tangalla and a net deposition in the eastern coasts creating barrier islands, spits and possibly new lagoons (HICZMP 1a 2000, Summerfield 1991).

The sea between Kudawella and Tangalla is deep and can reach a depth of 20 m only 2 km off the coast. East of Tangalla, the near shore sea becomes shallower and the continental shelf gradually widens to form what is called the Hambantota Bank (HICZMP 1a 2000). During the SW monsoon wave height is higher by up to one meter and has longer wave periods by up to five seconds than during the NE monsoon.

The sea roughness changes throughout the year:
May-Augt: The southern swell is reinforced by a south-western wind, with decreasing intensity from west to east
Sept-Oct: The inter-monsoonal period without any regional wind
Nov-Feb: The inter-monsoonal period without any regional wind
Feb-March: The north-eastern monsoon wind fades
April: The north-eastern monsoon winds counteract the waves
(NARA 1986)

2.2 Environmentally sensitive areas

2.2.1 Ecological zones with a large biodiversity

The Hambantota beaches host one of the largest dune systems of its kind in the world (HICZMP 2a 2000). The full stretch of this dune system is about 12.5 km stretching from the Godawaya point between Hambantota and Ambalantota to Talgasmadiya in the east. Our research area does not cover the full stretch (fig 2).

In a report made by HICZMP no4 in 2000, no less than 89 environmentally sensitive areas were registered along the Hambantota district coastline. The HICZIM project was carried out between 1997 and 2000 in cooperation with the Norwegian Government, the Southern Development Authority of Sri Lanka (SDA) and the Coast Conservation Department (CCD).

There are large resources of flora and fauna found along the Hambantota dune areas showing a large ecological diversity. The dunes could be divided into three categories: fore dunes (the primary dunes) which are covered with creeping vegetation (s.a. *Spinifix littorus* and *Ipomea asarifolia*), centre dune ridges mostly covered with creeping vegetation and stunted bushes and the back dunes which are the most stable and contain large trees and shrubs (figure 9). The intensity and the number of species increase progressively from the fore dunes back to the back dunes.

Some of the interesting natural vegetation types in the coastal part of this area are:
- ***Lowland seasonal flooded grasslands***, found in bottom lands of river flood plains
- ***Mangroves***, found in lagoonal water fringes and shallow waters
- ***Riverine forests/gallery forests***, found in major and medium river banks
- ***Sand dune and Beach vegetation***, found in sand dunes and beaches
- ***Sea grass beds***, found in sheltered shallows near shore marine and lagoonal waters

Figure 9. The image illustrates typical vegetation of sand dunes withlarge trees on the back dune. Photo: P. Seiron

2.2.2 Bundala National Park

The fact that half the length of the Hambantota district coastline is subject to protection through National Parks proves that the government regards the flora and fauna as sensitive. This stretch includes the Yala National Park, which is not included in the study, and the Bundala National Park which is located at the end (fig 2) with Kirinda as the finish point.Bundala covers most of map VII and VIII (fig 3). These two national parks together with the Kalamethiya lagoon, at the very west in our study area, host about 150 bird species of which the aquatic species outnumber the terrestrial ones. This includes one endemic species (the Sri Lanka Jungle Fowl), (HICZMP 1a, 2000). In Bundala a mapping of the biodiversity results in a grand total of 11 major habitats and vegetation types including 7 terrestrial vegetation types and 7 wetland types (Bambaradeniya *et al., 1a* 2003). The terrestrial habitats include dry thorny scrubland, arid zone forests, sand dune vegetation, gentle sea shore vegetation, arid zone maritime grasslands/pastures, riverine forests, and anomalous Mesquite (*Prosopis*) scrublands (Bambaradeniya, 1b). The wetland habitats are saltmarsh, mangrove, brackish water lagoons, sea shore (sandy and rocky), saltern, water holes/tanks and streams. Prior to the natural disaster of the Tsunami a total of 383 plant species, belonging to 90 families were documented in Bundala (Bambaradeniya *et al.,* 1a 2003). Out of these, six are endemics and seven species are nationally threatened, while 15 are invasive alien species (Bambaradeniya *1b*).

The mammals in Hambantota are more confined to the national parks and Yala more than Bundala. However, Bundala hosts a total of 324 vertebrate species. Out of these, 11 species are endemic and 29 species are nationally threatened. The vertebrates include 32 species of fish, 15 species of amphibians, 48 species of reptiles, 197 species of birds, and 32 species of mammals (Bambaradeniya, *1b*). For example, there are elephants, threatened sea turtles, two crocodile species and three species of terrapins. About 40 finfish species and approximately nine shell fish species have their habitat in the lagoons. The actual number of species abundance in the lagoons varies according to the water quality making the species sensitive to changes in their habitat. Around the Rekawa coral reef a low density of 21 coral species is reported.

As stated in the HICZMP report 1a 2000; ecologically, coastal areas are far more complex than inland areas. This is where land and sea interact, producing many biogeochemical phenomena and processes. These processes run wider than just the coastline and spread over a great length of coast.

2.3 Background to the Sea Level Rise (SLR)

According to the IPCC 2007 it is very likely that anthropogenic emissions of greenhouse gases (GHG) cause global warming and thereby significantly affect the earth's climate. The increase in global mean temperature is causing the global sea levels to rise at an accelerated rate due to increased glacial melting (eustatic change) in combination with thermal expansion (steric change) of ocean water (Komar, 1998). The latter is the primary reason why there is a need for change at present. Between 1993 and 2003 the global sea level rose at an average rate of 3.1 mm per year. This can be compared to the years between 1961 and 2003 when the rate was averaging at approximately 1.8 mm per year (IPCC, WG1). IPCC:s SRES emission scenarios predict an SLR between 18-56 cm by the end of the 21st century. The IPCC prediction does not include the contributions of melted snow from Greenland and the west Antarctic ice sheets (WAIS). With a collapse of WAIS together with business-as-usual sea level contributions the sea level could rise with as much as 6 meters between the years 2030-2130 (Nicholls et al, 2005, Hansen JE, 2007). Due to the time scales related to climate processes, the anthropogenic warming of the global climate and SLR will continue for centuries, regardless of whether a stabilization of greenhouse gas concentrations were to happen or not (IPCC 2007).

2.3.1 Sea Level Rise scenarios used in this study

The different levels of predicted sea level rise are 0.18, 0.59, 1.0, 2.0 and 6.0 meters. The 0.18 and 0.59 meter scenarios are predicted to occur by the end of the 21st century and the 1-6 meter scenarios within a time period of one hundred years starting from the year 2030 to the end of year 2130. The scenarios are taken from the imputed values in IPCC 2007 and Brooks et al, 2006. The later reference has slightly different values but attests the values in the IPCC as relevant. The details of the models and the work in GIS are accounted for below.

The ongoing research within the field of climate change is constantly revising the estimations and predictions of SLR at a high rate. The information is often updated on the magnitude of climate warming and the changes in SLR, but in this study the forecast presented above is the base for the calculations. It will still be easy to understand the effects of an SLR on the selected research areas regardless of the exact measurement of an SLR.

2.4 Erosion, inundation and flooding

There are two kinds of inundation: episodic inundation/ flooding and permanent inundation. Episodic inundation is often a result of episodic storm surges where low lying land will be flooded. The rise in sea level combined with the predicted increase in storm frequency (IPCC, 2007) will most likely lead to more severe flooding events globally (Nicholls, 1999). Permanent inundation is where terrestrial land is permanently submerged due to SLR. This study will focus on permanent inundation only. Moreover, with the help of the Bruun model, this study will investigate the movement of the beach profile and to some extent the sediment transport.

When discussing the impact of sea level rise it is important to differentiate between the effects of inundation and erosion. Inundation simply means that all land under a certain elevation will be flooded and as a result and a new coastline will be created. Erosion, on the other hand, means movement and redistribution of sand and sediment materials on the coast, with the result of moving and changing the beach profile. This is done during periods of storms accompanied by a local temporary SLR. Usually the sediments are transported back to the beaches after the storm event with the help of large coastal swell waves. With a more permanent SLR this might not be the case. Coastal erosion is something that takes place in all coastal parts of the world. Approximately 70% of the world's coasts are receding and erosion is a recognised problem according to Zhang et al, 2004.

2.5 Potential impacts of sea level rise

The potential impacts of SLR on coastal areas are generally predicted to be extensive. Sectors likely to be affected include economical, social and biological systems. The extent of the impact will vary from location to location depending on the scale of the SLR, on the coastal morphology and on human adaptation (Nicholls & Klein, 2000). The large tsunami in 2004, which hit many parts of East Asia also hit Sri Lanka severely with an estimated 30,880 casualties. Out of these, there were 4,500 casualties in the Hambantota district alone (web: Recoverlanka 2009 01 28) and also numerous houses, roads, and entire villages were partly or totally destroyed. This led to the introduction of a protective buffer zone of 200 meters along the coast where no buildings were allowed to be built in the case of a new tsunami. This buffer zone will in some ways be a protection zone from the SLR, but there is still a great deal of activities on the beaches such as close-laying infrastructure, hotels and factories. Additionally, the buffer zone law is not fully followed with regard to new settlements.

2.5.1 Socio-economic impacts

An increasing number of people live in the coastal areas of the world. In 1997, 20% of the global population were living less than 30 km from the coast (Gommes et al, 1997). Coastal areas serve as important economical zones containing infrastructure and industries like agriculture, fishing and tourism. A considerable portion of the global GDP is produced in coastal zones (Turner et al, 1996). Based on data from 1995, an SLR of about 5 meters would affect approximately 400 million people living along the world's coastlines (Nicholls et al, 2005). With more recent data even more people will be affected as the population in coastal areas has kept increasing these past 15 years.An SLR will have different consequences on a given population depending on location and a various other factors such as:

- The relative SLR (local amount of SLR)
- The effects the SLR could have on hazards such as storm surges
- The effects the SLR has on the interaction with other climate change induced hazards such as changes in the frequency and severity of storms
- The geomorphologic response of coasts to SLR. (This in turn depends on natural geomorphologic processes and human interventions in the coastal system)
- The physical exposure of the population and the ability of the population and related systems to cope with these impacts

(Brooks, Nicholls and Hall, 2006)

In the Hambantota district there are many salt production industries, plantations and agriculturally productive areas along the coastline. The opening of national parks and development of irrigation projects has enabled people to live in new areas and made the area more available both for the local population, and for tourism and industries. Infrastructures, such as roads, are vulnerable to erosion from the sea through SLR or storm surges in areas where they are within close distance to the sea. A collapse of the main transport route, the A2 road, could have effects both on local finances as well as on the national economy as this would cut off transport of merchandise and disturb people commuting.

The salt industry is a large employer in the Hambantota district which could be threatened by an increasing SLR. The sea could break through to the salt pans in the salt producing Lewayas and the profit can also be cut if a lot of time and money is spent on securing the saltpans from a threatening sea. A decrease in salt production or shut down of salt industry would affect many employees and affect the trade income in Hambantota

Fishing industries could also be affected if harbours were damaged, if there were a change of catching sites and if roads used for transporting the fish to markets were damaged etc.

Another local effect could be that agricultural land might be destroyed by sea water intrusion altering the salinity of the soil. This could also ruin plantations, house gardens and homesteads.

2.5.2 The biophysical effects of SLR

The biophysical effects of an SLR will include increased erosion, inundation, rising water tables, saltwater intrusion and an increase in flood frequency which could further result in effects on both flora and fauna. On a global level an SLR will seriously threaten sensitive coastal ecosystems such as coastal wetlands, especially if they are constrained on their landward side by anthropogenic interests (IPCC 2007, WGII). The loss of coastal wetlands will have consequences for many sectors such as food production, water treatment and nutrient cycling functions and wildlife habitats (Nicholls et al, 1999). In some areas, for example around the Bundala Lagoon (fig 10), the salinity has become a problem since the 1980s. The problems occur in the lowlands of settlement where it affects the paddy farming, water supplies and housing (HICZMP1a, 2000). The reason is thought to be the fact that the salt content in the lagoon has increased due to a new artificial opening from the Lewaya to the sea much closer to the village than before. This has raised the ground water table; coupled with drainage of fresh water for irrigation, there has been salt intrusion in the ground. This opening is man-made, but serves as a warning of what could be the case if the sea were to break through due to SLR.

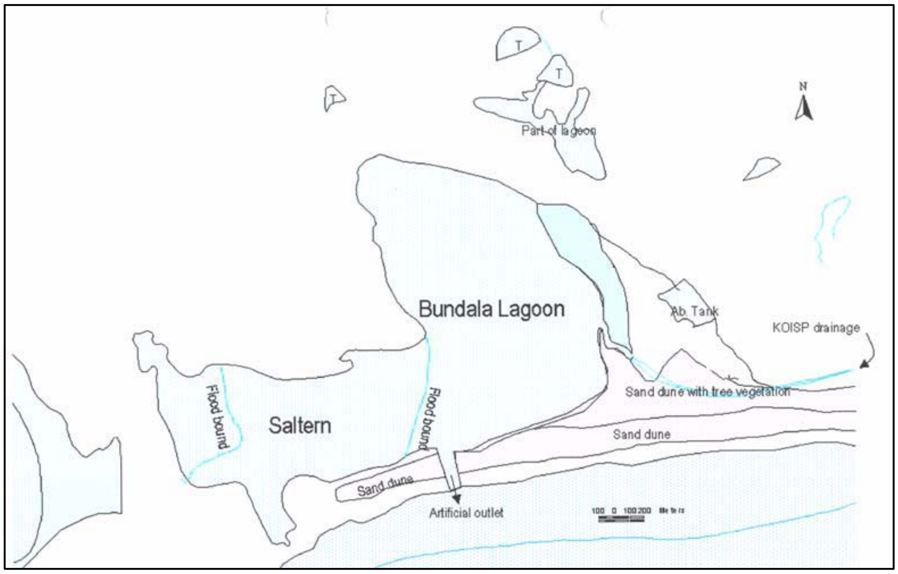


Figure 10. Map of Bundala lagoon with an artificial outlet which has contributed to salinity problems in the area. KOISP is an irrigation project. (Source HICZMP 1a, 2000)

2.6 How to make estimations of the impacts of SLR using two models

This study uses two different approaches, an interpolation of a surface model and a mathematical model, to make estimations of potential losses of land to SLR and of the effects on the coastal area in Hambantota Sri Lanka.

2.6.1 Background on Interpolation and DEM production

Primarily a Digital Elevation Model (DEM) is created by interpolating elevation points or lines using different interpolation algorithms. This is a basic and common approach for investigating the effects of a potential sea level rise. The three interpolation methods used in this study are TIN, Spline and IDW. The elevation points used in this study originate from vector layers consisting of points and lines. They are digitized by using photogrammetry in aerial photos done by the Sri Lanka Survey Department GIS division. The result of each interpolation will be evaluated using partly plain visual examination but mainly using Root Mean Square Error (RMSE) values. In this way the best fitted interpolation for creating this DEM is selected, given the type of data at hand. The DEM will be integrated with different sea level rise scenarios and land use data to study the effect of such a rise and to identify potentially threatened areas.

2.6.2 Background on the mathematical model

The second approach is the use of a mathematical model which calculates the erosion and the movement of a beach profile. The term mathematical model implies the fact that there is a mathematical equation behind the calculation of the recession of the beach and that there is a mathematical relationship between the rise of the sea level and the backward or forward movement of the beach profile. It can be, and is, argued whether this mathematical model can be used on natural processes such as these and this is an objection which will be dealt with in chapter 3.2 where the model is accounted for. The rule is used in this study with the original equation from Bruun and with additions from Hallermeier. It is a two dimensional model which calculates the movement of a coastal profile for sand beaches only. The model is applied using the different scenarios of predicted sea level rise, chosen for the study in this report.

2.6.3 The tools for the two models

The main tool in this study is the software for Geographical Information System (GIS), ArcGIS 9.2 that is, a product from the ESRI (Environmental Systems Research Institute). This is used for the surface modelling and the creation of the DEM. The calculations of the Bruun model, on the other hand, are made separately using GIS to evaluate the effects on the land use and visualise the imputed changes. The work on the different models is accounted for below in chapter 5, which is the methodology chapter

The schematic picture of a standard sand beach profile is shown below for basic knowledge of terminology and composition of a standard beach in the research are. The figure and zones are discussed in section 3.2

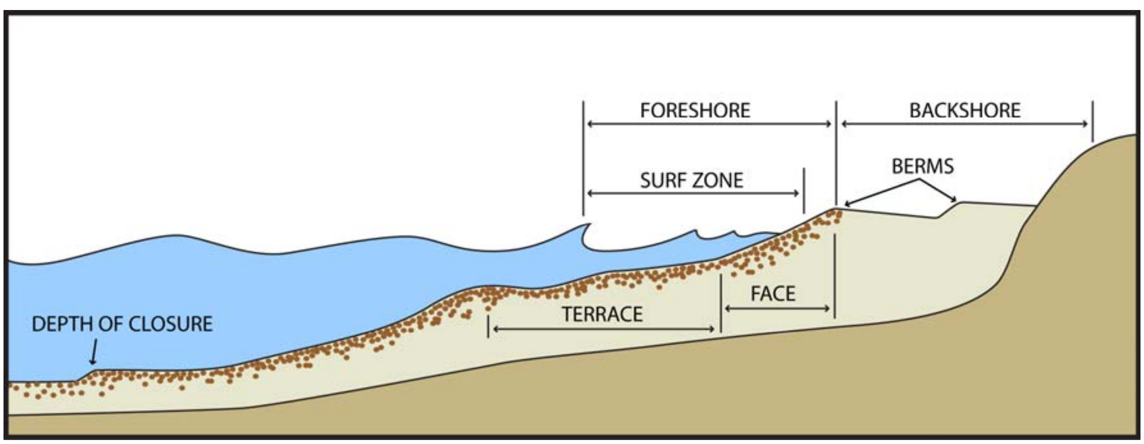


Figure 11. A schematic picture of a standard sand beach profile. The depth of closure is where near shore sediment exists (DoC), the berm is the portion of the beach that marks the landward limit of wave swash (Hugget, 2007). Their height is measured in this study.

3. The theory behind the models and modelling methods

There are two sections that make up the third chapter and the first describes the theories of DEMs and the general theories behind interpolation and the three interpolation methods used in the study. The second section outlines the theories of the Bruun rule.

3.1 Model one, interpolations and DEM

Three different interpolation methods are used when creating the digital elevation model: Spline, Inverse Distance Weighted (IDW) and Triangular Irregular Network (TIN).

3.1.1 Choice of interpolation methods and DEM

An interpolation is an estimation of unknown values on the basis of known samples of measured values in the same area. In this case, elevation values in measured data points which constituted the base to an interpolated continuous surface. The base for all spatial interpolations, such as this, is that an autocorrelation between the data points must exist. This is explained further below. There are several interpolation methods which all have a variety of different parameters that influence the resulting surface. There are forced interpolations and interpolations where a deviation from the measured points is allowed. The forced interpolations can lead to a non-filtering of errors whereas where deviations are allowed, such filtering will take place. The filtering of errors is a useful quality in an interpolation method. Other useful characteristics are the creation of continuous surfaces as opposed to non-continuous surfaces which give surfaces that are not suitable for this kind of inundation study.

This study uses three different interpolation methods to test the modelling of a terrain surface and they are as follows:

1. Spline Tension
2. Triangular Irregular Network (TIN)
3. Inverse Distance Weighted (IDW)

The IDW has the quality of filtering errors, which TIN does not. The Spline however is somewhere in between as the selected method is a spline tension interpolation which tunes the stiffness of the interpolant (Arc GIS Help). A more detailed presentation of each modelling method can be found below in next chapter.

The reason for selecting these interpolation methods is the fact that they are feasible given the data and the software at hand for this study and they are all immediate to carry out. All these methods are used in modern surface analyses which make them interesting to try further for this kind of analysis. The reason for not using for example Kriging interpolation is the time aspect and the quality of the data.

The three different interpolation methods are created and evaluated with the use of RMSE values as well as visually to see which constitutes the best surface interpolation in this case. The DEM with the best RMSE value is selected for further analysis given that it provides a satisfying visual evaluation. The selected surface model will be inundated to different predicted levels of a rising sea. The theory behind the RMSE evaluation is accounted for below.

3.1.2 The theories behind the Digital Elevation Model (DEM)

Elevation data is often a common factor in spatial analyses and modelling and is crucial in planning and constructing scenarios where the terrain, slope, aspect, field of view etc. are of interest. Stored digitally, the elevation data constitute an elevation database often called a DEM which is a digital description of ground surface topography stored in a raster or vector format. When dealing with spatial analysis in a DEM the raster model is the most commonly used format (Eklundh, 2003). Analysis of spatial data in digital form in general is predominantly preformed in different Geographical Information System (GIS) software.

The raster or vector based DEM is normally produced by the interpolation of point or line data (contour lines). The elevation data is often collected in field measurements with GPS, photogrammetry or the digitizing of topographical maps. Based on the data, different interpolation algorithms can be applied (Eklundh, 2003). This DEM is produced using elevation data from the Sri Lankan Survey Department where the data is retrieved from aerial photos using photogrammetry to digitalise the elevation.

When handling digital elevation data it is important to be aware of the quality and accuracy of the data. The accuracy of the data is dependent on several factors, for example, on the way the data was acquired (method), on the nature of the input data, on the interpolation method and on the data processing (Klang, 2006). The data acquisition method is the most critical of these factors as an error can propagate through the whole GIS based analysis leading to a false model (Weng, 2002). The data in this study has been purchased from a governmental department without the possibility of personally revising it in field. The interpolation process and interpolation method can also affect the accuracy and be a source of error in a DEM (Eklundh & Martensson, 1995) as mentioned above. It is therefore important to try to evaluate the DEM and assess its accuracy.

3.1.3 The theories of interpolating surfaces

The whole concept of interpolation of continuous spatial data is built on spatial autocorrelation. This means that two points close to each other are more likely to have a similar value than a point placed further away. In an interpolation one estimates the values between points based on spatial autocorrelation (Eklundh, 2003). As stated above, the choice of an interpolation algorithm is often based on the data available but also on the study at hand. Interpolation algorithms can be divided into two main groups, global or local. Global methods like trend surface analysis or Fourier series, take into account all observations in the data set when calculating the cell values. Global techniques will not take into account smaller local variations and are therefore used when general trends or main directions are of interest. Local methods such as IDW (Inverse Distance Weighted), kriging, splines, TIN (Triangular Irregular Network) and Thiessen polygons estimate cell values from adjacent data points and are consequently better fitted to deal with local variations. When interpolating a DEM local methods are best suited (Burrough, 1986) and all three methods used here are as noticeable local. The IDW, kriging and spline interpolations produce raster format DEMs while the TIN and Thiessen polygon interpolations generate vector DEMs (Eklundh, 2003). To be able to compare the three chosen methods on similar conditions the TIN vector is converted into a raster before the use of RMSE values.

Generally, point data yields a better result than contour line data, especially when applying an interpolation algorithm based on a radial search such as IDW. An acknowledged problem in this case is the formation of terraces. Terraces appear when the radial search finds several points in one direction (along the lines) and few or none in the other (across the lines) (Eklundh & Martensson, 1995). In this study the interpolation was made from vector layers including elevation points and lines and based on the information above all the lines were converted to points and only point data was used.

3.1.4 The theory behind Spline interpolation

Spline interpolation produces even and aesthetically pleasing interpolations. This is accomplished by applying piecewise polynomial functions to a small number of data points at a time and thereby avoiding the Runge's phenomenon where the oscillation of high polynomials can cause large errors in the data set. In the joins between the polynomial functions the first and second derivative is continuous making the modelled surface smooth. This also allows an adjustment of different segments at a time without recalculating the whole interpolation (Burrough, 1986). A polynomial is given by:

$$p(x) = b_o + b_1 x + \ldots + b_k x^k \qquad \text{Equation 1}$$

Where *p(x)* is the calculated polynomial,
$b_0, b_1, \ldots b_k$ is the coefficients that is to be decided and
k is the polynomial degree.

A polynomial in the first degree is a straight line, a polynomial in the second degree describes a squared curve, a polynomial in the third degree describes a cubic curve and so on, as shown in figure 12.

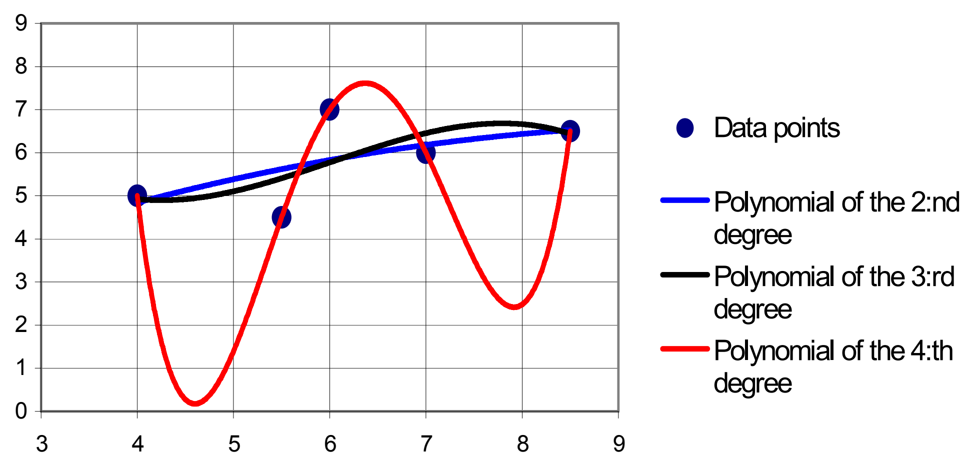


Figure 12. Illustration of polynomials in 2:nd, 3:rd and 4:th degree.

Polynomials that pass through *n* points must have a polynomial that is *n –1*. A cubic curve passes through four points and is mathematically expressed as:

$$p(x) = b_o + b_1 x + b_2 x^2 + b_3 x^3 \qquad \text{Equation 2}$$

There are two ways of calculating splines: an exact interpolation or a smoothing interpolation. In the exact interpolation the polynomial functions passes through all the data points whereas in the smoothing interpolations the polynomial functions are calculated so that the residuals between the original data points and the interpolated surface are kept as low as possible, thereby making the surface relatively smooth (Burrough, 1986; Eklundh, 2003). When studying local maxima or minima the exact interpolation is preferred while the smoothing interpolation can be useful if there is a known experimental error in the data points (Burrough, 1986).

This analysis uses a technique based on minimum curvature splines also known as Thin Plate Spline interpolation (TPS). This interpolation method is an exact interpolation where, as stated above, the splines pass exactly through all the data points. TPS is thought of as the bending of a thin metal plate where the plate is fixed at the grid points and the deflection is in the z direction. A documented disadvantage with TPS is the generation of so-called overshoots in areas with rapid gradient changes due to the "stiffness" of the plate (Mitasova & Mitas, 1993). This problem is also known as Runge's phenomenon. To minimise the overshoot problem one can apply TPS with tension. TPS with tension is an algorithm that reduces the stiffness of the plate and minimises the "bending energy" of the curves. This is accomplished by a weighting of the first derivative in the curves. A weight of zero generates a normal TPS while an increase in weight gradually reduces the stiffness. The equations for TPS with tension are complex. For details we refer to Franke (1985), Mitasova & Mitas (1993). The opposite is the Regularization which may be used to relax the requirement that the interpolant passes through the data points exactly.

When calculating the interpolation the entire output raster is divided into rectangular regions of equal size. The total amount of regions is determined by dividing the total amount of points in the data set with the specified number of points for local approximation (specified in the ArcGIS program). The specified number of points is only a rough average. This means that if the data points are very unevenly scattered some regions can contain more point than others. If this is the case the regions are expanded so that they contain a minimum of eight points each (ArcGIS Help).

3.1.5 The theory behind the Triangular Irregular Network (TIN)

The TIN interpolation produces a vector format DEM where the irregularly spaced data points are triangulated and connected to each other to generate a network of triangles. Each data point in each corner of the triangle is represented exactly and is not interpolated. These corner points can be the corner of one or more triangles. Between the corners of each triangle a plane is defined that has the same slope and direction gradient over the entire plane i.e. a linear trend surface. These surfaces need to be estimated and interpolated through a linear interpolation mathematically expressed as:

$$z(x, y) = b_0 + b_1 x + b_2 y \qquad \text{Equation 3}$$

Where: $z(x,y)$ is the interpolated value in the point x,y
b_0, b_1 and b_2 are the calculated coefficients for the data set creating the best fit.

A sample of how the TIN nodes are connected with triangles and what this looks like in a surface model is shown in fig 13

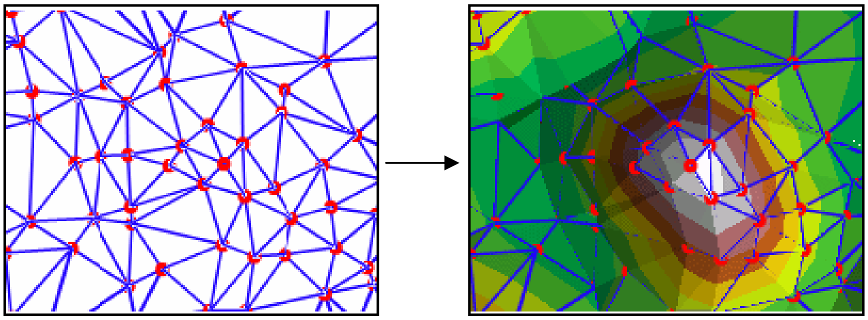


Figure 13. Example of interpolated surfaces with TIN nodes. (Source: Arg GIS Help)

The TIN method allows the size of the triangles to be adjusted to fit the terrain of the surface. Areas with complex relief can be represented by many small triangles while areas with simple relief can be represented by large triangles. This reduces the storage of unnecessary data in areas with homogeneous surfaces and also allows the TIN to be constructed to fit important topographical features like streams, ridges and lagoons (Eklundh, 2003 and Burrough, 1986).

One of the most common methods for triangulation is the Delauney triangulation which is the method used here. The triangles created have to follow the Delauney criterion which states that the circumcircle surrounding the triangle cannot contain any other data point (figure 14). Each edge has two nodes, but a node may have two or more edges (ArcGIS Help). This makes the triangles more equilateral by maximising the minimum angles of the triangle and thereby avoiding long, thin triangles. The main idea is to minimise the area of influence of each data point i.e. the area where each point influences the interpolation.

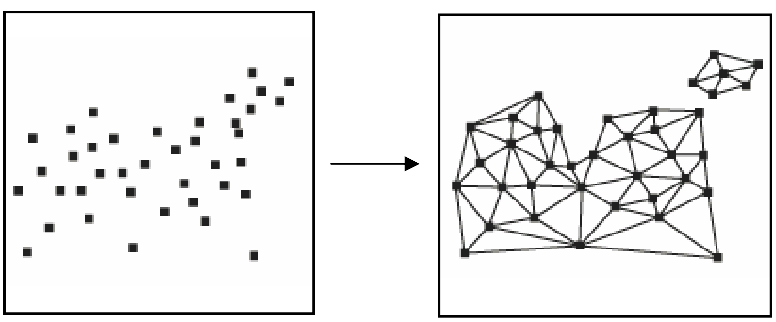


Figure 14. Showing data points or nodes which are joined with their nearest neighbour by never overlapping edges to form the Delauney triangles used in TIN interpolations. (Source: Arc GIS Help)

The TIN can be created from one or more types of input data such as sample points (mass points), breaklines and polygons. The mass points are the primary input into a TIN and determine the overall shape of the surface as they are the nodes in the network. Breaklines could be included at first or added at a later stage. They usually represent natural features such as ridgelines, elevation lines or streams. There are two kinds of breaklines: hard and soft. Hard breaklines capture abrupt changes in a surface and improve the display and analysis of TINs. Soft breaklines allow you to add edges to a TIN to capture linear features that do not alter the local slope of a surface (ArcGIS Help).

3.1.6 The theory behind Inverse Distance Weighted interpolation, IDW

As mentioned above, points located close to each other tend to be more alike than points located at a distance, so-called spatial autocorrelation. The IDW calculates the cell values for each cell by calculating the mean values of neighbouring points. Points that are located closer to the cell are given higher weights based on the inverse distance between the cell and the data points. This means that points located closer to the cell are given greater importance in the interpolation of the cell (Eklundh & Martensson, 1995).
The IDW is mathematically expressed as:

$$z(x_p) = \frac{\sum_{i=1}^{n} z(x_i) \cdot \frac{1}{d^k}}{\sum_{i=1}^{n} \frac{1}{d^k}} \qquad \text{Equation 4}$$

Where
n is the number of points;
$z(x_p)$ is the interpolated value;
$z(x_i)$ is the value in the point i;
d is the distance between point i and p, and
k is the exponent that governs the distance dependence.

If the exponent *k* is given the value 0 the end result is a standard none weighted average as the denominator equals n and all the weight equals 1. With an increase of the exponent *k* the points closer to the cell are given amplified importance and there is less influence from distant points. Normally the *k* exponent is given a value between 1 and 3 (Eklundh, 2003). In the ArcGIS Help manual the most reasonable results will be obtained using values between 0.5 and 3 and default is set to 2 (ArcGIS Help). When dealing with IDW interpolation there are a number of factors that need to be considered. Deciding on an exponent value (*k*) is central to IDW. If the exponent is set to "low", local variation in the data set can be missed. On the other hand, if the exponent value is set to "high", the influence of single points can be exaggerated. As mentioned before, the IDW is an interpolation algorithm that is dependent on radial searches. The radius of the search window determines how many data points (*n*) the interpolation of the cell will include. This could be set to a specific radius and the points within that area will be included, or it could be set to a number of points in the nearest radius (ArcGIS Help). If the radius is set too small not enough points will be included in the interpolation of the cell and it will not be assigned a value. If the search window is set too large the value of the cell tends to become more of a global mean because of the large number of points included in the interpolation (Eklundh, 2003). The optimal number of points that should be included in the search window is normally between 4 and 12 points (Burrough, 1986). The IDW is also sensitive to clustering of points and unevenly placed data. The calculated values can be misleading since the points included in the interpolation can come from one dominant direction and not from the other. Reducing the weights of some points or dividing the search window into sections where one uses the same amount of points from each sector can reduce this problem (Burrough, 1986and Eklundh, 2003).

3.1.7 Evaluation of an interpolated surface using Root Mean Square Error (RMSE)

The accuracy of the interpolation is normally guaranteed by comparing the interpolated surface (DEM) with elevation data not used in the interpolation and calculating the statistics (Eklundh, 2003), the so-called evaluation points. The most frequently used method is Root Mean Square Error (RMSE), which is mathematically expressed as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(z_{di} - z_{ri}\right)^2} \qquad \text{Equation 5}$$

Where: Z_{di} is the elevation value in the point *i* on the DEM;
Z_{ri} is the elevation value in the corresponding point in the evaluation data;
n is the number of elevation points.

A low RMSE means that the difference between the two data sets is low and the accuracy of the DEM is satisfactory. A high value implies that the DEM is not a good representation of the elevation of the area and a new interpolation might be done (Weng, 2002). It is also important to carry out a visual confirmation of the DEM to detect artificial patterns developed by the interpolation (Eklundh, 2003).

3.2 Model two, The Bruun Rule

The Danish coastal engineer Per Bruun first developed the Bruun Rule in 1954 and later revised it in 1962 and 1988. The rule is a 2- dimensional sandy shore model that is based on the assumption that the beach profile is in equilibrium with the current wave climate in response to a sea level rise. Considering such an assumption the beach profile would remain the same as the shoreline moved back and up in response to the rising sea. From the derivation of the Bruun rule and from studies, the focus of the model lies in long term equilibrium. It involves decades of profile adjustments to rising sea levels (The Coastal Response). However, as mentioned, the model is based on a few significant assumptions and these assumptions have been identified by another researcher, Zhang et al 2004 in *Global Warming and Coastal Erosion* and are rendered below:

- *"The active beach profile perpendicular to the shoreline tends toward an equilibrium form for a given wave regime, and extends out to the so called depth of closure (DoC). The DoC is the water depth at which ocean surface waves no longer significantly transport bottom sediments. The equilibrium active beach profile is thus defined as an idealsed statistical average profile over seasonal and storm-induced fluctuations, and includes an underwater part that makes up most of the profile".*

- *"If other conditions remain unchanged and sea level rises, the active beach profile will achieve equilibrium with the new sea level by shifting landward and upward. This will result in erosion of the upper shore face, with sediment deposition on the lower (mostly underwater) part of the profile".*

- *"Sediment eroded from the upper beach is equal to that sediment deposited on the near shore bottom. In addition, there is no net sediment exchange between the active beach profile and the outer shore face (i.e., beyond the DoC)".*

- *"The increase in elevation of the near shore bottom resulting from deposition of sediments from the beach face and dune is equal to the rise of sea level".*

Based on these assumptions Bruun developed a model as shown in figure 15.

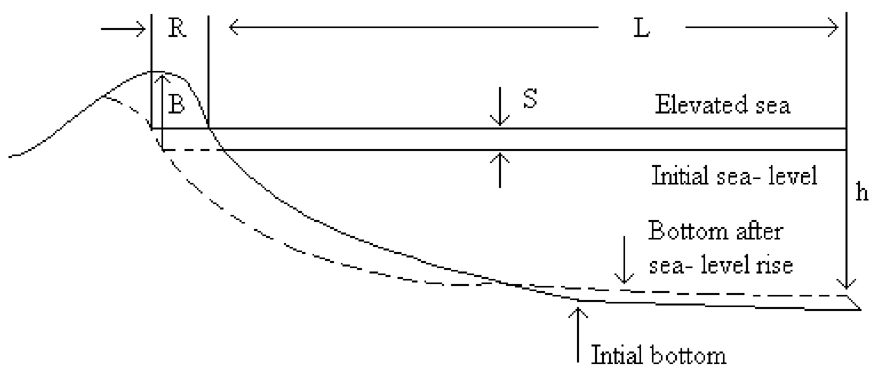


Figure 15. The graphic model of the Bruun Rule.

This model is explained by the following mathematical relationship:

$$R = \frac{L}{B+h} S$$ Equation 6

Where: *R* is the shoreline retreat, *B* is the height of the berm, *h* is the depth of the closure where near shore sediment exists (DoC), *L* is the cross-shore distance to the water depth *h* and *S* is the sea level rise. The berm is the portion of the beach that marks the landward limit of wave swash (Hugget, 2007).

The DoC (*h*) is the parameter that is the most difficult to determine. Per Bruun's first article generalises this edge by referring to the scientist Parker Trask who states that on sandy beaches "the sand does move…meanwhile it seems to be clear that little sediment is transported beyond a depth of 18m (60 ft)". The study area Bruun uses in his first application of his mathematical model assumes that the edge of the continental shelf is no nearer the shore than 18m depth. This is something Bruun will reappraise in his later models and do measurements for calculations in his formula. As a further development of the Bruun formula, Hallermeier (1977,1978) develops methods based on incident wave conditions and grain size estimates and calculates the DoC. Hallermeier divides the submerged beach profile into three zones: littoral, shoal and offshore zones. The littoral zone is characterized by intense sea bed activity caused by currents and near breaking waves. The offshore zone is situated in relatively deep waters where the bottom sediments are not affected by the wave climate. The shoal zone extends from the littoral zone out to the offshore zone and is located in an area where the wave climate is likely to have little effect on bottom sediments. The shoal zone interval is also known as the DoC which means that the DoC has a minimum and a maximum extent, d_{min} and d_{max} (Hallermeier, 1981). This study will focus on the DoC at d_{min}. Hallermeier (1977, 1978) developed an analytical approximation of an annual d_{min} mathematically expressed as:

$$d_{\min} = 2.28H_s - 68.5\left(H_s^{\,2} / gT_s^2\right) \qquad \text{Equation 7}$$

Where: d_{min} annual DoC below mean low water, H_s is the non-breaking significant wave height that is exceeded by 12 h per year (0.137 % of the time), T_s is the associated wave period and g is the acceleration due to gravity.

The equation is based on quartz sand with a median diameter between 0.16 and 0.42 mm, which typifies conditions in the near shore for most beaches (Nicholls et al, 1998). The equation is thoroughly tested in Nicholls et al. 1998 and Birkemeier 1985.

The Bruun Rule has been thoroughly tested in both laboratory environments with wave flume investigations and in the field, e.g. by Schwartz (1967), DuBois (1975, 1976, 1992), Fisher (1980), Rosen (1978, 1980), Hands (1980, 1983) and others. Its overall validity is therefore reasonable. However, other studies also point out flaws in the theory. The main criticism on the Bruun Rule is that it is basically a 2-dimensional model, and given that reality is 3-dimensional, care should be taken when applying it 3-dimensionally (Bruun, 1983, Cooper & Pilkey, 2004, SCOR Working Group,1991).

4. Data material and data preparation

This chapter is divided into two sections: Data presentation and Data preparation. The former presents the different kinds of data used in this study and the latter describes how this data was revised and harmonised for later use in the different analyses.

4.1 Data

For this study two different kinds of data are in situ assembled;

1. Publicly available data accessible at governmental departments, authorities and research associations
2. Data from in situ measurements on the beaches.

1. Data from the departments, authorities and research associations:

This data is gathered from different institutes and some was accessible and free of charge. The data is used for working both on the DEM and on the Bruun Rule along with the data used for classification of the land use, ecosystems, infrastructure and visual evaluation and localisation of the beaches. The primary data used for our research is:

- Digital Topographical data over Bundala and Hambantota town, projected in the local SL1999 coordinate system. 5m contour lines and photogrammetric measured elevation points with a mean error of about 2m produced by the Sri Lanka Survey Department. The topographical data will be used for interpolating the DEM.

- Satellite Images (IKONOS and Landsat ETM) of the full research area covering approximately 2 km inland. The images were registered in 2005. The satellite images are used for classification of land use and identification of ecosystems and infrastructure to assess the potential impact of the SLR.

- Digital land use data from 2003 in ESRI coverage format and CAD for the detailed deep study research area. The data was collected by the Sri Lanka Survey Department. The data was projected in the local SL1999 coordinate system. The land use data will be used to estimate the impact of the moving coastline.

- Compiled wave statistical data collected from a buoy outside Hambantota town and shows significant wave height, direction and time between successive up-crossings (Wave period). The data was collected throughout 2007 by the National Aquatic Resources Research and Development Agency of Sri Lanka (NARA). The wave data will be used to calculate the depth of closure with the help of the Hallermeier formula to be used in the Bruun Rule.

- Wave data from WaveWatch3 archived by NOAA, i.e. data of wind and wave on a global scale (1.25 by 1.00 degrees longitude/latitude grid between 78.0° north to 78.0° south). The wave data covers the area where we do not have buoy measurements and is used to determine significant wave height and wave periods for calculating the depth of closure.

- Digital bathymetric data from 2007 of the area outside Hambantota town collected by NARA. The data contains detailed depth measurement points and was projected in the WGS84 coordinate system. The bathymetric data is used to strengthen the estimated depth of closure calculated from the Hallermeier formula.

- Sea chart on paper with bathymetric data from the full research area. This is used to strengthen the estimate depth of closure where detailed bathymetric data is missing.

- Digital map with contour lines, a beach profile over sand dunes in the coastal area around Hambantota town. Scale 1:5000 and 1 m contour lines. This is used to calculate the Bruun Rule and model the movement of the beach without the field measurements.

2. Field work: measuring and mapping the beaches of Hambantota

All the beaches along the full stretch of our research area were studied on site. Through paper maps and satellite images all beaches which were “walkable” and accessible were identified. With the help of a Three wheeler and a driver with local knowledge of the area all the beaches were accessed and walked across from one end to the other. Using GPS, a clinometer, measuring tape, a camera and pen and paper, these beaches were measured and mapped. The measuring consisted in taking the berm angle into the sea and measuring the length of the foreshore and backshore as well as the distance from the waterline to the vegetation line.

Notes were taken on the vegetation or infrastructure behind the beach line as well as on the specific physical characteristics of the beach. Each beach was measured at a qualified number of sites that differed for each beach. For each measuring point the GPS position was noted and photos were taken.

4.2 Data preparation

Some of the data used in this thesis came in different formats and coordinate systems. To be able to carry out the analysis the data had to be harmonised.

4.2.1 Harmonisation and transformation of coordinate systems

The main part of our data was taken from the Sri Lankan coordinate system SL1999, but the GPS measurements and the bathymetric data were found in the WGS84 coordinate system and had to be transformed. Neither the Sri Lankan coordinate system, SL1999, nor the transformation parameters to transform the datum between WGS84 and SL1999 were defined in the GIS- software. The parameters for the transformations were acquired from the Survey Department of Sri Lanka. The parameters had to be defined before a transformation between the coordinate system could be made. The projection for the SL1999 coordinates system was defined according to the following parameters:

- Everest Ellipsoid, Transverse Mercator projection
- False Easting 200000
- False Northing 200000
- Longitude of Origin 80 46 18.16000 E
- Latitude of Origin 7 00 1.7290 N
- Scale Factor 0.9999238418

The datum transformation equation used was a seven-parameter method also known as a Helmert transformation or Coordinate Frame Rotation transformation. The seven parameters are three linear shifts (translation), three angular rotations around each axis and a scale factor. The parameters for SL1999 datum:

- Transformation Parameters - WGS 84 to Everest Ellipsoid
- Translation X= 0.2933 meters
  Y= -766.9499
  Z= -87.7131
- Rotation X= 0.1957040 seconds
  Y= 1.6950677
  Z= 3.4730161
- Scale Factor 1.0000000393 ppm

4.2.2 Land use data

The land use data was acquired from the Sri Lankan Survey Department. It came in two different formats; ESRI Coverage and CAD, the latter being an international design and blueprint format. The data had to be harmonised in order to process it in the ESRI ArcMap GIS software at hand. The Coverage and CAD files were converted into ESRI format shape files using conversion algorithms in the GIS software.

The converted CAD files were further converted into polygon layers. Since the converted files did not contain any land use attribute tables, a manual classification of the land use types was performed. The classification was primarily based on the land use annotations accompanying the CAD files. The codes were translated using an interpretation key also acquired from the Sri Lankan Survey Department. Some of the converted polygons were hard to classify when using the annotations as the standard of the data was poor. Some polygons missed annotations completely. Since this was a CAD format converted into first lines and then polygon features, the line features which were roads, power lines, channels etc. in the CAD layers were also converted. This created artificial polygons which had to be dissolved, merged or removed from the final land use layer. It was also hard to determine the land use in polygons bordering other layers were the annotations were missing. These problems complicated the classification process. To further assist in the classification procedure, visual interpretation of satellite images and ground controls in the field were utilised.

The harmonized land use data were finally merged into one single land use layer using a GIS algorithm (figure 16). The final land use layer contained the following classes:

Sand/Beach	Coastal areas under the influence of wave- and current actions.
Forest	High-growing natural vegetation
Homesteads	Residential areas consisting of gardens and smaller cultivated areas
House/Industry	Residential, industrial and other urban areas
Barren land	Abandoned agricultural land or cleared forest and scrub land areas
Chena	Agricultural chena cultivation
Grassland	Open grassland
Lagoon	Water body separated or partly separated from the sea by a narrow or exposed sandbank
Lewaya/Salt pan	Saline shallow lagoons often used for salt production
Marsh	Wetlands connected to the lagoons or Lewayas often sheltered by sand banks.
Paddy	Paddy cultivation of mainly rice
Plantation	Plantations of mainly coconut, banana and rubber
River	Rivers and streams
Rock	Often rock outcrops
Scrub land	Low vegetation with elements of bushes and trees
Tank	Water reservoir used for irrigation, food preparation etc.
Waterhole	Smaller than Tank

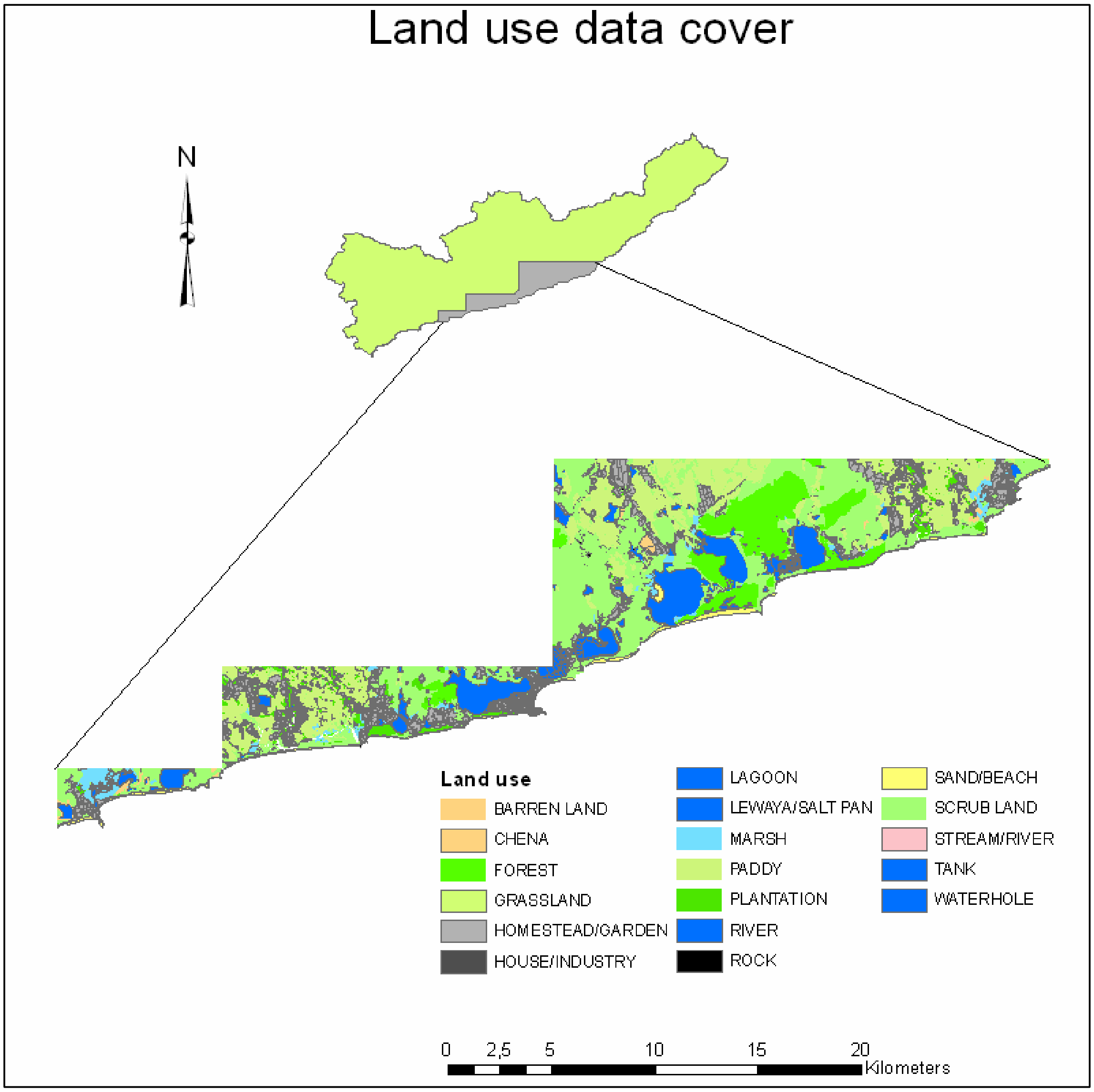


Figure 16. The map shows the land use data cover. Coord.syste: SL1999 (Source: data material from the Sri Lanka Survey Department)

4.2.3 Elevation data

The elevation data consisted of photogrammetric measured elevation points and contour lines in shape (ESRI GIS) format. Since the density of the point data was not satisfactory the contour lines were also used in the interpolations. To be able to use the contour lines in our interpolations they had to be converted into point features. This was accomplished by the use of a line to point algorithm in the GIS software. To avoid terrace building, which can be the case when lines are used, only the end vertices were used in the conversion. The elevation points around the coastlines and the zero contour line around the lagoons were condensed by using all vertices in the conversion from line to point to reinforce the elevation data in order to get a distinct zero line.

For visualisation and to get an accurate interpolation of the lagoons and the sea it was also important to have negative elevation values in these areas. For this reason, elevation points in the lagoons and in the sea were manually digitized. To ensure that the interpolated surface in the lagoons remained below zero, as there would otherwise be islands in the lagoons, the digitized depth values had to be exaggerated. This proved particularly important when using the Spline interpolation, were Runge's phenomenon could otherwise create problems. Values of as low as -10 meters were used.

As stated above, the study area contained some distinctive geomorphologic features such as estuaries and sheltered lagoons, with only a small land strip separating them from the ocean. Since the elevation data did not cover all these areas at a highly detailed level we had to manually digitize elevation points to preserve the true nature of the area. Especially the TIN interpolation was sensitive to this problem creating long thin triangles resulting in irregular coastlines and waterlines along lagoon edges and rivers which were inconsistent with the observations from the satellite images. To be as accurate as possible regarding the manual digitalization, the elevation in the digitized points was based on a linear interpolation algorithm, mathematically expressed as:

$$z_p = z_1 + \frac{z_2 - z_1}{x_2 - x_1} \cdot \left(x_p - x_1\right) \quad \text{Equation 8}$$

Where:
z_p is the interpolated value,
x_1 and x_2 is the location of the measured elevation points,
x_p is the location of the unknown point, and
z_1 and z_2 is the elevation for the known points.

All the layers of the elevation points manually created together with the original layer were merged into one layer, which was the base for all interpolation methods. To be able to assess which interpolation is the best it was important to use the same base for all of them.

5. Methodology

This chapter describes how we have worked with the GIS software when creating the DEM in chapter 5.1 and the Bruun rule in chapter 5.2.

5.1 Working with GIS to produce DEM

The creation of the DEM interpolations was carried out simultaneously as the digitalisation of elevation points was refined (chapter 4.2.3.) adding points from elevation lines and manual digitalisation etc. Each time additional digitalisation was done, the result was examined visually. In this way the best outcomes of the digitalisations were found. Below is the description of the work for each different method.

5.1.1 Interpolating with Spline

As mentioned above the Spline interpolation used for this study is based on minimum curvature splines also known as thin plate spline interpolation (TPS). The operation run with Tension Spline gave a much better surface than Regularized Spline after a visual examination after of a couple of test runs. The interpolation was run with eight different settings of the combination of weight, which defines the weight of the tension, and the number of points included in the radial search in the interpolation equation.

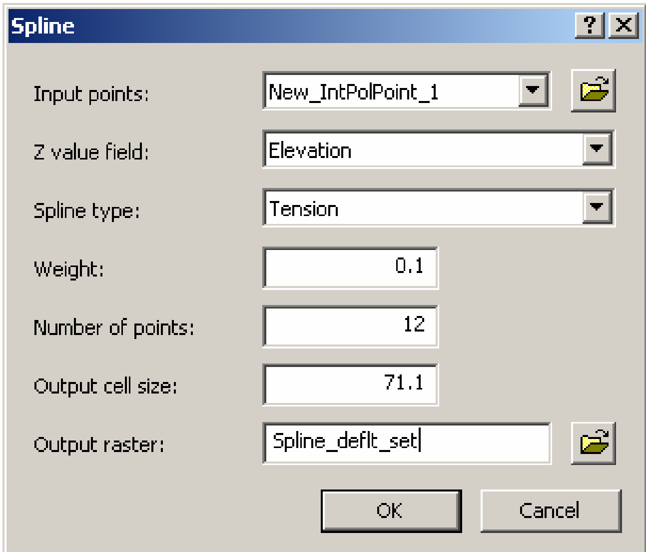


Fig 17. From ArcGIS 9.2 example to view Spline settings

The default for tension weight is normally 0.1. The weight parameter is a good tool when trying to control the overshots and fluctuations of the spline curve. The number of points has a default of 12 but was tested for eight points as well to study the difference with a smaller search window. The resulting raster would need to have a high resolution for the model to be detailed enough but still it is important that a condensation of the raster does not decrease the quality. For this reason different output cell sizes were also tried and the accuracy was tested using RMSE. This showed that the quality actually increased from a default setting of 71.1 to 10 meters and 5 meters was also satisfying.

The settings tried were:

Table 1 The setting for different trials in Spline interpolation

Type	Cell size (m)	Power	Points
Spline (deflt)	71.12	0.1	12
Spline	20	0.1	12
Spline	20	0.1	8
Spline	10	0.1	12
Spline	10	0.1	8
Spline	5	0.1	12
Spline	5	0.1	8

The work with T Spline interpolations showed a lot of problems with overshooting and controlling the spline polynomial which caused us to try different ways of digitalising the zero and sub-zero lines. To achieve the effects of a relatively exact and sharp edge along the water lines where the surface would hit zero at the water edge and then dive turned out to be harder than expected. This lead to the result that the amount of zero points along the edge sometimes had to be reduced from the input data and sometimes had to be increased since the input data largely varied. Too many points forced the spline to harden and too few made the transition from sub-zero in the water to above zero on land too weak. Furthermore, the levels of elevation in the digitalised points out in the water were placed at different levels depending on how large the water body (the polygon) was and how close the edges were to each other. This was the only way to control the spline curves and prevent overshoots creating islands in the water. The latter could also be controlled with the weight of tension that it turned out. Once the optimum digitalisation of elevation points for spline was found, this vector layer of elevation points was tried in the TIN surface interpolation causing another few points to be added and the result of these adjustments created the layer which was used as the original in all interpolations. When elevation points had been added due to the result of the TIN interpolations the Spline had to be redone as they should all be made from the same vector layer.

The interpolation was done without boundaries and then extracted by a mask created for the research area.

5.1.2 Creating the TIN surface

The TIN interpolation was made in the standard way by using the elevation points as the masspoints for the surface. The operation is done in the 3D analyst tool ***Create TIN from feature***. To further enhance the resulting surface the elevation lines from the same data layer were added as breaklines. This can be done after the initial interpolation by using the tool ***Add features to TIN***. The surface was interpolated with both hard breaklines and soft breaklines resulting in little or no difference between the two. The function "Hulls" was not used which might have been a mistake as this perhaps could have minimized the problems with digitizing the sub-zero levels in the lagoons and rivers.

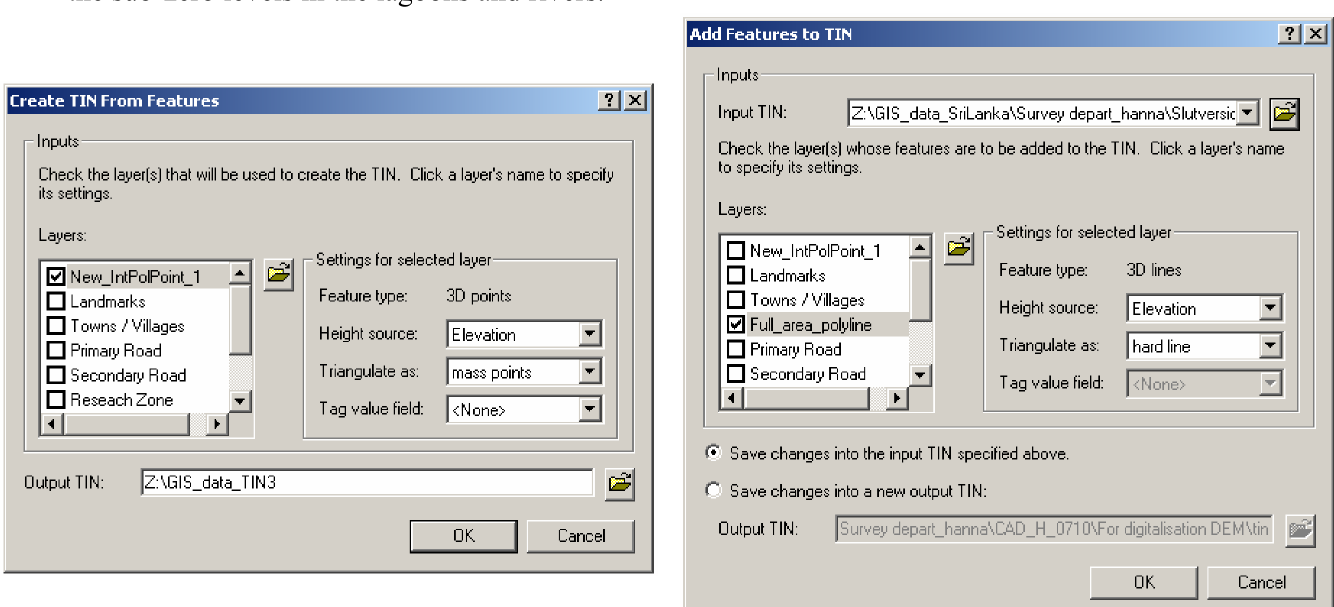


Figure 18 From ArcGIS 9.2 sample to view settings for creating the TIN and Add features after creation.

A TIN surface has a different data format than Spline and IDW as the former are polygons and the latter are raster files. In order to compare the outcome of each interpolation the TIN was converted into raster format. This was done in the 3D analyst ***Convert TIN to Raster***. After the conversion the raster files were extracted by a mask designed for the research area.

5.1.3 Interpolating Inverse Distance Weighted Interpolation

The IDW interpolation in this research was a straight forward operation in the 3D analyst ***Interpolate to Raster***. The same vector layer of elevation points was used as for the previous interpolations and all test runs were evaluated along the way. The interpolation was run with four different settings of the ***power*** (of *k* exponent) and a different amount of number of points (points in the radial search) as well as a different output cell size.

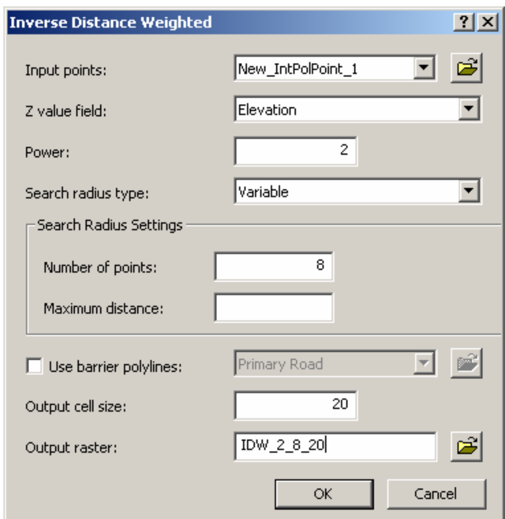


Figure 19. From ArcGIS 9.2 sample to view settings for Interpolation using Inverse Distance Weighted.

The different settings tested in the IDW were
<u>Power:</u> 1, 2, 3 and 4
<u>Number of points:</u> 8 and 12
<u>Output cell size:</u> 71, 20, 10, 5

Calculations of the best RMSE value soon showed that a radial search of 8 was better than 12 and the outcome using cell size 10 was satisfying. The use of mainly setting 8 radial search and cell size 10 or 5 combined with the different powers narrowed down the different combinations. The interpolation was carried out without barrier polylines and without boundaries and the result was extracted by a mask designed for the research area.

5.1.4 Evaluating the DEM

Prior to any interpolation a total of 30 random evaluation points were manually extracted from the elevation points in the vector layer used for the interpolation. They constitute the separate evaluation layer and were not part in any of the interpolations. Each resulting interpolation was evaluated for each different setting they had. This was done by using the evaluation layer to extract each raster cell in the interpolated surface represented at the same coordinates as the evaluation points. The two values, for the true elevation and the interpolated elevation, were retrieved and used in equation 5 above which calculated the RMSE value for each interpolation. The best RMSE value represents the best interpolated surface which will constitute the DEM used for further analyses. When using evaluation points to calculate RMSE values like this, it is important to take into consideration the location of the point within the cell. This is further explained in 7.1.3.

5.1.5 Inundating the DEM and calculating the effects

The DEM created and selected to be the best is inundated to simulate the elevated SLR. The so-called inundation was achieved by reclassing the interpolated surface for each different scenario using the ***reclass function*** in the Spatial Analyst tool. The reclassing in turn generated two classes which were below and above the selected height of each different SLR level; 0.18m, 0.59m, 1.0m, 2.0m and 6.0m. In this way all the land under for example 1m is classified as being subject to land under water in the case of a 1m SLR and remains so regardless of whether the land is situated inland or along the coastline.

To visualise a line for each selected SLR scenario the contour lines for these heights were drawn in the DEM using the ***Contour function*** in Spatial Analyst. The contour lines at the right heights were selected and converted into separate vector layers.

To calculate what areas in the land use classes were flooded the reclassed files were vectorised. These five vector files each consisted of polygons showing either an area under or above the new sea level. Through overlay operations between the land use layer and the reclassed vectorised files the impact on different land use types could be measured and quantified using GIS and Excel.

5.2 Working with the Bruun Rule

As mentioned above the Bruun rule is a model based on several parameters (equation 6). To establish the shore line retreat (R) several steps had to be made. The berm height (B) had to be measured; the DoC (h) had to be determined; the cross- shore distance (L) had to be measured; the potential sea level rise (S) had to be determined and finally the shore line retreat (R) had to be calculated. The results of the model were then applied on the study area.

Because the Bruun rule is only applicable to sandy beaches, all the beaches along the Hambantota district coastline were subject to inventory through visual examination. The parts with rock coasts were identified on maps and satellite images and accordingly left out. All the remaining beaches were examined and categorized into sand or mixed sand/ rock beaches. The sand beaches were mapped and measured excluding the mixed sand and rock parts as they can not be part of the calculations using the Bruun Rule. Only sand beaches were measured for a beach profile. Each stretch of sand beach varied in length from 1 km to 6 km. In total there are 16 separate sand beaches in the study area (table 2).

5.2.1 Measuring the Berm height (B)

For each of the 16 sand beaches the berm height was measured approximately every 400-600 meters. This should reasonably represent a calculated average of the berm height for the full stretch of the beach. To test this, detailed measurements every 50 meters were taken on one of the beaches, i.e. the beach in Hambantota Bay. Comparisons that were made showed that the difference between measuring every 50 meter and every 400-600 meters did not change to the average height of the berm.

Figure 20. Illustration of a typical profile of the beach areas. The crest identified in the centre of the image is the berm. Photo. H. Frykman

The angle of the beach was measured using a clinometer and measuring tape. The person measuring stood on the top of the berm and another was positioned in the swash zone at the approximate sea level, (fig 21). The angle and the distance a) was taken after which the distance b) from that point of the berm to the start of vegetation at the back of the beach was measured, this to give the depth of the beach.

The angle taken from the clinometer and the distance a) was used to calculate the height of the berm using the mathematics in equation 9.

$$B = \cos \alpha * d \qquad \text{Equation 9}$$

Where: B is the height of the berm
α is the measured angle in radians
d is the measured distance (hypotenuse)

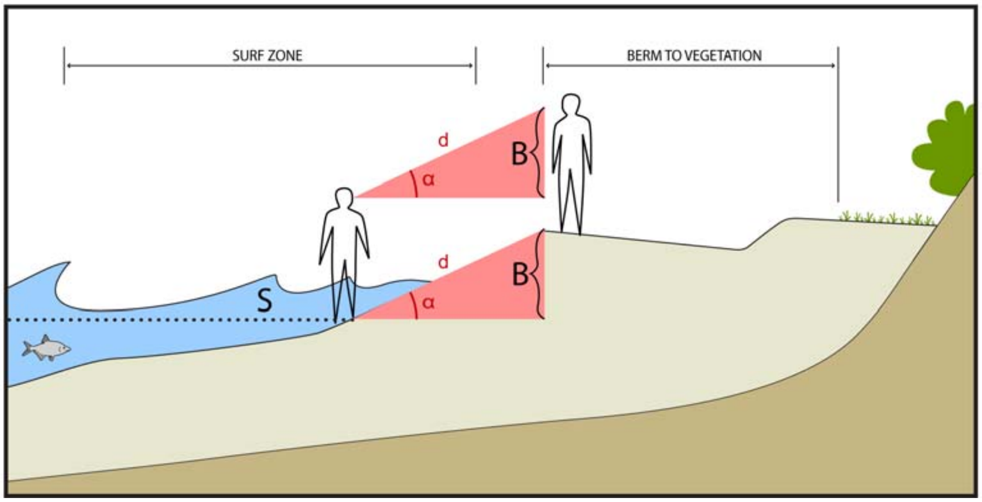


Figure 21. Graphic model of how the beach measurements were taken and calculated
The top triangle shows the measured triangle which is equivalent to the sought bottom triangle.
***B** is the sought berm height calculated by measuring **d** with a measuring tape and α with a clinometer. **S** is the average sea level estimated in the middle of the surf zone at the beginning of the face section of the terrace. The distance from berm to vegetation is measured in order to find out the backshore width.*

5.2.2 Establishing the DoC (h)

As mentioned above, the DoC (*h*) is the most difficult parameter to determine. Based on available data the d_{min} was calculated using the Hallermeier formula (Equation 7). On each beach, a sample of the sand was taken in the swash zone for estimating grain size. The sand was brought back from the beach to dry before being strained in a grain size strainer with three levels of mesh of different dimensions. The strainer had to be equipped on site with two new levels and the dimension of their mesh was measured back in Sweden using a slide caliper. The different meshes were 2mm, 1.15mm and 0.56mm. Unfortunately, no strainer with a finer mesh could be found in Sri Lanka; however a clear majority of the sand cleared the smallest mesh and therefore it seems reasonable to assume that the sand fulfils the Hallermeier criteria of 0.16 and 0.42 mm in sand diameter.

The wave data used in the calculations came from a S4 Directional Wave Current Meter buoy located just outside Hambantota town at a depth of 17 meters. The buoy data was collected through 2007 covering the different seasons of wave climate. The data contained compiled statistics on significant wave height and wave periods. The significant wave height of the area was 1, 5 meters and the associated wave period was 11, 64 seconds. This gave a DoC depth of 3, 3 meters which leads to the assumption that the wave climate retrieved from the buoy is similar in the whole study area. Such an assumption is supported by other wave data showing the identical wave climate in areas just outside the study areas (Garcin et al, 2007) and in the global wave model Wave Watch III (Wave Watch, NOAA). This means that the DoC will be the same in all the 16 study sites.

5.2.3 Measuring the cross-shore distance (L)

A DEM was produced on the basis of bathymetrical data retrieved from NARA (The National Aquatic Resources Research and Development Agency). The data covered an area just outside Hambantota: Hambantota Bay and West Hambantota. The bathymetrical data was interpolated using an IDW algorithm with a 12 point search and k-value of 2 producing a DEM with a spatial resolution of 10 meters and a RMSE of 0.36 meters (figure 22).
Based on the calculated DoC in combination with our berm height measurement positions the cross- shore distance (*L*) was measured using a GIS algorithm. The distance produced by the algorithm is a calculated average. Due to the lack of additional bathymetric data no parallel DEMs could be produced in the other study sites. Based on visual interpretation of paper sea charts were the depths and shorelines are very much the same as in the area covered by the data, it could be assumed that the cross-shore distances will be the same in all of our beaches. Even the flat beaches located in the western part of our study area falls within these assumptions. The value used for the cross-shore distance on the other beaches was a cross-shore distance average calculated from the two beaches covered by the available data.

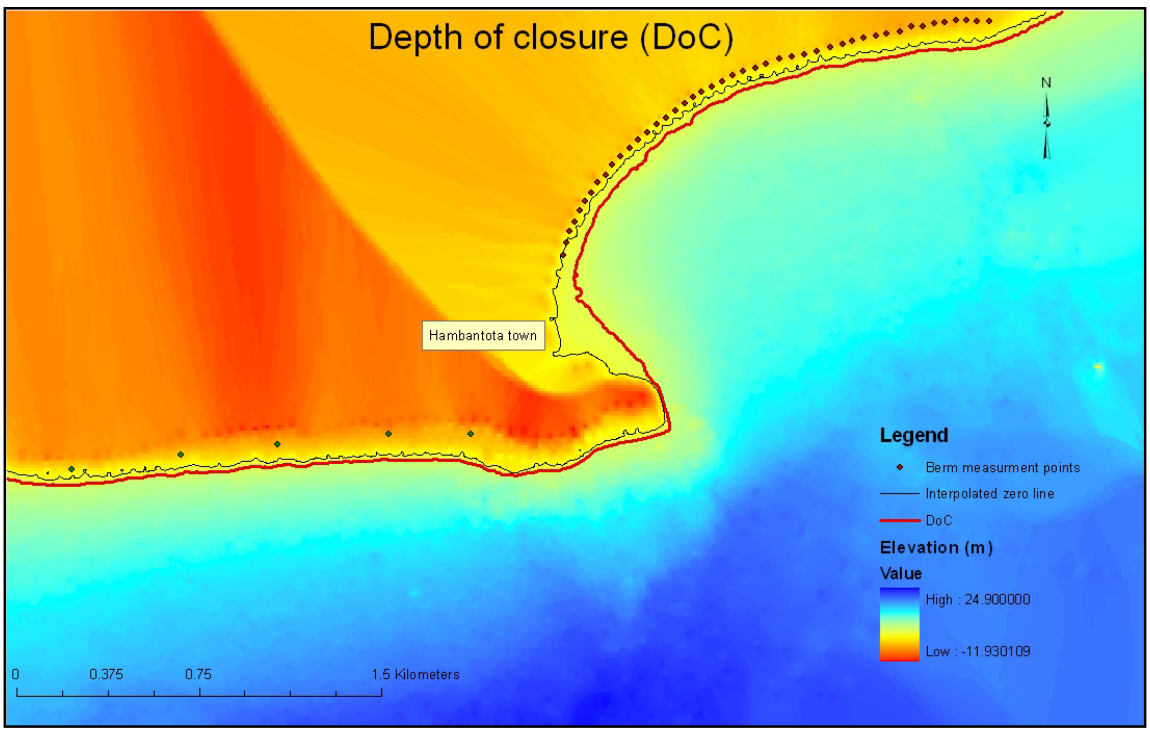


Figure 22. The map show the DEM interpolated with the IDW algorithm, the DoC and Berm measurement positions. The negative elevation values are on land while the positive values are the depth of the sea floor. The elevation and depth data only covered the costal areas and therefore the heights located further inland are extrapolated values.

5.2.4 Sea Level Rise (S) for Bruun

The different levels of sea level rise are based on the predictions in IPCCs SRES scenarios and a worst case scenario given in Nicholls (2005) where the sea level will rise by potentially as much as 6 meters. See also sub-section 2.3.1.
The levels used in the study are: 0.18m, 0.56m, 1.0m, 2.0m and 6.0m.

5.2.5 Shore line retreat (R)

The shore line retreats for each of the 16 beaches were calculated from the parameters stated and described above. All the calculations were made in Excel.

5.2.6 Applying the model

GIS-software from ESRI (ArcMap) was used to visualise and analyse the potential impact of the shoreline retreat. The data used in this step was land use data from the Sri Lanka Survey Department and satellite images from the IKONOS sensors.

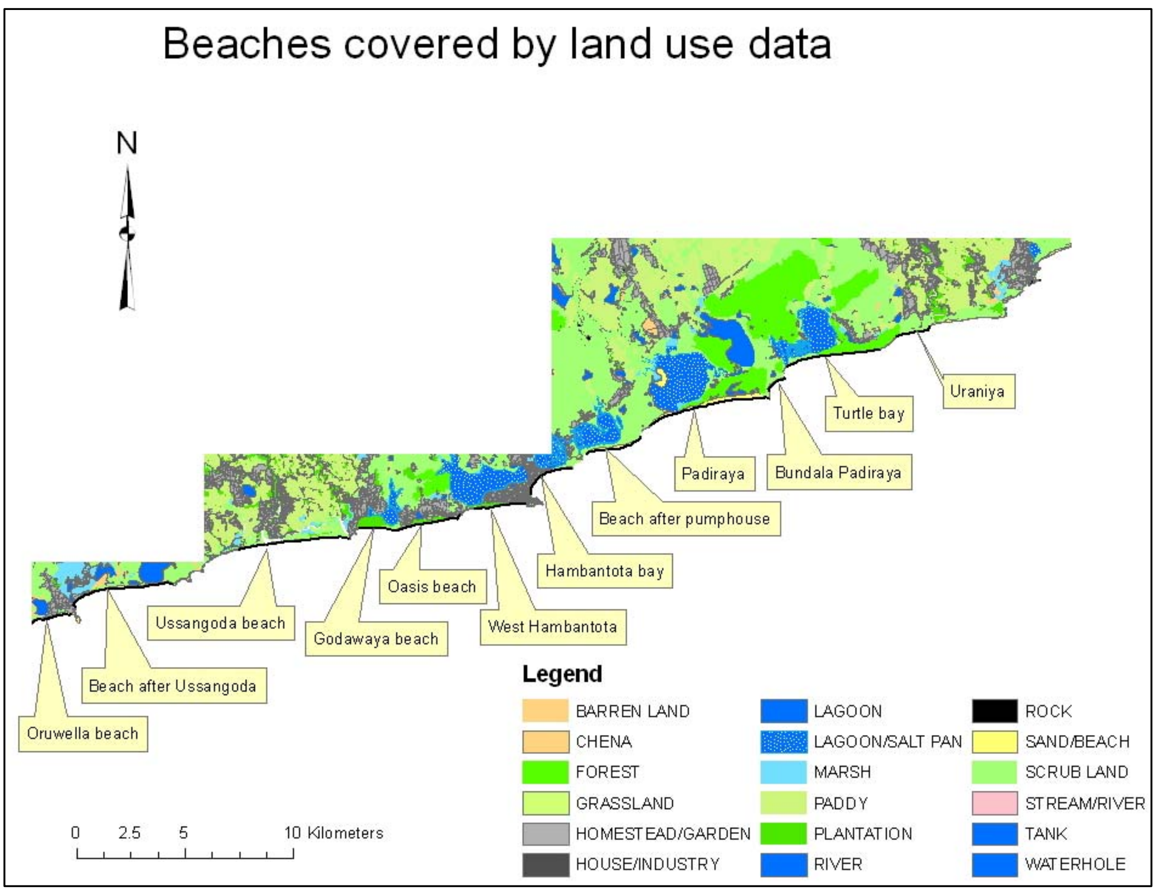


Figure 23. The map presents a view over the beaches covered by the land use data from Sri Lanka Survey department. Se also figure 16 for further information regarding the location of the beaches

Since the land use data did not cover the whole study area the impact on 4 sites could only be visualised in IKONOS satellite images (table 2 & figure 23, 24). In these areas the coastlines were manually digitized using the satellite images. The land use layer was divided into the 12 remaining study sites using a GIS algorithm. To extract the coastlines from the land use data, copies were made of the 12 sites and converted into line layers where the shorelines could be manually extracted.

Table 2. The table shows the data coverage of the study area.

Beaches	Land use data	Satellite data
West Hambantota	Yes	IKONOS/Landsat
Hambantota bay	Yes	IKONOS/Landsat
Oasis beach	Yes	IKONOS/ Landsat
Godawaya beach	Yes	IKONOS/Landsat
Ussangoda beach	Yes	IKONOS/Landsat
Beach after Ussangoda	Yes	IKONOS/Landsat
Oruwella beach	Yes	Landsat
Rekawa beach	No	IKONOS/Landsat
Tangalla beach	No	IKONOS/Landsat
Mawala beach	No	IKONOS/Landsat
Blowhole beach	No	IKONOS/Landsat
Beach after pumphouse	Yes	IKONOS/Landsat
Padiraya	Yes	IKONOS/Landsat
Bundala Padiraya	Yes	IKONOS/Landsat
Turtle bay	Yes	IKONOS/Landsat
Uraniya	Yes	IKONOS/Landsat

By applying a buffer on the extracted and digitized shorelines, based on the different sea level rise scenarios, the modelled shoreline could be visualised. Through overlay operations between the land use layer and the modelled results the impact on different land use types could be measured and quantified using GIS and Excel.

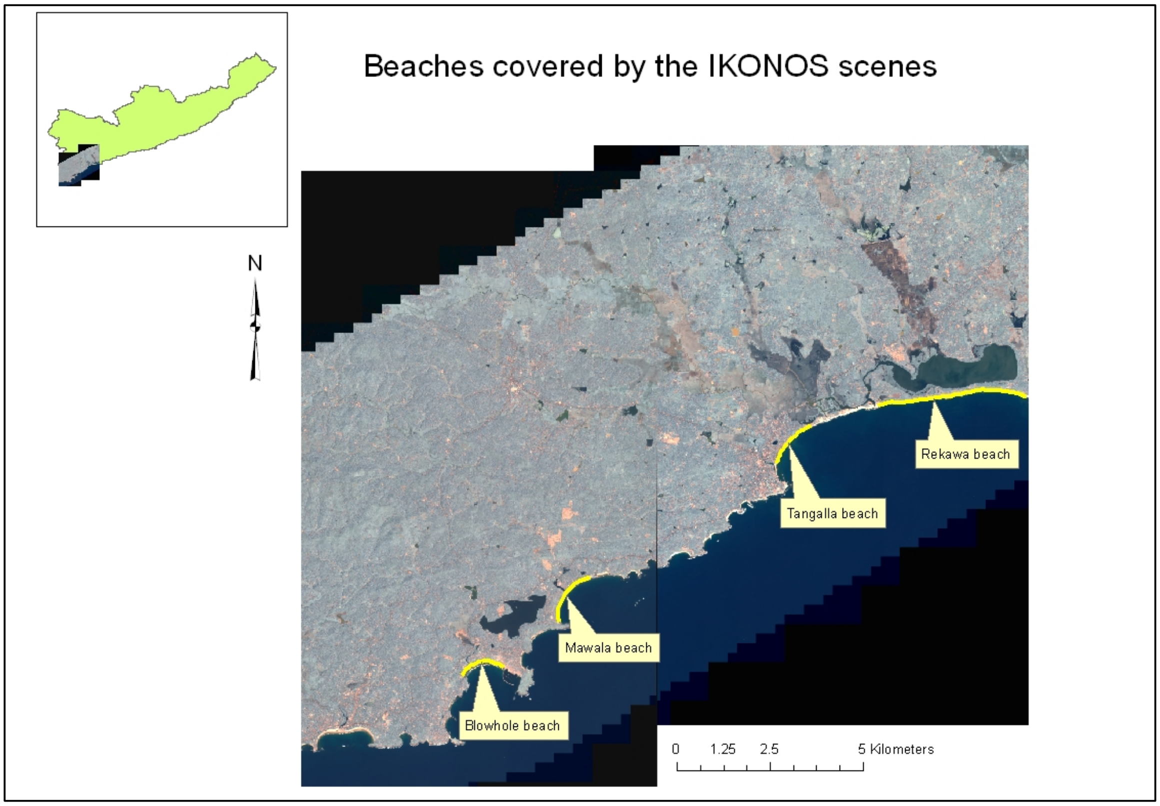


Figure 24. This map shows the location of the beaches covered by the IKONOS satellite data. Also figure 16 for further information regarding the location of the beaches.

6. Result

The results of the interpolations are shown in one of the close-up maps, Map VII. This particular map has been chosen because it contains long sand beaches which make applications of the Bruun Rule modelling as well as the DEM modelling possible. A section of Map VII i.e. Turtle bay is selected to visualise the Bruun rule calculated shoreline retreat. The DEM is also well represented in this map as the fitting of the interpolated surface compared to the land use data layer is satisfactory. These factors combined with the fact that Map VII is within the Bundala sanctuary makes it interesting. As both models are applied on the same area, comparisons can be made between potentially different outcomes of the models in the one map. However, the area consists of no close infrastructure or towns on which it could have been interesting to examine the effects of rising seas. The map next to this, Map IV, shows the major town of Hambantota.

6.1 Results of three different interpolation methods

The result of each interpolation was as mentioned above examined first visually (fig 25) and then for a more precise examination by calculating RMSE values. Different settings were tried for the different modelling methods and the resulting RMSE value is presented below in table 3.

Selection through RMSE

Table 3 The different RMSE values for each interpolation method with some different settings. The best result is highlighted in bold.

Type	Cell size	Power	Points	RMSE
Spline (default)	71.12	0.1	12	3.8150
Spline	20	0.1	12	3.3896
Spline	20	0.1	8	3.2121
Spline	10	0.1	12	3.2861
Spline	10	0.1	8	3.1608
Spline	5	0.1	12	3.2471
Spline	5	0.1	8	3.1822
TIN	10	-	-	2.2301
TIN	5	-	-	2.2222
IDW (default)	71.12	2	12	5.4774
IDW	71.12	3	8	5.2685
IDW	20	3	8	5.1757
IDW	10	2	8	4.9382
IDW	10	2	6	4.9485
IDW	5	2	8	5.0620

6.1.1 Spline

The best Spline interpolation was Spline tension using the power 0.1 with eight points in the search window in the output cell size of 10 meters. The Spline interpolation, *fig 25a,* has a much smoother surface, smoother than the TIN, but on visual examination it is evident that there are problems with the creation of overshots and small islands as well as false holes. These are caused by the fact that there are large distances in many places between the digitalisation points however in other places the density is satisfactory. The polynoma fitted to the points become largely affected by the so-called Runge's phenomenon and thus, these overshots are created.

6.1.2 TIN

TINs are typically used for high precision modelling of smaller areas, such as in engineering applications, and they then have a very high resolution. On larger areas like this, the model can be a bit coarse. However, in this study TINs show the most accurate surface model which are confirmed by good RMSE values. In this model the triangles were quite large but the model still has the most adequate interpolated surface. Visually it is easy to see that the typical structure of a TIN surface, *fig 25b,* has somewhat sharp edges and in larger areas with fewer points the triangular network is visible. However the surface looks true and the sought effect of creating a sharp zero line along coasts and the lagoon edges is very satisfactory.

6.1.3 IDW

The IDW in *fig25c* shows an uneven surface filled with bull's-eyes giving a false interpolated surface. The bull's-eye effect did not get noticeable improved when elaborating with the changing of cell size, search window (radial search) or different power. Settings for the IDW is cell size 5 (as for all), power of 2 and the number of points in radial search is 8.

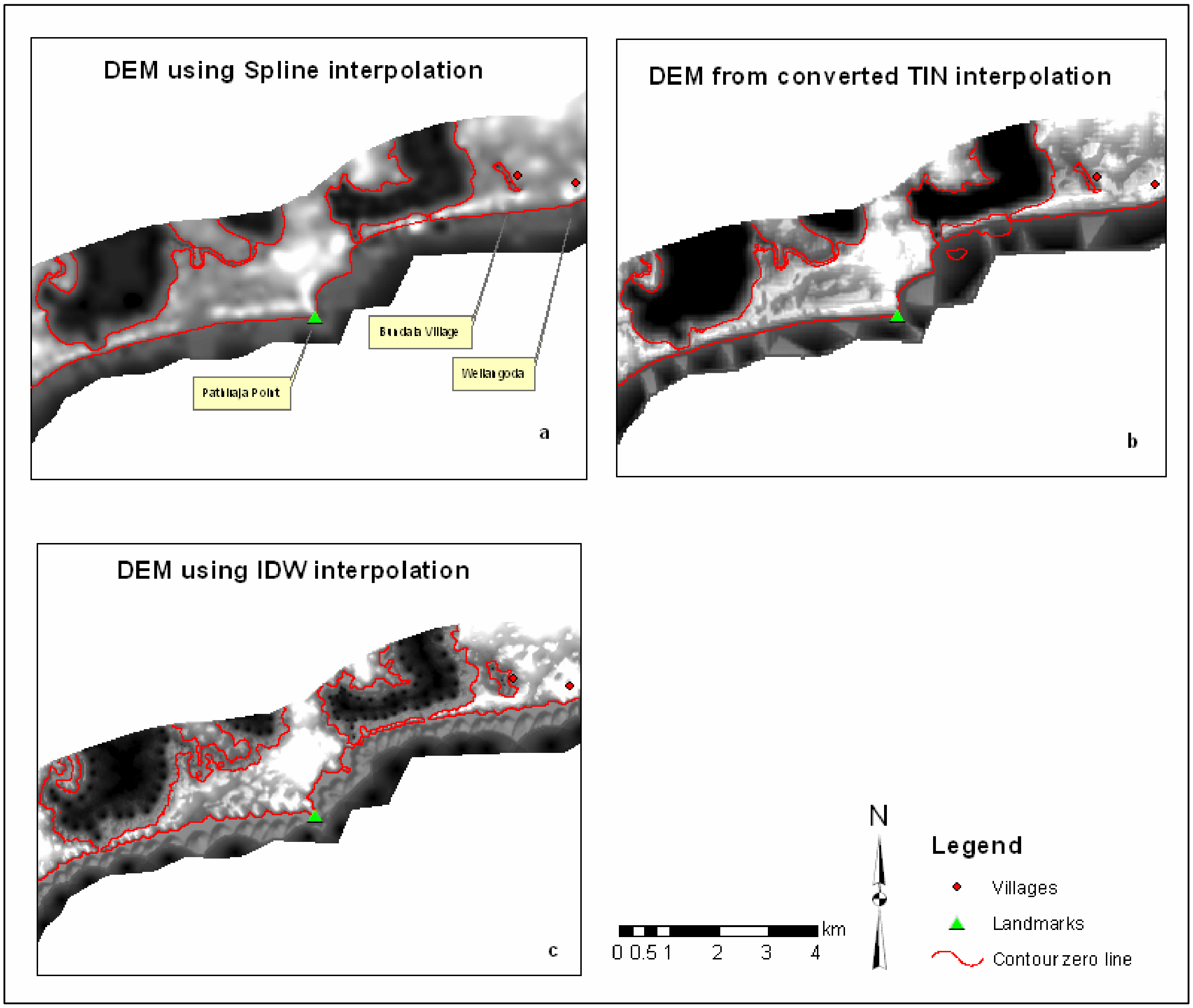


Figure 25a, b and **c** The result of interpolating with all three different methods viewed in close up map VII.

Both visually and in the RMSE values the TIN surface model is the best out of the three with a value of 2.2. This achievement is remarkable considering the fact that the output cell size is forced out of default from 70 meters to 5 meters. The reason why the TIN is better at these kinds of interpolations could be that TINs can have a higher resolution in areas where a surface is highly variable or where more detail is desired and a lower resolution in areas that are less variable. In the data material available for this study, the density of elevation points varies considerably. TINs allow you to model heterogeneous surfaces efficiently by including more mass points in areas where the surface is highly variable and fewer in places where the surface is less variable (Help, Arc GIS).

6.1.4 Fitting between interpolation and truth

When measuring the result of the inundation it is important to consider the fitting of the interpolated surface compared to the land use layers available. As mentioned above, estimations of what land use class will be damaged by intruding sea water as well as how much will be damaged are made through the intersections between the new sea levels and the old land use classes. Hence, the fit is important. In map VII the fitting is satisfactory but not perfect. A bad fit where the interpolated coastline may be perhaps only eight meters wrong can create a large difference. When this is compared to the land use the result of a receding coastline of as much as six or eight meters would still not show as a problem in the map where there is a eight meter fault.

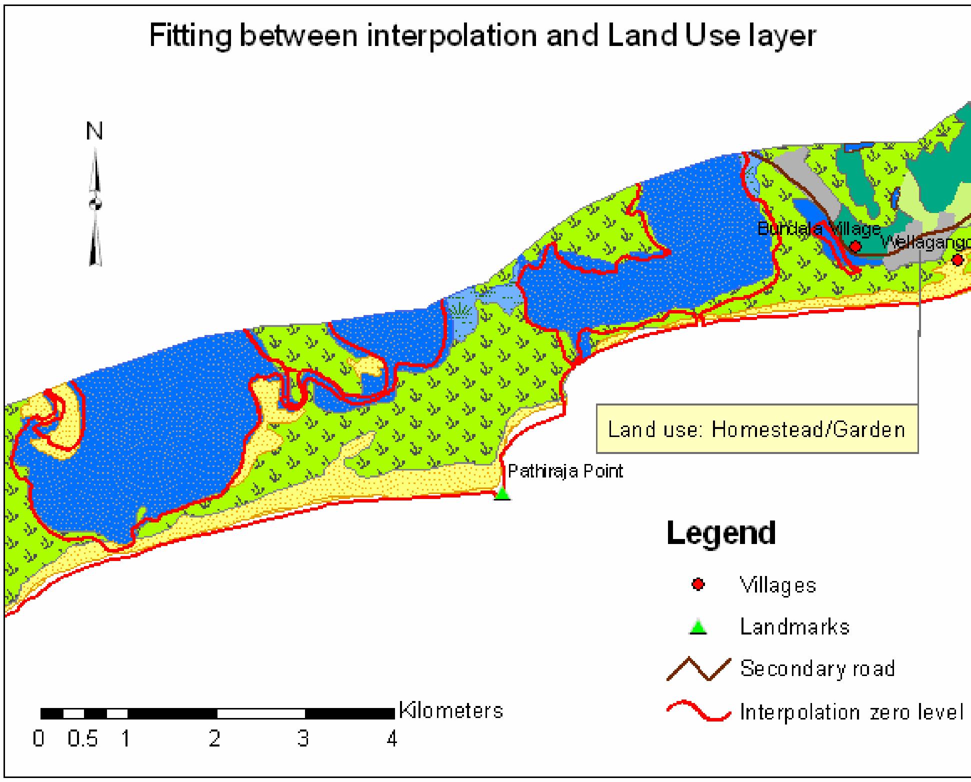


Figure 26. Map VII showing the fitting of the interpolated surface compared to the land use layer from publicly available data. This land use layer is used for calculations of effected areas due to sea level rise.

The fitting between the layers in the western most part of the research area for the DEM is not totally accurate as this is a very low-lying area and the elevation points were scarce in the vector layer. This area was enhanced with manually digitized elevation points with the help of satellite images. As this is a mixed area with many different kinds of water bodies and land strips it was nevertheless difficult to create a good and accurate DEM for it. The land use layer from the survey department did not compare well to the satellite images either.

6.2 A new coastline through inundation

On a map, inundation in the first scenarios of 0.18 meters, 0.59 meters and also in a 1m SLR, are barely visible to the eye. The location of the new coastline is calculated by reclassifying the DEM. These reclassified maps are a good visual aid by which to view the affected areas in the entire research zone. Even in this map where there is only land or water it can be hard to see the changes for the first scenarios. The most visual effect is in the reclassified maps of 2 and 6m SLR, (fig 27). These maps show where a possible future coastline could be situated for the two worst scenarios and can be seen to comprise the full stretch of this limited research site. In Fig. 27 this area is called the "New Zero". Map VII shows a detailed close-up of where a new possible future coastline could be (fig 28-30).

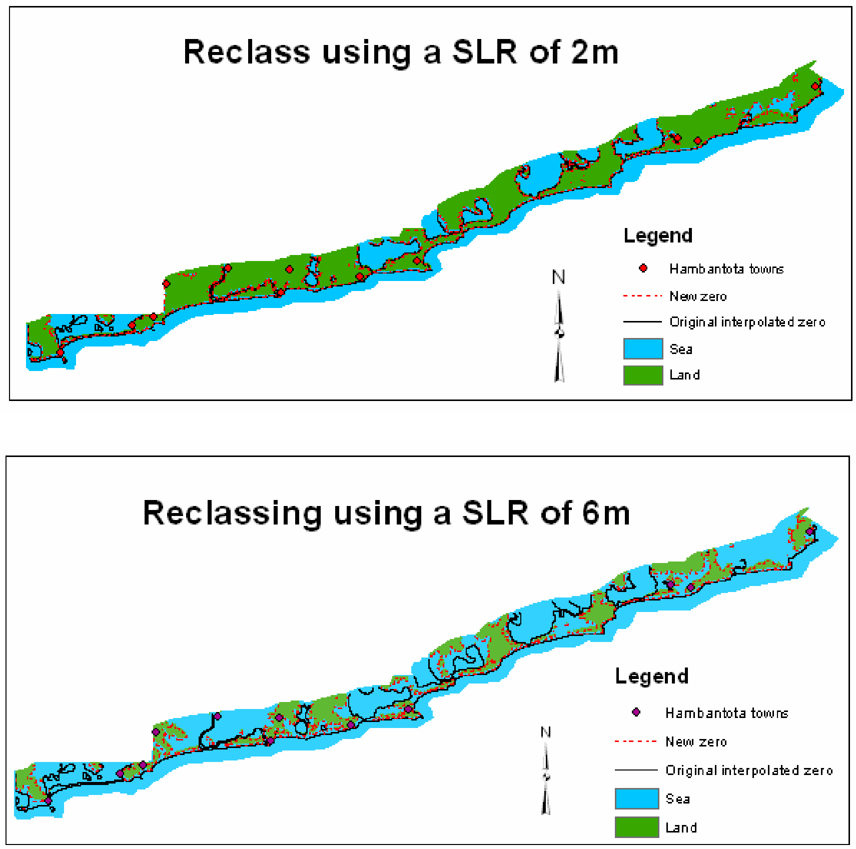


Figure 27. Illustration of the reclassified maps of 2 and 6 meter sea level rise with the two classes sea and land. To visualise the changes both the old original zero line is shown along with the new zero which is the new possible future coastline.

Table 4 demonstrates the land use classes, which are potentially threatened by the sea level rise, as well as how much of each class is under threat.

As the Lewayas or Salt Pans are all situated in flat areas at low elevation they are excluded from the result. They are immediately flooded even at a sea rise of 0.18m and as there are large flat areas surrounding them the figures are misleading as they show vast areas which should be under water. However, some of theses Leweyas are close to the sea and could in fact be influenced if the sea breaks through. This is only the case in one of the Lewayas in the 6m scenario and hence they are excluded in the compilation of affected areas. The Lagoons are also affected in the same way and in many cases for the same reason. They are simply located in flat areas at very low elevation and therefore they seem to be inundated when they in most cases are more subject to land under 1 meter than land under water. However, since they are in low-lying areas the ground water table can affect them and that is why they are still included in the table. Also the lagoons are excluded but for the first scenarios only. It would be misleading to involve them as this would point to an exaggerated amount of affected land.

Table 4. The affected areas and the size in km2 affected by inundation at different SLR scenarios. The land use class Lewaya /Salt pan is excluded for reasons stated above as well as the lagoons for some scenarios.

Effected land use areas and SLR (m)	0.18	0.59	1.0	2.0	6.0
Chena	0.094	0.118	0.153	0.233	1.220
Homestead/ Garden	0.595	0.728	0.929	1.850	9.655
Lagoon	-	-	-	2.993	3.405
Lewaya/Salt Pan	-	-	-	-	-
Marsh	1.821	2.327	2.646	3.375	4.526
Paddy	0.017	0.027	0.077	1.097	8.464
Plantation	0.117	0.174	0.229	0.375	0.844
River	0.357	0.440	0.542	0.761	1.063
Sand/Beach	1.342	1.500	1.654	2.057	5.084
Scrub land	1.571	1.812	2.070	2.763	9.480
Tank	0.025	0.031	0.042	0.091	0.867
Total	5.940	7.156	8.341	15.594	44.608

It is possible to see the changes on a more detailed level close up, and estimate the changes and impacts of the sea level rise. This close up is over Bundala where many sensitive ecosystems are found along the beaches. Bundala is also filled with many lagoons, the animal and vegetative composition and abundance of which will be affected if the sea breaks through.

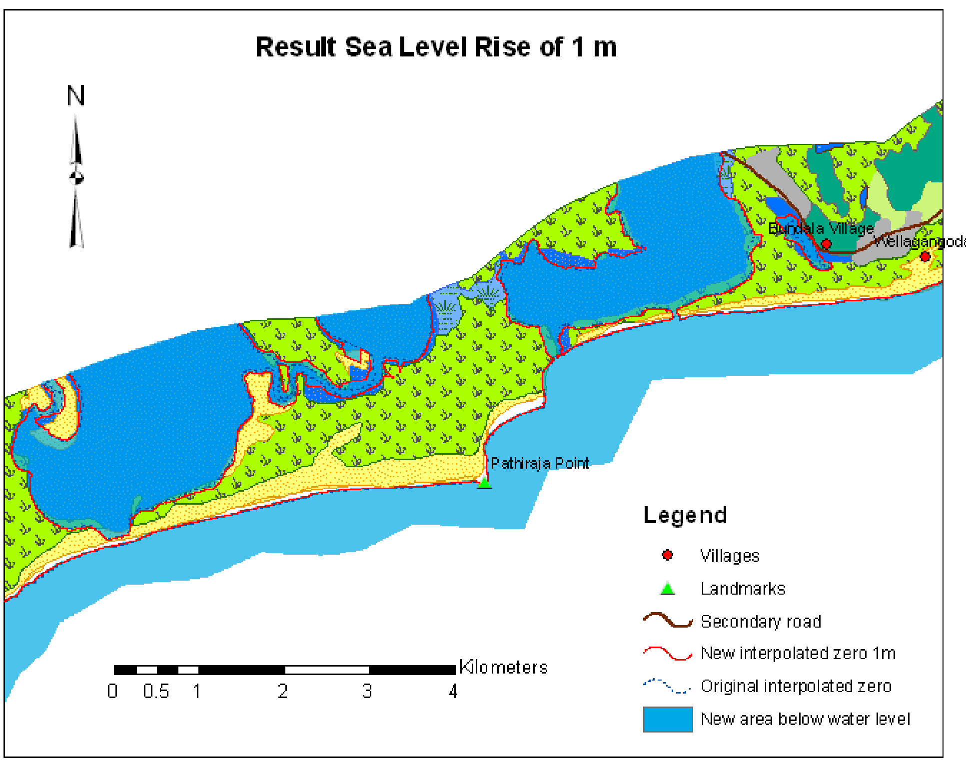


Figure 28. The inundated area in map VII, Bundala National Park. 1m scenario The beach in front of the eastern lagoon is the so-called Turtle bay.

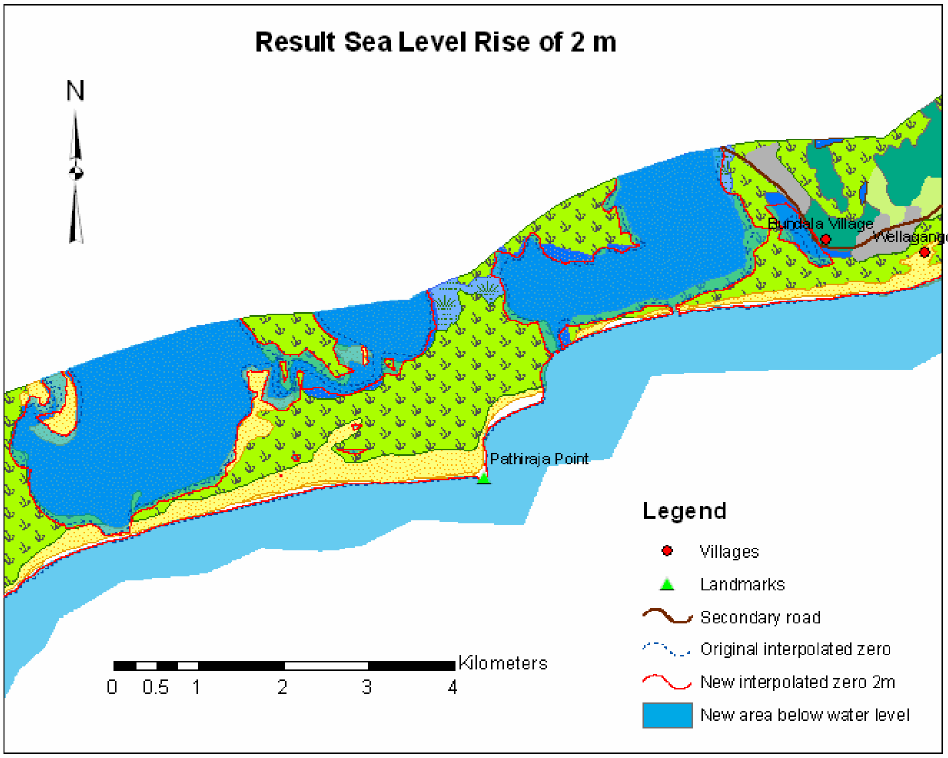


Figure 29. The inundated area in map VII, Bundala National Park. 2m scenario

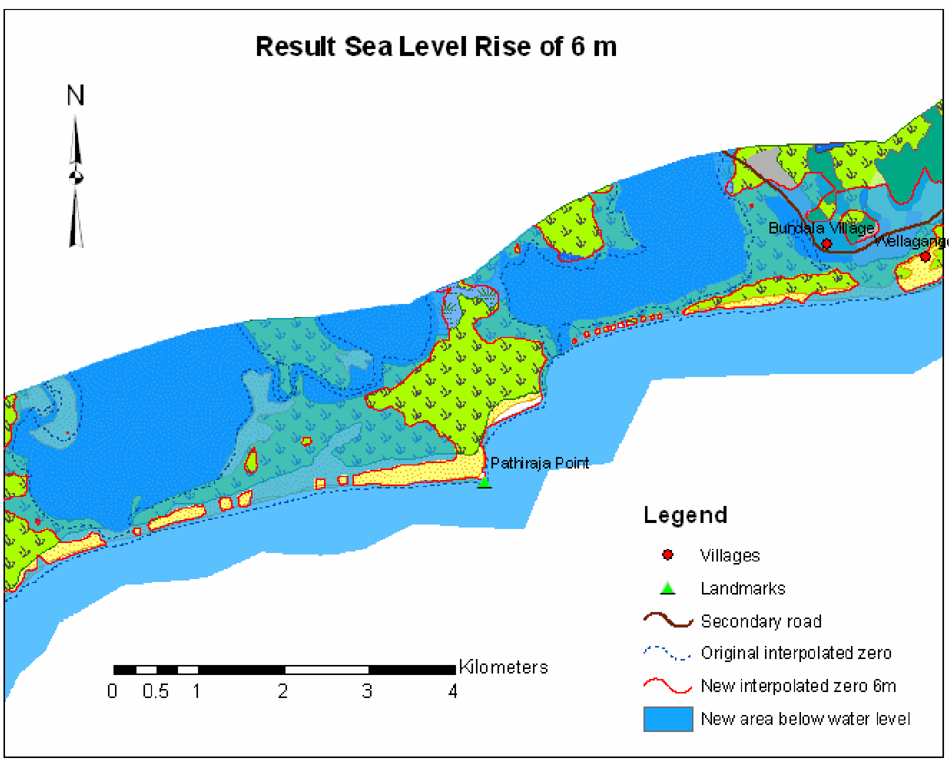


Figure 30. The inundated area in map VII, Bundala National Park. 6m scenario

6.5 New coastline through the Bruun rule

The result of the beach measurements and parameter calculations are compiled in table 5. The table shows the berm parameter (*B*), measured in the field, the cross-shore distance (*L*), measured using a DEM and the depth of closure (*h*) calculated using the Hallermeier formula. The measured values for the cross-shore distance and depth of closure for the beaches Hambantota bay and West Hambantota are based on data collected at these locations while *L* and *h* parameters for the other beaches are based on assumptions due to lack of data. The *L* parameter is a calculated average of the two West Hambantota and Hambantota bay measurements.

Table 5. The measured (B) and calculated (L and h) variables in for Equation 6

Beaches	B (m)	L (m)	h (m)
West Hambantota	2.87	79.18	3.3
Hambantota bay	3.10	69.78	3.3
Oasis beach	3.74	74.48	3.3
Godawaya beach	3.44	74.48	3.3
Ussangoda beach	2.97	74,48	3.3
Beach after Ussangoda	2.74	74.48	3.3
Oruwella beach	2.42	74.48	3.3
Rekawa beach	3.12	74.48	3.3
Tangalla bech	2.53	74.48	3.3
Mawala beach	1.11	74.48	3.3
Blowhole beach	1.29	74.48	3.3
Beach after pumphouse	2.57	74.48	3.3
Padiraya	3.35	74.48	3.3
Bundala Padiraya	3.45	74.48	3.3
Turtle bay	2.88	74.48	3.3
Uraniya	3.48	74.48	3.3

In areas with a low berm, the coastline will recede the most. The location of the new coastline is highly dependent on the different parameters in the equations. In our case, since we had to assume the *L* and *h* parameters for most beaches, the height of the berm (*B*) mainly governed the different results. The sea level rise parameter (*S*) used in the calculations where 0.18, 0.59, 1.0, 2.0 and 6.0 meters.

The shore line retreat (*R*), which was calculated using the Bruun rule, is summed up in table 6. The largest impact will be at Mawala beach and Blowhole beach where the 6 meter scenario will generate a 101.3 meter and 97.4 meter shoreline retreat respectively. The sand in these areas is finer and the berm is much lower than in the other beaches (se above).

Table 6. The retreat of the shoreline calculated with the Bruun rule for the different SLR scenarios

Beaches and Shoreline retreat (R) in meters	0.18	0.59	1.0	2.0	6.0
West Hambantota	2.31	7.57	12.85	25.71	77.10
Hambantota bay	1.96	6.43	10.90	21.81	65.42
Oasis beach	1.90	6.24	10.58	21.10	63.29
Godawaya beach	1.99	6.52	11.03	22.10	66.30
Ussangoda beach	2.13	7.01	11.88	23.76	71.27
Beach after Ussangoda	2.22	7.28	12.33	24.66	73.99
Oruwella beach	2.34	7.68	13.02	26.04	78.13
Rekawa beach	2.01	6.84	11.60	23.20	69.60
Tangalla bech	2.30	7.54	12.77	25.55	76.65
Mawala beach	3.04	9.96	16.89	33.78	101.33
Blowhole beach	2.92	9.57	16.23	32.45	97.36
Beach after pumphouse	2.28	7.49	12.69	25.38	76.13
Padiraya	2.02	6.61	11.20	22.40	67.20
Bundala Padiraya	1.99	6.52	11.03	22.10	67,20
Turtle bay	2.17	7.11	12.05	24.10	72,31
Uraniya	1.98	6.48	10.99	21.97	65.91
Average	2.22	7.3	12.38	24.76	74.32

The impact of the shoreline retreat is analysed in two different ways. The land use data acquired from the Sri Lankan survey department did not cover the whole study area (table 2) and therefore the impact could only be visualised in satellite images of the non-covered areas.

Table 7 shows the calculated impact of the Bruun rule on the land use. The most affected land use type is the sand beaches followed by scrub land. The total amount of affected land accumulates to 2759183.21 m^2 for the 6 meter scenario. In the 6 meter scenario even the salt pans and lagoons are affected. Since some land use classes are located far inland these will not be affected by the receding coastline.

Table 7. The calculated impact of the Bruun rule on the land use classes in m^2

Land use class and SLR scenarios (m)	0.18	0.59	1.0	2.0	6.0
Sand/beach	81803.46	265904.03	452840.02	875145.42	2010940.94
Scrub land	22.46	439.62	2756.51	24480.78	435145.46
Homestead	19.25	103.51	330.75	6091.01	75995.67
House/Industry	–	–	–	311.14	3664.33
Plantation	–	9.62	311.15	3579.42	96595.26
Forest	–	–	–	3534.52	131195.75
Lewaya/Saltpan	–	–	–	–	3999.87
Lagoon	–	–	–	–	1645.94
Total (m^2)	81845.16	266456.77	456238.43	913142.29	2759183.21

Because there were 16 different beaches studied, the result of the shoreline retreat will only be visualised in 2 beaches in the result section, one covered by land use data and one covered by the IKONOS satellite images. In the vector maps for the 0.18 m, 0.59 m and 1m scenarios the new coastline is barely visible to the eye, so they will not be shown in the result section. For the same reasons the IKONOS imagery will not illustrate the 0.18 scenario.

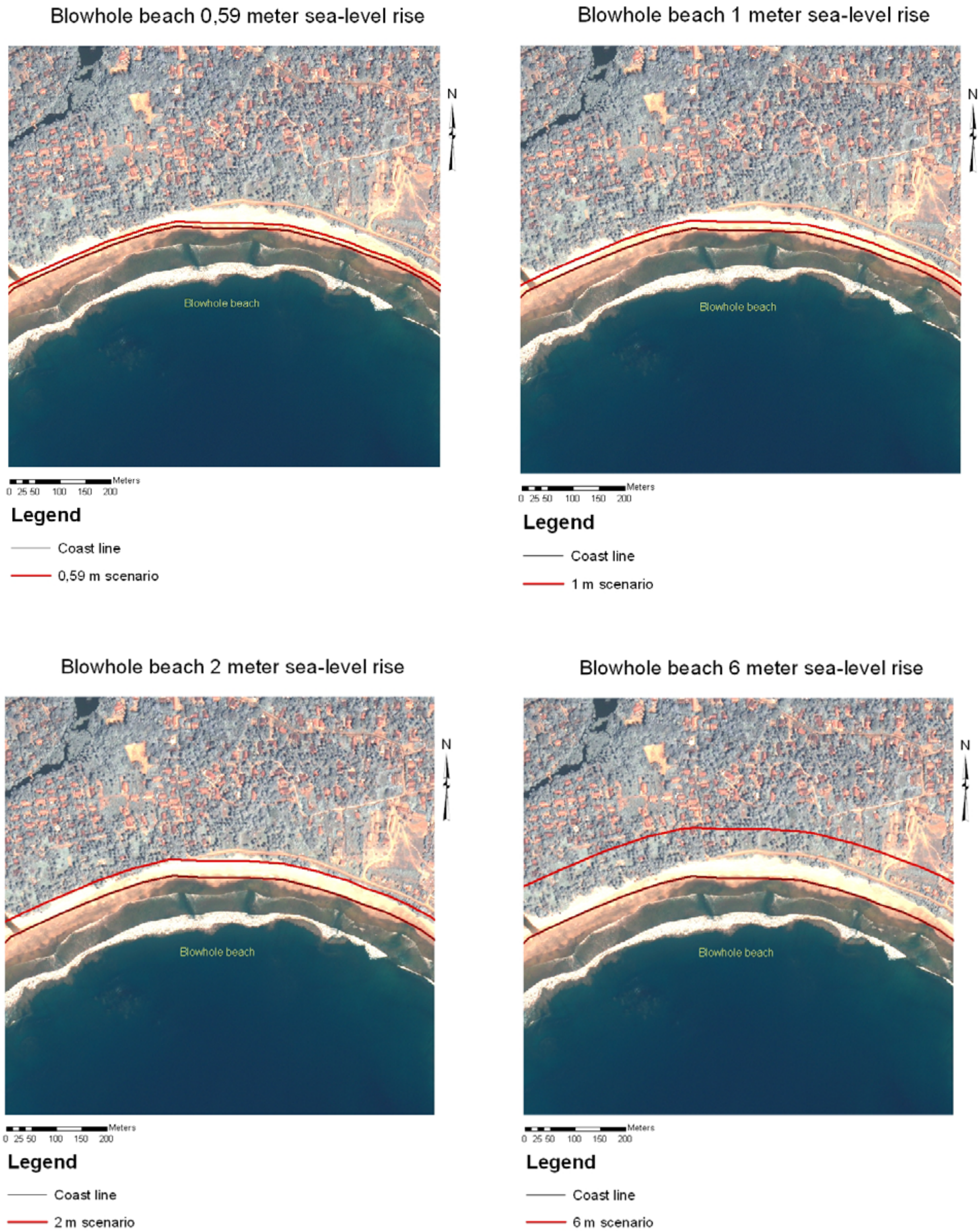
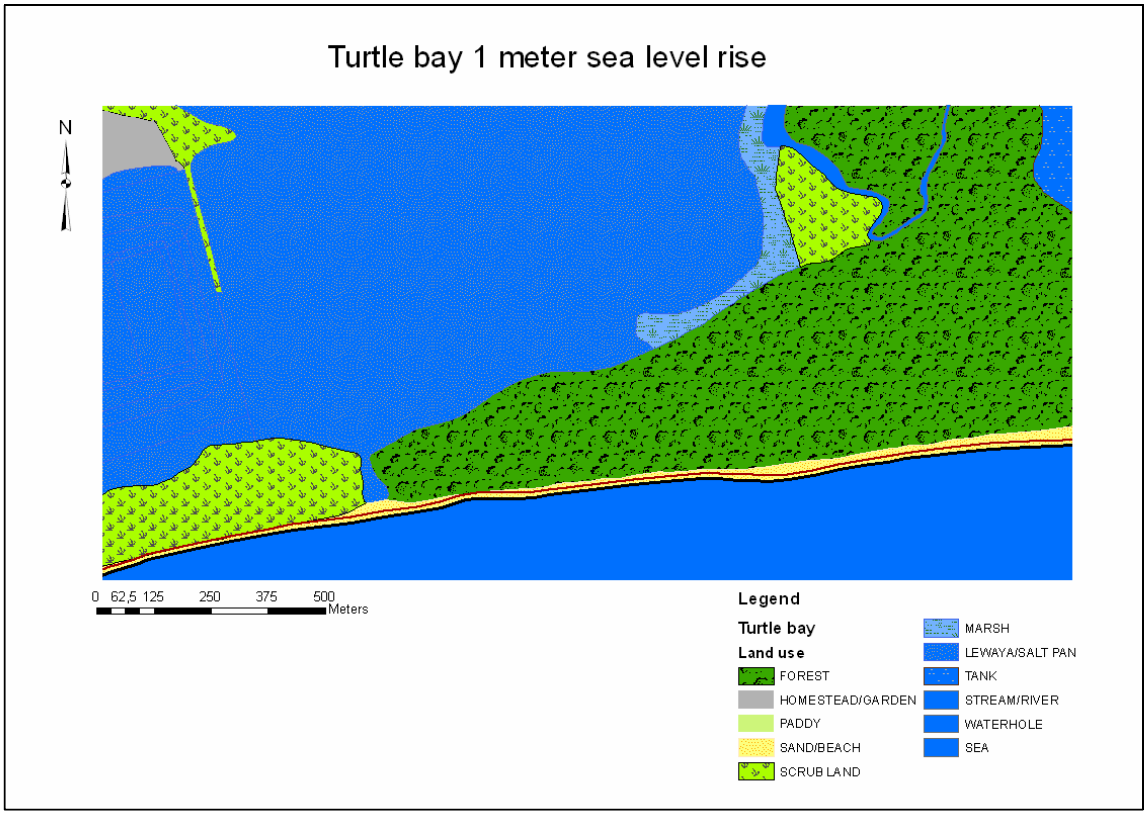
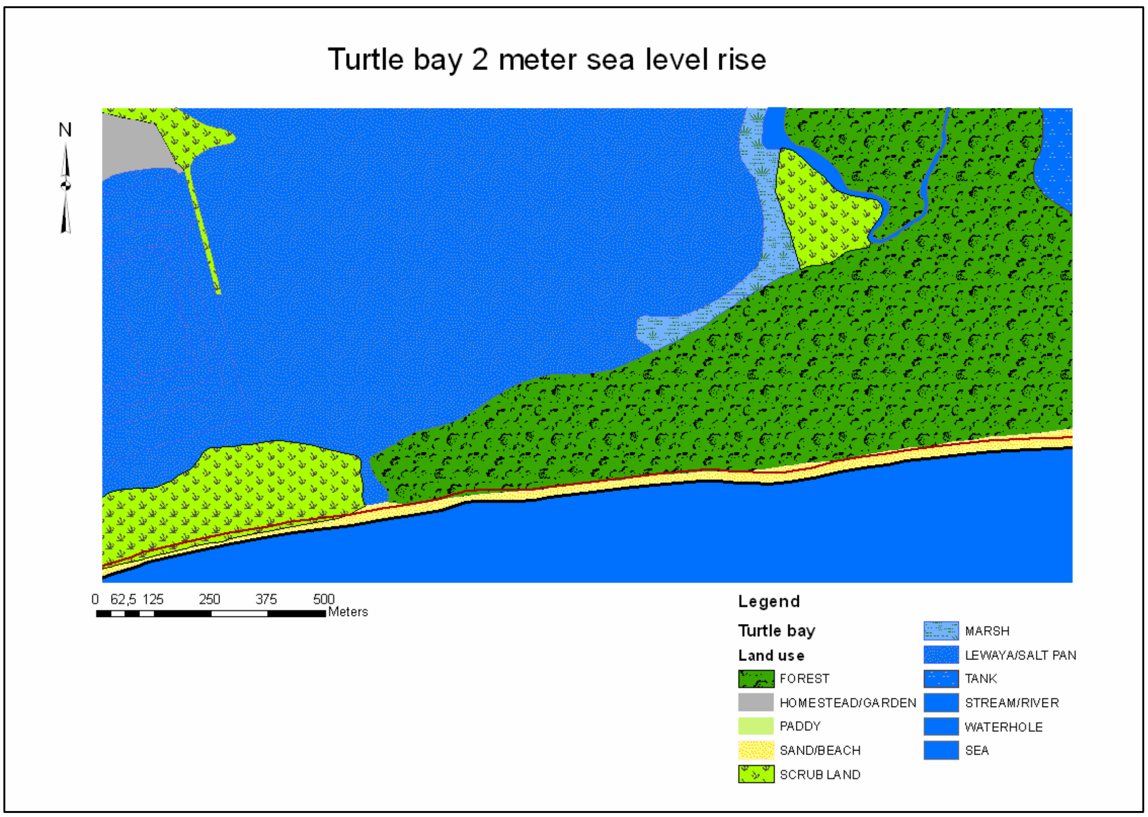
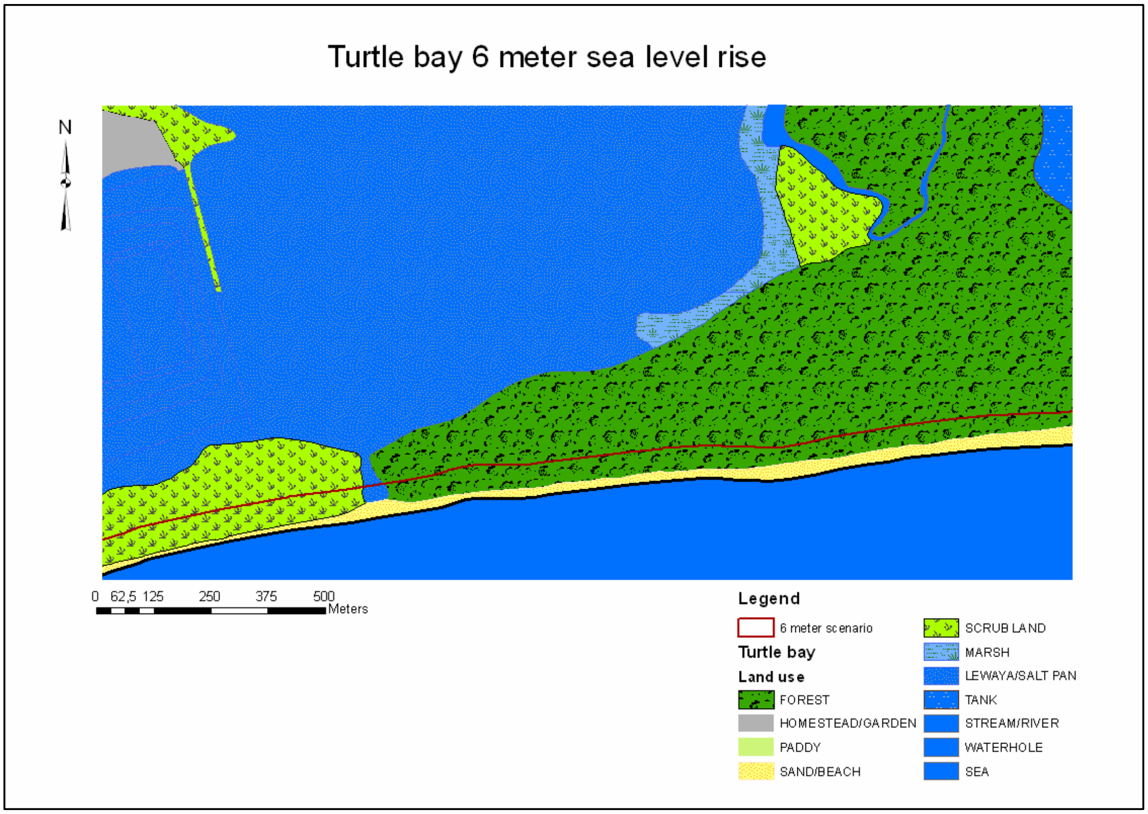


Figure 31 illustrates the impact for the 0.59m, 1m, 2m and 6m on Blowhole beach visualised in IKONOS imagery


Turtle bay 1 meter sea level rise
N
0 62,5 125 250 375 500
Meters
Legend
Turtle bay
Land use
FOREST
HOMESTEAD/GARDEN
PADDY
SAND/BEACH
SCRUB LAND
MARSH
LEWAYA/SALT PAN
TANK
STREAM/RIVER
WATERHOLE
SEA


Turtle bay 2 meter sea level rise
N
0 62,5 125 250 375 500
Meters
Legend
Turtle bay
Land use
FOREST
HOMESTEAD/GARDEN
PADDY
SAND/BEACH
SCRUB LAND
MARSH
LEWAYA/SALT PAN
TANK
STREAM/RIVER
WATERHOLE
SEA



Figures 32 shows the impact of the 1m, 2m and 6m scenarios visualised in vector maps

7. Discussion

The results of the two models show that the impact of SLR is evident in our study area. Although the models may be fairly rudimentary, their overall legitimacy is well documented and they can still serve as strong indicators as to the consequences of increased sea levels.

7.1 Discussion about the DEM

Access to accurate elevation data and an appropriate interpolation method are essential with regard to creating a trustworthy inundation simulation using a DEM. The vertical mean error of about 2m at the elevation points and a RMSE of about 2.2 m in the TIN interpolation, coupled with the manual condensation of points and the use of line data, comprise a considerable factor of uncertainty in the model. This means that there is an error in the interpolated surface, which directly influences the result of the study. A better RMSE and an enhanced accuracy of the elevation data are to be desired, but based on the quality of the data and the methods used, the RMSE was felt to be adequate and acceptable. In order to generate a more accurate DEM, better data material, for example the LIDAR data (**Li**ght **D**etection **a**nd **R**anging, an optical remote sensing technology that measures properties of scattered light to find range and/or other information of a distant target) would have been necessary. However, LIDAR data is very expensive to produce and therefore expensive to buy and furthermore not yet available in many areas, Sri Lanka included

7.1.2 Discussion about the use of selected interpolation methods

It should be noted that there are other interpolation algorithms that have not been used in this study and that might have generated different result had they been used. Kriging is a local interpolation method that uses geostatistical analyses of the spatial correlation. As mentioned above in 3.1.1., our reasons for not using the Kriging interpolation method have to do with time aspects and the quality of the data. Other useful tools could have been the hydro tool in an ArcGIS extension which unfortunately was not accessible at the time of the study.

7.1.3 Discussion about the use of RMSE for evaluation

The evaluation using RMSE values is standard method when evaluating DEM. However, it is important to acknowledge the fact that they contain a margin of error when used the way they are in this study. The evaluation points were extracted prior to any interpolation and the corresponding value of that particular cell was extracted. This means that the point can be at any location within the corresponding interpolated cell and is therefore not representative of the true elevation (fig 33). This may explain why the interpolations with smaller cell sizes generated better RMSE values. Conducting a local interpolation of each raster cell might solve this problem.

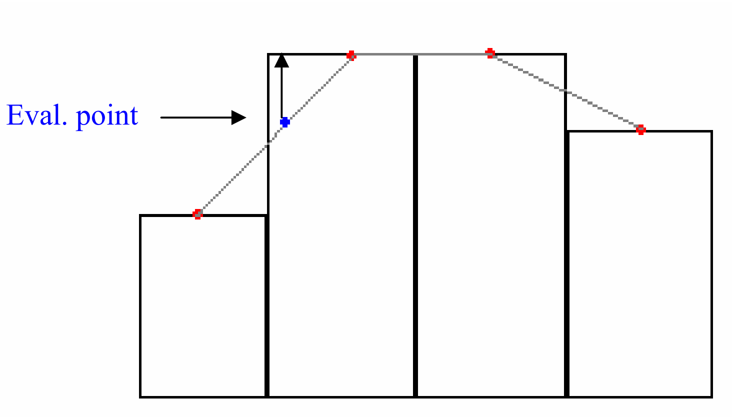


Figure 33 Shows an example of how an evaluation point can be located within the interpolated raster cell. The grey line is the true surface, the stacks are the interpolated surface in each raster cell. Had the evaluation point been further in along the grey line in the cell at the true surface it would have had a better RMSE value. Hence, the smaller the cell the larger the possibility of the evaluation point being close to the interpolated surface and achieving a good RMSE value.

7.1.4 Discussion about shortages in the use of DEM for estimating damages

Results are generally difficult to estimate when attempting to model sea level changes in a DEM. Application of DEM modelling alone calls for the consideration of several parameters, such as, for example, the many complex coastal processes that occur naturally as well as vegetative and anthropogenic influences. Moreover, this kind of immediate inundation does not take into account the gradual changes that would naturally occur. In this study inundation is carried out in a simplified manner as a reclassification by placing all land under a certain height. As expected, this method calls for some minor errors. All land at a certain height might not be flooded even though it is low lying. If the piece of land is far enough inland or has a high enough barrier to protect it, it might not be flooded. It could be saturated from the ground water if this rises which would probably be the case over a long time. This is dealt with in this study by excluding some of these areas of flat low laying land when calculating the area of affected land use areas.

With this in mind, the objective of this study was not to draw any conclusive statements about the appearance of the new coastline, but rather to identify areas that may be threatened by a potential SLR and to assess where the new coastline might be situated.

7.1.5 Discussion about data quality

When modeling a DEM at a 5m resolution as done in this study, it is evident that the data at hand was deficient. The research area has a highly interesting topography in many places with long sandbanks, which divide the sea from lagoons or river outlets. The area also consists of sand dunes and banks forming barriers inland to low lying flat land and marsh areas. Some of these sand banks are important not only as dividers and protectors of the land behind from the sea but also for transportation. With the resolution in the data for this study it was impossible to catch these interesting topographical features. However, this is not surprising, as that kind of detailed level demands highly technical investigations or a special detailed study of the area. Such a study would be possible with, for example, LIDAR scanning or time consuming digitalization from high resolution aerial photography.

Furthermore, the accuracy and the quality of the land use classification and digitalization of the area were not up to the required standards. It was evident after trying to harmonize the data and applying it on the DEM just how inaccurate it was and how important this was.

Much of the land use data was, as mentioned in 4.2.2, in CAD files. At a first look and trial while still in Sri Lanka this format was convertible to GIS standard format Shape file. However as it turned out there were large problems with the annotations and polygons and the classifications, which decreased the accuracy even more (further explained in 4.2.2). As this was noticed back in Sweden it was impossible to retrieve better data from the department. A request via email and a phone call to purchase additional data was denied, as they do not whish to send data without properly signed documents locally. Especially not at this detailed level with regard to the sensitive nature of the data and with regard to the political situation in the country.

One way to get around the problems where the interesting topography was missed would have been to manually digitize from high resolution satellite images. Parts of the study area was covered by the satellite images of IKONOS with 1m resolution, but as large areas were not covered, this was not a solution either.

7.2 Discussion about Bruun

Although the Bruun model is perceived by some to be an outdated and inaccurate model, the fact remains that its overall validity is well-documented and tested. Our results indicate that the impact predicted by the model will be evident. It is important to keep in mind that the results of the model are highly theoretical and that there are other factors that might affect the retreat which have not been taken into account in this study. These are, for example, anthropogenic interventions, the influence of vegetation, geology, topography and many other factors that involve decades of profile adjustments.

The most accurate model results come from the beaches: Hambantota bay and West Hambantota as they were modelled on available data from these areas e.g. bathymetrical data and wave data. Since there were no obtainable data like this covering the other beaches, a number of assumptions had to be made e.g. the cross-shore distance (L) parameter and DoC (h). Of course, assumptions inevitably create a significant factor of error, but by examining less detailed and up-scaled data, such as local sea charts, and Wave Watch III global models over these areas, we consider these assumptions to be appropriate and accurate. The fact that studies made in neighbouring districts also show the same data furthermore supports this.

Coast-and beach processes are extremely complex and attempting to predict/model the appearance of the coastal zone is virtually impossible in this type of study. It is plausible that under normal circumstances, the new beach zone will resemble the old one and therefore influence areas beyond the new coastline. This would mean that the impact of the sea level rise will be greater than we calculated. The focus of this study has therefore been on where the new coastline will be drawn and not on how the potential coastal zone will appear and affect land just beyond the coastline. One may also presuppose that the authorities will act on this potential threat and take appropriate measures in order to minimise the impact which will affect the appearance and form of the coastal zone.

The calculated DoC was based on the Hallermeier formula (Equation 7); the result gave the minimum extent of the DoC (d_{min}). Because there was no available data for calculating the maximum extent (d_{max}), this was excluded from the study. The data we had access to did not contain the standard deviation of the significant wave height, which was needed to calculate

$d_{max.}$ If the d_{max} had been used, the impact of the shoreline retreat would probably have been significantly greater.

7.3 Discussion about the effects of SLR in DEM and Bruun

The result of the two models clearly shows that an SLR will have a significant impact on the Hambantota coastline. Approximately 2.8 square kilometres of land will be affected by the potential sea level rise according to our 6m scenario in the Bruun model and 44.6 square kilometres for the TIN model. The new coastline will retreat inland averaging between 2 meters for the 0, 18 m scenario up to 74 meters for the 6 m scenario according to the Bruun calculations.

The land use class most affected in the Bruun model are the beach areas. Also in the DEM model the impact is severe. This may not be so surprising considering the fact that they are located right by the sea. The beaches of Hambantota contain some of the most sensitive ecosystems in the area and the beaches are often constrained on their landward side by human activities. It is therefore likely that many of these sensitive ecosystems will be greatly affected. The sensitive flora and fauna found along the sand dunes of Hambantota presented above on page 12 are all threatened since they occur close to the water line. However, the impacts on most of them do not occur before there is 2 m rise in this study. The effects are on the fore dunes and on the centre dunes if you look at an immediate effect. As this is a slow ongoing process these dunes will retreat in a more or less equilibrium state and the ecosystems might have time to “resettle”. The sand dunes and beaches in the west of the study area are flatter with finer sand (pg 10) and are therefore more sensitive and subject to changes at a low rate of sea level rise (table 6). This is where the largest retreat is noted of 101 meters at a 6 m sea level rise. However, in this area there are clearer abundance of protecting headlines and rocky beaches (pg 8) which will limit the erosion and the impact on the coastlines.

Other areas that are also greatly affected are scrub lands and forests. The unique flora and fauna found in these areas is likely to be affected through a decrease in habitat areas, an increase in saline intrusion and an invasion of invasive species threatening sensitive flora through competition. A rapid environmental impact assessment was preformed in Bundala national park a couple of week after the Tsunami hit the Hambantota coastline in 2004. It concluded that the increased saline conditions had a severe impact on the ecosystems of the area. A number of species, both flora and fauna, was killed through the change in saline conditions. The change in salinity also favoured some invasive species that spread over vast areas of the national park. To battle this threat is not easy and certainly not cheap. In Bundala the work combating the invasive species i.e. *Typha angustifolia*, *Opuntia dillenni* and *Prosopis juliflora*, has not had the desired effect. The change in vegetation had also changed the nesting conditions for some of the unique native aquatic avifauna. It is likely that an increase in salinity in other areas of Hambantota due to the SLR will have similar affects.

One has to remember that the land use data was collected between the years 2000-2003. This means the there could have been some land use changes in the area. This would naturally affect the result of the affected land use classes.

It is probable that the government and local authorities will act on the potential sea level rise and take measures to prevent the loss of valuable land. Such actions could be soft measures such as beach nourishment, sand dune stabilisation and beach drainage or hard measures such as the construction of seawalls, groynes and breakwaters. These measures are often quite expensive and can pose a great challenge to a developing country like Sri Lanka.
With access to more detailed data, which covered the whole study area, a more precise and accurate result would be possible.

The socio economical impact can be large if the beaches retreat as much as in the 2m and 6m scenario as some of the hotels, roads and infrastructure is affected. This is a problem particularly in western part close to Tangalla, and a small area close to Hambantota town (Oasis hotel). Other socio economical effects also include local fishing communities. The fish landings, where these communities are located, can be destroyed or moved obstructing their livelihood and forcing villages and people to move. The built harbours are not as sensitive.

8. Conclusions

The coastal areas are at risk, and taking measures to protect them should be a priority for the Sri Lankan government. The methods used in this study are recognised, widely used and acknowledged as user friendly for modelling sea level rise. They are somewhat basic as they do not take all the different influencing factors in coast erosion into account. Such a model is very intricate and not possible for a small scale study such as this. However, although the accuracy of the results from the two models used for this study can be debated, these results are important indicators of the processes at play in the studied areas. Thus, as a first measure the efficiency of these methods is praiseworthy. Additionally, these two methods are appropriate because they are immediate to carry out and easy to understand and the data required can be accessed quite easily and at a relatively low cost. Hence, their results can be useful to policy makers. However, it is true that for a fuller understanding and prediction of the coastal responses to sea level rise, more comprehensive and thorough studies are needed.

This study has reached the following solutions to our research questions, which are presented below.

1. ***Is the use of a DEM an accurate method for coastal modelling of SLR impacts and is the result credible?***

The result of the DEM for this study is not credible in terms of exact areas, which would be inundated. This is due to the quality of the digital elevation data and the interpolation methods resulting in a low resolution DEM with a coarse surface. It is, on the other hand, a good way to easily identify land areas threatened by rising seas and what could be subject to land under water.

2. ***Is the use of the mathematical Bruun model satisfactory and is the result credible for coastal modelling of potential SLR impacts?***

The results of the Bruun model are credible. Even though the model is rather rudimentary, its results could nevertheless serve as indicators as to what areas are possibly threatened in the study area. With access to more detailed data the accuracy of the model would be enhanced.

i. ***Based on predictions of rising sea levels, where will a possible future coastline be located?***

The coastline according to the Bruun calculations will be located between on average 2.2 meters in the 0.18m scenario and up to 74.3 meters for the 6m scenario.

ii. ***What land use classes and how much of each class is potentially threatened by the sea level rise?***

According to the DEM research the main threatened areas in the 2m scenario are; Marsh 3.4 km^2, Lagoons 3 km^2 and Scrub land 2.7 km^2. In the 6m scenario it is Homestead 9.7 km^2, Scrub land 9.5 km^2 and Paddy 8.5 km^2.

The Bruun rule is only applicable on sand beaches and hence the area behind any sand beach is threatened accordingly to the inland retreat depending on the SLR. The main land use classes affected are for a 2m scenario; Scrub land 24481 m^2, Homesteads 6091 m^2 and Plantation 3579 m^2, and for a 6m scenario; Scrub land 435145 m^2, Forest 131196 m^2 and Plantations 96595 m^2.

iii. Is the methodology suitable for the area?

The methodology is suitable for the area. The data required for performing this kind of study is relatively easy to access, acquire and process. The methods used are quite intuitive and easy to understand and although somewhat basic, deliver a credible result. For the time being, a great deal of the data required, such as bathymetric data, wave data, detailed elevation data, detailed and updated land use data, is not available for the study area. However at a reasonably low cost and with little effort this data can be gathered and collected by the local authorities.

As mentioned, the modelling in this study can be debated but the result still leads to important findings. Action must be taken to protect the coastline of Sri Lanka. The only other option is to let nature take its toll, but then a relocation of the residents might be necessary. Another important message is the fact that what at the beginning of this study was believed to be the worst case scenario according to the UN's Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report seems to constitute a drastic underestimation of the problem. Based on estimates made by Britain's Environment Agency, flood defences for 2100 on the basis of a one-metre rise in sea levels are being planned for – but a "worst-case scenario" of 2.7 metres is now more likely. In other words, over the next 100 years there will be severe impacts on coastal areas on sandy beaches in flat landscapes of at least 2 to 25 meters recession inland according to our figures. Also, as the DEM suggests, low-laying land along the coast will be flooded, farming and salt producing areas will be affected and natural habitats along the coast of Hambantota will be altered.

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