MASTER OF SCIENCE THESIS

Beach Nourishment to Mitigate the Impact of Sea Level Rise in Southeast Australia

J.M.P.A. Langedijk

November 2008

TU Delft Delft University of Technology

The University of Sydney

Disclaimer: This is a preliminary report. The final report will be uploaded to this website when all comments have been received and incorporated.

Cover pictures: The Gold Coast in southeast Queensland, Australia (left; Australian education information portal for overseas students, 2008), and a trailing suction hopper dredger rainbowing sand in the nearshore zone (right; Hollemans, 2005).

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MASTER OF SCIENCE THESIS

in partial fulfilment of the requirements for the degree of
Master of Science in Civil Engineering
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by

J.M.P.A. Langedijk

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Abstract

The global average sea level is rising at an increasing rate. It is projected that by the end of the 21st century, the sea level in southeast Australia will be 18 to 91 cm higher than the present level. According to the Bruun Rule, the most widely applied model for predicting the impact of sea level rise on a coastline, the rising sea level will cause sand from the nearshore zone to move offshore, resulting in beach erosion. Hence, sea level rise poses a significant risk to the beaches of southeast Australia, which are of great value to tourism and the safety of beachfront properties. This risk can be mitigated by means of beach nourishment, which is an effective way of combating beach erosion.

In Australia, beach nourishment is currently only applied on the Gold Coast in southeast Queensland, but the political and community support to nourish many other beaches in southeast Australia seem to be on the rise. The costs of nourishing the beaches in southeast Australia to mitigate the impact of the projected sea level rise in the 21st century have been estimated in the present study. The considerable uncertainty associated with sea level rise and its impact on the coast has been managed by adopting a probabilistic approach. This means that the results of the present study have been expressed in terms of probabilities rather than a single outcome.

In order to determine the future beach nourishment costs, the expected offshore sand losses due to sea level rise in the 21st century have been estimated first. For this purpose, the "raising the profile method" has been applied, which is a derivative of the Bruun Rule. The resulting offshore sand losses are between 1.3 and 2.9 billion m^3 in New South Wales and between 1.5 and 3.3 billion m^3 in southeast Queensland, where the actual value depends on the selected risk level (between 1 and 50%). The offshore sand resources in southeast Australia contain enough good quality sand to replenish these sand losses and can be extracted with a trailing suction hopper dredger in water depths of at least 20 m (on parts of the coast that will not be nourished), without causing significant impacts on the coastline and the marine environment.

Next, the amount of sand that needs to be replenished has been determined. The required amount of sand is a fraction of the offshore sand losses and depends on the number of beaches that will be nourished. Because the economic viability of applying beach nourishment depends strongly on the degree of beach development, it has been assumed that only the presently developed beaches and, in due time, the future developed beaches (the greenfield beaches) will be nourished. At present, about 20% of the sandy coastline of southeast Australia has been developed and this number may increase up to 60% within the 21st century.

Finally, the beach nourishment costs in the 21st century have been estimated by multiplying the required amounts of sand with the sand costs. The sand costs are the lowest in case of using offshore sand resources and a medium-sized dredger. In that case, the costs of nourishing the presently developed beaches are between 1.1 and 2.6 billion Australian dollars in New South Wales and between 1.5 and 3.7 billion Australian dollars in southeast Queensland, where the actual amount of money depends on the selected risk level (between 1 and 50%). In addition, when both the presently developed beaches and the greenfield beaches are nourished, these amounts of money increase to

between 3.7 and 8.9 billion Australian dollars in New South Wales and between 3.6 and 8.5 billion Australian dollars in southeast Queensland. Accordingly, the annual beach nourishment costs in case of offshore sand extraction are between 11 and 89 million Australian dollars in New South Wales and between 15 and 85 million Australian dollars in southeast Queensland. These costs can be decreased if the deployed dredger extracts sand for the building industry as well.

However, offshore sand extraction is currently prohibited in New South Wales. In case the beaches of New South Wales are nourished with sand that has been sourced onshore, the costs of nourishing the presently developed beaches are between 7.6 and 20 billion Australian dollars and the costs of nourishing the presently developed and greenfield beaches are between 26 and 69 billion Australian dollars, where the actual amount of money depends on the selected risk level (between 1 and 50%). The corresponding annual beach nourishment costs are 76 to 690 million Australian dollars, which is about seven times higher than in case offshore sand is used.

The results of the present study can be used to develop an economically optimum beach nourishment programme in southeast Australia. Starting to nourish the beaches that are already heavily eroding will be of great value to the development of such a programme. Due to the flexibility and scalability of beach nourishment, the high values of beach properties and the high tourism revenues from many beaches, it can be concluded that a beach nourishment programme will be an effective and economically viable method of mitigating the impact of sea level rise on the coast of southeast Australia.

Preface

This thesis is the result of my graduation project, which was carried out for the main part at the Coastal Studies Unit of the University of Sydney, Australia, between December 2005 and May 2006. The remainder of the project, including the writing of this report, was carried out at Delft University of Technology, the Netherlands, between June 2008 and November 2008.

At the University of Sydney I was supervised by dr. Peter Cowell. I am very grateful to Peter for his support, encouragement and advice throughout the course of my graduation project. My stay in Australia has been a very valuable and pleasant experience and I owe many thanks to Peter for the opportunity to come to Sydney.

During the writing of this report I was supervised by my cousin dr. ir. Akke Suiker at the Faculty of Aerospace Engineering of Delft University of Technology. I would like to deeply thank Akke for helping me and encouraging me to finish my thesis. Thanks to his support, trust and advice I regained the confidence and motivation required to complete my studies.

In addition, I would like to thank the members of my examination committee at Delft University of Technology, prof. dr. ir. M.J.F. Stive, dr. ir. J. van de Graaff and dr. ir. B. Enserink, for their support and supervision.

Furthermore, I would like to express my gratitude to all other people who have assisted me with my project. In this regard, I particularly would like to thank: Marc Daley, John Hudson, Genny Pezzimenti, Peter Roy, Andrew Short and Bruce Thom (University of Sydney), Darren Skene (Sydney Marine Sand), Sally Kirkpatrick and Greg Stuart (Griffith Centre for Coastal Management, Queensland), David Beharrell and Daylan Cameron (Warringah Council, Sydney), Geoff Withycombe (Sydney Coastal Councils Group), Bart Hollemans (Van Oord Australia), ir. G.L.M van der Schrieck and dr. ir. P.H.A.J.M. van Gelder (Delft University of Technology), Matthijs Boon, Frank Claessen and Richard de Jager.

I would also like to thank my friends for the great times in Delft, Sydney and elsewhere.

Finally, I would like to thank my family, and in particular my parents, for their support throughout my studies.

Jeroen Langedijk
Delft, November 2008

Contents

List of Acronyms

AR4	Fourth Assessment Report of the IPCC
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
GIS	Geographic Information System
GCCM	Griffith Centre for Coastal Management (Gold Coast)
IPCC	Intergovernmental Panel on Climate Change
ISSS	Inner Shelf Sand Sheets
K-S test	Kolmogorov-Smirnov test
NSCMG	North Sea Coastal Management Group
NSW	New South Wales
pdf	Probability Distribution Function
RSB	Regressive Sand Barriers
SCCG	Sydney Coastal Councils Group
SQld	Southeast Queensland
SSB	Shelf Sand Bodies
TAR	Third Assessment Report of the IPCC
TAW	Technical Advisory Committee on Water Defences (the Netherlands)

List of Symbols

symbol	definition	unit
A	seafloor area being raised by sea level rise	m^2
A_i	area between coastline and outer closure depth	m^2
b	beach berm or dune height	m
c	sand costs	$/$m^3$
C	beach nourishment costs	$
D	grain size	m
$f(x)$	equilibrium profile	m
g	gravitational acceleration	m/s^2
G_B	sediment budget term	m^3
h	closure depth/limiting depth of area being raised/ limiting depth of active beach profile	m
h_c	inner closure depth	m
h_i	outer closure depth	m
H_s	significant wave height	m
l	length of cross-shore beach profile	m
l_i	offshore distance to outer closure depth	m
L	coastline length	m
m	beach profile scale parameter	$m^{1/3}$
p	factor accounting for variable sediment properties	-
Q	sand demand	m^3
r	coastal recession	m
s	amount of sea level rise	m
T_s	significant wave period	s
V	offshore sand losses	m^3
x	cross-shore distance from coastline	m
y	alongshore distance	m
α	nourished proportion of sandy coast	-
Δ	amount of sediment eroded or deposited per meter coastline	m^3/m
ρ	proportion of rocks on seafloor	-
σ	standard deviation	depends

1 Introduction

1.1 Background

Australia has over 10,000 sandy beaches, more than almost any other country in the world. With the vast majority of the Australian population living near the coast and the favourable climate, it is not surprising that going to the beach is one of the favourite pastimes and that more and more beaches are being developed with houses, hotels and other buildings. It is clear that Australia's beaches are of great value. However, due to global warming sea level is rising at an increasing rate. The latest assessment by the Intergovernmental Panel for Climate Change (IPCC) projects a global average sea level rise of 18 to 79 cm by the year 2100 (IPCC, 2007). According to the Bruun Rule (Bruun, 1962), which is a widely applied model for predicting coastal recession due to sea level rise, the rising sea level will cause sand from the nearshore zone to move offshore, resulting in beach erosion. Hence, beaches run the risk of diminishing or even disappearing within this century, with possible detrimental effects on the beach amenity, tourism, economy, beachfront development, safety and ecology. A way to mitigate these effects is beach nourishment: Artificially replenishing beaches with large amounts of sand. Beach nourishment has been practiced for several decades in many places in the world and has proven to be an effective way of combating beach erosion, when applied carefully. In Australia beach nourishment is currently only applied on the Gold Coast in southeast Queensland.
The present study discusses the application of beach nourishment in southeast Australia to mitigate beach erosion caused by sea level rise in the 21st century. The southeast coast of Australia is most prone to the detrimental effects of beach erosion for two reasons: First, it is the most developed part of the Australian coast, with the country's largest and third largest cities (Sydney and Brisbane), many popular tourist destinations (such as Sydney, Brisbane, the Gold Coast and the Sunshine Coast) and a lot of beachfront development. Second, the southeast coast is subject to the high energy wave climate of the Southern Ocean, the Tasman Sea and the Coral Sea. The area considered in this study (the study area) comprises the coasts of New South Wales and southeast Queensland. It stretches from Cape Howe on the Victoria-New South Wales border in the south, to Sandy Cape on Fraser Island in the north (see Figure 1.1).

Figure 1.1. The coast of southeast Australia.

1.2 Problem Definition and Objective

The problem definition of this study is: The projected rise of sea level in the 21st century will result in beach erosion, which has detrimental effects on the beach amenity, tourism, economy, beachfront development, safety and ecology in southeast Australia.

Following the problem definition, the objective of this study is: To estimate the costs of applying beach nourishment in southeast Australia to mitigate the effects of beach erosion caused by the rise of sea level in the 21st century.

1.3 Approach

In order to achieve the objective of the present study, there are three main questions that need to be answered:

1. How much sand will be eroded on the southeast Australian coast due to sea level rise in the 21st century?
2. How can the eroded sand, or part of it, be replenished?
3. How much will it cost to replenish the sand?

Sea level rise and its impact on the coast are associated with considerable uncertainty. To manage this uncertainty, the approach that will be followed in the present study is probabilistic. That is, the stochastic parameters that are required to answer the above questions will be assigned a probability distribution. Correspondingly, the resulting estimates of the offshore sand losses due to sea level rise and the associated beach nourishment costs will be expressed in terms of probabilities. This probabilistic approach is distinctly different from the deterministic approach commonly used in coastal management problems dealing with sea level rise, which would result in a single estimate of the offshore sand losses and of the beach nourishment costs. Such an outcome generally has a high probability of being exceeded and would be inappropriate in terms of risk-aversion and, hence, in dealing with the risk posed by sea level rise. Instead, the current probabilistic approach will provide coastal managers with a useful tool for risk-based planning and decision-making in dealing with the projected rise of sea level.

1.4 Report Outline

The report is organized as follows: Chapter 2 provides a description of the southeast Australia coast and the beach nourishment practice on the Gold Coast. Chapter 3 addresses the first main question of this study: How much sand will be lost due to sea level rise? The replenishment of these sand losses is addressed in Chapter 4, which will answer the second main question. The third and last main question will be answered in Chapter 5 by estimating the costs of beach nourishment. Finally, in Chapter 6 the main conclusions and recommendations of this study are presented.

2 The Coast of Southeast Australia

The study area of this project, the coast of New South Wales and southeast Queensland between Cape Howe and Sandy Cape, has a length of approximately 2,340 km and contains 894 beaches. This chapter gives an overview of the study area by describing the coastal environment (Section 2.1) and the beaches of southeast Australia (Section 2.2). This will provide a better understanding of the problem definition (see Section 1.2) and the boundary conditions that are of importance to answering the main questions of the present study (see Section 1.3). In addition, the beach nourishment practice on the Gold Coast in southeast Queensland will be described in Section 2.3. The chapter ends with the conclusions and discussion (Section 2.4).

2.1 The Coastal Environment

The coastal environment of southeast Australia is a very dynamic environment that has been formed and constantly changed by the interaction of geology with climatic and oceanic processes (Figure 2.1). The geology of the southeast Australian coast is described in Section 2.1.1 and the climatic and oceanic processes are described in Section 2.1.2. The information that is presented in this section has been obtained from Short (1993, 2000).

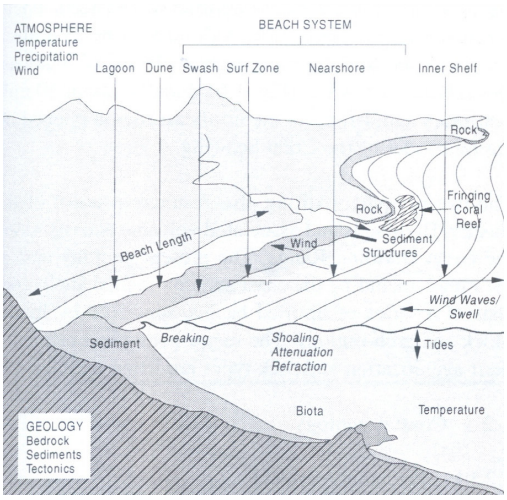

Figure 2.1. The coastal environment (Short, 2000).

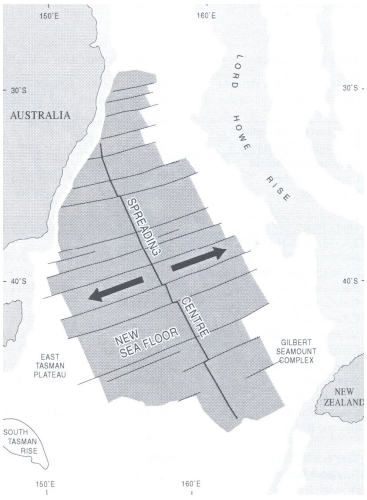

Figure 2.2. The separation of the Lord Howe Rise (Short, 2000).

2.1.1 Geology

Geological History

The coastline of southeast Australia was formed about 75 million years ago when the Lord Howe Rise plateau began migrating eastward and separated itself from the continental plate of Australia (see Figure 2.2). This spreading opened up the Tasman Sea and the southern Coral Sea and, hence, the coastlines of south Queensland and New South Wales were formed. In this process southeast

Australia lost its original continental shelf (the extended perimeter of the continent that is submerged during interglacial periods, like presently) to New Zealand and was left with a relatively steep and narrow shelf (20-80 km wide and up to 150 m deep). Since the end of the Lord Howe Rise separation 60 million years ago, the Australian southeast coast and its hinterland have been tectonically stable (except for the continuous northward migration of the Australian plate at about 6 cm per year). Ever since, the coast has been exposed to climatic and oceanic processes that have weathered and eroded the once plateau rock surfaces of the Great Dividing Range to form the coastal hills, valleys and plains that make up today's coast. The eroded material has been transported to the coast by rivers and streams and reworked by the tides, waves, currents and winds into deltas, estuaries, beaches and dunes.

Beach Formation

Most beaches in Australia began forming in the past 2 million years. During this time, sea level has risen and fallen up to 150 m over periods of 20,000 to 40,000 years. At the peak of the last ice age, 18,000 years ago, sea level stood 120 m below the present sea level and the New South Wales coast lay 20 to 60 km east of its present location. Subsequently sea level rose relatively fast for 11,000 years to reach its present level about 6,500 years ago. Correspondingly most beaches in southeast Australia are not older than 6,500 years. However, the present coast contains several remnants of former shorelines, such as large offshore sand bodies (which will be addressed in detail in Section 4.1.2). The rocks that make up a large part of the coastline are also much older than the beaches; They range in age from 60 million to 500 million years. In the northern part of the study area (southeast Queensland) these rocks are generally soft sedimentary rocks that have been heavily eroded over time and have virtually disappeared from the coastal zone. Without rocky headlands or bedrock reefs to trap the sediment, sand could be transported freely over long distances to be accumulated into large sand bodies. This has formed the sandy lowlands and shoals on the coast of southeast Queensland and the six large sand islands in front of the coast, including Fraser Island (the northern boundary of the study area). These islands have massive dunes (up to 280 m high) and beaches that, in the absence of headlands and reefs, are long, straight and unsheltered from the incoming waves (see Figure 2.3). For the same reason many of the mainland beaches in southeast Queensland and northern New South Wales are also relatively long and unsheltered.

In contrast, in central and southern New South Wales rocky headlands and cliffs still make up a large part of the coastline, as they are generally composed of hard metamorphic rocks that have not eroded as much as the softer rocks further north. These rocky outcrops have trapped much of the available

Figure 2.3. Long unsheltered beach on Fraser Island (own collection).

Figure 2.4. Pocket beach in the Royal National Park south of Sydney (own collection).

sand. As a result, most beaches in southern and central New South Wales are pocket beaches: Relatively short beaches that are bounded by rocky headlands (see Figure 2.4). These beaches are often deeply embayed, especially in the southern part of the state, which means they are sheltered from the incoming waves.

2.1.2 Climatic and Oceanic Processes

Climate

The study area extends from 25 to 38 degrees southern latitude and has a temperate to subtropical climate. The climate is dominated by the subtropical high pressure system that often covers most of Australia (see Figure 2.5). In New South Wales and southeast Queensland this high pressure system produces southeast to northeast winds and generally fine weather conditions. Besides the subtropical high pressure system, there are three types of cyclones that play an important part in the climate of southeast Australia: Tropical, east coast and mid-latitude cyclones. These low pressure systems produce the strongest winds and biggest seas and swells that occur in southeast Australia.

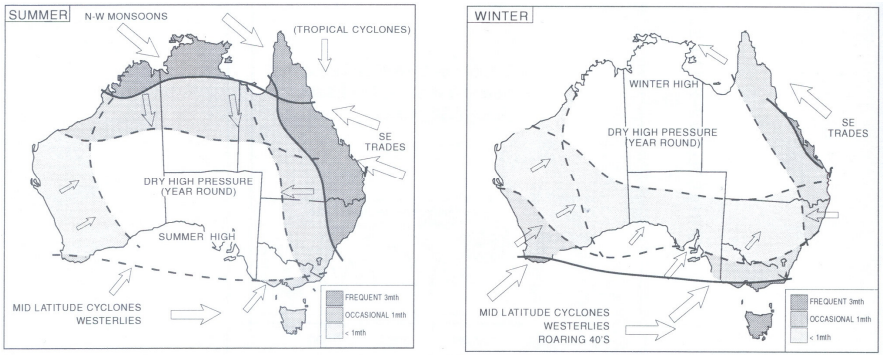

Figure 2.5. The high pressure system that dominates Australia's climate (Short, 2000).

Waves

The coast of southeast Australia is exposed to the energetic wave climate of the Southern Ocean, the Tasman Sea and the Coral Sea. Because of the extensive Waverider buoy wave recording system installed off the coast, the wave climate has been very well documented. The incoming waves originate from the cyclones off Australia's east coast and the subtropical high pressure system that covers much of Australia. The mid-latitude cyclones in the southern Tasman Sea produce most of the waves arriving in southeast Australia, resulting in about 200 days of southeastern waves per year. Because these waves have to travel a long distance before they reach the coast, they usually arrive as long, low to moderate swell (see Figure 2.6 below). The east coast cyclones produce the largest waves on the southeast coast, with a recorded biggest wave of 17 m by the Newcastle Waverider buoy (100 km north of Sydney) in 1978. Together, cyclones are responsible for 95% of the waves higher than 2.5 m. Most of the lower waves arriving on the coast of southeast Australia are generated by the subtropical high pressure system. These waves are usually 0.5 to 1.5 m high and arrive from the east or northeast. The wave climate of southeast Australia is summarized in Table 2.1.

The deepwater waves arriving on the southeast Australian coast have an average wave height of 1.6 m, but before they can reach the beaches, most of these incoming waves are affected by the presence of islands, headlands and bedrock reefs on the seafloor. These features cause wave attenuation, refraction and diffraction, which lower the incoming waves and alter their direction. This is especially the case in southern New South Wales, where the beaches are deeply embayed, and in southeast

Queensland behind the large sand islands. In both places the coastline is largely protected from ocean swell. In contrast, the long, unsheltered beaches of northern New South Wales and southeast Queensland are fully exposed to the ocean's energetic wave climate.

Table 2.1. Deepwater wave characteristics in southeast Australia (from: Short, 2000).

state	average wave height	average wave period	wave direction
New South Wales	1.6 m	10 s	NE (18%), E (41%), SE (40%)
southeast Queensland	1 - 1.2 m	9 - 10 s	SE (prevalent)

Tides and Currents

The southeast coast of Australia has a micro-tide with a mean range of 1.3 m and a maximum range of 2 m. The currents induced by the tides are negligible compared to the East Australian Current, which is a large and relatively warm ocean current that flows south from the Coral Sea into the Tasman Sea. Due to the East Australian Current and the subtropical climate, the water temperatures off the southeast Australian coast are relatively warm (15-25 °C).

2.2 The Beaches

All of Australia's 10,685 mainland beaches have been very well documented by the Australian Beach Safety and Management Program that commenced in 1986 (first as the New South Wales Beach Safety Program). This program, a joint project of the Coastal Studies Unit of the University of Sydney and Surf Life Saving Australia, aimed at compiling an overview of Australia's beaches and their safety. This has resulted, amongst others, in a very comprehensive database and seven beach guides that describe the beaches in detail. Part of these data (Short, 1993, 2000 and pers. comm.) have been utilised to provide an overview of beach characteristics (Section 2.2.1), beach erosion (Section 2.2.2) and beach development (Section 2.2.3) in New South Wales and southeast Queensland.

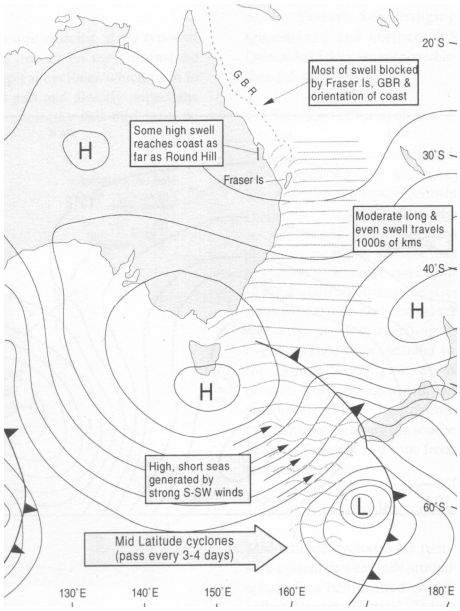

Figure 2.6. Southeast swell waves in southeast Australia produced by a mid-latitude cyclone (Short, 2000).

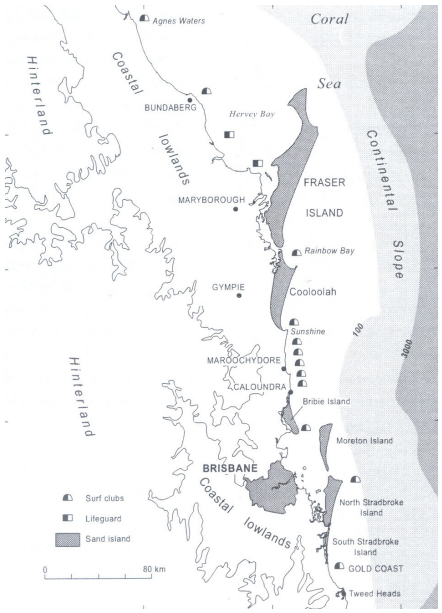

Figure 2.7. Sand islands in southeast Queensland (adapted from: Short, 2000).

2.2.1 Beach Characteristics

Beach Surveys

Under the Australian Beach Safety and Management Program the entire coast has been flown over at low altitude and every single beach in Australia has been inspected on-site to measure beach profiles, take sand samples, etc. Apart from this once-only survey, a number of beaches in southeast Australia are being surveyed regularly to monitor their behaviour, for example by means of visual inspections and periodic beach profile measurements. In recent years, cameras of the ARGUS coastal imaging system (a series of cameras operated by the University of New South Wales to monitor coastal behaviour) have been installed at three locations in southeast Australia (Short, 2006; Thom and Short, 2006).

Coastline and Beach Statistics

Table 2.2. lists a number of coastline and beach statistics in southeast Australia. As explained in Section 2.1.1, the presence of rocky headlands and reefs along much of the New South Wales coast limits the length of the beaches. Hence, the average beach length in New South Wales is about three times smaller than in southeast Queensland.

Table 2.2. Selected coastline and beach statistics of southeast Australia (from: Short, 1993, 2000 and pers. comm.).

state	**coastline**	**sandy (beach) coast**	**other coast** [b)]	**number of beaches**	**mean beach length**
New South Wales	1,590 km	971 km	619 km	772	1.26 km
southeast Queensland [a)]	750 km	462 km	288 km	122	3.79 km
total	2,340 km	1,433 km	907 km	894	1.60 km

[a)] The presented data include the coasts and beaches of the mainland and the six large sand islands in southeast Queensland, but exclude the numerous small islands in front of the coast and the west and north sides of Fraser Island (see Figure 2.7).

[b)] In New South Wales mostly rocky, in southeast Queensland mostly tidal flats.

Morphological Beach Types

Due to the high energy wave climate and the small tidal range, all beaches in southeast Australia are wave-dominated (instead of tide-modified or tide-dominated). This means that waves are the dominant factor in shaping the beach system. In sheltered locations, such as the bays of southern New South Wales and behind the large sand islands in southeast Queensland, the waves have produced beaches that are generally steep and narrow. On exposed parts of the coast, the beaches have been subjected to higher wave energy, which has resulted in generally wider beaches with a gentler slope (Short, 1993, 2000).

Sand Properties

The beach sands of southeast Australia are composed of predominantly well-sorted (i.e. there is little variation in grain size within a sample), fine to medium-sized (i.e. between 0.125 to 0.5 mm) quartz grains. Mean grain sizes are generally larger in the south than in the north and range from mostly 0.15-0.5 mm in New South Wales to 0.2-0.4 mm in southeast Queensland. The grains are well weathered due to the high wave and wind energy and due to the warm climate that causes chemical weathering. The latter process has also contributed to the relatively light colour of the sand, because it weathers out the darker minerals. The carbonate content (mostly from shells) of the beach sands is low (Roy, 2001; Short, 2006).

2.2.2 Beach Erosion

Long Term Beach Erosion

Most of the present-day beaches in southeast Australia are remnants of once larger beaches that were formed after the last ice age, which ended 10,000 years ago. During the last ice age sea level stood 120 m lower than today and rivers and streams were able to deliver large quantities of sand to the uncovered continental shelf. As sea level rose again, this sand was reworked shoreward and formed large energetic beaches. A reminder of these large beaches are the dunes that lie on many cliffs and headlands along the coast. When sea level approximately reached its present position about 6,500 years ago, there was an abundance of sand on the coast. But major erosion removed much of this sand and deposited it in the massive sand bodies that lie on the inner continental shelf of southeast Australia (these offshore sand deposits will be addressed in detail in Section 4.1.2). The beaches that have survived this major erosion are smaller, less energetic and more sheltered than they were 6,500 years ago (Short, 1993).

Most of the present-day beaches do not receive sediments anymore, but due to their sheltered position between headlands that trap the sand, many beaches in New South Wales do not loose any sand alongshore either. Hence, these beaches have remained more or less stable for several thousand years. However, many of the long, less embayed beaches in northern New South Wales and southeast Queensland are eroding because they loose sand to the littoral, or alongshore, drift and to estuaries. In contrast, a very few beaches in southeast Australia seem to be slowly accreting (Short, 1993, 2000).

Short Term Beach Erosion

In the short term, beaches constantly erode and accrete in response to varying wave conditions and tides. During storms, high waves transport sand to the offshore and cause beach erosion. In calmer periods between storm events the beaches are built up again by the waves (see Figure 2.8). There have been relatively few major storm events in New South Wales since the 1950's, which means that in recent decades major beach erosion has not occurred. The last major beach erosion event in southeast Queensland occurred in 1967 (see Section 2.3.1) (Cowell, pers. comm.).

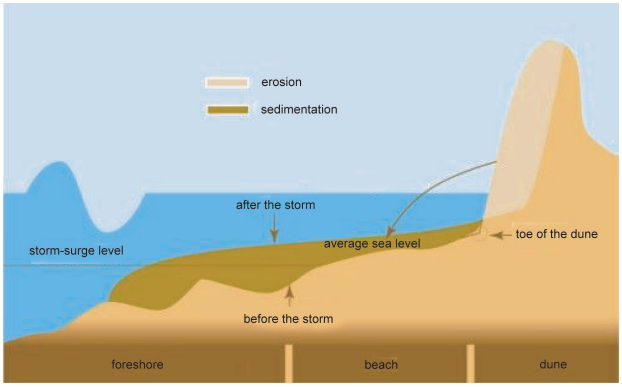

Figure 2.8. Short term beach erosion and accretion (Hoogewoning and Boers, 2001).

2.2.3 Beach Development

The majority of Australia's beaches are still in a natural state, but many beaches, especially on the east coast, have been developed for residential and recreational purposes. This ranges from small-

scale development, such as a campsite in the dunes, to large-scale development, such as the Gold Coast: A 36 km long stretch of coast that has been built over with hotels, high-rise apartment buildings and houses (see Figure 2.9). The degree of beach development is an important factor in the decision-making process of a beach nourishment project since it strongly determines the economic viability of the proposed investment. Prior to the present study there was no comprehensive overview of beach development in southeast Australia. Therefore, as part of this study, the degree of beach development has been mapped for the entire coast of New South Wales and southeast Queensland. This will be elaborated in Section 5.1. A summary of the results of this investigation is presented in Table 2.3. The presented values show that a large proportion of the beaches in southeast Australia has been developed, especially in southeast Queensland (which can be attributed to the highly developed Gold Coast). By length, though, the majority of the sandy coastline is still (largely) undeveloped. This implies that most of the developed beaches are relatively short, which can be explained by the fact that these beaches are usually located in cities and/or tourist resorts.

Table 2.3. Percentage of developed beaches in southeast Australia (see Section 5.1.2 for details).

state	**% of total number of beaches**	**% of sandy coastline**
New South Wales	32%	17%
southeast Queensland	66%	21%

2.3 Beach Nourishment on the Gold Coast

Currently the only place in Australia where beaches are artificially nourished is the highly developed Gold Coast in southeast Queensland, one of Australia's main tourist attractions (Figure 2.9). The experience with beach nourishment on the Gold Coast may be very useful for the development of a beach nourishment programme in southeast Australia. Therefore this section provides an overview of the beach nourishment practice on the Gold Coast by addressing the design aspects (Section 2.3.1) and the results and related issues (Section 2.3.2). The information that is presented in this section has been provided by the Gold Coast's Griffith Centre for Coastal Management (GCCM), unless indicated otherwise.

Figure 2.9. The Gold Coast (Australian education information portal for overseas students, 2008).

2.3.1 Design Aspects

Background

The beach nourishment projects commenced in the early 1970's, a few years after a series of cyclones had devastated the Gold Coast beaches in 1967. To prevent such severe erosion from happening again, the Queensland state government invited the Delft Hydraulics Laboratory to advise them on ways of minimising beach erosion. This resulted in the so-called "Delft Report" in 1971, which outlines a number of coastal protection works, including beach nourishment, the construction of groynes and an artificial reef. In 1973 it was decided to implement these proposals. Since then the Gold Coast City Council, in conjunction with the state government, has undertaken many beach nourishment projects.

The first nourishments on the Gold Coast were dune nourishments. In the years that followed the sand was placed on the beaches, which showed direct results (a wider beach) to the policymakers and the community. However, political and community support of the nourishments often quickly diminished after large storms had eroded the beaches and the nourished sand was apparently lost, even though it was still there in the offshore sand bar. That is the main reason why nowadays the preferred practice is to place the sand on the nearshore (i.e. below the low water level) rather than on the dry, visible beach.

In the 1970's the nourishment sand was extracted from local estuaries. But in the 1980's these sources proved to be insufficient and offshore sources were sought and found. Today nourishments larger than 50,000 m^3 are carried out with a trailing suction hopper dredger that extracts sand offshore off the Gold Coast. For small nourishments it is not worthwhile to deploy the dredger offshore because of the high mobilisation costs. These small projects use sand sourced during regular maintenance of the estuaries and canals.

Nourishment Volumes and Planning

The Delft Report stated that a sand volume of 400 m^3 per meter coastline is required on the Gold Coast to accommodate a storm event with the size of the one occurring in 1967. This is still the target value, but in practice this amount is too expensive to maintain. Instead, the amount of sand that is nourished each year is determined by the available budget of the Gold Coast City Council. On average several 100,000's m^3 of sand per year are nourished, though in some years there is no beach nourishment at all. The nourishments are commissioned by the Gold Coast City Council.

Generally, the roughest seas and swells on the Australian east coast occur in autumn, while the calmest periods occur in spring. Yet there is no definite time during the year that a dredge could not operate. However, most of the beach nourishment works on the Gold Coast are undertaken during the winter months, which is outside the tourism peak seasons and school holidays.

Sand Placement

As mentioned above, nowadays most of the beach nourishment sand on the Gold Coast (75%) is placed on the nearshore instead of on the dry, visible beach. Although the latter method directly increases the width of the beach, it has three significant disadvantages: First, when a storm hits the coast, most of the nourished sand will be transported to the lower part of the beach profile and is no longer visible. The public may view this as a waste of sand and, thus, a waste of money, which in turn may lead to the loss of political and community support for beach nourishment. Second, the placement of dredged up sand directly on a beach may decrease the recreational amenity of the beach

(this will be explained below). Third, sand that has been extracted offshore contains a lot of salt. When it is placed directly on a beach, the salt has not been washed out yet and it may harm the dune vegetation when it is blown landwards by the wind. For these three reasons, nearshore sand placement is now the preferred nourishment method on the Gold Coast. Since this method does not show direct results to the public, it is important to inform the local community how this method works and how their money is spent. In general, nearshore nourishments tend to increase the community's confidence that beach nourishment is a worthwhile investment.

Offshore Sand Extraction Areas and Dredging Equipment

The offshore sand extraction areas on the Gold Coast are located in water depths of more than 20 m, which is well past the annual closure depth: The depth beyond which in an average year (i.e. a year without extreme storm events) no significant sand transport takes place. In southeast Australia the annual closure depth is approximately 16 m (this will be elaborated in Section 3.3.1). There are no restrictions on the size or depth of the sand extraction areas, but it is common practice to make them as big as possible and to dredge only a thin layer of sand from the seafloor. The borrow sand that is extracted offshore on the Gold Coast is comparable in size and colour to the native sand on the Gold Coast beaches. However, the first period after the borrow sand has been dredged up it will look different than the native sand, because it contains other materials that have not been washed out yet (such as shells) and because it is slightly darker, since it has not been exposed to sunlight yet. This may decrease the recreational amenity of the nourished beaches.

The dredger that is used for offshore sand extraction and beach nourishment on the Gold Coast is a very small trailing suction hopper dredger with a hopper capacity of approximately 300 to 400 m^3 (for comparison, dredgers commonly used for beach nourishment in other countries have a hopper volume of at least several 1,000's of m^3; see Section 4.2.1). This dredger is operated by a small local dredging company and usually moored in an estuary on the northern Gold Coast. A combination with possible future beach nourishment projects in New South Wales or other parts of southeast Queensland might allow the Gold Coast City Council to deploy a larger dredger.

Costs

The price of sand that was extracted offshore and placed on Palm Beach on the southern Gold Coast in 2006 was 6.15 $/$m^3$ (Australian dollars[1]), for a nourishment volume of 300,000 m^3. There is no fee for offshore sand extraction (such as the Crown Estate in the United Kingdom) in Queensland. The nourishments are paid by the Gold Coast City Council (75%) and the state government (25%). Since the Gold Coast is a major tourist attraction and many Australians profit from its beaches, some people want the federal government to finance the nourishments as well.

2.3.2 Results and Related Issues

Results

The condition of the Gold Coast beaches and the effect of beach nourishment on these beaches are monitored by weekly visual inspections, ARGUS cameras and beach profile measurements, which are carried out annually and before and after each beach nourishment. These surveys have shown that the Gold Coast beaches and dunes have increased greatly since the early 1970's, when the nourishments

[1] All amounts of money cited in this report are in Australian dollars.

commenced and other coastal protection works were implemented. The beaches seem to be in good shape, but then there have been no cyclones on the Gold Coast since the ones that devastated the beaches in 1967. Hence, the nourished beaches have not been seriously tested yet, although it is expected that within the coming decades the Gold Coast will be hit by another cyclone.

Side Effects
There have always been environmental concerns with regard to beach nourishment, but the Delft Report stated that the environmental impact of sand extraction out on sea or in estuary channels is very small. Indeed, although it is not a strict indicator, after more than 30 years of beach nourishments on the Gold Coast there has been no noticeable decay of marine life. During the beach nourishment operations there is even an increased presence of fish: Nearshore dumping of sand stirs up the seafloor and releases small animals, attracting small fish that in turn attract sharks. The surfing conditions on the Gold Coast have definitely been changed by the beach nourishments, but this has never been researched in detail. The policy is that coastal protection is more important than surfing.

Community and Political Support
From the information above it is clear that financial, political and social aspects play an important part in beach nourishment projects. On the Gold Coast, the most difficult issue is probably retaining political and community support and, hence, money. The public has forgotten about cyclones and beach erosion and it is often hard to justify investments on the coast to the non-coastal divisions of the Gold Coast City Council. That is one of the reasons why nowadays coastal protection works often serve other purposes as well. For example, thanks to the beach nourishments the Gold Coast beaches become wider and dunes can be pushed seaward, which increases the parklands and recreational areas on the landside of the dunes. Another example is the Narrowneck surf reef on the northern Gold Coast, which was constructed not only to decrease the wave impact on the Narrowneck spit, but also to improve the surfing conditions.

2.4 Conclusions and Discussion

The 2,340 km long coastline of southeast Australia is characterised by short embayed beaches between rocky headlands and cliffs in the south, and long unsheltered beaches with large dunes in the north. These beaches have been shaped mainly by the interaction of geology with the energetic wave climate and are composed of predominantly fine to medium, well-sorted sand. Major beach erosion has not occurred in recent decades, but many of the unsheltered beaches are gradually loosing sand to the alongshore drift and estuaries. About one third of the 894 beaches have been developed; hence, the major part of the coastline is still in a natural state. A highly developed stretch of coastline is the Gold Coast, a major tourist attraction in southeast Queensland. At present, the Gold Coast is the only place in Australia where beaches are nourished. Most of these nourishments are carried out with a small dredger that extracts sand offshore and places it on the nearshore. The nourishments have resulted in much wider beaches, but related issues, such as the environmental impact and the community and political support, are points of concern.
This chapter has described the coast of southeast Australia, which has provided some of the boundary conditions of the present study, such as: The wave climate, the geology of the shoreface, the number and length of the beaches and the experience with beach nourishment in Australia. These data play an important part in estimating the future sand losses due to sea level rise, which is addressed in the next

chapter, and in determining the method and the costs of replenishing these sand losses, which will be addressed in the subsequent chapters.

3 Future Sand Losses due to Sea Level Rise

In this chapter the first main question of the present study will be answered: How much sand will be eroded on the coast of southeast Australia due to the predicted 21st century sea level rise? In this study, erosion is defined as a net loss of sediment from the nearshore zone, which leads to coastal recession (see Figure 3.2 on page 21). Coastal erosion in southeast Australia occurs both in the long-term and in the short-term and arises from natural and anthropogenic causes, such as: Storm events, gradients in alongshore transport and sand demand by estuaries and lagoons (see Section 2.2.2). These causes of erosion are, however, not considered in this study[2]. This study only addresses offshore sand losses due to sea level rise. It is important to note that sea level rise is a relatively slow process and that in the short-term, the erosion caused by sea level rise can be overridden by other forms of erosion, such as sand losses to estuaries and the alongshore drift. These sand losses can be superimposed to the sand losses due to sea level rise. This is however beyond the scope of this study. Besides, the alongshore drift along much of the coastline of southeast Australia is relatively weak (Cowell., pers. comm.) and the size of the estuaries and lagoons is very small compared to the length of the coastline and the size of the shoreface. Hence, when considering sand losses in the nearshore zone on the entire southeast Australian coast until the year 2100, the sand losses due to gradients in the alongshore drift, estuaries and lagoons are expected to be very small compared to the offshore sand losses caused by sea level rise.

It is generally accepted among coastal scientists and engineers that a rise in sea level will usually lead to coastal erosion, because increasing water levels allow larger waves to reach the shoreline and erode the beaches (Bird, 1996). The most widely applied model for predicting coastal erosion due to sea level rise is the Bruun Rule (Bruun, 1962). The Bruun Rule is a two-dimensional model that estimates the cross-shore landward and upward displacement of a beach in response to a rise in sea level and will be discussed in detail in Section 3.1.The objective of this study, however, is not to estimate the future displacement of southeast Australia's beaches, but to estimate the amount of sand that these beaches will loose due to sea level rise. These sand losses can be estimated with the "raising the profile method", which has been derived from the Bruun Rule. The raising the profile method is explained in Section 3.2. The raising the profile method applied in the present study has three input parameters, which are discussed in the following sections: The seafloor area that is being raised by sea level rise (Section 3.3), the amount of sea level rise (Section 3.4) and the rocky portion of the seafloor (Section 3.5). With these data the future sand losses due to sea level rise are estimated in Section 3.6. Section 3.7 contains the conclusions and discussion.

3.1 The Bruun Rule

As mentioned above, the Bruun Rule is the most widely applied model for predicting coastal erosion due to sea level rise. The original, standard Bruun Rule as developed by Bruun (1962) (usually simply

[2] It might be that some of these causes, like the alongshore drift, the occurrence of storm events and the wave climate, are altered by sea level rise and/or climate change. But these effects are highly uncertain and beyond the scope of this study (Dubois, 2002; Cowell, pers. comm.).

referred to as the Bruun Rule) is explained in Section 3.1.1. The validity of the Bruun Rule is discussed in Section 3.1.2, followed by the explanation of the extended version of the Bruun Rule, the generalised Bruun Rule (Section 3.1.3). Section 3.1.4 presents three more recent models of predicting shoreline evolution. The conclusions based on Sections 3.1.1 to 3.1.4 are presented in Section 3.1.5.

3.1.1 The Standard Bruun Rule

Concept and Formulation

Each shoreface has an equilibrium cross-shore profile, which is the average slope the shoreface tends to maintain for a given depth, balancing the forces that move sediment onshore and the forces that move sediment offshore (Slott, 2003). The resulting average shape of the shoreface is the equilibrium profile *f(x)*, for which Bruun (1962) has derived:

$$f(x) = mx^{2/3} \tag{3.1}$$

with m = profile scale parameter[3], and x = cross-shore distance from the shoreline. As the shoreface is subjected to varying wave and tidal conditions and constantly changing, the equilibrium profile is in fact "a statistical average profile which maintains its form apart from small fluctuations including seasonal fluctuations" (Bruun, 1962). In other words, the equilibrium profile is the average long-term profile that reflects the mean sea level, the wave climate and the size of the sediment on the shoreface.

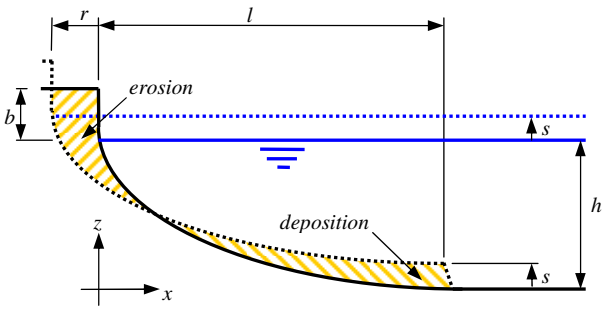

Figure 3.1. The Bruun Rule.

Bruun proposed that when sea level rises, the shoreface will adjust itself to re-establish an equilibrium profile at each depth, thus maintaining its shape. This means the profile will shift upward by an amount equal to the rise of sea level (see Figure 3.1). The upward displacement of an equilibrium profile *f(x)* over a distance l requires a sediment volume per meter coastline of:

$$\Delta = \int_0^l \left[f(x) + s \right] dx - \int_0^l f(x)\, dx = ls \tag{3.2}$$

with s = amount of sea level rise. Bruun assumes a conservation of sediment within the cross-shore profile (this will be further addressed below). This implies that the only way in which the sediment

[3] This parameter is usually indicated with the letter *A*, but in the present study *A* denotes the area that is being raised by sea level, see Eq. iderable size (i.e. larger than the very smal.

required for the upward displacement of the profile *f(x)* over a distance *l* can be obtained is by a landward shift of the entire profile, resulting in erosion of the upper shoreface. The amount of sediment per meter coastline that is obtained by the landward shift can be approximated as:

$$\Delta = \int_0^l f(x)\,dx + (h+b)\,r - \int_0^l f(x)\,dx = (h+b)\,r \tag{3.3}$$

with h = maximum depth of exchange of sediment between the nearshore and the offshore, often referred to as the closure depth, b = beach berm or dune height, and r = coastal recession. The sediment eroded from the upper shoreface will be deposited on the lower part of the shoreface. As Bruun assumes a sediment balance within the cross-shore profile, the amount of sediment eroded is equal to the amount of sediment deposited. Equating Eqs. (3.2) and (3.3), and solving for the coastal recession r gives the Bruun Rule:

$$r = \frac{ls}{h+b} \tag{3.4}$$

Many coastlines have a nearshore slope (h/l) of about 0.01 to 0.02. As a rule-of-thumb, the coastal recession is often calculated by substituting these values of (h/l) into Eq. (3.4) and ignoring the dune height b. This yields a coastal recession of about 50 to 100 times the amount of sea level rise (Ranasinghe et al., 2007). The coastal recession predicted by the Bruun Rule depends on the average slope of the entire beach profile, (h/l), which is usually considerably smaller than the slope of the dry, visible part of the beach (about 0.05 to 0.1). Hence, the direct effect of the inundation of a beach as sea level goes up is about five times smaller than the effect predicted by the Bruun Rule. It should also be noted that Eqs. (3.2) to (3.4) are independent of the profile scale parameter m from Eq. (3.1), but not of the profile's shape: As the profile is assumed to follow the concave shape described by Eq. (3.1), the shape can be determined from the relation between h and l alone, because this relation is fixed by the value of m. Since both h and l are included in Eqs. (3.2) to (3.4), these expressions implicitly include the shape of the profile. Apart from this, the amount of erosion and the coastal retreat due to sea level rise are independent of the presence of offshore bars on the shoreface (Davidson-Arnott (2005).

Assumptions and Hypotheses

The Bruun Rule is based on three explicit assumptions (Bruun, 1988; Slott, 2003; Davidson-Arnott, 2005; Ranasinghe et al., 2007):

1. The shoreface maintains an equilibrium profile in the long term, despite the presence of any short-term fluctuations;
2. The nearshore coastal system is closed, which means that there is no sediment transport landward of the dunes nor seaward of the closure depth. In other words, there is a conservation of sediment within the cross-shore profile;
3. The rule has been derived for a two-dimensional profile normal to the shoreline. Hence, variable alongshore bathymetry or alongshore sediment transport gradients are not taken into consideration.

In addition, the Bruun Rule has two implicit assumptions (Davidson-Arnott, 2005):

4. The profile consists entirely of easily erodable sand;
5. Enough large waves occur to redistribute sediment across the profile (if there were no waves, sea level rise would only result in the inundation of the dry beach).

Bruun formulated three hypotheses (that can be derived from the above assumptions) to construct the Bruun Rule (Bruun, 1988; Davidson-Arnott, 2005; Ranasinghe et al., 2007):

1. The landward migration of the profile due to sea level rise results in erosion on the upper shoreface;
2. The sediment eroded from the upper shoreface is deposited on the lower part of the shoreface, with the volume of erosion being equal to the volume of deposition;
3. The rise of the nearshore profile due to the deposition of sediment is equal to the rise in sea level.

3.1.2 Validity of the Bruun Rule

Support

Since its formulation in 1962, the Bruun Rule has been tested in several laboratory and field experiments. These experiments have confirmed the rule's basic concept that a shoreface subjected to a rising sea level will shift landward and upward (Ranasinghe et al., 2007). In addition, several laboratory tests and field measurements of shoreline recession under sea level rise have produced results that are in good agreement with the values predicted by the Bruun Rule (Hands, 1983; Slott, 2003). However, according to Ranasinghe et al. (2007) none of these tests have produced convincing support of the validity of the Bruun Rule's predictions. This can largely be attributed to: (i) Uncertainties in selecting appropriate values for the various parameters of the Bruun Rule and (ii) the existence of a lag time between sea level rise and the response of the profile (Bruun, 1988; Davidson-Arnott, 2005; Ranasinghe et al., 2007). Also, according to Davidson-Arnott (2005) it is not sufficient to validate the Bruun Rule by simply comparing measured laboratory or field data with the values predicted by the rule, since "it is quite possible for measured shoreline displacement to equal predicted values even though the volume transfers required by the Bruun Model do not occur". Instead, validation of the Bruun Rule would require a demonstration that Bruun's three hypotheses hold (Davidson-Arnott, 2005). From Ranasinghe et al. (2007) it seems that to date only Bruun's first hypothesis (a landward shift of the profile) and part of the third hypothesis (an upward shift of the profile) have been sufficiently proven.

Criticism and Limitations

Although the basic concept of the Bruun Rule (i.e. a rise in sea level will lead to coastal recession) is well-accepted among coastal scientists and engineers, the underlying process and the applicability of the rule are the subject of discussion. The underlying process is called into question by, amongst others, Dubois (2002), who states that erosion and deposition occur on the upper shoreface only and not as far out as the closure depth. This led to the conclusion that the application of the Bruun Rule should be limited to the shoreface landward of the first offshore sandbar only.

Furthermore, Pilkey et al. (1993) argue there is no scientific basis for the concept of an equilibrium profile, because: (i) The Bruun Rule ignores the action of alongshore currents and (ii) of the underlying geology (which affects sediment sources and fixes the slope of the shoreface in certain locations); (iii) the shoreface is not a closed system in its cross-shore direction and (iv) not all profiles assume the concave equilibrium shape described by Bruun. In addition, Ranasinghe et al. (2007) state

that the applicability of the Bruun Rule is limited since it does not accommodate for: (i) Profiles that are known not to be in equilibrium (e.g. due to ongoing steepening or flattening of the profile on top of normal seasonal fluctuations); (ii) three-dimensional variability; (iii) sediment exchange with the dunes and offshore areas beyond the closure depth; (iv) the presence of fine sediment that may be too fine to remain within the cross-shore profile and (v) a difference in sediment characteristics between the beach and the nearshore zone. Lastly, the Bruun Rule does not take into account the effect of an increased storminess, which climate change is likely to cause (e.g. IPCC, 2001).
In correspondence with the above criticism, it has been recommended to apply the Bruun Rule to areas where the alongshore transport gradients are insignificant, to profiles that consist entirely of sand and to use the results as order-of-magnitude estimates of predicted shoreline recession only (e.g. Ranasinghe et al., 2007). However, with regard to the material of which the profile is composed, Daley (2005) found that the application of the Bruun Rule is not affected by the presence of rocks on the shoreface, because the underlying geology does not influence the development of an equilibrium profile.

3.1.3 The Generalised Bruun Rule

To increase the applicability of the Bruun Rule, several efforts have been made to extend the rule to accommodate for three-dimensional effects, variable sediment properties and sediment losses or gains beyond the boundaries of the cross-shore profile as defined by Bruun. These efforts have resulted in extending the Bruun Rule, Eq. (3.4), with a dimensionless factor p accounting for variable sediment properties and an all-encompassing sediment budget term G_B:

$$r = \frac{ls}{p(h+b)} + \frac{G_B}{p(h+b)} \tag{3.5}$$

Eq. (3.5) is known as the "generalised" Bruun Rule (Ranasinghe et al., 2007). The factor p, with $0 < p \leq 1$, accounts for the proportion of sediment that is too fine to remain within the profile. For a larger proportion of fines, the factor p becomes smaller. This will increase the shoreline recession, r, because the volume of erosion per meter coastline, $(h+b)r$, which is required to provide the sediment deposition offshore, $ls+G_b$, will be larger. The term $ls+G_b$ is the sum of the sediment volume needed to re-establish equilibrium after a rise in sea level, ls, and the sediment losses or gains beyond the boundaries of the two-dimensional cross-shore profile considered in the Bruun Rule, G_B. These sediment losses or gains could be attributed to: Alongshore transport gradients, the presence of rivers and estuaries, windblown sand exchange between the beach and the dunes, losses of silt, clay and very fine sand particles to deepwater (i.e. beyond the closure depth), etc. (Bruun, 1988; Ranasinghe et al., 2007). If there is a net loss of sediment from the cross-shore profile, $G_B > 0$, implying an additional loss of sediment and, hence, increased erosion.
Due to the complex nature of the processes that determine G_B and/or insufficient data, estimating G_B is usually very difficult. Obtaining an accurate estimate of p is often equally difficult. Therefore, in practice coastal planners often determine an allowance for G_B and p in terms of shoreline recession or a volume of erosion, and add this value to the value of shoreline recession or erosion due to sea level rise as calculated with the Bruun Rule (Ranasinghe et al., 2007).

3.1.4 Other Shoreline Evolution Models

Apart from overcoming the limitations of the Bruun Rule by expanding it, over the years a number of new models to predict shoreline evolution have been put forward. Three of these models are briefly discussed here. The first one is a conceptual model by Davidson-Arnott (2005) that, like the Bruun Rule, predicts a landward migration of the profile in response to a rise in sea level. However, unlike Bruun's model, this model includes sediment exchange between the beach and the dunes and predicts a net landward movement of sediment in order to preserve the beach-dune system, instead of a net offshore sediment transfer as predicted by Bruun. To date this concept has not been further developed or tested, as far as is known.

Contrary to the Bruun Rule and the Davidson-Arnott model, the other two models discussed here predict shoreline evolution by means of numerical simulation rather than by a mathematical expression or a conceptual model. The first of these two models is the panel-based model that Stive and De Vriend (1995) developed on the basis of the dynamic processes that occur in the nearshore zone. This model divides the shoreface intro three distinct morphological zones (the upper, middle and lower shoreface), each responding differently to a rise in sea level. The upper shoreface, which comprises the duneface, beach and surfzone, responds rapidly to a change in sea level and maintains an equilibrium profile, thus following a similar response as in Bruun's model. The lower shoreface, which reaches down to the inner continental shelf, responds much slower than the upper shoreface. The middle shoreface forms a transition zone that adapts itself to the changes of the upper and lower shorefaces. One of the main difficulties in applying this model is choosing the transition points between the three zones. It is suggested that Hallermeier's lower and upper depths of closure (see Section 3.3.1) could be used to define the location of the transitions points (Stive and De Vriend, 1995). The panel-based approach of this model allows one to study the time-dependent nature of shoreline response to sea level rise (Slott, 2003).

The last model discussed here is the shoreface-translation model developed by Cowell et al. (1995). Like the model of Stive and De Vriend, this model divides the shoreface into different zones. Again, the response of the upper part of the shoreface to a rise in sea level is such that it maintains an equilibrium shape. The underlying assumptions of this model, however, are different, since the model is not based on the dynamic nearshore processes, but on historical shoreline evolution (a technique called inverse modelling). In addition, this model does not only predict the response of a shoreface to changes in sea level, but also to external gains or losses of sediment and to changes in the geometry of the shoreface itself. Therefore this model allows for studying the "comparative effects of various small changes to the dynamics of the nearshore system" (Slott, 2003).

Compared to the Bruun Rule, the models by Stive and De Vriend and by Cowell et al. require considerable more data, which are not available for the entire southeast Australian coast.

3.1.5 Conclusions and Discussion

Ideally, the impact of sea level rise on a shoreline would be predicted with complex numerical models that take into account all hydro- and morphodynamic processes that occur in the nearshore zone. But the development of such models is still in its infancy, as it has taken a long time to gain sufficient understanding of the complex nearshore processes. As a consequence, it is not yet fully understood how a shoreface responds to a rise in sea level (Stive and De Vriend, 1995; Dubois, 2002; Ranasinghe

et al., 2007). Bruun's model, though, is widely accepted and the most commonly used method to predict shoreline recession due to sea level rise. The Bruun Rule's basic concept (i.e. sea level rise leads to coastal recession) seems to be valid, even though its underlying assumptions are the subject of debate. In addition, unlike some recently developed more comprehensive coastline evolution models, the Bruun Rule does not require detailed data of a coast and can be readily applied to obtain a first estimate of coastal erosion due to sea level rise. Finally, according to Rosen (Ranasinghe et al., 2007), when Bruun's model is applied in a regional sense, the results will be relatively accurate.
For the above reasons, Bruun's model, or rather its corollary the raising the profile method (which conveys the procedure of estimating sand losses due to sea level rise more accurately; see Section 3.2), will be used in this study. The application of Bruun's model and the raising the profile method should be met with caution. This is especially true with regard to the presence of rocks on the seafloor, alongshore sediment losses or gains, the presence of fine sediment and the determination of the model's input parameters. These issues will be addressed elaborately in Sections 3.2 to 3.5.

3.2 The Raising the Profile Method

The main question to be answered in this chapter is: How much sand will be eroded on the coast of southeast Australia due to sea level rise in the 21st century? According to the Bruun Rule, which has been discussed in Section 3.1, sea level rise will cause sand from the upper shoreface to move offshore, resulting in a redistribution of sand within the cross-shore profile. Due to this redistribution, sand is eroded from the upper shoreface, which leads to coastal recession (see Figure 3.2). The offshore sand transport ensures that the profile is adjusted to the rise in sea level and requires an amount of sand that can be estimated with the raising the profile method, which has been derived from the Bruun Rule. In order to obtain this amount of sand, sand is lost from the beaches and the upper shoreface. Accordingly, in the present study the amount of sand that is required to adjust the profile to sea level rise is referred to as the (offshore) sand losses[4].

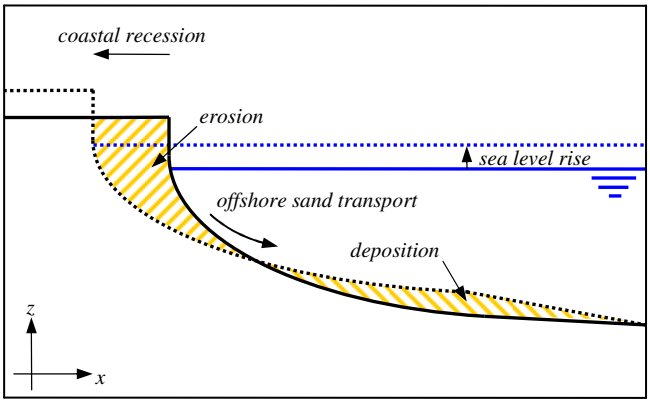

Figure 3.2. Redistribution of sand within the cross-shore profile due to sea level rise.

The formulation of the raising the profile method is presented in Section 3.2.1. Section 3.2.2 addresses the concept of sediment sharing systems, which is of importance to the application of the raising the profile method to the coastline of southeast Australia. To account for the presence of rocks

[4] The amount of sand required to adjust the profile to a rise in sea level is often referred to as the sand deficit or the sand demand.

on the seafloor of southeast Australia, the raising the profile method needs to be extended, which is explained in Section 3.2.3.

3.2.1 Formulation of the Raising the Profile Method

As explained in Section 3.1.1, the Bruun Rule predicts that the erosion per meter coastline due to sea level rise is equal to the height of the beach profile times the shoreline recession, see Eq. (3.3). In Bruun's model, the eroded volume is equal to the amount of sediment that is deposited offshore in order to adjust the profile to the new sea level, see Eq. (3.2). Hence, the eroded volume per meter coastline, Δ, can be calculated with Eq. (3.2), i.e.:

$$\Delta = ls \tag{3.6}$$

Eq. (3.6) implies that the entire beach profile is raised as much as the sea rises and therefore it is referred to as the "raising the profile method" (e.g. Leatherman, 1989), see Figure 3.3.

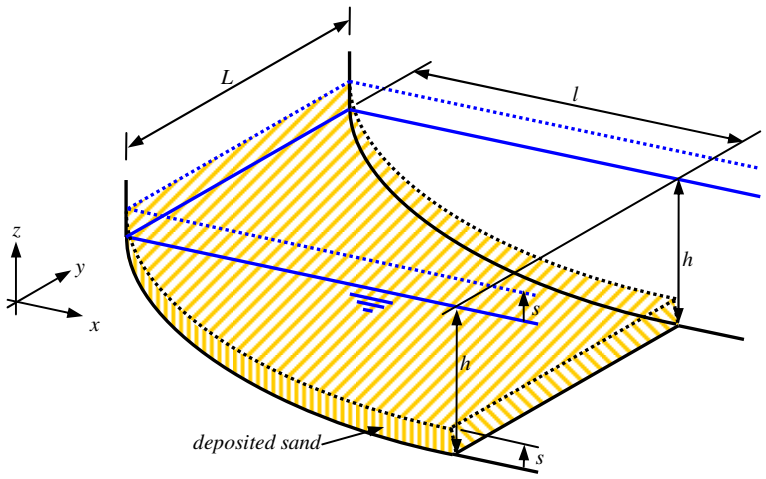

Figure 3.3. The raising the profile method.

When applying the raising the profile method in a three-dimensional sense, the length l of the cross-shore beach profile needs to be multiplied with the coastline length L, which results in an area $A = l \cdot L$. The area A is the area of the beach profile that is being raised as sea level rises. Substituting A into Eq. (3.6) gives the raising the profile method for a three-dimensional situation:

$$V = As \tag{3.7}$$

with V = offshore sand losses. This simply means that the "amount of sand required is equal to the area being raised times the rise in sea level" (Titus et al., 1991). Eq. (3.7) shows that in order to estimate coastal sand losses, it is not required to predict the shoreline recession with the Bruun Rule first. Therefore, this study does not apply the Bruun Rule, but the raising the profile method. Although the raising the profile method is a derivative of Bruun's model, it overcomes one of the main limitations of the Bruun Rule, which is the fact that it does not accommodate for alongshore sediment transport. When the raising the profile method is applied to an entire coast (which is the case in this

study), the net alongshore sediment losses or gains are negligible compared to the total amount of sand that is moved in the cross-shore direction (Titus and Greene, 1989). This notion is supported by the fact that the alongshore sediment transport along much of the coast of New South Wales is relatively insignificant (Cowell, pers. comm.).

3.2.2 Sediment Sharing Systems

The raising the profile method will be applied to the entire coast of southeast Australia. But much of the coastline is not sandy (about 38%, see Table 2.2). The major part of the non-sandy coast is comprised of rocks, especially in south and central New South Wales (see Section 2.1.1). Like the (sandy) seafloor adjacent to the beaches, the (sandy) seafloor in front of the rocky coast will be raised by a rise in sea level. But the amount of sand required for this rise cannot be fully provided by the rocky shores. Instead, this sand will be eroded from the sandy shores and delivered to the seafloor off the rocky coast by alongshore currents. This redistribution of sand between sandy and rocky shores is part of so-called sediment sharing: The interaction between coastal subsystems (beaches, tidal inlets, the upper and lower shorefaces, etc) that are different in terms of morphological behaviour (see Figure 3.4) (Cowell et al., 2003). Sediment sharing implies that coastal subsystems are coupled into one system and share a common pool of sediments. Hence, a change in one subsystem must cause corresponding changes in other subsystems.

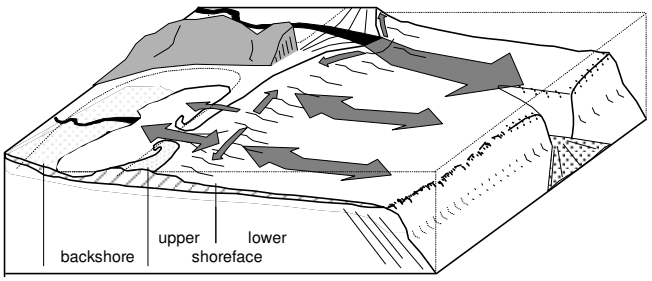

Figure 3.4. Sediment sharing between coastal subsystems (adapted from: Stive et al., 2008).

Due to sediment sharing, the rocky and sandy shores of southeast Australia more or less share a common pool of sand. When sea level rises, the amount of sand lost on the sandy shores will be such that the seafloor can be raised along the entire coastline, and not just in front of the sandy part. In other words, the predicted sand losses due to sea level rise are not decreased by the fact that part of the southeast Australian coastline is rocky. This means that the raising the profile method should be applied to the entire coastline of southeast Australia and not just the sandy part. It is noted that the extra sand losses on the sandy shores are likely to cause a larger coastal recession than predicted by the Bruun Rule.

3.2.3 Extended Raising the Profile Method

Like the Bruun Rule (see Section 3.1), the raising the profile method, Eq. (3.7), does not account for sand losses to estuaries or the alongshore drift, nor for variable sediment properties. However, as explained in the introduction of this chapter and in Section 3.2.1, these sediment losses are expected to be very small compared to the offshore sand losses due to sea level rise and are beyond the scope of

this study. Therefore the sediment budget term G_B (which accounts for the extra sand losses) from the generalized Bruun Rule, Eq. (3.5), is not considered in this study (i.e. $G_B = 0$). With regard to variable sediment properties, the dimensionless factor p (which accounts for variable sediment properties) from the generalized Bruun Rule is set as $p = 1$. This assumption is based on the fact that in the cross-shore direction the sands on the shoreface of southeast Australia have very uniform properties (Cowell et al., 1999). The above means that there is no need to extend the raising the profile method, Eq. (3.7), with the sediment budget term G_B nor the dimensionless factor p.

It is, however, required to extend the raising the profile method to accommodate for the presence of rocks on the seafloor. In New South Wales, a large proportion of the seafloor consists of rocky reefs instead of sand (this topic will be addressed in more detail in Section 3.5). As explained in Section 3.1.2, the presence of rocks does not affect the Bruun Rule's applicability and it is assumed that this holds for the applicability of the raising the profile method as well. But, since the rocks on the seafloor are not affected by sea level rise, the rocky part of the shoreface does not play a part in the adjustment of the profile to the new water level. Therefore, the rocky part must be excluded from the area that is being raised under the rising sea level. To achieve this, a dimensionless factor ρ is added to Eq. (3.7) to account for the presence of rocks. This results in the extended raising the profile method:

$$V = As(1-\rho) \tag{3.8}$$

with V = offshore sand losses, A = area being raised, s = future sea level rise, and ρ = proportion of rocks in the area being raised, with $0 \leq \rho \leq 1$. Despite adding the factor ρ, Eq. (3.8) will be referred to as the raising the profile method as well.

Consequently, calculating the future sand losses with the raising the profile method, Eq. (3.8), requires three input parameters: (i) The size of the area being raised, A; (ii) the amount of sea level rise by the year 2100, s; and (iii) the proportion of rocks on the seafloor off the southeast Australian coast, ρ. As explained in Section 1.3, the approach of this study is probabilistic. Therefore each of these three parameters will be treated as a stochastic variable with a certain probability distribution. In this way, applying the raising the profile method will result in a joint probability distribution for the estimated sand losses on the coast of southeast Australia due to sea level rise in the 21st century. In Section 3.3 to 3.5 each of the three input parameters will be quantified.

3.3 The Seafloor Area Being Raised by Sea Level Rise

The first input parameter of the raising the profile method, Eq. (3.8), is the area A of the seafloor that is being raised under a rising sea level. This area is bounded by the coastline and the offshore limit of the active beach profile (the part of the shoreface that is affected by sea level rise), which is often referred to as the closure depth. The concept of the closure depth will be explained in Section 3.3.1. As the closure depth is associated with a range of uncertainty, Section 3.3.2 proposes a probability distribution to manage this uncertainty. With these data, the size of the area being raised by sea level rise has been determined, which is the topic of Section 3.3.3. Section 3.3.4 presents the conclusions from Section 1.1.

A distinction will be made between the coast of New South Wales and the coast of southeast Queensland. This is because both states are rather different in terms of geomorphology (e.g.

predominantly short embayed beaches in New South Wales vs. predominantly long unsheltered beaches in southeast Queensland; see Sections 2.1.1 and 2.2.1) and in terms of coastal management practices (e.g. beach nourishment with offshore sand in southeast Queensland vs. a ban on offshore sand extraction in New South Wales; see Sections 2.3 and 4.1.1).

3.3.1 Closure Depth

Inner and Outer Closure Depths

The closure depth denotes the maximum depth of cross-shore sediment transport (the parameter h in Eq. (3.3)). There are several approaches to finding the value of the closure depth, such as comparing bottom profile surveys, sediment analyses and empirical formulations (Bruun, 1988; Ranasinghe et al., 2007). As detailed data of bottom profiles and sediment sizes are not available for the major part of the southeast Australian coast, the approach followed in this study is to use empirical formulations to estimate the closure depth.

The original formulation of the closure depth was developed by Hallermeier (1981) and represents the maximum water depth, h_c, where erosion and accretion result in measurable vertical changes of the seabed (i.e. larger than 0.3 m, which is approximately the resolution of standard survey techniques), in a typical year (i.e. a year with average storm conditions):

$$h_c = 2\bar{H}_s + 11\sigma \tag{3.9}$$

with $\bar{H}_s$ = mean annual significant wave height[5], and σ = standard deviation of $\bar{H}_s$ (Cowell et al., 1999; Cowell et al., 2006). The closure depth h_c is referred to as the inner or annual closure depth, because it approximates the adjustment of the profile in the period of a single year to a storm with a return interval of one year. Sand movements, though, still occur beyond the inner closure depth, but within a typical year both the volume of these movements and the changes they cause to the shoreface are negligible (i.e. they are not measurable) (Leatherman, 1989; Titus et al., 1991; Cowell et al., 1999; Ranasinghe et al., 2007).

Over longer periods of time or with the occurrence of severe storms (i.e. with a return interval of more than one year), sediment will be transported well beyond the inner closure depth in much larger quantities than within a typical year, resulting in measurable vertical changes to the shoreface much further offshore. This means that the value of the closure depth increases with the timescale considered. Therefore, besides the inner closure depth, Hallermeier developed a much deeper offshore limit to the active beach profile: The estimated limiting depth of significant cross-shore sand transport by waves in a typical year, h_i:

$$h_i = \left(\bar{H}_s - 0.3\sigma\right)\bar{T}_s\left(g/5{,}000D\right)^{1/2} \tag{3.10}$$

with $\bar{T}_s$ = mean annual significant wave period, g = gravitational acceleration, and D = characteristic grain size for the sand on the shoreface (Cowell et al., 1999; Cowell et al., 2006). The limiting depth h_i is also referred to as the outer closure depth, the ultimate limit for active sand movement or the

[5] The significant wave height is defined as the average height of the highest third part of the waves in a wave field.

wave base, beyond which "wave action ceases to stir sediments" (Bruun, 1988; Cowell et al., 1999; Ranasinghe et al., 2007).

Time Dependency

From the above it is clear that the inner closure depth h_c relates to relatively rapid changes of the seafloor and hence defines the seaward limit of the most active part of the shoreface, the upper shoreface (see Figure 3.5). The outer closure depth h_i is related to the behaviour of the shoreface on much larger timescales (in the order of decades) and defines the seaward limit of the lower shoreface. As sea level rise is a long-term process, it is suggested by some authors that the outer closure depth should be used as the limiting depth to the active beach profile in applications of the Bruun Rule or the raising the profile method. However, in practice it seems that the inner closure depth is applied in most cases (Cowell et al., 2006; Ranasinghe et al., 2007).

These different approaches may relate to the uncertainty regarding the response or adjustment time of the shoreface to a rise in sea level. As explained in Section 3.1.1, heavy storms are needed to redistribute sediment across the shoreface in response to sea level rise. Therefore, the occurrence of such storms controls the rate of profile adjustment (Hands, 1983). Titus and Greene (1989) proposed an alternative formulation for the raising the profile method that incorporates the profile adjustment time. Applying this formulation, however, would require detailed data of profile adjustment times and the predicted rate of sea level rise (i.e. the amount of sea level rise per year), which are both not available (see also Section 3.4 on sea level rise).

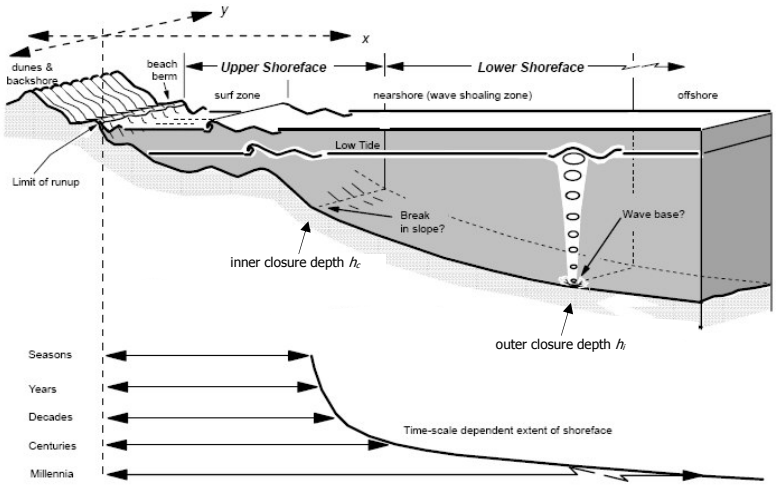

Figure 3.5. The shoreface (adapted from: Cowell et al., 1999).

Values of the Closure Depth in Southeast Australia

The values of the inner and outer closure depths in southeast Australia are presented in Table 3.1. The values of the inner closure depth h_c have been determined with Eq. (3.9) and the wave data that are listed in Table 3.1. The values of the outer closure depth h_i have been obtained from Cowell et al. (1999) and are supported by research from Bruun (1988) and Komar (1976) [6]. Bruun (1988) defined the ultimate limit of active movement as $h = 3.5H_{bs}$, with H_{bs} being the significant breaker wave height for storm conditions with a return interval in the order of decades. In southeast Australia $H_{bs} \approx$ 10 m, which, with the above expression, yields a limiting depth of $h \approx 35$ m. Komar (1976) defined

[6] Eq. (3.10) has not been applied to determine the outer closure depth in the present study, as there are no unambiguous values of the characteristic grain size for the shoreface, D, available.

the wave base as $h = L_o/4$, where L_o is the deepwater wave length, which in turn is defined as $L_o = gT^2/2\pi$. Substituting for the wave period T the value of $\bar{T}_s$ = 9.5 s (which is the mean annual significant wave period in Sydney; see Table 3.1), Komar found the wave base to be h = 35.2 m. Both values of h are in good agreement with the values of h_i for Sydney and Moruya that are listed in Table 3.1.

Table 3.1. Wave data ($\bar{H}_s$, σ and $\bar{T}_s$; see Eqs. (3.9) and (3.10) for explanation) and the inner (h_c) and outer (h_i) closure depths in southeast Australia, based on Hallermeier's estimates (wave data and h_i from: Cowell et al., 1999; h_c from: Eq. (3.9)).

location	$\bar{H}_s$	σ	$\bar{T}_s$	h_c	h_i
southeast Australia	1.5 m	1.2 m	NA	16.2 m	NA
Byron Bay	1.6 m	1.2 m	9.6 s	16.4 m	46.2 m
Sydney	1.6 m	1.2 m	9.5 s	16.4 m	36.3 m
Moruya	1.5 m	1.2 m	9.5 s	16.2 m	36.0 m

3.3.2 Probability Distribution

Bounding Values

In this study, the uncertainty regarding the limiting depth of the active beach profile that has been explained above, is managed by assigning a probability distribution function (pdf) to this parameter. The pdf is bounded by Hallermeier's inner and outer closure depths (see Table 3.1), which is a similar procedure as the one followed by Cowell et al. (2006). Although the accuracy of Hallermeier's estimates of the inner and outer closure depths is rather uncertain, these estimates are deemed to be sufficiently accurate for practical purposes (Cowell et al., 1999). For the lower bound of the limiting depth of the active beach profile a value of h_c = 16 m is adopted, which is the estimate of the inner closure depth based on wave data representative of the entire southeast Australian coast (see Table 3.1). The upper bound of the limiting depth is set as h_i = 40 m, because this value lies between the values of the outer closure depth estimated for south and central New South Wales (Moruya and Sydney respectively) and the value estimated for north New South Wales (Byron Bay; see Table 3.1). Also, the value of h_i = 40 m is chosen for practical reasons, as the 40 m depth contour is indicated on the bathymetric charts that are used to estimate the size of the area between the coastline and the offshore limit of the active beach profile (see Section 3.3.3). The upper bound of h_i = 40 m is assumed to be representative of the entire coast of New South Wales and southeast Queensland.

Probability Distribution Function

The actual value of the limiting depth of the active beach profile lies somewhere on the lower shoreface between the bounding values h_c = 16 m and h_i = 40 m, but where exactly is unknown, because the response of the lower shoreface to a rise in sea level is highly uncertain. On the one hand, as sea level rise is a long-term process, it is likely that the projected rise of sea level will affect the lower shoreface down to a water depth that lies closer to the outer closure depth h_i than to the inner closure depth h_c. In addition, since the outer closure depth is not the absolute limit of sand transport, but merely the limit of significant volumes of transport, cross-shore sand transport does occur beyond the 40 m depth contour. This has, for example, been demonstrated by recent studies in Australia that have shown interaction between the upper and lower shorefaces down to water depths of at least 45 to 50 m (Cowell et al., 2001, 2006).

On the other hand, it has been found that parts of the lower shoreface may act as a sediment source and supply sand to the beaches. Besides, changes on the lower shoreface are generally slow and small and, hence, the response of the lower shoreface to a rise in sea level has a lag time on the order of decades. These notions support adopting the inner closure depth h_c as the limiting depth of the active beach profile, which is the most common approach in the engineering practice (Cowell et al., 2001, 2006; Stive et al., 2008).

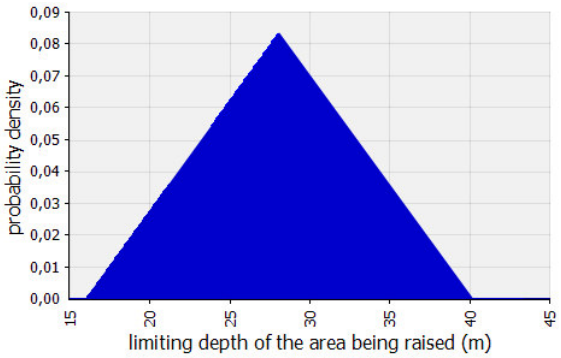

Figure 3.6. Triangular pdf for the limiting depth of the area being raised.

The uncertainty associated with the impact of sea level rise on the lower shoreface is managed by adopting a triangular pdf for h, which is a convenient approximation as it requires the definition of only three parameters: The lower and upper boundaries and the modal value (i.e. the most likely value, coinciding with the peak of the triangular pdf). By default, in the absence of detailed information, the modal value is assumed to lie midway between the lower and upper boundaries (Cowell et al., 2006). The resulting pdf is a symmetrical triangular pdf with a lower bound of h = 16 m, an upper bound of h = 40 m and a modal value of h = 28 m (see Figure 3.6).

3.3.3 Size of Area Being Raised

Measurements

Having defined the offshore limit of the area that is being raised by sea level rise, the size of this area can be estimated with the use of bathymetric charts. For this purpose, the bathymetric charts of the southeast Australian coast produced by the Division of National Mapping (scale 1:250,000) have been digitalized. Subsequently the area between the coastlines of New South Wales and southeast Queensland and the 40 m depth contour (corresponding to the upper bound of the offshore limit of the area being raised) has been determined with the use of GIS software. The results of this work are presented in Table 3.2. The measured values of the coastline lengths are almost equal to the values listed in Table 2.2 (1,590 km in New South Wales and 750 km in southeast Queensland), which have been obtained from the beach guides of New South Wales and southeast Queensland (Short, 1993, 2000). The slight deviations between these values can probably be attributed to inaccuracies in the bathymetric charts and inaccuracies in the procedure of digitalizing the charts and excluding the estuaries, lagoons and islands from the area that is being raised. The measured areas between the coastline and the 40 m depth contour in New South Wales and southeast Queensland are almost similar in size, despite the much longer coastline in New South Wales. This can be attributed to the fact that a large part of the coast of southeast Queensland consists of sandy lowlands with extensive sand shoals (see Section 2.1.1), which have a gentle slope compared to the relatively steep continental

shelf of New South Wales. Average values of the distance between the mainland and the 40 m depth contour are about 8.5 km in southeast Queensland, 4 km in northern New South Wales and 2 km in southern New South Wales. The values for New South Wales are in agreement with the fact that the inner continental shelf of New South Wales is steeper and narrower in the south than in the north (Roy, 2001).

Table 3.2. Measured coastline data in southeast Australia. The presented values do not include estuaries, lagoons and small islands.

state	coastline length	area between coastline and 40 m depth contour
New South Wales	1,575 km	5,282 km^2
southeast Queensland	752 km	4,874 km^2
total	2,327 km	10,156 km^2

Expressions

Since the 40 m depth contour represents the upper bound of the offshore limit of the active beach profile, the measured areas listed in Table 3.2 denote the *maximum possible* areas that are being raised under a rising sea level. In order to determine the area that is being raised if the limiting depth of this area is less than 40 m, it is assumed that the cross-shore profile of the southeast Australian shoreface is, on average, in equilibrium and follows the shape described by Eq. (3.1). This assumption is supported by two findings: First, most beaches in New South Wales have been stable for a long time (see Section 2.2.2). Second, as the raising the profile method is applied to the entire southeast Australian coast, the net alongshore sediment transport is negligible (see Section 3.2.1). Together with the second assumption of the Bruun Rule (of which the raising the profile method is a corollary) that there is no cross-shore sediment transport beyond the landward and offshore limits of the beach profile (see Section 3.1.1), this means that there is a conservation of sediment within the entire beach profile of the southeast Australian coast. On average, therefore, it may be assumed that the shoreface of southeast Australia is in equilibrium.

Apart from these considerations, any development of an equilibrium profile would not be disturbed by the presence of rocks (see Section 3.1.2) and the validity of the Bruun Rule (and hence the raising the profile method) for non-equilibrium profiles is currently being researched (Cowell, pers. comm.).

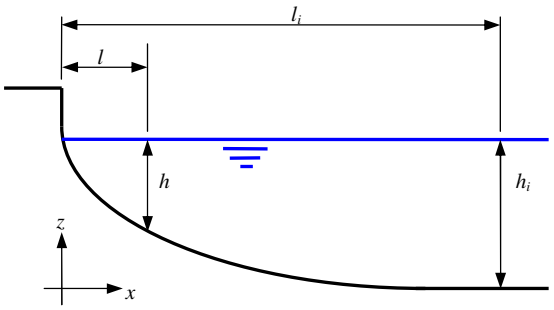

Figure 3.7. Cross-shore profile and closure depths.

Following the equilibrium profile described by Eq. (3.1), the offshore distance l to an arbitrary closure depth h and the offshore distance l_i to the outer closure depth h_i (see Figure 3.7) can be expressed as:

$$l = \left(\frac{h}{m} \right)^{3/2} \tag{3.11}$$

$$l_i = \left(\frac{h_i}{m} \right)^{3/2} \tag{3.12}$$

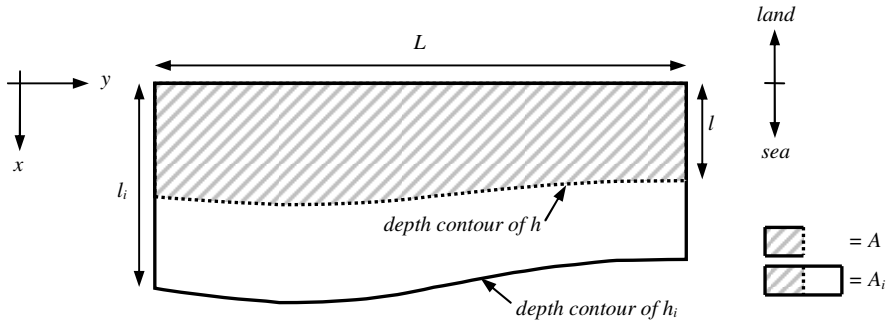

Figure 3.8. Offshore areas between coastline and closure depths (schematic view from above).

From Eqs. (3.11) and (3.12) follows the relation between l and l_i:

$$\frac{l}{l_i} = \frac{(h/m)^{3/2}}{(h_i/m)^{3/2}} = \left(\frac{h}{h_i} \right)^{3/2} \tag{3.13}$$

Note that, like the Bruun Rule, Eq. (3.4), Eq. (3.13) does not contain the profile scale parameter m, as the profile's shape is accounted for by the relation between h_i and l_i. As the offshore distances l and l_i vary along the coast with the alongshore distance y, the area A between the coastline L and an arbitrary closure depth h at an offshore distance l can be approximated as (see Figure 3.8):

$$A = \int_0^L l(y)\,dy \tag{3.14}$$

Substituting Eq. (3.13) into Eq. (3.14) yields:

$$A = \int_0^L \left[l_i(y) (h/h_i)^{3/2} \right] dy = (h/h_i)^{3/2} \int_0^L l_i(y)\,dy \tag{3.15}$$

The area between the coastline L and the outer closure depth l_i, i.e. the maximum possible area being raised as sea level rises, is denoted by A_i. This area is equal to the term $\int_0^L l_i(y)\,dy$ in the right hand side of Eq. (3.15). Therefore Eq. (3.15) can be written as:

$$A = A_i (h/h_i)^{3/2} \tag{3.16}$$

Substituting the measured values of A_i from Table 3.2 and the outer closure depth h_i = 40 m into Eq. (3.16) gives expressions for the offshore areas in both New South Wales and southeast Queensland that are being raised under a rise of sea level, as a function of the limiting depth of the active beach profile h:

New South Wales: $$A_{NSW} = 5,282 \cdot 10^6 \left(\frac{h}{40} \right)^{3/2} \quad (3.17)$$

Southeast Queensland: $$A_{SQld} = 4,874 \cdot 10^6 \left(\frac{h}{40} \right)^{3/2} \quad (3.18)$$

with 16 m $\leq h \leq$ 40 m.

3.3.4 Conclusions

The area being raised as a result of a rise in sea level depends on the limiting depth of the active beach profile (often referred to as the closure depth). In this study the limiting depth is defined by a symmetrical triangular probability distribution function with a lower bound of 16 m, an upper bound of 40 m and a modal value of 28 m. Based on the assumption that the southeast Australian shoreface is, on average, in equilibrium, the areas being raised in New South Wales and southeast Queensland can be estimated with Eqs. (3.17) and (3.18). This approach is distinctly different from the approach commonly used in coastal management problems regarding sea level rise, which is to apply the Bruun Rule or the raising the profile method with just the lower bound of the limiting depth, resulting in a single, low estimate for shoreline erosion due to sea level rise. Such a result has a high probability of being exceeded and would therefore be inappropriate in terms of risk-aversion and risk-based planning in coastal management (Cowell et al., 2006, 2007).

3.4 Sea Level Rise

The second input parameter of the raising the profile method, Eq. (3.8), is the amount of future sea level rise, *s*. This section first addresses the recent accelerated rise in sea level (Section 3.4.1). Future global sea level rise projections are presented in Section 3.4.2. As sea level rise varies spatially, the predicted amount of local sea level rise in southeast Australia is presented in Section 3.4.3. To manage the range of uncertainty associated with future sea level rise projections, in Section 3.4.4 a probability distribution function is assigned to the amount of sea level rise. Section 3.4.5 presents the conclusions on the basis of Sections 3.4.1 to 3.4.4.

3.4.1 Recent Sea Level Rise

Tide gauge data indicate that during the 20th century global sea level has risen by 10 to 20 cm (or 1 to 2 mm/year) on average (see Figure 3.9), which is considerably faster than the average rate of sea level rise in the preceding centuries (about 0.1-0.5 mm/year). The main contributions to this rise in sea level are from the thermal expansion of the oceans, the melting of glaciers and the melting (or growth due to increased snowfall) of the polar ice sheets on Greenland and Antarctica[7]. Given the slow response of the polar ice sheets to climatic changes, the ice sheets of Greenland and Antarctica are probably

[7] It is noted that the melting of polar sea ice has no effect on the sea level.

still adjusting to the temperature increase that followed the last ice age. Other contributions to sea level rise include the thawing of permafrost and changes in the storage of ground and surface water.
Recent satellite altimeter data show that the present rate of sea level rise is higher than the average rate in the 20th century: 3.1 mm/year on average between 1993 and 2003. Although this faster rate could reflect decadal variations in sea level, there is now strong evidence that the rate of global sea level rise will continue to accelerate in the 21st century due to global warming. (IPCC, 2001; Walsh, McInnes and Abbs, 2002; Walsh et al., 2004; Ranasinghe et al., 2007; IPCC, 2007).

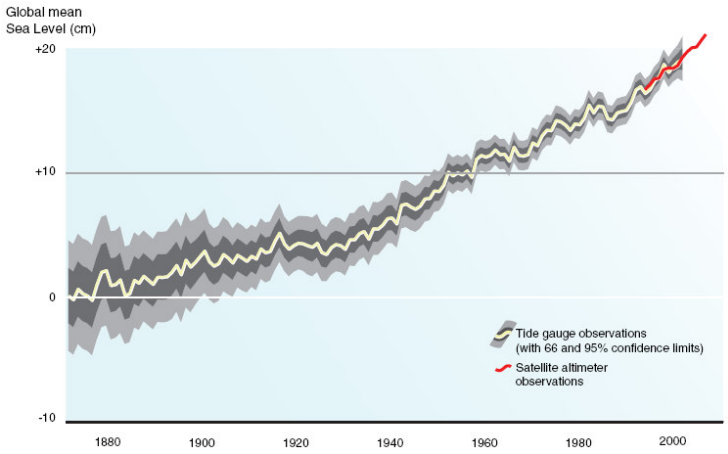

Figure 3.9. Global average sea level changes from 1870 to 2006 (Church et al., 2007).

3.4.2 Global Sea Level Rise Projections

IPCC Sea Level Rise Projections for the 21st Century

The most authoritative body on global warming and climate change is the Intergovernmental Panel for Climate Change (IPCC) (Walsh et al., 2004; Church et al., 2007; Ranasinghe et al., 2007). The assessment reports by the IPCC include projections of future sea level rise, which are based on future climate change estimates. These climate change estimates are computed with a wide range of climate models that follow multiple scenarios of the future emission of greenhouse gases. Given the incomplete understanding of the interaction between the concentration of greenhouse gases in the atmosphere, the earth's climate and sea level rise, and the uncertainty regarding the future amount of greenhouse gases, the prediction of future sea level rise is associated with a considerable range of uncertainty.
The range of global average sea level rise predicted by the IPCC in its latest assessment, the Fourth Assessment Report (AR4), is 18-59 cm by 2090-2099 compared to 1980-1999 (see Figure 3.10). This range does not include the full effects of possible rapid changes in the ice sheet dynamics. Very recent observations suggest that dynamical processes related to ice flow could increase the vulnerability of the polar ice sheets to global warming, resulting in unexpectedly high rates of sea level rise (IPCC, 2007; Rahmstorf, 2007). To account for the possible acceleration in ice cap decay, the AR4 recommends an additional allowance of 10-20 cm, resulting in a maximum range of sea level rise by 2090-2099 of 18-79 cm. The AR4 states that 79 cm is not to be considered an upper bound for sea level rise in the 21st century though, because the understanding of the ice sheet dynamics and other mechanisms that drive sea level rise is too limited to provide an upper limit. For the same reason, the AR4 does not assess the likelihood of various levels of sea level rise, nor does it give a best estimate.

Finally, it is important to note that the AR4 does not make any mention of the annual rate of sea level rise in the 21st century (IPCC, 2007).

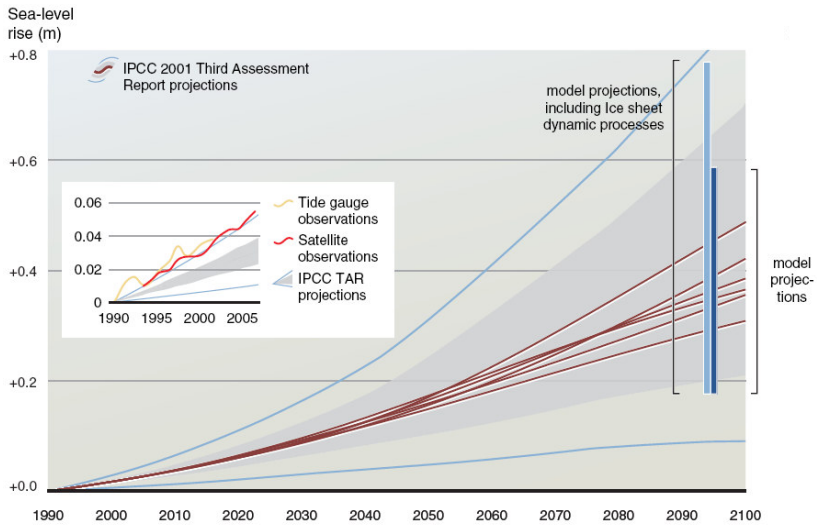

Figure 3.10. Sea level rise projections for the 21st century by the IPCC. The depicted Third Assessment Report (TAR) projections do not include additional uncertainties associated with land-ice changes, which would lead to a range of 9-88 cm sea level rise by 2100 (see Table 3.3) (Church et al., 2007).

Other Sea Level Rise Projections for the 21st Century

The uncertainty in estimating future sea level rise is reflected by recent studies that predict other values than the IPCC. These studies include sea level rise projections by Webster et al. (2003) and Rahmstorf (2007), which are shown in Table 3.3, together with the IPCC's latest (2007) and previous (2001) assessment results. The ranges of the IPCC's projections are becoming narrower with each assessment, thanks to a better understanding of sea level rise contributions and improving models. Webster et al. (2003) project sea level rise due to thermal expansion of the oceans and the melting of glaciers alone, thus ignoring the contribution from the polar ice sheets. The projections by Rahmstorf (2007) are based on the observed relation between the temperature increase and the rise of sea level in the 20th century.

Table 3.3. Recent projections of global average sea level rise by the end of the 21st century (from: IPCC, 2001; Webster et al., 2003; IPCC, 2007; Rahmstorf, 2007).

value	IPCC (2001)	Webster (2003)	Rahmstorf (2007)	IPCC (2007)
low	9 cm	15 cm	50 cm	18
middle	48 cm	30-45 cm	95 cm	NA
high	88 cm	87 cm	140 cm	59-79 cm

In addition to the above sea level rise projections, a very recent study by the Deltacommittee (2008) in the Netherlands recommends an upper value of 65 to 130 cm sea level rise by the end of the 21st century.

Longer Term Sea Level Rise

Due to their large thermal inertia, the oceans respond slowly to temperature changes. Hence, the oceans are currently still warming up as a result of past greenhouse gas emissions and it is only after about 2050 that the different greenhouse gas emission scenarios used by the IPCC will cause

substantial differences in sea level rise projections. After 2100, sea level rise will depend strongly on the present greenhouse gas emissions, as global warming and the thermal expansion of the oceans are projected to continue well beyond 2100, even if greenhouse gas concentrations were to be stabilised within the 21st century (Walsh, McInnes and Abbs, 2002; Walsh et al., 2004; IPCC, 2007).
As mentioned above, the response of the polar ice sheets to climatic changes is also very slow. Hence, they are likely to continue to respond to global warming and contribute to sea level rise for the next several thousand years, even if the climate is stabilised. In case the predicted higher temperatures will be sustained for millennia, the Greenland ice cap may virtually disappear, leading to a rise in sea level of about 7 m. The Antarctic ice sheet is likely to remain too cold to disintegrate completely (which would raise sea level by approximately 60 m) and may even gain mass due to increased snowfall. There are some concerns over the instability of the west Antarctic ice sheet though, but a "collapse" of this ice sheet (which could result in a significant increase in sea level rise) is highly unlikely to occur during the 21st century (IPCC, 2001; Walsh et al., 2004; IPCC, 2007; Rahmstorf, 2007; Church et al., 2007).

3.4.3 Local Sea Level Rise

Due to ocean circulations patterns and changes in ocean currents caused by global warming, the thermal expansion of the oceans is not globally uniform and, hence, nor is sea level rise. A recent study by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) suggests that future sea level rise values along the coast of southeast Australia will be slightly higher than the IPCC's latest projections. The CSIRO's climate models predict that global warming will strengthen the relatively warm East Australian Current (see Section 2.1.2), resulting in an additional warming of the sea surface temperatures in southeast Australia. This will cause a local additional rise in sea level of 0-12 cm in the second half of the 21st century (McInnes et al., 2007).
In addition to these regional variations in sea level rise, relative sea level changes (i.e. compared to the mainland) also depend on land subsidence or uplift. Widespread land subsidence or uplift are caused by geological effects, i.e.: Tectonic land movements and the slow, ongoing adjustment of the earth's crust to the melting of the large ice sheets after the last ice age. Local land subsidence often has man-made causes, such as the extraction of groundwater, oil and gas (IPCC, 2001; Walsh et al., 2004; Ranasinghe et al., 2007; IPCC, 2007).

3.4.4 Probability Distribution

Bounding Values
From the above discussion it is clear that for various reasons there is great uncertainty associated with future sea level rise. As with the first input parameter of the raising the profile method (the area being raised), this study manages the uncertainty by assigning a pdf to the amount of sea level rise in the 21st century. Firstly, this requires defining the range of future sea level rise values. Of the different sea level rise projections discussed in this section, the IPCC's assessments are considered to be the 'most authoritative' (Walsh et al., 2004; Church et al., 2007; Ranasinghe et al., 2007) and the 'best scientific estimate' (Walsh, McInnes and Abbs, 2002), as they provide the most comprehensive studies of climate change and sea level rise available. Hence, the IPCC's sea level rise projections are widely applied in coastal studies (e.g. Cowell et al., 2006; Ranasinghe et al., 2007) and coastal planning. The

values of sea level rise currently recommended by the New South Wales government to coastal managers are based on the AR4 projections of 18-59 cm sea level rise by the end of the 21st century, plus the allowance for uncertainties in ice sheet dynamics (max 20 cm) and the local effects of the East Australian Current (max 12 cm). The resulting range of sea level rise values recommended by the New South Wales government is 18-91 cm with a middle value of 55 cm (Cowell, pers. comm.).
However, due to the limited understanding of some of the mechanisms that affect global sea level (such as the polar ice sheet flow), the AR4 states that larger values than the predicted high value of 79 cm (91 cm in southeast Australia) cannot be excluded. As mentioned above, this possibility is confirmed by the recommendations of the Deltacommitte (2008) in the Netherlands and Rahmstorf (2007) that state that the maximum values of sea level rise by the end of the 21st century are 130 cm and 140 cm respectively.
Land subsidence or uplift in southeast Australia are not taken into account in this study. Detailed information on these phenomena is unavailable, but it is very likely that local land subsidence is negligible compared to the amount of sea level rise, because the substrate of the coastal regions of southeast Australia consists predominantly of rock (see Section 2.1.1). Widespread land subsidence in the east Australian region is also very small: 2 cm on the Gold Coast by 2050 (Walsh et al., 2004).
Based on the above considerations, the range of future sea level rise values adopted in this study is the range recommended by the New South Wales government (18-91 cm by 2090-2099 relative to 1980-1999), without excluding values larger than 91 cm.

Probability Distribution Function

The adopted range of future sea level rise values partially sets the requirements for defining the shape of the pdf for sea level rise, which is the second step in assigning a pdf to this parameter. Fitting a pdf to sea level rise is rather arbitrary, because the AR4 (on which the New South Wales government recommendations are based) does not assess the likelihood of future sea level rise and because there is no consensus on assigning probabilities to future climate change and its impacts (Walsh et al., 2004). There are a number of facts, though, that help to define the shape of the pdf: (i) The AR4 does not mention the possibility of a rise in sea level by the end of the 21st century below 18 cm (IPCC, 2007); (ii) the extremes of the range of sea level rise values must be less probable than the more central estimates, since the range is the result of the combination of various components that each have a range of uncertainty (Walsh et al., 2004); and (iii) the future sea level rise projections by Webster et al. (2003) include pdfs, which are depicted in Figure 3.11.

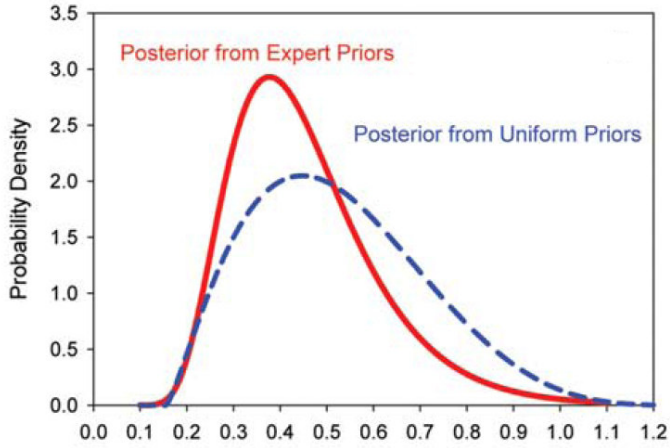

Figure 3.11. Pdfs of sea level rise projections for the 21st century by Webster et al. (2003). Expert and uniform priors refer to the method of determining the climate parameters' pdfs.

Following these three considerations, together with the above mentioned assumption there is no strictly defined upper limit for 21st century sea level rise, the shape of the pdf is more or less defined. It may be conveniently approximated by a Weibull distribution (again, it is emphasized that this is rather arbitrary, since there are several other distributions that would fit the proposed shape of the pdf, such as a Rayleigh or gamma distribution).

The third and last step in assigning a pdf to future sea level rise is to estimate the parameter values of the proposed Weibull distribution. An approach to achieving this is by assuming a symmetrical triangular pdf, which is common practice in case detailed information about a parameter's distribution is not available (Ranasinghe et al., 2007). Following the range of future sea level rise values recommended by the New South Wales government, the lower bound of the triangular pdf is set as 18 cm, the modal value as 55 cm and the upper bound as 91 cm. This pdf is used to determine the parameter values of the Weibull distribution, which is believed to reflect the uncertainty regarding future sea level rise more accurately. With the use of risk analysis software, a Kolmogorov-Smirnov (K-S) test is run to fit a Weibull pdf to the described triangular pdf (see Figure 3.12). This has resulted in a Weibull distribution with a shape parameter $\alpha = 2.6628$, a scale parameter $\beta = 0.41183$, a lower bound of 18 cm sea level rise and a modal value of approximately 55 cm sea level rise. The Weibull pdf has no theoretical maximum value.

As with defining the shape of the pdf for sea level rise, the procedure of determining the parameter values of the Weibull distribution is rather arbitrary. Still, the resulting pdf is based on well-founded scientific estimates of future sea level rise values.

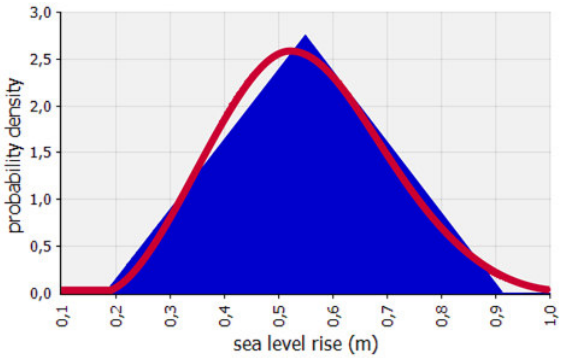

Figure 3.12. Triangular and fitted Weibull pdfs for 21st century sea level rise.

3.4.5 Conclusions

The global average sea level is rising at an increasing rate, mainly due to the thermal expansion of the oceans and the melting of glaciers and the polar ice caps. The greatest potential contributions to future sea level rise are by the Greenland and Antarctic ice sheets, but these contributions are also the most uncertain ones. Due to the large uncertainties associated with the mechanisms that drive sea level rise and the unknown future atmospheric greenhouse gas concentrations, predicting future sea level rise is not unambiguous. The 21st century sea level rise values adopted in this study are the values recommended by the New South Wales government (18 to 91 cm), which are based on the latest projections by the IPCC, the most authoritative body on climate change. The uncertainty associated with the range of values is managed by applying a Weibull probability distribution, which means the entire range of uncertainty associated with sea level rise is taken into account. This is a more appropriate approach than adopting just a single value (often the middle value), which is the most

commonly used approach in dealing with sea level rise. Finally, because of the slow response of the oceans and the polar ice sheets to climatic changes, sea level will continue to rise well beyond 2100, even if greenhouse gas concentrations were to be stabilised within the 21st century.

3.5 The Rocky Portion of the Seafloor

The third and last input parameter of the raising the profile method, Eq. (3.8), is the proportion of rocks on the seafloor, ρ, which is to be excluded from the area between the coastline and the limiting depth of the active beach profile, Eqs. (3.17) and (3.18). Field data of the presence of rocks on the southeast Australian seafloor are presented in Section 3.5.1. On the basis of these data a probability distribution function has been assigned to the rocky portion of the seafloor, which is explained in Section 3.5.2. As in Section 3.2, a distinction will be made between the coasts of New South Wales and southeast Queensland.

3.5.1 Field Data

The composition of the seafloor in southeast Australia is, for the most part, not known in detail, except for a number of locations where extensive bottom surveys have been carried out (e.g. Sydney and Byron Bay). But in general the coast becomes less rocky from south to north. The coast of south and central New South Wales features prominent rocky outcrops and reefs, while in north New South Wales and southeast Queensland these are virtually absent. In addition, the coast of southeast Queensland is fronted by sand shoals and sand islands (see Section 2.1.1 and Figure 2.7). Therefore it is a valid assumption that the seafloor of southeast Queensland is nearly 100% sandy (Cowell, pers. comm.), yielding $\rho \approx 0$.

In contrast, field surveys in New South Wales have shown that large parts of this state's seafloor consist of bedrock reefs (both isolated outcrops and reefs attached to rocky headlands) and that these are more common in the south than in the north: In the south, bedrock reefs make up more than 30% of the inner continental shelf of New South Wales (defined as the part of the seafloor between water depths of 20 to 60 m) and in the north less than 10% (Roy, 2001). Based on these findings, it is assumed that, like in southeast Queensland, the seafloor in the northernmost part of New South Wales is virtually 100% sandy ($\rho \approx 0$). In the south the seafloor is likely to be less than 70% sandy, but the lower bound for this value is unknown. It is assumed, somewhat arbitrarily but still founded, that the lower bound corresponds to the sandy part of New South Wales's coastline, which is approximately 62% (see Table 2.2) (Cowell, pers. comm.). This yields $\rho \approx 0.38$. It should be noted that obviously this assumption does not imply that the seafloor in front of a sandy coast is entirely sandy, nor that the seafloor in front of a rocky coast is entirely rocky.

3.5.2 Probability Distribution

The values of $\rho \approx 0$ and $\rho \approx 0.38$ define the lower and upper bounds of the proportion of rocks across the seafloor of New South Wales. The actual value of ρ varies along the coast and lies somewhere within the bounded range: In the north ρ is closer to 0, and in the south ρ is closer to 0.38. But since the raising the profile method is applied to the entire coast of New South Wales, an average value of ρ

for the entire coastline is required. Although the variation of ρ along the coastline of New South Wales is unknown, it is safe to assume that, as the coast becomes generally rockier from north to south, ρ becomes generally larger and increases from approximately 0 in the north to approximately 0.38 in the south in a more or less gradual fashion. Hence, it is assumed that the most likely value of ρ lies about midway between 0 and 0.38. This finding is supported by Roy (2001), who states that over 75% of the entire inner continental shelf of New South Wales is sandy, which suggests the average value of ρ for the entire coast is somewhat smaller than 0.25.

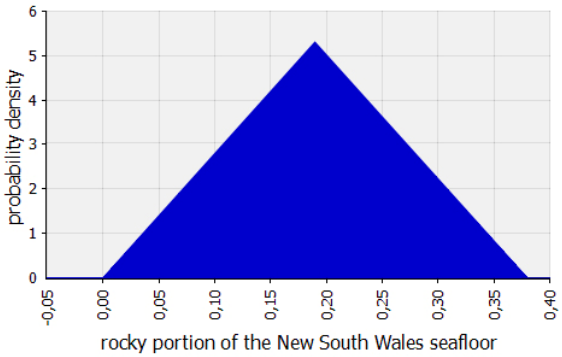

Figure 3.13. Triangular pdf for the portion of rocks on the New South Wales seafloor.

Like the first input parameter of the raising the profile method (the area being raised), the coastline-averaged value of the proportion of rocks on the seafloor of New South Wales, ρ_{NSW}, can be conveniently described by a symmetrical triangular pdf. This pdf has a lower bound of 0, an upper bound of 0.38 and a modal value of 0.19 (see Figure 3.13). It should be noted that this approximation does not account for the fact that values of ρ_{NSW} closer to 0 may outweigh values closer to 0.38, as the values close to 0 apply to the northern part of New South Wales where the area being raised is generally larger than in the southern part because of a gentler nearshore slope (see Sections 2.1.1 and 3.3.3). There is too little information about the alongshore variation of the offshore extent of the area being raised and the portion of rocks on the seafloor to properly evaluate this relation. To conclude, in southeast Queensland, the value of the proportion of rocks on the seafloor adopted in this study is simply $\rho_{SQld} = 0$.

3.6 Estimating the Future Sand Losses

With the presented input data of Sections 3.3, 3.4 and 3.5, the raising the profile method, Eq. (3.8), can be applied to the coast of southeast Australia to predict the 21st century sand losses due to sea level rise. The expressions that are used for this purpose are presented in Section 3.6.1, together with an overview of the input data. The expressions are evaluated by means of Monte Carlo-type simulations, which are explained in Section 3.6.2. The results of the simulations are presented in Section 3.6.3 and discussed in Section 3.6.4. The sensitivity of the simulation results to changes in the values of the input parameters is analysed in Section 3.6.5.

In correspondence with the distinction between New South Wales and southeast Queensland that has been discussed in the introduction of Section 3.3, the future sand losses are calculated separately for each state.

3.6.1 Expressions and Input Data

The sand losses due to sea level rise are estimated with the raising the profile method, Eq. (3.8). Substituting into Eq. (3.8) the expressions for the offshore areas in New South Wales and southeast Queensland that are being raised when sea level rises, Eqs. (3.17) and (3.18), gives expressions for the sand losses due to sea level rise in each state (in m^3):

New South Wales: $$V_{NSW} = 5,282 \cdot 10^6 \, s \left(1 - \rho_{NSW}\right) \left(\frac{h}{40}\right)^{3/2} \tag{3.19}$$

Southeast Queensland: $$V_{SQld} = 4,874 \cdot 10^6 \, s \left(\frac{h}{40}\right)^{3/2} \tag{3.20}$$

The values and the pdfs of the input parameters s (the amount of sea level rise in the 21st century), ρ_{NSW} (the average proportion of rocks on the seafloor of New South Wales) and h (the limiting depth of the area being raised) are listed in Table 3.4.

Table 3.4. Input parameters of Eqs. (3.19) and (3.20) (see Sections 3.3 to 3.5 for details).

parameter	low value	modal value	high value	pdf
s	0.18 m	0.55 m	n/a	Weibull (2.6628, 0.41183)
ρ_{NSW}	0	0.19	0.38	triangular
h	16 m	28 m	40 m	triangular

3.6.2 Simulation Settings

Eqs. (3.19) and (3.20) are evaluated with risk analysis software in order to combine the pdfs of the various input parameters and to determine the joint pdf for the estimated sand losses. All simulations run in this study use the Latin Hypercube sampling method, which is a Monte Carlo-type technique. Latin Hypercube sampling divides a pdf into intervals of equal likelihood and randomly draws a value from each interval. The number of intervals is equal to the number of iterations, and with every iteration a different interval is sampled. Thus each interval is represented in the sampled set of values. This semi-random approach ensures the sampled set reflects the input distribution more accurately and in fewer iterations than the original Monte Carlo sampling technique, which selects input values completely at random. Therefore, compared to the original Monte Carlo technique, Latin Hypercube sampling is more efficient and provides more accurate estimates of the tails of a distribution. This is of particular importance when a distribution includes low probability outcomes that could have a major impact on the results, such as the risk created by the possibility of an extremely high amount of sea level rise (e.g. Titus and Narayanan, 1995).

The stochastic input parameters of Eqs. (3.19) and (3.20) are sampled independently, which means any possible correlation between them is ignored. There might be a correlation between the limiting depth of the area being raised and the rocky portion of the seafloor (e.g. at a larger distance from the coast there might be less bedrock reefs), but there is too little information to quantify this relation and it is likely that its effect would be small compared to the considerable uncertainty already associated with these input parameters. Furthermore, sea level rise has no effect on the limiting depth of the area

being raised, nor on the rocky portion of the seafloor. Hence it is safe to assume all three input parameters are uncorrelated.
The number of iterations carried out in each simulation is 1,000. This number was found to produce a high degree of convergence between the input distributions and the sampled values: The sampled sets showed less than 1% deviation from the inputs distributions' mean, median and standard deviation values.

3.6.3 Results

The future sand losses due to sea level rise, as resulting from the simulations, are presented in Figure 3.14 (New South Wales) and Figure 3.15 (southeast Queensland) by means of cumulative probability curves. These curves allow for interpreting the results in terms of risk levels, i.e. the probability that a certain value of the estimated sand losses is being exceeded before the year 2100. For reasons of efficiency, the results reflect the outcome of a single simulation (with 1,000 iterations), rather than the outcomes of multiple simulations. Although each Latin Hypercube simulation draws different values from the input parameters and, hence, produces a different set of results, these differences are very small: After running 100 different simulations, it was found that for a 50% risk level, 90% of the sampled values deviate less than ± 2% from the values presented in Figure 3.14 and Figure 3.15. For risk levels of 10% and 1%, these deviations increase slightly to ± 3% and ± 6% respectively.

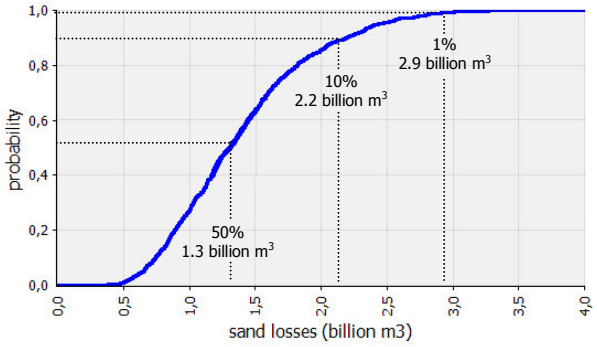

Figure 3.14. Sand losses due to sea level rise in the 21st century in New South Wales.

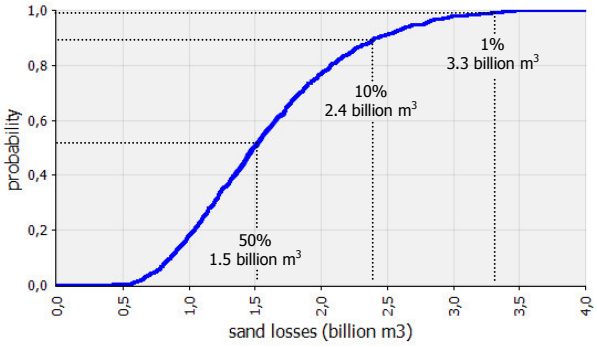

Figure 3.15. Sand losses due to sea level rise in the 21st century in southeast Queensland.

The three risk levels that are marked in the graphs, 50%, 10% and 1%, are listed in Table 3.5. It is noted that there is no (theoretical) maximum value of the future sand losses, since an upper limit for sea level rise has not been defined in this study (see Section 3.4.4 and Table 3.4).

Table 3.5. Selected values of estimated sand losses due to sea level rise in the 21st century in southeast Australia.

state	**risk level 50%**	**risk level 10%**	**risk level 1%**
New South Wales	1.3 billion m^3	2.2 billion m^3	2.9 billion m^3
southeast Queensland	1.5 billion m^3	2.4 billion m^3	3.3 billion m^3

3.6.4 Discussion of the Results

The results presented in Section 3.6.3 show that the median sand losses due to sea level rise in the 21st century are 1.3 billion m^3 in New South Wales and 1.5 billion m^3 in southeast Queensland. These

values have a 50% probability of being exceeded; in case a much lower risk level of 1% is adopted, the estimated sand losses are about 2.2 times higher: 2.9 billion m^3 in New South Wales and 3.3 billion m^3 in southeast Queensland. The results for both states are more or less similar, since the areas being raised by sea level rise are almost equal in size: 5,282 km^2 in New South Wales and 4,874 km^2 in southeast Queensland (see Table 3.2). In spite of the slightly smaller area being raised in southeast Queensland, the predicted sand losses in this state are slightly larger than in New South Wales. This is due to the fact that the seafloor of southeast Queensland is 100% sandy, while the seafloor of New South Wales contains a considerable portion of bedrock.
Given the lengths of the coastlines (see Table 3.2) of New South Wales (1,575 km) and southeast Queensland (752 km), the median sand losses per meter coastline are about 830 m^3/m (1.3 billion $m^3/1{,}575 \cdot 10^3$ m) in New South Wales and 2,000 m^3/m (1.5 billion $m^3/752 \cdot 10^3$ m) in southeast Queensland. These values are roughly on the same order of magnitude as the values found in a similar study in the USA (Titus and Greene, 1989). Like the present study, the study by Titus and Greene estimates the sand losses due to sea level rise in the 21st century with the raising the profile method. The resulting sand losses per meter coastline in the USA are about 600 m^3/m and 1,070 m^3/m for a rise in sea level of 50 cm and 100 cm respectively. It should be noted that the study by Titus and Greene applies a limiting depth to the area being raised that is equal to the annual closure depth, which varies between 5 to 10 m along the US coast. These depths are much smaller than the limiting depth applied in this study (16-40 m), which explains the lower sand losses per meter coastline in the USA compared to the values found in this study for southeast Australia. It should also be noted that the values for the USA include a contribution for raising barrier islands.

3.6.5 Sensitivity Analysis

To show the sensitivity of the results to a change in the input values, the Pearson product-moment correlation coefficients (referred to as the correlation coefficients) between the estimated sand losses and the input parameters of the raising the profile method are listed in Table 3.6. These correlation coefficients have been determined with the risk analysis software that has been used to run the simulations. They reflect the degree of linear relation between two variables and range from -1 to 1. A value of 1 indicates that a linear equation describes the relation perfectly and positively. A value of -1 indicates a perfectly linear, but negative relation and a value of 0 implies there is no linear relation between the variables.

Table 3.6. Correlation coefficients between sand losses and input parameters.

sand losses	***s***	***h***	ρ_{NSW}
V_{NSW}	0.69	0.68	-0.21
V_{SQld}	0.72	0.69	n/a

The largest correlation coefficients are those between the future sand losses, V_{NSW} and V_{SQld}, and the amount of sea level rise, s, and those between the future sand losses and the limiting depth of the area being raised, h. The correlation coefficient of approximately 0.7 shows there is a strong linear and positive relation between these parameters. This implies that when the amount of sea level rise and/or the limiting depth of the area being raised are large, it is very likely that the sand losses will be large as well. In contrast, the linear relation between the sand losses in New South Wales and the rocky portion of the seafloor, ρ_{NSW}, is rather weak and negative. This implies that for a larger portion of

rocks, the sand losses in New South Wales may very well be smaller, but not necessarily, as this effect is likely to be overridden by the impact of sea level rise and/or the limiting depth of the area being raised.

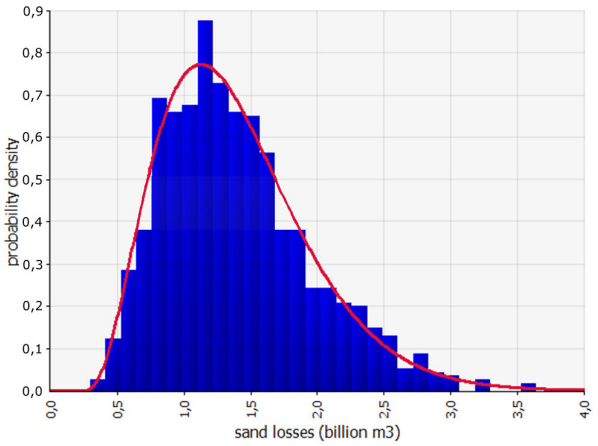

Figure 3.16. Sampled and beta general probability density curves of future sand losses in New South Wales.

The strong impact of the amount of sea level rise and the limiting depth of the area being raised on the future sand losses is demonstrated by Figure 3.16, which shows the probability density curve of the simulated future sand losses in New South Wales together with a fitted pdf. The pdf that fits the sampled probability density curve best (following a K-S test) is a beta general distribution. The beta general distribution has a shape that is roughly similar to the shape of the Weibull distribution, which is the pdf of sea level rise (see Figure 3.12). This suggests that the future sand losses are strongly influenced by the amount of sea level rise. The fitted beta general distribution is more asymmetrical and peaked than the Weibull distribution of sea level rise, though. This suggests that the triangular pdf of the limiting depth of the area being raised (see Figure 3.6) strongly affects the pdf of the future sand losses as well.

3.7 Conclusions and Discussion

The most widely applied and accepted model for predicting coastal erosion due to sea level rise is the Bruun Rule. Although the assumptions of the Bruun Rule are the subject of debate, its basic concept seems valid: A rise in sea level will cause sand to move offshore, resulting in beach erosion. A derivative of the Bruun Rule, the raising the profile method, has been applied in this chapter to estimate the offshore sand losses in southeast Australia due to sea level rise. The raising the profile method implies that the active beach profile is raised as much as the sea rises. The limiting depth of the active beach profile is highly uncertain and time-dependent. It is assumed that the limiting depth in southeast Australia is bounded by the inner (16 m) and outer closure depths (40 m) and has a symmetrical triangular pdf. The area between the coastline and the closure depths has been obtained from bathymetric charts and measures up to 5,282 km^2 in New South Wales and 4,874 km^2 in southeast Queensland. The rocky reefs on the seafloor have been excluded from this area, since they are not affected by sea level rise. Rocky reefs are virtually absent in southeast Queensland, but in New South Wales they make up between 0 and 38% of the seafloor. A symmetrical triangular pdf has been assigned to this range. The amount of sea level rise that is taken into account in this study is based on

the range recommended by the New South Wales government: 18 to 91 cm by the end of the 21st century, but without excluding values larger than 91 cm. The range of uncertainty associated with sea level rise is managed by adopting a Weibull pdf.

With the stochastic input data, the raising the profile method has been evaluated by means of simulations. The results show that the future sand losses due to sea level rise are 1.3 to 2.9 billion m^3 in New South Wales and 1.5 to 3.3 billion m^3 in southeast Queensland, where the actual value depends on the selected risk level (between 1 and 50%). The results depend most strongly on the amount of sea level rise and the value of the limiting depth of the active beach profile. Because sea level rise is projected to continue to rise well beyond the 21st century, it is expected that sea level rise will remain a major cause of erosion in the centuries to come.

The future sand losses that have been estimated in this chapter can be replenished by means of beach nourishment, which is explained in the next chapter.

4 Replenishing Future Sand Losses with Beach Nourishment

In Chapter 1 the sand losses on the southeast Australian coast due to 21st century sea level rise have been estimated. This chapter addresses the question how these sand losses and the resulting beach erosion can be dealt with. In principle, coastal communities have several options of responding to beach erosion. These include: (i) Allowing the sea to advance, with a possible relocation of any existing buildings and infrastructure; (ii) counteracting beach erosion by constructing seawalls or levees and (iii) replenishing the sand losses by means of beach nourishment. It is commonly assumed that the first option, no coastal protection measures, is only economically viable in case of little or no coastal development, because the costs of protecting the coast against sea level rise would be greater than the value of the land to be protected (e.g. Titus et al., 1991). This issue will be further addressed in Section 5.1.

Until the late 20th century, it was common practice to defend a coast against beach erosion by building "hard" structures like seawalls and levees. These structures, however, are often expensive to construct and maintain, and they usually decrease the amenity of a beach. Also, these structures do not protect the beach itself, which may lead to a great reduction in beach size and undermine the stability of the seawall or levee as sea level rises. In case communities wish to both protect their properties against sea level rise and preserve their beaches, the only feasible response is beach nourishment, possibly in combination with the construction of a seawall. In recent decades, beach nourishment has become very common in many countries as it provides a more flexible and generally cheaper method of combating beach erosion than applying hard defence structures (e.g. TAW, 2002).

This study is about the protection of the beaches of southeast Australia against the impact of sea level rise. In order to preserve the present beaches ("hold the line"), the predicted sand losses need to be replenished. Therefore, this study focuses on coastal protection by means of beach nourishment; the possibility of combining this protection measure with constructing seawalls is not considered. The sand resources that are potentially available for beach nourishment in southeast Australia are described in Section 4.1. As will be explained in Section 4.1, it is generally preferred to use offshore sand resources for beach nourishment purposes instead of onshore resources. The extraction of offshore sand resources is discussed in Section 4.2. Section 4.3 gives an overview of overseas beach nourishments practices that are relevant for the intended beach nourishment works in southeast Australia. Section 4.4 discusses a few issues that are related to beach nourishment and play an important role in southeast Australia. Section 4.5 presents the conclusions and discussion.

4.1 Sand Resources for Beach Nourishment

This section describes the potential sand resources for beach nourishment in southeast Australia. Section 4.1.1 compares onshore sand resources with offshore sand resources. Section 4.1.2 provides an overview of sand resources on the inner continental shelf of southeast Australia and discusses their suitability for beach nourishment. The sand quantities contained in these offshore sand resources have been estimated and are presented in Section 4.1.3.

4.1.1 Onshore vs. Offshore Sand Resources

Given the estimated quantities of sand lost on the southeast Australian coast due to sea level rise (see Section 3.6.3) and the approach of this study to replenish those losses with beach nourishment, the next step is to determine the available sand resources for beach nourishment. The first question that arises is whether to source sand onshore or offshore. In New South Wales, current state policies prohibit the offshore extraction of sand because of potential ecological damage. This limits the sand resources currently available for beach nourishment (and the building industry; see Section 4.4.2) to onshore resources, such as dunes, rivers, estuaries and friable sandstone quarries. But mining these sources often leads to great damage to the landscape and the environment, increased road traffic and high sand freight costs. In addition, onshore sand sources are often limited in size compared to the quantities of sand required for large beach nourishment projects and in many places in the world (including New South Wales) they are either close to depletion or unavailable for use due to competing land uses or zoning (Skene, 2005; SMH, 2005; Cowell, pers. comm.). Consequently, the vast majority of beach nourishment works throughout the world use offshore sand resources (about 95%; Dean, 2002). For these reasons, this study focuses on offshore sand extraction (implicitly assuming that the ban on offshore dredging in New South Wales will be lifted in due time), but does not exclude the possibility of onshore sand sourcing for beach nourishment.

4.1.2 Inner Continental Shelf Sand Deposits

As mentioned in Sections 2.1.1 and 2.2.1, the inner continental shelf of southeast Australia harbours massive sand deposits that are remnants of former shorelines when sea level stood much lower than today. The inner continental shelf of New South Wales is defined by Roy (2001) as the part of the seafloor between the nearshore and the middle continental shelf. It occupies a zone in water depths of 20-60 m that extends 1-15 km offshore and has an area of about 8,000 km^2. When considering offshore sand extraction for beach nourishment, the sand deposits on the inner continental shelf are the most appropriate potential source. This is because offshore sand extraction is limited to water depths that are neither too shallow (at least 20 m on parts of the coast that will not be nourished; see Section 4.2.3 for details) nor too deep (because dredgers commonly deployed for beach nourishment have a maximum dredging depth of about 50 m; see Section 4.2.1 for details).

Roy (2001) discerns three main types of inner shelf sand deposits in New South Wales: (i) Inner shelf sand sheets (ISSS); (ii) shelf sand bodies (SSB) and (iii) regressive sand barriers (RSB). The ISSS are thin, extensive sand layers that cover about 70% of the inner continental shelf and are interrupted by bedrock reefs and the SSB. The SSB are thick sand bodies that are located in the vicinity of prominent headlands. In the south, where the continental shelf of New South Wales is steeper than in the north, they are generally located in deeper water and a bit further offshore. Little is known about the RSB, which are subsurface sand bodies (covered by the ISSS) in front of coastal embayments. Table 4.1 lists various dimensions and characteristics of these sand deposits.

Table 4.1 shows there is a broad variety of sand sizes available on the inner continental shelf of New South Wales. In general, most of the shelf is covered with 1 to 50 m thick sand deposits that are composed of uniform fine to medium-sized, relatively well-rounded quartz grains with almost no mud content. The underlying substrate is mostly bedrock. Much of the marine sand is similar in size, sorting and colour to the beach sands of southeast Australia (which are also composed of

predominantly well-sorted, fine to medium-sized (0.125-0.5 mm), light-coloured grains; see Section 2.2.1) and located in water depths that are accessible by dredgers (max 50 m for dredgers commonly deployed for beach nourishment), making it suitable for beach nourishment. This means that New South Wales has massive potential offshore sand resources for beach nourishment and that "every coastal site in NSW is within 20 km of virtually unlimited quantities of marine sand" (Roy, 2001).

Table 4.1. Properties of sand deposits on the inner continental shelf of New South Wales. The presented numbers denote the most commonly found values. The SSB data represent the properties of 10 SSB for which sufficient data are available (from: Ferland, 1990; Roy, 2001).

property	**ISSS**	**SSB**	**RSB**
thickness	0.25-1.5 m	10-50 m	10-20 m
width	5-10 km	1-4 km	NA
length	n/a	5-35 km	NA
offshore distance	1-15 km	2-5 km	NA
water depths	20-60 m	30-90 m	30-70 m
sand volume	NA	0.1-1.6 billion m^3 each	NA
mean grain size	0.2-0.7 mm (fine to coarse)	0.16-0.5 mm (fine to medium)	fine
sand sorting	moderately well	well	well
sand coloration	yellow, orange	NA	NA

4.1.3 Offshore Sand Quantities

An estimate of the sand volume contained in the offshore sand deposits of New South Wales is obtained by adding the sand volumes of the ISSS and the SSB (there are not sufficient data available to estimate the sand volumes of the RSB). The ISSS cover about 70% of the inner continental shelf, which has a size of 8,000 km^2. From Table 4.1 it is assumed that the ISSS have an average thickness of 1 m, which means the amount of sand contained in the ISSS is about $0,7 \cdot 8,000 \cdot 10^6$ $m^2 \cdot 1$ m = 5.6 billion m^3. The aggregated amount of sand contained in the SSB is obtained by adding the sand volumes of the ten SSB for which sufficient data are available. This yields 7.75 billion m^3 (Roy, 2001). Thus, together the ISSS and SSB contain about 13.35 billion m^3 of sand. It should be noted that this figure almost certainly underestimates the actual volume contained in the offshore sand deposits of New South Wales, as it does not include the contributions of all SSB nor of the RSB. This notion is supported by figures in Ferland (1990), which suggest that the volume of marine sands in southern and central New South Wales amounts to 16.2 billion m^3 (it is not clear though whether this figure includes a contribution from the RSB and/or the nearshore zone). However, a significant part of the estimated 13.35 billion m^3 of sand is contained in parts of the SSB that are located in water depths that are too deep to reach for dredgers commonly used for beach nourishment (deeper than 50 m; see Table 4.1 and Section 4.2.1)[8]. In addition, on the stretches of coast that will be nourished, there should be no offshore sand extraction within the 40 m depth contour (this will be explained in Section 4.2.3), which means that parts of the ISSS and SSB are located in water depths that are too shallow (see Table 4.1). In any case, the figure of 13.35 billion m^3 shows that the offshore sand resources are much larger than the predicted sand losses due to sea level rise in New South Wales in the 21st century: 1.3 billion m^3 at a risk level of 50% and 2.9 billion m^3 at a risk level of 1% (see Section 3.6.3). kjf

[8] Apart from this, a significant part of the ISSS is located further than 3 nautical miles (5.55 km) offshore, which is the seaward limit of the territorial jurisdiction of New South Wales. They do lie completely within the territorial waters of Australia, though, which extend up to 12 nautical miles (22.22 km) offshore.

Detailed information on offshore sand resources in southeast Queensland is not available. But southeast Queensland's seafloor is virtually completely sandy (see Section 3.5.1) and its inner continental shelf is covered with sand sheets similar to the ISSS in New South Wales (Cowell, pers. comm.). In addition, most of the sand used for the Gold Coast beach nourishments is extracted offshore (see Section 2.3.1), which indicates that (at least part of) southeast Queensland's marine sand deposits are suitable for beach nourishment. Therefore it is safe to assume that southeast Queensland has massive potential offshore sand resources for beach nourishment as well (on the order of billions of m^3).

4.2 Offshore Sand Extraction

As explained in Section 4.1 the most appropriate sand resources for beach nourishment in southeast Australia are the huge inner shelf sand deposits. These marine sands can be extracted with trailing suction hopper dredgers, which are deployed for beach nourishment works around the world and are briefly discussed in Section 4.2.1. Section 4.2.2 mentions the potential impacts of offshore sand extraction on a coastline. As will be explained in Sections 4.2.3 and 4.2.4, these (and other) impacts can be avoided if offshore sand extraction is met with caution, such as establishing minimum water depth requirements (Section 4.2.3) and requirements with regard to the location and size of offshore sand extraction areas (Section 4.2.4). Much of the information presented in this section is based on the offshore sand extraction experiences and practices overseas and on the Gold Coast. It will be shown how this information is relevant to the potential use of offshore sand resources for beach nourishment purposes in southeast Australia.

4.2.1 Trailing Suction Hoppers Dredgers

Trailing suction hopper dredgers, or trailers in short, are self-propelled vessels with a suction pipe, a storage capacity in their hull (the "hopper") and a discharge pipe (see Figure 4.1). They can singlehandedly extract, transport and dispose of sediments.

Figure 4.1. Artist impression of a trailing suction hopper dredger (Delft Center for Systems and Control, 2008).

Table 4.2 lists a number of capabilities that are indicative of various hopper sizes. Beach nourishment works are usually carried out with medium trailers with a hopper capacity of 5,000 to 10,000 m^3, a maximum dredging depth of 50 m and a dredging draught of less than 10 m, so they can discharge

close to the coast (Hollemans, 2005; Hollemans, pers. comm.). For comparison, the dredger used on the Gold Coast has a hopper capacity of 300 to 400 m^3 (see Section 2.3.1). Trailers remove sand from the seafloor along extraction tracks of about 2-3 m wide and 15-40 cm deep, depending on the dredger size, sand permeability, sailing speed, dredging depth, etc. Extraction areas are preferably at least 1 km in length (because turning the vessel costs time and production) and 250 m in width (Hollemans, pers. comm.; Roy, 2001).

Table 4.2. Indicative capabilities of trailing suction hopper dredgers ($H_{s,max}$ is the maximum significant wave height at which a dredger can operate) (from: Hollemans, 2005; Hollemans, pers. comm.).

dredger size	hopper volume	maximum dredging depth	dredging draught	$H_{s,\,max}$
small	<5,000 m^3	35 m	3–6 m	<2 m
medium	5,000–10,000 m^3	50 m	5–10 m	2 m
large	10,000–16,000 m^3	70 m	9–11m	2.5 m
jumbo	16,000–30,000+ m^3	>100 m	>10 m	3 m

4.2.2 Impact on the Coastline

Determining the location of offshore extraction areas should be met with caution, because, in principle, dredging a pit on the seafloor may lead to coastal erosion. This is due to three main reasons: First, the extraction pit may be filled in with sand transported from the shoreline, a process called beach drawdown. Second, the wave impact on a coast may increase locally as the extraction pit alters wave refraction patterns and decreases the dissipation of wave energy. And third, the extraction pit may change sediment transport rates and patterns by altering local currents and/or by acting as a trap for the littoral drift. However, various field and analytical studies around the world (e.g. Van Alphen et al., 1990; Metromix, 1993; Van Rijn and Walstra, 2004) have shown that the impact of an offshore extraction pit on a coastline is negligible if the pit is located in sufficiently deep water. That is, the extraction pit should be located beyond the limit of significant sand transport processes (see Section 3.3.1), such as not to be part of the active beach profile where any human interference with the seabed would lead to significant morphological changes on the coastline.

4.2.3 Minimum Water Depth Requirements

Based on experience and the studies mentioned in Section 4.2.2, minimum water depth requirements for offshore sand extraction have been established in several countries. These requirements are listed in Table 4.3, together with local wave heights, wave periods and outer closure depths. As mentioned in Section 4.2.2, offshore sand extraction areas should be located beyond the limiting depth of significant sand transport. The upper bound of this limiting depth has been defined in Section 3.3 by Hallermeier's outer closure depth, h_i. Table 3.4 shows that in France, the Netherlands and New Zealand the minimum required depths for offshore sand extraction are (more or less) similar to the outer closure depth. On the Gold Coast, however, the minimum required depth (20 m) is much smaller than the outer closure depth (40 m), and as far as is known, this has not lead to any detrimental effects on the coastline (see Section 2.2). In addition, Metromix (1993) found that in New South Wales marine sand extraction will have virtually no impact on the coastline if dredging is carried out in water depths of 25 m or greater. These notions suggest that offshore sand extraction in southeast Australia can be carried out safely in water depths of 20-25 m or greater. This ensures that the

extraction pits are located seaward of the most active part of the seafloor, the upper shoreface, which has a limiting depth of 16 m (Hallermeier's inner closure depth; see Table 3.1).

Table 4.3. Offshore sand extraction requirements, average significant wave height (H_s), average wave period (T) and outer closure depth (h_i) in a number of countries (from: North Sea Coastal Management Group (NSCMG), 2000; Short, 2000; Nielsen, 2005).

country	minimum water depth	H_s	T	h_i
United Kingdom	18–22 m	1 m	5–8 s	NA
France	20 m	0.8 m	NA	22 m
Germany	10 m	NA	NA	NA
Netherlands	20 m	1.5 m	6 s	20 m
Denmark	20 m	NA	NA	NA
Japan	30 m	1.7 m	7 s	NA
New Zealand	25 m	1–2 m	5–7 s	27 m
Australia (Gold Coast)	20 m	1.6 m	9–10 s	40 m

However, in the present study the estimated sand losses due to sea level rise are based on the assumption that the seafloor may be raised as far out as the outer closure depth, 40 m (see Section 3.3.2). This implies that offshore sand extraction in southeast Australia should occur beyond the 40 m depth contour instead of the 20 or 25 m depth contour. This is a rather strict requirement, though, given the minimum extraction depths listed in Table 3.4 and the fact that the limiting depth of the area being raised by sea level rise may very well be considerably less than 40 m (see Figure 3.6). Therefore it is suggested that on parts of the coast that will not be nourished (i.e. the rocky shores and the beaches that are excluded from the intended beach nourishment programme; the latter issue will be addressed in detail in Section 5.1), the minimum required water depth for offshore sand extraction is 20-25 m instead of 40 m. This implies that (a considerable part of) the inner shelf sand deposits that are located closest to the coast (i.e. in water depths of about 20-25 m; see Section 4.1.2) are potentially available for beach nourishment.

4.2.4 Location and Size Requirements

Besides the minimum required water depth, another important restriction to the location of offshore sand extraction areas is the distance from cables, pipelines, offshore platforms, offshore wind parks, etc. Even though well-planned offshore sand extraction will have little or no impact on the coastline, it will alter flow patterns in the vicinity of the extraction area through flow acceleration and deceleration. This, in turn, will lead to erosion of the seafloor surrounding the extraction area for decades after dredging, as the pit is slowly filled in with nearby sediments (Van Alphen et al., 1990; Van Rijn and Walstra, 2004). Hence, to prevent the instability of offshore infrastructure like cables and pipelines, there needs to be a buffer zone between these objects and the extraction pit. Current legislation in the Netherlands requires a buffer zone of 500 m (Boers, 2005); in New South Wales, Metromix (1993) recommends a buffer zone of 250 m.

Other requirements for offshore sand extraction include restrictions to the size of the extraction pit and the minimum distance from the shoreline. For example, in the Netherlands, when the intended extraction pit exceeds 10 million m^3 in volume or 500 hectares in area, an environmental impact assessment is required, and when the intended extraction depth exceeds 2 m below the initial seafloor, an ecological study needs to be undertaken (Boers, 2005). Examples of minimum required offshore distances are 600 m in the United Kingdom, 1 km in Japan and 5.5 km in France (Nielsen, 2005). In

Australia there are no such restrictions, but Metromix (1993) recommends a maximum extraction depth of 5 m below the initial seafloor. Extensive research on a temporary deep sand pit in the Netherlands has indicated that deep sand extraction (i.e. with an extraction depth of 5-12 m) "will be an interesting alternative for shallow sand pits with a volume of more than 10 million m^3" (Boers, 2005). Finally, with regard to the orientation of offshore extraction pits, Van Rijn and Walstra (2004) recommend they should be designed with their longest axis normal to the shoreline to minimize the trapping of nearshore sand during large storms. However, as discussed above, this effect is deemed to be very small.

Apart from specifying the minimum required water depth for safe dredging (20-25 m on parts of the coast that will not be nourished), the designing and positioning of offshore sand extraction areas for the intended beach nourishment programme in southeast Australia is beyond the scope of this study.

4.3 Overseas Beach Nourishment Practices

This section provides a description of overseas beach nourishment practices that are relevant to the intended beach nourishment works in southeast Australia. The following topics are covered: The method of placing the nourishment sand on or near the beach (Section 4.3.1); the return interval between subsequent nourishments (Section 4.3.2); a number of design aspects of beach nourishment projects (Section 4.3.3) and the ecological impacts of beach nourishment and offshore sand extraction (Section 4.3.4). Where applicable, the beach nourishment practices on the Gold Coast (described in Section 2.3) are addressed as well. As explained in Section 4.1.1, the focus in this study is on using offshore sand resources for beach nourishment rather than onshore resources. Therefore, the presented overview of beach nourishment practices is based on the use of offshore sand resources.

4.3.1 Sand Placement

Trailing suction hopper dredgers can discharge sand either by pumping it ashore with pipelines, by dumping it directly onto the seafloor or by pumping it over the bow ("rainbowing") (see Figure 4.2). The first method places the nourishment sand directly onto the dry, visible beach, where it can be redistributed with bulldozers. In contrast, the second and third method place the sand underwater in the nearshore zone (usually in water depths of 5 to 10 m), where it can be picked up and redistributed by waves and currents. Subsequently, the nourished sand is transported to the shoreline by natural processes and will eventually feed the beach. In the last 10 years or so, nearshore placement has become the preferred practice in an increasing number of beach nourishment works around the world, like on the Gold Coast (see Section 2.3.1) and in most North Sea countries (NSCMG, 2000). This is because nearshore placement has a number of major advantages compared to placing sand on the beach: (i) It is cheaper than pumping sand ashore as it does not require additional equipment; (ii) it is based on natural erosion and accretion processes; (iii) it causes less trouble to beach recreation than operations on the beach and (iv) nearshore sand buffers may decrease coastal erosion as they reduce the energy of incoming waves (Mulder, 2000; Roelse, 2002). In addition, as explained in Section 2.3 about the Gold Coast nourishments, placing sand directly onto the beach may decrease the political and community support for beach nourishment and may affect the amenity and natural values of the beach and the dunes. A disadvantage of nearshore placement compared to pumping sand ashore is the

fact that the trailing suction hopper dredgers need to sail in shallower water (less than 10 m deep) in order to dump or rainbow their load. This means that jumbo trailers (see Table 4.2) can generally not perform this kind of operations.

Nearshore nourishments are aimed at replenishing sand losses and/or creating a sand buffer in the nearshore zone. Experiences in various countries have shown that this generally is an effective way of counteracting coastal erosion and that the seaward losses of the nourished sand are negligible. However, when the purpose of a nourishment is to address a critical erosion problem (or to create a wide recreation beach), it is advisable to place the sand directly onto the beach (NSCMG, 2000; Mulder, 2000; Roelse 2002; TAW, 2002). In this study, the objective of the intended beach nourishment works in southeast Australia is to mitigate the impact of sea level rise. As sea level rise is a slow process that does not pose an immediate threat to coastal communities, it is assumed that these beach nourishment works will be carried out by means of nearshore sand placement (mainly because of the relatively low costs).

Figure 4.2. Trailing suction hopper dredgers pumping sand ashore (left; Roelse, 2002) and rainbowing sand (right; Hollemans, 2005).

By definition, nearshore nourishments occur on the upper shoreface. They should be carried out as close to the coastline as possible, to ensure the nourished sand is quickly transported to the beaches (Mulder, 2000; TAW, 2002). In southeast Australia this means that the sand is to be placed well within the 16 m depth contour (which is the value of the inner closure depth, see Section 3.3.1). The minimum water depth depends on the draught of the trailing suction hopper dredger and is generally about 5 m. Thus, common depths for nearshore nourishment are 5-10 m. When placing sand underwater, the cross-shore profile of the nourishment does not have to meet any requirements: Wave and current action will (tend to) rework the nourished sand such that a new equilibrium profile is established (TAW, 2002).

4.3.2 Return Interval

From an economic point of view it is not advisable to nourish a small amount of sand, since this would require very frequent renourishments. With each renourishment, a dredger needs to be mobilised, which adds to the m^3-price of the nourishment. A large return interval provides for a good m^3-price, because the dredger mobilisation costs are divided over a larger quantity of sand (economies of scale). Besides, large return intervals cause less trouble to beach recreation and marine flora and fauna (see Section 4.3.4 for details on the ecological impacts of beach nourishment). With regard to capitalised investment costs though, large return intervals are less favourable, as the money is spent

long before it is actually required. In addition, small return intervals provide for more flexibility, since they allow for rapid adjustment to changes in beach erosion rates. Other factors that may determine the return interval of nourishments include: A possible combination with other dredging works in the vicinity (such as marine sand extraction for the building industry; see Section 4.4.2) and contractual obligations. Return intervals in the North Sea countries are generally 1-5 years, which is in agreement with the economic optimum in the Netherlands (about 5 years) and Bruun (1996), who argues that "more frequent nourishments" (approximately every 2-4 years) are "justified technically as well as economically" (NSCMG, 2000; Roelse, 2002; TAW, 2002).

4.3.3 Design Aspects

Naturally, nourishment volumes depend on the return interval, which determines the projected lifetime of a nourishment. A larger lifetime means that the expected amount of erosion within the nourishment's lifetime is larger and, hence, that the required volume of sand is larger. In addition, the required volume of sand may be based on the wish to maintain a certain coastline position or a minimum amount of sand within the beach or nearshore zone (e.g. in the United Kingdom and the Netherlands). Often, an allowance (10-50%) is added to this volume of sand to account for uncertainties in future rates of beach erosion, offshore losses of nourished sand, etc. Other factors that may determine nourishment volumes are the available budget and political decisions (e.g. on the Gold Coast, see 2.3.1). Nourishment volumes are generally on the order of hundreds of thousands to a few million m^3. In many cases there is a minimum required volume, because deploying a dredger for a small nourishment is not economical (economies of scale). For example, on the Gold Coast, the minimum required nourishment volume for deploying a small dredger is 50,000 m^3. In the Netherlands, where larger dredgers with higher mobilisation costs are used, this value is usually 200,000 m^3 (NSCMG, 2000; TAW 2002).
As explained in the section on the Gold Coast nourishments (Section 2.3), there are several other aspects associated with the design beach nourishment projects. These aspects include: The timing of the works during the year (e.g. outside the storm and tourism peak seasons), beach monitoring (e.g. to measure erosion rates and the effect of the nourishments), informing the public about the works (e.g. to retain political and financial support) and the impact of the works on the environment and on the surfing conditions. The ecological impacts will be further addressed in Section 4.3.4, the surfing conditions in Section 4.4.1 and the political and community support in Section 4.4.3. Apart from this, prior to the undertaking of beach nourishment works, usually several approval procedures and investigations are required, such as: The application for a licence for offshore sand extraction, an environmental impact assessment and field surveys to determine water depths and sediment properties. These procedures and investigations add to the costs of beach nourishment.

The designing and planning of the intended beach nourishment works in southeast Australia is beyond the scope of this study.

4.3.4 Ecological Impacts

The current prohibition of offshore sand extraction in New South Wales effectively blocks the undertaking of large scale beach nourishment works in this state. The main reason for this ban are the

feared ecological impacts of offshore sand dredging and beach nourishment due to the disturbance of the marine environment. This disturbance is mainly caused by: The removal and burial of organisms and vegetation on the seafloor (known as benthos); the loss of feeding grounds for marine animals that feed on benthos and the creation of turbid plumes that reduce underwater light levels (Metromix, 1993; Lincoln-Smith, 2005). However, research and experience in various countries have shown that the impact of offshore sand extraction and beach nourishment on the marine environment is limited and temporary. Naturally, the seafloor is disturbed during the dredging operations, but most benthic species fully recover within months to a year after completion of the works, which is relatively quick in ecological terms. This may be due to the fact that benthic species are adapted to unstable conditions anyhow, since the seafloor is regularly disturbed by large waves. In addition, the impact of offshore sand extraction on benthos can be reduced by well-planned dredging. For example: By giving disturbed areas time to recover and by positioning the length of the sand extraction area parallel to the prevalent flow direction to allow for quick water refreshment in the pit, thus avoiding low oxygen levels. Furthermore, given the quick recovery of benthos and the relatively small size of the nourishment and extraction areas compared to the feeding grounds for fish and other marine animals, the risk of these works to marine animals is considered negligible. Indeed, on the Gold Coast the beach nourishment works have not lead to an observed decrease of marine life and, in fact, the dredging operations seem to attract small fish and sharks (see Section 2.3.2). Lastly, the impact of turbid plumes can be reduced with the use of a fine sediment diffuser pipe to ensure that sediment concentrations in the water column do not become too high (Metromix, 1993; Essink, 1997; Hoogewoning and Boers, 2001; Lincoln-Smith, 2005).

Apart from these findings, the inner continental shelf of New South Wales, where the intended sand extraction areas for New South Wales are to be located (see Section 4.1), is naturally bare of vegetation due to low light levels (Roy, 2001). Also, in general, offshore sand extraction areas are very small (mostly smaller than 10 km^2) compared to the size of the inner continental shelf on which they are located (1,000's of km^2) (Metromix, 1993). Finally, Roy (2001) states that, when compared to onshore sand mining, "carefully planned marine dredging is less disruptive".

In summary, the beaches of southeast Australia can be nourished with sand that has been extracted offshore without causing significant ecological damage. But still, ecological studies, proper planning and monitoring would be required to ensure the ecological impacts are limited to the minimum (Lincoln-Smith, 2005).

4.4 Issues Related to Beach Nourishment in Southeast Australia

This section discusses three issues that play an important role in southeast Australia and are related to the intended beach nourishment works: The impact of these works on the surfing conditions (Section 4.4.1), a cooperation with the building industry to extract marine sands (Section 4.4.2) and the community and political support for beach nourishment (Section 4.4.3).

4.4.1 Surfing Conditions

When the sand used for beach nourishment is coarser than the native beach sand, the nourished beach profile will be steeper than the original profile. This will change the wave breaking pattern and, hence, the surfing conditions. Therefore, surfers in southeast Australia fear that beach nourishment will have

an adverse effect on the surfing conditions (Cowell, pers. comm.). The surfing conditions on the Gold Coast have indeed been altered by the beach nourishments, but how exactly is not known (see Section 2.3.2). However, considering the fact that the beach sands and the inner continental shelf sands of southeast Australia are both predominantly fine to medium-sized and well sorted (see Sections 2.2.1 and 4.1.2), it is very likely that in most cases the intended nourishment sand will be similar to the native sand. This means that the eventual nourished profile will resemble the original beach profile and that the surfing conditions should remain more or less the same. But still, any placement of sand in the surf zone will effect the wave breaking pattern and the surfing conditions. Assessing or minimizing this effect is, however, beyond the scope of this study. It is assumed that, like on the Gold Coast, coastal protection will be considered more important than the surfing conditions.

4.4.2 Cooperation with the Building Industry

The building industry in southeast Australia uses large amounts of construction sand: 7 million tonnes per year in Sydney alone (about 4.4 million m^3), and this number is on the rise. Currently all construction sand in southeast Australia is obtained from onshore resources, such as dunes, rivers and sandstone quarries. But, as mentioned in Section 4.1.1, many of these sand resources are close to depletion, not available due to other land uses or zoning, far away from the big cities and/or located in environmentally sensitive areas. As a result, construction sand is becoming scarcer and sand costs are increasing. In addition, onshore sand mining often requires the destruction of vegetation and the creation of vast pits, which causes great damage to the landscape and the environment. Therefore, the huge sand deposits on the inner continental shelf of southeast Australia are being considered as a potential replacement for onshore resources, in particular with regard to fine to medium-sized concrete sand. However, to date all proposals to explore or extract Sydney's offshore sand resources for construction purposes have been rejected by the New South Wales state government, because of the potential damage to the environment and the beaches (Gardiner, 2005; Skene, 2005; SMH, 2005).
As explained in Sections 4.2 and 4.3.4, the fear of the state government for potential adverse effects of offshore sand extraction is unfounded. In fact, an increasing number of parties involved in the Sydney sand market, as well as some environmental organisations, are recognizing the environmental and economic benefits of marine sand resources compared to onshore resources. They are supported by scientists, coastal managers and coastal residents, who believe that the commercial extraction of marine sand for the building industry offers an opportunity for developing a beach nourishment programme: Deploying a dredger for beach nourishment would be more economical if the dredger is used for commercial sand extraction as well, owing to the high costs of mobilizing a dredger. A trailing suction hopper dredger is suitable for both tasks and could, for example, carry out beach nourishment works outside the tourism peak season and extract construction sand in the remaining months. The construction sand can be stored in large onshore stockpiles, which can be harvested throughout the year. In such a way, the allowance of offshore sand extraction for the building industry could be very important to the development of a beach nourishment programme in southeast Australia, and vice versa (Skene, 2005; SMH, 2005; Hollemans, 2005).
It is noted that offshore sand extraction for the building industry occurs in various places, such as in Western Australia and on the North Sea. In Western Australia, currently 2.3 million tonnes of cement sand (about 1.4 million m^3) are extracted annually by a small trailing suction hopper dredger (1,200 m^3) that operates 30-35 weeks per year (Hollemans, pers. comm.). The amount of construction sand

that is extracted annually on the Dutch part of the North Sea is about 15 million m^3 (Hoogewoning and Boers, 2001).

4.4.3 Community and Political Support

As explained in Section 2.3 about the Gold Coast nourishments, community and political support are essential to obtaining or retaining funds for beach nourishment. In recent years, the political attention and support for beach nourishment in southeast Australia seem to be on the rise. For example, the coastal councils in Sydney are working together under the Sydney Coastal Councils Group (SCCG) that set up a Beach Management Working Group in 2005. The objective of this working group is, amongst others, to gain a better understanding of offshore sand resources and to scope locally desired beach management strategies, such as beach nourishment. An inquiry by the working group in 2005 has learned that 7 of the 15 coastal councils in Sydney have expressed current or potential needs for beach nourishment, and that 75% of all 38 coastal councils in New South Wales support an investigation into the use of offshore sand extraction for beach nourishment purposes. In 2006, the SCCG lodged an application under the Natural Disaster Mitigation Programme for a scoping study into the use of offshore sand for nourishing eroding beaches in Sydney. This application focused on the protection of beach properties that are under immediate threat from coastal erosion and storm damage. Like earlier proposals for offshore sand extraction in New South Wales (see Section 4.4.2), this application was rejected. Nonetheless, the "momentum" for the development of a beach nourishment programme in Sydney is being built up and the SCCG believes that the New South Wales government will lift the ban on offshore sand extraction in due time to allow for large scale beach nourishment (Cameron and Corbett, 2005; SCCG, 2006; Beharrell, Cameron and Withycombe, pers. comm.).

Figure 4.3. Collaroy/Narrabeen beach after a storm in 1995 (Warringah Council, 2005).

Coastal communities in Sydney seem to be favourable to beach nourishment as well. As explained in Section 4.4.2, many coastal residents support the idea of offshore sand extraction for the building industry as this could allow for the development of a beach nourishment programme. Besides, coastal communities seem to be strongly opposed to other means of coastal protection: In 2005, the proposal to built a seawall to protect properties on the heavily eroding Collaroy/Narrabeen beach (see Figure 4.3) in Warringah (north Sydney) met heavy protests from local residents. Subsequently, Warringah Council decided to cancel this plan. In 2005, Warringah Council purchased two properties that were under immediate threat from erosion. But this approach has not proven to be sustainable due to the

high costs and it is probably not very popular with the community either (Cameron and Corbett, 2005; SCCG, 2005; SMH, 2005). On the Gold Coast, it seems likely that the public is favourable to beach nourishment as well, because nourishments have greatly increased the size of the Gold Coasts beaches and dunes (see Section 2.3.2). But as the experience on the Gold Coast has shown, providing information to the public and justifying the investments in coastal protection may be very important for obtaining or retaining community and political support.

The local initiatives and activities described in this section, together with the increasing attention for climate change and sea level rise, have contributed to the growing public awareness of the risk of beach erosion in Australia, as well as the increasing recognition of beach nourishment as an effective measure against beach erosion.

4.5 Conclusions and Discussion

The future sand losses on the coast of southeast Australia can be replenished by means of beach nourishment, which has proven to be an effective method of mitigating coastal erosion in various countries. For beach nourishment purposes, the use of offshore sand resources is preferred to the use of onshore sand resources, but offshore sand extraction is currently only allowed in southeast Queensland and not in New South Wales. The offshore sand resources in southeast Queensland and the potential offshore sand resources in New South Wales are contained in the inner continental shelf sand deposits. These deposits offer billions of m^3 of good quality sand within 20 km from each location on the coastline, and can be extracted with a trailing suction hopper dredger in water depths of at least 20 m (on parts of the coast that will not be nourished) without causing significant impacts on the coastline. The preferred method of placing the nourishment sand is on the nearshore in water depths of about 5 to 10 m, which is cheaper than pumping the sand ashore. Nourishments are typically carried out every 1 to 5 years with volumes on the order of 100,000's of m^3; more frequent and/or smaller nourishments are generally not economical due to the high dredger mobilisation costs. Deploying a dredger in southeast Australia could be more economical if the intended beach nourishment works are combined with the extraction of marine sand for the building industry. The political and community support for offshore sand extraction and beach nourishment seem to be on the rise, despite concerns over the adverse impacts on the surfing conditions and the marine environment. These impacts are limited when the dredging operations are carried out with caution.
In this chapter it has been explained how the sand losses that have been calculated in Chapter 3 can be replenished with beach nourishment. In the next chapter, the costs of applying beach nourishment to the coast of southeast Australia will be estimated.

5 Future Beach Nourishment Costs

In Chapter 4 it has been explained how the predicted sand losses on the southeast Australian coast due to sea level rise can be replenished by means of beach nourishment, which has provided the answer to the second main question of this study (see Section 1.3). This chapter deals with the third and last main question: How much will it cost to replenish the predicted sand losses? By answering this question the objective of this study is achieved, which is: To estimate the costs of applying beach nourishment in southeast Australia to mitigate the effects of beach erosion caused by the rise of sea level in the 21st century (see Section 1.2).
As has been briefly explained in Section 2.2.3 and the introduction to Chapter 4, beach nourishment is not always an economically viable option of responding to beach erosion, because the economic viability strongly depends on the degree of development of a beach. Therefore this chapter begins with partitioning the coast of southeast Australia on the basis of the degree of beach development (Section 5.1). This will result in two spatial scenarios for the application of beach nourishment in southeast Australia that each demand a different amount of sand to be replenished. These sand demands are elaborated in Section 5.2, together with the costs of sand. With these data the costs of applying beach nourishment to the coast of southeast Australia can be estimated, which is the topic of Section 5.3. Section 5.4 will show how the results of the present study can be of use to coastal management. The chapter ends with the conclusions and discussion (Section 5.5). As in Chapter 3, a distinction is made between New South Wales and southeast Queensland, where applicable.

5.1 Partitioning the Coast on the Basis of Beach Development

The economic viability of beach nourishment is, for a large part, determined by the degree of beach development. As has been indicated in Section 2.2.3, the degree of beach development varies considerably along the coastlines of New South Wales and southeast Queensland. Prior to the present study there were no detailed data available of the degree of beach development in southeast Australia. Since these data are required to construct spatial scenarios for the application of beach nourishment, the degree of beach development has been mapped for the entire coast of southeast Australia, as part of this study. This required the setting up of a beach development classification, which is explained in Section 5.1.1. The results of applying this beach development classification to the coastline of southeast Australia are presented in Section 5.1.2. On the basis of these results, two spatial scenarios for the application of beach nourishment in southeast Australia have been constructed, which are presented in Section 5.1.3.

5.1.1 Beach Development Classification

The beach development classification that has been constructed in the present study is based on the notion that applying beach nourishment is usually not economically viable in case of no or little coastal development (e.g. Titus et al., 1991). No coastal development means that a beach and its dunes are still in a natural state (see Figure 5.1). Little coastal development is defined in this study as either a

largely undeveloped beach (i.e. the major part of the beach is in a natural state, but there is some development along a small part of the beach) or a beach with small-scale development (e.g. a campsite in the dunes, a single row of houses along the beach). Hence, beaches that are largely undeveloped and beaches with small-scale development are to be distinguished from beaches that are largely or entirely developed with large-scale development, which are mostly located in towns, cities and tourist resorts (see Figure 5.2).

In addition to the division of presently (un)developed beaches, the potential future beach development should also be taken into account, as the coast of southeast Australia is being rapidly developed (Cowell, pers. comm.). Beaches that are potentially available for future development are (located in) the so-called greenfield sites, i.e. lands that can be developed. These "greenfield beaches" comprise all (largely) undeveloped beaches that are located outside nature reserves. This implies that the (largely) undeveloped beaches within nature reserves are to be distinguished from those outside nature reserves. The above considerations have resulted in the following classification of beach development in southeast Australia:

1. Nature reserves;
2. Greenfield beaches, which are:
    a. Presently undeveloped;
    b. Presently largely undeveloped;
3. Presently largely or entirely developed beaches, with:
    a. Small-scale development;
    b. Large-scale development.

In order to apply the above classification to the coast of southeast Australia and determine the degree of development of each beach, the following criteria have been used: (i) The presence of any beach development; (ii) the length of the developed stretch of beach relative to the beach length; (iii) the landward extent of the beach development; (iv) the density of the beach development and (v) the presence of a nature or other reserve. The first of these criteria speaks for itself; the other four require some explanation. Criterion (ii) determines whether a beach is largely undeveloped or largely developed. Criteria (iii) and (iv) are a measure for the scale of the development. No strict indicator of these criteria has been defined, but as mentioned above, beaches in towns, cities and tourist resorts are usually characterised by large-scale development, while beaches with small-scale development are often located in rural areas and are backed by, for example, a campsite or a small settlement. Lastly, criterion (v) is important as it excludes any future coastal development.

Figure 5.1. Undeveloped beaches in the Royal National Park south of Sydney (own collection).

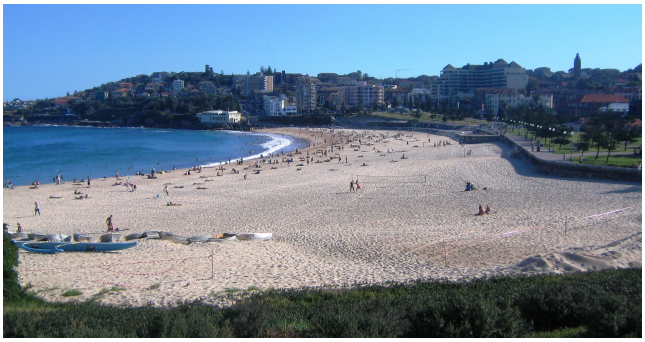

Figure 5.2. The highly developed Coogee beach in Sydney (own collection).

It should be noted that the used classification does not account for the occurrence of some small-scale coastal development in nature reserves, the occurrence of some large-scale development on largely undeveloped beaches and the fact that largely undeveloped beaches are not entirely available for future development. Also, the distinction between small-scale and large-scale development is sometimes rather arbitrary. Apart from this, the classification is based entirely on the degree of beach development and the presence of natures reserves. This means that it does not include other factors that might influence the (economic) viability of beach nourishment, such as: The tourism revenues related to the beach; the available distance or sand buffer between the sea and the beach development; and the presence of a hard barrier (a seawall or cliffs) between the sea and the beach development. However, the majority of popular tourist beaches in southeast Australia are beaches that are characterised by large-scale development (e.g. Sydney's beaches, the Gold Coast and the Sunshine Coast). Should a beach nourishment program be developed in southeast Australia, it is likely that these beaches would be nourished anyhow (as is already the case on the Gold Coast). The sand buffers and hard barriers that protect beach development against the sea are beyond the scope of this study, as this study focuses on preserving the beaches ("holding the line"; see the introduction to Chapter 4), which is independent of the available sand buffer and the presence of a hard barrier on the coast.

5.1.2 Overview of Beach Development in Southeast Australia

The beach development classification explained in Section 5.1.1 has been applied to the coast of southeast Australia. On the basis of the five criteria mentioned in Section 5.1.1, the degree of beach development of all 894 beaches in New South Wales and southeast Queensland has been mapped. This was achieved with the use of satellite images (Google Earth), the beach database and beach guides of New South Wales and southeast Queensland (Short, 1993, 2000 and pers. comm.), a few site visits and data from the national and state park services of Australia, New South Wales and Queensland (Australian Parks and Reserves, 2008). The resulting overview of beach development in southeast Australia is presented in Table 5.1 for New South Wales and Table 5.2 for southeast Queensland. It is noted that a number of nature reserves contain some small-scale coastal development, that part of the greenfield beaches are not available for future development and that the reserve and greenfield lands contain a number of popular tourist beaches. But as mentioned in Section 5.1.1, these issues are not taken into consideration.

The results in Table 5.1 show that the majority of New South Wales' beaches, 68% (35% + 33%), are still entirely or largely undeveloped and that by length, they make up an even larger portion of all beaches, 83% (42% + 41%). This implies that the (largely) undeveloped beaches are generally longer than the developed beaches, which make up 32% by number and 17% by length of all beaches. Most of these relatively short developed beaches are beaches with large-scale development (e.g. Sydney's beaches). By number, 33% of all beaches (and 41% by length) are greenfield beaches and, thus, potentially available for future development. This means that up to 65% by number (32% + 33%) and 58% by length (17% + 41%) of New South Wales' beaches can be developed, provided that the present nature reserves will not be opened for development and that there will be no new reserve beaches.

Table 5.1. Overview of beach development in New South Wales.

type of beach development	number of beaches (% of total)	combined beach length (% of total)
1. Nature reserves	270 (35%)	408 km (42%)
2. Greenfield beaches	257 (33%)	400 km (41%)
2a. Undeveloped	*191 (25%)*	*203 km (21%)*
2b. Largely undeveloped	*66 (8%)*	*197 km (20%)*
3. Presently developed	245 (32%)	162 km (17%)
3a. Small-scale development	*51 (7%)*	*28 km (3%)*
3b. Large-scale development	*194 (25%)*	*134 km (14%)*
total	772	970 km

Table 5.2. Overview of beach development in southeast Queensland.

beach development	number of beaches (% of total)	combined beach length (% of total)
1. Nature reserves	21 (17%)	237 km (51%)
2. Greenfield beaches	21 (17%)	130 km (28%)
2a. Undeveloped	*15 (12%)*	*75 km (16%)*
2b. Largely undeveloped	*6 (5%)*	*55 km (12%)*
3. Presently developed	80 (66%)	95 km (21%)
3a. Small-scale development	*7 (6%)*	*3 km (1%)*
3b. Large-scale development	*73 (60%)*	*92 km (20%)*
total	122	462 km

The results for southeast Queensland (see Table 5.2) sketch a somewhat different picture: Contrary to New South Wales, the majority of southeast Queensland's beaches, 66%, have already been developed and just 34% are still in a more or less natural state. But most of the developed beaches are located on the highly developed Gold and Sunshine Coasts. Like in New South Wales, the highly developed beaches are generally shorter than the undeveloped beaches. Therefore, by length, the majority of southeast Queensland's sandy coastline, 79% (51% + 28%), is still entirely or largely undeveloped. Nevertheless, a considerable part of the beaches, 17% by number and 28% by length, are greenfield beaches. Thus, the potentially developed stretch of the coastline of southeast Queensland takes up 83% of all beaches (66% + 17%) and 49% of the total beach length (21% + 28%).

In general, most of southeast Australia's sandy coastline is still (largely) undeveloped, but in due time, over half of the sandy coastline may be developed. At present about a fifth of the sandy coastline is developed, but fuelled by population growth, economic growth and property developers aiming at maximum development, this number is rapidly on the rise (Cowell, pers. comm.; SMH, 2006). Therefore it is not unlikely that within several decades or within the 21st century the greenfield sites will indeed be developed, leaving just the nature reserves (less than half of the sandy coastline) undeveloped.

5.1.3 Spatial Scenarios for Beach Nourishment

On the basis of the overview of beach development in southeast Australia presented in Section 5.1.2, two scenarios for the application of beach nourishment in southeast Australia have been constructed:

1. Nourishing presently developed beaches;
2. Nourishing presently developed beaches and greenfield beaches.

These scenarios will be referred to as spatial scenarios (for beach nourishment), to distinguish them from the cost scenarios associated with the sand resources that will be used for beach nourishment in

New South Wales (i.e. the costs of offshore sand vs. the costs of onshore sand, which will be addressed in Sections 5.2.2 and 5.2.3 respectively). In each spatial scenario a different number of beaches will be nourished. These numbers, as well as the combined length of the nourished beaches, have been derived from Table 5.1 and Table 5.2 and are listed in Table 5.3.

Table 5.3. Number and combined length of nourished beaches in each spatial scenario.

	New South Wales		southeast Queensland	
beach nourishment scenario	**number**	**length (% of total)**	**number**	**length (% of total)**
1. Presently developed beaches	245	162 km (17%)	80	95 km (21%)
2. Presently developed & greenfield beaches	502	562 km (58%)	101	225 km (49%)

The first spatial scenario assumes that all presently developed beaches will be nourished, including the beaches with small-scale development. Although it is more likely that beaches with large-scale development will be nourished than beaches with small-scale development, Table 5.1 and Table 5.2 show that both in New South Wales and southeast Queensland the beaches with small-scale development are relatively small in number and length. Hence, the sand demand of the beaches with small-scale development is much smaller than the sand demand of the beaches with large-scale development, which means that making a distinction between the two types of beach development will not result in significantly different outcomes. Therefore the beaches with small-scale and large-scale development are combined into a single scenario that includes all presently developed beaches.
In principle, the first scenario implies that there will be no more development of beaches in southeast Australia. This is, of course, not a very realistic scenario. In fact, as explained in Section 5.1.2, it is not unlikely that within 100 years all greenfield beaches in southeast Australia will be developed. Therefore the second spatial scenario for beach nourishment assumes that both the presently and the potential future developed beaches (i.e. the greenfield beaches) will be nourished. This assumption ignores the fact that future developed beaches do not require any sand at present nor for some years to come (depending on the rate of coastal development, which is beyond the scope of this study). Thus, this scenario should be regarded as a high estimate of the required amounts of sand and associated beach nourishment costs.

5.2 Sand Demand and Sand Costs

The costs of beach nourishment, C, are calculated by multiplying the required amount of sand, Q (in m^3), with the sand costs, c (the m^3-price):

$$C = Qc \tag{5.1}$$

The sand demand Q is different in each spatial beach nourishment scenario (see Section 5.1.3). This will be elaborated in Section 5.2.1. The sand costs c include the costs of extracting the sand from its source area, transporting it from the source area to the coast and discharging it on coast. These costs vary considerably between using offshore sand resources and onshore sand resources. As explained in Section 4.1.1, the focus in this study is on using offshore sand resources for beach nourishment. But with the present ban on offshore sand extraction in New South Wales, the use of onshore sand resources needs to be considered as well. Therefore the costs of offshore sand will be addressed in detail first (Section 5.2.2), followed by a more concise description of onshore sand prices in New

South Wales (Section 5.2.3). Other costs associated with beach nourishment, such as the costs of beach monitoring and pre-nourishment approval procedures (see Section 4.3.3), are not considered in this study.
It is important to note that all dollar values presented in this study are in 2008 Australian dollars. All earlier prices and costs that are cited have been corrected for inflation and foreign currencies have been converted into Australian dollars.

5.2.1 Sand Demand in Each Spatial Scenario

In correspondence with the sediment sharing principle explained in Section 3.2.2, as sea level rises, the sandy coast will loose part of its sediment to the seafloor in front of the rocky coast. Accordingly, the amount of sand that is eroded from southeast Australia's beaches is equal to the total amount of sand that is lost on the southeast Australian coast, i.e. the future sand losses V that have been estimated in Chapter 3. If all beaches were to be nourished, the total sand demand Q (i.e. the required amount of sand) would be equal to V. But in the spatial beach nourishment scenarios considered in this study (see Section 5.1.3), not every beach is nourished. It is assumed that in each spatial scenario the sand demand Q is a fraction α of the total sand losses V:

$$Q = \alpha V \tag{5.2}$$

with:

$$\alpha = \frac{combined\ length\ of\ nourished\ beaches}{total\ beach\ length} \tag{5.3}$$

The values of α have been presented in Table 5.3 (as percentages). It is noted that the sand demand Q does not include an overfill factor (i.e. an allowance for extra sand losses; see Section 4.3.3), which is beyond the scope of this study.

5.2.2 Offshore Sand Costs

At present, the Gold Coast is the only place in Australia where beach nourishment works are carried out with sand that has been extracted offshore. In 2006 the costs of this sand were 6.15 \$/m^3, but this sand price applies to a limited nourishment volume at a specific location with the use of a very small dredger (see Section 2.3.1). Hence, the Gold Coast sand costs cannot be applied one-to-one to the intended beach nourishment works on the entire coast of southeast Australia. Therefore the costs of offshore sand for future beach nourishment purposes in southeast Australia will be based not only on the Gold Coast sand costs, but also on the sand costs of beach nourishments overseas and the cost price of dredging operations. It is important to note that only the costs of nearshore nourishments are considered, as it is assumed in this study that the nourishment sand will be placed nearshore rather than on the dry beach (see Section 4.3.1).
Although nearshore nourishments are applied in several countries, the only places for which the offshore sand costs of nearshore nourishments are available are Denmark and the Netherlands. These sand costs, as well as the offshore sand costs on the Gold Coast (which are assumed to apply to nearshore nourishments), are presented in Table 5.4. The shown prices include the costs of mobilizing

and demobilizing a trailing suction hopper dredger. Table 5.4 also lists three factors that strongly influence the offshore sand costs: The sailing distance between the extraction area and the coast, the nourishment volume and the size of the trailing suction hopper dredger (NSCMG, 2000; Hollemans, pers. comm.).

Table 5.4. Offshore sand costs of nearshore nourishments in various countries, with indicative values of three major price factors. Prices are in 2008 Australian dollars (from: NSCMG, 2000; TAW, 2002; GCCM, pers. comm.).

country	sand costs	sailing distance	nourishment volumes	dredger size
Australia (Gold Coast)	6.54 $/m^3 [a)]	6 km	100,000's of m^3	very small
Denmark	5.36 $/m^3 [b)]	6 km	100,000's of m^3	NA
Netherlands	2.06-3.09 $/m^3 [b)]	7-17 km	1-2 million m^3	mostly medium

[a)] 2006 price (6.15 $/m^3) increased with 2.9% and 3.4% inflation in 2007 and 2008, respectively.

[b)] 1999 prices (2.6 €/m^3 in Denmark, 1-1.5 €/m^3 in the Netherlands) increased with 9 years of 2.5% inflation and converted into Australian dollars using the average exchange rate over 2005-2008 (1 € = 1.65 $).

Table 5.4 shows that the sand costs of nearshore nourishments vary considerably. Given the larger sailing distances in the Netherlands compared to the Gold Coast and Denmark, the lower sand costs in the Netherlands can probably be attributed to larger nourishment volumes and the use of larger dredgers, which offer economies of scale (see below). The influence of the sailing distance, the nourishment volume and the dredger size on the cost price of dredging (in terms of the costs per m^3 sand) is shown in detail in Figure 5.3 and Figure 5.4. These figures are based on the calculation of the cost price of dredging for nearshore nourishments, which is elaborated in the Appendix. The maximum considered value of the sailing distance between the offshore sand extraction areas and the beaches is takes as 20 km, since, according to Roy (2001), every location on the coast of New South Wales is within 20 km of huge quantities of marine sand[9]. It is assumed that this value also holds for southeast Queensland (see Section 4.1.2 for details on the offshore sand resources in southeast Australia). The selected range of nourishment volumes, 0.5-2 million m^3, is typical of nourishment projects in various countries (e.g. NSCMG, 2000).

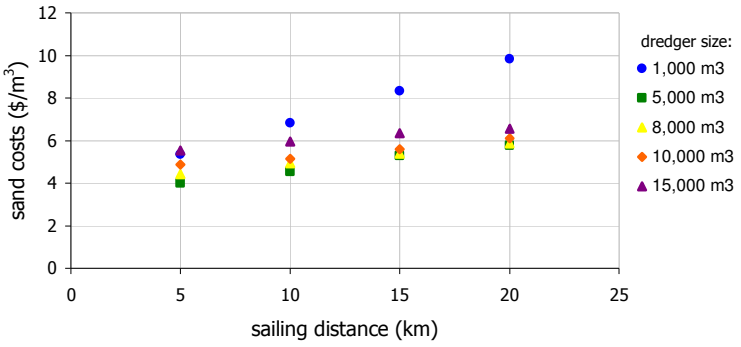

Figure 5.3. Indicative cost price of dredging (per m^3 sand) for various sailing distances and dredger sizes, with a fixed nourishment volume of 1 million m^3 (see the Appendix for details).

Figure 5.3 and Figure 5.4 show that for relatively large sailing distances (≥ 10 km) and nourishment volumes (≥ 1 million m^3), the selected medium (5,000 m^3 and 8,000 m^3) and large (10,000 m^3 and 15,000 m^3) trailing suction hopper dredgers offer economies of scale compared to small (1,000 m^3)

[9] Sailing distances may be larger than 20 km if only a few sites along the coast will be opened for offshore sand extraction. This possibility, however, is not considered.

dredgers. Although operational costs of medium and large dredgers are much higher than those of small dredgers, their production rates are disproportionally larger (see Table 5.5), which becomes more profitable with increasing sailing distances and nourishment volumes. In general, as the graphs show, for all considered sailing distances and nourishment volumes the deployment of a medium-sized trailer results in the lowest sand costs.

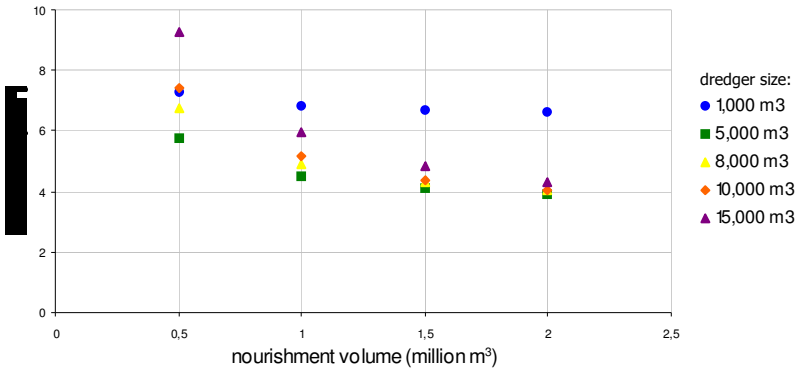

Figure 5.4. Indicative cost price of dredging (per m^3 sand) for various nourishment volumes and dredger sizes, with a fixed sailing distance of 10 km (see the Appendix for details).

Table 5.5. Selected dredger sizes with indicative costs and production rates (see the Appendix for details).

dredger size	hopper volume	operational costs per week	production per week
small	1,000 m^3	$ 300,000	32,000-61,000 m^3
medium	5,000 m^3	$ 800,000	175,000-285,000 m^3
medium	8,000 m^3	$ 1,200,000	296,000-456,000 m^3
large	10,000 m^3	$ 1,500,000	390,000-570,000 m^3
large	15,000 m^3	$ 2,200,000	675,000-990,000 m^3

From the above it is clear that the offshore sand costs depend on a number of future factors that are largely unknown at present (e.g. sailing distances and nourishment volumes). This uncertainty can be conveniently managed by adopting a symmetrical triangular pdf, which is common practice with regard to the prices of raw materials (such as oil; Van Gelder, pers. comm.). The lower bound of the triangular pdf is set as 3 $/$m^3$. This is slightly less than the lowest values of the estimated cost price of dredging (about 4 $/$m^3$; see Figure 5.3, Figure 5.4 and Table A.5 in the Appendix), but given the low sand costs in the Netherlands (about 2-3 $/$m^3$; see Table 5.4) and the fact that sailing distances may be less than 5 km (which is the minimum considered sailing distance in the Appendix), it is assumed that the dredging costs estimated in the Appendix may have been overestimated. It is unlikely, though, that the offshore sand costs in southeast Australia will be as low as the lowest sand price in the Netherlands, as the sailing distances between nourishment sites and to harbours (for restocking) are expected to be much longer in Australia.

It is assumed that a medium-sized dredger (with a hopper volume of about 5,000-8,000 m^3) will be deployed for the intended beach nourishment works in southeast Australia, because, as explained above, this is most economical. Based on this assumption, the upper bound of the pdf for the offshore sand costs is set as 7 $/$m^3$, which is approximately the highest estimated cost price of deploying a medium-sized dredger (see Figure 5.3, Figure 5.4 and Table A.5 in the Appendix). It is also slightly higher than the current offshore sand costs at the Gold Coast, because it is expected that, for the entire southeast Australian coast, the sailing distances between the sand extraction areas and the coast will be

generally longer than the relatively short sailing distances on the Gold Coast (see Table 5.4). It is unlikely that the offshore sand costs will be considerably higher than those on the Gold Coast, though, because the intended deployment of medium or large dredgers will offer economies of scale compared to the very small dredger currently deployed on the Gold Coast. The resulting pdf for the offshore sand costs is depicted in Figure 5.5.

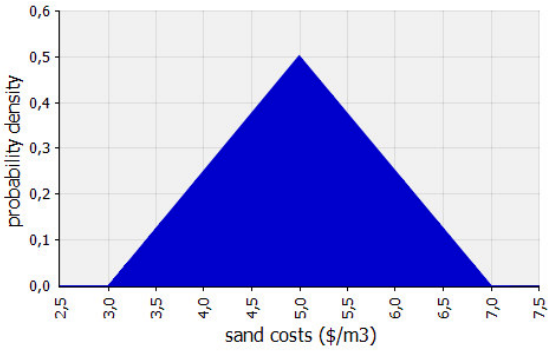

Figure 5.5. Triangular pdf for offshore sand costs.

5.2.3 Onshore Sand Costs

Compared to offshore sand resources, the costs of using onshore sand resources for beach nourishment are usually considerably higher. As indicated in Sections 4.1.1 and 4.4.2, this may be due to the scarcity of onshore sand resources, competing sand consumers and road transportation costs. Current (2008) prices of delivering sand sourced from dunes, rives and sandstone quarries in the Sydney region to Sydney's central business district (which is close to the coast) are 12-31 $/tonne (Skene, pers. comm.), or about 20-50 $/m^3 of dry sand. These prices include the costs of producing and trucking the sand. The production of sand includes mining the sand and some processing of material to make it suitable for the building industry (e.g. sorting). The latter action may not be necessary for beach nourishment purposes. Hence, on the one hand the costs of delivering sand from onshore sources to the coast may be somewhat lower than the prices cited above. But on the other hand, these prices do not include the costs of distributing the delivered sand across the beach with bulldozers[10], which would add to the sand costs. The trucking costs, finally, are highly dependent of the road distance between the sand source and delivery areas. The road distances associated with the cited sand prices are between 2 and 187 km, thus covering a wide range.

Based on the above considerations and in the absence of more information, it is assumed that the range of 20-50 $/m^3 is representative of the costs of delivering onshore sand to the coast and placing it onto the beaches in entire New South Wales. As with the offshore sand costs, a symmetrical triangular pdf is assigned to the onshore sand costs. Following the cited price range, the pdf for the onshore sand costs has a lower bound of 20 $/m^3, a modal value of 35 $/m^3 and an upper bound of 50 $/m^3 (see Figure 5.6).

[10] This implies that the nourishment sand is placed on the dry beach rather than on the nearshore. As explained in Section 2.3.1, nearshore placement has several advantages over dry beach placement, but in case of using onshore sand sources and delivering the sand to the coast with trucks, nearshore placement would be very unusual and inefficient.

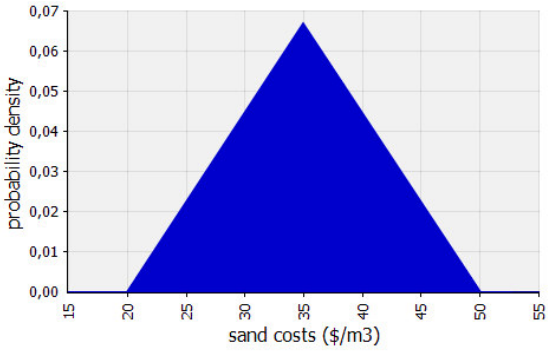

Figure 5.6. Triangular pdf for onshore sand costs in New South Wales.

5.3 Estimating the Future Beach Nourishment Costs

With the data presented in Sections 5.1 and 5.2, the future beach nourishment costs in southeast Australia can be estimated. The expressions that are used for this purpose, as well as an overview of their input data, are presented in Section 5.3.1. In correspondence with the calculation of the future sand losses in Section 3.6, the expressions are evaluated by means of Latin Hypercube simulations. The settings of these simulations are provided in Section 5.3.1 as well. The results of the simulations are presented in Section 5.3.2 and discussed in Section 5.3.3. In Section 5.3.4 the sensitivity of the results to changes in the input data is analysed.

5.3.1 Expressions, Input Data and Simulation Settings

Substituting Eq. (5.2) into Eq. (5.1) and making a distinction between New South Wales and southeast Queensland gives expressions for the costs of applying beach nourishment in each state:

New South Wales: $$C_{NSW} = \alpha V_{NSW} c \tag{5.4}$$

Southeast Queensland: $$C_{SQld} = \alpha V_{SQld} c \tag{5.5}$$

The future sand losses V_{NSW} and V_{SQld} have been determined with Eqs. (3.19) and (3.20) and have been presented in Section 3.6.3. The values of α, the proportion of the sandy coast that is nourished in each spatial scenario, and c, the sand costs for both offshore and onshore sand sourcing, are listed in Table 5.6 and Table 5.7 respectively. In time, both offshore and onshore sand resources available for extraction may become scarcer and/or located further away from the coast. Also, when sea level rise continues to accelerate, when more beaches are nourished and/or when the building industry continues to expand, the future demand for sand may grow. Such developments are expected to cause an increase in the sand prices. Conversely, an increasing demand for sand will offer economies of scale with regard to deploying a dredger, which will lower the sand prices. The above developments are very uncertain, though, and are not considered in more detail. Essentially, the sand costs are assumed to remain constant (in 2008 Australian dollars) throughout the 21st century, and thus supposed to be independent of the sand demand, αV.

Table 5.6. Nourished proportion of the sandy coast α in each spatial beach nourishment scenario (see Sections 5.1.3 and 5.2.1 for details).

beach nourishment scenario	New South Wales	southeast Queensland
1. Presently developed	17%	21%
2. Presently developed & greenfield beaches	58%	49%

Table 5.7. Sand costs c for offshore and onshore sand resources (see Sections 5.2.2 and 5.2.3 for details).

sand resources	low value	modal value	high value	pdf
offshore	3 \$/m^3	5 \$/m^3	7 \$/m^3	triangular
onshore	20 \$/m^3	35 \$/m^3	50 \$/m^3	triangular

A total of six sets of results will be evaluated to estimate the future beach nourishment costs: Four for New South Wales (two spatial scenarios · two sand costs scenarios) and two for southeast Queensland (two spatial scenarios · one sand costs scenario, i.e. offshore sand sourcing). Eqs. (5.4) and (5.5) are evaluated by means of Latin Hypercube simulations with 1,000 iterations per simulation (see Section 3.6.2 for details on this sampling method). For reasons of efficiency, the results that are presented in Section 5.3.2 reflect the outcome of a single simulation. This simulation has the same seed[11] value (i.e. 18) as the simulation used to present the estimated future sand losses in Section 3.6.3. This means that both simulations use the exact same sequence of random numbers and draw the same samples from the input pdfs. Hence, the values of the future sand losses V_{NSW} and V_{SQld} evaluated here to estimate the beach nourishment costs are identical to the values presented in Section 3.6.3.

5.3.2 Results

The future costs of beach nourishment in southeast Australia, as resulting from the simulations, are presented in Figure 5.7, Figure 5.8 and Figure 5.9 by means of cumulative probability curves. The risk levels that are marked in the graphs, 50%, 10% and 1%, are also listed in Table 5.8. The results represent the outcome of a single simulation, which is allowed since the spread in the results of 100 different simulations was found to be very small: For a 50% risk level, 90% of the sampled values deviate less than ± 3% from the values presented here. For risk levels of 10% and 1%, these deviations increase to ± 4% and ± 9% respectively.

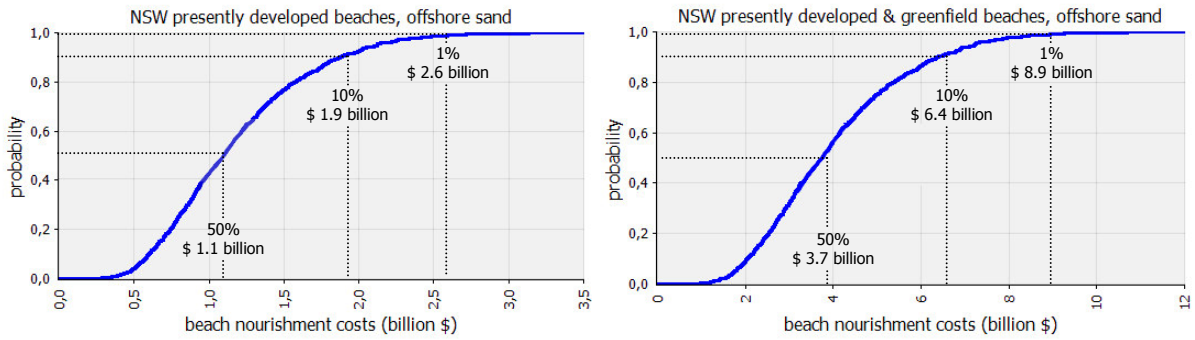

Figure 5.7. Beach nourishment costs in New South Wales until 2100 with the use of offshore sand resources.

[11] The seed is the number that initializes the selection of numbers by a random number generator.

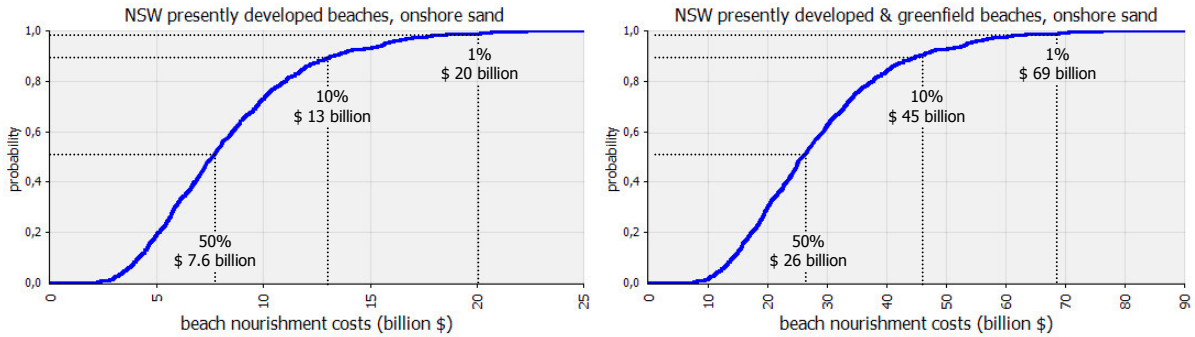

Figure 5.8. Beach nourishment costs in New South Wales until 2100 with the use of onshore sand resources.

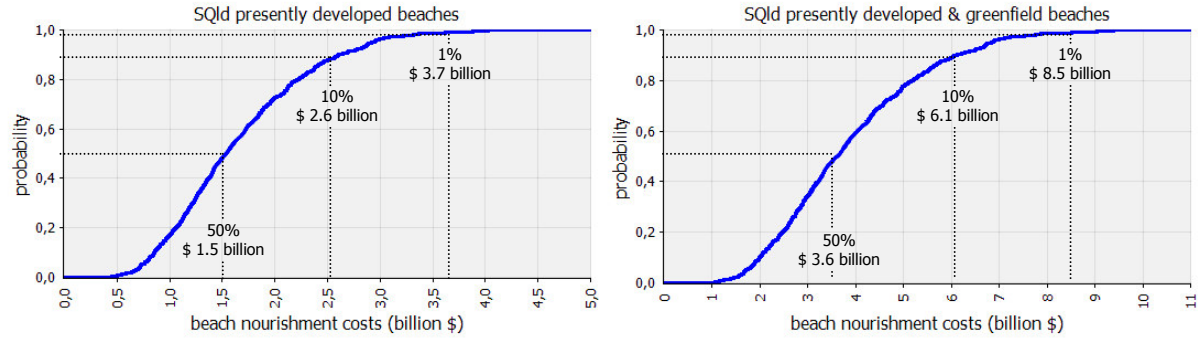

Figure 5.9. Beach nourishment costs in southeast Queensland until 2100 with the use of offshore sand resources.

Table 5.8. Selected values of beach nourishment costs until 2100 for each spatial beach nourishment scenario.

	presently developed beaches			**presently developed & greenfield beaches**		
beach nourishment costs	**50% risk**	**10% risk**	**1% risk**	**50% risk**	**10% risk**	**1% risk**
$C_{NSW;offshore}$	$ 1.1 billion	$ 1.9 billion	$ 2.6 billion	$ 3.7 billion	$ 6.4 billion	$ 8.9 billion
$C_{NSW;onshore}$	$ 7.6 billion	$ 13 billion	$ 20 billion	$ 26 billion	$ 45 billion	$ 69 billion
C_{SQld}	$ 1.5 billion	$ 2.6 billion	$ 3.7 billion	$ 3.6 billion	$ 6.1 billion	$ 8.5 billion

5.3.3 Discussion of the Results

The results presented in the previous section show that in case of using offshore sand resources, the 21st century beach nourishment costs in New South Wales, $C_{NSW;offshore}$, and southeast Queensland, C_{SQld}, are more or less equal. In the first spatial scenario (i.e. nourishing all presently developed beaches), the values for New South Wales are slightly lower than the values for southeast Queensland. This is in correspondence with the fact that in New South Wales the proportion of the sandy coast that is nourished in this scenario (see Table 5.6) and the future sand losses (see Section 3.6.3) are smaller than in southeast Queensland. In the second spatial scenario (i.e. nourishing all presently developed and greenfield beaches), the opposite is true, since the portion of the sandy coast that is nourished in this scenario is considerably larger in New South Wales than in southeast Queensland (see Table 5.6). Following the linear relation of Eqs. (5.4) and (5.5) between the beach nourishment costs and the nourished portion of the sandy coast, at each risk level the ratio between the beach nourishment costs in the first and second spatial scenarios are equal to the corresponding ratios between the values of the nourished portion of the sandy coast: Approximately 3.4 in New South Wales and 2.3 in southeast Queensland (see Table 5.6).

At a risk level of 1% the future beach nourishment costs are roughly 2.5 times higher than the beach nourishment costs at a risk level of 50%. This ratio is similar to the ratio between the estimated future sand losses at a risk level of 1% and 50%, which is about 2.2 (see Section 3.6.3).

In case of using onshore sand resources in New South Wales, the estimated costs of beach nourishment, $C_{NSW;onshore}$, are about seven times higher than in case of using offshore sand resources. This is in correspondence with the fact that the costs of onshore sand are about seven times higher than the costs of offshore sand (see Table 5.7). As a result, if the ban on offshore sand extraction is New South Wales is not lifted and onshore instead of offshore sand resources are used for the intended beach nourishment programme, the associated costs will be approximately seven times higher. In correspondence with the linear relation of Eq. (5.4) between the beach nourishment costs and the sand costs, the ratios between the values of $C_{NSW;onshore}$ at different risk levels and in different spatial scenarios are the same as for $C_{NSW;offshore}$.

Given the length of the sandy coastline (970 km; see Table 5.1) and the proportion of the sandy coast that is nourished in the first spatial scenario (17%; see Table 5.6), the median costs of nourishing New South Wales' beaches with offshore sand amount to about $ 6,670 per meter beach ($ 1.1 billion/(0.17·970,000 m)). In southeast Queensland (with a sandy coastline of 462 km, of which 21% is nourished in the first spatial scenario; see Table 5.2 and Table 5.6), this value is about $ 15,460 per meter beach ($ 1.5 billion/(0.21·462,000 m)). These numbers are roughly on the same order of magnitude as the costs estimated in a similar study in the USA (Titus and Greene, 1989), which has been addressed in Section 3.6.4. Titus and Greene found that the costs of replenishing the 21st century sand losses due to sea level rise are about $ 12,000 and $ 21,000 (in 2008 Australian dollars[12]) per meter beach for a rise in sea level of 50 cm and 100 cm respectively. It should be noted that these numbers are based on beach nourishment by means of pumping the sand ashore (which is generally more expensive than placing the sand on the nearshore) and that they include a contribution for the raising of a number of barrier islands.

When assuming the intended beach nourishment works in southeast Australia are equally divided over the planning period considered in this study (100 years), the future annual beach nourishment costs can be straightforwardly obtained by dividing the values of Table 5.8 by 100 years. The resulting values are presented in Table 5.9.

Table 5.9. Estimated future annual beach nourishment costs in southeast Australia.

	presently developed beaches			**presently developed & greenfield beaches**		
beach nourishment costs	**50% risk**	**10% risk**	**1% risk**	**50% risk**	**10% risk**	**1% risk**
$C_{NSW;offshore}$	$ 11 million	$ 19 million	$ 26 million	$ 37 million	$ 64 million	$ 89 million
$C_{NSW;onshore}$	$ 76 million	$ 130 million	$ 200 million	$ 260 million	$ 450 million	$ 690 million
C_{SQld}	$ 15 million	$ 26 million	$ 37 million	$ 36 million	$ 61 million	$ 85 million

5.3.4 Sensitivity Analysis

The correlation coefficients listed in Table 5.10 (see Section 3.6.5 for an explanation of the correlation coefficients) show there is a strong linear and positive relation between the future beach nourishment costs, *C*, and the amount of sea level rise, *s*, and between the future beach nourishment costs and the limiting depth of the area being raised, *h*. There is also a moderately strong linear and positive relation

[12] 1989 US dollars have been increased with 19 years of 2.5% inflation and converted into Australian dollars using an exchange rate of 1 US$ = 1.5 AU$.

between the beach nourishment costs and the sand costs, c, while the linear relation between the beach nourishment costs and the rocky portion of the New South Wales seafloor, ρ, is rather weak and negative.

Table 5.10. Correlation coefficients between beach nourishment costs and input parameters.

beach nourishment costs	s	h	ρ	$c_{offshore}$	$c_{onshore}$
$C_{NSW;\ offshore}$	0.64	0.63	-0.20	0.35	n/a
$C_{NSW;\ onshore}$	0.64	0.61	-0.18	n/a	0.40
C_{SQld}	0.65	0.65	n/a	0.36	n/a

The above findings are supported by Figure 5.10, which shows the sampled and fitted probability density curves of the future beach nourishment costs in New South Wales in case all presently developed beaches are nourished with offshore sand. Based on a K-S test, the pdf that fits the sampled values best is a gamma distribution. The gamma pdf is roughly similar in shape to the Weibull pdf, which is the pdf that has been assigned to sea level rise (see Figure 3.12). This suggests that the future beach nourishment costs are strongly influenced by the amount of sea level rise. The fact that the fitted gamma distribution is more asymmetrical and peaked than the Weibull distribution of sea level rise suggests that the triangular pdf of the limiting depth of the area being raised (see Figure 3.6) also strongly affects the future beach nourishment costs.

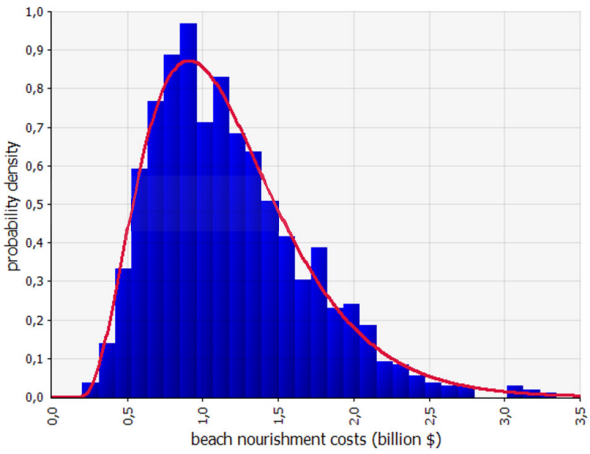

Figure 5.10. Sampled and gamma probability density curves of future beach nourishment costs in New South Wales in case all presently developed beaches are nourished with offshore sand.

Hence, in order to assess the future costs of beach nourishment in southeast Australia more accurately, the key factor is to reduce the uncertainties associated with sea level rise and the limiting depth of the area being raised.

5.4 Valorisation of the Results

The results of the present study can be used to develop a beach nourishment programme in southeast Australia. Developing such a programme can be considered as being part of strategic planning to manage the risk posed by the projected rise of sea level. Strategic planning with regard to beach nourishment requires, amongst others, an insight into the amounts of sand and money that are involved. These amounts have been determined in the present study (in Chapter 3 and 5, respectively).

It also requires an understanding of the tactical issues involved with beach nourishment, such as the engineering aspects (e.g. dredging operations), the available sand resources and the ecological impacts. An overview of these issues has been provided by this study as well (in Chapter 4). Furthermore, the estimated beach nourishment costs can be used to determine an economically optimum beach nourishment strategy. This will be demonstrated in Section 5.4.1. Lastly, a key question related to the development of a beach nourishment strategy is: When and where to start nourishing? This question will be addressed in Section 5.4.2.

5.4.1 Economic Optimisation of Beach Nourishment

As mentioned in Section 5.1.1, the economic viability of applying beach nourishment may depend on several factors, such as the value of the beach properties, tourism revenues from the beach and the presence of a hard barrier between the sea and the beach properties. When a beach is not protected against sea level rise and suffers erosion, these factors pose a financial risk (e.g. possible damage to the beach properties and the loss of tourism revenues). This financial risk can be compared to the beach nourishment costs, for example with the stochastic economic optimisation model for the coastal zone developed by Van Vuren et al. (2003, 2004). In this model the total costs of a beach nourishment project are defined as the beach nourishment costs plus the financial risk, i.e. the expected damage to beach properties, tourism, etc (see Figure 5.11). Figure 5.11 shows how large beach nourishment efforts (indicated by high beach nourishment costs and a low risk level) are accompanied by a low financial risk (i.e. the expected damage is low), and vice versa. The economic optimum risk level (or safety level) of a beach nourishment project can be obtained by finding the minimum total costs.

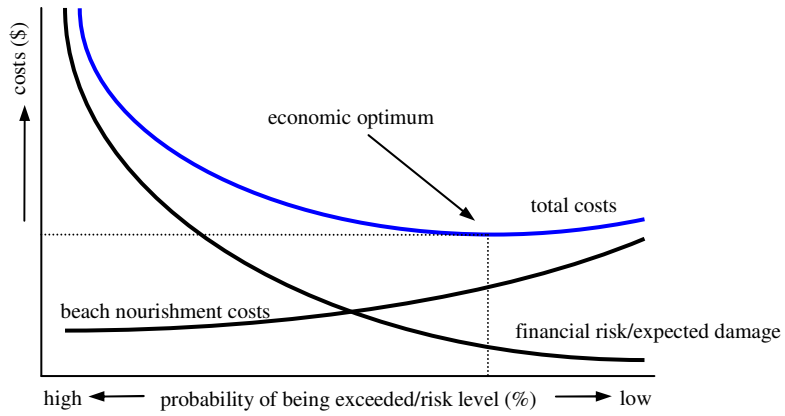

Figure 5.11. Economic optimisation of beach nourishment.

The future beach nourishment costs in southeast Australia have been determined in the present study, but detailed data of the financial risk posed by sea level rise is largely unknown at present, except for Collaroy/Narrabeen beach in Sydney (Hennecke et al., 2004). Hence, determining the economically optimum risk (or safety) level for each stretch of coast in southeast Australia would first require a study into the expected damage on the coast due to sea level rise. Nevertheless, it can be expected that it will be economically viable to nourish many of the developed beaches in southeast Australia against the impact of sea level rise and to adopt a relatively low risk level (or high safety level). This is indicated by the low costs of beach nourishment (generally several millions of dollars per project) compared to the estimated value of the properties along Collaroy/Narrabeen beach (at least $ 300

million; Cameron and Corbett, 2005), the estimated tourism revenues from Sydney's Manly beach (at least $ 70 million per year; SCCG, 2006) and the estimated benefit-cost ratio of over 60 to 1 of a coastal protection project (including a large beach nourishment) on the northern Gold Coast in the late 1990's (Raybould and Mules, 1998).

5.4.2 When and Where to Start Nourishing Beaches?

One of the main problems in dealing with climate change and sea level rise is the large uncertainty regarding the magnitude, the impacts and the costs. Consequently, the debate over policy responses to climate change and sea level rise "is often framed as a choice of acting now or waiting until the uncertainty is reduced" (Webster, 2002). Delaying action avoids the future regret of having spent too much on mitigation measures if, after some time, the impacts of climate change turn out to be relatively low. Conversely, taking action now avoids the future regret of having underestimated the impacts of climate change. Hence, Webster (2002) argues that in case the damage due to climate change is expected to be low, it is often preferred to delay action, and vice versa.

With regard to the present study, the above implies that one of the key issues related to the intended beach nourishment programme in southeast Australia is the question whether to start nourishing immediately or after 10 years or so, when the effects of sea level rise are probably better understood or more visible. On the one hand, sea level rise is a slow process and does not pose an immediate threat to coastal communities in southeast Australia. Thus, the expected damage due to sea level rise within the next 10 years or so is relatively low. In addition, the costs of beach nourishment are considerable and nourishing beaches prematurely could be a large waste of money. According to Webster (2002), these notions support delaying action and waiting until the effects of sea level rise are more visible or better understood. On the other hand, in the unlikely event of an extreme storm hitting the coast within the next 10 years, the damage to beach properties and tourism will be huge. Already, the beach properties along a number of beaches in southeast Australia that suffer heavily from erosion (so-called erosion hotspots, like Collaroy/Narrabeen; see Figure 4.3) are under significant threat. As mentioned in Section 5.4.1, the benefits of nourishing such beaches are expected to outweigh the costs amply. These notions support taking action and starting to nourish immediately.

Within the context of developing a beach nourishment strategy for the entire coast of southeast Australia, addressing the erosion hotspots now is favourable as well. Starting to nourish the erosion hotspots requires the acquisition of an initial limited capacity to nourish beaches (i.e. a dredger, beach monitoring, ecological studies, etc). This "capacity building" then allows for the tactical issues (e.g. the engineering aspects, the ecological impact) to be evaluated, such that when the effects of sea level rise are more visible and large-scale action is required, the experience is there and the knowledge is far more advanced than if nothing at all is done. If more beaches need to be nourished, the initial limited capacity can be "scaled up" to meet the required capacity. Beach nourishment is a highly flexible coastal protection measure and can be readily scaled up to meet future demands (e.g. by deploying a dredger for a longer period of time). To sum up, starting to nourish the erosion hotspots now would be of great value to the development of a beach protection strategy for the entire coast of southeast Australia.

5.5 Conclusions and Discussion

The economic viability of applying beach nourishment depends strongly on the degree of beach development. A beach development classification has been set up to map the degree of beach development along the coast. The resulting overview of beach development shows that currently about 20% of the sandy coastline of southeast Australia is developed. This number may increase up to 60% if all greenfield beaches are developed, leaving only the nature reserves undeveloped. On this basis, two spatial scenarios for the application of beach nourishment have been constructed: (i) Nourishing presently developed beaches and (ii) nourishing presently developed and greenfield beaches. Each of these two spatial scenarios requires a different amount of sand to be replenished. The costs of replenishing the sand are calculated by multiplying the sand demand in each spatial scenario with the sand costs. In case of offshore sand extraction, the deployment of a medium-sized trailing suction hopper dredger results in the lowest sand costs, which range between 3 and 7 $\$/m^3$ and have been assigned a symmetrical triangular pdf. Offshore sand extraction is currently prohibited in New South Wales; onshore sand prices range from 20 to 50 $\$/m^3$ and have also been assigned a symmetrical triangular pdf.

The resulting 21st century beach nourishment costs in case of offshore sand extraction and in case of nourishing the presently developed beaches only, are \$ 1.1 to 2.6 billion in New South Wales and \$ 1.5 to 3.7 billion in southeast Queensland, where the actual amount of money depends on the selected risk level (between 1 and 50%). In addition, when both the presently developed beaches and the greenfield beaches are nourished, these amounts of money increase to \$ 3.7 to 8.9 billion in New South Wales and \$ 3.6 to 8.5 billion in southeast Queensland. Accordingly, the annual beach nourishment costs are \$ 11 to 89 million in New South Wales and \$ 15 to 85 million in southeast Queensland, depending on the selected risk level and spatial scenario.

Conversely, when the beaches of New South Wales are nourished with sand that has been extracted onshore, the costs of nourishing the presently developed beaches are \$ 7.6 to 20 billion and the costs of nourishing the presently developed and greenfield beaches are \$ 26 to 69 billion, where the actual amount of money depends on the selected risk level (between 1 and 50%). Hence, in case of onshore sand extraction, the annual beach nourishment costs in New South Wales are \$ 76 to 690 million, depending on the selected risk level and spatial scenario. Besides the used sand resources (offshore vs. onshore), the future beach nourishment costs depend strongly on the amount of sea level rise and the value of the limiting depth of the active beach profile.

The above results can be used to develop an economically optimum beach nourishment programme in southeast Australia. Within the context of developing such a programme, starting to nourish the beaches that are already heavily eroding now will be of great value.

6 Conclusions and Recommendations

6.1 Conclusions

The present study has resulted in an estimate of the offshore sand losses due to sea level rise in southeast Australia and the associated beach nourishment costs. By following a probabilistic approach instead of a more commonly used deterministic approach, the results have been expressed in terms of their probability distributions rather than a single outcome. A deterministic approach would not be appropriate in dealing with sea level rise, because it does not take into account the considerable uncertainty associated with sea level rise and its impact on the coast. Instead, with the current probabilistic approach this uncertainty has been expressed in terms of probabilities, which can be used to develop an economically optimum beach nourishment strategy in southeast Australia and which have led to the following conclusions:

- The offshore sand losses due to sea level rise in the 21st century are between 1.3 and 2.9 billion m^3 in New South Wales and between 1.5 and 3.3 billion m^3 in southeast Queensland, where the actual value depends on the selected risk level (between 1 and 50%).

- The offshore sand resources of southeast Australia contain enough good quality sand to replenish the estimated sand losses.

- Offshore sand extraction and beach nourishment can be undertaken without causing significant impacts on the coastline, the marine environment and the surfing conditions in southeast Australia.

- At present, about 20% of the sandy coastline of southeast Australia has been developed. Within the 21st century, this number may increase up to 60%, leaving only the nature reserves undeveloped.

- The lowest beach nourishment costs are achieved by extracting sand offshore with a medium-sized trailing suction hopper dredger and placing the sand on the nearshore. These costs can be decreased if the dredger is utilized for commercial sand extraction as well (i.e. for the building industry).

- In case of offshore sand extraction, the costs of nourishing all presently developed beaches against the impact of sea level rise in the 21st century are between 1.1 and 2.6 billion Australian dollars in New South Wales and between 1.5 and 3.7 billion Australian dollars in southeast Queensland. In addition, the costs of nourishing all presently and future developed beaches are between 3.7 and 8.9 billion Australian dollars in New South Wales and between 3.6 and 8.5 billion Australian dollars in southeast Queensland. The actual amount of money depends on the selected risk level (between 1 and 50%).

- If the ban on offshore sand extraction in New South Wales is not lifted, the beach nourishment costs in New South Wales in the 21st century are about seven times higher than in case offshore sand extraction is allowed. With the use of onshore sand resources, the costs of nourishing all presently developed beaches are between 7.6 and 20 billion Australian dollars and the costs of nourishing all presently and future developed beaches are between 26 and 69 billion Australian dollars, where the actual amount of money depends on the selected risk level (between 1 and 50%).

- Given the high value of beach properties and the high tourism revenues from many developed beaches in southeast Australia, beach nourishment will be an economically viable method of protecting these beaches against the impact of sea level rise.

- Due to its flexibility and scalability, beach nourishment is an appropriate protection measure against the impact of sea level rise, which is associated with considerable uncertainty.

Based on the above findings, it can be concluded that beach nourishment will be an effective method to mitigate the impact of sea level rise on the coast of southeast Australia.

6.2 Recommendations

The main recommendations of the present study are:

- The beaches that are already heavily suffering from erosion should be nourished straight away. Besides protecting the properties along these beaches, this allows for capacity building and the gaining of experience and knowledge, which will be of great value to the development of a beach nourishment programme for the entire coast of southeast Australia.

- Given the uncertainty associated with the limiting depth of the area being raised by sea level rise, initial beach nourishments should be aimed at maintaining the sand volume within the nearshore zone. Monitoring the response of the shoreface to the rising sea level will provide a better understanding of the actual sand losses due to sea level rise, to which the beach nourishment capacity can be adjusted.

- In order to develop an economically optimum beach nourishment programme, it is required to undertake a study into the expected damage on the coast due to sea level rise. The expected damage should be based not only on the degree of beach development, but also on the tourism revenues related to the beach, the sandy buffer between the sea and the beach properties, the presence of a hard barrier between the sea and the beach properties and the value of the beach properties.

- The rate of coastal development should be incorporated in the formulation of the amount of sand required to nourish the greenfield beaches, such as to account for the fact that this amount of sand is presently zero, but will increase with time.

- In order to account for uncertainties associated with the sharing of sediment between the beaches and the rocky coast and, hence, the amount of sand the beaches loose to the rocky coast, the fraction of the total future sand losses that is required to nourish the beaches should be assigned a range of values and a probability distribution, rather than a single value.

- In order to assess the future sand losses and beach nourishment costs more accurately, the focus should be on reducing the uncertainties associated with the amount of sea level rise and the limiting depth of the area being by sea level rise.

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Appendix The Cost Price of Dredging

The cost price of nearshore nourishments performed by trailing suction hopper dredgers can be estimated with the data listed in Table A.1. Five trailer sizes have been selected; trailers with a hopper volume of more than 15,000 m^3 are generally to deep to perform nearshore nourishments (see Section 4.2.1).

Table A.1. Indicative capabilities and costs of trailing suction hopper dredgers. Costs are in 2008 Australian dollars (from: Bray et al., 1997; Hollemans, 2005; Hollemans and Van der Schrieck, pers. comm.).

	dredger size				
dredger properties	**small**	**medium**	**medium**	**large**	**large**
hopper volume	1,000 m^3	5,000 m^3	8,000 m^3	10,000 m^3	15,000 m^3
sand load [a)]	1,000 m^3	5,000 m^3	8,000 m^3	10,000 m^3	15,000 m^3
sailing speed [b)]	10 knots	12.5 knots	14 knots	15 knots	16 knots
loading time [c)]	0,5 hr	1 hr	1 hr	1 hr	1 hr
unloading time [c) d)]	0,5 hr	0,5 hr	0,5 hr	0,5 hr	0,5 hr
sea conditions downtime per week [e) f)]	34 hrs (20%)	25 hrs (15%)	25 hrs (15%)	25 hrs (15%)	17 hrs (10%)
mechanical downtime per week (3%) [f)]	5 hrs	5 hrs	5 hrs	5 hrs	5 hrs
operational downtime per week (5%) [f) g)]	8 hrs	8 hrs	8 hrs	8 hrs	8 hrs
operational costs per week [h)]	$ 300,000	$ 800,000	$ 1,200,000	$ 1,500,000	$ 2,200,000
(de)mobilization costs per week [i)]	$ 225,000	$ 600,000	$ 900,000	$ 1,125,000	$ 1,650,000

[a)] For sand the load factor of the hopper volume is close to 100%.

[b)] 1 knot ≈ 1.85 km/hr.

[c)] Larger dredgers usually have more powerful pumps, which means average (un)loading times are more or less similar for various dredger sizes (only the smallest dredgers have a much shorter (un)loading time).

[d)] In case of dumping and/or rainbowing (see Section 4.3.1) the sand on the nearshore, which is the assumed method of sand placement in the present study (see Section 4.3.1).

[e)] The maximum wave height at which a dredger can operate increases with size of the dredger (see Table 4.2).

[f)] Percentages of the service time per week, 168 hrs (in case of 24/7 operations).

[g)] Required for restocking.

[h)] Including the costs of running the vessel, the costs of the crew and a risk and profit margin.

[i)] Assumed to be 75% of the weekly operational costs.

In order to estimate the dredging costs, the production rates of the selected dredgers need to be determined. The production of a dredger is strongly dependent of the sailing distance between the sand extraction area and the nourished beach and is explained in Table A.2. Because this procedure is the same for any given dredger size and sailing distance, only one example is shown: A trailer with a hopper volume of 5,000 m^3 and a sailing distance of 10 km.

The procedure explained in Table A.2 has been repeated for the five selected trailers (see Table A.1) and for four different sailing distances: 5 km, 10 km, 15 km and 20 km (20 km is assumed to be the maximum distance between the coastline and the intended offshore sand extraction areas in southeast Australia; Roy, 2001). The resulting production rates are presented in Table A.3.

Table A.2. Example of calculating the weekly production of a trailing suction hopper dredger (hopper volume 5,000 m^3, sailing distance 10 km; see Table A.1. for the used data) (from: Van der Schrieck, pers. comm.).

cycle time:	loading time in sand extraction area	1 hr
	sailing time between sand extraction area and coast [a)]	0.6 hr
	unloading time at coast	0.5 hr
	sailing time between coast and sand extraction area [b)]	0.6 hr +
	total cycle time	2.7 hrs
operational time:	service time per week [c)]	168 hrs
	sea conditions downtime	-25 hrs
	mechanical downtime	-5 hrs
	operational downtime	-8 hr +
	operational time per week	130 hrs
cycles per week:	130 hrs/2.7 hrs	48
production per week:	48 · 5,000 m^3	240,000 m^3

a) Assuming it takes the vessel 2.5 km to gain and 2.5 km to loose speed, in which, on average, it sails at half speed.
b) Assumed to be equal to the sailing time in case the hopper is filled with sand.
c) Assuming 24/7 operations.

Table A.3. Indicative production rates of trailing suction hopper dredgers for various sailing distances.

	dredger size				
sailing distance	**1,000 m^3**	**5,000 m^3**	**8,000 m^3**	**10,000 m^3**	**15,000 m^3**
5 km	61,000 m^3/week	285,000 m^3/week	456,000 m^3/week	570,000 m^3/week	990,000 m^3/week
10 km	47,000 m^3/week	240,000 m^3/week	384,000 m^3/week	520,000 m^3/week	825,000 m^3/week
15 km	38,000 m^3/week	195,000 m^3/week	336,000 m^3/week	450,000 m^3/week	720,000 m^3/week
20 km	32,000 m^3/week	175,000 m^3/week	296,000 m^3/week	390,000 m^3/week	675,000 m^3/week

With the production rates presented in Table A.3, the operational costs of dredging (per m^3 sand) can be calculated by dividing the trailers' operational costs (see Table A.1) with their weekly production volumes. The results of these calculations are presented in Table A.4.

Table A.4. Indicative operational costs (per m^3 sand) of trailing suction hopper dredgers for various sailing distances.

	dredger size				
sailing distance	**1,000 m^3**	**5,000 m^3**	**8,000 m^3**	**10,000 m^3**	**15,000 m^3**
5 km	\$ 4,92/m^3	\$ 2,81/m^3	\$ 2,63/m^3	\$ 2,63/m^3	\$ 2,22/m^3
10 km	\$ 6,38/m^3	\$ 3,33/m^3	\$ 3,13/m^3	\$ 2,88/m^3	\$ 2,67/m^3
15 km	\$ 7,89/m^3	\$ 4,10/m^3	\$ 3,57/m^3	\$ 3,33/m^3	\$ 3,06/m^3
20 km	\$ 9,38/m^3	\$ 4,57/m^3	\$ 4,05/m^3	\$ 3,85/m^3	\$ 3,26/m^3

The costs listed in Table A.4 do not include the costs of mobilising and demobilising the dredgers. The time required to mobilise and demobilise a dredger to the coast of southeast Australia is highly uncertain. On the one hand, at present there are no trailers of considerable size (i.e. larger than the very small dredger used on the Gold Coast; see Section 2.3.1) that operate in southeast Australia. The mobilisation of such a dredger from southeast Asia would take about 2-3 weeks (Hollemans, pers. comm.). On the other hand, it may very well be that in time a trailer of considerable size will be deployed on the coast of southeast Australia permanently or for several months in a row. In that case, (de)mobilisation times will be much shorter (on the order of days). Based on these considerations, it is

assumed that both the average mobilisation time and the average demobilisation time of deploying a dredger in southeast Australia are one week (Van der Schrieck, pers. comm.).
To add the dredger (de)mobilisation costs per m^3 sand to the operational costs listed in Table A.4, the (de)mobilisation costs (see Table A.1) need to be divided by the volume of the nourishments. For this purpose, four nourishment volumes have been selected: 0.5, 1, 1.5 and 2 million m^3. These values are typical of nourishment projects in various countries (e.g. NSCMG, 2000). For each selected nourishment volume, the (de)mobilisation costs per m^3 sand have been added to the operational costs of dredging listed in Table A.1. This has resulted in an overview of the cost price of dredging for various dredger sizes, sailing distances and nourishment volumes, which is shown in Table A.5. A number of results from Table A.5 have been graphically presented in Figure 5.3 and Figure 5.4.

Table A.5. Indicative cost price of dredging (per m^3 sand) for various trailing suction hopper dredgers, various sailing distances and nourishment volumes (including dredger (de)mobilisation times of one week).

		dredger size				
sailing distance	**nourishment volume**	**1,000 m^3**	**5,000 m^3**	**8,000 m^3**	**10,000 m^3**	**15,000 m^3**
5 km	0.5 million m^3	\$5,82/m^3	\$5,21/m^3	\$6,23/m^3	\$7,13/m^3	\$8,82/m^3
	1 million m^3	\$5,37/m^3	\$4,01/m^3	\$4,43/m^3	\$4,88/m^3	\$5,52/m^3
	1.5 million m^3	\$5,22/m^3	\$3,61/m^3	\$3,83/m^3	\$4,13/m^3	\$4,42/m^3
	2 million m^3	\$5,14/m^3	\$3,41/m^3	\$3,53/m^3	\$3,76/m^3	\$3,87/m^3
10 km	0.5 million m^3	\$7,28/m^3	\$5,73/m^3	\$6,73/m^3	\$7,38/m^3	\$9,27/m^3
	1 million m^3	\$6,83/m^3	\$4,53/m^3	\$4,93/m^3	\$5,13/m^3	\$5,97/m^3
	1.5 million m^3	\$6,68/m^3	\$4,13/m^3	\$4,33/m^3	\$4,38/m^3	\$4,87/m^3
	2 million m^3	\$6,61/m^3	\$3,93/m^3	\$4,03/m^3	\$4,01/m^3	\$4,32/m^3
15 km	0.5 million m^3	\$8,79/m^3	\$6,50/m^3	\$7,17/m^3	\$7,83/m^3	\$9,66/m^3
	1 million m^3	\$8,34/m^3	\$5,30/m^3	\$5,37/m^3	\$5,58/m^3	\$6,36/m^3
	1.5 million m^3	\$8,19/m^3	\$4,90/m^3	\$4,77/m^3	\$4,83/m^3	\$5,26/m^3
	2 million m^3	\$8,12/m^3	\$4,70/m^3	\$4,47/m^3	\$4,46/m^3	\$4,71/m^3
20 km	0.5 million m^3	\$10,28/m^3	\$6,97/m^3	\$7,65/m^3	\$8,35/m^3	\$9,86/m^3
	1 million m^3	\$9,83/m^3	\$5,77/m^3	\$5,85/m^3	\$6,10/m^3	\$6,56/m^3
	1.5 million m^3	\$9,68/m^3	\$5,37/m^3	\$5,25/m^3	\$5,35/m^3	\$5,46/m^3
	2 million m^3	\$9,60/m^3	\$5,17/m^3	\$4,95/m^3	\$4,97/m^3	\$4,91/m^3