Technologies for Climate Change Adaptation - Coastal Erosion and Flooding

Zhu, Xianli; Linham, Matthew M.; Nicholls, Robert J.

Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Zhu, X., Linham, M. M., & Nicholls, R. J. (2010). Technologies for Climate Change Adaptation - Coastal Erosion and Flooding. Roskilde: Danmarks Tekniske Universitet, Risø Nationallaboratoriet for Bæredygtig Energi. (TNA Guidebook Series).

TNA Guidebook Series

Technologies for Climate Change Adaptation

– Coastal Erosion and Flooding –

UNEP RISØ CENTRE
ENERGY, CLIMATE AND SUSTAINABLE DEVELOPMENT

UNIVERSITY OF Southampton

Technologies for Climate Change Adaptation

– Coastal Erosion and Flooding –

Editor

Xianli Zhu,
UNEP Risø Centre

Authors

Matthew M. Linham
School of Civil Engineering and the Environment, University of Southampton

Robert J. Nicholls
School of Civil Engineering and the Environment and Tyndall Centre for Climate Change Research, University of Southampton

November 2010

UNEP

UNEP Risø Centre on Energy, Climate and Sustainable Development
Risø DTU National Laboratory for Sustainable Energy
P.O. Box 49,
4000, Roskilde
Denmark
Phone +45 4677 5129
Fax +45 4632 1999
http://www.uneprisoe.org/
http://tech-action.org/

ISBN: 978-87-550-3855-4

Pre-production and printing:

Magnum Custom Publishing
New Delhi, India

Photo acknowledgement:

Front cover photo—Looking east as southern edge of Bay Parkway bikeway crumbles into Sheepshead Bay in Brooklyn, New York on a sunny midday. Courtesy of Jim Henderson. Accessed from Wikimedia Commons

Back cover photo—Coastal erosion in Papaula Point, Maui County, Hawaii. Courtesy of Forest and Kim Starr

Disclaimer:
This Guidebook is intended to be a starting point for developing country governments, coastal zone development planners, and stakeholders who are doing technology needs assessment and technology action plans for adaptation to costal erosion and flooding due to climate change. The findings, suggestions, and conclusions presented in this publication are entirely those of the authors and should not be attributed in any manner to the Global Environment Facility (GEF), the United Nations Environment Program (UNEP), and the UNEP Risø Centre.

Contents

List of Figures and Tables

List of Figures

List of Tables

Abbreviations

AR4	IPCC 4th Assessment Report (published in 2007)
BIS	Beach Improvement Scheme
BMD	Bangladesh Meteorological Department
CBA	Cost-Benefit Analysis
CDMP	Caribbean Disaster Mitigation Project
CEA	Cost-Effectiveness Analysis
CIDA	Canadian International Development Agency
CLIFFPLAN	Numerical cliff erosion model (Meadowcroft et al., 1999)
CPP	Cyclone Preparedness Program (Bangladeshi national programme)
dGPS	Differential Global Positioning System
FEMA	US Federal Emergency Management Association
GIS	Geographic Information System
GPS	Global Positioning System
HAT	Highest Astronomical Tide
ICZM	Integrated Coastal Zone Management
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging (survey system)
MCA	Multi-Criteria Analysis
MHW	Mean High Water
MHWM	Mean High Water Mark
MHWS	Mean High Water Spring Tide
MLW	Mean Low Water
MLWS	Mean Low Water Spring Tide
NAPA	National Adaptation Programme of Action (a process for identifying priority activities for adapting to climate change in least developed countries, reported to the UNFCCC)
NCC	National Coordination Committee (Bangladeshi organisation)
NFIP	National Flood Insurance Programme (of FEMA)
NGO	Non-Governmental Organisation

OAS	Organization of American States (an international organisation including the 35 independent states of the Americas)
RSLR	Relative Sea Level Rise
SCAPE	Soft Cliff and Platform Erosion (numerical cliff erosion model; Walkden & Hall, 2005)
SLR	Sea Level Rise
SPARRSO	Space Research & Remote Sensing Organisation (Bangladeshi organisation)
SST	Sea Surface Temperature
TAOS	The Arbiter of Storms – Caribbean storm hazard model used in flood hazard mapping (Watson & Johnson, 1999)
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USAID	US Agency for International Development
USDA	United States Department of Agriculture
VAT	Value Added Tax
WMO	World Meteorological Organisation
WRDS	Wetland Resource Development Society (voluntary research & development organisation)
WWF	World Wildlife Fund

Preface

Coastal zones in many parts of the world are densely populated centres of critical economic activity. Sea level rise and more intense storms, waves, and surges due to climate change pose a serious threat to large numbers of people living in these areas. Consequently many developing countries have identified coastal zones as a priority area for climate change adaptation. These countries, however, often need assistance to identify adaptation options, formulate adaptation strategies and plans, and implement adaptation measures that lower the risk and actual losses from climate change impacts.

This publication aims to support good adaptation planning. It covers thirteen major adaptation technologies that reduce impacts of coastal erosion and flooding due to climate change. For each, the technology is described, advantages and disadvantages assessed, costs and benefits estimated, institutional or organisational requirements outlined, and detailed examples provided that illustrate how the technology can be applied. It is hoped that this comprehensive approach will make the guidebook a useful reference for policy makers and coastal zone project planners. Its reader-friendly style and extensive coverage also make it a good resource book for anyone interested in the topic.

This guidebook has been co-authored by Matthew M. Linham and Professor Robert J. Nicholls, both of the University of Southampton in the United Kingdom. Professor Nicholls is one of the top international experts on coastal impacts and adaptation to climate change, and has a particular interest in sea level rise. He is also a lead author of chapters on coastal zones for several reports of the Intergovernmental Panel on Climate Change (IPCC). The production of this guidebook has been coordinated by Dr. Xianli Zhu of the UNEP Risø Centre on Energy, Climate and Sustainable Development (URC). Valuable comments and suggestions were provided by Professor John Hay of Ibaraki University, Dr. Leonard Nurse of the University of the West Indies, Marten Hillen of Royal Haskoning, Dr. Travis Mason of the Channel Coastal Observatory, Sara Traerup from the URC, and Pia Zevallos from Libelula. Their collective inputs were invaluable and are much appreciated.

This publication is one of the adaptation and mitigation technology guidebooks produced by URC as part of the Technology Needs Assessment (TNA) Project (http://tech-action.org/). UNEP and URC are implementing the TNA Project in 36 developing countries. Funding for this project is provided by the Global Environment Facility (GEF).

Jyoti Prasad Painuly
Project Manager
UNEP Risø Centre

Mark Radka
Energy Programme Coordinator
UNEP DTIE

November 2010

Executive Summary

This guidebook is intended to be a practical tool for use by coastal zone managers in developing countries. The aim is to provide best practice guidance and assist these managers in assessing their evolving adaptation needs and help them to prepare action plans for adapting to climate change in the coastal zone.

The guidebook first reviews the main physical and societal impacts of climate change in the coastal zone. It then considers the process of adaptation to erosion and flooding/inundation hazards where major impacts may occur and a range of adaptation technologies are best developed. Thirteen of these adaptation technologies are presented in this guide, representing examples of the protect, accommodate or (planned) retreat approaches to adaptation. While this does not represent an exhaustive list of the adaptation technologies that are available, these technologies are among those most widely used/considered in the coastal zone today. All the technologies considered are relevant to climate change adaptation and collectively, more widespread application is expected in the future under climate change and rising sea levels.

For each adaptation technology the following issues are addressed: (1) definition and description; (2) technical advantages and disadvantages; (3) institutional and organisational requirements; (4) potential costs and opportunities; and (5) barriers to implementation; followed by a case study example. We have endeavoured to include developing country examples wherever possible, but as there is less activity and less documentation of developing world projects and some technologies are barely used in the developing world, this is not always possible. Knowledge and capacity building requirements and monitoring technologies are considered and contrasted across all 13 adaptation technologies. Finally, more detailed sources are indicated.

Each adaptation technology has widely varying advantages and disadvantages. As such, selection of measures should be undertaken on a case-by-case basis, which accounts for local conditions. It is widely accepted that the most appropriate adaptation options will vary from area to area. In some cases adaptation technologies can be complimentary; hence, the development of appropriate portfolios of measures should be considered where appropriate.

Three decision-making frameworks are also briefly considered. These techniques help coastal mangers to compare and select between the available adaptation options.

The guidebook makes clear that appropriate knowledge is a highly important prerequisite of successful adaptation. The more that is known about a coastal system, the more targeted and effective adaptation measures can be. It should be noted that communities often lack the knowledge to determine whether adaptation is appropriate and which designs and standards are appropriate. Hence, a degree of technical guidance and assistance from organisations with a well-developed science and technology base is likely to benefit coastal adaptation in general as well as support appropriate use of individual technologies.

Finally, this guidebook stresses to its users that adaptation is more than the simple implementation of a suitable practice or technology. Adaptation should instead be viewed as an ongoing process whereby risks and opportunities are prioritised, risk reduction measures are implemented and the effectiveness of the outcomes is reviewed. Hence, the performance of any adaptation technology should be carefully monitored and assessed, and the lessons fed back through the cycle to improve maintenance and future interventions.

1. Introduction and Outline of the Guidebook

This guidebook aims to support developing countries in adapting to climate change in the coastal zone by providing best practise guidance. It is designed to help these countries to identify their evolving needs for equipment, techniques, practical knowledge and necessary skills which will be used for reducing vulnerability to the adverse impacts of climate change at the coast.

Adaptation to climate change is growing in importance, as actual and potential impacts become more apparent, including increased shoreline erosion and more frequent, widespread and deeper coastal flooding. Even with significant climate mitigation, the inertia of climate change means that coastal adaptation remains essential, especially for sea level rise (SLR) (Nicholls et al., 2007a). Growing populations and economies in the coastal zone reinforce this need.

This guidebook provides information on 13 of the most widely used and discussed adaptation technologies for coastal flooding and erosion. Adaptation technologies are defined as the broad set of processes covering the know-how, experience and equipment used by humans to reduce the adverse consequences of coastal change and exploit any benefits: here the main focus is climate change as a driver of coastal change These technologies can be sub-divided into technologies involving (1) capital goods such as dikes or seawalls; and (2) technologies focussing on information, capacity building, institutional arrangements and policy and strategy development[1].

It is important to note, that adaptation consists of more than simply implementing a specific technology. As a result, this guidebook also considers the wider process within which adaptation technologies are implemented, including information collection and dissemination, awareness building, design, implementation and monitoring. By applying such an approach, it is hoped that users of this guidebook will have a better basis to select the most appropriate measures and implement them within an Integrated Coastal Zone Management (ICZM) context, therefore increasing the likelihood of an effective and successful project.

One of the reasons for developing this guidebook is the limited experience of adaptation to coastal change in many developing countries. As such, while developing country experiences have been presented wherever possible, much of the information drawn together for this guidebook is taken from developed nations, because this is where the vast majority of coastal adaptation experiences exist. The experiences from developed nations that are provided are selected to be relevant to the developing world.

The target audience of this guidebook comprises a broad range of stakeholders, including individuals in government institutions, non-government organisations, the private sector and coastal communities. This guidebook intends to be an essential and useful source of information on climate change adaptation in the coastal zone for such a diverse set of stakeholders.

---

1 These are sometimes termed ‘hard’ and ‘soft’ technologies, but this guidebook refrains from using these terms to avoid confusion with hard and soft engineering

The layout of this guidebook is explained below.

Chapter 2 will summarise the main physical and societal impacts of climate change on coastal zones, as determined by previous studies, including the review of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. There are a range of climate change impacts and resulting impacts in coastal areas.

Chapter 3 will focus on the process of adaptation and on typologies of adaptation approaches, particularly the protect, accommodate and (planned) retreat division (c.f. IPCC CZMS, 1990) that is used in this guidebook. Many previous studies have highlighted the importance of considering adaptation as a multi-stage process. Implementation of a given technology is only one step within this process; the success or failure of a selected intervention is heavily dependent on the overall process.

In Chapter 4, thirteen adaptation technologies to adapt to erosion and flooding hazards in coastal areas are described. They are grouped under the three adaptation approaches of (1) protect; (2) accommodate; and (3) retreat. For each adaptation technology, several aspects will be considered, including specific details of the technology, its advantages and disadvantages, knowledge and capacity building requirements, approximate costs and opportunities and barriers to implementation. This includes relevant case study examples, normally from the developing world, supplemented by developed world examples where appropriate. Additionally, the knowledge and capacity building requirements and monitoring technologies are considered and contrasted across all 13 adaptation technologies. Note that detailed design issues are not considered.

Chapter 5 will briefly address the issue of decision analysis, or deciding how to identify the most appropriate technology for a specific situation. This includes discussion of relevant decision-making frameworks, including cost-benefit analysis, cost-effectiveness analysis and multi-criteria analysis.

Finally, Chapter 6 provides a synthesis of the key findings and recommendations related to the use of adaptation technologies in the coastal zone.

A glossary of technical terms is presented at the end of this document alongside sources of additional information for those readers who wish to explore the individual adaptation technologies or the broader issues covered in this guidebook in more detail. The recommended sources include general coastal adaptation and engineering texts, relevant guidance for developing countries and specific texts relating to the adaptation technologies covered in this guidebook.

2. Background

In 2007, the Intergovernmental Panel on Climate Change (IPCC) published its 4th Assessment Report (AR4). The report provides one of the most detailed summaries of the underlying causes and impacts of climate change available to date. AR4 evaluated the potential impacts of climate change on a number of areas and regions, including the coastal zone.

The main physical effects of climate change on the coastal system are restated below; they have been taken from the Bindoff et al. (2007). It is important to note that due to the diversity and variation present in natural coastal systems, and due to the local and regional differences in relative sea level rise (RSLR), the occurrence and response to the effects of climate change as detailed here will not be uniform around the globe (Nicholls & Cazenave, 2010).

2.1 Climate Change in Coastal Areas

Sea surface temperatures (SSTs) are rising globally due to absorption of additional heat energy at the Earth's surface. Global observations of the heat content of the oceans shows considerable yearly and decadal variability superimposed on a longer-term rise.

Global mean sea level (MSL) is rising. This is caused by two factors: (1) thermal expansion of seawater caused by increases in SSTs; and (2) water inputs into the oceans from melting land-based ice. However, the spatial trend is highly non-uniform due to regional oceanic variations such as non-uniform warming. Hence, some regions will experience SLR above the mean rise, and vice versa.

While global MSL is important, the local or relative sea level[1] is the dominant factor in determining impacts on the coast. As opposed to global mean SLR, RSLR accounts for the regional variations in sea level and localised vertical movements of the land relative to the ocean's surface such as subsiding deltas (Syvitski et al., 2009). RSLR raises both mean and extreme sea levels.

Climate change may also cause increases in both extreme wave heights and in the intensity of storms, although the uncertainties are high. In particular, tropical storms may become more intense but less common.

Finally, it is apparent that the carbon content of the world's oceans has increased. This has been caused by the absorption of carbon dioxide which is released into the atmosphere through the burning of fossil fuels. This has caused a decline in surface ocean pH which is likely to continue into the future[2].

2.2 Physical Impacts of Climate Change on the Coastal Zone

The likely impacts of these physical changes on the coastal zone are described by Nicholls et al. (2007a). A range of impacts are apparent and these are discussed below.

---

[1] Sea level measured by a tide gauge with respect to the land upon which it is situated.

[2] This is termed 'ocean acidification' even though ocean waters remain alkaline.

While some impacts will be applicable to all coastal types, different coastal types will respond differently to the impacts of climate change. As such, they must be viewed separately. Climate change impacts applicable to all coastal types are presented first, followed by impacts upon specific coastal types.

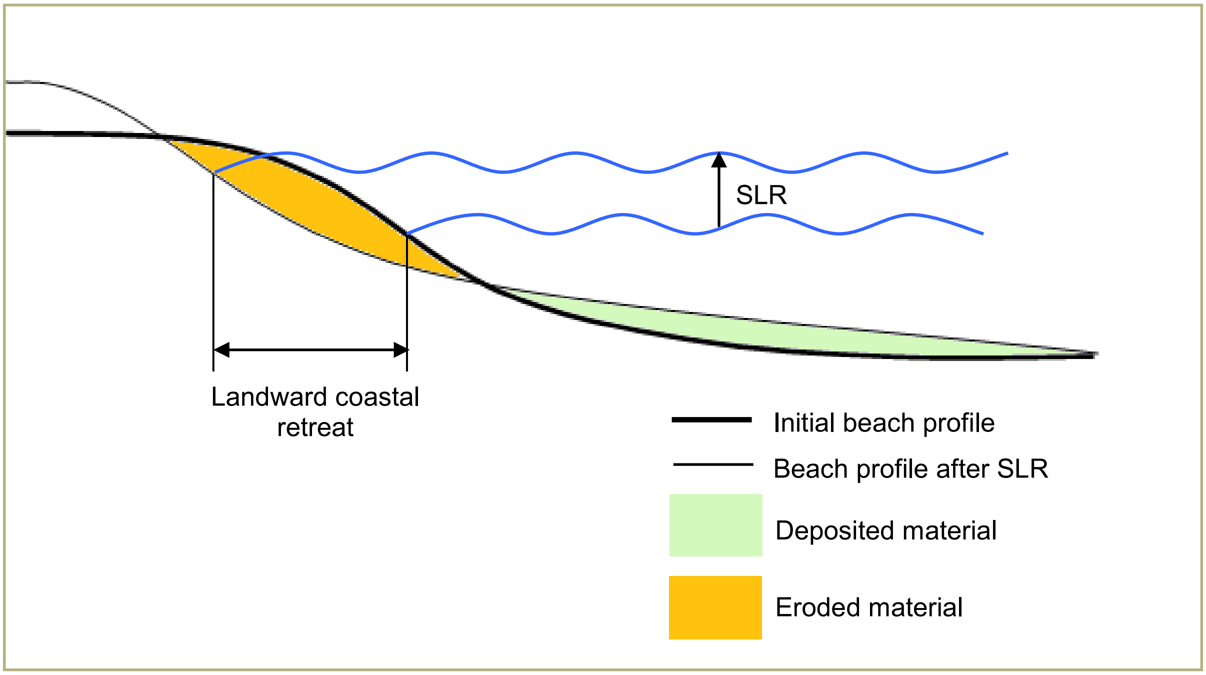
General Impacts

SLR will contribute to increased shoreline erosion rates

Erosion is the physical movement of sediment away from the shore via wave and current action. SLR has the capacity to exacerbate erosion by promoting offshore transport of sediment.

The best known and most widely applied modelling of this process is offered by Bruun (1962) and is illustrated in Figure 2.1. The 'Bruun Rule' suggests that shoreline recession is in the range of 50 to 200 times the rise in relative sea level and is caused by a beach's desire to maintain an equilibrium beach profile[3]. To maintain the equilibrium profile in the presence of SLR, sediment is removed from the shoreline, causing erosion. It is subsequently deposited offshore so that the nearshore zone gains elevation at a rate equal to the rise in sea level. As sea level rises, the beach profile adjusts by shifting landwards and upwards by removing sediment from the shoreline and depositing it in the nearshore zone. Hence, the volumes of eroded and deposited material are equal.

Figure 2.1: Simplified model of landward coastal retreat under SLR (based on the Bruun Rule)



Source: Adapted from French, 2001

---

[3] Beach profiles are surveyed section lines perpendicular to the shoreline (CIRIA, 1996). Profiles essentially describe beach cross-sectional shape, including the area above the waterline and the in-shore underwater portion.

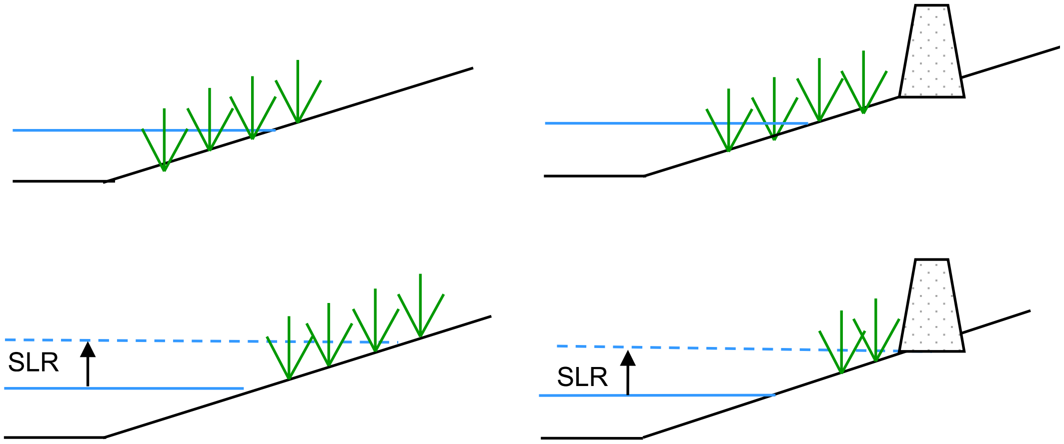
An equilibrium profile is the preferred cross-sectional shape that a beach will assume if conditions such as the wave climate remain constant for long enough. In reality, wave climate and other factors are constantly changing and therefore so too does the equilibrium shape. However, the concept remains useful when considering profile change, including assessing the impacts of SLR.

Note however, that the Bruun Rule greatly simplifies the behaviour of the coastal zone and in reality, numerous processes other than profile adjustment to SLR will influence beach profile shape and position, hence, a complete sediment budget[4] is ideally required to fully predict shoreline response to SLR (e.g. Stive et al, 2009).

Natural inland habitat migration with SLR will be prevented by hard coastal defences

'Coastal squeeze' is a widespread result of shoreline retreat which affects areas located between rising seas and hard defences. As sea levels rise, coastal habitats are expected to migrate inland so as to keep pace with the change. However, in the presence of hard defences, these habitats are unable to migrate landward and are effectively squeezed between the rising sea and the unmoving hard defence. This causes the area in front of the defence to narrow significantly and can cause drastic reductions in the areal extent of saltmarshes and other habitats typically found in the intertidal zone. This phenomenon is shown in Figure 2.2.

Figure 2.2: The process of coastal squeeze



Where hard defences are not present, coastal habitats (shown in green) migrate upwards and landwards with SLR, as shown on the left. Where hard defences are present, they block the migration of coastal habitats therefore reducing the available area these plants can survive in, as shown on the right

Impacts on one part of the coastal system can cause secondary impacts elsewhere

Detrimental impacts upon one part of the coastal system are likely to cause erosion or inundation of other parts of the coast. For example, in many locations, sandy barrier islands reduce wave heights inside bays. Erosion and especially removal of barrier islands can lead to increased wave heights in neighbouring bays. This then leads to enhanced shoreline erosion rates around the bay.

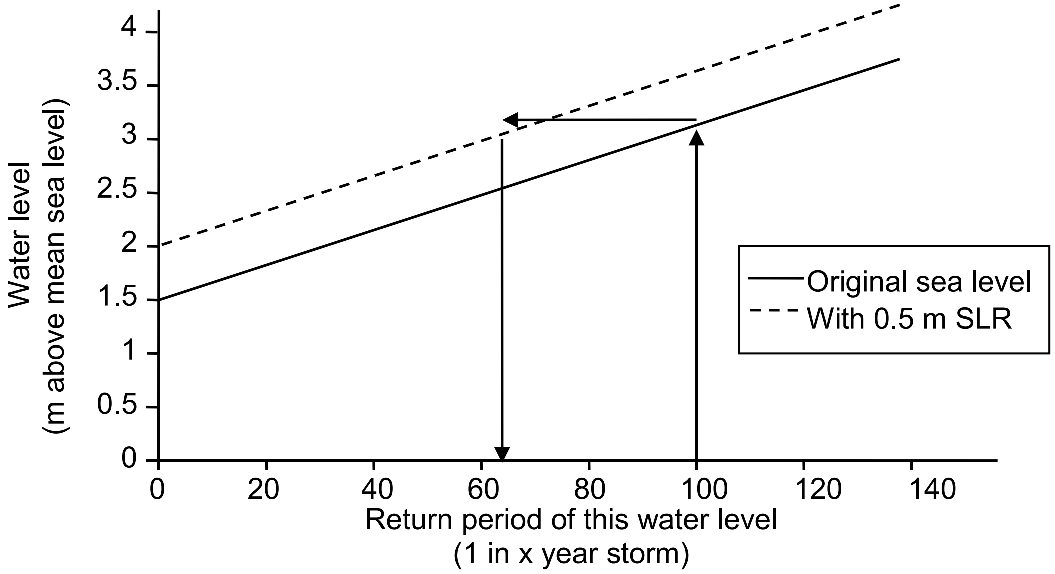
SLR will increase the probabilities and depths of flooding

SLR increases the probability of flooding in coastal zones, unless flood protection measures can be upgraded. This can be illustrated through the use of a 'flood frequency probability curve', shown in Figure 2.3. Increased flood risk is linked to higher storm water levels with the capacity to cause greater damage, threats to drinking water supplies and potentially, increased risk to life.

---

[4] An accounting of gains and losses of sediment within defined boundaries over a period of time (Kana, 1995).

Figure 2.3: SLR raises extreme water levels and increases the probability of flooding without adaptation



In the example, a 50 cm rise in sea level causes a sea level previously seen only once every 100 years on average, to occur approximately once every 65 years instead

The more frequent occurrence of extreme water levels will be exacerbated by the degradation of natural coastal systems such as marshes and dunes which currently serve as natural coastal defences. Many coastal communities rely upon these natural defences in extreme events.

SLR and the possibility of more frequent storms will increase flood risk even where defences exist

Locations where artificial coastal defences exist are still susceptible to extreme events when water levels exceed the defence height or the defence fails – this is termed residual risk. This will become increasingly likely as sea level rises. In addition, more intense storms may also cause damage to existing coastal protection works and other infrastructure (Nicholls et al., 2007a). Hence, the problem of coastal flooding is expected to increase with SLR unless there is adaptation to cope with these changes.

Beaches, Rocky Shores, and Cliffed Coasts

Beaches are landforms composed of non-cohesive, loose material such as sand, shingle or pebbles. They occur at the interface between land and sea. These landforms most frequently occur in areas influenced by wave action. Rocky coasts include shores composed of materials ranging from hard rocks, such as granite and basalt, to relatively soft erodible material (Finkl, 2004). Cliffed coasts are formed over long timescales by erosional processes or alternatively, by uplift. Cliffs occur in a wide variety of forms and are by definition, erodible. Nevertheless, retreat rates are highly variable with soft cliffs retreating at long-term rates of 1-2 m/year, ignoring episodic falls.

The impacts of climate change and SLR on beaches, rocky shores and cliffed coasts are summarised below. These impacts are in addition to those impacts applicable to all coastal types.

Soft cliff retreat will increase as a result of SLR and climate factors

Cliffs have differing susceptibilities to erosion depending on the material from which they are composed. Hard rock cliffs are relatively resistant to erosion while softer cliffs are likely to retreat more rapidly in future due to erosion of their bases caused by SLR (Walkden & Dickson, 2008). Cliff failure may also be amplified by increased precipitation and higher groundwater levels. Soft cliff retreat is likely to be episodic and has been found to be sensitive to SLR, changes in wave conditions and changes in sediment supply.

Tourism preferences may change as a result of the direct and indirect effects of climate change

Climate change has the potential to cause major impacts on coastal tourism which is heavily dependent on ‘sun, sea and sand’. For example, warmer air and sea temperatures could make previously unattractive destinations more appealing for tourism and make existing resorts ‘too warm’ for tourists. Additionally, changes caused by SLR and resulting coastal erosion could negatively affect an area’s value for tourism.

Deltas

Deltas form at locations where large rivers, carry large quantities of sediment into the sea. A delta is formed by continuous deposition of sediment from the river and subsequent reworking by coastal processes such as wave, currents and tides. Worldwide, deltas are estimated to be home to about 500 million people because of the presence of important environmental services in these locations (Syvitski et al., 2009).

Land subsidence will contribute to more rapid relative SLR in deltas

The rate of SLR can greatly exceed the global average in heavily populated deltaic areas (Ericson et al., 2006; Syvitski et al., 2009). This is due to land subsidence caused by compaction of the relatively young, deltaic sediments under their own weight. Groundwater, gas and oil withdrawals can greatly exacerbate this natural subsidence. Parts of some cities in deltas subsided several metres during the 20th century (Nicholls, 2010). As many deltas are associated with significant and expanding urban areas and populations; this could contribute to a significant problem through the 21st century (Nicholls et al., 2008).

The interaction between SLR, climate change & human pressures is particularly threatening

In addition to subsidence, human influences which affect the ability of deltas to cope with climate change include sediment starvation due to dams, alterations in tidal flow patterns, navigation and flood control works and changes in surface water run-off. Reduced sediment supply puts these areas at risk of increased erosion, permanent submergence and more frequent flooding.

At present, deltaic wetland losses are largely caused by human development, for example, through direct destruction and rapid changes to the natural delta environment. As well as causing direct destruction, such changes will reduce the adaptive capacity of deltas to cope with SLR and other climate change impacts.

In addition to wetland loss directly caused by human development, SLR and an increase in tropical storm intensity are likely to exacerbate present rates of wetland loss. With the adverse interaction of other climate and human pressures, SLR poses an especially serious threat to deltaic environments.

Estuaries and Lagoons

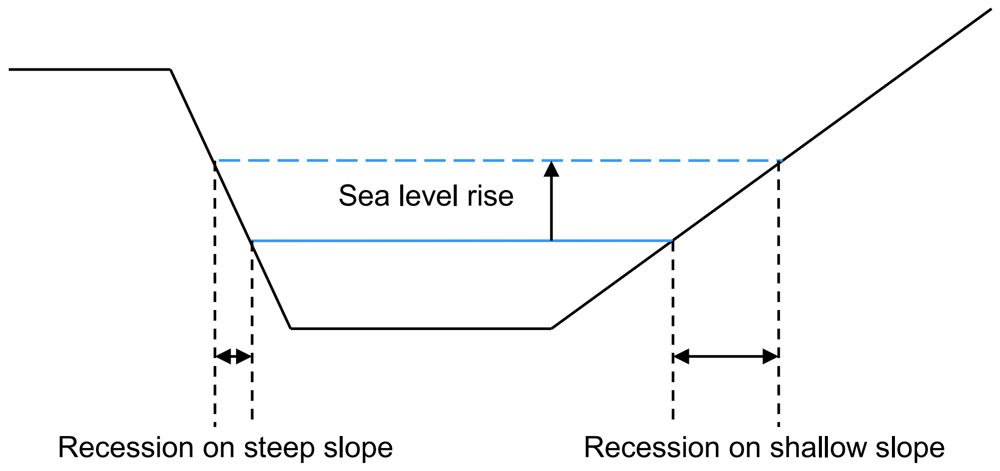
Estuaries are the seaward, tidally-influenced ends of rivers, which open toward the sea. They are usually subject to tidal movements and mixing of fresh and salt water (Bird, 2005). These environments are usually sheltered from wind and wave action. Coastal lagoons however, are areas of shallow, coastal, salt water, wholly or partially separated from the sea by sandbanks, shingle or, less frequently, rocks (JNCC, 2010).

SLR will trigger inland migration of coastal habitats and submergence of low-lying land

SLR will generally lead to higher water levels and saltwater intrusion in estuarine systems. This will mean that existing plant and animal communities will be displaced inland. If their migration is not impeded, and if the rate of change is not so rapid that the natural systems cannot keep pace, these communities will continue to exist as sea level rises.

The rate of landward movement of the shoreline with SLR, and the degree of permanent submergence of coastal lands, will depend on both the rate of SLR and the slope of the coastal land. Shallower coastal slopes will cause greater recession of the shoreline, as shown in Figure 2.4. Since estuaries and lagoons typically have shallow coastal slopes, landward movement of the shoreline can be significant for only small increases in relative sea level.

Figure 2.4: Shoreline recession caused by SLR



As can be seen in the figure, the rate of recession is highly dependent on the gradient of the coastal slope

Climate change may alter coastal water quality

Harmful algal blooms could be encouraged by increased water temperatures and dissolved carbon dioxide concentrations also caused by climate change. Changes in freshwater inputs may further affect water quality: increases will promote flushing and vice versa.

A projected increase in the intensity of tropical cyclones and coastal storms could also alter a number of other processes in estuarine systems, including the movement of sediments on the seabed, the input of organic material important in plant and animal growth, plankton and fishery populations and salinity and oxygen levels.

Coral Reefs

Coral reef coasts occur almost entirely between the Tropics of Cancer and Capricorn (Sheppard, 2005). Coral reefs are collections of marine organisms which have hard, rock-like skeletons. The reef component of corals is constrained by the requirements of the corals themselves. This includes clear, warm waters, neither too fresh nor too salty, with temperatures between 15 and 30oC and without high levels of sediment in the water (Sheppard, 2005). Reefs act as natural coastal defences by providing effective wave energy dissipation (French, 2001).

Increased sea surface temperatures will increase coral bleaching and mortality

Corals have a preferred temperature range in which they live. When the ambient temperature increases, corals become stressed and may undergo ‘bleaching’. Coral bleaching refers to a loss of the coloured algae which live within coral organisms. This is problematic because corals depend upon these algae for nutrition and energy, and hence for growth and, ultimately, survival. Coral bleaching does occur naturally to some extent as a result of seasonal fluctuations in water temperature. However, prolonged temperature rises caused by global warming are likely to threaten the long-term survival of corals.

Although some organisms may be capable of adapting to higher temperatures, there is limited evidence of this being the case for corals. As a result, it is very likely that future increases in SSTs will result in more frequent and larger-scale bleaching and death of corals.

Ocean acidification will affect coral growth rates

A reduction in seawater pH due to rising carbon dioxide concentrations reduces the rate at which marine organisms are able to build reefs by producing hard, outer skeletons. Coupled with an increased frequency of coral bleaching, this has the capacity to cause reef disintegration which is likely to lead to increased wave energy across reef flats and consequent increases in the potential for shoreline erosion.

Tropical storm intensification may increase damage to reefs

An intensification of tropical storms caused by climate change could have devastating effects on reefs themselves, on other parts of the marine ecosystem and on the inhabitants of low-lying islands. More intense tropical storms could cause breakage of fragile corals and if a storm is sufficiently energetic, it may even cause destruction of the majority of corals present on a reef. Considering all of the above impacts, coral reefs appear highly threatened by climate change and other stresses.

Saltmarshes, Mangroves, and Seagrasses

Saltmarshes, mangroves and seagrasses are intertidal and shallow sub-tidal habitats which occur in sheltered to moderate ‘wave’ energy environments.

Saltmarshes are areas of land covered principally by salt-tolerant, grass-like vegetation and inundated by the tides. They occur in many temperate and high-latitude estuaries and on sections of open coast which are protected from extreme wave action by wide intertidal flats and barrier complexes (Allen & Pye, 1992).

Mangroves are woody trees or shrubs that occur naturally in brackish waters or estuarine wetlands along sheltered tropical and subtropical shores and estuaries.

Seagrasses are flowering, underwater plants that are typically found in marine or estuarine waters continuously flooded by the sea. Most seagrasses root in silty or sandy sediments in shallow waters (Merlin, 2005).

Saltmarshes, mangroves and seagrasses perform important coastal functions including sediment trapping, stabilising the seabed against erosion, attenuating wave energy and providing habitats for many fish, birds and insects. These coastal wetlands are however, very sensitive to climate change and SLR because their location is closely linked to sea level (Nicholls et al., 2007a).

The most pronounced effects will occur in freshwater & fresh/saltwater transition marshes

SLR will increase the proportion of time which saltmarshes are submerged during the tidal cycle. Climate change is also likely to cause changes to the number and severity of extreme events experienced at the coast. These impacts will be felt most severely by marshes located in freshwater and freshwater/saltwater transition areas.

Rapid SLR may drown the seaward margin of saltmarshes and mangroves

If the supply of sediment is sufficient, marshes and mangroves should be capable of keeping pace with SLR. However, if sediment availability is insufficient, SLR outpaces the accumulation of sediment. The response largely depends on the sediment budget. The threshold at which this occurs varies widely, and is largely dependent on changes due to erosion and sedimentation. Intertidal habitats in areas with high tidal ranges and high sediment inputs are least at risk from SLR.

Climate change will have both positive and negative impacts on mangroves

Climate change impacts on mangroves will be mixed. Impacts may include enhanced growth caused by higher carbon dioxide levels in the atmosphere and higher temperatures. However, negative impacts may also occur, including increased saltwater intrusion into mangrove areas and increased erosion. When coupled with widespread conversion of mangroves to other land uses by humans, for example shrimp ponds, it is likely that the negative impacts will be overriding and mangroves will decline further in future.

Seagrass decline is likely to be exacerbated by climate change

Currently, seagrasses appear to be declining around many coasts due to human impacts. This decline is expected to accelerate if climate change alters environmental conditions such as salinity, temperature, sea level, atmospheric carbon dioxide, storm activity and ultraviolet light intensity in coastal waters.

On balance, coastal wetlands will decline into the future

The survival of coastal wetlands is dependent on sediment availability and the potential for landward migration. Where sediment is readily available and where landward migration is uninhibited, most wetlands will be capable of coping with SLR. But on balance, it would appear that coastal wetlands will decline with rising sea levels and increased frequency of storms and other extreme events. Other climate and human-related pressures, such as reduced sediment inputs and coastal squeeze, will exacerbate these losses.

2.3 Socio-economic Impacts of SLR

SLR is likely to cause saltwater intrusion into surface waters and coastal aquifers, advance of saltwater into estuaries and coastal river systems, more extensive coastal inundation, higher levels of sea flooding, increases in the landward reach of sea waves and storm surges and new or accelerated coastal erosion (Nicholls et al., 2007a). These consequences are expected to be overwhelmingly negative and particularly serious in deltas and small islands.

Climate change and climate variability is also expected to impact agriculture, largely through a decline in soil and water quality (Nicholls & Klein, 2005). To a lesser extent, forestry and fisheries in coastal and estuarine waters are also likely to be affected.

Increased atmospheric carbon dioxide concentrations are likely to benefit plant growth rates, although temperature increases can shorten growing cycles. An increased frequency of extreme climate events may also negatively affect crop yields.

2.4 Summary

It should be borne in mind that due to the local and regional differences in relative SLR and temperature, the occurrence and response to the effects of climate change will not be uniform around the globe (Klein & Nicholls, 1998). The impacts of climate change on the coastal zone are expected to be largely site specific, due to the influence of local factors.

The impacts of climate change are many and varied, but from a human perspective, the five most important effects of climate change in the coastal zone are: increased probabilities of (1) coastal flooding and inundation; (2) coastal erosion; (3) rising water tables; (4) saltwater intrusion into surface and groundwater and (5) biological effects (Klein et al., 2006).

This guidebook will not attempt to cover adaptation technologies for all of the impacts of climate change on the coastal zone. Instead, the guidebook will focus specifically on protection of the coastline against increased flooding, inundation and erosion as these are major impacts of SLR and climate change with adverse socio-economic impacts, and adaptation technologies are well developed and the lessons are transferrable in media such as this guide. Technologies to cope with rising water tables, saltwater intrusion and biological effects are much less developed and will not be discussed in this guide. There is a need for more work on adaptation technologies for these impacts.

3. Adaptation Approaches, Options and Practices

In the broadest sense, adaptation technologies can be defined as the equipment, techniques, practical knowledge, skills or institutional instruments required to reduce the impacts of coastal hazards, including climate change. To date, adaptation has had a widespread benefit in reducing society's vulnerability to coastal hazards (Klein et al., 2000, 2001; VonKoningsveld et al., 2008). Considering climate change, adaptation enables coastal communities to reduce its detrimental impacts by averting or reducing the potentially negative consequences, while benefitting from potentially positive consequences (Tol et al., 2008; USAID, 2009).

This guidebook will focus on the typology of adaptation approaches first suggested by IPCC CZMS (1990) and illustrated in Figure 3.1. Three generic options for adaptation exist;

1. Protect: defend vulnerable areas, especially population centres, economic activities and natural resources
2. Accommodate: continue to occupy vulnerable areas, but accept the greater degree of flooding by changing land use, construction methods and/or improving preparedness
3. (Planned) retreat: abandon structures in currently developed areas, resettle inhabitants and require that new development be set back from the shore, as appropriate. Unplanned retreat is not considered

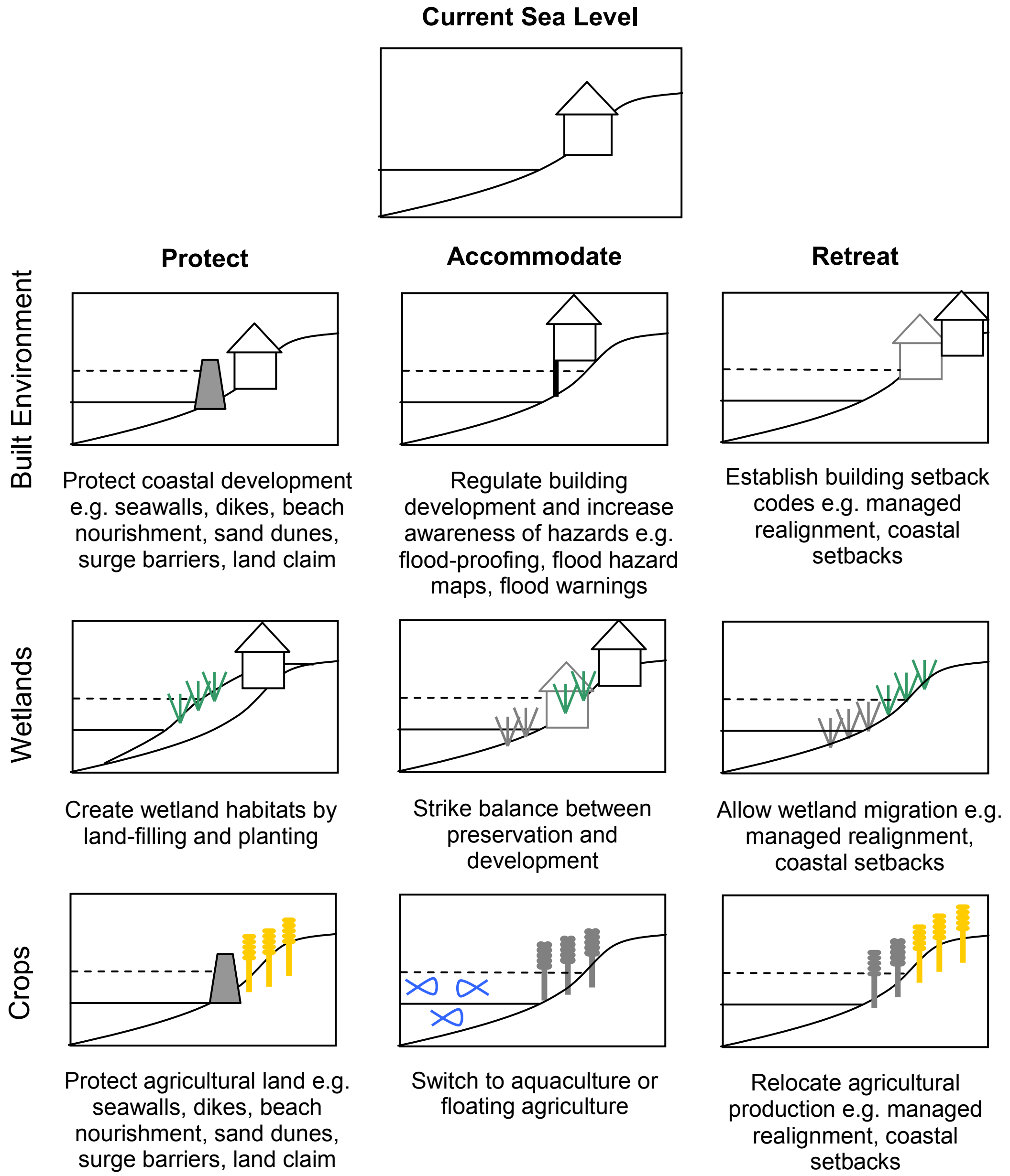
Although, numerous other typologies for adaptation have been developed (see Figure 3.2), the threefold typology suggested by IPCC CZMS (1990) is widely applied and is effective to describe the adaptation technologies to respond to erosion and increased flooding described in this guidebook, as shown in Figure 3.1 and Figure 3.2. It is noted that 'improving awareness and preparedness' is a cross-cutting measure that is relevant to varying degrees to all the technologies considered here.

While selection of a protect, accommodate or retreat approach is important, it is essential to note that coastal adaptation consists of more than just implementing one of the three basic interventions. Rather, adaptation is a policy and implementation process involving comprehensive decision making and technology

Box 3.1: Aims of ICZM (French, 2005; USAID, 2009)

- Aims to manage coastal zones in a sustainable and informed fashion which accounts for the wide range of important factors in coastal decision-making
- Attempt to promote compatibility and balance of coastal uses
- Promote cooperation between departments, ministries or agencies which have control over specific aspects of the coast. Also, promote cooperation with other formal institutions such as universities and user groups
- Apply preventative and precautionary approaches in respect to coastal development. I.e. attempt to limit coastal development in unsustainable areas
- Account for both the economic and environmental costs and benefits of coastal management strategies in order to ensure the most beneficial use of the coastal zone
- Facilitate communication with all interested parties on coastal planning and decision-making processes to ensure that all viewpoints are considered
- Ensure the scope and complexity of the climate change issues selected as priorities for adaptation measures are appropriate to the capacity of the institutions involved

Figure 3.1: Schematic illustrations of the protect accommodate and (planned) retreat responses to SLR



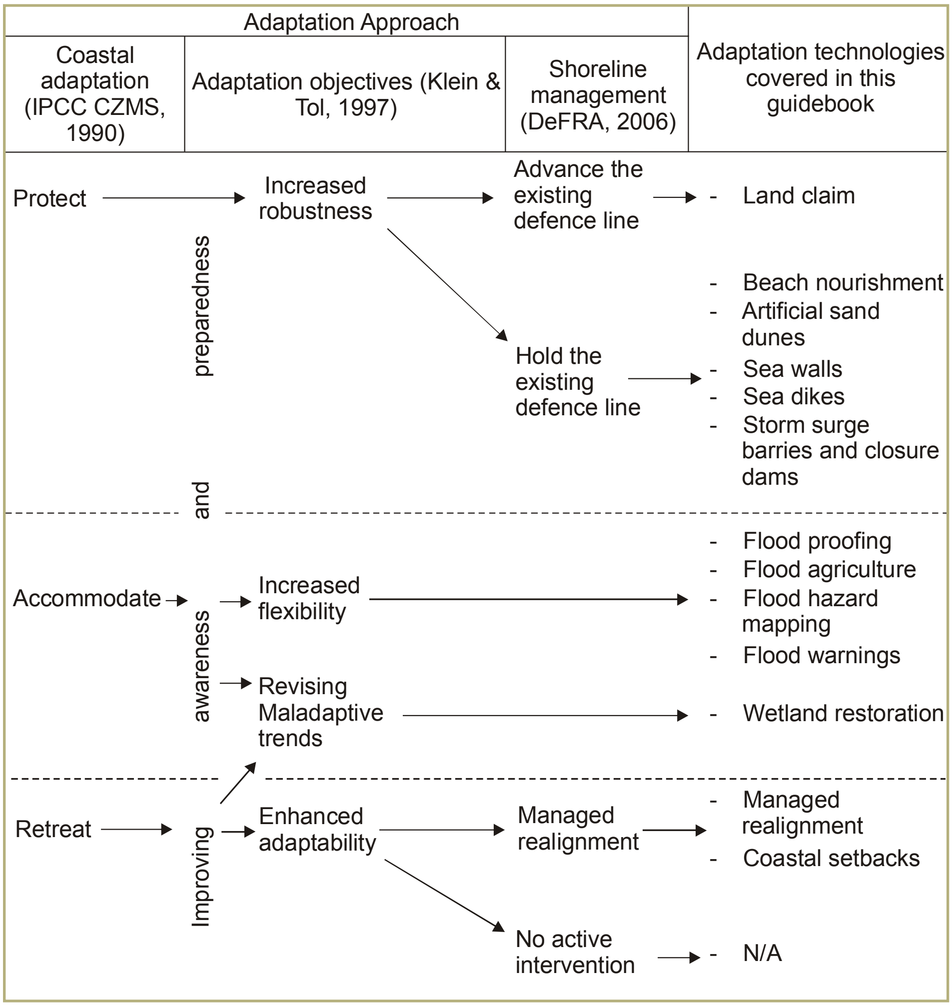
The dashed line represents future SLR. Grey houses and vegetation indicate their previous locations prior to relocation or natural migration

Source: Drawn by the authors based on IPCC CZMS (1990)

application. The most successful adaptation is integrated within the activities of all planning departments, rather than taking place in isolation (Tompkins et al., 2005; USAID, 2009). Successful adaptations should also consider the full context in which the impacts of climate change arise and include the consideration of climate and non-climate issues (Tol et al., 2008).

Integrated Coastal Zone Management (ICZM) is a useful framework which aids the achievement of these objectives. Some of the main requirements of ICZM are outlined in Box 3.1.

Figure 3.2: Linkages between different typologies of coastal adaptation approach and the adaptation technologies considered in this guide



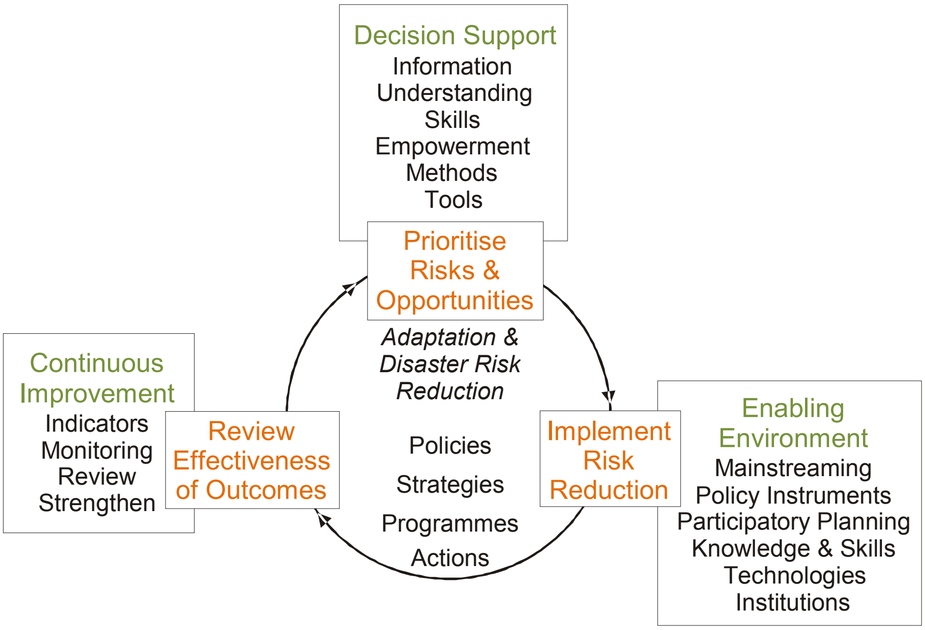
Source: Adapted from Nicholls et al., 2007a

Simply implementing an adaptation technology is not an endpoint; instead, adaptation is an ongoing process requiring constant prioritisation of risks and opportunities, implementation of risk reduction measures and review of their effectiveness. Hence, the performance of any adaptation technology should be carefully monitored and assessed and the lessons fed back through the cycle to improve maintenance and future interventions, as shown in Figure 3.3. There are three basic steps within this cycle:

1. Prioritisation of risks and opportunities
2. Implementing risk reduction
3. Review of the effectiveness of outcomes

Utilising this framework, it should be possible to provide well-planned and effective adaptation which in turn promotes sustainable development of the coastal zone. It is important to note however, that although coastal adaptation measures can reduce vulnerability to coastal hazards, total protection from coastal flooding and erosion is not achievable. To accomplish each of these three steps, a range of technologies and approaches may be employed. In developing countries, this process may be more difficult to implement

Figure 3.3: Conceptual framework for implementing coastal adaptation measures



This shows the need for information and understanding, in order to plan, design and implement effective adaptation measures and the need for continuous improvement through monitoring and evaluation

Source: Hay 2009

due to a lack of adaptive capacity, but the need for all three stages remains and should be addressed appropriately. The three steps are discussed in Sections 3.1 to 3.3.

3.1 Prioritisation of Risks and Opportunities

A key element in developing an adaptation approach involves understanding basic facts about climate change and determining what impacts it will have on your region (Tompkins et al., 2005). Relevant hazard information is crucial to knowledgeable decision-making (Hay, 2009) with more relevant, accurate and up-to-date information enabling more targeted and effective adaptation interventions (Klein et al., 2001).

Developing the most effective solutions is always important, but this is especially so in the developing world as these countries are likely to have limited resources (Tompkins et al., 2005). Current practices in some developing countries, whereby poorly understood or blindly copied designs are applied, contradicts this guidance and often results in exaggerated socio-economic and environmental costs (UNFCCC, 1999).

In general, a requirement for a multi-disciplinary approach has been recognised for provision of the most effective adaptations. This has been learned in countries with a long history of coastal engineering, such as the Netherlands (VanKoningsveld et al., 2008) and it is hoped that developing countries can learn from their extensive experience.

Compiling clear and concise information on the potential impacts of climate change on your region may be difficult as specific information is often lacking (Tompkins et al., 2005). It is possible to obtain information relevant to the coastal zone from several large-scale, global and regional data repositories (see Klein et al., 2001). However, adaptation usually requires more detailed information than these large-scale datasets can provide (Klein et al., 2006). As such, dedicated, local data collection programmes would be highly beneficial. Information about the relevant technologies that may be used to collect information on the coastal system are explored in Section 4.4 and can also can be found in Klein et al. (2001).

When a need for adaptation is identified, decision makers should then identify what action could best be taken. Actions which may be considered include technologies focussed on the utilisation of capital goods such as sea dikes and seawalls, or technologies focussed on information, institutional arrangements and the building of adaptive capacity. Different country contexts will drive the need to tailor adaptations to local conditions. The selection of technologies must bear in mind the realities of time, funding, personnel and institutional capacity (USAID, 2009).

Determining when adaptations should occur is also important. Implementation can be either reactive or anticipatory. Reactive adaptation occurs after the initial impacts of climate change are manifest, while anticipatory adaptation occurs before impacts are apparent. While all technologies can be implemented in an anticipatory fashion, not all can be employed reactively and the benefits of accommodation and retreat approaches are much greater if applied in a proactive manner. In general, incorporating an allowance for climate change in the planning and design of coastal infrastructure is recommended.

There are a number of decision tools available to assist decisions on what technologies to employ and when and where they should be implemented. These include cost-benefit analysis, cost-effectiveness analysis and multi-criteria analysis. These methods are discussed in more detail in Chapter 5.

The spatial planning element of coastal adaptation can be greatly enhanced by the application of Geographic Information Systems (GIS). These have proven to be a highly useful tool in analysing problems, and identifying appropriate technologies and locations for adaptation options (Klein et al., 2006) and can provide excellent decision-making support to coastal managers. GIS combines computer mapping and visualisation techniques with spatial databases and statistical, modelling and analytical tools (Klein et al., 2001). Numerical models can also be included and the results stored (Dawson et al., 2009; Mokrech et al., 2009) GIS is also a valuable tool for the remaining adaptation steps and can be used throughout the adaptation process.

Throughout adaptation, stakeholder engagement, communication and awareness raising are essential. Decision-makers should aim to facilitate communication with all interested parties, in line with the recommendations of ICZM (Box 3.1). These activities will help communicate the justification for adaptations as well as the associated uncertainties. They also help to improve the effectiveness of the planning and design process.

3.2 Implementing Risk Reduction

Once an adaptation approach has been decided upon, the selected technology or technologies must be implemented. Pursuing a protect, accommodate or retreat approach is likely to entail implementation of one or more complementary technologies; using this approach, a region should be able to more effectively respond to a wide range of climate change impacts (USAID, 2009).

An additional benefit of simultaneously applying complementary adaptation technologies is the reduction of the risk of catastrophic failure. Implementing complementary technologies also serves as an added safety measure (IOC, 2009). For example, flood warning systems (Section 4.2.5), which are classed as an accommodate measure, are frequently implemented alongside protective measures such as dike systems and storm surge barriers (Sections 4.1.4 and 4.1.5 respectively). In part, this addresses the issue of residual risk or what happens if a rare event that will overwhelm the defence occurs.

Unfortunately, there is no single or generic ‘best solution’ for coastal adaptation. Instead, each situation must be evaluated and treated on its particular merits (IPCC CZMS, 1990). This will lead to the implementation of different adaptation measures at different sites in order to work most effectively with local conditions (Evans et al., 2004). Implementing a portfolio of responses has proven to be both more effective and less costly because local differences are accounted for and synergies between adaptation technologies are expected. The approach is therefore recommended to be widely applied. Table 4.1 should help coastal managers identify possible portfolios of complementary, as opposed to competing, technologies.

The use of ‘flexible’ approaches to coastal management should also be given considerable attention (Thorne et al., 2007). Flexible approaches ensure that we can provide the next generation with the same range of options which are available to us today. To do so, coastal management strategies should be reversible. In a similar vein, ‘no regrets’ measures should also be a priority; these measures provide benefits regardless of climate change. For example, wetland restoration (Section 4.2.2) enhances coastal ecosystems which are already vulnerable due to numerous other reasons (USAID, 2009).

3.3 Reviewing the Effectiveness of Outcomes

Following implementation of an adaptation approach, an ongoing and appropriate process of monitoring and evaluation should take place. This allows coastal managers to assess whether adaptations have achieved their specified goals. The information gained is also likely to provide an insight into how well the adaptation is performing. This may give rise to strategy adjustments as appropriate (Klein et al., 2001). This process of learning and improving is essential because an attitude of ‘getting it right the first time’ is likely to mean there is little chance that beneficial changes and modifications will be made, or that anyone will admit to mistakes (Tompkins et al., 2005). Looking at the adaptation process (Figure 3.3), most time will be spent in a preferred system state, assuming that the earlier steps are properly followed. If monitoring shows problems, there is a feedback which restarts the adaptation process (Figure 3.3).

Effective monitoring and evaluation requires the regular collection of a set of meaningful and reliable indicators related to the initial project objectives. Adaptation options should be periodically reviewed against these explicit goals so that their success or failure can be reviewed (Nicholls & Klein, 2005). When the objective of adaptation is to protect against extreme events, however, it may be difficult to assess if technologies have achieved their objectives because design conditions are, by definition, rare events. In these cases, both models and experience with similar infrastructure elsewhere in the world may be informative. This requires an outward looking coastal management culture.

Because the effects of climate change on a region are also uncertain, the likely impacts of climate change on a locale must also be periodically monitored and reviewed. This will feed back into the prioritisation of risks and opportunities, outlined in Section 3.1, whereby knowing the impacts of climate change can help coastal managers to implement the most cost effective adaptations. Improved knowledge of the local impacts of climate change will inform the need to adjust the adaptation approach as we learn more about the specific regional impacts of climate change.

There is a need to sustain monitoring activities over many decades. As such, monitoring should be planned accordingly (Klein et al., 2006). However, sustaining monitoring may be difficult in developing countries, not least due to cost (Tompkins et al., 2005). If the importance of monitoring is not recognised, this important activity may be threatened by a desire to make cost savings. Hence, fully implementing this three step adaptation process is a challenge.

Collection of data for monitoring purposes generally uses the same technologies as for the initial description of the coastal system (see Section 3.1). Monitoring requirements are discussed in detail in Section 4.5.

4. Adaptation Technologies and Practices

In this chapter we present 13 adaptation technologies for responding to coastal erosion and flooding, grouped under the protect, accommodate and retreat approaches. Under each technology, we describe (1) the technical advantages and disadvantages; (2) institutional and organisational requirements; (3) costs and financial requirements; (4) Barriers and opportunities to implementation; and (5) a relevant case study. In Section 4.4, we consider knowledge and capacity building requirements and in Section 4.5, monitoring technologies. Further sources are provided in Appendix II.

It should be noted here, that an effective adaptation strategy is likely to comprise a portfolio of adaptation technologies. Table 4.1 shows those measures which are complementary and those which are competing to assist in identifying possible portfolios. It is apparent that a wide range of combinations are possible.

Table 4.1: Complementary and competing adaptation technologies

	Coastal Setbacks	Managed Realignment	Floating Agricultural Systems	Flood Warnings	Flood Hazard Mapping	Wetland Restoration	Flood Proofing	Land Claim	Storm Surge Barriers	Sea Dikes	Seawalls	Artificial Dunes and Dune Rehabilitation
Beach Nourishment	■	■ a	■	■	■	□ b	■	□	■	■	■	■
Artificial Dunes & Dune Rehabilitation	■	■ a	■	■	■	□ b	■	□	■	■	■	
Seawalls	■	■ a	■	■	■	■	■	■ c	■	□		
Sea Dikes	■	■ a	■	■	■	■	■	■ c	■			
Storm Surge Barriers	■	■	■	■	■	■	■	■				
Land Claim	■	□	□	■	■	□	■					
Flood Proofing	■	■	■	■	■	■						
Wetland restoration	■	■	■	■	■							
Flood Hazard Mapping	■	■	■	■								
Flood Warnings	■	■	■									
Floating Agricultural Systems	■	■										
Managed Realignment	■											

■	Complementary
□	Competing

a Complementary when these features are realigned landward of their present location.
b Wetlands and sandy beaches are rarely coincident.
c When used to protect claimed land.

The level of experience and knowledge in the application of these 13 adaptation technologies varies around the world. For the most part, experience and knowledge of coastal adaptation is more advanced in developed countries. The present level of experience in the application of adaptation technologies is summarised in Table 4.2, for developed and developing countries.

Table 4.2: Current degree of experience in the application of adaptation technologies

Technology	Developed country			Developing country			Comments
	Low	Med	High	Low	Med	High	
Beach nourishment			✓		✓		Rapid growth in application
Artificial dunes & dune rehabilitation			✓	✓			
Seawalls			✓			✓	Developing country approaches are often ad-hoc
Sea dikes			✓			✓	East Asian countries have a long legacy of dike construction
Surge barriers		✓		✓			A more specialised technology which is likely to see more widespread application
Closure dams			✓			✓	
Land claim			✓			✓	Most common in areas of high population density
Flood-proofing		✓			✓		Growing application worldwide
Wetland restoration			✓	✓			
Floating agricultural systems	✓					✓	Application only occurs in a few delta environments (e.g. Bangladesh)
Flood hazard mapping			✓			✓	Rapid growth in application
Flood warnings			✓			✓	Rapid growth in application
Managed realignment			✓	✓			Applied in areas of historic land claim – mainly in NW Europe and USA to date
Coastal setbacks			✓			✓	Rapid growth in application

4.1 Protection Approaches

Shore protection, in its widest usage refers to the reduction or elimination of damage to the shore and back land, as might be caused by flooding, wave attack and erosion by using barriers to exclude hydraulic influences (Kraus, 2005). Society's desire to build infrastructure close to the coast and to utilise the coast and its resources has commonly led to the protect option being implemented preferentially (Cooper & Harlow, 1998).

A protect approach involves defensive measures and other activities to protect areas against inundation, tidal flooding, the effects of waves on infrastructure, shore erosion, salinity intrusion and the loss of natural resources. The measures may be drawn from an array of 'hard' and 'soft' structural solutions. They can be applied alone or in combination, depending on the specific conditions of the site (IPCC CZMS, 1990). Hard and soft protective measures are introduced below.

Hard Defences

Hard defences are the traditional approach to coastal defence. It utilises structures which provide a solid barrier between the land and sea and resist the energy of the tides and waves, thus preventing any land/sea interaction from taking place (French, 2001). Examples of hard defences include seawalls, sea dikes, revetments, armour units and breakwaters. Historically, hard defences have been employed because they provide tangible protection and they are trusted by protected populations. In time however, it has become clear that while these structures provide benefits to the hinterland they protect, they do little to prevent the physical process of erosion. Instead the problem is transferred from the shoreline to the seabed immediately in front of the structure (Pilarczyk, 1990b) or the adjacent coast (Nicholls et al., 2007b). Hence, use of hard defences should anticipate these problems and be prepared to respond to the consequences (e.g. Leafe et al., 1998; DEFRA, 2006).

Perhaps the main problem with hard defences is that once built, they fix the location of the coastline in the position at the time of construction. Although this is beneficial, at least initially, in terms of halting shoreline erosion, fixing the position of the coastline is problematic because coastlines are naturally dynamic landforms which respond to factors such as rising sea levels and wave climate. Additional problems exist in the fact that hard structures can impede the recreational use of beaches and can be costly to construct and maintain (USACE, 2002). These costs and benefits need to be considered when considering the application of these adaptation technologies.

Increasing awareness of the negative side-effects of hard structures on erosion and sedimentation patterns has led to growing recognition of the benefits of 'soft' protection and the adaptation strategies of retreat and accommodate (Klein et al., 2006). Alternatively, hard defences (Sections 4.1.3 to 4.1.6) can be combined with soft defences, such as beach nourishment. Using this approach, nourishment would maintain beach levels, while the hard defence continues to protect the coastline against the most extreme events.

Soft Defences

While hard defences fight against natural forces such as wave energy, soft engineering technologies adapt to and supplement natural processes (Bermingham et al., 2000). Soft defences have largely been stimulated as a response to the negative impacts of hard defences. They also represent a major shift in approach from ad-hoc reaction to coastal hazards to the adoption of a more holistic and proactive approach (Dean, 2002; Hanson et al., 2002; Williams & Micallef, 2009). Examples of soft defence include beach nourishment (Section 4.1.1) and dune building (Section 4.1.2).

By adopting soft engineered measures we can help to avoid many of the negative consequences of hard defences. This approach is particularly attractive on wave exposed coasts with beaches. Additionally, application of soft defences helps maintain the natural landscape and habitat function of the coast. By working with natural processes, there is also an increased potential for maximising the benefits of a scheme while minimising environmental impact and also creating environmental opportunities (Chadwick et al., 2004).

However, a key consideration when applying soft engineered measures is that these solutions require ongoing and regular monitoring, maintenance and engineering; this will need the ongoing involvement of engineers, planners, designers and others to a greater degree than hard defences (Edge et al., 2003). Hence, these additional costs and capability needs should be considered when selecting an option.

Summary

While there has been a widespread move to soft defences, both types of technology will continue to be applied in the future. Hard defences are likely to be particularly important in protecting coastal urban areas against flooding. Soft defences are more likely on sedimentary coasts composed of beaches. Combinations of soft and hard defences are also likely in many cases as such schemes may be more economic in many cases.

4.1.1 Beach Nourishment

Definition

Beach nourishment is an adaptation technology primarily used in response to shoreline erosion, although flood reduction benefits may also occur. It is a soft engineering approach to coastal protection which involves the artificial addition of sediment of suitable quality to a beach area that has a sediment deficit. Nourishment can also be referred to as beach recharge, beach fill, replenishment, re-nourishment and beach feeding.

Description

Addition of beach material rebuilds and maintains the beach at a width which helps provide storm protection. This approach is mainly used on sandy beaches but the term can also refer to nourishment with shingle or even cobbles. The aim, however, should be to ensure that nourishment material is compatible with the existing natural (or native) beach material (Reeve et al., 2004). Nourishment is often used in conjunction with artificial dune creation (see Section 4.1.2).

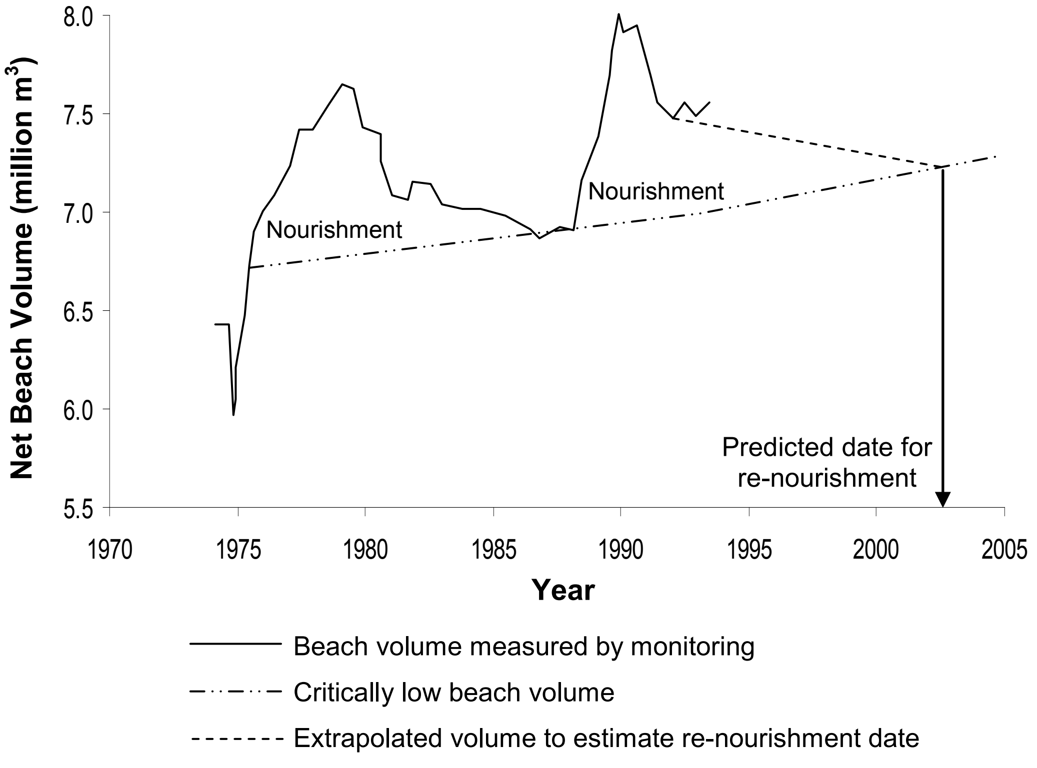
The benefit of beach nourishment comes from wave energy dissipation; when waves run up a beach and break, they lose energy. Different beach profile shapes and gradients interact with waves to differing extent. The cross-sectional shape of a beach therefore affects its ability to attenuate wave energy. A ‘dissipative’ beach – one that dissipates considerable wave energy – is wide and shallow while a ‘reflective’ beach – one that reflects incoming wave energy seawards – is steep and narrow and achieves little wave energy attenuation. The logic behind beach nourishment is to turn an eroding, reflective beach into a wider, dissipative beach, which increases wave energy attenuation (French, 2001).

As well as helping to dissipate incoming wave energy, beach nourishment addresses a sediment deficit: the underlying cause of erosion. This is achieved by introducing large quantities of beach material to the coastal sediment budget from an external sediment source, also referred to as a borrow site. The term ‘sediment budget’ is used to describe the careful balance which exists between incoming and outgoing sediment. Much like a bank account, when more material is added than removed, a build-up occurs and the shore builds seaward; conversely, when more material is removed than deposited, erosion occurs (Morton, 2004). Nourishment addresses a sediment deficit – the cause of erosion – by introducing large quantities of beach material to the nearshore system. In turn, this can cause the shore to build seaward.

It is important to note that beach nourishment does not halt erosion, but simply provides sediment from an external source, upon which erosional forces will continue to act. In this sense, beach nourishment provides a sacrificial, rather than a fixed barrier against coastal erosion.

Continuing erosional forces will likely return the beach to a state where re-nourishment is required. Figure 4.1 shows the beach volume at a nourished beach in the UK, over time. It can be seen that over time the volume of the beach declines as a result of natural erosion. When the beach reduces to a critical volume, re-nourishment should be undertaken to avoid damage to coastal infrastructure.

Figure 4.1: Data illustrating beach volume at Bournemouth Beach, UK



Source: Adapted from Harlow and Cooper (1996)

Several methods of nourishment can be utilised, including placement by dredge, trucks or conveyor belts. Sand can be placed to create an extension of the beach width or as an underwater deposit which will be gradually moved onshore under the normal action of waves – this follows current practice in the

Netherlands (VanKoningsveld et al., 2008). Placement as an underwater deposit also serves to encourage the dissipation of wave energy, therefore reducing its impact at the shore (Dean, 2002).

Supply of nourishment material by offshore dredging is often favoured because it allows for large quantities of material to be obtained from an area where its removal and onshore transport is reasonably non-disruptive to shoreline communities (Dean, 2002). During dredging, sediment is removed from the seabed along with significant quantities of water. The mixture is referred to as a 'slurry' and its liquid characteristics allow for it to be transferred ashore by floating or submerged pipelines or by the 'rainbow method' (see Figure 4.2).

Figure 4.2: Rainbow method for transferring nourishment material ashore

Slurry is discharged via a jet at the bow of the ship once it has been sailed as close to the shore as possible
Source: Courtesy of Dredging International

An alternative to offshore dredging is the removal of beach-grade sediment from land-based sources. Sediment is then transported to the target site by truck haul. Only a small percentage of nourishments are carried out in this way and the approach is more suited to smaller-scale operations because of the more labour-intensive way of transportation (Dean, 2002).

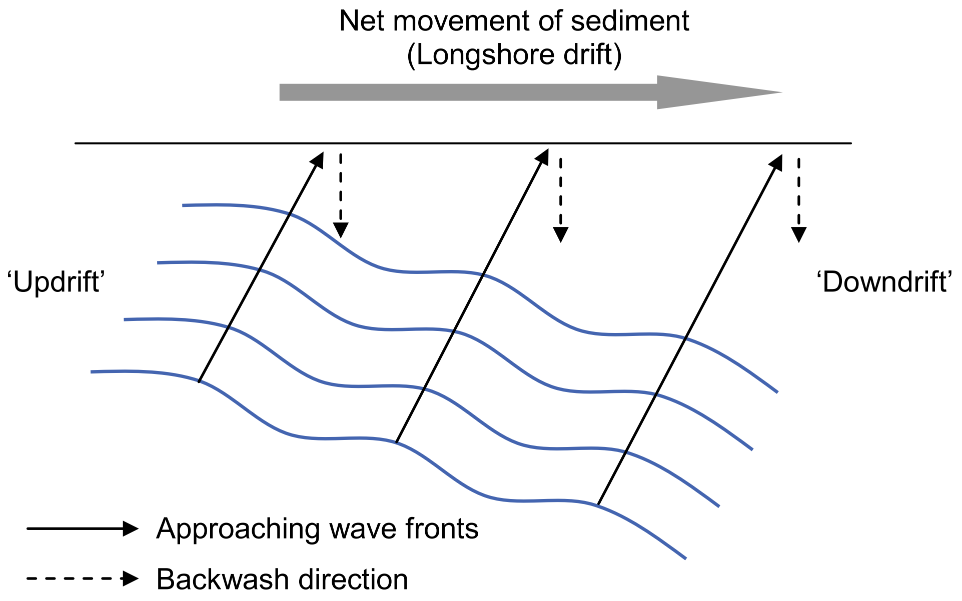
Once sediment has been transported to the target beach, it must be deposited appropriately. If utilising offshore dredge sites, sediment can be dumped as an underwater deposit. However, nourishment more commonly brings sediment ashore. Once ashore, sediment may be reworked to form a flat beach. If desired, artificial dunes may also be created on the landward portion of the beach (see Section 4.1.2), through the use of bulldozers or other means.

Advantages of Beach Nourishment

If performed well, the benefits of nourishment are many and varied. Most importantly, beach nourishment reduces the detrimental impacts of coastal erosion by providing additional sediment which satisfies erosional forces. Shoreline erosion will continue to occur, but the widened and deepened beach will provide a buffer to protect coastal infrastructure and other assets from the effects of coastal erosion and storm damage. Beach nourishment is a flexible coastal management solution, in that it is reversible. This is highly beneficial as it allows the widest range of coastal management options to be passed to the next generation.

Alongshore redistribution of the added material will occur through a process known as longshore drift, under the action of waves, tides and wind. Longshore drift is caused by waves approaching the shore obliquely, carrying beach sediments with them. When waves return to the sea however, the movement is always perpendicular to the shore. This initiates a gradual alongshore movement of sediment as shown in Figure 4.3. As a result of sediment redistribution by longshore drift, beach nourishment is likely to positively impact adjacent areas which were not directly nourished. This may provide wider benefits including reduced beach and cliff erosion for the entire coastal cell[1].

Figure 4.3: Schematic illustration of longshore drift



Incoming waves approach from an angle causing sediment to gradually move sediment alongshore in a zig-zagging manner. The terms 'updrift' and 'downdrift' refer to locations either up- or down-stream of this movement of sediment

Source: Adapted from French, 2001

Beach nourishment can complement hard protection measures such as seawalls (see Section 4.1.3), which may continue to be used as a last line of defence. The existence of a wide, sandy beach in front of such structures greatly reduces the wave energy reaching them, thus providing additional protection.

---

[1] A coastal cell is a stretch of coastline within which sediment movement is self-contained. Sediment within one coastal cell is not transported or shared with adjacent cells.

Addition of sediment which closely resembles the native beach material will help retain the natural landscape of the beach, while providing an increased capacity for coping with coastal erosion and flooding. The natural appearance of nourishment projects also means these schemes are aesthetically pleasing.

As mentioned in Chapter 2, coastal tourism heavily depends on 'sun, sea and sand'. As a result, beach nourishment has the potential to promote recreation and tourism through beach widening (Nicholls et al., 2007b). This may serve to enhance pre-existing tourism or may serve to attract tourists to the area, thus encouraging development.

It is also possible to provide ecological benefits through beach nourishment. Schemes have been shown to provide enhanced nesting sites for sea turtles when designed with the requirements of these creatures in mind (Dean, 2002). This in turn, may serve to promote 'eco-tourism', with consequent development benefits.

Today, nourishment is very popular in developed countries but has also found application in developing nations, such as Brazil (Vera-Cruz, 1972; Elfrink et al., 2008), Nigeria (Sunday & John, 2006; see also Table 4.4), Korea (Kim et al., 2008), Ghana (Nairn et al., 1998) and Malaysia (Brøgger & Jakobsen, 2008). The technology and methods involved are well established and many contractors experienced in beach nourishment are available worldwide to undertake such projects.

Disadvantages of Beach Nourishment

As already stated, nourishment is not a permanent solution to shoreline erosion. Periodic re-nourishments, or 'top-ups', will be needed to maintain a scheme's effectiveness. This will require regular re-investment but can be viewed as a maintenance cost, such as those associated with hard engineered structures.
As with any type of shore protection works, reducing the risk of coastal flooding and erosion will result in an increased sense of security. To some extent, this is desirable. However, even in the presence of protective measures, the coastal zone remains susceptible to extreme coastal flooding and erosion events, and will remain exposed to natural disasters with long return periods. If not carefully regulated, protective measures may promote unwise development in these risky areas as a result of the increased sense of security.

Depositing sediments onto beaches can generate a number of negative environmental effects, including direct burial of animals and organisms residing on the beach, lethal or damaging doses of water turbidity – cloudiness caused by agitation of sediments – and altered sediment compositions which may affect the types of animals which inhabit the area (Dean, 2002). As a result, projects must be designed with an understanding of, and concern for, the potential adverse consequences for the environment. Special consideration should be given to the impacts upon important or rare species resident in the coastal zone.

Placement of fill material on the beach can disrupt beach and ocean habitats, such as bird and sea turtle nesting, if schemes are not designed appropriately. This is especially the case if sand grain size/composition does not match the native beach materials (IOC, 2009).

The application of beach nourishment is expected to grow in the future and as a result, there may be higher demand for high quality sediment. Limited availability of large contractors, coupled with an increase in demand for nourishment projects have already caused cost increases for nourishment projects in the Netherlands where it is widely applied (Hillen et al., 2010). This upward trend is likely to be observed elsewhere in future.

Costs and Financial Requirements

Linham et al. (2010) extensively researched the unit costs of beach nourishment. Costs were shown to typically vary from US$3-15/m^3 (at 2009 price levels) where dredge sites are available locally (Linham et al., 2010). The most important determinant of nourishment costs appears to be the transport distance for the beach material.

Most of this data was collected in developed countries because this is where the vast bulk of nourishment occurs today. In developing countries, costs would, in general, be expected to be similar or possibly higher, due to their less developed coastal engineering industry.

Wide variation in costs is apparent between and within countries. This is a result of the numerous factors detailed in Box 4.1.

Box 4.1: Factors affecting unit costs of nourishment

- Project size and resulting economies of scale
- Distance between dredge and target sites
- Number of journeys required between dredge site and nourishment area
- Seabed shape at the borrow site – determinant of the dredger size which can be used and therefore affects the number of journeys that must be made
- Recharge material – coarser material causes greater equipment wear and tear which is likely to be passed on to customers by contractors
- Estimated material losses
- Availability (and size) of dredgers
- Degree of site exposure – determines type of dredger to be used and may also shorten working hours when a site is subjected to energetic winds and waves
- Tidal range – large tidal ranges provide time constraints on when dredgers are able approach close enough to shore to deposit material. This is turn can affect the time required to complete a project
- Third party requirements

Source: CIRIA, 1996; Linham et al., 2010

Payment to contractors is usually based on the delivered volume of sediment. This normally requires surveys of the visible and underwater sections of the beach to be completed both pre- and post-nourishment.

The ongoing cost of monitoring should be accounted for when considering the overall cost of nourishment. Monitoring costs are likely to vary with local labour costs and, as such, could vary significantly between countries (Mason, pers. comm.).

Institutional and Organisational Requirements

Large-scale beach nourishments will typically require extensive engineering studies and specialised knowledge and equipment. This may include dredgers and pipelines that need to be hired from a specialised contractor. However, it is also possible to conduct nourishment on a smaller scale. Beach-grade sediment can be transferred from land-based sources or from depositional to erosional areas by truck haul. Because of the smaller-scale nature of this approach and because readily available equipment could be used, nourishment by truck haul may be more practicable at a local level.

Once nourishment has been carried out, ongoing beach monitoring is needed in order to evaluate nourishment success and to determine when re-nourishment will be required. Given appropriate training and technology, monitoring should be possible at a local/community level. Nourishment schemes should be evaluated as a whole, however, which may require the participation of multiple communities if nourishment is undertaken on a large scale.

Barriers to Implementation

Beach nourishment requires a suitable source of sediment to be identified in close enough proximity to the nourishment site. This ensures that costs are kept at a reasonable level. Sediment availability is highly variable around the globe and suitable sources may not be easily found. The increasing popularity of beach nourishment worldwide may therefore cause sediment availability problems as demand increases. This problem is already being experienced in small island settings where sand is frequently carried large distances for nourishment projects.

Beach nourishment requires highly specialised equipment and knowledge including dredgers and pipelines that will need to be hired from a specialised contractor. Hillen et al. (2010) have noted the limited number of large contractors available and also highlighted the associated cost increase due to high demand. Local site characteristics will also influence the type and size of dredger which can be used – this can further limit the availability of dredgers.

Public awareness of how beach nourishment schemes work can also present a barrier. This is especially the case when using shoreface nourishment or underwater sediment deposition. Using these techniques, the advantages of nourishment may not be immediately noticeable and unless the public are educated on how the scheme works, they may doubt the benefits of nourishment and oppose such projects. The public should also be made aware that nourishment is not a permanent solution and that re-nourishments will be required. If this is not communicated, the public may again believe the scheme has failed and resent further spending on re-nourishment. This will be especially the case if public funding is used to cover nourishment costs.

Opportunities for Implementation

Beach nourishment can act as a cost-effective disposal option for maintenance dredging of harbours and channels. The use of dredge material also combats the potential lack of suitable sediments offshore. Care must be taken when utilising dredge material however, as harbour dredges can contain high levels of pollutants which must be carefully monitored.

Beach nourishment can also be employed in conjunction with other adaptation technologies and can help to address the drawbacks of these hard technologies, which include beach lowering and downdrift sediment starvation.

If nourishment provides ecological benefits, it can also serve to encourage ecotourism and will provide an income stream for the local economy.

Case Study: Bournemouth Beach, Poole Bay, UK

No well-documented case studies of repetitive beach nourishment in developing countries were located, and hence, Poole Bay is used here. However, the principles could be applied globally.

Poole Bay, located on the south coast of England, has undergone periodic re-nourishment from the 1970s to the present day. To date, three large-scale nourishment projects have been undertaken during the periods 1974-1975, 1988-1990 and 2005-2009. As shown in Figure 4.4, these nourishments have helped to maintain a wide, sandy beach which is important to the tourist economy of the area. The nourishment activities, coupled with regular and systematic monitoring, provide a best practice case study of beach nourishment.

Figure 4.4: Bournemouth Beach, Poole Bay, UK

Source: Courtesy of Robert Courtman, Wikimedia Commons

The decision to employ nourishment at this site was taken following a period of damage to hard defences such as seawalls and groynes in the 1960s. These hard protection measures had achieved limited success in retaining beach material (Harlow & Cooper, 1996). Nourishment was selected to address these problems and because it was seen as beneficial to the area's tourist economy, generated largely due to the presence of golden, sandy beaches (Cooper & Harlow, 1998).

A pilot scheme known as Beach Improvement Scheme 1 (BIS1) was conducted in 1970, placing 84,500 m^3 of dredged sand at MLW along 1.8 km of frontage (Lelliott, 1989). The results and experience gained during this pilot scheme gave local authorities the confidence to undertake a full-scale replenishment in 1974/5 (BIS2). During this scheme, 654,020 m^3 of marine dredged sand was pumped directly onto 8.5 km of beach frontage (Cooper & Harlow, 1998).

During the 1974/5 scheme, a further 749,300 m^3 of material escaped into the nearshore zone during placement. Beach monitoring revealed that a large portion of this material ultimately moved onshore in the following months and further nourished the beach (Hodder, 1986).

BIS2 remained effective for 13 years and in 1987, beach monitoring revealed critically low beach volumes and a requirement for re-nourishment. The low beach volume caused damage to the seawall which backed the beach and actually caused Mean High Water (MHW) to migrate landward up to the base of the seawall itself (Harlow & Cooper, 1996). BIS3 was initiated as a result and undertaken in three phases during 1988-1990.

BIS3 involved placement of 998,730 m^3 of material directly onto the beach. Fill material was pumped onshore above MHW. Sand was redistributed under natural processes such as wave action to form its own beach profile (Harlow & Cooper, 1996). Coincidentally, Poole Harbour was also being dredged at the time – availability of material from this source substantially reduced the costs of nourishment (Turner, 1994).

By using sand dredged from harbours and channels, the costs of nourishment can be reduced. If this can be achieved in developing countries, it is likely that nourishment will become more feasible. For example, in India, nourishment is usually too expensive to use as a coastal erosion defence tool. It has been shown though, that in certain areas, where sediment has been dredged from navigation channels and harbours, the cost of nourishment is reduced sufficiently to allow its application (Rao et al., 2009).

To avoid costly damage to coastal infrastructure as occurred in 1987, the approach to nourishment changed following BIS3. Future nourishments are planned to be not only more frequent, but localised, using lower volumes of sediment (Linham, 2008). This is different from the previous practice of not implementing re-nourishment until much of the beach material was lost. It aims to maintain beach volume at a level where damage to infrastructure can be avoided and may also lead to smaller initial sediment losses following replenishment (Cooper & Harlow, 1998). Following this guidance, BIS4 was split into a number of smaller projects, spaced through time from 2005 onwards (see Table 4.3). Each project concentrated on a specific section of beach, rather than nourishing the entire system.

Table 4.3: Poole Bay beach nourishments 2005 – 2009

Improvement Scheme	Year	Volume of beach fill added (m^3)	Material Source
BIS4.1	2005/06	600,000	Harbour dredging
BIS4.2	2006/07	898,000	Offshore dredging area
BIS4.3	2008	70,000	Offshore dredging area
BIS4.4	2009	70,000	Offshore dredging area
BIS4.5	2010	TBC	TBC

Beach fill volumes added to specific beach sections in Poole Bay from 2005 to 2009

Beach monitoring has been an important aspect of nourishment at Bournemouth since the first nourishment activity at the site[2]. The new 'little and often' nourishment approach means that monitoring is more important now than ever before.

---

[2] See www.channelcoast.org for more information on beach monitoring at Bournemouth.

Bi-annual beach profiling surveys were initiated in 1974 and have been maintained since (Harlow & Cooper, 1996). The origin of profile lines has been fixed by a pin in the seawall and the orientation of profiles are also fixed, to enable repeated surveys (Cooper & Harlow, 1998). Profiles are measured in two portions; a topographic survey above MLW and a bathymetric survey extending from MLW to approximately 450 m offshore, a point roughly calculated to represent the depth of closure[3] (Harlow & Cooper, 1996). Detailed spot height surveys are also taken annually and used to model fluctuations in beach levels. Aerial surveys and LiDAR[4] are used approximately every five years to gain a detailed picture of the local topography (Mason, pers. comm.).

The collection of beach profile information has a number of advantages. It allows the net beach volume and current erosion rates to be calculated, so that the likely dates for future replenishment can be estimated. This allows fund raising to be planned for future re-nourishments. Monitoring also indicates when re-nourishment is required, before unacceptable damages occur to coastal defences and infrastructure. It also ensures consistent beach volumes are maintained for amenity purposes. Finally, by analysing erosion rates in the period following nourishment, future projects can be improved. For example, by adjusting the fill volume to reduce accelerated post-fill erosion.

The benefits of the monitoring programme can be summarised as a shift in the management philosophy from a reactive to a proactive one. In the long run, this will have the economic benefit of reducing seawall damage costs and will also allow funding for re-nourishments to be found in advance (Cooper & Harlow, 1998). By informing the need for re-nourishment, monitoring also ensures that the standard of coastal flood and erosion protection does not drop below acceptable levels. This shift to a proactive approach is an important one. If this example can be followed elsewhere, significant cost savings may be made and the effectiveness of long-term coastal management may be improved.

4.1.2 Artificial Sand Dunes and Dune Rehabilitation

Definition

Naturally occurring sand dunes are wind-formed sand deposits representing a store of sediment in the zone just landward of normal high tides (French, 2001). Artificial dunes are engineered structures created to mimic the functioning of natural dunes.

Dune rehabilitation refers to the restoration of natural or artificial dunes from a more impaired, to a less impaired or unimpaired state of overall function, in order to gain the greatest coastal protection benefits. Artificial dune construction and dune rehabilitation are technologies aimed at reducing both coastal erosion and flooding in adjacent coastal lowlands.

Description

Dunes naturally occur along most undeveloped, sandy coastlines. A typical example is shown in Figure 4.5. Where they are present, their coastal defence role is two-fold:

1. They represent a barrier between the sea and land, in a similar way to a seawall
2. Dunes are ‘dynamic’, i.e. the dune/beach system interacts a great deal and is constantly undergoing small adjustments in response to changes in wind and wave climate or sea level. As such, dunes are able to supply sediment to the beach when it is needed in times of erosion, or store it when it is not (French, 2001).

---

[3] An offshore point beyond which, sediment movement is expected to be negligible (Hallermeier, 1981).

[4] An airborne approach to surveying topography which uses lasers to measure distances.

Figure 4.5: Coastal sand dunes at Aberffraw, Anglesey, UK

Source: Courtesy of David Rayner, Wikimedia Commons

Clearly natural sand dunes are an effective defence against coastal flooding and erosion. However, a problem arises in that wide, sandy beaches – the environment where most sand dunes occur – are highly appealing for development. As such, natural sand dunes are in decline. Coupled with an increased chance of dune erosion caused by SLR and more energetic wave climates, sand dunes are at risk.

The importance of dunes in coastal protection has now been recognised however, and the construction of artificial dunes and rehabilitation of existing ones are potential technologies for adapting to climate change in the coastal zone.

At its simplest, artificial dune construction involves the placement of sediment from dredged sources on the beach. This is followed by reshaping of these deposits into dunes using bulldozers or other means. As a result, dune construction is most frequently carried out at the same time as beach nourishment (see Section 4.1.1), because sand is readily available.

There are a number of methods of dune rehabilitation. One such method is to build fences on the seaward side of an existing dune to trap sand and help stabilise any bare sand surfaces (USACE, 2003). This method can also be used to promote dune growth after a structure has been created using bulldozers (Nordstrom & Arens, 1998). Natural materials such as branches or reed stakes are commonly used for fence construction, because they break down once they have accomplished their sand-trapping objective (Nordstrom & Arens, 1998).

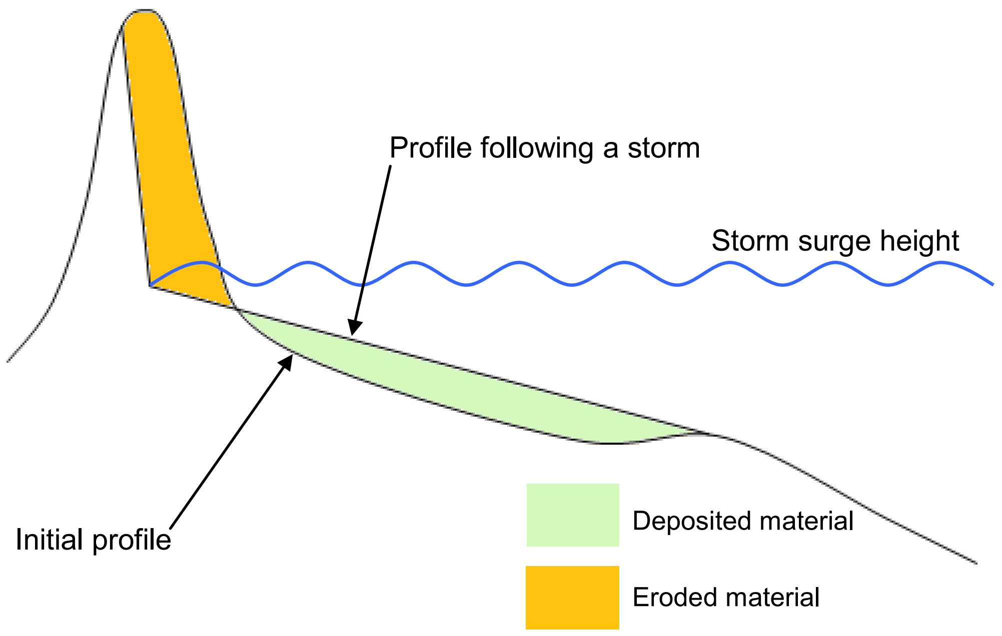
Alternatively, vegetation planting may be used to stabilise natural or artificial dunes. This promotes the accumulation of sand from wind-blown sources around their stems – over time, this causes dune growth. Planting can be achieved by transplanting vegetative units from nursery stocks or nearby intact dunes (USACE, 2003). It can be undertaken at the community level using widely available tools. Over time, dune vegetation root networks also help to stabilise the dune.

Artificial dune creation and dune restoration can be carried out on existing beaches, beaches built through nourishment, existing dunes, undeveloped land, undeveloped portions of developed areas and areas that are currently fully developed but may be purchased so that dunes can be restored (Nordstrom et al., 2000).

Advantages of Artificial Sand Dunes and Dune Rehabilitation

Section 4.1.1 has already stated the importance of sandy beaches in dissipating wave energy. However, sandy beaches are in a constant state of flux, because they continuously react to constantly changing wave climates and sea levels. As such, the volume of sand held upon a beach is constantly fluctuating. During periods of low beach volume, the shoreline is susceptible to erosion and it is at these times, that sand dunes can be particularly valuable as a store of sediment which can be accessed in order to satisfy erosional forces. This compensates for the sand removed from a beach and helps to maintain wide, sandy beaches which will continue to dissipate incoming wave energy. This process is illustrated in Figure 4.6. The volume of erosion can be calculated using the Vellinga (1983) equation which requires knowledge of wave height, extreme water level and sediment fall velocity.

Figure 4.6: Simplified illustration of dune erosion caused by storm surge



Vellinga (1983) found that during storms, sediment is eroded from dunes and deposited on the underwater portion of the beach profile. This maintains a wide, sandy beach which continues to dissipate wave energy

Source: Adapted from Charlier & De Meyer (1998) Ref: Charlier, R.H. and De Meyer, C.P. (1998) Coastal Erosion: Response and Management, Volume 70. Berlin: Springer Verlag

With careful management, dunes are able to offer a high degree of protection against coastal flooding and erosion. Because dunes provide both a physical and tangible defence, they may even serve to encourage sustainable development within the coastal zone.

Dunes are naturally occurring features, and provided the construction/initiation of artificial dunes is completed in a sympathetic manner, they do not necessarily spoil the local landscape. Many sandy beaches would have had naturally occurring sand dune complexes prior to coastline development; as such, the initiation of artificial dunes may even restore a degree of natural character to the site.

Sand dunes also provide a valuable coastal habitat for many highly specialised plants and animals. As such, sand dunes may be considered important both ecologically and recreationally.

Disadvantages of Artificial Sand Dunes and Dune Rehabilitation

Despite being a natural feature of many sandy coastlines, dunes also represent a barrier to beach access. In many cases, dunes have been removed as a result of development and communities have grown used to direct access to beaches and views straight onto the sea. Reconstruction of dunes may receive local opposition if it affects these factors.

Land loss is another issue; dunes have a reasonable sized footprint. This space requirement increases further if dunes are to be given sufficient room to adapt to SLR, thus avoiding coastal squeeze. It could be controversial to use land with development potential for dune creation and rehabilitation if the full benefits are not made clear. Alternatively, sand dune construction may take place on an area of beach important for tourism and recreational purposes, therefore restricting its use by the public.

Costs and Financial Requirements

Since the most basic sand dune construction projects consist simply of the deposit of dredged material onshore, followed by shaping using bulldozers, simple dune construction costs are not expected to be significantly different from beach nourishment costs in terms of cost per cubic metre of sediment used (see Section 4.1.1). Additional costs may however, be introduced through the requirement for dune grass planting and fencing.

Factors which are likely to influence the unit costs of dune construction are explored in Box 4.2.

Box 4.2: Factors affecting the unit costs of dune construction

- Whether dredged material is required for dune construction/restoration or whether fences or vegetation can be used to promote sand accumulation
- Availability and proximity of appropriate construction material from onshore or offshore sites
- Dredger type, size and availability
- Requirement to fence newly constructed dunes to prevent erosion
- Requirement for planting new dunes with vegetation
- Frequency with which the dune needs to be artificially replenished or whether the structure naturally accumulates sand
- Project size and resulting economies of scale

Institutional and Organisational Requirements

While dune construction using dredged sand may require specialised knowledge and equipment as detailed in Section 4.1.1, rehabilitation and maintenance of naturally occurring and artificially created dunes is accomplishable at a community level.

The application of fences to stabilise bare sand and encourage dune growth is possible using local, naturally occurring materials such as branches and reed sticks (Nordstrom & Arens, 1998). The measure therefore requires very little external provision of materials or guidance. Fencing can also prevent dune erosion caused by human access.

As already mentioned, vegetation planting is frequently accomplished at the community level with subsequent maintenance also left to communities (Nordstrom & Arens, 1998). The success of this approach has been found to vary considerably with local commitment (Nordstrom & Arens, 1998). Local awareness raising campaigns could help local communities better understand the coastal protection role of dunes, which may promote local efforts to continue to preserve dunes.

Once sufficient material for the creation of dunes is available, dune creation either through naturally occurring processes or through artificial placement, movement and reshaping of the material is another task achievable with limited technology requirements. The use of a bulldozer or other earth moving equipment is sufficient to undertake ad-hoc operations to reshape or repair dunes. Sediment may even be bulldozed from dune crests and placed in lower areas if the dune crest height exceeds design specifications (Nordstrom & Arens, 1998).

Barriers to Implementation

Previous experience of artificial dune creation or rehabilitation projects has shown that one major barrier is the difficulty in convincing the public and municipal officials of the need for dune construction or heightening (Nordstrom et al., 2000).

Conflicts of interest may also arise, especially if dune construction takes place in an area primarily used for residential or tourism purposes, where local landowners may be concerned about maintaining sea views. In these cases it may be possible to keep new dunes relatively low and linear, although this could affect the level of protection offered. If the full coastal protection benefits of dunes are communicated, opposition may be kept to a minimum.

In the USA, coastal managers have sometimes constructed sub-optimal dunes to minimise public opposition and to familiarise local communities with the presence of dunes. By gaining acceptance in this way, it may be possible in future to gain approval for dunes of larger dimensions, offering better levels of protection (Nordstrom et al., 2000).

Opposition may also be caused by the land-take requirements of dunes. Greater width on the ocean side could reduce beach space and on the landward side would bring dunes closer to human settlements such as housing.

Sand dunes are a dynamic form of coastal defence which respond to coastal processes such as the wave and wind climates. For example, in the summer months, dunes may grow as they accumulate sediments, while during winter storms, the sediment stored in the dunes may be accessed by the beach to satisfy erosion. Many communities are only familiar with static defences which do not react to the local conditions. The drastically different way in which dunes react to storm events may cause communities to object to their use, especially in communities where coastal stabilisation has been the long-term goal (Nordstrom et al., 2000).

Opportunities for Implementation

Dune restoration can be much more than mitigation or reparation, in that it can lead to increased understanding and appreciation of a threatened ecosystem (Nordstrom et al., 2000). Restoration programs can be linked to environmental education initiatives aimed at re-establishing an appreciation for naturally functioning coastal landscapes. This may increase the likelihood of implementing similar programs elsewhere (Nordstrom et al., 2000).

Due to factors such as urbanisation, development, trampling and conversion, sand dunes are becoming increasingly damaged and in decline (French, 2001). With an improved understanding of the role of sand dunes in coastal defence and with greater awareness of the ecological importance of sand dunes for coastal species, dune construction and rehabilitation is likely to become more popular. This will bring advantages for coastal defence and nature.

Dune protection meets multiple management objectives, such as habitat protection, public access to environmental and recreational resources and hazard mitigation. Because of these benefits and the fact that they are less expensive and more aesthetically pleasing than some engineering solutions, dunes are likely to find broader public support in future (Moser, 2000).

Case Study: Avalon, New Jersey, USA

No well-documented case studies of artificial dune construction and rehabilitation in developing countries have been found by the authors. Hence, the dune construction programme at Avalon, USA is used here. The principles could be applied globally.

Avalon is located at the northern end of an Atlantic-facing barrier island in the state of New Jersey, USA. The area is highly urbanised and extensive infrastructure is present in the coastal zone. The current coastal management approach at the site consists of an aggressive programme of dune management. This decision was taken (1) to protect the large number of low-lying houses and (2) because evacuation in the event of a flood is difficult, due to large summer populations and low elevation roads. The following case study is summarised from a study by Nordstrom et al. (2002).

The dune management programme started with two activities: (1) building dunes along the entire seafront, using sand fences and vegetation planting; and (2) raising money to buy undeveloped shorefront lots to create an undeveloped segment of coastline which provides space for landforms to evolve naturally, a source of sand for replenishing critically eroding areas and a location for experimenting with environmentally compatible management strategies. It also prevented further development from taking place in the hazard zone. Another aspect of the management strategy authorised land owners to plant dune vegetation to initiate natural dune building processes.

Although the dune construction programme encountered early resistance because of the associated costs, restricted beach access and restricted views, this was overcome by raising awareness of the effectiveness of dunes as a means of coastal protection. As the programme progressed, it was even possible to gradually increase dune height and volume in line with advice from organisations experienced in flood engineering: the US Army Corps of Engineers (USACE) and the Federal Emergency Management Association (FEMA). Dune strengthening has been supplemented by repetitive beach nourishment using sediments from a nearby tidal inlet.

The early 1990s brought a change in management at the site. The municipality purchased three large pieces of surplus earth moving equipment which would be used to remove sand from sections of coast where a sand surplus existed, and deposit it on eroding sections of beach in order to maintain beach and dune dimensions. This is an effective but low technology solution that could be applied in both developed and developing countries.

Current dune management practices at Avalon concentrate on flood mitigation. Dunes are fertilised aerially in spring while dune planting, using local volunteers occurs in the autumn. Quarterly beach and dune monitoring is undertaken to ensure that dune volume is sufficient to withstand extreme events, while visual inspections for damage are made in spring and autumn. Critically eroding sections are nourished using earth moving equipment and truck haul, while repair and replacement of damaged dune fences is undertaken as necessary.

To date, the beach and dune management programme has had a number of beneficial consequences for residents. Flood insurance premiums have come down as a result of reduced flood risk, the beach has retained a natural image while accommodating human uses, and the flood hazard reduction properties of dunes have also qualified these structures for external funding to replace lost sediments.

The success of the scheme has been attributed to a number of factors. One essential feature of the programme is education and awareness raising among the public. Stakeholders are encouraged to actively educate themselves by visiting local information displays and attending local meetings. A borough newsletter and flood hazard information are also regularly sent to property owners in order to maintain the collective memory of flood hazards. Secondly, gaining a good knowledge of the local sediment budget is seen as essential in maintaining control over local sediment supplies. Thirdly, the timing of property purchases and dune building programmes to coincide with damaging storms helps minimise public opposition to these activities. Finally, dune building and maintenance aims to work in harmony with natural processes. This has improved the effectiveness of these measures and helped maintain the natural appearance of the coastline.

This management approach can serve as a model for implementation in other developed shorefront municipalities that wish to institute programmes for dune restoration and management. The principles should be applicable in both developed and developing countries.

4.1.3 Seawalls

Definition

Seawalls are hard engineered structures with a primary function to prevent further erosion of the shoreline. They are built parallel to the shore and aim to hold or prevent sliding of the soil, while providing protection from wave action (UNFCCC, 1999). Although their primary function is erosion reduction, they have a secondary function as coastal flood defences.

The physical form of these structures is highly variable; seawalls can be vertical or sloping and constructed from a wide variety of materials. They may also be referred to as revetments.

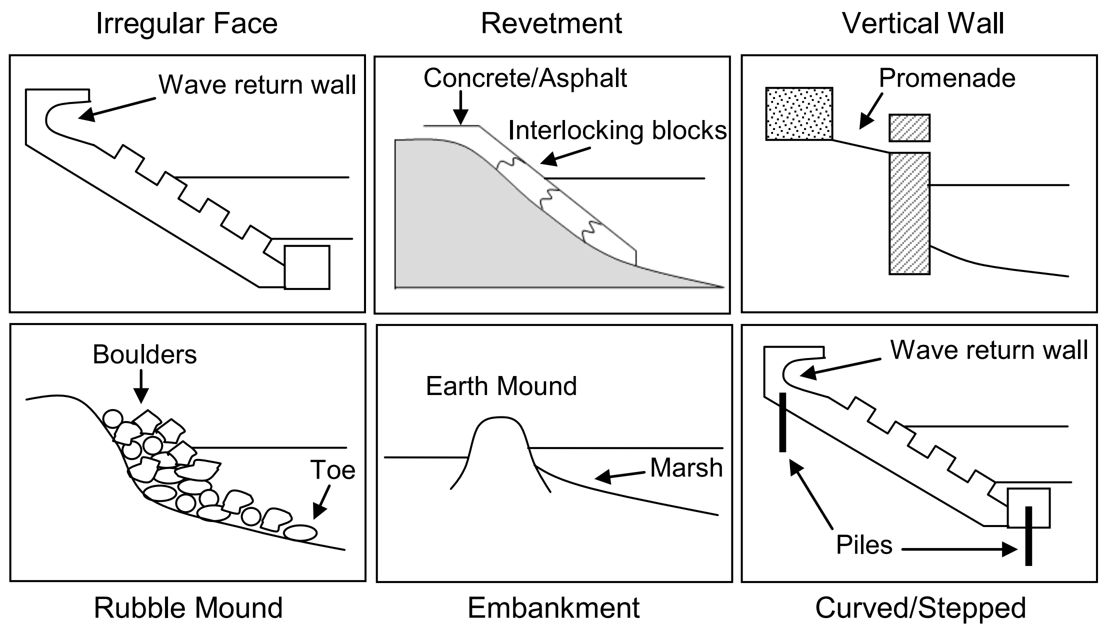
Description

Seawalls are very widespread around the world’s coasts and many ad-hoc seawalls are found in developing countries. Here, we emphasise best practice guidance, although these principles could be used for more ad-hoc structures.

Seawalls form a defining line between sea and land. They are frequently used in locations where further shore erosion will result in excessive damage, e.g. when roads and buildings are about to fall into the sea. However, while they prevent further shoreline erosion, they do not deal with the causes of erosion (French, 2001).

Seawalls range in type and may include steel sheetpile walls, monolithic concrete barriers, rubble mound structures, brick or block walls or gabions[5] (Kamphuis, 2000). Some typical seawall designs are shown in Figure 4.7. Seawalls are typically, heavily engineered, inflexible structures and are generally expensive to construct and require proper design and construction supervision (UNFCCC, 1999).

Figure 4.7: Variation in design type of seawalls



Hard, concrete structures are typically replaced by revetments and embankment-type structures in more sheltered environments

Source: Adapted from French, 2001

The shape of the seaward face is important in the deflection of incoming wave energy; smooth surfaces reflect wave energy while irregular surfaces scatter the direction of wave reflection (French, 2001). Waves are likely to impact the structure with high forces and are also likely to move sand off- and along-shore, away from the structure (Kamphuis, 2000). Since seawalls are often built as a last resort, most are continually under severe wave stress.

Seawalls usually have a deep foundation for stability. Also, to overcome the earth pressure on the landward side of the structure, 'deadmen' or earth anchors can be buried upland and connected to the wall by rods (Dean & Dalrymple, 2002).

---

[5] Wire baskets filled with rocks.

Advantages of Seawalls

The main advantage of a seawall is that it provides a high degree of protection against coastal flooding and erosion. A well maintained and appropriately designed seawall will also fix the boundary between the sea and land to ensure no further erosion will occur – this is beneficial if the shoreline is home to important infrastructure or other buildings of importance.

As well as fixing the boundary between land and sea, seawalls also provide coastal flood protection against extreme water levels. Provided they are appropriately designed to withstand the additional forces, seawalls will provide protection against water levels up to the seawall design height. In the past the design height of many seawalls was based on the highest known flood level (van der Meer, 1998).

Seawalls also have a much lower space requirement than other coastal defences such as dikes (Section 4.1.4), especially if vertical seawall designs are selected. In many areas land in the coastal zone is highly sought-after; by reducing the space requirements for coastal defence the overall costs of construction may fall. The increased security provided by seawall construction also maintains hinterland values and may promote investment and development of the area (Nicholls et al., 2007b). Moreover, if appropriately designed, seawalls have a high amenity value – in many countries, seawalls incorporate promenades which encourage recreation and tourism.

When considering adaptation to climate change, another advantage of seawalls is that it is possible to progressively upgrade these structures by increasing the structure height in response to SLR. It is important however, that seawall upgrade does not compromise the integrity of the structure. Upgrading defences will leave a 'construction joint' between the new section and the pre-existing seawall. Upgrades need to account for this weakened section and reinforce it appropriately.

Provided they are adequately maintained, seawalls are potentially long-lived structures. The seawall in Galveston, Texas was constructed in 1903 and continues to provide coastal flood and erosion protection to the city to this day (Dean & Dalrymple, 2002).

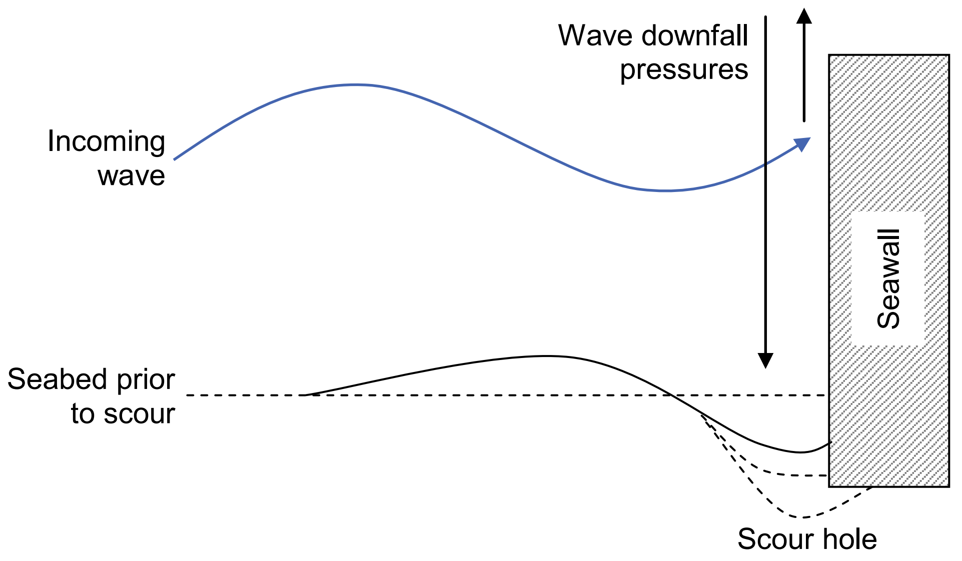
Disadvantages of Seawalls

Seawalls are subjected to significant loadings, as a result of wave impact. These loadings increase with water depth in front of the structure because this enables larger waves close to the shoreline. Seawalls are designed to dissipate or reflect incoming wave energy and as such, must be designed to remain stable under extreme wave loadings. The effects of SLR, increased wave heights and increased storminess caused by climate change must all be taken into account.

Smooth, vertical seawalls are the least effective at dissipating wave energy; instead, the structures reflect wave energy seawards. Reflection creates turbulence, capable of suspending sediments (Bush et al., 2004), thus making them more susceptible to erosion. In a worst-case scenario, reflected energy can interact with incoming waves to set up a standing wave which causes intense scouring of the shoreline (French, 2001).

Scour at the foot of a seawall is a particular problem with vertical seawall designs. This phenomenon is caused by the process shown in Figure 4.8. Incoming waves impact the structure, causing water to shoot upwards. When the water falls back down, the force on the seabed causes a scour hole to develop in front of the structure. This can cause structural instability and is an important factor leading to the failure of many seawalls. As a result, seawall maintenance costs can be high (Pilarczyk, 1990a). A similar process occurs on inclined seawalls but in this case scour will occur away from the foot of the structure (see Figure 4.12).

Figure 4.8: Schematic cross-section illustrating seawall scour



Scour occurs at the foot of a seawall as a result of wave impact. Dashed lines at the base of the wall indicate potential future scenarios with seawall undermining

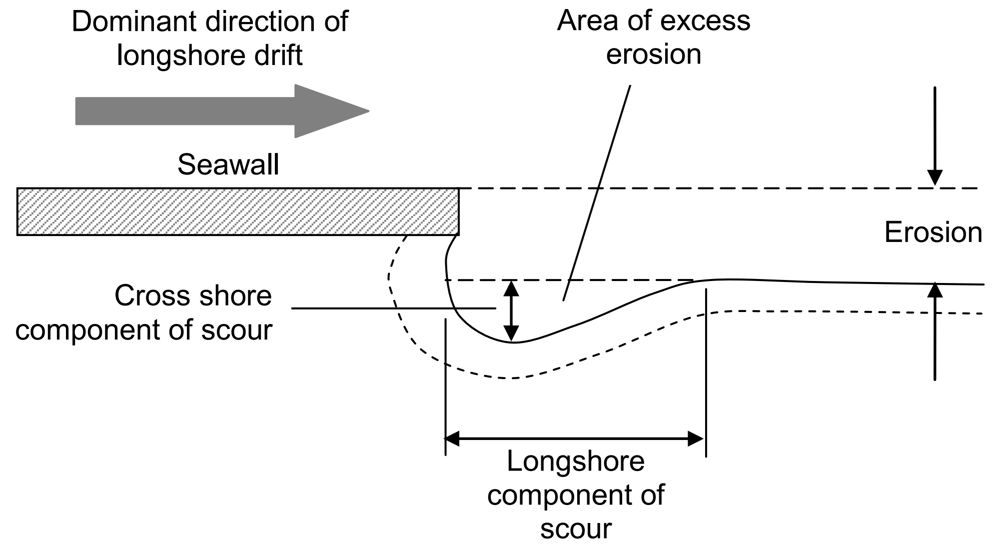
The problems of wave reflection and scour can be reduced to some degree by incorporating slopes and irregular surfaces into the structure design. Slopes encourage wave breaking and therefore energy dissipation while irregular surfaces scatter the direction of wave reflection (French, 2001). Pilarczyk (1990a) recommends the use of maximum seawall slopes of 1:3 to minimise scour due to wave reflection.

Sediment availability is also affected by seawall construction. The problem is caused by replacing soft, erodible shorelines with hard, non-erodible ones. While this protects the valuable hinterland, it causes problems in terms of sediment starvation; erosion in front of the seawall will continue at historic or faster rates but the sediment is not replaced through the erosion of the hinterland (French, 2001). This can cause beach lowering, which reduces beach amenity value and increases wave loadings on the seawall by allowing larger waves close to the shore.

In the absence of a seawall, natural shoreline erosion would supply adjacent stretches of coastline with sediment, through a process known as longshore drift (see Figure 4.3). Once a seawall is constructed however, the shoreline is protected from erosion and the supply of sediment is halted. This causes sediment starvation at sites located alongshore, in the direction of longshore drift and this has the capacity to induce erosion at these sites.

Although seawalls prevent erosion of protected shorelines, where the seawall ends, the coast remains free to respond to natural conditions. This means that undefended areas adjacent to the wall could move inland causing a stepped appearance to the coast (French, 2001). The downdrift end of the seawall is also typically subjected to increased erosion as a result of natural processes (see Figure 4.9). This flanking effect can cause undermining and instability of the wall in extreme cases.

Figure 4.9: A seawall as viewed from above, showing typical end effects associated with the structure



The dotted line indicates possible future shoreline position, with outflanking behind the barrier and undermining of the structure

Source: Adapted from McDougal et al., 1987

Because seawalls are immovable defences, they can also interfere with natural processes such as habitat migration which is naturally induced by sea level change. Seawalls obstruct the natural inland migration of coastal systems in response to SLR, therefore causing coastal squeeze (discussed in Chapter 2). This process causes a reduction in the area of intertidal habitats such as sandy beaches and saltmarshes because these environments are trapped between a rising sea level and unmoving, hard defences.

In estuaries, seawalls also cause changes to the area inundated by the tides thus, reducing the available area for occupation by water on a high tide. With the same volume of water flowing into the estuary, the level of the water after seawall construction will be higher. This may mean areas in front of the defence remain submerged longer and by greater depths. In turn, this is likely to affect the distribution of vegetation and could increase tidal range upstream of the defence (French, 2001).

Another potential problem is overtopping. This occurs when water levels exceed the height of the seawall, resulting in water flow into areas behind the structure. Overtopping is not a continuous process but usually occurs when individual high waves attack the seawall, causing a temporary increase in water level which exceeds the structure height (Goda, 2000). If the structure is too low, excessive overtopping can remove considerable amounts of soil or sand from behind the wall, thus weakening it. Further, overtopping water saturates and weakens the soil, increasing pressures from the landward side, which can cause the foot of the structure to ‘kick out’ and collapse (Dean & Dalrymple, 2002). Overtopping will become increasingly problematic with SLR, increased wave heights and increased storminess.

As mentioned in the advantages section, seawalls increase security by reducing the risk of flooding and erosion. However, the coastal zone remains a high risk location not least due to the presence of residual risk. To combat unwise development of the coastal zone, future developments need to be carefully planned.

Additionally, by encouraging development, hard defences necessitate continued investment in maintenance and upgrades, effectively limiting future coastal management options. Although authorities may not have a responsibility to continue providing protection, the removal of defences is likely to be both costly and politically controversial (Nicholls et al., 2007b).

Seawalls also reduce beach access for handicapped people and for emergency services. This can be problematic if the beach fronting such structures is to be used for recreation. The appearance of seawalls can be aesthetically displeasing which can further negatively affect beaches dependent upon a tourist economy.

Costs and Financial Requirements

A study by Linham et al. (2010) indicates that the unit cost of constructing 1 km of vertical seawall is in the range of US$0.4 to 27.5 million. The study found seawall costs for around ten countries. Most were developed country examples, although a number of newly developed and developing countries, such as Egypt, Singapore and South Africa were also found. Problems arise in the reporting of unit costs for vertical seawalls as the effect of height on unit costs is rarely considered. As such, these costs are likely to relate to seawalls of various heights; this explains some of the significant variation in costs between projects.

Some of the best unit cost information is given by the English Environment Agency (2007), for unit costs relevant to the UK. This source gives an average construction cost for seawalls of US$2.65 million (at 2009 price levels). This cost includes direct construction costs, direct overheads, costs of associated construction works, minor associated work, temporary works, compensation events and delay costs. This does not include Value Added Tax (VAT) or external costs such as consultants, land and compensation payments.

Variation in costs between projects is a result of numerous factors, detailed in Box 4.3:

Box 4.3: Factors affecting unit costs of seawall construction

- Design height is a major factor affecting costs per unit length of seawall. Height affects the volume of materials required for construction and the build time
- Anticipated wave loadings will affect how resilient the structure needs to be; deeper waters and exposed coasts cause higher wave loadings which will mean the structure needs to be more robust, thus higher costs
- Single or multi stage construction; costs are lower for single stage (Nicholls & Leatherman, 1995)
- Selected seawall design and the standard of protection desired. Certain design features will increase costs and more robust seawalls will be more costly
- Construction materials (e.g. rubble blocks, pre-cast concrete elements, metal, soil, etc.)
- Proximity to and availability of raw construction materials
- Availability and cost of human resources including expertise

Maintenance costs are another significant and ongoing expense when a hard defence is selected. These costs are ongoing for the life of the structure and are therefore likely to result in significant levels of investment through a project's lifetime. Continued investment in maintenance is highly recommended to ensure defences continue to provide design levels of protection (Linham et al., 2010).

It has been noted that construction and maintenance costs are likely to increase into the future in response to SLR (Burgess & Townend, 2004; Townend & Burgess, 2004). This is caused by increases in water depth in front of the structure which, in turn cause increased wave heights and wave loadings on the structure.

Maintenance costs are also likely to be higher when seawalls are poorly designed or constructed of inappropriate materials. In many cases, design can be of secondary importance to the availability of raw materials, especially in locations where appropriate construction materials are scare. This was found to be the case in a study of shoreline protection in rural Fiji by Mimura and Nunn (1998). Their study highlights the problem that inappropriate design often leads to unfavourable effects, such as wave reflection and toe scour. In the absence of improper design, it is not unusual for designs from one location to be blindly copied at another. Such an approach is likely to result in exaggerated socio-economic and environmental costs (UNFCCC, 1999). The provision of even, basic design guidance would improve project performance in many cases.

Institutional and Organisational Requirements

Seawall construction is possible on a community scale. There are many examples of ad-hoc construction to protect individual properties and communities. However, ad-hoc seawalls are likely to give much less consideration to the water levels, wave heights and wave loadings during an extreme event. This is largely because these events are hard to foresee without a well-developed science and technology base. For example, traditional seawall construction methods in Fiji involved poking sticks into the ground to create a fence, behind which logs, sand and refuse would be piled to pose a barrier to the sea. This type of traditional construction has shown to have low effectiveness against significant events, however, and in many cases, these defences are washed away during extreme events (Mimura & Nunn, 1998). A degree of technical guidance would be of benefit in the design and construction of effective seawalls. This would improve their effectiveness during extreme events and would also help to reduce adverse impacts on adjacent coastlines.

Although it is clearly possible to construct ad-hoc, or traditional, low technology seawalls at a community level, these structures have been shown to afford lower levels of protection against extreme events than designs with a solid science and technology base. They have also been known to exacerbate existing problems.

At present, the advice given in developing countries for modern seawall construction appears to be informal, if given at all. If effective design and construction is to occur, local communities must be given at least basic design guidance. This may come from government or voluntary organisations.

Seawall maintenance is likely to be possible at a community level when given appropriate training. This may include educating maintenance engineers on the likely failure mechanisms, how often to survey the structure, what to look for and how to identify weaknesses in the design. If major weaknesses are found, it may be necessary to employ a professional organisation to repair the structure in the most effective manner.

Barriers to Implementation

One of the main barriers to the implementation of a well designed seawall is cost. The design of an effective seawall requires good quality, long-term environmental data such as wave heights and extreme sea levels.

This is frequently unavailable in developing countries and can be costly to collect. Secondly, because seawalls are frequently exposed to high wave loadings, their design must be highly robust, requiring good design, significant quantities of raw materials and potentially complicated construction methods. In locations of high energy waves, additional cost must be expended on protective measures such as rip-rap[6] to protect the structure's toe.

A case study from the Pacific island of Fiji (Mimura & Nunn, 1998) shows seawall construction to be very costly even when local materials were utilised in conjunction with other materials supplied by the government. Seawall construction in Fiji consumed the villagers' time and also required significant time and money to be spent on the provision of catering services for workers.

The availability of experience, materials, labour and specialised machinery for the construction of seawalls may also pose a barrier to the implementation of this technology.

French (2001) recommends proactive construction of seawalls at some distance inland. This reduces interference with coastal processes and creates a buffer zone to protect against coastal flooding and erosion. A key barrier to this type of approach lies in convincing and educating landowners of the necessity for, and benefits of, these measures (Mimura & Nunn, 1998).

Opportunities for Implementation

Seawall construction is one of several options available when high value land cannot be protected in other ways. The approach provides a high level of protection to valuable coastal areas although the long-term sustainability of the approach should also be taken into account.

Less technologically advanced designs can be implemented at local levels, utilising local knowledge and craftsmanship. This requires less investment and a reduced need for involvement of large organisational bodies such as national or sub-national government or non-governmental organisations (NGOs). While ad-hoc implementation is possible, technological guidance from expert organisations is desirable to ensure sufficient levels of protection.

Seawalls can also be implemented as part of a wider coastal zone management plan which employs other technologies such as beach nourishment (see Section 4.1.1) and managed realignment (see Section 4.3.1). Placement of seawalls inland, following managed retreat, reduces interference with coastal zone processes and creates a buffer zone to protect against coastal flooding and erosion (French, 2001). The seawall therefore acts as a last line of defence. Use of seawalls in conjunction with beach nourishment can also address some of the negative impacts of seawall construction, such as beach lowering and downdrift erosion.

Case Study: Bar Beach, Victoria Island, Nigeria

Nigeria is located on the west coast of Africa with a coastline onto the Atlantic Ocean. Victoria Island is in the west of the country in the city of Lagos; the island itself sits in the Lagos Lagoon.

Bar Beach on Victoria Island has been experiencing severe erosion since the construction of two jetties at the entrance to Lagos harbour (Awosika et al., 2002). Jetties are long structures, positioned at right-

---

[6] Wide-graded quarry stone normally used as a protective layer to prevent erosion (Coastal Research, 2010)

angles to the shoreline. They are designed to intercept the longshore transport of large quantities of sediment. This is beneficial to the harbour because these sediments have the potential to cause the harbour's navigation channel to silt up. However, the interception of sediments is detrimental to Bar Beach because, in the absence of the jetties, these sediments would naturally be deposited on the beach, helping to maintain its sediment volume.

Locally, landward erosion rates on Bar Beach were observed to be up to 30 m per year (Mehrotra et al., 2009). The problem of beach erosion is further aggravated by periodic storm surges. These surges are accompanied by plunging waves which cause the offshore transport of Bar Beach's remaining sediments (Awosika et al., 2002).

Since 1958, a number of engineering solutions have been applied at the beach, as illustrated in Table 4.4. These have had limited success in addressing the erosion problem however. Importantly, inadequate information and historical data of shoreline change has meant that determination and execution of an effective shoreline erosion management plan has not been possible (Sunday & John, 2006).

Table 4.4: History of erosion control measures, Bar Beach, Nigeria

Period	Measures Applied
1958	Construction of a groyne at the foot of eastern breakwater to avoid undermining
1958-60	Dumping of dredged sediment from the harbour channel for dispersal along the beach by waves
1960-68	Permanent pumping station built on eastern breakwater supplying an average 0.66 million m^3 of sediment from the channel to the beach
1964	Shore-parallel timber groyne constructed 26 m from the shoreline
1969-74	Artificial sand replenishment
1974-75	3 million m^3 sand dumped and spread on beach
1981	2 million m^3 sand dumped and spread on beach
1985-86	3 million m^3 sand dumped on beach
1990-91	5 million m^3 sand dumped on beach (all the sand deposited from 1985-86 had been washed away in most places)
1995-97	6 million m^3 sand dumped on beach (2 million m^3 per year)
1998	Groyne constructed
1999	2 million m^3 sand dumped and spread on beach using dredger
2002-03	Dredging of more than 2 million m^3 of sand

Source: Sunday & John, 2006

Following a lack of success with the measures described in Table 4.4, the local government commissioned further works to address erosion in 2006. The main feature of this scheme was a 1 km long seawall, constructed of large x-shaped, pre-cast concrete elements and designed to interlock and dissipate wave energy upon impact. The top of the seawall is 4 m above MSL (Chagoury Group, 2006) and the blocks are designed to withstand the impact of numerically modelled waves with a return period of 100 years (HiTech, 2006).

The seawall is coupled with other coastal engineering measures in order to provide the most effective solution to the area's coastal erosion problems. Further beach nourishment was carried out and additional rock armour was also placed on the beach. The crest of the seawall was capped with a 10 m wide concrete slab (HiTech, 2006). This provides the area with a promenade that can be used for recreational purposes. The finished structure is shown in Figure 4.10.

Bar Beach was battered by strong storms during July 2007 and the structure provided adequate protection against flooding and erosion. However, areas without protection were still hit hard by the storms. As such, extension of the seawall for a further 500 m is currently under consideration.

Figure 4.10: Bar Beach seawall, Victoria Island, Lagos, Nigeria

Source: Courtesy of B. Winder

4.1.4 Sea Dikes

Definition

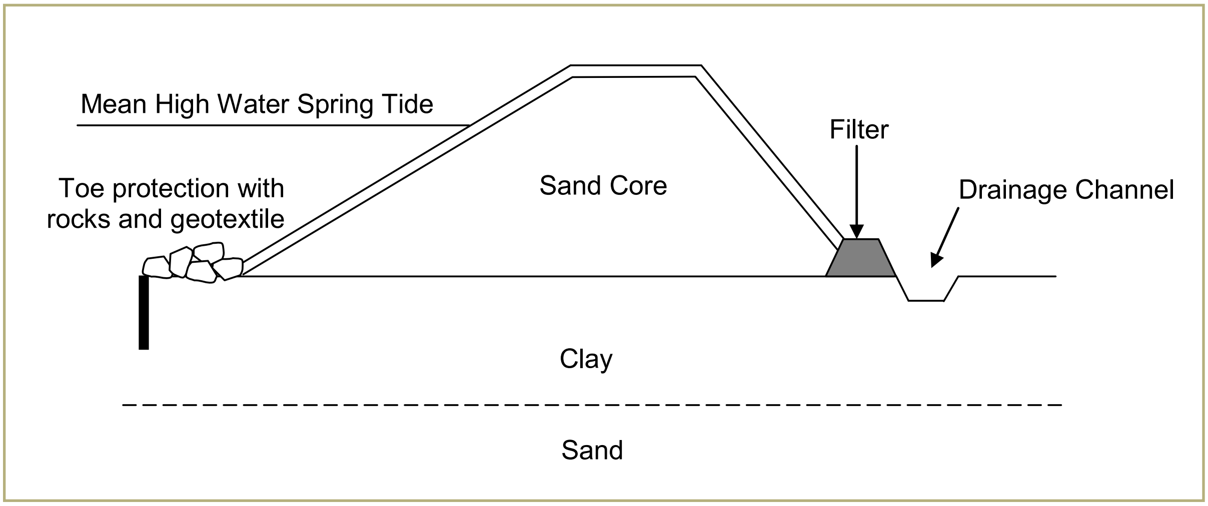
The primary function of sea dikes is to protect low-lying, coastal areas from inundation by the sea under extreme conditions (Pilarczyk, 1998a). Dikes are not intended to preserve beaches which may occur in front of the structure or any adjoining, unprotected beaches.

These structures have a high volume which helps to resist water pressure, sloping sides to reduce wave loadings and crest heights sufficient to prevent overtopping by flood waters. They may also be referred to as dykes, embankments, levees, floodbanks and stopbanks.

Description

Dikes are widely used to protect low-lying areas against inundation. As such, they have been widely applied in countries such as Vietnam, Bangladesh, Thailand, the Netherlands and the USA. Figure 4.11 shows a typical dike cross-section. It is a predominantly earth structure consisting of a sand core, a watertight outer protection layer, toe protection and a drainage channel. These structures are designed to resist wave action and prevent or minimise overtopping.

Figure 4.11: Typical sea dike cross section



Dikes have been extensively utilised as flood defences in the Netherlands over the past several hundred years. As such, the Dutch have extensive experience in their design. As a result, many countries apply Dutch design practice in dike construction.

Typical Dutch practice employs the following design guidelines:

- Sloped seaward face at a gradient of between 1:3 to 1:6 – this can reduce wave loadings
- Sloped landward face at a gradient of between 1:2 to 1:3 – this minimises land take and maximises stability
- Impermeable cover layer – this is usually composed of clay but is sometimes supplemented by asphalt. It serves to protect the sand core (Barends, 2003)

- Toe protection – used as supplemental armour for the beach and prevents waves from scouring and undercutting the structure (Pilarczyk, 1998b)
- Dike core usually composed of sand to ensure that water that does enter can drain away. The core provides support for the cover layer and gives the structure sufficient volume and weight to resist high water pressures (Barends, 2003)
- Drainage channel – allows any water which does enter the structure to drain away, therefore ensuring the structure is not weakened by water saturation (Barends, 2003)

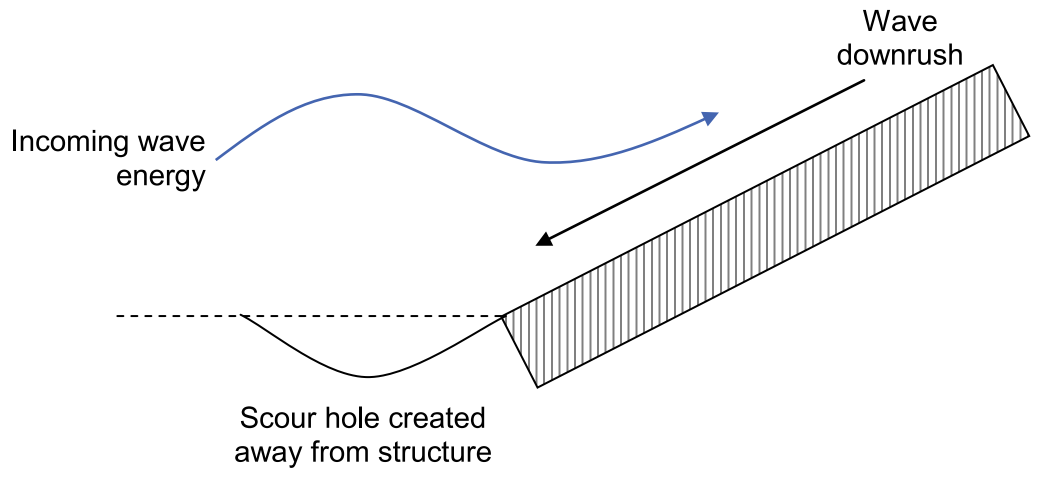
A number of zones can be distinguished on the seaward slope of a sea dike. The base of the dike, up to MHW will be regularly submerged and will experience constant, low-level loadings. The zone above MHW can be heavily attacked by waves, but the frequency of this occurrence reduces as you move further up the slope. Toward the dike crest, above the design water level, the structure should only be subjected to wave run-up.

Advantages of Sea Dikes

Dikes provide a high degree of protection against flooding in low-lying coastal areas. They often form the cheapest hard defence when the value of coastal land is low (Brampton, 2002).

The sloped seaward edge of a dike leads to greater wave energy dissipation and reduced wave loadings on the structure compared to vertical structures. This is achieved because the seaward slope forces waves to break as the water becomes shallower. Wave breaking causes energy dissipation and is beneficial because the process causes waves to lose a significant portion of their energy. Because the waves have lost energy, they are less capable of causing negative effects such as erosion of the shoreline. By reducing wave loadings, the probability of catastrophic failure or damage during extreme events is also reduced.

Figure 4.12: Toe scour on sloping structures



Toe scour is reduced in sloping dikes compared to vertical structures because the downrush is directed away from the toe

When compared to vertical structures, dikes also have reduced toe scour. This is because the wave downrush is directed away from the base of the structure, as shown in Figure 4.12. This is beneficial for structural stability and helps to reduce the risk of undermining.

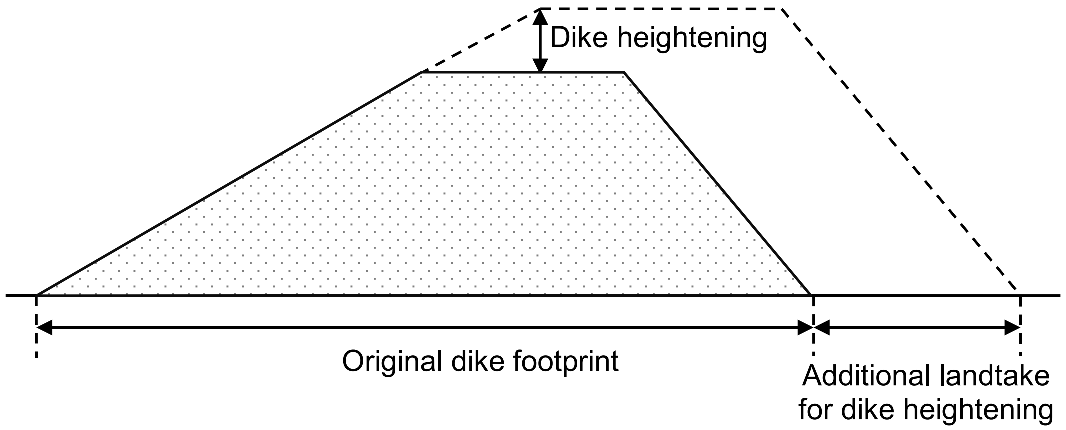
Disadvantages of Sea Dikes

Dikes require high volumes in order to resist high water pressures on their seaward faces (Barends, 2003). As a result, their construction uses large volumes of building materials, including sand, clay and asphalt, which can be costly.

Another disadvantage of applying dikes is that the shallow slopes applied to facilitate wave energy dissipation cause dikes to have large footprints; i.e. their construction requires significant areas of land. This can increase dike construction costs where coastal land is valuable.

Raising dikes in response to SLR can cause the area of land required for dike construction to grow if slope gradients are maintained (see Figure 4.13). The area of land take can be problematic as coastal areas often have high associated land values. Further, construction of dikes prevents use of the coastal area for other development, hence, leading to competition for land. Extending dikes seaward may overcome this problem, but it raises costs significantly.

Figure 4.13: Land area requirements for sea dikes



Schematic illustration of the large land areas required for dike construction and the additional land take required upon dike heightening

As with all hard defences, dikes can create a false sense of security on the landward side of defences, promoting further development landward of the dike. Hence, once protected, it is difficult to change the management policy.

The construction of hard defences permanently fixes the position of the coastline. This can have detrimental impacts because the coast is a naturally dynamic system. Fixing the position of the coastline can prevent natural coastal processes, such as responses to sea level changes, beach/dune interactions and sediment input from coastal erosion (French, 2001). Stopping these processes not only impacts the immediate environment, but because the coastal system shares sediments within a coastal cell, knock-on impacts can also be felt elsewhere along the coast.

Significant shoreline hardening measures can be aesthetically displeasing, especially in areas which are dependent on a tourist economy where natural shorelines are valuable (IOC, 2009).

Costs and Financial Requirements

The best available cost information for sea dikes is compiled by Hillen et al. (2010) in a review of Vietnam, the Netherlands and New Orleans. The information is presented as the cost of dike heightening in millions of US dollars per linear km of defence. Heightening of dikes is reported to cost from US$0.9 to 29.2 million per metre rise in height, per km length (in 2009 US dollars) (Hillen et al., 2010).

Vietnamese costs of dike construction, reported in Hillen at al. (2010) are perhaps most relevant to developing countries. In Vietnam, dike construction costs were shown to vary from US$0.9 to 1.6 million per metre rise in height, per km length – significantly less costly than construction in either the Netherlands or New Orleans (Hillen et al., 2010). Costs were variable due to varying costs of material, land-use and applied inner/outer protection of the dike's slopes. When comparing completed projects within Vietnam, labour costs were observed to be highly variable even within the country.

Dike construction costs are shown by Hillen et al. (2010) to vary considerably between rural and urban areas with dike construction in rural areas shown to be consistently less costly. This is the case worldwide. Costs are also influenced by a number of other factors, detailed in Box 4.4.

Box 4.4: Factors affecting unit costs of sea dike construction

- Land availability and cost. As shown in Figure 4.13, dike construction needs significant land input. Accurate cost studies often draw a distinction between rural and urban construction costs to reflect differential land values
- Selected dike design and in-built margin for safety. This can affect the volume of the structure and the required materials
- Anticipated wave loadings; higher wave loadings require more robust and expensive structures. Wave loading is affected by wave breaker types, cleanness of the breaking wave, seabed shape and individual storm characteristics such as storm duration, wind strength and storm orientation in relation to the structure
- Single or multi stage construction; aggregate costs are lower for single stage construction (Nicholls & Leatherman, 1995)
- Proximity to and availability of raw construction materials
- Availability and cost of human resources including expertise

Maintenance costs are an ongoing requirement for sea dikes, to ensure the structure continues to provide design levels of protection. Information on maintenance costs is limited, although annual dike maintenance costs per linear km of dikes are reported to range from US$0.03 million in Vietnam (Hillen, 2008) to US$0.14 million in the Netherlands (AFPM, 2006). These costs are presented in 2009 US dollars. The variability in these costs is largely due to the fact that while dike maintenance in the Netherlands is well organised and given high priority, in many other locations, maintenance programmes are less rigorous. To a lesser extent, local factors such as labour and material costs, and the presence of different types of dikes/coastal defence measures will also influence costs (Hillen, pers comm.).

The construction and maintenance costs are likely to increase into the future in response to SLR (Burgess & Townend, 2004; Townend & Burgess, 2004). This is caused by increases in water depth in front of the structure which in turn, causes increased wave heights and wave loadings on the structure.

Institutional and Organisational Requirements

Construction of sea dikes is possible on a local scale (Section 4.1.2). However, the improved science and technology base that the involvement of larger organisations brings can significantly improve a structure's effectiveness. This is seen in Vietnam (a detailed case study is shown at the end of this section) where poor dike design and insufficient funding resulted in dikes providing lower levels of protection than initially intended (Mai et al., 2008).

Ad-hoc construction of coastal defences is likely to give much less consideration to the water levels, wave heights and wave loadings occurring during an extreme event. This is largely because these events are hard to foresee without a well-developed knowledge. As such, ad-hoc defences typically offer lower levels of protection.

Dikes designed and constructed by local communities are likely to employ local materials and traditional methods. This may not necessarily constitute the most effective approach, although it may be the only available option. Provision of design and construction guidance, even for small details such as recommended slopes and materials, is likely to improve the performance of defence structures.

As shown below, dikes can be expensive measures to employ with costs ranging between US$1 and 7.6 million per km length of dike depending on the global location (Linham et al., 2010) and with additional annual maintenance costs. As such, external funding may be required before a successful dike construction project can proceed.

If community level implementation goes ahead, it is essential that the wider impacts of hard defences on the coastal zone are not overlooked. When implementing projects at a local level, it is easy to focus on local benefits and neglect the bigger picture. As stated under the disadvantages of dikes, some impacts of dike construction may be felt considerable distances from the implementation site. Dike implementation at a local level may pay little attention to reduce these impacts.

Extreme caution should be exercised if ad-hoc, community implementation of sea dikes goes ahead. Because dikes are often designed to protect extensive areas of low-lying land, catastrophic failure caused by poor design is likely to be associated with a threat to the lives of significant numbers of people.

Barriers to Implementation

The high space requirement for sea dikes is one barrier to implementation. This factor will be especially important in areas where the value of the coastline plays an important role in deciding adaptation technologies. The availability of materials, labour and specialised machinery for the construction of dikes may also pose a barrier to the implementation of this technology.

The cost of implementing an effective dike system can prove a barrier in some cases. This will especially be the case in high wave-energy areas where additional protective elements such as rip-rap will be required (IOC, 2009).

The most effective dikes are those designed in accordance with good quality, long-term environmental data, such as wave height and extreme sea level information. One of the main barriers to the building of an effective dike which accounts for local conditions is therefore the availability of long-term datasets. The cost of collecting such data can be expensive. However, by accounting for these local conditions, dike design is typically more effective. The additional costs of data collection and exclusive design may for a barrier to implementation in some circumstances.

Opportunities for Implementation

Where large areas of high value coastal land, which cannot be surrendered to the sea under a managed realignment policy, exist at elevations close to, or below sea level, there are often few other choices available than the construction of dikes.

Dikes are capable of providing very high levels of protection against coastal flooding if designed appropriately. This can enable significant development to take place behind them, even if land is low-lying. This is demonstrated by Schiphol Airport, Amsterdam, in the Netherlands – the area is enclosed by dikes but lies 4.5 m below MSL (Pilarczyk, 2000). Long-term sustainability considerations should be borne in mind if this technology is adopted, however.

Dikes are a tried-and-tested method of coastal protection. Construction methods and design principles for these structures are well known and publicised. Although specialised dikes, designed with local conditions in mind pose the most effective defences, it is also possible to implement more generic or lower quality designs at a lower cost. This makes diking more affordable but does compromise safety and protection levels.

Dikes can be implemented in conjunction with other erosion and flood protection works, such as beach nourishment (Section 4.1.1) and managed realignment (Section 4.3.1). This has the potential to address the negative impacts associated with the technology and also means the benefits associated with each technology can be realised.

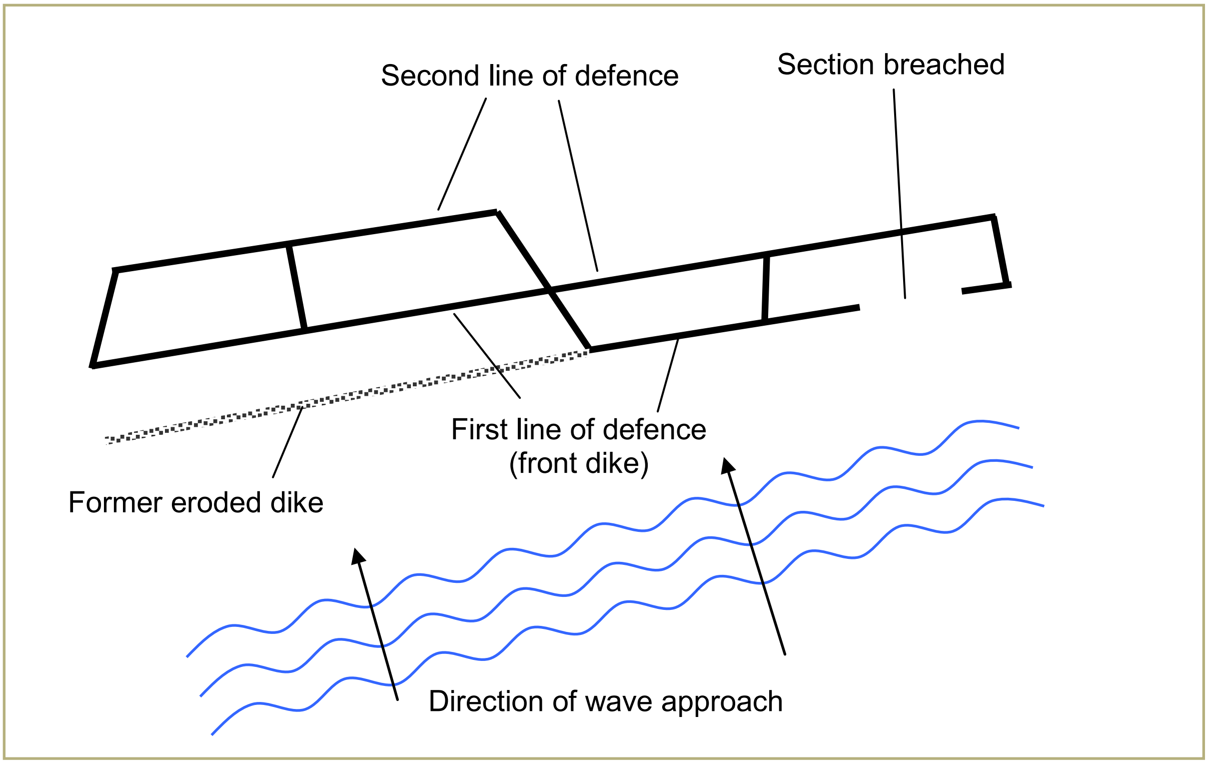
Case Study: Nam Dinh Province, Vietnam

Vietnam is situated in the tropical monsoon area of south-east Asia and is also prone to typhoons. A large portion of the Vietnamese population is concentrated in low-lying river flood plains, deltas and coastal margins. These populations are involved mainly in the agriculture and fishery sectors (Mai, 2004).

Nam Dinh Province is part of the Red River Delta in the northern part of Vietnam. The area is low-lying and the province has a coastline length of approximately 70 km, of which 95% is protected by dikes (Mai, 2004). Most of this stretch of coastline is protected by two lengths of dike, one behind the other, as illustrated by Figure 4.14. This helps to limit inland flooding if a breach occurs (Mai, 2008).

Nam Dinh's coastline is subject to severe erosion and storm surges. As such, the dike system has two main functions: (1) flood defence and (2) protecting the inland from erosion (Mai, 2004). It is important to prevent these processes because erosion reduces available agricultural land while flooding and

Figure 4.14: Schematic illustration of the double dike system utilised in Nam Dinh Province, Vietnam



Source: Adapted from Mai, 2004

defence overtopping poses a risk to human life and causes saltwater intrusion which reduces agricultural productivity. Furthermore, the constant risk of flooding discourages farmers from adopting new technology or to invest in other income-generating activities (Mai, 2004).

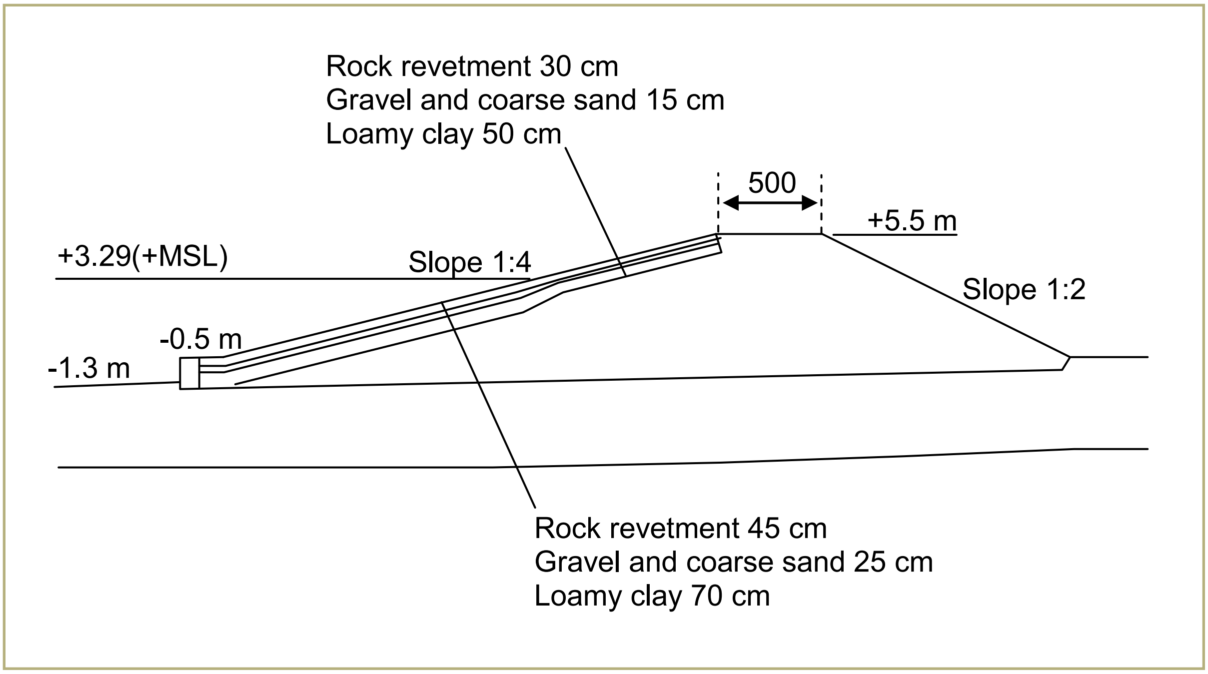
The dikes in Nam Dinh Province have crest elevations which account for high tides, storm surges and wave run-up. They also have an additional margin for safety. However, funding problems and a shortage of equipment have affected the construction of dikes and resulted in weakened structures and overtopping (Mai, 2004). A typical dike cross-section for Nam Dinh is shown in Figure 4.15. Structures typically have an earth core of local sand and clay and revetments of natural stone, artificial blocks or a clay layer. Use of local clay is problematic as the material is fine and therefore readily flushed out to sea (Mai, 2004).

Although constructed to resist loads with a 1 in 20 year recurrence, dikes in Nam Dinh have a much lower design standard in reality. Dike failures may be expected to occur almost annually (Mai et al., 2008). Lower than predicted design standards are largely due to budget constraints, a lack of information on sea boundary conditions, such as water levels and wave heights, and a lack of suitable design methods (Mai et al., 2008).

In response to these problems, the Vietnamese government has set up a huge sea dikes programme with two important tasks:

1. Research safety standards, boundary conditions and find optimal solutions for sea defences for the whole country

Figure 4.15: Representative cross-section of sea dikes in Nam Dinh Province, Vietnam



Source: Mai, 2008

2. Design and construct new dikes at places where dikes have not existed before, or have been breached. This includes reinforcement of existing dikes based on the findings of task 1

The case of Nam Dinh raises several important points which must be borne in mind when implementing any coastal adaptation measures:

1. It is important to select an appropriate coastal management approach. Given the high shoreline erosion rates around Nam Dinh and the limited funds available for construction of hard defences, it may be worth considering accommodation and retreat options over the long term
2. It is vitally important to design adaptation measures with local conditions in mind. The design of an effective coastal structure will require information on boundary conditions such as water levels and wave climate
3. The ability to fund coastal protection measures is of paramount importance. In Vietnam, budget constraints led to weakened coastal structures which offer a false sense of security. Construction of sub-standard defences may encourage development in highly risky locations
4. Continued investment in maintenance measures is essential to repair damage caused by extreme events

4.1.5 Storm Surge Barriers and Closure Dams

Definition

Storm surge barriers and closure dams are hard engineered structures with a primary function of preventing coastal flooding. Their secondary role is to shorten the required length of defences behind the barrier. This reduces the risk of defence failure and reduces the cost of providing the additional defences. Surge barriers are movable or fixed barriers or gates which are closed when an extreme water level is forecast in order to prevent flooding. Closure dams are fixed structures that permanently close off a river mouth or estuary. For these and fixed barriers, water is discharged through, or pumped over the barrier (IOC, 2009).

Description

Storm surge barriers and closure dams are large-scale coastal defence projects, capable of protecting tidal inlets, rivers and estuaries from occasional storm surge events (UNFCCC, 1999). They provide a physical barrier which prevents storm surges travelling upstream. This helps to keep upstream water levels low and therefore minimises coastal flooding. The two solutions are most frequently applied at narrow tidal inlets, where the length of the structure is not required to be so great and where defences behind the barrier can be reduced in height or length. An example of the construction of a closure dam in Bangladesh is shown in Figure 4.16.

Figure 4.16: Closure dam under construction at Jamuna river, Bangladesh

Clay bags have been used to construct this closure dam – they can be seen piled across the mouth of the river in the background of this picture

Source: Courtesy of K. Pilarczyk

Storm surge barriers most commonly consist of a physical, movable barrier across the mouth of a tidal inlet or estuary. While there are no known examples in the developing world, a number of projects have been completed in developed countries, mainly in Europe. For example, the Thames Barrier, London, the Maeslantkering Barrier, Rotterdam and the St. Petersburg Flood Protection Barrier, while the MOSE project in Venice is scheduled for completion in 2012. Although each of these projects has roughly the same objective, the design of these structures varies significantly.

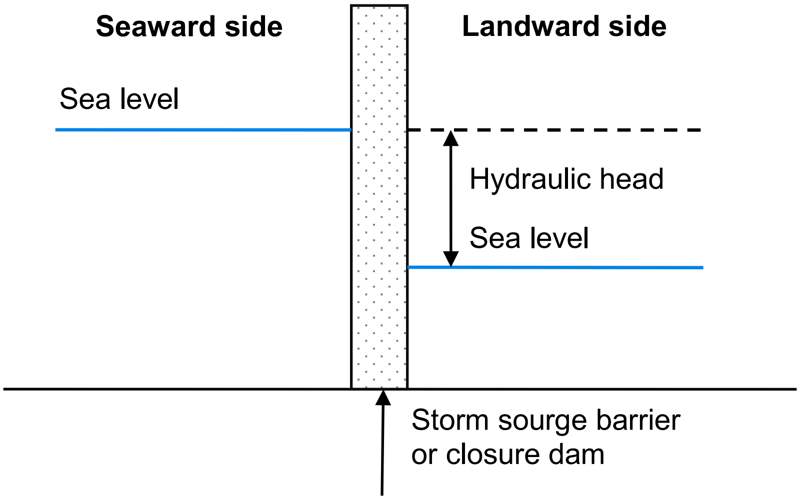
Fixed barriers and closure dams are a lower technology option which may be more appropriate in developing countries. These are non-movable barriers across tidal inlets or estuaries. They constructed through gradual or sudden closure of an inlet. Gradual closure can be accomplished through land-based construction which gradually narrows the inlet, or by water-based construction which builds a barrier up, layer by layer, from the seabed. Alternatively, sudden closure blocks an inlet in a single operation, using pre-installed gates or by the placement of a caisson[7].

Examples of completed closure dams include the Feni closure dam in Bangladesh, constructed mainly to provide a freshwater reservoir for irrigation purposes, several projects in Korea to close tidal basins, mainly for land claim (van Houweninge & de Graauw, 1982) and the Afsluitdijk, in the Netherlands, which separates what is now Lake IJsselmeer from the North Sea.

Movable barriers will require the simultaneous implementation of a storm surge monitoring and forecasting system (an adaptation option in its own right and discussed in Section 4.2.5). This will allow the barrier to be moved into position before a storm surge arrives. Because closure dams are fixed structures, they do not require these systems.

While there are clear differences between storm surge barriers and closure dams, the coastal defence purpose of the structures is the same; to prevent extreme water levels penetrating an estuary. The method, by which this is achieved, is illustrated in Figure 4.17.

Figure 4.17: Schematic illustration of how storm surge barriers and closure dams prevent coastal flooding



During an extreme event, a storm surge will cause a rise in sea level on the seaward side of the barrier. The presence of a physical barrier such as a closure dam or storm surge barrier prevents high waters from penetrating the estuary. As a result, the water level on the landward side remains low

---

[7] A retaining, watertight structure.

Surge barriers and closure dams can be easily integrated into a larger, overall flood prevention systems. For example, barriers may be present alongside additional flood prevention works such as dikes and flood warning systems (Sections 4.1.4 and 4.2.5).

An important characteristic of surge barriers is that they are movable. As such, they are often partly opened during normal conditions. This will allow tides and saltwater to enter the areas behind the barrier (Hillen et al., 2010) and allows continued use of waterways for shipping and transport. Conversely, closure dams permanently close off estuarine areas. This prevents interactions between freshwater and the sea and also prevents use of the waterway for shipping and transport.

Advantages of Storm Surge Barriers and Closure Dams

Storm surge barriers and closure dams provide a high degree of protection against coastal flooding by preventing storm surges from entering low-lying estuarine areas. Although permanently closing off the estuary mouth using a closure dam, would achieve the same outcome, the use of a movable barrier allows waterways to remain open during normal conditions. This can be beneficial to trade if the estuary also acts as a trading port and is also valuable for estuarine species reliant on brackish water[8] conditions.

The two technologies effectively reduce the height of extreme water levels in the area behind the barrier, if closed in a timely fashion. Doing so may allow the strength of existing defences behind the barrier to be reduced (Hillen et al., 2010). This will reduce both construction and maintenance costs for defences on the landward side of these structures.

By reducing the height of extreme water levels inside of the barrier, the length of a coastal flood defence system may also be shortened (Hillen et al., 2010). This too, would have the effect of reducing maintenance and construction costs of defences on the landward side of the barrier.

More than one barrier may be constructed to close off narrow inlets into a tidal system, such as a lagoon. This is the case in Venice under the MOSE project where three barriers are under construction to close three of the lagoon's narrow tidal inlets. Through the construction of multiple barriers, the scheme offers the additional benefit of enhancing the lagoon's natural capacity to clean itself. This is achieved by independently opening and closing selected barriers, depending on wind direction. By closing barriers it enhances the ability of the wind to drive water out of the lagoon, therefore increasing the turnover of water, dispersing pollutants.

Closure dams can provide additional benefits by forming a permanent barrier between freshwater and the sea. For example, in Bangladesh, the Feni closure dam was constructed primarily to provide a reservoir of freshwater for irrigation purposes. Closure dams may also be used in conjunction with land claim (see Section 4.1.6) and may even be used for the production of tidal energy (van Houweninge & de Graauw, 1982).

Disadvantages of Storm Surge Barriers and Closure Dams

One of the key disadvantages of the storm surge barrier is the high capital and maintenance costs. Significant investment is required to construct these structures and to continually maintain them. In addition, movable barriers also require simultaneous investment in flood warning systems which provides

---

[8] A mixture of salt and fresh water—brackish water is salty but not as salty as sea water.

Table 4.5: Overview of storm surge barriers, types and costs

Barrier and Location	Barrier Type	Hydraulic Head (m)	Construction Costs (2009 price level) (US$ mil.)
Ems Germany	Sector gates	3.8	519
Thames Barrier, London, UK	Sector gates	7.2	2043
IHNC Barrier, New Orleans, USA	Sector gates	4	730
Seabrook Barrier, New Orleans, USA	Vertical lifting gates/ sector gates	4	162
Hartel Barrier, Hartel Channel, NL	Vertical lifting gates	5.5	202
Eastern Scheldt Barrier, NL	Vertical lifting gates	5	5670
Maeslantkering Rotterdam, NL	Floating sector gate	5	925
MOSE Project, Venice, IT	Flap gates	3	6596
Ramspol, Near IJssellake, NL	Bellow barrier	4.4	186

Source: Hillen et al., 2010

information on when to close the barrier. This cost is avoided through the use of a closure dam, which also has lower capital and maintenance costs.

A potential disadvantage of both surge barriers and closure dams is they can cause flooding on the landward side of the barrier when river levels are high and, in the case of movable barriers, if the defence remains closed for an extended period. Landward flooding occurs as a result of water backing up on the landward side of the barrier due to the obstruction of continued river discharge by the barrier. This should not present a problem, provided closure dams are designed to cope with extreme river discharges and that studies to determine the maximum duration of closure have been undertaken in the case of movable barriers.

Both surge barriers and closure dams have the capacity to change the chemical, physical and biological properties of estuarine systems by altering the inflow and outflow of water from the estuary. This may include alterations to water salinity, temperature, suspended matter, nutrients which all have the potential to affect local communities of organisms (Elgershuizen, 1981). These changes will be more significant in the case of a closure dam as the barrier is permanent. The application of movable rather than fixed gates can mitigate these impacts (IOC, 2009).

Costs and Financial Requirements

Table 4.5 shows the costs for storm surge barrier construction of both completed projects and projects near completion. Since there are no known examples of movable surge barriers in the developing world, it has unfortunately, not been possible to include costs estimates for developing countries.

Storm surge barrier construction costs are highly variable, as shown in Table 4.5. Influential factors in the cost of these structures include the design and hydraulic head over the barrier (see Figure 4.17).

Hillen et al. (2010) investigated the unit costs of storm surge barriers and found that the hydraulic head will be an important determinant for the forces on the barrier and the required construction properties and costs. They also found that there is a weak relationship between the head and the unit costs, although the factors determining unit costs still need to be investigated further. They concluded that unit costs for storm surge barrier construction range between US$0.7 and 3.5 million per unit metre width, at 2009 price levels. Maintenance costs are an ongoing expense which must also be accounted for; annual costs have been estimated at approximately 5-10% of the capital, for movable barriers (Nicholls et al., 2007b).

The costs of constructing closure dams in Bangladesh are given in Table 4.6. The three projects for which cost data is available, were constructed largely of traditional materials but with the guidance of experienced coastal engineering consultancies. Traditional Dutch construction methods were used in all three projects.

Table 4.6: Costs of completed closure dams in Bangladesh

Project	Year Completed	Barrier width x depth (m)	Construction Materials	Cost (2009 value)[1]
Feni River	1985	1200 m width Unknown depth	Clay filled sacks Bamboo Reed rolls Steel beams Bricks & blocks	US$38 million
Chaka Maya Khal	1979	210 x 5.5	Bamboo Palm leaves Reed bundles Timber piles Jute	US$1.3 million
Amtali Khal	1982	130 x 8	Reed bundles Golpata leaves Clay filled sacks Timber piles	Tk[2] 16 million

[1] Due to the absence of historic exchange rate data, it has not been possible to convert costs to a common currency.
[2] Bangladesh Taka – the currency of Bangladesh.

Source: DHV Haskoning, 2007

Box 4.5: Factors affecting unit costs of storm surge barrier and closure dam construction

- Type of barrier
- Local soil characteristics
- Desired height of the barrier
- Required hydraulic head for the structure
- Anticipated wave loadings; higher wave loadings require more robust and expensive structures
- Single or multi stage construction; costs are lower for single stage construction (Nicholls & Leatherman, 1995)
- Proximity to and availability of raw construction materials
- Availability and cost of human resources including expertise

As shown in both Table 4.5 and Table 4.6, the costs of surge barrier and closure dam construction are highly variable with project costs likely to be influenced by the factors shown in Box 4.5.

It has been noted that construction and maintenance costs are likely to increase into the future in response to SLR (Burgess & Townend, 2004; Townend & Burgess, 2004). This is caused by increases in water depth in front of the structure which in turn, cause increased wave heights and wave loadings on the structure.

Institutional and Organisational Requirements

Effective implementation of storm surge barriers always requires considerable engineering studies to design and install these structures (IOC, 2009). Barrier design is likely to be technologically challenging and almost impossible to undertake at the community level. Additionally, as seen under the costs and financial requirements section, surge barriers can be highly expensive and funds may be lacking at a local level. As such, technical assistance may be sought from coastal engineering consultancies or other experienced organisations, while funding may be obtained from external organisations such as NGOs or local government and enterprises which benefit from the structure.

In addition to the hardware, effective forecast and warning systems are required when implementing a movable storm surge barrier (see Section 4.2.5 for more information on flood warning services). This may require significant institutional capacity (IOC, 2009). Implementation of a flood warning system requires some or all of the following tasks to be conducted: system design, management and forecasting of floods, operation, detection of storms and warning dissemination (Sene, 2008).

Closure dams and non-movable barriers are lower technology alternatives to movable surge barriers. A number of such projects have been successfully constructed in countries such as Bangladesh and Korea. To make these projects more feasible at a local level, construction methods may employ local materials and labour, although guidance from experienced contractors would also prove beneficial (e.g. DHV Haskoning, 2007).

Barriers to Implementation

The high cost of surge barrier construction (shown in Table 4.5) and the requirement for specialist knowledge in the design and implementation phases may prove a barrier to implementation of storm surge barriers.

Additionally, surge barriers and closure dams are not suitable for all locations. They are most appropriate in locations where a narrow river mouth or inlet can be closed. Alternatively, they are appropriate where the length behind the barrier that would otherwise require defending can be substantially reduced; in the case of a short defensive length, it may be more effective to upgrade defences than to construct a barrier.

Although barrier construction across narrow channels is cheaper, it is apparent that surge barriers can be implemented where narrow inlets are absent, provided sufficient funds for construction are available and the political will exists. For example, the St. Petersburg Flood Protection Barrier employs two movable storm surge barriers within a man-made 25.4 km long barrier, across the mouth of the Neva Bay on the Gulf of Finland.

Opportunities for Implementation

Opportunities for the implementation of storm surge barriers are numerous. The MOSE project in Venice, Italy, has demonstrated the capacity for surge barriers to offer co-benefits alongside flood protection. For example, opening and closing specific barriers depending on the wind direction can facilitate dispersion of pollutants thus helping to improve coastal water quality. This is beneficial for both recreation and tourism.

Storm surge barriers can also provide additional services such as recreation, amenity and water supply when appropriately designed. The Marina Barrage in Singapore was completed in 2008 and provides an excellent example of the additional benefits which can be gained from a well designed surge barrier. As well as providing protection against coastal flooding, construction of the barrier has also provided a large reservoir which will help meet water demand in one of the island's most urbanised catchments (Moh & Su, 2009). By eliminating tidal influence inside the reservoir the area is now an ideal venue for recreational activities such as boating, windsurfing and water skiing (Moh & Su, 2009). By integrating an art gallery and retail outlets into the barrier design, the defence is also now a significant tourist attraction.

Storm surge barrier projects have also been seen to act as a catalyst for development of newly protected areas. This was observed following construction of the Thames Barrier, when London's derelict docklands were regenerated with new transport links, homes, businesses and the important financial district around Canary Wharf (Nicholls, 2006).

In future there could even be opportunities to integrate storm surge barrier or closure barrier design with the production of renewable hydroelectricity. This will provide long-term, sustainable energy as well as security of energy supply for local communities.

Case Study: Chaka Maya Closure Dam, Bangladesh

Chaka Maya is located in the south-western district of Patuakhali, in Bangladesh. During the period 1978-79, a closure dam was constructed across a tidal channel of the Andharmanik River, primarily for flood control purposes. The following project information is taken from DHV Haskoning (2007).

The channel in which the dam was constructed is 210 m wide with an average depth of 5.5 m below MWL. Due to the size and depth of the channel, traditional methods could not be used. Instead, the dam was constructed using traditional Dutch methods, as recommended by an experienced, international coastal engineering consultancy. This method involved the use of readily available, local materials and manual labour, to gradually close the channel by building up the barrier, layer by layer, from the seabed.

The closure dam was constructed in four stages. Firstly, large bottom protection mattresses, measuring 17 x 45 m, were installed on the channel bed. Their aim was to prevent erosion by high water velocities and turbulence. The mattresses were constructed of layered bamboo, reeds and palm leaves, tied with jute ropes. They were sunk to the channel bed by ballasting them with clay filled bags, and then anchored using ropes.

Next, a total of 5500 clay filled bags were used to build a sill to the lowest water level. The sill was then topped by more protection mattresses which were ballasted using soil filled bags. Thirdly, a large, watertight chamber was constructed on top of the sill and filled with clay filled bags. The purpose of this activity is to stop the water flow. The chamber, known as a cofferdam, consisted of three chambers with walkways founded on timber piles.

To complete the closure dam, the 8 m wide, watertight chamber was filled with soil to the design dimensions and levels. This earth-filled dam was designed with sufficient cross-section and crest height to withstand the water levels and wave climate associated with the statistically modelled 1 in 20 year storm return period.

The final cost of the project in 1979, was US$500,000 and required 180,000 man days of employment to complete; this labour was obtained from the local communities. When adjusted for inflation, the cost of this project is roughly equivalent to US$1.3 million at 2009 price levels.

4.1.6 Land Claim

Definition

The main objective of land claim is neither erosion nor storm reduction. The aim of land claim is instead, to create new land from areas that were previously below high tide. However, if land claim is designed with the potential impacts of climate change in mind, measures can be taken to reduce the exposure of these areas to coastal flooding. For example, in Singapore and Hong Kong, there are enforced minimum reclamation levels to account for future SLR.

Land claim is likely to be accomplished by enclosing or filling shore or nearshore areas (Bird, 2005). Several alternative terms may be used when referring to land claim; these may include land reclamation, reclamation fill and advance the line.

Description

This is a more aggressive form of coastal protection which may more accurately be termed ‘attack’ or ‘advance the line’ under the shoreline management typology outlined in Figure 3.2. Land claim is typically undertaken to gain land, for agricultural or development purposes (French, 1997). It is particularly common around coastal cities, such as Singapore and Hong Kong, where land values are very high, therefore justifying the costs. In recent years, large-scale land claims have also been conducted in Dubai, for residential, leisure and entertainment purposes. These developments include the Isle of Palms and the World.

By shortening the coastal length, land claim can contribute to coastal defence, as has been accomplished on the North Sea coast of Germany (Sterr, 2008). In the future, the main benefit of land claim will remain the additional land, but under a rising sea level, coastal defence benefits will also be considered.

Coastal land claim is most frequently employed in estuaries or deltas due to the shelter afforded to potential industrial developments, such as ports and due to the availability of large areas of cheap, flat land, accessible from both land and sea (French, 1997). In areas such as deltas, with positive sediment budgets, land claim has often been facilitated by steady accretion (e.g. Li et al., 2004), but this is likely to be increasingly less common through the 21st century, as sediment supplies fail (e.g. Syvitski et al., 2009). However, engineered land claim will continue, such as the Isle of Palms, Dubai and the implications of SLR will still need to be considered.

In order to enclose areas for land claim, hard coastal defences must be constructed seaward of the existing shoreline. Dikes (Section 4.1.4) and seawalls (Section 4.1.3) are typically constructed to protect the claimed land from flooding by the sea (Burgess et al., 2007).

Land claim generally takes place on the higher areas of the intertidal zone. This is because the higher elevation means wave energy will be reduced through interaction with lower intertidal habitats, and because less material will be required to build up the claimed land in relation to sea level. Higher elevation areas are also selected because the required defences will not need to be as high in order to prevent overtopping. Finally, if required for agriculture, the upper intertidal zone presents the most mature soil and will be more suited to farming than lower areas (French, 1997).

Lower elevation intertidal areas and sub-tidal areas can also be used for land claim, although these projects will require greater engineering and investment. If low-elevation areas are to be claimed, it is necessary either to heavily protect these areas from inundation or significantly increase their elevation through the deposit of sediments. The latter can be achieved in a similar way to the deposition of sediments during beach nourishment (see Section 4.1.1). Ambitious land claim projects have been implemented in both Singapore and Hong Kong where both intertidal and sub-tidal areas have been reclaimed by elevation raising, for development purposes.

As mentioned above, the two main methods of land claim are: (1) enclosing and defending shore or nearshore areas; and (2) filling shore or nearshore areas, often using the same techniques used in beach nourishment. These approaches are illustrated in Figure 4.18. When considering adaptation to climate change, land claim using fill methods is perhaps more appropriate as it does not carry such a great flood risk.

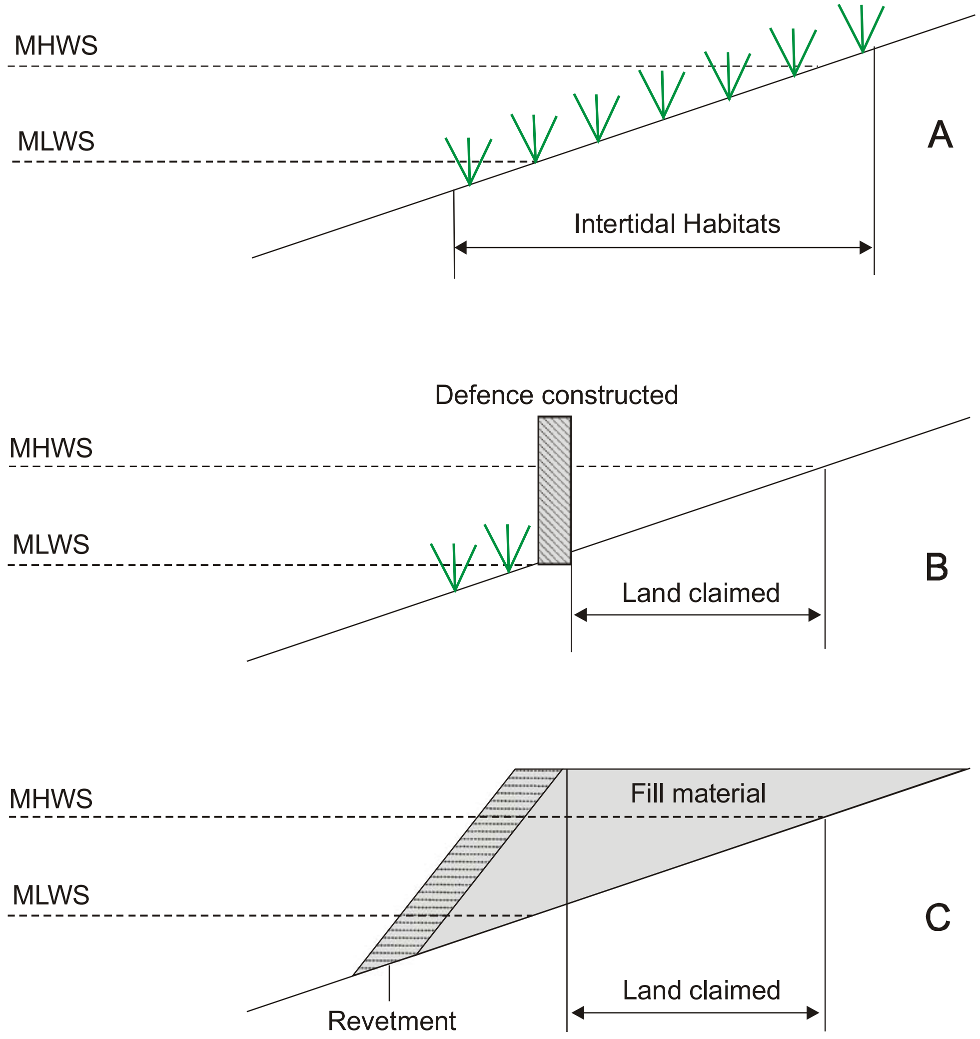
Advantages of Land Claim

The key advantage of land claim is the gain of additional coastal land for uses such as agriculture or development. In terms of development, coastal land can be very valuable due to accessibility by both land and sea which is essential for port development and due to its highly desirable location for housing and leisure facilities.

Disadvantages of Land Claim

Land claim can be traced back approximately 2000 years. Early on, land claim was carried out largely to provide agricultural land, particularly in areas where the hinterland was unsuitable for cultivation. More recently, land has been claimed for port and harbour facilities and for the construction of industrial sites (French, 1997). Although the physical gain of land is beneficial, it is now understood that land claim can also generate a number of negative impacts.

Figure 4.18: The main methods of land claim



There are two main methods of land claim: (A) shows the initial situation while (B) claims land by enclosing shore or nearshore areas to create a low-lying 'polder', most suitable for agriculture and (C) uses fill material to raise the elevation of shore and nearshore areas and is suitable for development purposes

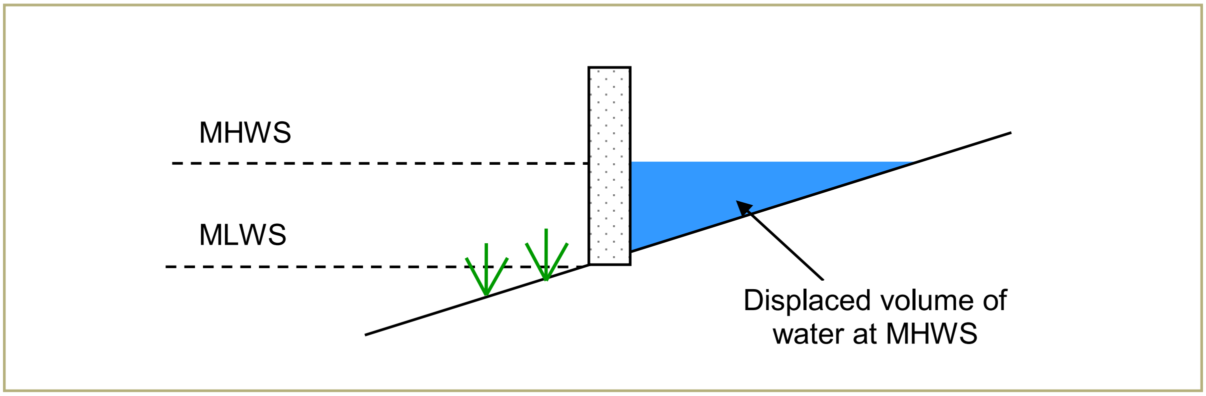
The process of land claim requires either the enclosure of intertidal habitats by hard defences, or the raising of their elevation above that of sea level to prevent inundation. This causes the direct loss of intertidal habitats such as saltmarshes, intertidal flats and sand dunes (French, 1997). This is significant because many bird and plant species have specifically adapted to life in these zones. Furthermore, these areas are largely in decline due to coastal squeeze and human development.

Another disadvantage is dewatering. By draining reclaimed land which has a high water content, land is caused to dry out, compact and shrink (French, 1997), thus reducing its elevation in relation to sea level. This causes a difference between land elevations inside the flood defences, where compaction and shrinkage has occurred and outside, where natural intertidal environments continue to naturally accrete sediments. This difference in elevation is also exacerbated by SLR and results in an ever increasing requirement for flood defences (Burgess et al., 2007). It also requires an ongoing commitment to defend these areas (French, 1997).

The use of hard defences to claim low-lying land, as shown in Figure 4.18, can be detrimental because these structures cause erosion and scour of the shoreline. Hard defences also prevent habitat adjustment in response to changing factors such as SLR (French, 1997). Other negative impacts associated with hard defences can be found in Sections 4.1.3 to 4.1.5.

Any type of land claim will cause the displacement of water during a natural tidal cycle. This is illustrated by Figure 4.19. Because of this displacement, incoming tides have a smaller area to inundate. This will cause water depths to increase and will mean intertidal areas are submerged for longer – this has the potential to cause negative biological consequences and can also increase the tidal range upstream (French, 1997).

Figure 4.19: Illustration of the displaced volume of water at MHWS caused by land claim



By displacing large volumes of water, land claim can also alter the basic erosional/accretional characteristics of an estuary. An estuary's erosional/accretional characteristics are closely linked to the magnitude of incoming and outgoing tides. Estuaries naturally accrete sediment when they are flood-dominant, i.e. when the incoming tide is greater in magnitude than the outgoing tide. However, by displacing water on the incoming tide, land claim can cause estuaries to switch to ebb-dominance, thus enhancing seaward sediment transport, erosion and increases in depth (Friedrichs et al., 1992). This can cause a previously stable estuary to develop erosion problems if the volume of land claim is sufficient.

The construction of hard defences prevents interactions between the sea and the hinterland. If coastal deposits such as sand dunes, mudflats or saltmarshes are located behind these defences, they are prevented from contributing to the local sediment budget. This can be problematic because these sediment deposits are required during times of erosion. Without them, a future sediment deficit and consequent erosion problems are likely to occur (French, 1997).

Land claim can also introduce contamination to the coastal zone and acidification of coastal waters. This can be problematic if claimed land is to be used for agriculture or when coastal waters are important for fishing. Contaminants may be introduced through the use of dredged sediments for land elevation raising – caused by the input of hazardous chemicals from industries located on the coast, from ships or from upstream river sources. Acidification on the other hand, has been linked to the action of bacteria in estuarine sediments which create sulphuric acid when exposed to air (Anderson, 1991).

Costs and Financial Requirements

Work by Linham et al. (2010) into coastal defence unit costs, found that the cost of land claim by elevation raising in South-East Asia varies from US$3-5 per cubic metre of material used, at 2009 price levels. For land claim in Hong Kong Harbour, Yim (1995) stated the costs of land claim per square metre of claim are US$3.9 when utilising marine fill and US$6.4 when using land-based fill material (prices normalised to 2009 levels).

While these costs may be representative of South-East Asia, global unit costs for land reclamation are not widely available. The financial costs of land reclamation are dependent on a number of factors (see Box 4.6).

Box 4.6: Factors affecting the cost of land reclamation projects

- Chosen method of reclaim (enclosing previously intertidal areas using hard defences or raising the elevation of previously submerged land)
- Availability and proximity of fill material from onshore or offshore sites
- Number, type, size and availability of dredgers
- Requirement for hard protection measures to defend reclaimed land from coastal flooding and erosion
- Project size and resulting economies of scale
- Estimated material losses

If land claim is conducted by enclosing previously intertidal areas, the additional costs of providing hard protective measures, such as seawalls or dikes (Sections 4.1.3 and 4.1.4 respectively), to prevent flooding and erosion of these areas is important. The cost of providing these measures has been described in Sections 4.1.3 and 4.1.4 respectively. Ongoing maintenance costs for these structures must also be considered.

If land claim is achieved by raising the elevation of previously submerged land, the cost of fill material is likely to be the main determinant of project cost. In turn, this cost will be influenced by the availability of appropriate materials, their proximity to the construction site and the characteristics of the reclaim site – this influences the type of dredging equipment which can be used. Changes in the cost of fill material are likely to occur in future due to increased demand and greater restrictions on dredging.

Institutional and Organisational Requirements

The institutional and organisational requirements of land claim projects are likely to depend on the scale and ambition of the project. Small-scale land claim for agricultural uses is more likely to be achievable at the community level than large-scale island enlargement and creation as seen in Singapore or Dubai. These large-scale projects will require the involvement of large organisations and large amounts of funding.

Land claim on the upper intertidal margins will be the easiest to accomplish at a local level, due to the presence of a lower energy wave climate and reduced fill material requirements. Land claim in greater water depths will require the construction of significant defensive measures and will call for significant quantities of fill material.

Small-scale land claim projects have been undertaken for centuries and as such, the technological requirements of these schemes appear minimal. Historic projects tended to consist of dike construction to exclude the sea, followed by drainage measures. However, historic land claims have led to significant environmental problems which were not foreseen. These problems are discussed under the disadvantages of land claim. Therefore, while land claim may be possible at a local level, the impacts must be borne in mind and weighed carefully against the benefits. If a project goes ahead, involvement of organisations with a good scientific and technology base could serve to reduce negative impacts.

Barriers to Implementation

One barrier to the use of land claim is potential long-term costs. Land claim creates land which will require protection from coastal flooding and/or erosion. This requires construction of defences such as seawalls or dikes (discussed in Sections 4.1.2 and 4.1.4 respectively) with associated construction and ongoing maintenance costs.

Environmental concerns may provide another barrier to implementation. Land claim is most frequently undertaken in estuaries, due to the shelter afforded and availability of large areas of cheap, flat land, accessible from both land and sea (French, 1997). However, a number of bird, plant and animal species have specifically adapted to life in these zones. By reclaiming land in these areas, environmentally important intertidal habitats are lost, and knock-on impacts such as alterations to ebb/flood dominance may also occur. As a result, environmental opposition to land claim may mount. In the EU, compensation for lost habitats is required; this is likely to become more widespread in other countries throughout the 21st century.

As outlined in the disadvantages section, the detrimental impacts of land claim are now better understood than in the past. Our knowledge of these impacts is likely to reduce the uptake of land claim projects based on the precautionary principle.

Opportunities for Implementation

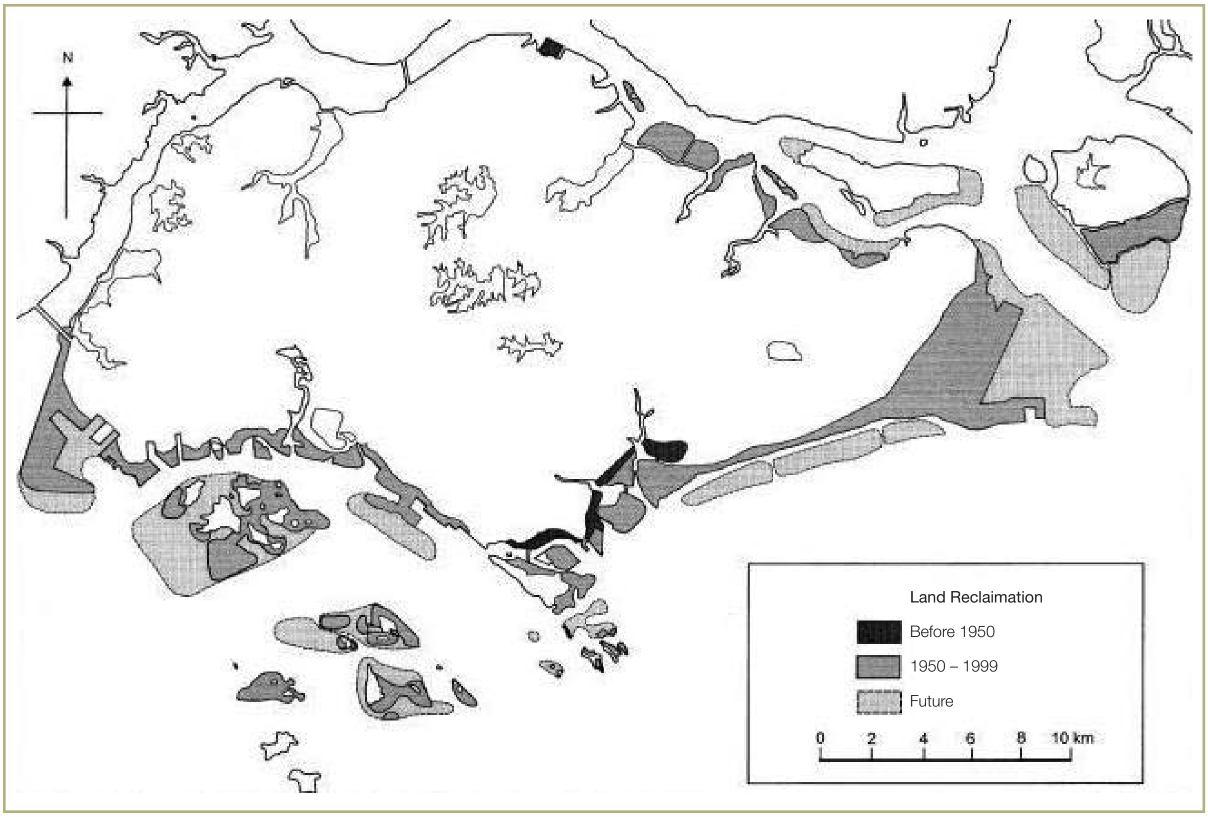
Opportunities for land claim exist where demand for land in the coastal zone is high. Coastal land is required for three main uses; (1) transport – mainly ports and airports; (2) leisure; and (3) residential. Due to these uses, land claim mainly takes place around cities. With projected increases in coastal zone populations, land claim may provide a highly valuable source of land. The creation of high value coastal land may also have beneficial developmental impacts.

Land claim through elevation raising may also be a cost-effective method of disposing of dredged material from ports, harbours and navigation channels. This could reduce the overall cost and eliminate the need to identify offshore disposal sites for dredge material. As with beach nourishment, pollutant levels in the dredge material should be carefully monitored.

Case Study: Singapore

The small island nation of Singapore, located in the South China Sea, has undertaken numerous large-scale land claim projects since the 1960s. By 1991, it was estimated that reclaimed land accounted for

Figure 4.20: Past and future land claim works in Singapore



Source: Schwartz, 2005

10% of the country's surface area (Glaser & Walsh, 1991). The extent of reclaimed land is illustrated in Figure 4.20, along with planned future projects.

Land claim has been part of the island's history since the establishment of the territory in 1819. Early land claim projects used material from the surrounding hills to raise the elevation of land flooded at the very highest tides. Land was claimed in particular through the drainage of mangrove swamps (Glaser & Walsh, 1991).

Since the country declared its independence in 1963, Singapore has been growing at a rapid rate. This led to increases in demand for land for industry, transport, infrastructure, commerce and housing (Glaser & Walsh, 1991). Major land claim projects were seen as a viable method of creating the additional land required. The scale of land reclamation since autonomy can be understood as a response to rapid economic growth and the associated increase in building activity set in motion (Glaser & Walsh, 1991).

More recently, land claim projects have stopped using material from the island's hills. The majority now employ sand mined offshore of countries such as Indonesia and Malaysia. This material is imported by reclamation contractors (Eisma, 2006).

One recent land claim project designed to meet demand for industrial land is the Jurong Industrial Estate construction project. The project involved reclamation of around 6 km2 from the sea (Glaser & Walsh, 1991) and merged seven smaller islands off the Singaporean coast into one larger island through phased reclamation of the channels between the islands (Eisma, 2006). Numerous offshore areas have also been reclaimed for the expanding petrochemical industry (Glaser & Walsh, 1991).

In 1984, the Singaporean government also approved a reclamation scheme on the north shore. The project would reclaim 8.75 km2 of shallow foreshore and swampland upon completion and would be mainly used for the construction of residential properties (Omar, 2007). The project also involved the diking of swamplands and bays to encourage/initiate land infilling processes (Glaser & Walsh, 1991). An estimated 76 million m^3 of soil were required for the reclamation; half of which was to be obtained from Housing Development Board development sites and the other half imported (Omar, 2007). The development was halted by economic problems but has now been revived.

Several approaches to protect the reclaimed land have been adopted. On the east and north coasts, reclaimed land is protected by a series of breakwaters which act as headlands. Beaches form between the headlands and can be used for recreational purposes (Wong & Pask, 2008). Elsewhere, seawalls or revetments are often used as protective measures. This is more common in areas where recreational value is low.

Coastal flood hazards are factored into the design of land claim projects in Singapore by enforcing minimum reclamation levels of +3 m above MSL on the south shore and +3.5 m above MSL on the north shore. This allows for protection against coastal flooding without the need for dikes. Climate-induced SLR is likely to be accounted for in future by raising minimum reclamation elevations by 1.0 m (Linham et al., 2010). Existing reclamation areas may also be raised as part of the redevelopment cycle.

4.2 Accommodation Approaches

The accommodate approach involves the continued occupancy and use of vulnerable zones by increasing society's ability to cope with the effects of extreme events. This approach must be implemented proactively as it requires advanced planning and acceptance that some coastal zone values could change (IPCC CZMS, 1990).

The adaptation technologies discussed in this chapter can be placed in one of two sub-divisions: (1) technologies which comprise of physical changes to accommodate increased flooding and erosion; and (2) information systems which enhance our understanding and awareness of coastal risks and enable coastal populations to undertake appropriate responses to minimise the impact of these events. Both of these approaches enable coastal populations to continue to occupy vulnerable areas. In these guidelines, flood-proofing, floating agricultural systems and wetland restoration represent the first approach, while flood hazard mapping and flood warnings are the second approach.

4.2.1 Flood-Proofing

Definition

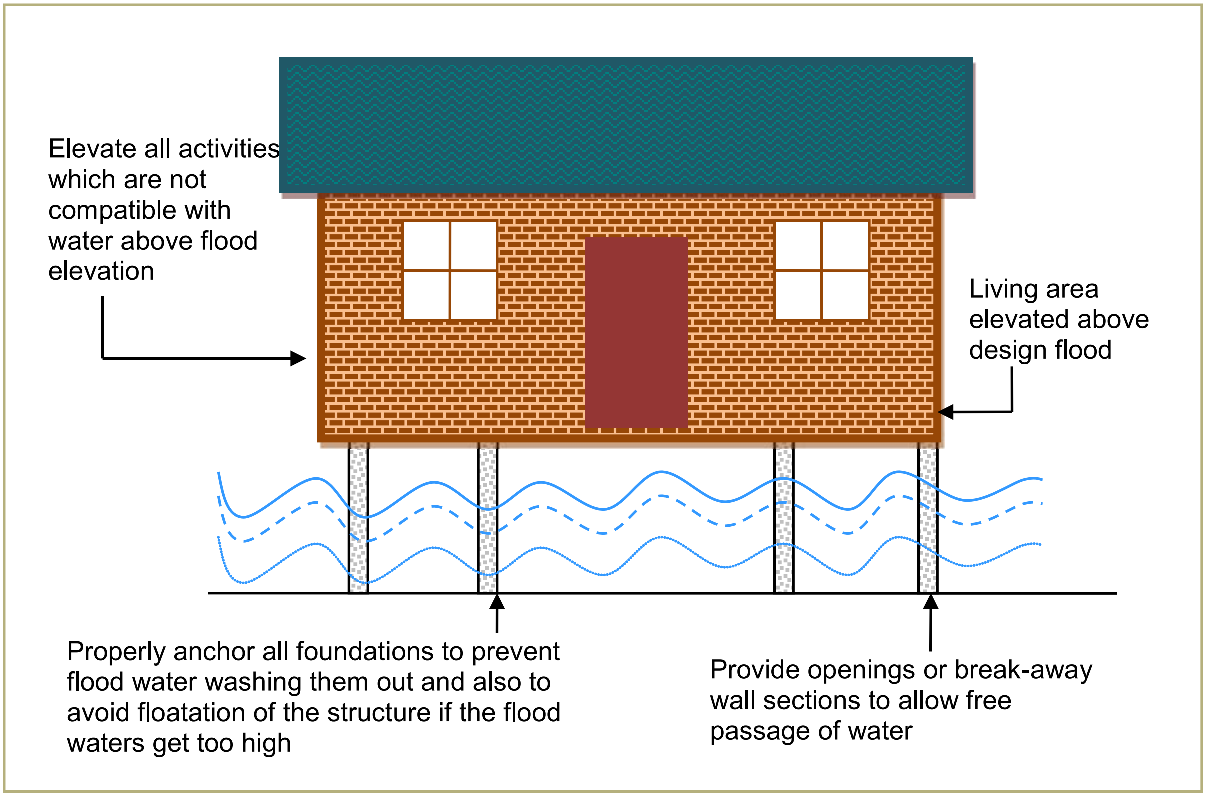
The primary objective of flood-proofing is to reduce or avoid the impacts of coastal flooding upon structures. This may include elevating structures above the floodplain, employing designs and building materials which make structures more resilient to flood damage and preventing floodwaters from entering structures in the flood zone, amongst other measures.

Description

Flood-proofing measures are widely applied in the USA where two types of flood-proofing are widely recognised: wet and dry. Wet flood-proofing reduces damage from flooding in three ways; (1) allowing flood waters to easily enter and exit a structure in order to minimise structural damage; (2) use of flood damage resistant materials; and (3) elevating important utilities. On the other hand, dry flood-proofing is the practice of making a building watertight or substantially impermeable to floodwaters up to the expected flood height (FEMA, 2008).

Wet flood-proofing measures typically include structural measures, such as properly anchoring structures against flood flows, using flood resistant materials below the expected flood depth, protection of mechanical and utility equipment and use of openings or breakaway walls to allow passage of flood waters without causing major structural damage (FEMA, 2010). A typical example of wet flood-proofing is shown in Figure 4.21.

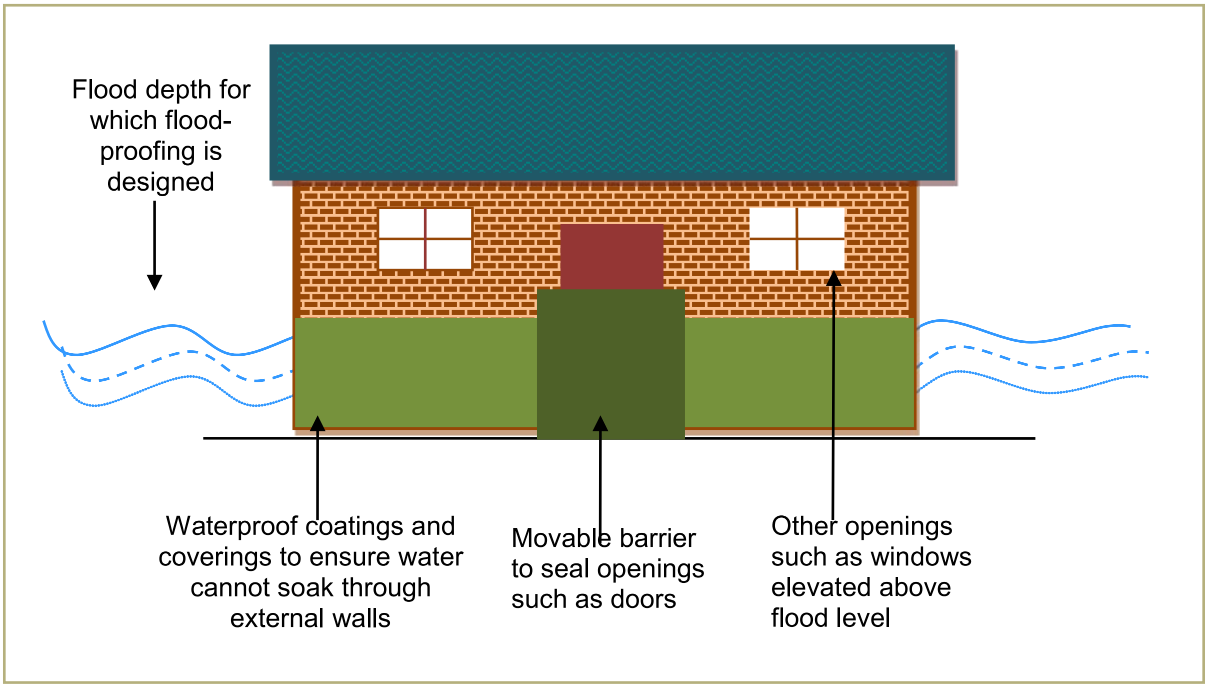
Figure 4.21: Basic wet flood-proofing measures for a residential structure



A dry flood-proofed structure is made watertight below the expected flood level in order to prevent floodwaters from entering in the first place. Making the structure watertight requires sealing the walls with waterproof coatings, impermeable membranes, or a supplemental layer of masonry or concrete, installing watertight shields on openings and fitting measures to prevent sewer backup (FEMA, 2007). A typical example of dry flood-proofing is shown in Figure 4.22.

Flood-proofing can be applied in residential and non-residential buildings and the principles of flood-proof design can also be applied to other important infrastructure such as electricity substations and sewage treatment works. Obviously, the decision to choose wet or dry flood-proofing should be influenced by the use of the structure being protected and the compatibility with flood waters.

Figure 4.22: Basic dry flood-proofing measures for a residential structure



Advantages of Flood-proofing

One of the main advantages of flood-proofing is that it avoids the need to elevate, demolish or relocate structures and as a result, is often a much more cost effective approach to reducing flood risk (Powell & Ringler, 2009). Flood-proofing measures are also much more affordable than the construction of elaborate flood protection works such as seawalls and dike systems (FEMA, 2007).

Flood-proofing is also advantageous because it does not require the additional land that would be needed to offer the same degree of flood protection through seawalls or dikes.

Wet flood-proofing measures are beneficial because they allow internal and external hydrostatic pressures[9] to equalise during a flood therefore lessening the loads on walls and floors (FEMA, 2007). This means structures are less likely to fail during floods.

Although flood-proofing will not allow residents to continue living in their house during flooding, flood-proofing measures will make it much quicker and easier to clean up and repair flood damage (FEMA, 1992).

Flood-proofing can also be undertaken by individuals, rather than requiring funding from central or local government bodies. Even small, inexpensive flood-proofing efforts are likely to result in worthwhile reductions in flood damage. Availability of funds to undertake more expensive flood-proofing measures will no doubt encourage the uptake of flood-proofing however.

---

[9] Relating to fluids which are not in motion (for example, the maximum still water level caused by extreme events).

Disadvantages of Flood-proofing

Flood-proofing measures require the current risk of flooding to be known and communicated to the public through flood hazard mapping studies and flood warning systems (see Sections 4.2.4 and 4.2.5 for further information). This will allow flood-proofing measures to be appropriately applied and will allow time for residents to vacate flood-proofed buildings in the event of an emergency. In the case of dry flood-proofing, it will also allow residents to close barriers in a timely fashion. Although the provision of flood hazard maps and flood warnings bring benefits themselves, it is an additional cost that must be borne when implementing flood-proofing measures.

Since residents are not able to continue living in flood-proofed houses during flooding, amenities for accommodating evacuated people must also be provided. These facilities may be required for some period after a flood event, as wet flood-proofing may leave the structure uninhabitable for a small period following flooding.

Flood-proofing measures are most effective when applied in areas where flood depth is low. The application of flood-proofing measures does little to minimise damage caused by high velocity flood flow and wave action (FEMA, 2007). If a flood larger than the design specification occurs, the effect will be as if there was no protection at all (FEMA, 2001).

Another disadvantage is that in the case of dry flood-proofing, flood shields are not aesthetically pleasing (FEMA, 2007). Shields for doors and windows are left in place in most circumstances, so that they can be quickly closed when required. However, this means that these measures are permanently on display. Ongoing maintenance of flood-proofing measures is also required to ensure they continue to provide appropriate protection (FEMA, 2007).

When wet flood-proofing measures are applied, flood waters still enter the structure. Therefore significant clean up may be required following floods to remove water borne materials such as sediments, sewage or chemicals (FEMA, 2007). The choices of materials used in these structures will still enable clean up to progress much more quickly than in non-flood-proofed structures.

In the case of dry flood-proofing, if design loads are exceeded, walls may collapse, floors buckle and homes may even float. This has the potential to cause more damage than if the home were just allowed to flood (FEMA, 2009).

Costs and Financial Requirements

In the absence of cost information from developing countries, cost estimates for a number of flood-proofing measures in the US are provided. The US is one country which widely applies flood-proofing measures.

In the US, the cost of elevating a structure above flood depth is likely to be between US$29 and US$96 per square foot of house footprint (FEMA, 2009). The range in cost is due to the construction and foundation type and the required elevation.

Wet flood-proofing measures are likely to include the addition of wall openings for the entry and exit of floodwaters, installing pumps, rearranging or relocating utility systems, moving large appliances and coating surfaces in coverings which make it easier to clean up after flood waters recede. According to FEMA (2009), the cost of wet flood-proofing in the US is likely to be between US$2.20 and US$17.00 per square foot of house footprint when considering basement flood-proofing up to a depth of approximately 2.4 m.

Table 4.7: Approximate costs of dry flood-proofing measures in the USA

Component	Cost	Per
Sprayed on cement	$55.10	Linear metre of wall covered
Waterproof membrane	$18.70	Linear metre of wall covered
Asphalt	$39.36	Linear metre of wall covered
Drainage line around perimeter of house	$101.68	Linear metre
Plumbing check valve	$1060	Each
Sump and sump pump	$1710	Lump sum
Metal flood shield	$1230	Linear metre of shield surface
Wood flood shield	$383.76	Linear metre of shield surface

Costs are relevant for flood proofing to a depth of approx. 0.9 m. Costs are presented in 2009 US$

Source: FEMA, 2009

Dry flood-proofing measures in the US include sealing walls with waterproof coatings, impermeable membranes or supplemental layers of masonry or concrete and equipping doors, windows and other openings below the flood elevation with permanent or removable shields. Installation of backflow valves on sewer lines and drains is also likely to be required (FEMA, 2009). US cost estimates for these measures are given in Table 4.7.

Wet flood-proofing is generally less expensive than dry flood-proofing since any action to reduce the number of items that are exposed to flood damage is considered a wet flood-proofing measure (FEMA, 2007). For example, moving valuable items to an upper story is a wet flood-proofing measure that can be undertaken at negligible cost.

The costs of dry flood-proofing a structure will depend on the following factors (FEMA, 2007):

- The size of the structure
- The height of the flood protection elevation
- Types of sealant and shield materials used
- Number of openings that have to be covered by shields
- Plumbing measures required to prevent water back-up

At the community level, flood-proofing costs will depend largely on the number of properties in the flood hazard zone and associated costs such as flood hazard mapping and modelling exercises to determine properties at risk (for more information, see Section 4.2.4).

Institutional and Organisational Requirements

Flood-proofing measures are very much possible at the community level. At its simplest, wet flood-proofing involves moving valuable objects to higher ground in order to avoid the effects of flooding. Since this can be undertaken at negligible cost, wet flood-proofing is highly achievable on a local level provided sufficient warning time is provided.

More advanced flood-proofing measures are not as capital intensive as the construction or realignment of coastal defences and therefore should also be achievable at the community scale. Implementation of this technology will however, require a proactive planning approach.

It may even be possible for individual households to finance basic flood-proofing measures themselves. This may include elevating valuable items and utilities above the expected level of flooding. This will be possible if households are given adequate information on the likely level of flooding. However, more advanced flood-proofing measures are likely to require the assistance of specialists. For example, the construction of houses within the flood zone will require experienced, professional engineers or architects to develop and/or review structure designs to ensure that structures are capable of functioning as designed.

Although flood-proofing is achievable at the community level, its effectiveness depends on community uptake and the standard to which measures are implemented. Few benefits will be gained from flood-proofing if the uptake is low or if measures are completed to a low standard. Potential unwillingness to undertake flood-proofing such measures has been highlighted by Mathis and Nicholson (2006) who found that only 63% of new buildings are in compliance with flood regulations in the US. Due to reluctance to undertake flood-proofing measures on an individual basis, it may be necessary to inspect properties in the hazard zone to ensure that flood-proofing measures have been employed and to an acceptable standard.

Funding may be provided to local communities in order to increase uptake of flood-proofing projects. This may increase uptake in poorer communities and may help to protect those at risk rather than just those who can afford such measures. A similar outcome may be achieved if flood insurance is regionally important. Reduced premiums for flood-proofed properties will encourage the uptake of flood-proofing.

Before communities can go ahead with flood-proofing measures, it will be necessary to undertake some form of flood hazard mapping (see Section 4.2.4). This will inform decision-makers on which buildings require flood-proofing and to what depth. It can also support the appropriate design of flood-proofing measures.

Barriers to Implementation

Although basic flood-proofing measures can be undertaken at negligible cost, the cost of implementing more advanced flood-proofing may be prohibitive in poorer communities. This may prevent implementation but could be addressed by providing funding opportunities.

For more advanced flood-proofing measures, such as anchoring structures and installing breakaway walls, specialist knowledge is likely to be required. This may require the input of experienced architects or engineers.

In areas where flood hazard maps do not currently exist, the uptake of flood-proofing measures may be problematic. Non-availability of flood hazard maps will make identification of properties at risk and the minimum specification of flood-proofing measures difficult to define.

Opportunities for Implementation

The main opportunity for the implementation of flood-proofing lies in the capacity to allow development in the flood hazard zone to go ahead albeit, with explicit limitations. Where there is high demand for coastal land, flood-proofing measures present an opportunity to utilise this land. This is in contrast to policies such as building setbacks (see Section 4.3.2) which prevent coastal development.

Case Study: The National Flood Insurance Programme, USA

There is no well-documented flood-proofing programme in the developing world. Hence, the long-established National Flood Insurance Programme (NFIP) in the USA is used. The NFIP provides federally guaranteed flood insurance to communities that agree to regulate development in the mapped floodplains. If communities do their part in ensuring that future floodplain development meets certain criteria, FEMA (the Federal Emergency Management Association) will provide flood insurance for properties in the community.

The NFIP requires that all new non-residential developments within a flood hazard area are either elevated above the floodplain or are flood-proofed. Residential buildings must be elevated above the base flood elevation. Flood-proofing measures described in Figure 4.21 and Figure 4.22 are taken from FEMA publications in line with the NFIP.

For the purposes of regulating new construction, NFIP defines flood-proofing as measures incorporated into the design of the building so that below base flood elevation:

- Walls are watertight
- Structural components can resist hydrostatic and hydrodynamic[10] loads, as well as buoyancy effects
- Utilities are protected from flood damage

Under these regulations, a registered professional engineer or architect is required to prepare building plans and certify flood-proofing measures (FEMA, 1998). The minimum requirement of flood-proofing under NFIP is to provide protection up to the 1 in 100 year flood.

According to the NFIP, buildings within the flood hazard zone must be appropriately anchored in order to stabilise the structure against flood forces. This means ensuring adequate protection against hydrostatic and hydrodynamic forces and erosion and scour that can undercut the foundation (FEMA, 1998).

In shallow flood areas, normal construction practices may suffice. Where deeper flooding occurs, additional anchoring such as extra bolts to connect the sill to the foundation, or installing rods into the foundation may be required. This is recommended in three cases (FEMA, 1998):

- Where the flood flows faster than approx. 1.5 m/s
- In coastal areas subject to waves and high winds
- In manufactured or mobile homes

Under the NFIP, all parts of flood-proofed buildings exposed to flood waters must be made of flood-resistant materials. 'Flood-resistant materials' include building products capable of withstanding direct and prolonged contact with floodwaters without significant damage. A list of materials recommended under the NFIP is provided in Table 4.8.

---

[10] Relating to fluids which are in motion (in this case, potentially caused by wave action or flowing water).

Table 4.8: NFIP recommended flood-resistant materials

Concrete, concrete blocks or glazed bricks
Clay, concrete or ceramic tiles
Galvanised or stainless steel nails, hurricane clips and connectors (when subject to saltwater)
Indoor-outdoor carpeting with synthetic backing (do not fasten down)
Vinyl, terrazzo, rubber or vinyl floor covering with waterproof adhesives
Metal doors and window frames
Polyester-epoxy paint
Stone, slate or cast stone (with waterproof mortar)
Mastic, silicone or polyurethane formed-in-place flooring
Pressure treated or naturally decay resistant lumber and marine grade plywood
Water-resistant glue

Source: FEMA, 1998

The USA's NFIP is a long-established, national programme which serves to encourage flood-proofing of properties in the flood hazard zone. It may provide a useful template for application in developing countries. For example, the NFIP is regulated by FEMA, a national organisation with extensive expertise in coastal flood hazard reduction and mitigation. This provides the benefit of having a dedicated, capable organisation from which advice and guidance can be sought. The establishment of such organisations in developing countries would be highly beneficial. Additionally, many of the design guidelines used in NFIP will also be applicable in developing nations. For example, the use of the 1 in 100 year flood-plain and references to dangerous flood velocities. The case study also highlights the need for capacity building in developing nations in order to train architects and engineers in the construction of flood-resilient structures.

4.2.2 Wetland Restoration

Definition

The primary objective of wetland restoration can be three-fold. These projects can serve to reduce coastal flooding and erosion and can also provide new habitats and environmental benefits.

The term 'wetland' refers to a diverse range of shallow water and intertidal habitats, which occur in various locations around the world. Wetland restoration relates to the rehabilitation of previously existing wetland functions from a more impaired to a less impaired or unimpaired state of overall function.

Although similar to managed realignment (Section 4.3.1), wetland restoration can be distinguished by the goal to maintain the present position of the coastline as opposed to realigning landward, as occurs under managed realignment.

Description

The most commonly restored wetland ecosystems for coastal protection are saltmarshes and mangroves. Seagrasses may also be employed as a coastal defence, to dampen waves but on their own they are seldom considered an adequate shore protection alternative (USACE, 1989).

Wetland habitats are important because they perform essential functions in terms of coastal flood and erosion management. They induce wave and tidal energy dissipation (Brampton, 1992) and act as a sediment trap for materials, thus helping to build land seawards. The dense root mats of wetland plants also help to stabilise shore sediments, thus reducing erosion (USACE, 1989). Wetland restoration re-establishes these advantageous functions for the benefits of coastal flood and erosion protection.

Restoration is required because many of the world's wetlands have become increasingly degraded through both natural and human activities.

Techniques have been developed to reintroduce coastal wetlands to areas where they previously existed and to areas where they did not, but conditions will allow. The diversity of wetland types means there are numerous methods for restoring wetlands. The method adopted will depend on the habitat which is being restored.

Saltmarshes are widely re-established through managed realignment schemes (see Section 4.3.1). However, this involves retreating the present line of defence. Saltmarshes can also be re-established whilst maintaining the present coastline position through vegetative transplants from healthy marshes. Transplant types often include sprigs, stems with leaves or pot-grown seedlings; seeding is not likely to be effective on sites subject to erosion (USACE, 1989). Re-establishment of saltmarshes may require the site's elevation to be raised using appropriate fill material.

For mangrove restoration, it is necessary to collect plant propagules[11] from a sustainable source, prepare the restoration site for planting and directly plant propagules at regular intervals at an appropriate time of year (de Lacerda, 2002). In re-establishing mangroves, it may also be desirable to establish nurseries to stockpile seedlings for future planting (de Lacerda, 2002). Mangrove re-establishment can also be achieved by planting dune grasses. These grasses provide a stable, protective substrate for mangroves to establish their root systems in. However, as the mangroves grow, they will eventually overshadow the dune grasses, causing them to die. Thereafter, the mangrove becomes the dominant species (USACE, 1989).

Advantages of Wetland Restoration

In terms of climate change adaptation in the coastal zone, the main benefit of wetland restoration is the reduction of incoming wave and tidal energy by enhancing energy dissipation in the intertidal zone. This is achieved by increasing the roughness of the surface over which incoming waves and tides travel (Nicholls et al., 2007b). This reduces the erosive power of waves and helps to reduce coastal flood risk by diminishing the height of storm surges.

---

[11] A structure, such as a cutting, seed or spore that propagates a plant.

A reduction in installation and maintenance costs of sea defences may occur when such structures are located behind large areas of saltmarsh (see Section 4.3.1). A similar effect exists for mangroves which absorb the energy and slow the water flow of storm surges (Barbier, 2008). Evidence from the 12 Indian Ocean countries affected by the 2004 tsunami disaster suggested that coastal areas with dense and healthy mangrove forests suffered fewer losses and less damage to property than those areas in which mangroves had been degraded or converted to other land use (Kathiresan & Rajendran, 2005). Observations indicate that a mature mangrove stand will reduce the costs dike maintenance by 25-30% assuming a stand width at least comparable to the characteristic wavelength of incident waves (Tri et al., 1998).

In contrast to hard defences, wetlands are capable of undergoing ‘autonomous’ adaptation to SLR, through increased accumulation of sediments to allow the elevation of the wetland to keep pace with changes in sea level (Nicholls & Klein, 2005). Provided wetlands are not subjected to coastal squeeze, and the rate of SLR is not too rapid to keep pace, wetlands are capable of adapting to SLR without further investments.

Coastal wetlands also provide a number of important ecosystem services including water quality and climate regulation, they are valuable accumulation sites for sediment, contaminants, carbon and nutrients and they also provide vital breeding and nursery ground for a variety of birds, fish, shellfish and mammals. They are also a sustainable source of timber, fuel and fibre (White et al., 2010).

The restoration and recreation of wetlands can also reduce or even reverse wetland loss as a result of coastal development. This is important in terms of maintaining the global area of wetlands and in sustaining wetlands in the face of climate change. Wetland creation may also fulfil legal obligations for the compensation of habitats lost through development.

Disadvantages of Wetland Restoration

The disadvantages of wetland restoration are minimal. The restoration of natural ecosystem services, including flood and erosion protection benefits, largely outweighs any disadvantages.

One possible disadvantage is the space requirement in locations which are often of high development potential. This must be carefully weighed against the range of benefits accrued.

Wetland restoration is also likely to require a degree of expertise, especially in locations where wetland re-colonisation has to be encouraged by transplanting wetland plants. Some wetland habitats will no doubt be more difficult to recreate than others and could require greater expertise.

Costs and Financial Requirements

Tri et al. (1998) studied the costs and benefits of mangrove restoration in Vietnam. The project involved the expansion of an existing mangrove forest on the seaward side of a dike system. The study estimates planting, capital and recurrent costs at approximately US$41 per hectare of mangrove planted, at 2009 price levels. This estimate includes planting costs and the cost of thinning from year six onwards (Tri et al., 1998).

Because the term ‘wetland’ refers to a diverse range of habitats, it is difficult to give accurate cost estimates. Different types of wetland will require different restorative measures with varying costs and labour requirements. A number of factors which are likely to contribute toward variations in costs are given in Box 4.7.

Box 4.7: Factors affecting costs for wetland restoration

- Type of wetland to be restored, expertise availability, and consequent chances of success
- Degree of wetland degradation and consequent restoration requirements
- Intended degree of restoration (for example, it may not be possible to restore all the ecosystem functions of a wetland if it is located in a highly industrialised/urbanised environment and the planned restoration measures may be less ambitious)
- Land costs if land purchase is required to convert to wetlands
- Labour costs
- Transportation distance between seedling source and planting site
- Seedling mortality rate between collection and planting
- Cost of raising specific species in nurseries before transplantation because they cannot be directly planted on mud flats due to strong wind and wave forces
- Scale of post-implementation monitoring operations

Source: Adapted from Tri et al., 1998

Clearly, estimating the costs of wetland restoration is complex and depends on a large number of factors. The cost of individual projects should be calculated on a case-by-case basis.

Institutional and Organisational Requirements

At a local level, proactive measures can be implemented to ensure wetland habitats are maintained and used in a sustainable manner. This will preserve habitats into the future and reduce or even avoid the cost of restoration and planting schemes. By preventing wetland loss or degradation, it is also possible to avoid the many potential problems encountered in the course of wetland restoration efforts (NRC, 1992).

It is important that the multiple agencies involved in shoreline management avoid providing conflicting guidance. In the Pacific islands, many communities were advised to clear mangroves on medical advice in the 1930s and 1940s because these areas were seen as a breeding ground for malaria-transmitting mosquitoes. Today however, the ecosystem services provided by mangroves, including their coastal protection function, is valued. As such, many communities have been encouraged to replant mangroves to prevent shoreline erosion (Mimura & Nunn, 1998).

Past wetland restoration projects have been conducted on an experimental basis through ‘learning by doing’ with limited technological experience (e.g. Saenger & Siddiqi, 1993). Using this approach, it is foreseeable that communities could implement wetland restoration on a local scale, although with improved understanding, failures could be minimised and costs reduced.

At a larger scale, it is useful for governments to adopt proactive coastal management plans to protect, enhance, restore and create marine habitats. Without such a framework, action to restore wetlands is likely to be fragmented and uncoordinated (NRC, 1994). This is compounded by the involvement of multiple federal agencies with overlapping responsibilities and different policies (NRC, 1994).

Barriers to Implementation

One of the most significant barriers to the use of wetlands as a measure to combat coastal flooding and erosion is a lack of public awareness of the flood and erosion protection benefits offered by these ecosystems. Unless the public is educated on the benefits that wetlands provide, the link between coastal flood and erosion protection and wetland restoration is likely to be unclear. This will hinder the uptake of these projects as communities press for more tangible, hard defence options, for which the protective benefits are more widely understood.

Another barrier to successful implementation is an incomplete understanding of the ability of a degraded wetland to recover, and of the success rates of wetland creation. We still do not fully understand the needs of wetland plants and animals. As such, uncertainty also surrounds the effectiveness of wetland restoration activities and whether the full range of ecosystem functions will be restored during wetland repair. Monitoring of completed schemes will enhance our understanding of wetland restoration.

The adoption of wetland restoration and (re)creation as a response to coastal flooding and erosion requires a sustainability-focussed and anticipatory coastal management plan. The establishment of wetlands which provide full coastal flood and erosion protection takes time, and the approach does not offer immediate benefits. As such, wetland recreation may not be practicable where coastal management is reactive and focussed on hard defences. A desire to improve wetland habitats also needs to exist before the strategy can go ahead. This may involve raising public awareness of the benefits of wetland restoration and (re)creation.

Wetlands only exist under specific conditions and it is not always clear if habitat restoration will be achievable or successful, especially when coastal managers have limited predictive capabilities for shoreline change (NRC, 1994). Although studies have shown that it is possible to create wetlands in areas where they did not previously exist (Platong, 1998), sites with the potential for wetland restoration or creation should be identified on a case-by-case basis.

Identifying individuals and organisations qualified to undertake wetland restoration and recreation work can also prove a barrier to implementation. The qualifications and know-how of the implementing organisations directly influence the effective application of scientific knowledge and engineering capabilities and ultimately, project performance (NRC, 1994). To address problems associated with limitations in knowledge and capabilities, it is advisable to seek direct involvement or guidance by experienced and qualified organisations.

Opportunities for Implementation

One of the biggest opportunities that exists to aid implementation of wetland restoration programmes is a growing concern regarding wetland loss and the associated loss of ecosystem functions such as habitat provision, food production and water quality improvement. The implementation of wetland restoration projects not only compensates for wetlands lost through development and natural processes but also provides the additional benefits of coastal flood and erosion protection. This option also helps reduce wetlands losses as a result of climate change.

Wetland creation can bring about various economic, social, and environmental benefits to local communities. For example, it has the capacity to improve the productivity of coastal waters for fishing. Given the importance of the fishing sector in many coastal communities in developing countries, this is likely to be highly beneficial. Such an effect may increase incomes of local communities and contribute toward local sustainable development. Other goods and services provided by wetlands, such as the provision of wood and fibres could also prove highly beneficial to local communities, especially in developing countries. Wetland recreation can also create opportunities for eco-tourism and increase recreational opportunities. Creation of wetlands, especially in or in close proximity to urban areas can even serve to increase awareness of the important functions performed by these habitats.

Because wetland restoration meets multiple management objectives – such as habitat protection, public access to environmental and recreational resources and hazard mitigation – and is less expensive and more aesthetically pleasing than some engineering solutions, the approach is likely to find broader public support in the future (Moser, 2000).

There is also the opportunity to implement wetland restoration or creation together with hard defences such as dikes or seawalls. In such a case, the presence of wetlands on the seaward side of the defence leads to lower maintenance costs over the lifetime of the structure (Tri et al., 1998).

Case Study: Mangrove Afforestation, Bangladesh

The coastal areas of Bangladesh have a high frequency of cyclones and historic events have caused significant damage, high death tolls and significant numbers of casualties.

It was realised that mangrove forests in the Sundarbans, in the south-west of Bangladesh, protected the local costs from cyclone damage. Therefore in 1966 a programme of mangrove planting was initiated on the seaward sides of protective embankments in the coastal districts of Patuakhali, Barisal, Noakhali and Chittagong. The following information is taken from Saenger and Siddiqi (1993).

The initial objective of the afforestation programme was to create a shelter belt to protect the lives and properties of coastal communities. The early success of these plantations resulted in the setting of additional objectives which included: (a) providing forest products for a range of uses; (b) developing forest shelter belts to protect inland life and property from tidal surges; (c) producing resources such as timber into the national economy; (d) creating employment opportunities in rural communities; and (e) providing an environment for wildlife.

By 1990, approximately 1200 km2 of mangroves had been planted, with funding support from the World Bank. To complement the accelerated planting scheme, a more systematic investigation of techniques was initiated, to refine seedling nursery and planting methods. The organisation responsible for this activity also identified the need for a management-oriented research programme to deal with pest outbreaks, the development of thinning schedules, pilot planting, etc.

The Bangladeshi mangrove planting programme mainly utilised two mangrove species, despite the occurrence of approximately 27 species in the country. These two species were selected because of their encouraging survival rates.

Nursery and planting techniques differed between the species. Depending on the species, the mangroves used in the Bangladeshi scheme were propagated through one of the following methods:

- Collecting and planting seeds, growing the seedling in a nursery and transplanting them to afforestation sites when they are large enough
- Sowing seeds directly onto sheltered intertidal areas

- Collection of propagules22 and plantation directly onto sheltered areas
- Collection of propagules to be raised in nurseries for subsequent planting at an afforestation site
- A number of lessons were learnt through the implementation of this scheme:
- Due to the highly dynamic nature of the Bangladesh coastline, mangrove survival could be poor and replacement planting was often required for up to three years
- After 4-5 years, trees become congested and require thinning
- Burial of mangrove seedlings can occur where accretion rates are high
- Smothering of seedlings may occur where wave action reworks large volumes of sediment landward
- During stormy periods fine sediments can be lost, with negative consequences for the establishment of seedlings
- Infestations and diseases appear to be more common when single species stands of mangroves are planted

It was found that as well as providing protection against coastal erosion, mangrove planting also helped create large areas of land through accretion, provided large quantities of wood and other forest products and provided employment for local villagers throughout the duration of the scheme. Additionally, it was seen that although mangrove plantations were damaged during significant storms, full recovery was expected; the system is therefore self-repairing.

4.2.3 Floating Agricultural Systems

Definition

Floating agriculture is a way of utilising areas which are waterlogged for long periods of time in the production of food. The technology is mainly aimed at adapting to more regular or prolonged flooding.

The approach employs beds of rotting vegetation, which act as compost for crop growth. These beds are able to float on the surface of the water, thus creating areas of land suitable for agriculture within waterlogged regions. Scientifically, floating agriculture may be referred to as hydroponics. In Bangladesh, it has regional names such as baira, geto, dhap and bed.

Description

Floating agriculture can be used in areas where agricultural land is submerged for long periods; the approach is reasonably widespread in Bangladesh where agricultural land is inundated for extended periods during the monsoon season (APEIS & RIPSO, 2004). The practice is similar to hydroponic agriculture whereby plants can be grown on the water on a floating bed of water hyacinth, algae or other plant residues (Saha, 2010).

A typical example of floating agriculture in Bangladesh involves a floating layer of water hyacinth, straw or rice stubble to which is added upper layers of small and quick-rotting waterworts which make for good manure (APEIS & RIPSO, 2004). The structure of the floating raft is strengthened with bamboo, while bamboo poles are used to fix it in position to avoid damage caused by wave action or drifting (Saha, 2010). This floating raft can then be transferred to any submerged location for agricultural purposes (APEIS & RIPSO, 2004). An example of a floating agricultural system is shown in Figure 4.23.

Figure 4.23: Floating agriculture at Lake Inle, Burma

Source: Courtesy of Wikimedia Commons

Advantages of Floating Agricultural Systems

The practice helps mitigate land loss through flooding, by allowing cultivation of these areas to continue. In this way, the total cultivatable area can be increased and communities can become more self sufficient. In addition to this, the area under floating cultivation is up to 10 times more productive than traditionally farmed land (Haq et al., 2004) and no additional chemical fertilisers or manure is required. When the crops have been harvested and floating rafts are no longer required, they can be used as organic fertilisers in the fields or incorporated into the following years floating beds as a fertiliser (AEPIS & RIPSO, 2004; Saha, 2010).

The approach uses water hyacinth, a highly invasive weed with prolific growth rates, in a highly beneficial way. By harvesting water hyacinth, areas covered by the weed are cleared, with the beneficial side-effect of reducing breeding grounds for mosquitoes and improving conditions for open-water fishing (Saha, 2010). By cultivating crops in water, it is also possible to simultaneously harvest fish populations which reside in the beds (APEIS & RIPSO, 2004).

The practice of floating agriculture also helps supplement the income of local communities and contributes to alleviation of poverty (Saha, 2010). It also provides greater food security by increasing the land output and supporting capacity for poor and landless people (Irfanullah et al. 2007). People practicing floating-bed cultivation are enjoying a better life economically, than those in other flood-affected areas who have not yet adopted this practice (Saha, 2010).

Because the system is fairly labour intensive, it also has the capacity to provide employment opportunities within communities (Haq et al., 2004). As both men and women can carry out the floating agriculture practices, it can also lead to improvements in gender equity.

Disadvantages of Floating Agricultural Systems

While this technology works well in some areas today, it is unclear how it may be affected by SLR and increases in salinity, which are likely to occur under scenarios of climate change. Additionally, while the technique is applicable in several mega-deltas such as the Ganges-Brahmaputra, the success of a more general application of this approach seems unlikely and we recommend caution in applying this approach more widely.

The methods used in floating agriculture have the drawback of encouraging insect and rodent infestation. This may cause health problems and damage to crops (Saha, 2010).

The technology can also cause conflict within the community if common property areas are dedicated to the practice. Such an approach may lead to politically more powerful individuals attempting to acquire these areas for their own gains (Islam & Atkins, 2007)

Although this technology provides the advantage of maintaining food production, it may be difficult to transport produce to market because the area remains waterlogged most of the time (APEIS & RIPSO, 2004).

Costs and Financial Requirements

Floating agriculture practices have minimal infrastructure and very little capital requirement (Saha, 2010). Costs can also be kept low because raw materials for the construction of floating beds are readily available from local waterways.

Haq et al. (2004) conducted an analysis of the costs of implementing floating agriculture in Bangladesh. Their findings are shown in Table 4.9.

Table 4.9: Costs of implementing a floating agricultural system in Bangladesh

Activity	Duration	Total Cost (Tk)	Total cost converted to US$ (in 2009 US$)
Construction of floating beds	60 man days	3000	63
Collection of raw materials (weeds)	20 man days	1000	21
Seed and/or seedling purchase		600	13
Bamboo, rope, crop harvesting and maintenance		1000	21
Total		Tk 5600	US$ 118

The use of floating agriculture as an adaptive measure also provides direct economic benefits. Vegetables and spices produced on the floating beds can be sold at markets and since the approach is fully organic, the produce receives special attention from local buyers and consumers (Haq et al., 2004).

Institutional and Organisational Requirements

Due to a lack of awareness of floating agriculture and its methods, it will be necessary to raise awareness and educate local communities. A recent scheme in Bangladesh was promoted by the Wetland Resource Development Society (an international research and development organisation), which provides training and technical support to local communities.

Provided communities are furnished with the appropriate knowledge, implementation of floating agricultural systems should be achievable at the community scale. This is because raw materials are widely available and costs are low and offset by the production and sale of food stuffs.

In order to implement these schemes at the local level, communities are required to work together. It has been observed that in doing so, the local community and communal harmony can be strengthened (APEIS & RIPSO, 2004).

Through a programme to encourage floating agriculture in Bangladesh, it was found that one of the most important aspects of implementation is to organise small-scale and poor farmers at grass-roots level and build up their entrepreneurial capacity for running small businesses (LEISA, 2009). This builds the benefits to less well-off farmers and can be accomplished on a local level.

Barriers to Implementation

The availability of high volumes of fast growing organic material may be limited in some areas and may be problematic if the uptake of this technology becomes widespread. As this is an essential material for floating agriculture, a limited supply will limit the uptake of this technology.

It is essential that knowledge of this technology be passed on to local communities in areas where floating agriculture is not carried out. To an extent, this has naturally occurred in Bangladesh where the practice has spread throughout the country (APEIS & RIPSO, 2004), but on a global scale, the approach will require local awareness raising.

Poorer farmers can be prevented from participating in floating agriculture schemes if their rights to common property and ownership of technology are not protected. While many wetland areas with plentiful water hyacinth may exist, they are likely to be grabbed by the upper levels of the rural and urban society if extensive and persistent advocacy is not considered by the implementing bodies (LEISA, 2009).

Opportunities for Implementation

Floating agriculture is an environmentally-friendly option for increasing the land available for agriculture. As such, the practice could be sustainable and profitable in developing countries, helping to supplement incomes and to increase food security (APEIS & RIPSO, 2004).

Regular, land-based agriculture requires farmland to be protected behind embankments or reclaimed from estuarine systems. Both of these activities can have detrimental side effects upon the local environment and economy. In contrast, floating agriculture can be conducted without land claim and hard defences (see Section 4.1.6). The procedure can even contribute toward maintaining healthy wetlands (Haq et al., 2004), which have coastal defence functions and also support a wide range of biodiversity.

Aquatic invasive species used in floating agriculture are considered to be the second largest reason for biodiversity loss worldwide (Haq et al., 2005). Clearing waterways to collect these plants is therefore beneficial to the health of wetland ecosystems and may contribute toward maintaining high biodiversity and associated benefits.

The practice is already widely applied in some developing countries such as Bangladesh, and the uptake of the technology is already increasing due to its sustainable, positive features (APEIS & RIPSO, 2004).

Case Study: Chandra, Bangladesh Floating Agriculture Scheme

In 2004, a floating agriculture project was begun in the village of Chandra, Bangladesh. The project was proposed by the Wetland Resource Development Society (WRDS), a voluntary research and development organisation. Implementation was funded by CIDA (the Canadian International Development Agency). The following case study is based on research by Haq et al. (2004).

Chandra is located in the southwest of Bangladesh on the banks of the River Kabodak. In the past, villagers depended on the river for agriculture, aquaculture, transport and other activities. The annual floods deposited silt onto agricultural land, making it fertile and suitable for agricultural activities.

Over time however, the floods became a nuisance rather than a blessing and in the 1960s, the East Pakistan Water and Power Development Authority implemented the Coastal Embankment project to reclaim seasonally flooded wetlands for permanent agriculture. Although this brought temporary benefits, the reclaimed land is now isolated from the fertile flood silts which are instead, deposited into the river, block drainage, and lead to permanent water-logging.

Due to regular flooding, water-logging and the availability of aquatic weeds, the local situation was deemed suitable for floating agriculture. It was also hoped that the system would provide landless farmers with productive lands.

Villagers were supplied by the supporting agencies, with training and technical support on the methods of floating agriculture. Prior to this, villagers were unaware of the technique, despite its prevalence in other areas of the country. More than 150 farmers began to apply the technology in water-logged areas and within a short period of time many other villagers began to appreciate the benefits of the system.

The people of Chandra currently grow 23 types of vegetable and five spices through floating agriculture (Haq et al., 2005). Their techniques are broadly similar to those described at the start of this section.

The project ran from 2003-2005 and following its success, a second phase was started in the Jessore District of Bangladesh, this time funded by ActionAid and running from 2007-2008 (LEISA, 2009). Although the project only lasted a short time, immediate results were observed. Farmers were able to produce and sell goods out of season, for high returns. When Cyclone Sidr passed through the area, participating farmers observed no negative effects on their vegetable and spice growth and were also able to sell produce for a higher price (LEISA, 2009). This has obvious benefits for adapting to a stormier climate as a result of climate change.

While this approach has been effective to date, it is less clear how well it will perform under a changing sea level, as processes such as saltwater intrusion may destroy crops. Hence, continued application requires careful monitoring and flexible strategies in the case of the most adverse effects.

4.2.4 Flood Hazard Mapping

Definition

Flood hazard mapping is an exercise to define those coastal areas which are at risk of flooding under extreme conditions. As such, its primary objective is to reduce the impact of coastal flooding. However, mapping of erosion risk areas may serve to achieve erosion risk reduction. It acts as an information system to enhance our understanding and awareness of coastal risk.

Description

Flood Hazard Mapping is a vital component for appropriate land use planning in flood-prone areas. It creates easily-read, rapidly-accessible charts and maps which facilitate the identification of areas at risk of flooding and also helps prioritise mitigation and response efforts (Bapulu & Sinha, 2005).

Flood hazard maps are designed to increase awareness of the likelihood of flooding among the public, local authorities and other organisations. They also encourage people living and working in flood-prone areas to find out more about the local flood risk and to take appropriate action (Environment Agency, 2010).

It is important to note here, that climate change must be carefully considered when implementing flood hazard mapping. Flood hazard mapping typically provides a ‘snapshot’ of flood risk at a given point in time. When considering the effects of climate change however, it is important to consider the dynamic nature of flood risks. For example, SLR and changes in storm intensity, occurring as a result of climate change, will causes changes in the areas susceptible to flooding. See, for example, Figure 4.24.

Due to climate change and changes in relative sea level, it is important to note that flood hazard maps will require periodic updates in order to reflect the changing risk of flooding. These updates should account for RSLR, erosion, changes in storm frequency and intensity, etc.

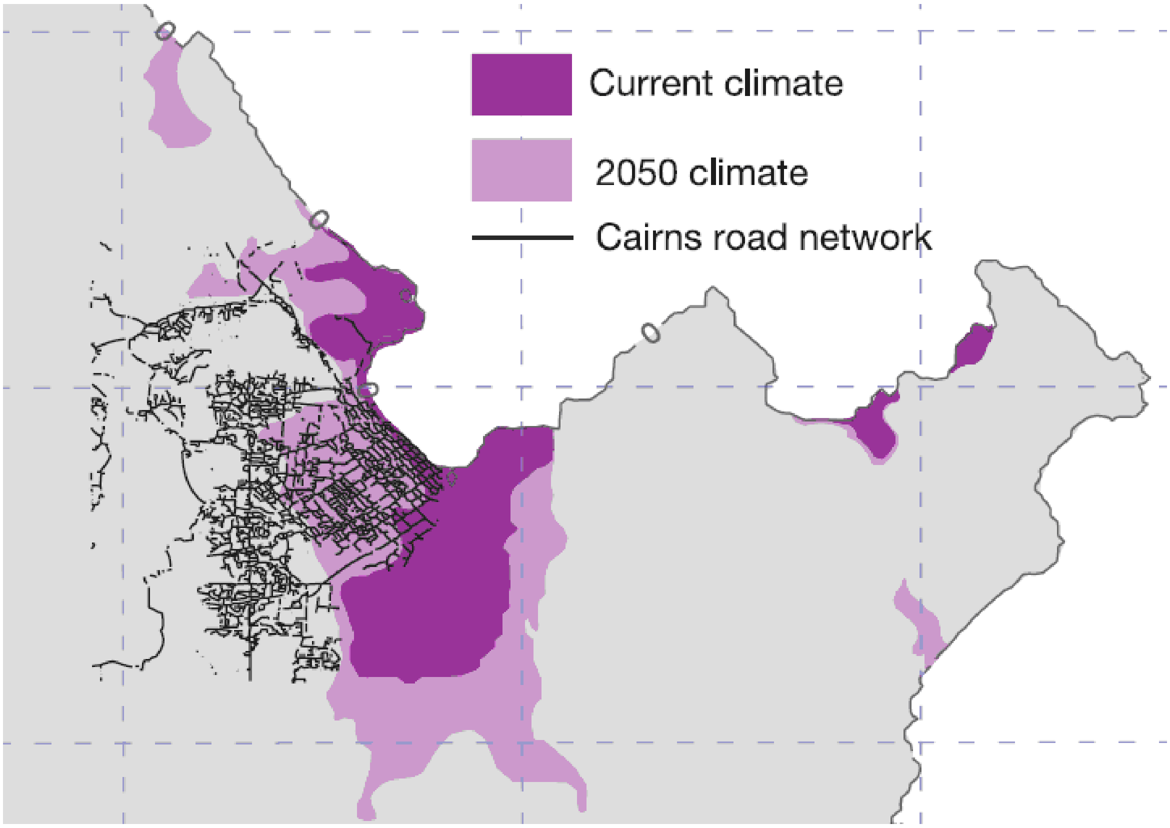
Flood hazard maps can be used by developers to determine if an area is at risk of flooding, and by insurers to determine flood insurance premiums in areas where flood insurance exists.

Due to sparse empirical records and the statistical rarity of extreme coastal events, coastal flood prediction often relies on complex numerical models that approximate the processes and phenomena that lead to coastal floods (Water Science and Technology Board, 2009). Coastal flood hazards are determined by the interaction of storm surges and waves with seabed bathymetry and coastal land cover. These factors determine the inland extent of flooding. Coastal flood models must therefore account for these features, as well as the processes associated with storm surges and waves (Water Science and Technology Board, 2009).

The creation of flood maps usually combines topographic data with historic or modeled information on extreme sea levels and wave heights. This allows determination of the water level at the coast under extreme conditions and shows how this water could flood inland. This is likely to involve the deployment of storm surge and wave models.

The level of protection offered by existing coastal defences should also be accounted for. This helps to determine when overtopping of defences will occur, causing flooding of defended areas.

Figure 4.24: Flood hazard map for the area around Cairns, Australia



The map shows both flood hazard under the present climate and under a projection of climate in 2050. It can be seen that under a scenario of climate change, developed areas that are presently not susceptible to flooding are likely to flood in future. The map also highlights currently undeveloped areas are at flood risk

Source: Nicholls et al., 2007a

Geographic Information Systems (GIS) are frequently used to produce flood hazard maps. They provide an effective way of assembling information from different maps and digital elevation models (Sanyal & Lu, 2003). Using GIS, the extent of flooding can be calculated by comparing local elevations with extreme water levels.

Advantages of Flood Hazard Mapping

Identification of those areas at risk of flooding will help inform emergency responses. For example, areas that are likely to require evacuation can be identified, and evacuation routes can be planned and clearly signposted so local communities are made aware in advance of an emergency. The identification of flood risk areas will also help in the location of flood shelters for evacuees.

Identification of flood risk areas is likely to help in the planning of a more effective emergency response. It is essential that certain infrastructure, such as electricity supplies, sewage treatment, etc., and services, such as the emergency services, continue to function during a flood event. The creation of flood hazard maps will therefore allow planners to locate these elements in low risk areas so that they can continue to serve during an extreme event. Alternatively, flood hazard mapping may highlight a requirement to defend these elements from flooding.

Flood hazard mapping will allow quantification of what is at risk of being flooded such as the number of houses or businesses. This will help identify the scale of emergency and clean-up operations.

The creation of flood hazard maps should promote greater awareness of the risk of flooding. This can be beneficial in encouraging hazard zone residents to prepare for the occurrence of flooding. In order to achieve this however, local authorities must ensure that emergency procedures are established, and that information about what to do in the event of a flood is made available to the general public.

By identifying buildings at flood risk, awareness raising campaigns can also be targeted at high risk properties. This may include raising awareness of emergency flood procedures and may also promote the implementation of flood-proofing measures (see Section 4.2.1).

In the longer-term, flood hazard maps can support planning and development by identifying high risk locations and steering development away from these areas. This will help to keep future flood risk down and also encourages sustainable development. In order for this to occur, the consideration of flood hazard maps must be integrated into planning procedures.

Disadvantages of Flood Hazard Mapping

In itself, flood hazard mapping does not cause a reduction in flood risk, It must be integrated into other procedures, such as emergency response planning and town planning, before the full benefits can be realised.

More advanced, accurate flood hazard maps are likely to rely on complex numerical models due to the lack of observed extreme event data. This requires a degree of expertise to implement. The collection of topographic and bathymetric data to complement extreme water level and wave height information could also be expensive to collect.

To realise the full benefits of flood hazard mapping, it is important to provide people in the hazard zone with information about emergency procedures and ways of reducing flood risk. If information on what to do in the event of an emergency is not provided, flood hazard maps may serve only to increase fear and anxiety as residents are more aware of the risk of flooding.

Costs and Financial Requirements

The costs of flood hazard mapping are not widely known. Therefore it is not possible to provide likely cost estimates here. However, Box 4.8 provides a number of factors which are likely to contribute toward the cost of flood hazard mapping.

Box 4.8: Factors contributing toward the cost of flood risk mapping exercises

- External expertise on numerical modelling of flood risk brought in from academic institutions or commercial organisations
- Topographic surveys (LiDAR or remote sensing) to provide information on land elevation which will feed back into the flood risk model
- Historic costs of collecting extreme event data such as water levels, wave heights, etc.
- Cost of employing a Geographic Information System (GIS)

Institutional and Organisational Requirements

Flood hazard mapping may be difficult to undertake at the community level due to the need for complex numerical modelling for the forecast of extreme water levels, storm surges and wave heights. The required expertise and modelling capacity is unlikely to be locally available, especially in developing countries. As such, it may be necessary to enlist the help of external organisations. Following developed country examples, this type of mapping has been accomplished via national programmes.

Barriers to Implementation

Flood hazard mapping relies on the availability of topographic, and long-term extreme event data and complex numerical modelling techniques. This requires specific modelling capabilities and expertise which may not be readily available.

A lack of public understanding about the benefits of flood hazard mapping may also provide a barrier to implementation. If the public is unaware of the benefits of flood hazard mapping, they may prefer to see public money spent on more tangible flood and erosion protection measures.

Opportunities for Implementation

Flood hazard mapping complements and strengthens other adaptation options, such as flood-proofing measures (Section 4.2.1), emergency planning, provision of flood shelters and evacuation planning. As such, this approach could be applied almost universally, irrespective of the other adaptation technologies that are used.

Case Study: Montego Bay, Jamaica

Between 1994 and 1997, the Caribbean Disaster Mitigation Project (CDMP) undertook three storm hazard assessments in Montego Bay, Jamaica. The purpose of these assessments was to produce maps of hurricane storm surge hazards for use in emergency management and land development planning in Montego Bay. The following case study is taken from Smith Warner International (1999).

The flood hazard mapping study was undertaken by CDMP, a joint effort of the Organization of American States (OAS) and the US Agency for International Development (USAID). The CDMP itself, was initiated in response to a dramatic increase in the level of destruction caused by hurricanes and tropical storms in the Caribbean.

The study produced maps of storm surge height for the 1 in 10, 25, 50 and 100 year storms. This was accomplished through the use of the TAOS model, a storm hazard model set up especially for use in the Caribbean.

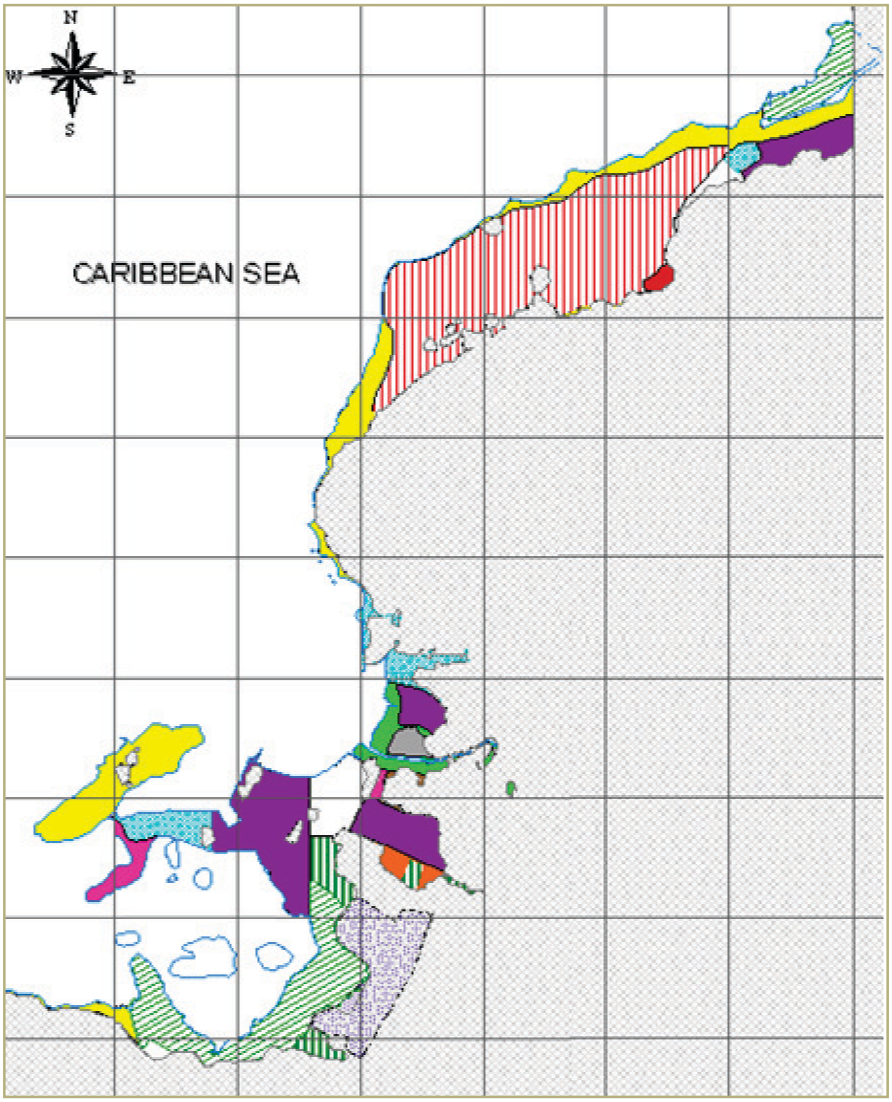
The TAOS model is a PC-based numerical model. It is able to estimate the storm surge height associated with any historic or foreseeable storm in the Caribbean Islands. This is achieved using complex equations which account for the effects of wind, waves, tides and other factors important in determining storm surge height. Long-term SLR is also accounted for in the model as this will slowly increase the datum upon which, the surge will be computed. UNEP recommended a conservative estimate of SLR in the Caribbean of 5 mm/year.

The TAOS model was used to predict storm surge heights in Montego Bay by running the model for all of the storms held in the National Hurricane Centre database. From these results, the annual maximum surge heights were extracted and then fitted to a statistical distribution. This produces a type of graph, from which, it is possible to estimate storm surge heights associated with any return period.

The storm surge heights produced by TAOS were then compared against other numerical models and against anecdotal and historical data. This provides important validation of the model and helps to ensure that the results obtained are realistic.

Once the storm surge heights for a given return period were known, the results then had to be displayed in map format. It was decided to display the results on a map based on colour aerial photographs of the area. This base map was then imported into a Geographic Information System (GIS). The GIS provided an easy way of manipulating and analysing the information. Its use also meant that outputs like maps and statistics could easily be produced. Information about the different land uses in the city were also imported into the GIS to allow the implications of a storm surge on these land uses to be assessed – the result of this analysis is shown in Figure 4.25.

Figure 4.25: Flood hazard map of Montego Bay, Jamaica



The coloured areas on the map indicate the extent of flooding caused by the 1 in 50 year storm surge. The different colours indicate different land uses, such as residential, industry, agriculture, etc.

Source: Smith Warner International, 1999

At the time, the coastal zone of Montego Bay was planned for development of resorts, residential areas, commercial buildings and many other uses. The flood hazard maps helped to highlight which areas would be best left undeveloped. They also showed that the town's use of a 100 ft (30.48 m) building setback from the high water line was insufficient to protect many land uses (see Section 4.3.2 for more information on coastal setbacks). In addition, the study highlighted the vulnerability of critical infrastructure, such as the police station, sewage pumps and airport, to flooding from storm surges, particularly in the presence of SLR. Emergency planning measures were therefore required to ensure that these infrastructures were able to return to active service as soon as possible following flooding.

The case study shows how flood hazard mapping can be effectively undertaken in a developing country. The use of the TAOS model was beneficial in this case because it is PC-based and therefore has a much larger potential user base than models which require more advanced systems. The model was also designed to be user-friendly so that limited training is required. The production of the flood hazard maps helped to improve public education, emergency management planning and development planning.

4.2.5 Flood Warnings

Definition

A flood warning system is a way of detecting threatening events in advance. This enables the public to be warned en masse so that actions can be taken to reduce the adverse effects of the event. As such, the primary objective of a flood warning system is to reduce exposure to coastal flooding.

Description

The purpose of a flood warning service is to detect and forecast threatening flood events so that the public can be alerted in advance and can undertake appropriate responses to minimise the impact of the event. This is a particularly important technology in developing countries, where flooding results in massive loss of life and property.

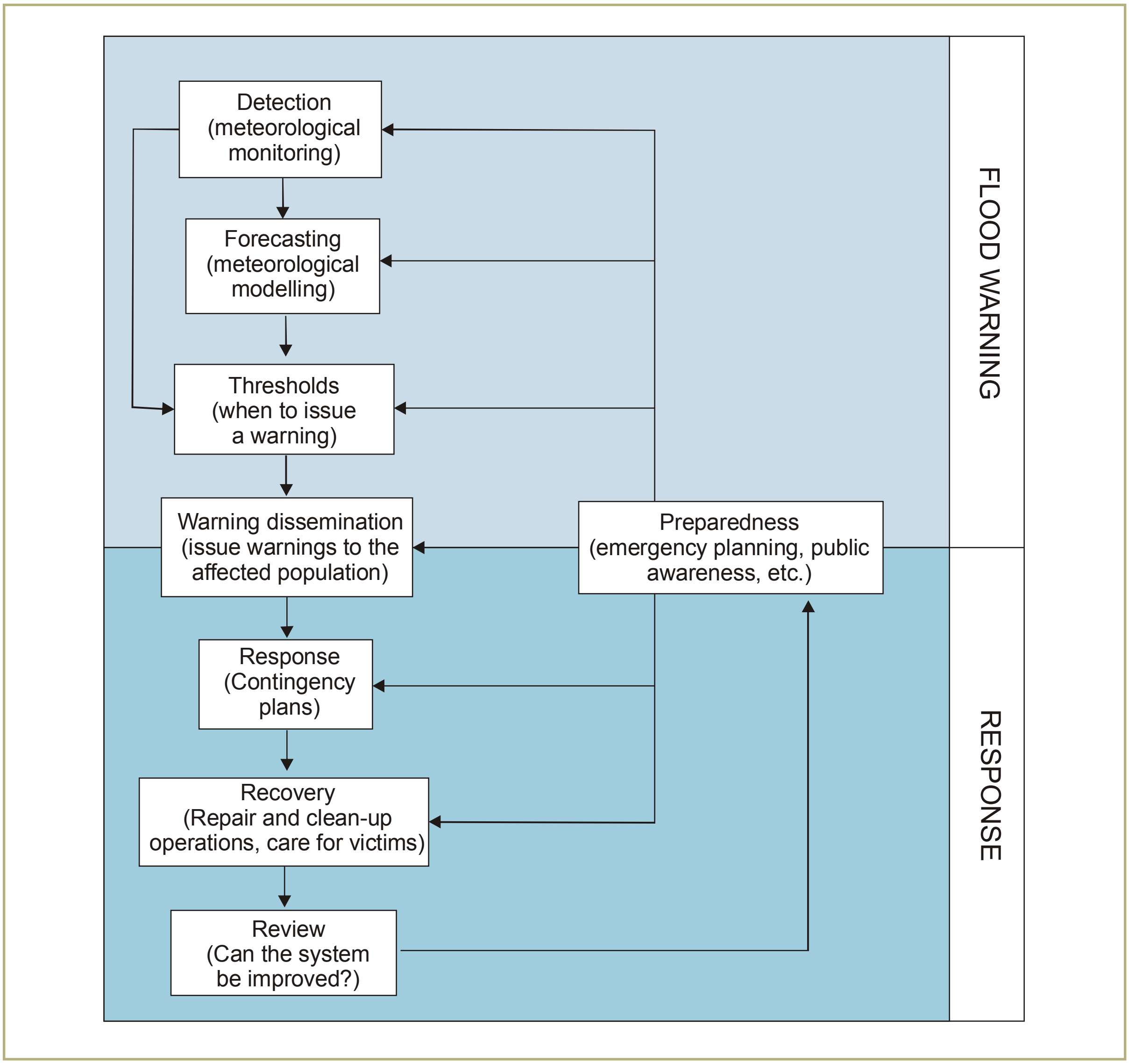
Flood warnings are a highly important adaptive measure where protection through large scale, hard defences, is not desirable or possible. This may be the case if defences would cause adverse environmental or social problems, or where the cost of defence construction would be prohibitive.

A flood warning process has two distinct stages: (1) flood warning and (2) response. These stages are composed of a number of sub-stages and are linked through the dissemination of warnings as shown in Figure 4.26.

The flood warning stage requires constant monitoring of meteorological conditions. This allows detection and assessment of threatening events to take place before it hits a community. Forecasts may also be made to help decision-makers model how an event is likely to develop, how significant it will be upon arrival, and what sections of the population are likely to be at risk. This is necessary because simple detection of an event will not provide enough time to undertake appropriate responses. To achieve monitoring and forecasting, it is likely that a flood warning system will include meteorological and tidal detection systems and river and coastal flood forecasting models.

Once an event exceeds a given threshold, a warning will be issued. This message is likely to be disseminated to the 'at risk' population via a number of channels. The media, services such as the police and fire departments and basic signals such as sirens and flags all have important roles to play.

Figure 4.26: Components of a flood warning system



Source: Adapted from Sene, 2008

After the at risk population have been warned, the second stage of the flood warning service is initiated; the response. Communities in the hazard zone are required to take action to minimise their exposure to the hazard and to reduce the consequences of flooding. It is important that appropriate actions are communicated to the public through awareness raising campaigns, prior to an emergency. Doing so, will mean actions can be quickly taken, helping to mitigate the consequence of flooding to the greatest degree.

An effective flood warning service requires cooperation between different agencies, such as the government, relief agencies and local communities. As such, this approach not only provides technical challenges but also, organisational ones.

At its simplest, the task of flood warning consists of answering the following five questions (EMA, 1999):

1. How high will the flood reach and when?
2. Where will the water go at that predicted height?
3. Who will be affected by flooding?
4. What information and advice do the people affected by flooding need to respond effectively?
5. What is the best way of giving the people affected by flooding the appropriate information?

Some of the essential components required in an effective coastal flood warning system are shown in Table 4.10.

Table 4.10: Typical components of a flood warning, forecasting and emergency response process

Item	Component	Examples
Flood Warning	Detection	Monitoring meteorological, river & tidal conditions Meteorological forecasting (e.g. weather prediction)
	Thresholds	The meteorological, river & coastal conditions under which decisions are taken to issue flood warnings
	Dissemination	Procedures and techniques for issuing warnings to the public, local authorities, emergency services, etc.
Flood Forecasting	Rivers/Coasts	Models for forecasting future river and coastal conditions
Response	Response	Emergency works. E.g. temporary barriers, flow control, evacuation, recue, incident management, decision support
	Recovery	Repair, debris removal, reuniting families, emergency funding arrangements Providing shelter, food, water, medical care, counselling
	Review	Review performance of all components of the system Recommendations for improvements
	Preparedness	Emergency planning, public awareness campaigns, training, systems improvements, flood risk mitigation

Source: Sene, 2008

It is important to note that a flood warning system is not a standalone response to minimisation of the impacts of coastal flooding. An early warning system should be coupled with emergency planning measures, such as the provision of evacuation routes and flood shelters, and should also contain an awareness raising element. These systems are only useful when everybody knows what the system of warning means, what the stages of warning are and what to do when the warnings are given (Tompkins et al., 2005).

Coupling this measure with technologies, such as flood hazard mapping (see Section 4.2.4), will improve the effectiveness of flood warnings and will help to further raise awareness of the local risk of flooding.

Advantages of Flood Warnings

HR Wallingford (2006) state that flood warning systems provide advance warning of flood events which can potentially allow:

- The risk to life to be minimised
- Evacuation of vulnerable groups
- Residents to move assets (e.g. food, livestock, personal effects) to safer locations
- Timely operation of flood control structures (e.g. storm surge barriers, temporary flood defences, etc.) to prevent inundation of property and land
- Installation of flood resilience measures (e.g. sandbags, property flood barriers)
- Pre-event maintenance operations to ensure free channel conveyance

If warnings can be disseminated to the public, it will also be possible to give communities advice on what to do in the event of a flood, as well as providing further information to limit losses. This may include areas to be evacuated, evacuation routes and the location of refuges for evacuees. It is likely that advice and guidance can be issued through the same channels used to notify communities of the flood risk as well as being made available prior to flood events.

Flood warning technologies are relatively low-cost and have been successfully employed in a diverse range of countries from developed countries, such as the USA, to developing ones, like Bangladesh (IOC, 2009).

Disadvantages of Flood Warnings

As stressed above, a flood warning system is not sufficient on its own to reduce risk; people's reactions to warnings – their attitude and the nature of their response – has an important bearing upon the effectiveness of a warning system (Haque, 1995). Flood warnings must be disseminated to local communities and responses must be made to minimise risks. Without these elements, the effectiveness of flood warning systems is compromised. It is therefore highly important that warnings can be communicated effectively to the public and that emergency responses are implemented. It is thus essential that the public are educated about appropriate responses to flood warnings, in advance of a flood emergency.

It is also essential that the flood warning system is accurate – system inaccuracies may lead to complacency if previous warnings were unfounded, or fear by causing unnecessary anxiety (UNFCCC, 1999). In order for a flood warning system to be successful, it is essential that communities heed the warnings issued – this requires the public to trust the agency providing the warning.

Costs and Financial Requirements

The costs of implementing flood warning systems are expected to differ widely, depending on the level of sophistication of monitoring and forecasting technologies.

In developing countries, meteorological observations are frequently made using basic methods, which may include ground-based methods and weather balloon observations, coupled with limited computing. In these cases, annual running costs are expected to be in the hundreds of thousands of pounds. It is also not unusual for flood warning schemes in developing countries to be heavily funded by international civil society organisations (UK POST, 2005).

In more developed countries, where more sophisticated meteorological observations are made, and where computing power is more advanced, annual running costs are expected to be in the hundreds of millions of pounds (UK POST, 2005).

It is not necessarily the case that lower technology systems offer less effective protection against flooding. Community-based, early warning systems such as those frequently applied in developing countries can sometimes be more effective than top-down, centralised systems. This is attributed to the fact that they can be more directly integrated into local response and risk reduction strategies (DFID, 2004).

The effectiveness of flood warnings can even be improved by involving local communities, for example, in the creation of flood hazard maps, scientific monitoring and contingency planning, because these activities help to increase awareness and understanding of the impacts of natural hazards (UKPOST, 2005). People-centred strategies which increase access to, and understanding of, information can even help to provide a more robust defence against a number of stresses, not just those related to climate change (Hay, 2009).

Because of their ability to drastically reduce property losses and loss of life, flood warning services may be seen as a cost-effective means of mitigating flood hazards. This is especially the case when compared against hard technologies, such as seawalls and dikes, which are often prohibitively expensive to construct.

Some of the key factors which contribute to variations in the cost of flood warning systems are provided in Box 4.9.

Box 4.9: Factors influencing the cost of implementing a flood warning system

- Extent of meteorological monitoring network
- Cost of sourcing meteorological data
- Set up costs of warning dissemination system and its degree of sophistication
- Training and employment costs of meteorological data analysts
- Cost of associated measures:
  - Provision of flood shelters
  - Creation of evacuation routes
  - Awareness raising
  - Training of emergency services

Institutional and Organisational Requirements

The organisation of a flood warning service varies widely between countries and depending on the scale of the overall system. Sene (2008) indicates that it may include some, or all, of the following activities:

- Detection: design, installation and operation of rainfall, river level, tidal level, wind, wave and other monitoring equipment

- Design: design of flood warning schemes, including contributing to decisions on who should receive warnings, setting flood warning thresholds, deciding how flood warnings should be disseminated and under what circumstances
- Dissemination: monitoring measurements and forecasts against thresholds and issuing warnings following agreed procedures and public awareness activities
- Operation: suggesting actions which should be taken to mitigate flooding risks/losses
- Management: general management activities, including defining staff rotas, procurement, performance monitoring and reporting, research and development, etc.
- Forecasting: development and operation of flood forecasting models to provide estimates of river levels, river flows, tide levels, wave overtopping, etc.

Some of these tasks may be unnecessary for a small-scale, community-based warning system where the primary needs are for detection and dissemination of warnings. However, for a regional or national programme, most of the tasks will be necessary, although some may be shared with other organisations (Sene, 2008).

It is possible to employ low technology methods in warning systems. For example, in Bangladesh, warnings are disseminated by local trained volunteers or alternatively, through channels such as newspapers, television and radio. The use of volunteer messengers has been very successful in Bangladesh, since warnings may even be viewed as more relevant and person-specific when delivered by other members of the community. This demonstrates real potential for flood warnings in developing countries.

Responses to flood warnings can also be conditioned at the community level. This may include the provision of sandbags, designing and implementing evacuation procedures, or distributing relief goods, amongst other activities. In Bangladesh, this is undertaken by local volunteers. Education may also be offered to communities at risk in advance of a significant event. This is likely to make people more aware of the severity of hazards and of the precautionary options available (Haque, 1995).

It may also prove beneficial to teach coping strategies at a community level. Strategies may include swimming lessons or providing information on evacuation. Haque (1995) found that the majority of communities in Bangladesh had not received information from government departments regarding coping strategies for cyclones.

It can be seen that to be effective, warning systems require the development, implementation and coordination of quite diverse flood responding technologies (IOC, 2009). This may prove challenging for local communities to achieve, especially given the involvement of multiple organisations in flood warning.

Despite the fact that these actions can take place on a local level, involving larger organisations, with superior resources, knowledge and know-how may still prove beneficial in improving the quality of warning messages from the warning systems. Better still, by working together with neighbouring countries that may also operate flood warning systems, it may be possible to obtain more complete and timely meteorological data, better dissemination of warnings and improved responses.

Barriers to Implementation

One of the main barriers to implementation of flood warning systems in developing countries is the availability of communication channels, through which warnings can be disseminated to the public. In developed countries this can be achieved through radio and television channels and the internet. These resources are less widely available in developing countries therefore sending out the warning messages in a timely manner to the targeted audience can be problematic.

The approach also requires significant volumes of detailed information to be collected and analysed in order to detect flood threats. It needs significant investment in equipment and training. This has, however, been achieved in developing countries such as Bangladesh (Haque, 1995; Mirza et al., 2005) and Vietnam (Pilarczyk & Nuoi, 2010) with the help of foreign organisations who can supply information and real-time data on weather patterns (Haque, 1995). Locally recognised indicators may also be important when developed by coastal communities with a close relationship with the land and sea.

Even once a warning system has been implemented, significant barriers to the effectiveness of this approach may still exist. In a field study following the April 1991 cyclone in Bangladesh, Haque (1995) found that despite receiving flood warnings, a large proportion of the population took no deliberate emergency action. Therefore, a large segment of the population remained vulnerable. Three main factors were cited as reasons for failing to take action:

1. Fear of losing household assets through looting if the house is abandoned
2. Fatalism
3. Disbelief of flood warnings

Fear of looting may be addressed by providing a denser network of smaller shelters to reduce the distance between homes and shelters and to allow better protection of property (Haque, 1995). Improved law enforcement is also needed for better protection of private property during disaster events.

Fatalism typically stems from a sense of powerlessness to influence events. It has been suggested that some individuals believe flooding is God’s will and that individuals must instead just learn to live with the consequences (Haque, 1995).

Disbelief of flood warnings may be due to past false warnings. It can be hard to forecast significant flood events due to their unpredictable nature. Therefore, it may be wise to implement a trade-off between the gains of advance warning when the hazard probability is low, and gains resulting from enhanced responses when the incidence of false alarms is reduced (Haque, 1995).

Additional reasons noted by Haque (1995) for failing to take action include disbelief that floods would occur in that area due to a lack of experience within living memory, over-filled shelters, the fact that shelters were crowded by men, which discouraged females users and finally, a lack of awareness of the limited amount of protection that homes would provide.

Opportunities for Implementation

It is possible to implement flood warning systems together with other adaptation measures , as part of an integrated flood risk management plan. Complementary actions could be part of a protect, accommodate or retreat approach. In London, flood warnings inform operation of a storm surge barrier and embankments have also been constructed along the majority of the riverside.

The costs involved in implementation of a flood warning system could be offset through the construction of multi-purpose shelters which could also serve as schools, health facilities and agricultural extension centres (Haque, 1995). This has already proven successful in Indian communities (Mishra & Prakash, 1982).

Technology used for detecting flood risk may also be used for forecasting rainfall when flood risk is low. This could benefit agricultural practices in these regions.

Case Study: Cyclone Warning System, Bangladesh

The Bay of Bengal on the Bangladeshi coastline is one of the world's most active areas for the development of tropical low pressure systems, which can lead to tropical cyclones (Haque, 1995).

Tropical cyclones in Bangladesh have historically been associated with high death and casualty rates but because of the country's low per capita income, capital intensive preventative measures to prevent or avoid hazard loss were unfeasible (Haque, 1995). As a result, Bangladesh decided to implement the Cyclone Preparedness Programme (CPP). The CPP activities are centred on three infrastructures: the cyclone early warning system, public cyclone shelters for pre-disaster evacuation and shelters for cattle during storm surges (Paul, 2009).

As already stated, warning systems consist of three interconnected phases; (1) evaluation, (2) dissemination/warning and (3) response. The Bangladesh flood warning procedure also consists of these stages, with the involvement of multiple bodies and a constant flow of information between them.

Evaluation is undertaken by the Bangladesh Meteorological Department (BMD), responsible for preparing all weather forecasts and disaster warnings. The centre gathers data from a number of sources including:

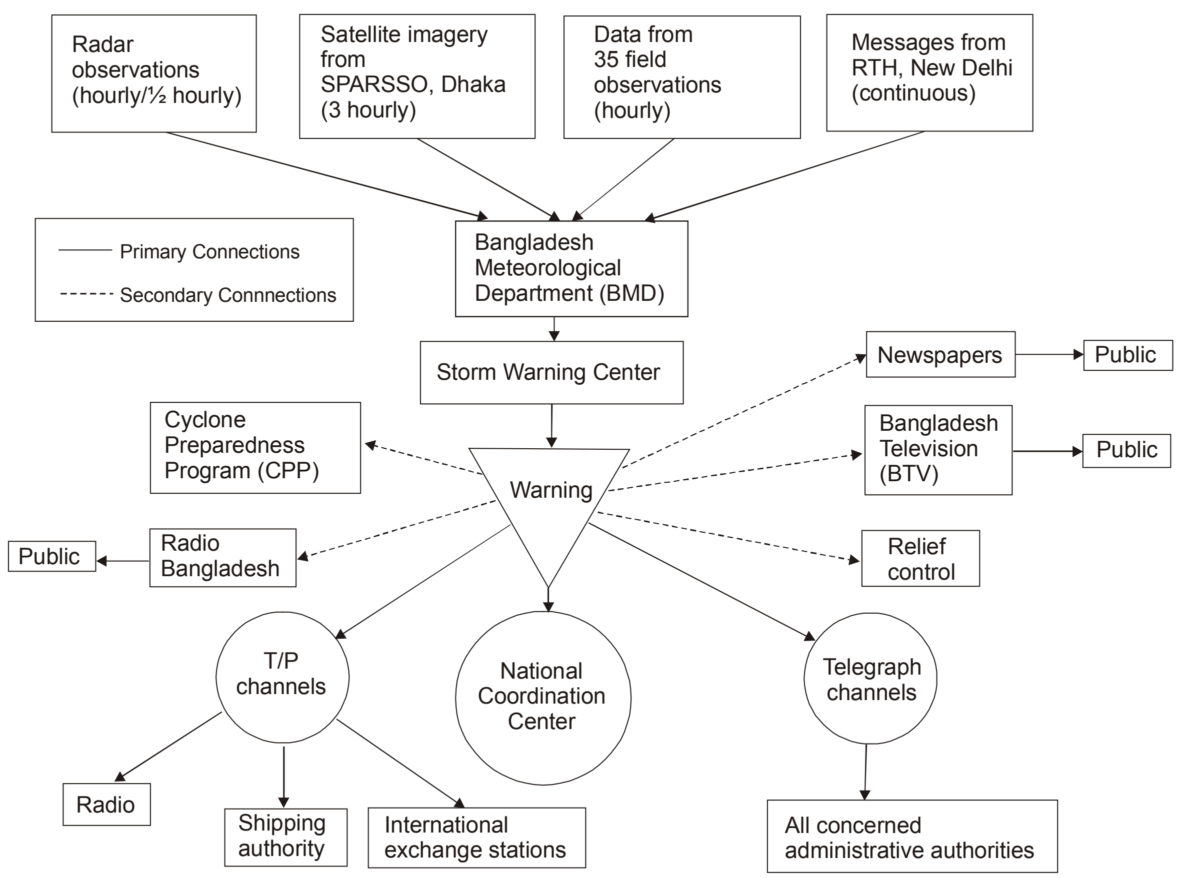
- Surface observatories which collect hourly wind speed, direction, humidity, air temperature and other meteorological data
- Radar stations which transmit hourly and half-hourly weather data
- US National Oceanic and Atmospheric Administration (NOAA) satellite imagery
- Japanese satellite imagery via the Bangladesh Space Research and Remote Sensing Organisation (SPARRSO)
- World Meteorological Organisation (WMO) network

Highly trained forecasters at the BMD scour the data received, looking for indications that a storm is developing. Forecasters in Bangladesh constantly look for impending threats such as storm surges or cyclones. Once an impending threat is detected, storm and cyclone warnings are disseminated by the BMD through a number of channels. The flow of information is illustrated in Figure 4.27.

The Bangladesh Storm Warning Centre (SWC) sends warnings to multiple organisations with roles to play within communication of flood risk and hazard response. These organisations are summarised in Table 4.11. The SWC also sends warnings directly to the National Coordination Committee (NCC), an organisation which acts as the central national body in flood risk communication and response.

There are nearly 43,000 CPP volunteers, stationed in the coastal districts of Bangladesh. They are responsible for disseminating cyclone warnings among villagers. These volunteers use megaphones and house-to-house contact to raise the alarm. They also assist people in the evacuation process, execute rescue operations, provide first aid, and assist in distributing relief goods (Paul, 2009). The nation's army, navy and air force are also given specific functions and responsibilities during pre-disaster, disaster occurrence and post-disaster stages (Haque, 1995).

Figure 4.27: Information flows in the Bangladesh CPP



The figure illustrates the flow of information administered by the Bangladesh Meteorological Department

Source: Haque, 1995

Upon receiving warnings, the public are encouraged to take refuge in cyclone shelters, which are multi-storey buildings, raised above the ground in order to resist storm surges. Almost 4000 shelters have been built in the coastal zones of Bangladesh. Each shelter can accommodate between 500 and 2500 people. Although people are encouraged to uses these shelters in the event of flooding, recent experience during Cyclone Sidr in 2007, has shown that more shelters are needed to accommodate all of the people in these areas. In some cases, shelters are also located more than 3.5 miles away from the villages – too far to travel in an emergency (Paul, 2009). Existing shelters have further problems, including insufficient lighting, broken windows and doors, lack of water and sanitation facilities, and a lack of separate space for women (Paul & Dutt, 2010).

Nevertheless, the Bangladeshi flood warning service has largely been considered as a success. This is demonstrated well by the reduced death tolls of recent cyclones; the 1970 cyclone which spurred the implementation of the flood warning service resulted in 300,000 deaths, whereas a cyclone of similar intensity in 1991 killed 138,000 people (ADRC, 2005). Cyclone Sidr in 2007, the second strongest cyclone to make landfall in Bangladesh since 1877, caused 3406 deaths, far fewer than both (Paul & Dutt, 2010).

However, proximity of shelters and availability of space within them remains a problem. During Cyclone Sidr, more than 25% of flood victims stated that inaccessibility of a shelter dissuaded them from evacuating

Table 4.11: Bangladesh SWC warning message dissemination system

Organisations notified by the Storm Warning Service
Prime minister's secretariat
Bangladesh Betar (Radio)
Bangladesh Television (BTV)
Control room, Ministry of Disaster Management and Relief
Control room, Disaster Management Bureau
Cyclone Preparedness Program (CPP)
Coastal volunteers
Media
General population
Armed Forces
Bangladesh Navy
Bangladesh Air Force
Maritime and Riverine Ports
NGOs
Flood Forecasting and Warning Centre

Source: adapted from ADRC, 2005

(Paul & Dutt, 2010). Additionally, a large number of people continue to react passively to warnings (Haque, 1995; Paul, 2009; Paul & Dutt, 2010).

Reasons for inaction among the at risk population are numerous. Many quote disbelief of the warnings – this is often due to the occurrence of false alarms in the recent past. Others failed to receive warnings because they were located upwind of auditory signals, such as alarms and sirens. Condition and proximity of shelters has also been stated as a reason not to use them. Other victims failed to take action because they did not fully understand the seriousness of the event or because they had no previous experience of storm surges. Many others stated that they feared their homes would be looted if they sought shelter (Haque, 1995; Paul & Dutt, 2010). To improve the effectiveness of the CPP in future, it appears that further investment is required in shelter construction and awareness raising.

4.3 Retreat Approaches

Retreat here, refers to a proactive or planned withdrawal from the coast, rather than an unplanned or forced retreat, which is also potentially possible in the face of SLR and climate change. The retreat option relates to the reduction of the risk of an erosional or flood event by limiting its potential effects. This may involve preventing development in coastal areas, allowing development to take place on the condition that it will be abandoned if necessary, or having no direct government role other than through withdrawal of subsidies and provision of information about associated risks (IPCC CZMS, 1990).

Governmental efforts to limit development generally involve land acquisition, land use restrictions, prohibited reconstruction of property damaged by storms and reductions of subsidies and incentives for development in vulnerable areas (IPCC CZMS, 1990). These approaches have multiple benefits, including flood and erosion protection and provision of space for habitat creation and leisure activities. Examples of the retreat approach explored in this guidebook are managed realignment and coastal setbacks.

4.3.1 Managed Realignment

Definition

Managed realignment is able to reduce both coastal flooding and erosion. It is the deliberate process of altering flood defences to allow flooding of a presently defended area. Managing this process helps to avoid uncertain outcomes and negative impacts. It also helps to maximise the potential benefits (Leggett et al., 2004). A number of terms may be used as an alternative to managed realignment. These include managed retreat, dike realignment, dike (re)opening, de-embankment and de-polderisation.

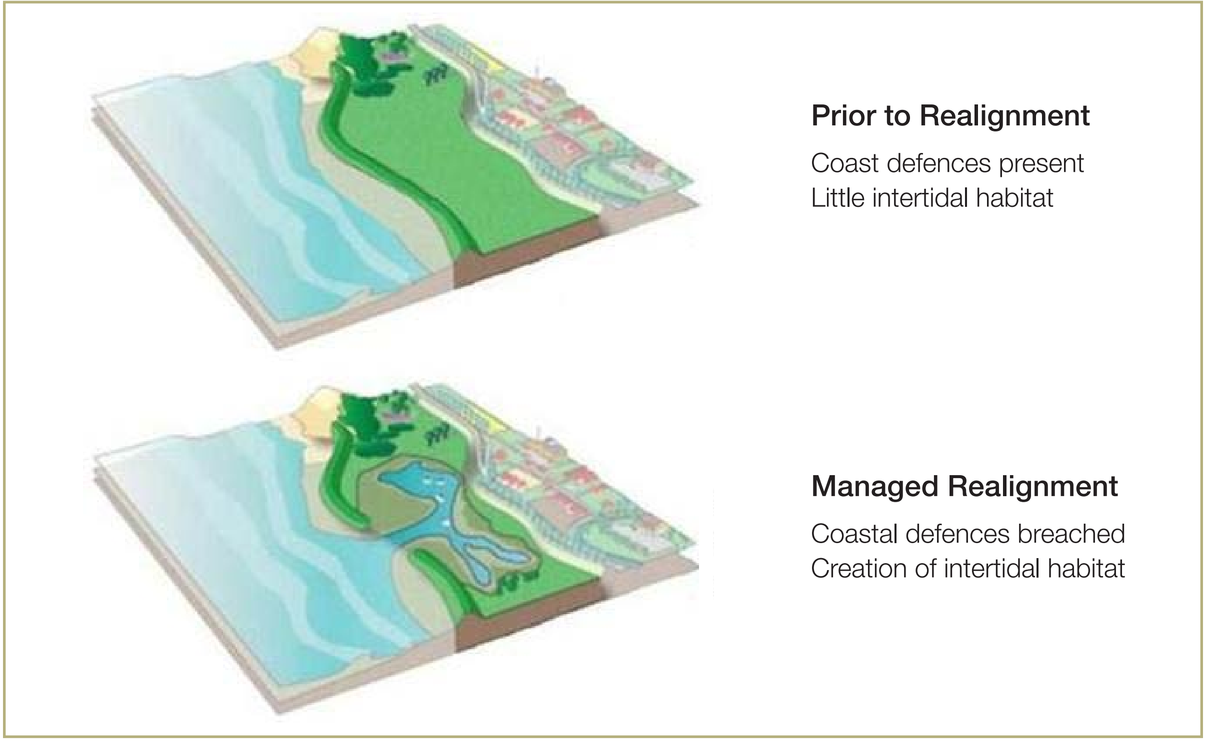
Description

Managed realignment generally involves setting back the line of actively maintained defences to a new line, inland of the original or preferably, to rising ground. Doing so should promote the creation of intertidal habitat between the old and new defences, as shown in Figure 4.28. In most cases, the objective of realignment is to create saltmarshes. Saltmarshes develop between mean high water springs (MHWS) and mean low water springs (MLWS), in areas shaped predominantly by tidal processes and where silts and mud are predominant (French, 1997).

The benefit of creating intertidal habitats lies in the fact that they are highly effective at attenuating wave energy. This helps to reduce offshore sediment transport and therefore erosion. Intertidal habitats also form dense root mats which increase the stability of intertidal sediments, helping to reduce erosion rates (USACE, 1989).

This section uses the creation of saltmarshes through managed realignment as an example because, to date, the managed realignment approach has only been applied in North-West Europe and North America, where saltmarshes are the dominant intertidal habitat. There appears to be no reason why creation of

Figure 4.28: The process of managed realignment



Prior to Realignment

Coast defences present
Little intertidal habitat

Managed Realignment

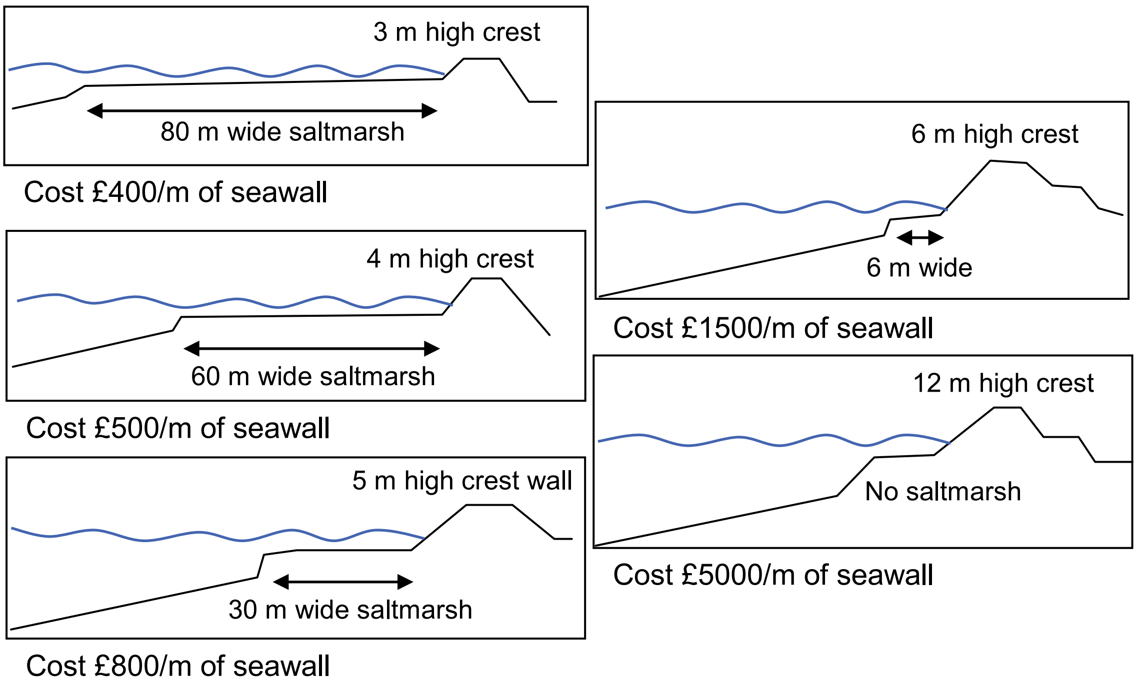
Coastal defences breached
Creation of intertidal habitat

Source: Adapted from ComCoast, 2006

other wetland habitats, such as mangroves, should not be possible through realignment, although such an approach has not been undertaken to date.

Studies on saltmarshes have shown they are capable of attenuating up to 97% of incoming wave energy depending on the width of the marsh (Doody, 2008). This can have highly beneficial implications for coastal protection. For example, if defences are realigned to an inland location, the presence of intertidal habitats can greatly reduce the cost of installing and maintaining protective measures (Doody, 2008). This is illustrated in Figure 4.29. Alternatively, if realignment to higher ground is undertaken, defences may not be required at all.

Figure 4.29: Effect of saltmarshes on required seawall standards and consequent costs



Indicative costs and heights of sea defences with different widths of saltmarsh fronting. Costs presented in early 1990s prices. Information drawn from south east England

Source: Adapted from Doody, 2008

Managed realignment may involve deliberate breaching or the complete removal of a current coastal defence. The process can be planned through abandonment or relocation of existing defences or unplanned through abandonment of defences if, for example, financial resources for maintaining defences are not available (Nicholls et al., 2007b).

In order to undertake managed realignment, a number of conditions must be present. Six of the most important conditions are given below (Gardiner et al., 2007; Rupp-Armstrong and Nicholls, forthcoming):

1. presence of coastal defences
2. availability of low-lying land
3. desire or need to improve flood or coastal defence systems
4. presence of a sustainability-oriented coastal management attitude
5. desire or need to create intertidal habitats
6. societal awareness about the benefits of managed realignment

Advantages of Managed Realignment

As already mentioned, managed realignment can significantly reduce the cost of providing a given level of protection against coastal flooding and erosion. Intertidal habitats attenuate incoming wave energy, meaning that waves reaching the shore are smaller in height and less powerful. This is advantageous as it may mean hard defences are not required, or if they are necessary, that they can be of reduced height and strength. Reduced incident wave energy is also likely to result in reduced defence maintenance costs. Further cost savings can be made if realignment allows the defensive line to be shortened or completely abandoned (Nicholls et al., 2007b).

The effectiveness of saltmarshes at attenuating wave energy means that the coastal zone is less reliant on engineered hard defences for reducing coastal flood and erosion risk. By increasing the coastal zone's natural flood and storm buffering capacity, the long-term sustainability is also improved (Leggett et al., 2004). The widespread application of managed retreat could significantly reduce the need for coastal defences in the future (Nicholls et al., 2007b). In addition, the approach is highly robust against unexpected climate change futures and generally enhances resilience to unexpected changes (Nicholls et al., 2007b).

As well as helping us respond to unexpected futures, this approach helps to mitigate carbon dioxide and methane emissions because the gases are stored within the sediment deposits. Another major benefit of managed realignment is that intertidal habitats are encouraged to return on surrendered land. This is a real benefit because coastal squeeze and human development have caused a marked decline in these habitats in many areas in recent years. Managed realignment contributes toward the reinstatement of intertidal habitats which are important to specialised birds, plants and commercially exploited fish and shellfish (Leggett et al., 2004; UK POST, 2009). A beneficial by-product of intertidal habitat creation is that these areas can then be used to promote recreation and ecotourism (Nicholls et al., 2007b). In the UK and elsewhere, intertidal habitats are popular areas for walking, sailing and bird watching.

As well as habitat benefits, the creation of new intertidal areas would also help to maintain water quality and avoid saltwater intrusion due to inappropriate land use. This is achieved by reducing the undesirable effects of eutrophication[23] (Leggett et al., 2004). This would be of benefit in locations where drinking water supply is threatened by SLR, in highly populated locations where water availability is limited, and in areas where water bodies are required to meet a certain standard.

Disadvantages of Managed Realignment

One of the biggest drawbacks of managed realignment is that the option requires land to be yielded to the sea. This may require the relocation of important infrastructure or buildings, potentially at significant cost. Alternatively, the land may be able to be used in other ways, such as for recreation. In both instances, valuable land on the seafront is required to be relinquished.

For this reason, the managed realignment option is often of high political and social controversy. The schemes frequently suffer from a lack of public acceptance, perhaps because of a perceived threat from the sea coming closer or because of a reluctance to lose land which forefathers fought hard to (re)claim from the sea (Rupp-Armstrong & Nicholls, forthcoming).

Managed realignment is further complicated by the frequent involvement of numerous land owners. It is important to involve those affected in the planning and decision making process in order to increase acceptability.

Managed realignment is also likely to be highly disruptive and expensive if relocation of relocation of coastal infrastructure is required (Nicholls et al., 2007b). Care should be taken to ensure that if infrastructure is abandoned rather than relocated, that nearby areas do not become isolated, thus leading to increased poverty (Nicholls et al., 2007b). As a result, managed realignment must be strategically planned to minimise problems and avoid detrimental local impacts. If a scheme is well planned, it may even be possible to improve local opportunities.

Another disadvantage of this approach which may become more significant in the future is the conflict between the need for wetland creation and the need to retain valuable agricultural and historical sites (UK POST, 2009). At present, a significant portion of realignment projects are carried out on agricultural land, largely because these sites do not require such significant relocation of infrastructure. However, inundating agricultural land may lead to reductions in local agricultural production. This is likely to become a more significant issue in future as the issue of food security becomes more pertinent and may be particularly problematic in some developing countries.

Although experience in the application of managed realignment is growing, the approach is still relatively young and uncertainties still exist. For example, it is not fully understood how long it will take to create typical intertidal habitats that deliver the full benefits of naturally occurring systems (UK POST, 2009). In addition, the approach is not necessarily conducive to all environments; wetlands and saltmarshes tend to occur in locations where wave energy is low and where high volumes of sediment are available. It is therefore important to carefully evaluate the feasibility and effects of this approach in specific locations.

Costs and Financial Requirements

As no reference on the application of managed realignment in any developing countries has been found, the authors are unable to present cost information for the developing world. Developed country costs are instead presented to give some indication of costs and how they are likely to vary.

Rupp-Armstrong and Nicholls (forthcoming) state that the average cost of managed realignment in Britain is approximately US$97,000 per hectare (at 2009 prices), where construction of a new defence was also required. However, the costs of managed realignment schemes can vary widely as a result of numerous factors outlined in Box 4.10.

Box 4.10: Factors affecting unit costs of managed realignment

- Cost of the land where managed realignment will be performed
- Requirement for compensation to land owners/occupiers
- The need to dismantle human-made structures present on the site to prevent marine pollution
- Requirement for and size of sea defences to protect the hinterland
- Availability and cost of human resources including expertise
- Scale and frequency of monitoring

In developed countries, where experience of managed realignment is greatest, the main cost of managed realignment is usually the cost of purchasing the land to be flooded. This may differ in developing countries where land prices are not so high and may already be owned by the state. Land costs can vary widely depending on the current landuse and as such, so too will realignment costs. As an example, agricultural land is usually less costly than land used for housing or industry, largely due to the presence of infrastructure. If land is used for housing or industry it may also be necessary to provide additional compensation for relocation.

Costs may increase further if it is necessary to dismantle human-made infrastructure present in the realignment zone. This may include structures such as buildings and roads, underground pipes for gas delivery or wires for electricity, internet or television, to name but a few.

Costs are likely to be lowest if existing defences are left to breach naturally. This saves money which would have been spent on the creation of artificial breaches. In Germany, the cost of realignment is seen as a major barrier to implementation of managed realignment, since the majority of the North Sea defences are in excellent condition (Rupp & Nicholls, 2002).

The scale of monitoring operations post-realignment will also influence costs. The more rigorous the monitoring schedule, the higher the likely costs.

Institutional and Organisational Requirements

Both planned and unplanned managed realignment could be achieved at the community level. Breaching or abandonment of defences is inexpensive and straightforward and is therefore unlikely to require the involvement of external organisations. However, in order to obtain the greatest benefits from managed realignment, implementation must be more carefully planned. Pre-implementation monitoring and modelling will help to determine the effect of managed realignment and will help to maximise the benefits.

To avoid unwanted consequences of managed realignment, detailed planning and pre-implementation modelling studies will be required. These studies will furnish decision makers with information on how the scheme is likely to function and whether the full range of benefits will be realised. Managed realignment schemes completed to date have used modelling to determine if alterations to the site before defence breaching, such as creek excavation or elevation raising, can encourage formation of beneficial features. Additionally, pre-implementation modelling will provide information on environmental changes caused by the scheme, such as changes to estuarine ebb/flood dominance. A higher degree of certainty regarding the behaviour of managed realignment sites can be gained through modelling but this activity is likely to require the involvement of external organisations.

It is essential that coastal managers involve stakeholders including local communities in the realignment planning process. Leggett et al. (2004) claim that effective stakeholder and local community engagement is essential to successful implementation of managed realignment schemes. They also claim participation can help to:

1. Understand legitimate concerns and interests
2. Explain and convince the local community of a scheme’s merits
3. Manage expectations
4. Develop stakeholder ownership

Barriers to Implementation

Barriers to implementation have only been investigated in developed countries; to date, managed realignment has only been applied in North-West Europe and North America. However, barriers which are relevant to developed countries will also have relevance in the developing world.

Rupp-Armstrong and Nicholls (forthcoming) investigated the main barriers to implementation of managed realignment in England, Scotland, the Netherlands and Germany. Their findings are summarised below:

A lack of public acceptance is the main barrier. It is thought that opposition is caused by the perception that loss of land is a retrograde step. Concerns over loss of land with high perceived property value and development potential may also contribute to a lack of acceptance (Leggett et al., 2004). Public acceptance may also be reduced by peoples' understanding of how the technology mitigates coastal flooding and erosion. In order to overcome this barrier, it is important to communicate the true advantages and disadvantages of the approach and fully engage stakeholders in the process of managed realignment.

The second most important barrier in the studied countries relates to farming communities. These groups are frequently affected by managed realignment which is mainly implemented on agricultural land. The main barrier in this case is a lack of adequate compensation for the loss of land. If sufficient compensation were available, many farmers would be more willing to sell their land (Rupp-Armstrong & Nicholls, forthcoming).

The potentially high cost of managed realignment also poses a barrier. An analysis of existing British schemes has shown an average cost of approximately US$97000 per hectare, for schemes involving the construction of a substantial new defence line. In addition, the relocation of infrastructure located in the managed realignment zone is potentially costly.

In other studies, legal and financial difficulties have been identified as a barrier to implementation. As previously stated, it is frequently the case that the process of managed realignment must deal with numerous coastal land owners who will be affected by the scheme. As a result there can be difficulties concerning the responsibilities and liabilities of certain land owners or authorities.

Availability of land is another significant barrier to implementation. The relocation of any infrastructure present in the realigned area requires land elsewhere. In densely populated coastal areas this may be very difficult.

As stated at the beginning of this chapter, managed realignment is not necessarily an option that can be applied in any location. Rupp-Armstrong and Nicholls (forthcoming) identified a number of criteria which are required in order to implement managed realignment. Firstly, the presence of low-lying land sheltered by existing coastal defences is an essential requirement. Without low-lying land, intertidal habitats will not be created and the full benefits of managed realignment will therefore not be realised. This must be coupled with the presence of a sustainability-oriented coastal management attitude and a societal willingness to entertain the notion of managed realignment. Without these conditions, managed realignment is either prevented from going ahead, or is likely to encounter further, significant barriers.

An extra barrier to implementation may be related to the existence of important or protected habitats behind existing coastal defences. Managed realignment can bring about detrimental impacts on such areas through tidal inundation. In the UK, coastal grazing marsh frequently occurs behind coastal defences. This environment is important for many plants, animals and endangered aquatic invertebrates. As such, coastal grazing marshes are of national and international importance for nature conservation. Managed realignment can lead to the destruction of such important habitats, causing negative impacts on the local environment.

Opportunities for Implementation

Managed realignment can be part of a 'strategic' shoreline management plan. These plans typically consider tens of kilometres of coastline in a holistic sense, and address a variety of needs within the targeted area. This approach is often seen as a desirable way to maximise benefits and overcome potential constraints (Leggett et al., 2004).

Managed realignment can also help recreate intertidal habitats lost through human development and SLR. In this way, provision for coastal defence may be made but not at the expense of important intertidal habitats. In some cases, legal obligations to offset previous and predicted losses of these habitats may exist – the managed realignment response could play a role in meeting these requirements.

Opportunities for the implementation of managed realignment may also occur as a result of more site-specific factors (Leggett et al., 2004). These may include, the opportunity to reduce defence maintenance costs, opportunity to create a new nature reserve and the availability of funding for realignment.

Case Study: Abbotts Hall Farm, Essex, UK

To date, we are unaware of any managed realignment in the developing world. Therefore, a European example is used here.

In 2002, a managed realignment scheme was undertaken at Abbotts Hall Farm in Essex, UK. The site had a total area of 0.84 km2 and had been protected from inundation by seawalls for more than 200 years (ABPMER, 2010b).

Managed realignment was pursued at the site with the primary objectives of flood defence cost reduction and intertidal and coastal habitat creation. These objectives were selected because the existing seawall was in a poor state of repair and because in the UK, coastal habitats are in decline.

Monitoring was carried out by the Environment Agency, English Nature and the Essex Wildlife Trust for three years prior to implementation. This helped ensure that the scheme design would achieve the desired results. Monitoring also provided a baseline for evaluating the effects of the project. Following realignment, a further five year monitoring programme was undertaken to assess the effects and provide information to aid the design of future schemes (Essex Wildlife Trust, 2003).

Pre-implementation monitoring included surveys of local hydrodynamics[12], bathymetry, water levels, currents, suspended sediments, salinity, temperature, water quality and the presence of plants, animals and birds (Essex Wildlife Trust, 2003).

For seven years prior to breaching, 0.2 km2 of the site had been subject to regulated tidal exchange[13]. This helped to facilitate a significant build up in the site's surface elevation and gave a 'head start' to both the ground conditions at the site and to the availability of suitable plants to initiate colonisation by intertidal species (Nottage & Robertson, 2005).

Realignment was conducted by creating five breaches in some 3 km of hard defences. The largest breach was 100 m wide with a level at approximately MHWN. The four remaining breaches were smaller in size, at 10-20 m width and higher levels (ABPMER, 2010a). No new defences were created as the naturally higher ground behind provided an adequate secondary defence (Environment Agency, 2003). It was necessary

---

[12] The study of fluids in motion.

[13] Regulated tidal exchange involves the use of pipes, culverts or sluice gates to allow regular tidal flushing and thus facilitates the creation of saline or brackish habitats behind sea walls (Sharpe et al., 2002).

to construct counter walls however, to prevent flooding of neighbouring land (Essex Wildlife Trust, 2010). A new creek system was also excavated to encourage saltmarsh formation (Essex Wildlife Trust, 2003).

Monitoring continued at the site post-implementation. This focussed on measuring accretion/erosion on and off site, scour within the breaches, bathymetry, tidal levels and velocities, suspended solids off site, salinity off site, invertebrates off site and vegetation, birds, fish, amphibians and reptiles within the newly created area (ABPMER, 2010b).

No major environmental impacts were observed outside of the managed realignment site (Environment Agency, 2003). This means the scheme has not negatively impacted the surrounding environment. By spring 2003 the site had been colonised by several pioneer saltmarsh species (Environment Agency, 2003) and by 2010, it has become a haven for birds and fish (ABPMER, 2010b).

The final cost of the project was US$7.7 million (at 2009 price levels) and was funded by the World Wildlife Fund (WWF) and the English Heritage Lottery Fund. The scheme has been considered a success as the objectives of flood defence, cost reduction and coastal habitat creation were all realised and confirmed by monitoring results. The length of flood defences at the site were reduced by 87% and approximately 0.4 km2 of saltmarsh, 0.35 km2 of coastal grassland and 0.09 km2 of mudflat have been created (ABPMER, 2010b). In addition, large numbers of birds and fish now living in the area indicate that the habitat has been successfully created (Essex Wildlife Trust, 2010).

4.3.2 Coastal Setbacks

Definition

Coastal setbacks are ‘a prescribed distance to a coastal feature such as the line of permanent vegetation, within which all or certain types of development are prohibited (Cambers, 1998). A setback may dictate a minimum distance from the shoreline for new buildings or infrastructure facilities, or may state a minimum elevation above sea level for development. Elevation setbacks are used to adapt to coastal flooding, while lateral setbacks deal with coastal erosion (see Figure 4.30).

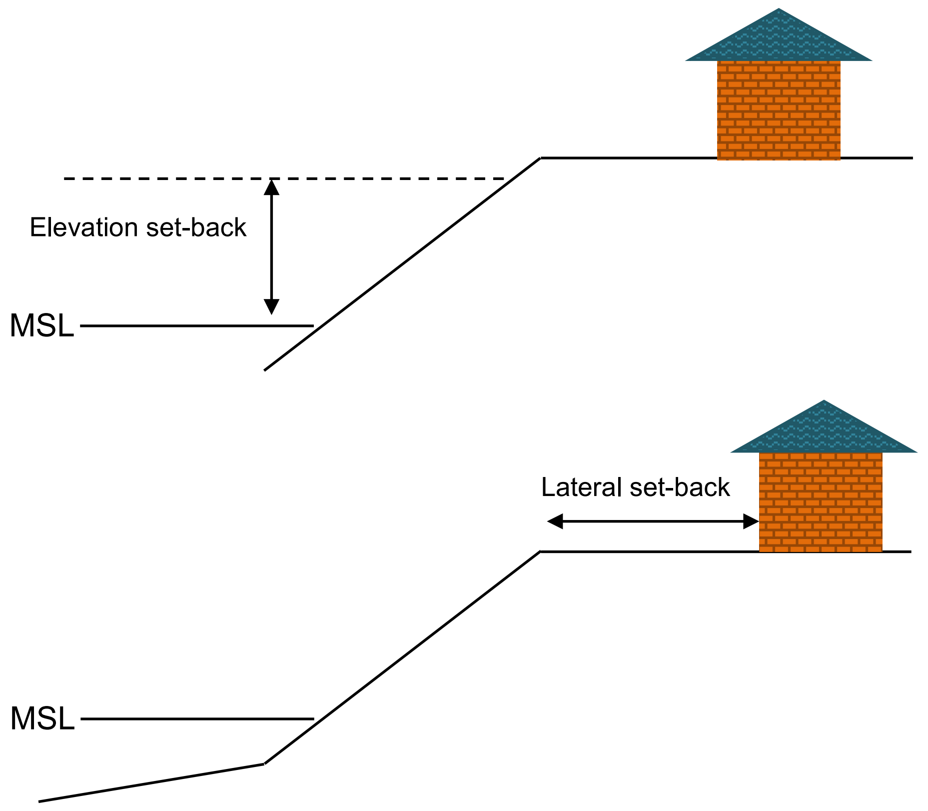
Description

The ‘setback’ area provides a buffer between a hazard area and coastal development (Fenster, 2005). The idea is to allow room for the average high water mark to naturally move inland by SLR throughout the economic lifetime of the property. Setbacks provide protection to properties against coastal flooding and erosion by ensuring that buildings are not located in an area susceptible to these hazards. Two types of setback can be distinguished; elevation setbacks to deal with flooding and lateral setbacks to deal with erosion (see Figure 4.30).

The approach allows erosion to continue along strategic sections of coast while further development is restricted. This allows eroded sediment to be transported to areas alongshore, thus enhancing the level of protection afforded by helping to maintain wide, natural beaches. By managing the coast in this natural state, adjustments by the coastline to changing conditions such as SLR can be made without property loss (Kay, 1990).

Setback distances are determined either as: (1) a fixed setback which prohibits development for a fixed distance landward of a reference feature; or (2) a floating setback which uses dynamic, natural phenomenon

Figure 4.30: Types of coastal setback



Elevation setback (top) to cope with coastal flooding and lateral setback (bottom) to cope with coastal erosion

to determine setback lines and can change according to an area's topography or measurements of shoreline movement (Fenster, 2005).

Control of development is achieved either by defining a linear exclusion zone along the whole of an administrative unit, or by specifying distinct coastal exclusion zones (Kay, 1990). Ideally, setbacks should be established based on historic erosion rates or extreme water levels rather than adopting arbitrary distances which do not truly represent the threat from erosion or coastal flooding.

Setback policies are widely used across the world; schemes have been implemented in many countries including Canada, Barbados, Aruba, Antigua, Sri Lanka, USA, Australia (McLean et al., 2001), Denmark, Germany, Norway, Finland, Poland, Spain, Sweden and Turkey (Fenster, 2005).

Advantages of Coastal Setbacks

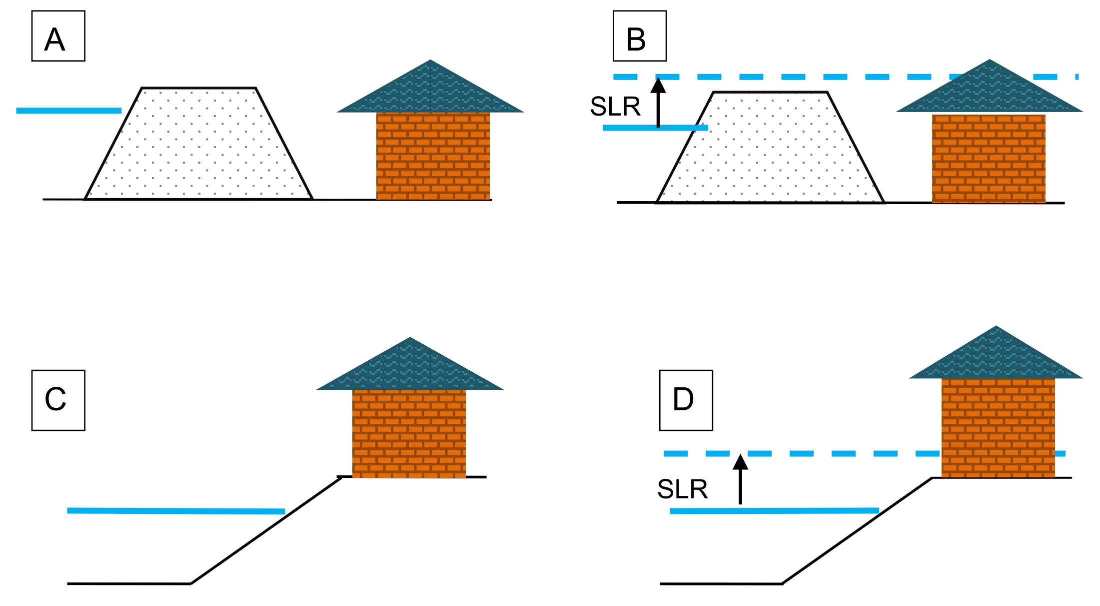
Setbacks provide a highly effective method of minimising property damage due to coastal flooding and erosion, by removing structures from the hazard zone. They provide a low-cost alternative to shoreline erosion or flood protection works such as seawalls or dikes which have their own disadvantages (see Sections 4.1.2 and 4.1.4 respectively).

Unlike hard structures, setbacks help to maintain the natural appearance of the coastline and preserve natural shoreline dynamics (NOAA, 2010). This allows natural erosion/accretion cycles to occur (Fenster, 2005) and helps to maintain the local sediment budget. Enhanced downdrift erosion as observed when using hard defences is also less likely to occur. As such, setbacks can contribute significantly to sustainable management of coastal systems (Fenster, 2005).

Setbacks also help to maintain shoreline access by preventing development immediately on the seafront (NOAA, 2010) as well as providing open space for the enjoyment of the natural shoreline. Coastal setback zones are commonly promoted as open public recreational space and they can also provide recreational and beach access.

Minimum elevation setbacks also provide higher levels of protection when compared to hard defences. For example, if a water level in excess of the design standard occurs, an elevation setback will result in shallower and less extensive flooding of developed areas than would occur if hard defences were employed instead; this is shown in Figure 4.31.

Figure 4.31: Differing flood impacts after failure of structural defences and setbacks



In the event of a flood event in excess of design standard, vertical setbacks lead to shallower, less extensive flooding

Source: Linham et al., 2010

Disadvantages of Coastal Setbacks

Over time, SLR will reduce the size of the buffer zone between structures and the sea. As a result, setbacks will need to be periodically reviewed to ensure that buffer zones continue to provide sufficient protection; in the US states of South Carolina and Florida, setback distances are reassessed every 10 years (Healy & Dean, 2000).

It is important to emphasise that the establishment of setback does not guarantee that the coast in question will be shielded from strong storms and the associated coastal flooding and erosion (Healy & Dean, 2000). As with all coastal adaptation measures, residual risk will remain, meaning that the protected areas are still subject to some risk in the case of an event larger than the measure can cope with. More cautious measures can be taken to reduce residual risk.

Problems may arise as a result of setback review. For example, reviews may reclassify coastal areas as no-build zones. This could create conflict if these areas have already been purchased with development in mind. Secondly, revision of the setbacks may mean existing structures are now within the buffer zone. Typically, these structures would be allowed to remain, but if significantly damaged or destroyed by a storm, they would usually be required to be reconstructed in line with the new setback line. In both these instances, compensation may be required for land owners who have lost development potential or have experienced physical loss of property (NOAA, 2010).

Good quality scientific or historic data are required to establish setbacks according to coastal flood or erosion threats. Such data is not always readily available, especially in developing countries where monitoring programmes are less well established. In the absence of such data, it is possible that setbacks established either provide too little protection or are too restrictive of shoreline development (Fenster, 2005).

Setbacks do not serve to protect existing structures in the hazard zone. If these are to be protected, other adaptation approaches are required. Additionally, setback policies only serve to prolong the lifetime of structures built on the shoreline. With continued shoreline erosion or SLR, another shoreline policy will eventually be needed if these structures are to be preserved (NOAA, 2010).

Costs and Financial Requirements

Again, the costs of implementing a coastal setback approach will be variable, depending on local conditions. A number of costs will be incurred when implementing setback in any situation. They are discussed below.

Firstly, a decision must be taken as to how far to set back. Costs involved in taking this decision include the collection and analysis of historic erosion rates or water levels, the cost of modelling likely shoreline evolution, and the associated cost of buying in modelling services and expert consultation. The cost at this stage will vary depending on the method used to determine setback distance. Less technical solutions are likely to be cheaper.

Secondly, the setback policy must be communicated to relevant bodies in order that the policy is taken into account in the planning process. Costs involved at this stage may also involve the additional costs of incorporating coastal setback into local planning policies.

Finally, enforcement is essential. The cost of enforcement may however be low as it is possible to enforce setback via pre-existing local planning bodies.

Additional costs may be incurred if private landowners are required to be compensated for loss of development potential and also when the setback distance undergoes periodic review.

Coastal setbacks are generally accepted to be an inexpensive solution. In a study by Shows (1978), engineering costs of installing a coastal setback line in Florida, USA, were estimated to be US$11,700/

km with mandatory five-year reviews expected to cost US$23,000/km. Annual administrative costs were estimated at approximately US$4,800/km (costs converted to 2009 prices) (Shows, 1978).

Implementation of a setback policy is likely to have the lowest costs when implemented proactively, before significant, inappropriate development occurs. In this way it should be possible to minimise compensatory payments to private landowners.

Institutional and Organisational Requirements

In order to implement setbacks as an adaptive response to climate change, it is necessary to implement the measure proactively. Because of the largely predictable nature of coastal erosion and the long lead times involved in SLR, planning policies can be put in place now to restrict inappropriate development which would be susceptible to coastal flooding or erosion in future (Kay, 1990).

In the past, hard defences have been employed, sometimes for political reasons such as wanting to be ‘seen to be doing something’. A proactive setback policy must bear this political factor in mind by stressing the acceptability of a setback policy via a full coastal research and monitoring programme, together with public education and participation schemes (Kay, 1990).

It should be relatively straight forward to implement setbacks at a local level. The approach can be incorporated into pre-existing land-use planning regulations and building codes, where these exist. If a meaningful rather than arbitrary setback is to be employed however, factors such as the coast type, presence of physical defences and the influence of coastal processes must be accounted for (Sanò et al., 2010).

In addition to the differences in the type of setback which may be used, variations exist with respect to how setbacks are administered and who administers them. The technical standards for establishing setbacks vary widely in practice (Fenster, 2005).

Although setbacks distances may be best informed when based on the findings of scientific models[14], defining a setback need not be a highly scientific endeavour. Arbitrary setbacks require less advanced technology and therefore, may be more usable on a local scale. Even using high technology, the degree of uncertainty in assigning a setback is significant. Therefore, investing heavily in high-tech modelling solutions which provide more accurate setbacks may still be misguided. Ultimately, it is preferable to be conservative (Healy & Dean, 2000) although this can lead to implementation of sub-optimal setback distances.

Barriers to Implementation

One of the most significant barriers to the implementation of setbacks, is public opposition. This is especially likely to be the case if the public believe setbacks are too large or, in the case of individual landowners, if their land packets fall within the new restricted development zone. In this case it is important to communicate the need for large setbacks to the public. Compensating private landowners for lost development potential is also likely to make implementation smoother.

---

[14] The SCAPE model (Walkden & Hall, 2005) predicts shoreline erosion based on the type of material the coast is composed of, wave conditions and other forcing factors. CLIFFPLAN (Meadowcroft et al., 1999) is another process-based simulation model for cliff erosion

Setbacks may also be opposed by residents who are now deemed to live within the new building exclusion zone. Although in most cases, structures will be allowed to persist within the no build zone, restrictions may be placed upon rebuilding in the event of damage or destruction during storms. In most cases, it is accepted practice that reconstruction or significant modifications to structures within the exclusion zone are not permitted.

Retroactive application of coastal setbacks is unlikely in a number of cases: (1) coastal cities and urbanisations, (2) industrial areas and uses associated with maritime activities and, (3) traditional developments integrated with the coastal landscape (Sanò et al., 2010). This may prove a barrier to the effectiveness of coastal setbacks because coastal vulnerability remains for those who are allowed to persist in the hazard zone.

In order to implement effective and meaningful setbacks, information on historic erosion rates or extreme water levels is required. Without this information, creation of effective setbacks is problematic. It is also recommended that coastal process-based models be used to help predict long-term shoreline evolution. In order to operate these models, a degree of expertise is required. Although setback may be more effective when these approaches are used, it is nevertheless possible to implement setbacks in their absence, using conservative but more arbitrary setback distances.

In many coastal areas, there is pressure to develop the coastal zone, especially when attempting to encourage tourism. As a result, coastal regulations are often ineffective and developments within the exclusion zone proceed regardless (Sanò et al., 2010).

Opportunities for Implementation

A significant opportunity for the implementation of setbacks lies in the potential to tie the policy in with existing land use and building regulations. There is potential for the same bodies that regulate building standards and planning permissions to ensure that new developments do not occur within the setback zone.

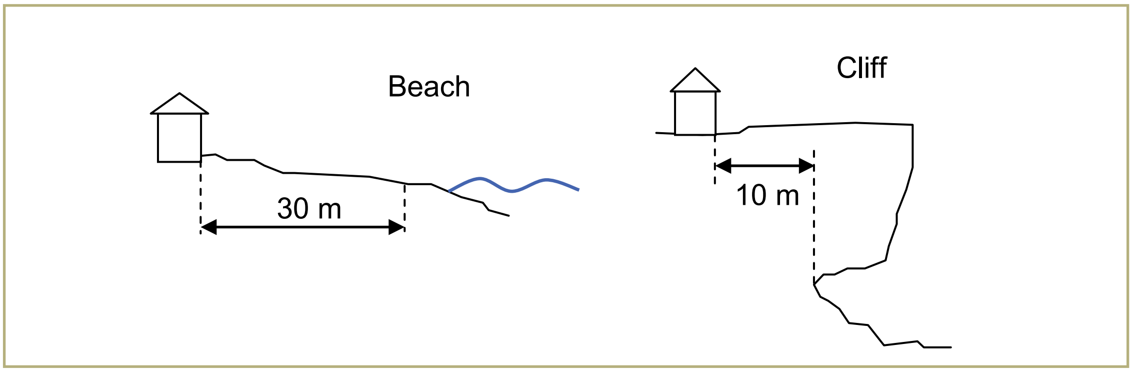
Setbacks can also be implemented in combination with complementary schemes such as sand dune reconstruction (Section 4.1.2) or wetland restoration (Section 4.2.2). Setbacks would ensure that these environments are given sufficient space to develop and adapt to climate change. This provides the double benefit of maintaining natural protective features, as well as providing a buffer zone against coastal flooding and erosion.

Case Study: Barbados, Caribbean Islands

The Caribbean island of Barbados has used coastal setbacks as a regulatory measure for development in the coastal zone for the past 30 years. Coastal setbacks in the country are supported by the Town and Country Planning Act, the Coastal Zone Management Act and the Integrated Coastal Management Plan.

Two setback distances are used on the island. Along sandy beaches, buildings are required to be a minimum of 30 m from the Mean High Water Mark (MHWM). In the case of development on coastal cliffs, there is a minimum setback distance of 10 m from the cliff edge. When the cliff is cantilevered, the setback is measured from the most landward location of the undercut portion of the cliff, not from the cliff edge. This is illustrated in Figure 4.32.

Figure 4.32: Setback distances employed in Barbados



Source: CZMU, 2005

In some special cases, these setbacks can be increased when rare, threatened or endangered ecosystems, or important historical or archaeological sites exist. Such features may include mangroves or turtle nesting sites, to name but two. Conversely, decreases in the setback extent may occur where there are existing buildings already within the exclusion zone (CZMU, 2010).

The adoption of fixed setbacks has simplified the process of implementing this measure for the whole island. However, they have also been criticised because they do not consider the historical nature of specific beach erosion trends (Daniel & Abkowitz, 2005). Also, the use of the MHWM as the baseline for measurement of setbacks can create problems because the position of this marker varies from day to day. Consequently, planners and developers may have different interpretations of the setback limit (Mycoo, 2006).

The setback distance has also been questioned, because properties may still by inundated during tropical storms and hurricanes. The distance adopted in Barbados is much smaller than in the neighbouring Caribbean island of Nevis, which requires major hotel structures to be located at least 91 m from the high tide mark (Mycoo, 2006). In Jamaica, where a 30 metre setback was also implemented, flood hazard mapping studies highlighted the fact that this distance was insufficient for provision of flood protection (see Section 4.2.4).

However, it is clear that setting coastal setbacks is a tricky task which requires the advantages and disadvantages to be carefully evaluated. Setbacks do utilise a large area of highly priced coastal land. This is particularly important in Barbados and other Caribbean islands because of the importance of the tourism industry and the consequent need for coastal hotels and accommodation. Developers often object to setbacks because they think that insurance would cover impending property damage (Mycoo, 2006). Additionally, large and strict coastal setbacks can mean that governments lose much needed tax revenues from prime beachfront properties if development is not allowed in these areas (Mycoo, 2006). For a developing country, this may be particularly troubling.

Nevertheless, setbacks have still been beneficial in Barbados. They help to preserve the coast's natural capacity for protecting against extreme events, preserve natural coastal landscapes, protect informal recreation areas and help to conserve the island's biodiversity.

4.4 Knowledge and Capacity Building Requirements

This section discusses the knowledge and capacity building requirements associated with the 13 adaptation technologies discussed in this guidebook, as there are similarities between requirements for the different technologies.

Table 4.12: Essential and secondary knowledge requirements for the 13 adaptation technologies discussed

■	Essential
▨	Secondary
☐	Irrelevant

	Beach Nourishment	Artificial Dunes & Dune Rehabilitation	Seawalls	Sea Dikes	Storm Surge Barriers & Closure Dams	Land Claim[1]	Flood Proofing	Wetland Restoration	Floating Agricultural Systems	Flood Hazard Mapping	Flood Warnings	Managed Realignment[2]	Coastal Setbacks
RSLR scenarios	▨	▨	■	■	■	■	■	▨	▨	■	▨	▨	▨
Extreme water levels[3]	▨	■	■	■	■	■	■		▨	■			▨
Wave climate[3]	■	■	■	■	■	■	■	■		■	▨	■	▨
Nearshore bathymetry	■	■	■	■	■	■	■	▨		■	■	▨	▨
Tidal regime[4]	▨	▨	▨	▨	▨	▨	▨	■	▨	▨	▨	■	▨
Historic flood information	▨	▨	▨	▨	▨	▨	▨	▨		▨	▨	▨	▨
Land cover										■	■	▨	▨
Coastal topography							■	■		■	■	■	▨
Level of coastal protection							■			■	■		▨
Settlement[5]	▨	▨	▨	■		■							
Sediment characteristics	■	■	▨	▨	▨	▨		■				■	
Availability of suitable dredge sites[6]	■	■[7]				■[8]		▨				▨[9]	
Local sediment budget	■	■	▨	▨	▨	▨		▨				▨	
Desired dry beach width	■	▨											
Historic erosion rates	■												■[10] ▨
Historic habitat distribution & cause of decline		■						■				▨	
Vegetation	▨	■						■				■	
Floodwater velocity							■			▨	▨		
River discharge[3]					■[11]						■		
Meteorological observations/forecasts					■[11]						■		
Effective warning dissemination											■		
Warning threshold					■[11]						■		
Construction of floating beds									■				
Cropping patterns									■				

Table Notes

1 Hard defences are likely to be employed on the seaward edges of the claimed land. There will be a number of other essential and secondary knowledge requirements associated with these defences.

2 The knowledge requirements associated with managed realignment schemes vary depending on the objective of realignment (e.g. coastal defence, habitat creation, etc.).

3 Present and future conditions, as appropriate.

4 Due to normal tides as opposed to extreme water levels.

5 Of the structure or its environs.

6 Dredge sites to source suitable material.

7 If providing artificial nourishment.

8 If undertaking land claim by elevation raising.

9 If elevation raising is required.

10 Arguably, this should be essential in the selection of a setback distance, but the survey of literature indicates otherwise.

11 As part of a flood warning system.

Knowledge requirements can be sub-divided into essential and secondary requirements. Knowledge of essential requirements is crucial if a project is to be successful. Secondary requirements are not so fundamental, although knowledge of these factors will improve project performance to some degree and could also help to minimise the impact of adaptations on the local environment. The knowledge requirements are shown in Table 4.12 and are discussed in more detail below.

4.4.1 Knowledge Requirements for Protect Approaches

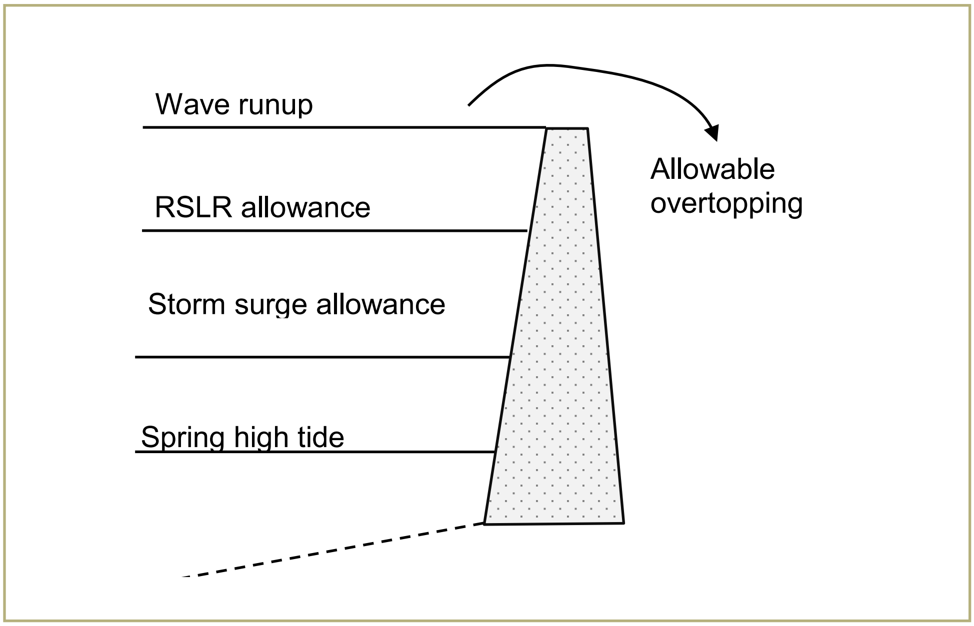
Of primary importance to all protection approaches is the need for knowledge of RSLR scenarios[38]. This is not surprising given that these technologies are primarily aimed at adapting to SLR and coastal erosion. This knowledge will allow climate change considerations to be built into the initial design of an adaptation project. This is beneficial because designing and building a robust system which offers sufficient protection from the beginning, is also less expensive than building a less robust system which requires periodic upgrades to cope with climate change.

Accounting for RSLR is especially important for technologies implemented within estuarine and deltaic environments. Due to the presence of relatively young and uncompressed sediments in these environments, estuaries and deltas are particularly susceptible to accelerated RSLR due to non-climate causes.

Knowledge of extreme water levels is also of importance so that hard and soft engineered structures are constructed with sufficient crest height in order to minimise overtopping to acceptable levels. Crest heights must account for both hydrostatic20 and hydrodynamic21 water levels (see Figure 4.33). Acceptable levels of risk are likely to be based on the land use behind the defence and hence, this judgement is likely to vary widely (see Pullen et al. (2007) for guidance).

The most extreme water levels are likely to occur during the joint coincidence of spring high tides and meteorologically induced storm surges caused by low atmospheric pressure and wind set-up (Pugh, 1987). Based on the joint probabilities, a series of water levels against return period can be determined. Ideally, this will be derived from the series of sea level but these are generally not available. When this is so, models must be used to make estimates. In order to make these estimates, knowledge of an area's tidal regime is important, as is knowledge of historic flood events. In general, design for water levels is conservative because underestimating water levels can lead to catastrophic failure (Kamphuis, 2000).

Figure 4.33: Contributing factors to the design water level and required crest height of a hard defence



An area's wave climate also contributes significantly to extreme water levels, as shown in Figure 4.33. In turn, wave climate can be significantly affected by nearshore bathymetry. For hard engineered structures, wave climate is a key determinant of the loadings to which structures are subjected – structures must be robust enough, and construction materials have sufficient mass, to prevent damage or removal during storm events. Larger waves are associated with increases in wave loadings, run-up and overtopping which must all be factored into the initial design.

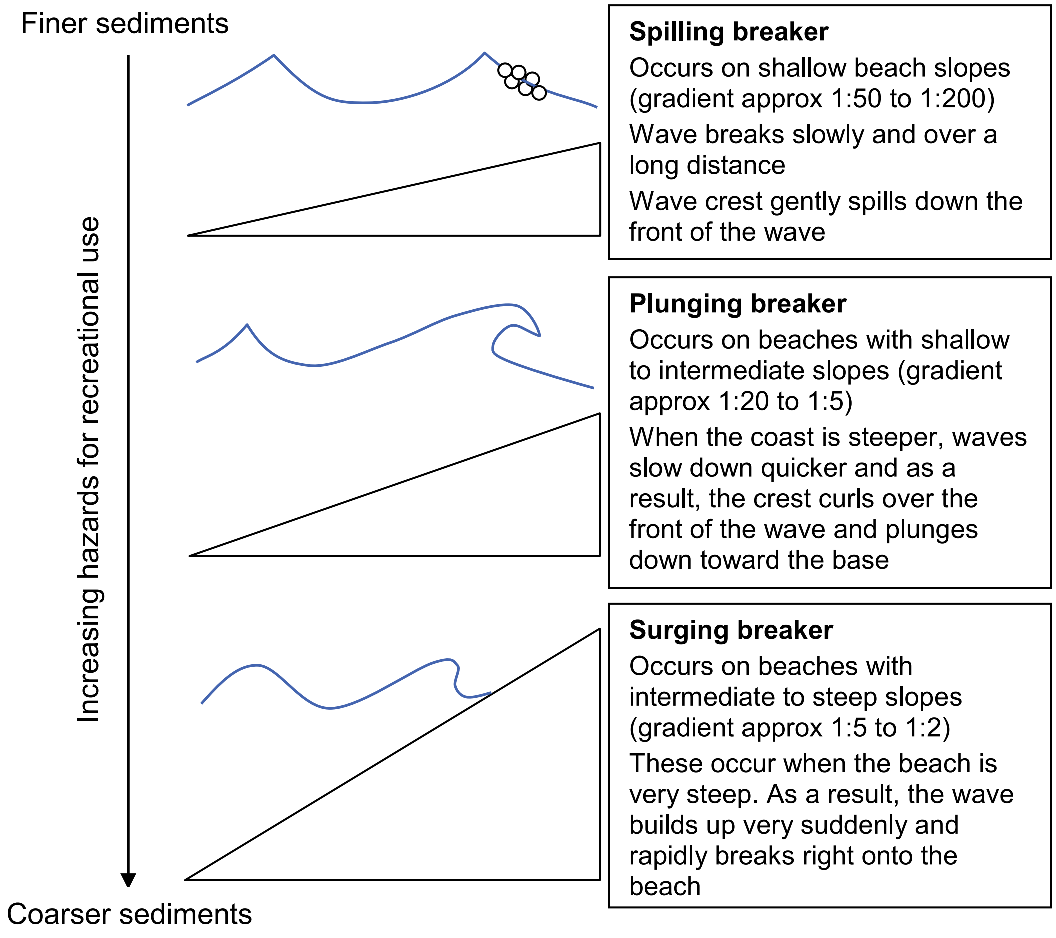
For soft engineered structures, such as nourished beaches and dunes, wave climate is a primary influence on sediment redistribution and potential erosion rates. More energetic wave climates cause sediment movement to greater depths (Hallermeier, 1981; Nicholls et al., 1998); meaning that material added to beaches with more energetic wave climates will be redistributed over a greater area. Hence, greater volumes of material may be required. The direction of wave approach is important as a major contributor to rates of longshore drift. This process is important for sediment budgeting and will allow long-term beach changes to be calculated (CIRIA, 1996).

Generally speaking, wave climate observations are extremely limited so knowledge of wave climate is most likely to be achieved by extrapolation and/or modelling. Changes of wave climate due to climate change are in the early stages of development and unlikely to be available for design purposes. One factor which could be considered is the effect of SLR on depth limited waves. SLR may causes waves to increase in height, hence, this needs to be investigated.

Settlement is potentially important in assessing structure height in relation to extreme water levels. Settlement here refers to the distortion or disruption of parts of a defence structure during or after construction. This causes a reduction in the level of protection offered against extreme water levels. It can occur in both hard and soft engineered structures and where this it is expected to occur, an allowance should be incorporated into the project design. Settlements may occur in either the adaptation structure itself, for example, a dike, dune or nourished beach, or in the subsoil on which the structure is situated. The phenomenon is heavily influenced by the sediment characteristics of the project site.

Knowledge of an area's sediment characteristics is also important for soft engineered adaptations which require the addition of sediment to a beach, i.e. beach nourishment and dune construction. When undertaking these projects, it is important to maintain the local character of a site by adding sediment of similar grain size, composition and colour. In areas which are important for tourism, sediment characteristics are also important because coarser sands are less popular for tourism and are associated with more dangerous breaking wave types (see Figure 4.34) and an increased frequency and intensity of rip currents, which are dangerous and highly undesirable on recreational beaches (Reeve et al., 2004). Sand grain size and colour are also important for maintaining the ecological conditions[15] of the beach. Most frequently, grain sizes slightly larger than the native material are used because coarser materials increase project longevity.

Figure 4.34: Beach slopes and wave breaker types



Spilling breaker

Occurs on shallow beach slopes (gradient approx 1:50 to 1:200)

Wave breaks slowly and over a long distance

Wave crest gently spills down the front of the wave

Plunging breaker

Occurs on beaches with shallow to intermediate slopes (gradient approx 1:20 to 1:5)

When the coast is steeper, waves slow down quicker and as a result, the crest curls over the front of the wave and plunges down toward the base

Surging breaker

Occurs on beaches with intermediate to steep slopes (gradient approx 1:5 to 1:2)

These occur when the beach is very steep. As a result, the wave builds up very suddenly and rapidly breaks right onto the beach

Illustration of breaker types, their associated characteristics and the environments in which they occur. Finer sediments lead to the creation of shallower slopes which are associated with safer breaking wave types

Source: Adapted from Coastal Carolina University (2010) Oceans in Motion: Waves and Tides. Carolina: Kingfish. Available from: HYPERLINK "https://risowa.risoe.dk/exchweb/bin/redir.asp?URL=http://kingfish.coastal.edu/biology/sgilman/770Oceansinmotion.htm" \t "_blank"http://kingfish.coastal.edu/biology/sgilman/770Oceansinmotion.htm [Accessed: 07/07/10].

---

[15] Sand colour can affect incubation temperatures for nesting sea turtles while grain size can affect compaction of sediments and hence, suitability for nesting.

If adaptation involves artificial addition of sediment to a coastline, identification of potential sediment sources is highly important. Suitable dredge sites must contain a sufficient volume of sediments which are not dissimilar to the native beach material, must be in reasonable proximity to the nourishment site to minimise transportation costs, must not contain unacceptable levels of contamination and must not cause detrimental environmental impacts at the borrow site. The borrow site must also have bathymetric characteristics which make it suitable for dredging.

Before suitable dredge sites can be identified, the required volume of fill material needs to be estimated. An understanding of the local sediment budget will inform borrow site selection and will also help to quantify the inflows and outflows of sediment on a coastline (see Section 4.1.1). This will, in turn, help to calculate the volume of sand required to maintain a given beach width and volume. The required beach width and volume is likely to be influenced by the desired dry beach width and historic erosion rates.

An understanding of the local sediment budget is a secondary requirement for most hard engineered protection measures. This is because hard coastal protection measures prevent erosion of the shoreline and as such, eliminate sediment input into the local sediment budget. This can, in turn, cause sediment deficits and consequent erosion on adjacent stretches of coast. A thorough understanding of the local sediment budget is likely to promote more holistic management of the coastal zone and may encourage sympathetic design of coastal structures.

Finally, when undertaking dune planting, knowledge of the native vegetation is important in order to avoid planting non-native species which can have detrimental ecological impacts on an area. Non-natives can also disrupt the local character of an area. This is required during beach nourishment, only when vegetation planting is used to stabilise the nourished beach. For dune rehabilitation, an understanding of the historic habitat distribution and cause of decline is also valuable because if adaptation is confined to repair and reconstruction, without tackling the cause of decline, problems will re-occur.

4.4.2 Knowledge Requirements for Accommodate Approaches

Key to applying accommodation approaches to coastal adaptation is the determination of areas which will be at risk of flooding and hence, where accommodation measures need to be implemented. RSLR scenarios are important to all accommodate technologies either as an essential or secondary knowledge requirement. This knowledge allows adaptations to be designed to cope with expected changes in relative sea level, helps to assess the changing nature of flood risk into the future and also helps to assess whether specific projects are feasible. For example, wetland restoration would not be viable if RSLR is expected to outpace a wetland's ability to accrete sediments.

Knowledge of extreme water levels will also help to determine those areas at risk of flooding. As stated in Section 4.4.1, extreme water levels are likely to occur during the joint coincidence of spring high tides and meteorologically induced storm surges caused by low atmospheric pressure and wind set-up (Pugh, 1987). As such, knowledge of an area's tidal regime is important for determining the level of high tides, wave climate and nearshore bathymetry is important in establishing wave run-up heights and historic flood events are useful in ascertaining potential flood depths. This information is likely to feed into a flood risk model as discussed in Section 4.4.1.

In order to determine which areas are at risk of flooding, information on coastal topography is required. This is likely to be combined with knowledge of potential extreme water levels and wave heights. This will help to map how high waters are likely to move inland.

In order to determine the likely inland extent of a storm surge, it is also necessary to have knowledge of the local level of coastal protection and land cover. For example, in the presence of natural or artificial coastal defences, flood waters will be prevented from travelling inland. Hence, knowledge of the locations of flood defences and of the level of protection offered are essential for effective flood-proofing, flood hazard mapping and flood warning technologies. Land cover is important in determining both flood mechanisms and extent, and the assets that might be impacted.

Once the potential inland extent and depth of flooding has been estimated, knowledge of potential floodwater velocities is also likely to be useful. Water velocity is important because high velocities can be damaging to buildings and threatening to life. An understanding of potential floodwater velocities will help to appropriately flood-proof buildings, for example, ensuring structures are properly anchored and that walls are capable of resisting flow velocities. Where high velocity flows are a risk to human life, this information may help to map flood hazards and may be an important factor in the issuance of flood warnings.

Flood warning systems have a number of specific knowledge requirements. Firstly, meteorological observations are required as an input into numerical, predictive models of flood risk. This information must be received rapidly to be of significant use. Forecasting capabilities are then required, to forecast how meteorological conditions are likely to interact and to predict the likely extent and severity of a flood event. Meteorological observations which are likely to be required include water levels, wave heights and river flows. River discharge is obviously only required where a river is present. In the case of movable barriers and closure dams, structure designs should account for peak river discharge. Scenarios of change in response to climate change should also be accounted for in the design.

Once a flood warning system is capable of detecting flood threats, there is also a requirement to identify a threshold for warning those at risk. It is important to strike a balance between offering sufficient warning time and minimising the risk of issuing false alarms. This is followed by warning dissemination which requires identification of the most effective communication channels in order to notify the largest possible number of people in the hazard zone.

Wetland restoration also has a number of specific knowledge requirements. This is largely because these habitats only occur in the presence of sheltered to moderate wave climates and in the presence of specific sediment characteristics, i.e. continued accretion of fine, organic sediments. Furthermore, wetlands only establish within a specific part of the tidal frame, between the lowest and highest astronomical tides. As such, knowledge of both the tidal regime and coastal topography of an area is important. This knowledge will inform coastal managers whether wetlands will become established. Areas where the coastal topography is too low or high can be engineered to encourage intertidal habitat creation, hence a secondary knowledge requirement for suitable dredge sites.

When planting wetland vegetation, knowledge of the native vegetation is also important because the type of wetland which naturally develops, depends on the geographic location and environmental conditions. For example, mangroves only occur along sheltered tropical and subtropical shores and estuaries (Alongi, 2002), while saltmarshes occur in temperate and high-latitude estuaries (Allen & Pye, 1992). There are also numerous wetland subcategories; more than 50 species of mangrove exist worldwide (Woodroffe, 2004) and a multitude of saltmarsh species which are all adapted to specific conditions such as the duration of tidal inundation, salinity, nutrient levels and available oxygen. An understanding of the historic habitat distribution and cause of decline is also beneficial as this will help to identify areas where these environments once existed and hence, where conditions may be appropriate for reinstatement. It will also help to address the cause of habitat loss and hence, tackle the cause of decline. Finally, an understanding of the local sediment budget is likely to prove beneficial as wetland restoration projects have the potential intercept sediment supplies, therefore negatively affecting adjacent shorelines. Knowledge of the local sediment budget may therefore, help to mitigate detrimental impacts.

Finally, floating agricultural systems have very specific knowledge requirements which include knowledge of cropping patterns and of the methods of constructing floating beds. At present, many communities are unaware of the ability to grow crops on floating beds. Therefore, they have no idea how to construct these beds. By providing training and technical support to local communities, knowledge of how to construct beds can be established. This knowledge can then be shared within communities and with neighbouring areas as well as being passed down through generations over time. Additionally, because floating agriculture allows the cultivation of plants out of season and also of plants which may be unfamiliar to traditional farmers, knowledge should be provided on suitable crops and when they should planted and harvested.

4.4.3 Knowledge Requirements for Retreat Approaches

RSLR scenarios are a secondary knowledge requirement for both managed realignment and coastal setbacks. By incorporating RSLR into the design of these adaptations, their effectiveness can be maintained throughout the lifetime of the project. For managed realignment, RSLR scenarios allow coastal managers to determine whether wetland creation is viable or whether RSLR is expected to outpace a wetland's ability to accrete sediments.

Knowledge of extreme water levels is also of use, in order to determine areas at risk of flooding through combining this information with coastal topographical data. This can be used to inform decisions on the required size of a setback. An understanding of extreme water levels can be obtained through modelling studies as detailed in Section 4.4.1. To undertake such studies, data on tidal regime, wave climate, nearshore bathymetry and historic flooding is likely to prove beneficial. This can then be combined with information on coastal topography, land cover and the level of coastal protection in order to determine the potential inland extent of flooding, as detailed in Section 4.4.2.

In addition to determining areas at risk of flooding, coastal setbacks require additional knowledge on historic erosion rates and sediment characteristic in order to be most effective. It is possible to extrapolate historic erosion rates into the future in order to estimate future erosion. It is also possible to project these values upwards to allow for accelerated SLR. The local sediment characteristics are closely linked to erodibility – this information contributes to our understanding of historic and future erosion rates.

There are several more knowledge requirements for effective managed realignment projects. Because the greatest benefits of realignment are gained when intertidal habitats are encouraged to form, we must understand whether a realignment site is likely to support the development of these habitats. For example, wetlands have specific requirements with regards to wave climate, sediment characteristics, coastal topography and tidal regime. Without these specific conditions, these habitats are unlikely to emerge. See Section 4.4.2 on wetland restoration for more details. There is a secondary knowledge requirement for suitable dredge sites if project sites require engineering in order to encourage the formation of intertidal habitats. In addition, knowledge of the coastal topography will inform decisions on whether or not a new coastal defence is required at the rear of a managed realignment scheme.

Knowledge of the historic habitat distribution and cause of decline, the local sediment budget and native vegetation is also likely to prove beneficial to managed realignment projects, see Section 4.4.2 on wetland restoration for further details.

4.4.4 Sources of Knowledge

Each of these knowledge requirements can be satisfied using the potential sources of knowledge outlined in Table 4.13.

Table 4.13: Potential sources of knowledge for the knowledge requirements outlined in Table 4.12

Knowledge Requirement	Potential Source of Knowledge
Relative SLR	- Downscaled climate scenarios
Extreme water levels	- Tide gauge records - Numerical modelling
Wave climate (present & future)	- Wave buoys - Wave hindcasting[1] - Remote sensing[2]
Nearshore bathymetry[3]	- Nautical charts - Single-beam echo sounder - Multi-beam echo sounder - Differential GPS (dGPS) - LiDAR (shallowest depths)
Tidal regime	- Admiralty tide tables - Field measurements - Tide gauges
Potential flooding	- Historic flood records - Anecdotal evidence[4] - Numerical modelling
Land cover	- Aerial photographs - Ground level photographs - Remote sensing - Field surveys
Coastal topography	- Total stations[5] - Terrestrial laser scanner - Differential GPS (dGPS) - LiDAR
Level of existing coastal protection	- Local survey - Aerial photographs - Engineering judgement - Fragility analysis
Settlement	- Geotechnical investigations
Native sediment characteristics	- Sample analyses
Availability of suitable dredge sites	
- Sediment grain size	- Core boring collection - Sand testing and analysis
- Proximity	- Area maps
- Environmental impacts	- Environmental Impact Assessment
- Dredge site characteristics	- Sub-bottom profiling[6] - Side-scan sonar[7] - Bathymetric mapping[8]

Knowledge Requirement	Potential Source of Knowledge
Local sediment budget	- Sediment budget analysis (See CIRIA, 1996)
Desired dry beach width	- Design decision
Historic erosion rates	- Historic maps - Aerial photographs - Nautical and topographic maps
Historic habitat distribution and cause of decline	- Historic maps - Aerial photographs - Anecdotal evidence
Native vegetation	- Biological survey
Floodwater velocity	- Numerical modelling
River discharge	- River gauging stations (present) - Scenarios (future)
Meteorological observations: - Rainfall - River discharge - Wind speed - Tidal levels - Atmospheric pressure - Wave heights	- Surface observatories, gauges and sensors - Weather balloons - Remote sensing[2] - External organisations (such as NOAA and WMO observations
Meteorological forecasting: - Rainfall - River discharge - Wind speed - Tidal levels - Atmospheric pressure - Wave heights	- Numerical models - Nowcasting techniques[9] - External organisations
Warning threshold and dissemination	- Local study - Social science surveys
Construction of floating beds	- Development agencies - Awareness raising schemes
Cropping patterns	- Development agencies - Awareness raising schemes

Table Notes

1. Hindcasting using proxy data (extreme wind data in the case of wave climate).
2. The science of observation without touching. Often used to refer to Earth observation from satellite platforms using electromagnetic sensors (Heywood et al., 2006).
3. Measurement of the depths of seas or oceans to produce an underwater elevation model.
4. For many developing countries, this is likely to be an essential source of information – its importance should not be underestimated.
5. A survey instrument which combines an electronic theodolite with an electronic distance meter to measure the distances and angles to a certain point.
6. Surveying method which identifies and measures the sedimentary layers that exist below the topmost seabed.
7. Surveying method which creates a 3D image of the seafloor.
8. Surveying method which measures water depth and the shape of the seabed.
9. A technique for very short-range forecasting that maps the current weather then uses an estimate of its speed and direction of movement to forecast the weather a short period ahead (Met Office, 2010).

4.5 Monitoring Technologies

Monitoring is an important aspect of adaptation because it helps to assess whether adaptation has achieved its goals and can also yield new insights and information which give rise to strategy adjustments as appropriate (Klein et al., 2001).

Monitoring requirements are not presented within Sections 4.1.1 to 4.3.2 for the individual technologies because many of the requirements are similar for different adaptation options. Instead, requirements are outlined in Table 4.14 with data collection methods given in Table 4.15.

Monitoring requirements will largely be dictated by the goals of the project. Common goals are likely to include coastal defence and habitat creation/improvement. The goals of adaptation should be clear before a scheme goes ahead and monitoring should collect appropriate information to help determine whether the scheme has achieved these goals.

Because monitoring requirements vary with the project goals, it is foreseeable the application of one adaptation technology at two different sites could have very different monitoring requirements, if the project goals are different.

4.5.1 Monitoring Requirements

The main monitoring requirements for evaluating the 13 adaptation technologies discussed in this guidebook are shown in Table 4.14. They are then discussed in more detail below. There are some similarities between monitoring knowledge requirements (c.f. Section 4.4). For example, topographic and bathymetric surveys are used both for monitoring purposes and in the assessment of coastal topography and nearshore bathymetry before project implementation.

Topographic Survey

Topographic surveys essentially monitor the shape of a beach above low water at designated points along a coast. When conducted along a length of beach, they allow estimates of the beach volume to be made and can also highlight problems such as scour in front of protective structures. Survey results can be used to create digital surface maps which can be imported into a GIS so that easy comparisons of annual change can be made.

Topographic surveys may record elevations along a cross-shore transect, or alternatively, a dense network of spot height measurements may be used to build a detailed map of beach topography.

When conducting beach nourishment, topographic surveys are likely to be used in conjunction with bathymetric surveys, extending to the depth of closure. This enables estimation of the total sediment volume on a nourished section of coast and is highly useful for a number of reasons (CIRIA, 1996):

- To identify when re-nourishment is required
- To determine cost-effectiveness of a scheme
- To help calibrate mathematical longshore sediment transport models which can then be used to refine future recharge schemes
- To help determine optimal recharge material type and grading

Table 4.14: Evaluative monitoring requirements for the 13 adaptation technologies discussed

	Beach Nourishment	Artificial Dunes & Dune Rehabilitation	Seawalls	Sea Dikes	Storm Surge Barriers & Closure Dams	Land Claim[1]	Flood Proofing	Wetland Restoration	Flood Hazard Mapping	Flood Warnings	Floating Agricultural Systems	Managed Realignment	Coastal Setbacks
Topographic survey	■	■	■	■		■						■	
Bathymetric survey	■		■	■									
Shoreline position	■		■	■				■ 2					■
Flood events									■	■			■
Ecological survey	■ 3	■ 3						■ 3			■ 3	■ 3	
Structural integrity			■	■	■	■	■ 4						
Scour & morphological change					■	■						■	
Compliance with regulations							■						
Intertidal accretion & erodibility								■ 2				■	
Crop yields											■		
Uptake of the technology							■				■		

Table Notes

1 Land claim will also require monitoring of the protective measures employed, such as seawalls and dikes (see also, the relevant monitoring requirements for these structures).

2 If erosion reduction was a project objective.

3 If habitat creation or improvement was a project objective.

4 Of individual flood-proofing measures.

For sand dune construction projects, topographic surveys are important as a source of information on dune dimensions. It is important that dunes have sufficient height and volume to resist the erosion expected during storms. The required volume can be calculated using the Vellinga (1983) equation (see Section 4.1.2). Topographic surveys will identify when further sand addition is required and will also provide information on whether dunes are obstructing beach access or coastal views.

For seawalls, dikes and land claim, topographic surveys are required in order to monitor beach and seabed levels adjacent to protective structures (CIRIA, 1996). This will identify problems, such as beach erosion and scour. Beach levels should be carefully monitored because scour can lead to structural undermining and instability.

Topographic surveys are also useful when implementing land claim, especially when land elevation has been employed. Monitoring will ensure that the land remains sufficiently far above sea level to prevent inundation – this is especially important because post-construction settlement, sediment compaction and RSLR are likely to lead to reductions in land elevation.

Finally, when implementing managed realignment, topographic surveys help to show in general, which areas are accreting, eroding or stable. This enables judgement on whether the developing conditions are suitable for a specific habitat.

Bathymetric Survey

Bathymetric surveys are frequently undertaken at the same time as topographic surveys. When this is the case, the surveys should be integrated by ensuring that survey ranges overlap between low and high water, and that the two surveys are tied to the same datums. In this way, the shape of the beach profile from the exposed beach to the depth of closure can be mapped.

Bathymetric surveys are an important monitoring requirement for beach nourishment projects as they allow the total volume of a nourished beach to be estimated. This has a number of important benefits, as outlined under the topographic survey section.

Bathymetric surveys are also important when implementing defence measures such as seawalls and dikes. By monitoring the underwater shape of the beach profile, it is possible to identify problems such as beach lowering and toe scour. These phenomena are indicative of erosion and can cause structural instability.

Shoreline Position

Monitoring of the shoreline position provides an indication of how the beach environment changes over time. It also gives some indication of erosion and accretion rates. This is important information for evaluating projects aiming to reduce erosion.

For coastal setbacks, monitoring of the shoreline position is important because this provides information on the current erosion trends and helps to evaluate whether the proposed setback is providing adequate protection. Monitoring the position of the shoreline also gives an indication of the actual, as opposed to the planned life of the setback. For example, when the shoreline retreats faster than expected, the planned lifetime of a coastal setback is reduced. In this situation, the setback will need to be re-evaluated, based on current trends.

Flood Events

For flood hazard mapping and flood warnings, comparing the occurrence and magnitude of observed flood events against predictions from models provides important validation of the methods used. This will also provide feedback which improves the accuracy of future flood predictions and warnings.

Similarly, monitoring of coastal water levels provides information which helps to validate the predictions and models used in determining a coastal elevation setback.

Ecological Survey

Ecological surveys may be important if habitat creation or improvement was a project objective. This is expected to be a more pressing requirement when implementing technologies where ecology is able to provide coastal protection co-benefits. For example, saltmarshes attenuate wave energy and stabilise intertidal areas and are therefore encouraged to thrive.

Ecological surveys are likely to focus on locally important plants or animals; these will be defined by the project objectives. For example, the use by sea turtles and nesting birds may be a focus for post-nourishment monitoring, while saltmarsh or mangrove species will be much more important monitoring subjects for wetland restoration projects.

Surveys may investigate the types and percentage cover of plants or record the number and types of animals occurring at a project site. In the case of floating agricultural systems, surveys may focus on the reduction in waterway weeds, such as water hyacinth. If the project objectives identified a specific species which was to be encouraged, surveys may wish to concentrate on that organism and its habitat requirements.

Structural Integrity

Regular structural monitoring is required for all hard defence options. This helps to ensure that structures continue to provide the design levels of protection. Structural monitoring also enables planning of repair works and assessment of long term performance. The following monitoring frequencies are recommended by CIRIA (1996), as a minimum – similar frequency arrangements should be applied in developing countries:

- Immediately after construction to provide baseline measurements
- Immediately after extreme events
- Annually for all elements in the intertidal zone
- Every five years for submerged elements

Structural monitoring should include visual inspection of the structure at low water and should pay particular attention to construction joints and other points on the structure where wave impacts could cause high internal pressures, potentially compromising the structure. Attention should be paid to toe detail and the structure should also be inspected for voids (CIRIA, 1996).

For dikes, it is particularly important to monitor the structure for weaknesses in the seaward and landward faces. For example, surveyors should be particularly aware of rodent holes and discontinuities in the armour layer. If these are not identified and repaired, wave action could compromise the integrity of the structure. Also of importance to structural integrity are the gradients of seaward and landward slopes, toe and heel details, revetment interlock and permeability and stability (de Quelerij & van Hijum, 1990). Particular attention should also be paid to drainage, as saturation of the dike can lead to failure of the landward slope.

It is important to monitor structure height because settlement can lead to reductions in crest height, with consequent reductions in the standard of protection offered by hard defences.

For defences with movable elements, such as storm surge barriers, the defence should undergo regular scheduled closures to check corrosion, free movement, and the seabed seal.

For flood-proofing measures, property owners will be required to monitor the condition and functionality of flood-proofing measures such as barriers and water resistant coatings to ensure they remain operational.

Scour & Morphological Change

Storm surge barriers, closure dams, land claim projects and managed realignment schemes are significant scale projects which have the capacity to cause considerable, permanent changes to the environments in which they are undertaken. For example, land claim projects may intercept longshore sediment transport, causing erosion on adjacent sections of coast while closure dams are likely to permanently alter upstream environments. These changes should be monitored so that damaging impacts can be rectified or mitigated.

Some adaptation technologies may also lead to changes in the location and flow characteristics of channels conveying water to the sea. For example, surge barriers may include pier structures or solid wall sections. These structures have the capacity to alter flows and water velocities in the channel which can lead to channel scour and consequent environmental damage. Again, it is important to monitor these changes so that damaging impacts can be rectified or mitigated.

Compliance with Flood-Proofing Regulations

Under a flood-proofing policy, it is important to monitor compliance with flood-proofing regulations and guidance. This is most important at the time of construction but needs to be reviewed when properties are improved.

Intertidal Accretion and Erodibility

Sedimentation and erosion are very important process in the intertidal zone, in terms of controlling bed elevation and therefore, vegetation coverage. Because of their ability to influence vegetation cover, they are also able to influence the overall form of a restoration or realignment site. As such, monitoring of intertidal accretion and erodibility is an important requirement of wetland restoration and managed realignment projects. Since variations in current velocities also play an important role in determining sedimentation and erosion rates, monitoring of this aspect may also prove beneficial.

Accretion, erodibility and flows may be monitored both at the project site and in surrounding areas. Such an approach would allow the impacts of these projects on the wider environment to be quantified.

Crop Yields

Crop yields are an important monitoring requirement for floating agriculture only. This is because the main objective of floating agricultural systems is to provide a more effective means of food production than traditional, land-based agriculture.

Uptake of the Technology

Monitoring the uptake of adaptation options is essential for both flood-proofing measures and floating agriculture. If local communities fail to implement distributed adaptation technologies such as these technologies, the benefits of adaptation will not be realised.

4.5.2 Required Technologies

The specific monitoring tools and techniques used to achieve each of these monitoring requirements are outlined in Table 4.15.

Table 4.15: Specific tools and techniques used for monitoring adaptation options

General description	Specific tools and techniques
Topographic Survey	Land-based methods - Traditional levelling methods Total stations[1] Differential GPS (dGPS)[2] Terrestrial laser scanner Aerial methods - LiDAR (light detection and ranging) - Photogrammetry - Synthetic Aperture Radar (SAR)
Bathymetric Survey	Boat-based methods - Single beam echo sounder - Multi beam echo sounder - dGPS Aerial methods - LiDAR
Spot Height Survey	- Kinematic GPS readings at regular, dense intervals across the beach surface to MLWS
Shoreline Position	- Fixed aspect photography - Aerial photography - Shoreline mapping - Topographic and bathymetric surveys
Occurrence and Magnitude of Flood Events	– Maintenance of tide and river gauge records – Mapping depth and extent of historic events
Water Levels (Coastal and River)	- Tidal gauges - River gauging stations
Ecological Survey	- Aerial photography - Bird surveys and counts - Fish surveys and counts - Invertebrate surveys and counts - Fixed aspect photography - Fixed quadrat surveys - Random quadrat surveys
Structural Integrity	- Regular inspections (particularly at low tide): • Drainage channel inspection • Inspection for holes, burrowing animals, etc. - Regular 'test' closures of movable barriers

General description	Specific tools and techniques
Scour & Morphological Change	Scour - Topographic surveys - Bathymetric surveys Current Velocity - ADCP - Impeller metres - Electromagnetic current metre Morphological Change - Aerial (and other photographic) imagery - Mapping exercises
Compliance with Regulations	- Building inspections
Intertidal Accretion & Erodibility	Accretion - Artificial marker horizons - Sedimentation-erosion tables (Boumans & Day, 1993) - Sediment traps - Tracer sediments - Topographic surveys - Datable horizons Erodibility - Measuring the onset of erosion in situ using suspended sediment meters, optical backscatter devices and velocity meters Flow monitoring - Dye tracers - Drogue tracking - Impeller metres - Electromagnetic current meters - Acoustic current meters (e.g. Acoustic Doppler Current Profiler or ADCP)
Uptake of Technology	- Building inspections - Community surveys

Table Notes

1. A survey instrument which combines an electronic theodolite with an electronic distance meter to measure the distances and angles to a certain point.
2. An enhanced GPS which uses a fixed base station at a known position to help find the location of a roving receiver.

5. Prioritisation of Technologies and Practices

After the vulnerability of a location to the impacts of climate change have been analysed and potential adaptation technologies have been identified, they have to be prioritised. This occurs during the planning and design stage of coastal adaptation (see Section 3.1). This requires a decision-making framework to compare and select between the possible options. This is necessary because there is a need to evaluate all the costs, benefits and physical and environmental impacts associated with coastal adaptation options over the affected area for the whole life of the scheme (Pearce & Turner, 1992; MAFF, 2001). This is because few coastal adaptation schemes have a totally local and short-term impact. As such, they cannot be regarded as truly ‘stand alone’.

Three decision making frameworks are widely used today and these have all been recommended for use in the National Adaptation Programmes of Action (NAPAs) under appropriate circumstances (UNFCCC, 2002):

1. Cost-Benefit Analysis (CBA): An assessment of all the costs and benefits of alternative options (e.g. Penning-Rowsell et al., 2003; DCLG, 2009)
2. Cost-Effectiveness Analysis (CEA): An assessment of the costs of alternative options which all achieve the same objective. The costs need not be restricted to purely financial ones (e.g. DCLG, 2009)
3. Multi-Criteria Analysis (MCA): Comparative assessment of options, taking account of several criteria simultaneously. Mainly used to assess impacts that can not be readily quantified in monetary terms (e.g. NI Direct, 2007)

Economic assessments such as CBA and CEA attempt to convert all costs and benefits to monetary terms. This helps to achieve goals such as optimisation of the use of public money, sustainability, accountability and quality assurance (MAFF, 1999). However, some impacts cannot readily be valued in economic terms and others may not be given their full weight in economic analysis (MAFF, 1999). Hence, there is an increasing tendency for CBA and CEA to be influenced by the MCA approach, but economic criteria remain dominant.

For CBA, the costs of a scheme are likely to include design, construction, maintenance and monitoring costs. The main component of the benefits will be the reduction in damage caused by coastal flooding or erosion. It is likely that CBA will struggle to include the more intangible quantities such as loss of life and long-term health costs from people affected by flooding or erosion however (Sene, 2008). In coastal management, factors such as the impact on down-drift sediment budget is of great importance and it is likely that monetary terms will not adequately express its importance. In practice it is hardly ever realistic to value all the costs and benefits of options in monetary terms. As a result, most cost-benefit analyses will incorporate some additional items which it is either not possible to value, or not economic to do so (DCLG, 2009). This approach is the norm in the UK and USA.

CEA may be used where the overall goal is agreed, but the best means of achieving this goal is uncertain. An example is where there is a legal requirement to achieve a certain outcome, or where an option has been justified through the normal appraisal process and an intervention (such as investment in a like-for-like replacement) is necessary to continue to deliver that option (DEFRA, 2009). Essentially, CEA is used to assess the least costly way of achieving a given objective (DCLG, 2009). This approach is applied in both Germany and the Netherlands where defence standards are laid down in law.

MCA is a decision-making framework that utilises a tool known as a performance matrix. Each row of a performance matrix describes an option and each column describes the performance of the options against each criterion. The individual performance assessments are often numerical, but may also be expressed as 'bullet point' scores, or colour coding (DCLG, 2009). Using this approach, a diverse range of monetary and non-monetary advantages and disadvantages can be directly compared and weighted according to their importance.

MCA does not consider the economic case in as much detail as CBA and CEA. It is therefore more subjective in the way decisions are reached, although the approach can be combined with economic analyses (Sene, 2008). The advantage of MCA is that it accounts for significant environmental and social impacts which are not easily assigned monetary values as measurement of indicators does not have to be undertaken in monetary terms.

MCA techniques can be used to identify a single most preferred option, to rank options, to short-list a limited number of options for subsequent detailed appraisal, or simply to distinguish acceptable from unacceptable possibilities (DCLG, 2009). The objective is to determine the performance of a number of options in regard to a set of criteria thought to be relevant in a community's choice between different approaches.

Some of the criteria which may be deemed important in determining the most acceptable adaptation option for coping with coastal flooding or erosion are given in Table 5.1. The weighting given to these different criteria will vary between applications, as decided by the relevant stakeholders.

Chapter 4 has already outlined the requirements for knowledge and expertise associated with each adaptation option. Additionally, advantages and disadvantages have also been presented. MCA provides a practical framework within which these widely varying factors can be assessed in relation to local environments and needs. A combination of the three decision-making frameworks outlined here is likely to offer support which will allow the most effective solutions for coping with the effects of climate change in the coastal zone to be identified.

Of the three approaches outlined, CBA is able to handle optimisation and prioritisation of options. Using this method, it is not even necessary to measure potential options against each other. Its limitation is that both costs and benefits must be expressed in monetary terms and that the chief objective is economic efficiency. In contrast, MCA only allows ranking of alternative options. However, it is more capable of evaluating measures for which, more criteria are deemed relevant and when quantification and valuation in monetary terms is not possible. Finally, CEA is a method which falls somewhat in between the CBA and MCA approaches. Its main use is in costing of different options that achieve the same objective. As with MCA, the CEA approach can also handle cases with multiple objectives or criteria (UNFCCC, 2002).

For further information, users are advised to go to UNFCCC (2002), Appendix D, for discussion of these methods in the context of NAPAs. Examples of coastal zone projects covered under the NAPAs are provided in UNFCCC (2008).

Table 5.1: Potentially important criteria for determining effectiveness of coastal flood and erosion adaptation

Criteria
Total scheme cost
Value of flood/erosion avoidance benefits
Effect on local economy
Implications for down-drift sediment supply
Impact on intertidal habitats
Effects on tourism
Functional effectiveness
Durability/Maintenance requirements
Sustainability
Ease of construction
Flexibility in the face of climate change
Impacts on coastal flora/fauna
Degree of specialist knowledge/equipment required
Access to the shoreline
Social acceptability
Space requirements
Equity
Information and capacity requirements

6. Conclusions

This guidebook is designed to help developing countries assess their needs and prepare action plans for the development, diffusion and deployment of a rage of adaptation technologies for coping with climate change in their coastal zones.

To achieve this aim, the guidebook has introduced 13 adaptation technologies within the IPCC CZMS (1990) framework of the protect, accommodate and retreat adaptation approaches. It should be noted here, that the 13 adaptation technologies outlined in this guidebook do not represent a comprehensive catalogue of options for coastal adaptation, but rather a selection of the most widely used and discussed adaptation technologies today. These technologies may be implemented individually, or simultaneously combined with other complementary adaptation technologies to develop a portfolio of measures. Hence, the 13 technologies can translate into a much larger number of portfolios of measures.

It is recommended here, that adaptation decisions, including which technologies to implement, should take place within the framework of Integrated Coastal Zone Management (ICZM), following earlier guidance (e.g. Bijlsma et al., 1996; Cicin-Sain and Knecht, 1998; Klein et al., 2001; Kay and Alder, 2005). Such an approach provides a platform for considering the broad range of adaptation options available, and the large number of stakeholders involved in decision-making in the coastal zone. The approach should also aid the management of coastlines in view of both climate and non-climate stresses and will promote adaptation as a process, rather than an endpoint (see Chapter 3).

Within this guidebook, each of the 13 adaptation technologies are defined and described, and the main technological advantages and disadvantages are discussed. Information on the institutional and organisation requirements is then provided, along with cost data, where available, and a discussion of the barriers and opportunities to implementation. Case studies of where these technologies/practices have been employed were also presented. Where possible, developing country cases have been used, although it is noteworthy that suitable case studies are not always available due to a lack of experience and/or documentation of experience. It is hoped that a by-product of this guidebook will be the occurrence of more developing country adaptation projects and documentation.

Knowledge and capacity building requirements were addressed for all the technologies. Recurring requirements emerged, such as the need for knowledge of relative sea-level rise (RSLR) scenarios, extreme water levels, local wave climate, tidal regime and nearshore bathymetry and also, the flooding potential of a locale. Monitoring requirements were also outlined and again, recurring requirements emerged. These included the need for topographic and bathymetric surveys and investigations into structural integrity.

The guidebook then introduced three decision-making frameworks, comprising Cost-Benefit Analysis, Cost-Effectiveness Analysis and Multi-Criteria Analysis. These frameworks are used to compare and select between the possible adaptation options. It is recognised that although economic assessments such as CBA and CEA have been seen to be increasingly influenced by the more qualitative MCA approach, economic criteria remain dominant in decision-making today.

A recurring theme with all the adaptation technologies considered is that, while many can be implemented at the community level, communities often lack the technical ability to determine whether measures are appropriate and whether design standards are acceptable. This lack of knowledge can also translate into adverse environmental impacts beyond the immediate project site. This is because coastal systems are coupled by water and sediment exchange, and hence implementation of adaptation at one location can affect the wider coastal system in ways that are often not fully appreciated or anticipated. As such, while adaptation may be technically possible at the community scale, the availability of technical support and guidance from organisations with a well-developed science and technology base is likely to be highly beneficial. Hence, developing an accessible capacity for technical guidance within developing countries would be complementary to these guidelines.

The settings within which adaptations take place have also been seen to have a significant bearing on the success of adaptation interventions. Historically, coastal adaptation has been localised and this is still often true, especially in developing countries. However, the modern approach in countries with a long history of coastal engineering involves an interdisciplinary approach and long-term planning measures for significant stretches of coastline. For example, in England and Wales, coastal cells and sub-cells have been used as the starting basis for national shoreline management planning (Leafe et al., 1998; DEFRA, 2006) and this approach has been advocated more widely (Klein et al., 2000; Eurosion, 2004). By attempting to develop and apply an appropriate regional framework, it is hoped that developing countries can avoid some of the costly mistakes experienced in the coastal management histories of developed nations.

While a number of specific adaptation technologies have been introduced in this guidebook, it is important to note that effective adaptation consists of more than simply implementing an adaptation technology. Successful adaptation is a process of information and awareness raising, planning and design, implementation and evaluation. This process ensures that the most appropriate adaptations are implemented, that their design is effective and that they are evaluated and adjusted in response to changing environmental conditions (and socio-economic needs), in order to continue providing the most effective adaptation into the uncertain future.

7. References

ABPMER (Associated British Ports Marine Environmental Research) (2010a) Abbotts Hall (Stage 2). Southampton: ABPMER. Available from: http://tiny.cc/59f7o [Accessed: 05/08/10].

ABPMER (Associated British Ports Marine Environmental Research) (2010b) The Online Managed Realignment Guide: Details for Abbotts Hall Stage 2. Southampton: ABPMER. Available from: www.abpmer.net/omreg/index.php?option=com_wrapper&Itemid=57 [Accessed: 05/08/10].

ADRC (Asian Disaster Reduction Centre) (2005) Total Disaster Risk Management – Good Practices 2005. Kobe: ADRC. Available from: http://tiny.cc/2cis5 [Accessed: 04/08/10].

AFPM (Adviescommissie Primaire Waterkeringen) (2006) Tussensprint naar 2015 – advies over de financiering van primaire waterkeringen voor de bescherming van Nederland tegen overstromingen (in Dutch).

Allen, J.R.L. and Pye, K. (1992) Coastal saltmarshes: their nature and importance in Allen, J.R.L. and Pye, K. (eds.). Saltmarshes: Morphodynamics, Conservation and Engineering Significance. Cambridge: Cambridge University Press, 1-18.

Alongi, D.M. (2002) Present state and future of the world’s mangrove forests. Environmental Conservation, 29 (3), 331-349.

Anderson, I. (1991) Land reclamation poisons coastal waters. New Scientist, 1797, p 11.

APEIS and RIPSO (2004) Floating Agriculture in the flood-pr one or submerged areas in Bangladesh (Southern regions of Bangladesh). Bangladesh: APEIS and RIPSO. Available from: http://enviroscope.iges.or.jp/contents/APEIS/RISPO/inventory/db/pdf/0146.pdf [Accessed: 22/07/10].

Awosika, L., Dublin-Green, C.O. and Folorunsho, R. (2002) Bar Beach Victoria Island Erosion Problem: A Critical Assessment as at October 30th 2002 and Need for Urgent Mitigating Measures. Lagos: Nigerian Institute for Oceanography and Marine Research. Available from: www.oceandocs.org/bitstream/1834/540/1/AssWA_BB2002.pdf [Accessed: 01/09/10].

Bapulu, G.V. and Sinha, R. (2005) GIS in Flood Hazard Mapping: a case study of Kosi River Basin, India. Noida: GIS Development. Available from: http://home.iitk.ac.in/~rsinha/PDF's/2006_FloodGISdevelopment.pdf [Accessed: 21/07/10].

Barbier, E.B. (2008) In the wake of tsunami: Lessons learned from the household decision to replant mangroves in Thailand. Resource and Energy Economics, 30, 229–249.

Barends, F.B.J. (2003) Groundwater mechanics in flood risk management in Kono, I., Nishigaki, M. and Komatsu, M. (eds.). Groundwater Engineering: Recent Advances. Rotterdam: A.A. Balkema, 53-66.

Bermingham, S., Ferretti, J., King, L, Kinninment, D., Ryan, C., Tidmarsh, C., Totterdell, R., Yates, G., Flintoff, I., Owen, A. and Digby, B. (2000) Changing Environments. Oxford: Heinemann Educational Publishers.

Bijlsma, L., Ehler, C.N., Klein, R.J.T., Kulshrestha, S.M., McLean, R.F., Mimura, N., Nicholls, R.J., Nurse, L.A., Péres Nieto, H., Stakhiv, E.Z., Turner, R.K. and Warrick, R.A. (1996) Coastal zones and small islands in Watson, R.T., Zinyowera, M.C. and Moss, R.H. (eds.). Climate Change 1995 – Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Bindoff, N.L., J. Willebrand, V. Artale, A, Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L.D. Talley and A. Unnikrishnan (2007) Observations: Oceanic Climate Change and Sea Level in Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Bird, E. (2005) Appendix 5: Glossary of Coastal Geomorphology in Schwartz, M.L. (ed.). Encyclopedia of Coastal Science. The Netherlands: Springer, 1155-1192.

Boumans, R.M.J. and Day, J.W. (1993) High precision measurements of sediment elevation in shaloow coastal areas using a sedimentation-erosion table. Estuaries, 16 (2), 375-380.

Brampton, A.H. (1992) Engineering significance of British saltmarshes in Allen, J.R.L. and Pye, K. (eds.). Saltmarshes: Morphodynamics, conservation and engineering significance. Cambridge: Cambridge University Press, 115-122.

Brampton, A. (2002) ICE Design and Practice Guides: Coastal Defence. London: Thomas Telford.

Brøgger, C. and Jakobsen, P. (2008) Beach nourishment combined with SIC vertical drain in Malaysia in McKee Smith, J. (ed.). Coastal Engineering 2008, Hamburg, 31 Aug – 5 Sept, 2008. Singapore: World Scientific Publishing, 4725-4737.

Bruun, P. (1962) Sea level rise as a cause of shore erosion. Proceedings of the American Society of Civil Engineers, Journal of Waterways and Harbors Division, 88, 117-130.

Burgess, K. and Townend, I. (2004) The impact of climate change upon coastal defence structures. 39th DEFRA Flood and Coastal Management Conference, University of York, UK, 29 June-1 July, 2004.

Burgess, K., Jay, H. and Nicholls, R.J. (2007) Drivers of coastal erosion in Thorne, C.R., Evans, E.P. and Penning-Rowsell, E.C. (eds.). Future Flooding and Coastal Erosion Risks. London: Thomas Telford, 267-279.

Bush, D.M., Neal, W.J., Longo, N.J., Lindeman, K.C., Pilkey, D.F., Esteves, L.S., Congleton, J.D. and Pilkey, O.H (2004) Living with Florida's Atlantic Beaches: Coastal Hazards from Amelia Island to Key West. USA: Duke University Press.

Cambers, G. (1998) Planning for Coastline Change: Coastal Development Setback Guidelines in Antigua and Barbuda. Paris: UNESCO. Available from: http://tiny.cc/j5va7 [Accessed: 19/08/10].

Chadwick, A., Morfett, J. and Borthwick, M. (2004) Hydraulics in Civil and Environmental Engineering, 4th ed. London: Spon Press.

Chagoury Group (2006) Bar Beach – Shore Protection. Lagos: The Chagoury Group. Available from: www.chagouryconstruction.com/barbeach.html [Accessed: 01/09/10].

Cicin-Sain, B. and Knecht, R. (1998) Integrated Coastal and Ocean Management Concepts and Practices. Washington DC: Island Press.

CIRIA (Construction Industry Research and Information Association) (1996) Beach Management Manual. CIRIA Report 153. London: Construction Industry Research and Information Association.

Coastal Carolina University (2010) Oceans in Motion: Waves and Tides. Carolina: Kingfish. Available from: http://kingfish.coastal.edu/biology/sgilman/770Oceansinmotion.htm [Accessed: 07/07/10].

Coastal Research (2010) Glossary. Utrecht: Utrecht University. Available from: www.coastalresearch.nl/glossary/5/view [Accessed: 19/08/10].

ComCoast (2006) Innovative flood management solutions and spatial development - A wider approach in coastal management. Delft (the Netherlands): Rijkswaterstaat.

Cooper, N.J. and Harlow, D.A. (1998) Beach replenishment: implications for sources and longevity from results of the Bournemouth schemes in Hooke, J. (ed.). Coastal Defence and Earth Science Conservation. London: Geological Society of London, 162-177.

CZMU (Coastal Zone Management Unit of Barbados) (2005) Guidelines for the assessment of planning applications. Barbados: CZMU. Available from: http://www.coastal.gov.bb/UserFiles/File/GUIDELINES_for_the_ASSESSMENT_OF_PLANNING_APPLICATIONS.doc [Accessed: 29/09/10].

CZMU (Coastal Zone Management Unit of Barbados) (2010) What are the Coastal Setbacks? Barbados: CZMU. Available from: www.coastal.gov.bb/info.cfm?category=2&catinfo=9 [Accessed: 29/09/10].

Daniel, E.B. and Abkowitz, M.D. (2005) Improving the Design and Implementation of Beach Setbacks in Caribbean Small Islands. URISA Journal, 17 (1), 53-65.

Dawson R.J., Dickson, M., Nicholls, R. J., Hall, J., Walkden, M., Stansby, P.K., Mokrech, M., Richards, J., Zhou, J., Milligan, J., Jordan, A., Pearson, S., Rees, J., Bates, P.D., Koukoulas, S. and Watkinson, A. (2009) Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change. Climatic Change, 95, 249-288.

DCLG (Dept. for Communities and Local Government) (2009) Multi-Criteria Analysis: A Manual. London: DCLG. Available from: www.communities.gov.uk/documents/corporate/pdf/1132618.pdf [Accessed: 26/08/10].

de Lacerda, L.D. (2002) Mangrove Ecosystems: Function and Management. Berlin: Springer.

de Quelerij, L. and van Hijum, E. (1990) Maintenance and monitoring of water retaining structures in Pilarczyk, K.W. (ed.). Coastal Protection. Rotterdam: A.A. Balkema, 369-401.

Dean, R.G. (2002) Beach Nourishment Theory and Practice. Singapore: World Scientific Publishing.

Dean, R.G. and Dalrymple, R.A. (2002) Coastal Processes with Engineering Applications. Cambridge: Cambridge University Press.

DEFRA (Dept. for Environment, Food and Rural Affairs) (2006) Shoreline Management Plan Guidance. Volume 1: Aims and Requirements. London: DEFRA.

DEFRA (Dept. for Environment, Food and Rural Affairs) (2009) Appraisal of flood and coastal erosion risk management. London: DEFRA. Available from: www.defra.gov.uk/environment/flooding/documents/policy/guidance/erosion-manage.pdf {accessed: 26/08/10].

DFID (Department for International Development) (2004) Disaster Risk Reduction: A Development Concern. Norwich: University of East Anglia. Available from: www.sheltercentre.org/sites/default/files/DFID_DisasterRiskReductionADevelopmentConcern.pdf [Accessed: 21/09/10].

DHV Haskoning (2007) Study and review of methods and materials for closing of tidal channels in Bangladesh. The Netherlands: DHV Haskoning. Available from: http://edpbwdb.org/rep/tc03.pdf [Accessed: 27/09/10].

Doody, J.P. (2008) Saltmarsh conservation, management and restoration. Dusseldorf: Springer.

Edge, B., Ewing, L., Erickson, K.M. and Magoon, O. (2003) Application of coastal engineering in coastal zone management in Mohan, R.K., Magoon, O. and Pirrello, M (eds.). Advances in Coastal Structure Design. Virginia: ASCE.

Eisma, D. (2006) Dredging in Coastal Waters. Leiden: Taylor & Francis.

Elfrink, B., Accetta, D. and Mangor, K. (2008) Shoreline Protection Scheme at Conceicao da Barra, Brasil in McKee Smith, J. (ed.). Coastal Engineering 2008, Hamburg, 31 Aug – 5 Sept, 2008. Singapore: World Scientific Publishing, 2458-2470.

Elgershuizen, J.H.B.W. (1981) Some environmental impacts of a storm surge barrier. Marine Pollution Bulletin, 12 (8), 265-271.

EMA (Emergency Management Australia) (1999) Flood Warning: An Australian Guide. Canberra: Emergency Management Australia. Available from: www.ses.nsw.gov.au/multiversions/2770/FileName/Flood_warning_An_Australian_Guide.pdf [Accessed: 12/07/10].

Environment Agency (2003) Sustainable Flood Defences – Monitoring of the Managed Realignment Scheme at Abbots Hall, Essex. Unpublished report.

Environment Agency (2007) Flood Risk Management Estimating Guide. Unit Cost Database 2007. Environment Agency: Bristol.

Environment Agency (2010) Flood Map - your questions answered. Rotherham: Environment Agency. Available from: www.environment-agency.gov.uk/homeandleisure/31662.aspx [Accessed: 21/07/10].

Ericson, J. P., Vorosmarty, C. J., Dingman, S. L., Ward, L. G., and Meybeck, M. (2006) Effective sea-level rise and deltas: causes of change and human dimension implications. Global and Planetary Change, 50, 63-82.

Essex Wildlife Trust (2003) Abbotts Hall Farm Fact Sheet 4: Consents for coastal realignment. Great Wigborough: Essex Wildlife Trust. Available from: http://tiny.cc/w8msn [Accessed: 05/08/10].

Essex Wildlife Trust (2010) Abbotts Hall Farm. Great Wigborough: Essex Wildlife Trust. Available from: www.essexwt.org.uk/visitor_centres__nature_reserves/abbotts_hall_farm/ [Accessed: 05/08/10].

European Commission (1999) Towards a European Integrated Coastal Zone Management (ICZM) Strategy: General Principles and Policy Options. Luxembourg: Office for Official Publications of the European Communities. Available from: http://ec.europa.eu/environment/iczm/pdf/vol1.pdf [Accessed: 27/08/10].

Eurosion (2004) Living with Coastal Erosion in Europe: Sediment and Space for Sustainability. Available from: http://www.eurosion.org/shoreline/Shoreline_management_guide_FINAL.zip [Accessed: 01/09/10].

Evans, E., Ashley, R., Hall, J., Penning-Rowsell, E., Sayers, P., Thorne, C. and Watkinson, A. (2004) Foresight. Future Flooding. Scientific Summary: Volume II. Managing future risks. London: Office of Science and Technology.

FEMA (Federal Emergency Management Agency) (1992) Repairing your flooded home. Washington DC: US Dept. of Homeland Security. Available from: http://tiny.cc/mrzv8 [Accessed: 21/07/10].

FEMA (Federal Emergency Management Agency) (1998) Managing Floodplain Development Through the National Flood Insurance Programme. Washington DC: US Dept. of Homeland Security. Available from: www.fema.gov/pdf/floodplain/is_9_complete.pdf#nameddest=wet-flood [Accessed: 27/07/10].

FEMA (Federal Emergency Management Agency) (2001) Engineering Principles and Practices for Retrofitting Flood Prone Residential Structures. Washington DC: Dept. of Homeland Security.

FEMA (Federal Emergency Management Agency) (2007) Selecting Appropriate Mitigation Measures for Floodprone Structures. Washington DC: US Dept. of Homeland Security. Available from: www.fema.gov/library/viewRecord.do?id=2737 [Accessed: 21/07/10].

FEMA (Federal Emergency Management Agency) (2008) Floodplain Management Bulletin: Historic Structures. Washington DC: US Dept. of Homeland Security.

FEMA (Federal Emergency Management Agency) (2009) Homeowner's Guide to Retrofitting. Washington DC: Dept. of Homeland Security. Available from: http://tiny.cc/kfnxq http://www.fema.gov/hazard/map/firm.shtm - 1[Accessed: 10/08/10].

FEMA (Federal Emergency Management Agency) (2010) Wet Floodproofing. Washington DC: US Dept. of Homeland Security. Available from: www.fema.gov/plan/prevent/floodplain/nfipkeywords/wet_floodproofing.shtm [Accessed: 21/07/10].

Fenster, M.S. (2005) Setbacks in Schwartz, M.L. (ed.). Encyclopedia of Coastal Science. The Netherlands: Springer, 863-866.

Finkl, C.W. (2004) Coastal classification: systematic approaches to consider in the development of a comprehensive scheme. Journal of Coastal Research, 20 (1), 166-213.

French, P.W. (1997) Coastal and Estuarine Management. London: Routledge.

French, P.W. (2001) Coastal defences: Processes, Problems and Solutions. London: Routledge.

French, P.W. (2005) Coastal Zone Management in Schwartz, M.L. (ed.). Encyclopedia of Coastal Science. The Netherlands: Springer, 313-319.

Friedrichs, C.T., Lynch, D.R. and Aubrey, D.G. (1992) Velocity asymmetries in frictionally-dominated tidal embayments: longitudinal and lateral variability in Prandle, D. (ed.). Dynamics and Exchanges in Estuaries and the Coastal Zone. Washington DC: American Geophysical Union, 277-312.

Gardiner, S., Hanson, S., Nicholls, R., Zhang, Z., Jude, S., Jones, A., Richards, J., Williams, A., Spencer, T., Cope, S., Gorczynska, M., Bradbury, A., McInnes, R., Ingleby, A. and Dalton, H. (2007) The Habitats Directive, coastal habitats and climate change - case studies from the south coast of the U.K. Norwich: The Tyndall Centre for Climate Change Research. Available from: www.tyndall.uea.ac.uk/sites/default/files/wp108.pdf [Accessed: 13/10/10].

Glaser, R. and Walsh, R.P.D. (1991) Land reclamation in Singapore, Hong Kong and Macau. GeoJournal, 24 (4), 365-373.

Goda, Y. (2000) Random Seas and Design of Maritime Structures. Singapore: World Scientific Publishing.

Hallermeier, R.J. (1981) A profile zonation for seasonal sand beaches from wave climate. Coastal Engineering, 4, 253-277.

Hanson, H., Brampton, A., Capobianco, M., Dette, H.H., Hamm, L., Laustrup, C., Lechuga, A. and Spanhoff, R. (2002) Beach nourishment projects, practices, and objectives – a European overview. Coastal Engineering, 47, 81-112.

Haq, A.H.M.R., Ghosal, T.K. and Ghosh, P. (2004) Cultivating wetlands in Bangladesh. India: LEISA. Available from: http://bit.ly/c3Ah0o [Accessed: 05/08/10].

Haq, A.H.M.R., Ghosh, P. and Islam, M.A. (2005) Wise use of wetland for sustainable livelihood through participatory approach: A case study of adapting to climate change. Bhubaneswar: Asian Wetland Symposium. Available from: http://bit.ly/95hEqV [Accessed: 05/08/10].

Haque, C.E. (1995) Climatic hazards warning process in Bangladesh: Experience of, and lessons from, the 1991 April cyclone. Environmental Management, 19 (5), 719-734.

Harlow, D.A. and Cooper, N.J. (1996) Bournemouth beach monitoring: the first twenty years in Fleming, C.A. (ed.). Coastal Management: Putting Policy into Practice. London: Thomas Telford, 248-259.

Hay, J.E. (2009) Institutional and Policy Analysis of Disaster Risk Reduction and Climate Change Adaptation in Pacific Island Countries. United Nations International System for Disaster Reduction (UNISDR) and the United Nations Development Programme (UNDP), Suva, Fiji.

Healy, T.R. and Dean, R.G. (2000) Methodology for delineation of coastal hazard zones and development setback for open duned coasts in Herbich, J.B. (ed.). Handbook of Coastal Engineering. New York: McGraw-Hill, Chapter 19.

Heywood, I., Cornelius, S. and Carver, S. (2006) An Introduction to Geographic Information Systems, 3rd ed. Harlow: Pearson Education.

Hillen, M.M. (2008) Safety Standards Project, Risk Analysis for New Sea Dike Design Guidelines in Vietnam. Technical Report Delft University of Technology / Hanoi Water Resources University; Sea Dike Project.

Hillen, M.M., Jonkman, S.N., Kanning, W., Kok, M., Geldenhuys, M., Vrijling, J.K. and Stive, M.J.F. (2010) Coastal Defence Cost Estimates. Case Study of the Netherlands, New Orleans and Vietnam. The Netherlands: TU Delft. Available from: http://tiny.cc/lwlkh [Accessed: 07/07/10].

HiTech (2006) Shoreline Protection. Lagos: HiTech. Available from: www.hitech-company.com/BarBeachShorelineProtection.html [Accessed: 01/09/10].

Hodder, J.P. (1986) Coastal Sediment Processes in Poole Bay, with Particular Reference to the Bournemouth Beach Replenishment of 1974/75. Thesis (M.Phil.), University of Southampton.

HR Wallingford (2006) Assessing the benefits of flood warning: A scoping study. Edinburgh: SNIFFER. Available from: http://tiny.cc/i88jm [Accessed: 21/07/10].

IOC (2009) Hazard Awareness and Risk Mitigation in Integrated Coastal Area Management (ICAM). Intergovernmental Oceanographic Commission (IOC) Manual and Guides No. 50, ICAM Dossier No. 5. Paris: UNESCO.

IPCC CZMS (1990) Strategies for Adaptation to Sea Level Rise. Report of the Coastal Zone Management Subgroup, Response Strategies Working Group of the Intergovernmental Panel on Climate Change. The Hague: Ministry of Transport, Public Works and Water Management.

IPCC CZMS (1992) A common methodology for assessing vulnerability to sea-level rise—second revision in Global Climate Change and the Rising Challenge of the Sea. Report of the Coastal Zone Management Subgroup, Response Strategies Working Group of the Intergovernmental Panel on Climate Change. The Hague: Ministry of Transport, Public Works and Water Management.

Irfanullah, H. M., Adrika, A., Ghani, A. and Khan, Z.A. (2007) Introduction of Floating Gardening in the North-eastern Wetlands of Bangladesh for Nutritional Security and Sustainable Livelihood. Renewable Agriculture and Food Systems, 23(2), 89–96.

Islam, T. and Atkins, P. (2007) Indigenous Floating Cultivation: A Sustainable Agricultural Practice in the Wetlands of Bangladesh. Development in Practice, 4(1), 130–136.

JNCC (Joint Nature Conservation Committee) (2010) Habitat Account – Marine, Coastal and Halophytic Habitats. Peterborough: JNCC. Available from: www.jncc.gov.uk/protectedsites/sacselection/habitat.asp?featureintcode=h1150 [Accessed: 19/08/10].

Kamphuis, J.W. (2000) Introduction to Coastal Engineering and Management. Singapore: World Scientific Publishing.

Kana, T.W. (1995) A mesoscale sediment budget for Long Island, New York. Marine Geology, 126, 87-110.

Kathiresan, K., and Rajendran, N. (2005) Coastal mangrove forests mitigated tsunami. Estuarine Coastal and Shelf Science, 65, 601–606.

Kay, R. (1990) Development controls on eroding coastlines: Reducing the future impact of greenhouse-induced sea level rise. Land Use Policy, 7 (4), 169-172.

Kay, R. and Alder, J. (2005) Coastal Planning and Management, 2nd ed. Oxon: Taylor and Francis.

Kim, K.H.K., Widayati, A.Y.W. and Yoon, S.J. (2008) Comprehensive approach for beach erosion mitigation in Korea in McKee Smith, J. (ed.). Coastal Engineering 2008, Hamburg, 31 Aug – 5 Sept, 2008. Singapore: World Scientific Publishing, 4687-4698.

Klein, R.J.T. and Nicholls, R.J. (1998) Coastal Zones in Feenstra, J.F. et al. (eds.). Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies. Kenya: UNEP, chapter 7.

Klein, R.J.T., Aston, J., Buckley, E.N., Capobianco, M., Mizutani, N., Nicholls, R.J., Nunn, P.D., Ragoonaden, S., Bartlett, D.J., Boyd, J.G., Lecomte, E., Loizidou, X.I., Volonté, C.R. and Niang-Diop, I. (2000) Coastal Adaptation Technologies in Metz, B., Davidson, O., Martens, J., Van Rooijen, S. and Van Wie Mcgrory, L. (eds.). Methodological and Technological Issues in Technology Transfer. Cambridge: Cambridge University Press.

Klein, R.J.T., Mozaharul, A., Burton, I., Dougherty, W.W., Ebi, K.L., Fernandes, M., Huber-Lee, A., Rahman, A.A. and Swartz, C. (2006) Application of environmentally sound technologies for adaptation to climate change. Bonn: UNFCCC. Available from: http://unfccc.int/resource/docs/2006/tp/tp02.pdf [Accessed 01/07/10].

Klein, R.J.T., Nicholls, R.J. and Mimura, N. (1999) Coastal adaptation to climate change: can the IPCC technical guidelines be applied? Mitigation and Adaptation Strategies for Global Change, 4, 239-252.

Klein, R.J.T., Nicholls, R.J., Ragoonaden, S., Capobianco, M., Aston, J. and Buckley, E.N. (2001) Technological options for adaptation to climate change in coastal zones. Journal of Coastal Research, 17 (3), 531-543.

Kraus, N.C. (2005) Shore Protection Structures in Schwartz, M.L. (ed.). Encyclopedia of Coastal Science. The Netherlands: Springer, 875-877.

Laessing, D.E. (2005) Depth of Closure at Bournemouth. Dissertation (MSc.), University of Southampton.

Leafe, R., Pethick, J. and Townend, I. (1998) Realising the benefits of shoreline management. Geographical Journal, 164, 282-290.

Leggett, D.J., Cooper, N. and Harvey, R. (2004) Coastal and Estuarine Managed Realignment – Design Issues. London: CIRIA.

LEISA (2009) Soil-less agriculture gains ground. India: LEISA. Available from: http://tiny.cc/a3g0y [Accessed: 05/08/10].

Lelliott, R.E.L. (1989) Evolution of the Bournemouth defences in Coastal Management. L:ondon: Thomas Telford, 263-277.

Li, C.X., Fan, D.D., Deng, B. and Korotaev, V. (2004) The coasts of China and issues of sea level rise. Journal of Coastal Research, 43, 36-47.

Linham, M. (2008) Depth of Closure at Bournemouth, Poole Bay, UK: Evaluating the Effectiveness of the Hallermeier (1981) Equation. Dissertation (BSc.), University of Southampton.

Linham, M.M., Green, C.H. and Nicholls, R.J. (2010) AVOID Report on the Costs of adaptation to the effects of climate change in the world's large port cities. AV/WS2/D1/R14, www.avoid.uk.net.

MAFF (Ministry of Agriculture, Fisheries and Food) (1999) Flood and Coastal Defence Project Appraisal Guidance: Economic Appraisal. London: MAFF. Available from: http://bit.ly/bRnFQB http://www.safecoast.org/editor/databank/File/002_fcdpag1.pdf[Accessed: 26/08/10].

MAFF (Ministry of Agriculture, Fisheries and Food) (2001) Flood and Coastal Defence Project Appraisal Guidance. London: MAFF. Available from: www.safecoast.org/editor/databank/File/002_fcdpag1.pdf [Accessed: 26/08/10].

Mai, C.T. (2008) The Application of a Tandem Dike System in Vietnam. Dissertation (MSc.), UNESCO-IHE Institute for Water Education, Delft, The Netherlands.

Mai, C.V., van Gelder, P.H.A.J.M., Vrijling, J.K. and Mai, T.C. (2008) Risk Analysis of Coastal Flood Defences - A Vietnam Case in Simonovic, S.P., Bourget, P.G. and Blanchard, S.F. (eds.). The 4th international symposium on flood defence; managing flood risk, reliability & vulnerability, Toronto, 6-8 May, 2008. Toronto: Institute for catastrophic loss reduction.

Mai, V.C. (2004) Safety Assessment of Sea Dikes in Vietnam: A Case Study in NamDinh Province. Dissertation (MSc.), UNESCO-IHE Institute for Water Education, Delft, The Netherlands.

Mathis, M.L. and Nicholson, S. (2006) An Evaluation of Compliance with the National Flood Insurance Program Part B: Are Minimum Building Requirements Being Met? Washington DC: American Institutes for research. Available from: www.fema.gov/library/viewRecord.do?id=2590 [Accessed: 28/08/10].

McDougal, W.G., Sturtvant, M.A. and Komar, P.D. (1987) Laboratory and field investigations of the impact of shoreline stabilisation structures on adjacent properties in Kraus, N.C. (ed.). Coastal Sediments ’87, Louisiana. New York: ASCE, 961-973.

McLean, R.F., Tsyban, A., Burkett, V., Codignotto, J.O., Forbes, D.L., Mimura, N., Beamish, R.J. and Ittekkot, V. (2001) Coastal zones and marine ecosystems in Bijlsma, L. and Sanchez-Arevalo, I. (eds.). Climate Change 2001 – Impacts Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Meadowcroft, I.C., Hall, J.W., Lee, E.M. and Milheiro-Oliveira, P. (1999) Coastal Cliff Recession: Development and Application of Prediction Methods. HR Wallingford Report SR549.

Merlin, M.D. (2005) Pacific Ocean islands: coastal geomorphology in Schwartz, M.L. (ed.). Encyclopedia of Coastal Science. The Netherlands: Springer, 746-753.

Met Office (2010) Nowcasting. Exeter: Met Office. Available from: www.metoffice.gov.uk/science/creating/hoursahead/nowcasting.html [Accessed: 22/07/10].

Mimura, N. and Nunn, P.D. (1998) Trends of beach erosion and shoreline protection in rural Fiji. Journal of Coastal Research, 14 (1), 37-46.

Mirza, M.M.Q., Patwardhan, A., Attz, M., Marchand, M., Ghimire, M., Hanson, R. (2005) Flood and Storm Control in Chopra, K.R. (ed.) Ecosystems and Human Wellbeing Volume III Policy Responses. Washington DC: Island Press, p337-352.

Mishra, D.K. and Prakash, H.R. (1982) An evaluation of the Andhra Pradesh cyclone shelters programme: guidelines for the Orissa programme. Disasters, 6, 250-255.

Moh, W.H. and Su, P.L. (2009) Marina Barrage – A Unique 3-in-1 Project in Singapore. Structural Engineering International, 19 (1), 17-21.

Mokrech, M., Hanson, S., Nicholls, R.J., Wolf, J., Walkden, M.J.A., Fontaine, C., Nicholson-Cole, S., Jude, S.R., Leake, J., Stansby, P.K., Watkinson, A.R., Rounsevell, M.D.A., Lowe, J.A. and Hall, J.W. (2009) The Tyndall coastal simulator. Journal of Coastal Conservation: Planning and Management. DOI: 10.1007/s11852-009-0083-6

Morton, R.A. (2004) Physical Agents of Land Loss: Sediment Budget. Reston, VA: USGS. Available from: http://pubs.usgs.gov/of/2003/of03-337/budget.html [Accessed: 06/01/10].

Moser, S.C. (2000) Community responses to coastal erosion: implications of potential policy changes to the National Flood Insurance Programme. Appendix F. In Evaluation of Erosion Hazards. A project of the H. John Heinz II Centre for Science, Economics and the Environment. Prepared for the Federal Emergency Management Agency, Washington DC. Available from: http://tiny.cc/af9kx [Accessed: 17/08/10].

Mycoo, M. (2006) Sustainable Tourism Using Regulations, Market Mechanisms and Green Certification: A Case Study of Barbados. Journal of Sustainable Tourism, 14 (5), 489-511.

Nairn, R.B., MacIntosh, K.J., Hayes, M.O., Nai, G., Anthonio, S.L. and Valley, W.S. (1998) Coastal erosion at Keta Lagoon, Ghana – large scale solution to a large scale problem in Edge, B.L. (ed.). Coastal Engineering 1998, Copenhagen, June 22-26, 1998. Reston, Virginia: ASCE, 3192-3205.

NALMS (North American Lake Management Society) (2008) Water Words Glossary. Madison: NALMS. Available from: www.nalms.org/nalmsnew/glossary.aspx?Al=B [Accessed: 10/08/10].

NI Direct (Northern Ireland Direct) (2007) Glossary. London: NI Direct. Available from: www.dfpni.gov.uk/eag-glossary [Accessed: 26/08/10].

Nicholls, R.J. (2006) Storm surges in coastal areas in Arnold, M. et al. (eds.). Natural Disaster Hotspots. Case Studies. Washington DC: The World Bank, 79-108.

Nicholls, R.J. (2010) Impacts of and Responses to Sea-Level Rise. In: Church, J.A., Woodworth, P.L., Aarup, T. and Wilson, W.S. (eds.). Understanding Sea-Level Rise and Variability. Chichester: Wiley-Blackwell, 17-51.

Nicholls, R.J. and Cazenave, A. (2010) Sea Level Rise and its Impact on Coastal Zones. Science, 328, 1517-1520.

Nicholls, R.J. and Klein, R.J.T. (2005) Climate change and coastal management on Europe’s coast in Vermaat, J.E. et al. (eds.). Managing European Coasts: Past, Present and future. Berlin: Springer-Verlag, 199-225.

Nicholls, R.J. and Leatherman, S.P. (1995) Global sea level rise in Strzepek, K.M. and Smith, J.B. (eds.). As Climate Changes: International Impacts and Implications. Cambridge: Cambridge University Press, 92-123.

Nicholls, R.J., Birkemeier, W.A. and Lee, G. (1998) Evaluation of depth of closure using data from Duck, NC, USA. Marine Geology, 148, 179-201.

Nicholls, R.J., Wong, P.P., Burkett, V.R., Codignotto, J.O., Hay, J.E., McLean, R.F., Ragoonaden, S. and Woodroffe, C.D. (2007a) Coastal systems and low-lying areas. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 315-356.

Nicholls, R.J., Cooper, N. and Townend, I.H. (2007b) The management of coastal flooding and erosion in Thorne, C.R. et al. (Eds.). Future Flood and Coastal Erosion Risks. London: Thomas Telford, 392-413.

Nicholls, R.J., Hanson, S., Herweijer, C., Patmore, N., Hallegatte, S., Corfee-Morlot, J., Château, J. And Muir-Wood, R. (2008) Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes. OECD Environment Working Papers, No 1. Available from: www.olis.oecd.org/olis/2007doc.nsf/linkto/env-wkp(2007)1 [Accessed: 29/03/10].

NOAA (National Ocean and Atmospheric Administration) (2010) Construction Setbacks. Charleston, SC: NOAA. Available from: http://tiny.cc/ibrme [Accessed: 22/07/10].

Nordstrom, K.F. and Arens, S.M. (1998) The role of human actions in evolution and management of foredunes in The Netherlands and New Jersey, USA. Journal of Coastal Conservation, 4, 169-180.

Nordstrom, K.F., Jackson, N.L., Bruno, M.S. and de Butts, H.A. (2002) Municipal initiatives for managing dunes in coastal residential areas: a case study of Avalon, New Jersey, USA. Geomorphology, 47 (2-4), 137-152.

Nordstrom, K.F., Lampe, R. and Vandemark, L.M. (2000) Re-establishing naturally functioning dunes on developed coasts. Environmental Management, 25 (1), 37-51.

Nottage, A. and Robertson, P. (2005) The saltmarsh creation handbook: a project manager's guide to the creation of saltmarsh and intertidal mudflat. RSPB: Sandy.

NRC (National Research Council) (1992) Restoration of Aquatic Ecosystems. Washington DC: National Academy Press.

NRC (National Research Council) (1994) Restoring and Protecting Marine Habitat: The Role of Engineering and Technology. Washington DC: National Academy Press.

Omar, M. (2007) Punggol Reclamation. Singapore: National Library Singapore. Available from: http://infopedia.nl.sg/articles/SIP_1011_2008-10-28.html [Accessed: 26/07/10].

Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Hanson, C.E. (eds.) (2007) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007. Cambridge: Cambridge University Press.

Paul, B.K. (2009) Why relatively fewer people died? The case of Bangladesh's Cyclone Sidr. Natural Hazards, 50, 289-304.

Paul, B.K. and Dutt, S. (2010) Hazard warnings and responses to evacuation orders: The case of Bangladesh's Cyclone Sidr. Geographical Review, 100 (3), 336-355.

Pearce, D.W. and Turner, R.K. (1992) Benefits, estimates and environmental decision making. Paris: Organisation for Economic Cooperation and Development.

Penning-Rowsell, E.C., Johnson, C., Tunstall, S., Tapsell, S., Morris, J., Chatterton, J., Coker, A. and Green, C. (2003) The Benefits of Flood and Coastal Defence. Flood Hazard Research Centre, Middlesex University.

Pilarczyk, K. and Nuoi, N.S. (2010) Experience and Practices on Flood Control in Vietnam. Water International, 30 (1), 114-122.

Pilarczyk, K.W. (1990a) Design of seawalls and dikes – Including overview of revetments in Pilarczyk, K.W. (ed.). Coastal Protection. Rotterdam: A.A. Balkema, 197-288.

Pilarczyk, K.W. (1990b) Introduction to coastal protection in Pilarczyk, K.W. (ed.). Coastal Protection. Rotterdam: A.A. Balkema, 1-14.

Pilarczyk, K.W. (1998a) Design philosophy and methodology in Pilarczyk, K.W. (ed.). Dikes and Revetments: Design, Maintenance and Safety Assessment. Rotterdam: A.A. Balkema, 11-40.

Pilarczyk, K.W. (1998b) Other design considerations in Pilarczyk, K.W. (ed.). Dikes and Revetments: Design, Maintenance and Safety Assessment. Rotterdam: A.A. Balkema, 407-428.

Pilarczyk, K.W. (2000) Design of dikes and revetments – Dutch practice in Herbich, J.B. (ed.). Handbook of Coastal Engineering. New York: McGraw-Hill, Chapter 3.

Platong, J. (1998) Status of mangrove forests in southern Thailand. Wetlands International – Thailand Programme. Hat Yai, Thailand, Publication 5.

Powell, M. and Ringler, R. (2009) Yorklin, DE, and other cities adopt plans to protect buildings in floodplains from water in Kemp, R.L. (ed.). Cities and Water: A Handbook for Planning. Jefferson: McFarland and Company, 180-184.

Pugh, D.T. (1987) Tides, surges and mean sea level: a handbook for engineers and scientists. Chichester: John Wiley & Sons.

Pullen, T., Allsop, N.W.H., Bruce, T., Kortenhaus, A., Schüttrumpf, H. and van der Meer, J.W. (2007) EurOtop. Wave Overtopping of Sea Defences and Related Structures: Assessment Manual. Hamburg: Archive for research and technology on the North Sea and Baltic coast. Available from: www.overtopping-manual.com [Accessed: 20/08/10].

Rao, S., Radheshyam, B., Subrahmanya, K., Chandramohan, V.R., Raju, D.H., Shetty, U. and Jayappa, K.S. (2009) Failure analysis of seawalls along Karnataka coast and recent trends in coastal protection in Jayappa, K.S. and Narayana, A.C. (eds.). Coastal Environments: Problems and Perspectives. New Delhi: I.K. International Publishing House, 226-235.

Reeve, D., Chadwick, A. and Fleming, C (2004) Coastal Engineering: Processes, Theory and Design Practice. Abingdon: Spon Press.

Rupp, S. and Nicholls, R.J. (2002) Managed Realignment of Coastal Flood Defences: A Comparison between England and Germany. Middlesex: Flood Hazard Research Centre. Available from: www.safecoast.org/editor/databank/File/managed%20 realignment.pdf [Accessed: 27/07/10].

Rupp-Armstrong, S. and Nicholls, R. (forthcoming) Managed realignment and regulated tidal exchange – implications for coastal habitat adaptation in the European Union. Journal of Coastal Research, in review.

Saenger, P. and Siddiqi, N.A. (1993) Land from the sea: The mangrove Afforestation program of Bangladesh. Ocean and Coastal Management, 20, 23-39.

Saha, S.K. (2010) Soilless Cultivation for Landless People: An Alternative Livelihood Practice through Indigenous Hydroponic Agriculture in Flood-prone Bangladesh. Beppu: Ritsumeikan Asia Pacific University. Available from: http://tiny.cc/8ncx1 [Accessed: 22/07/10].

Sanò, M., Marchand, M. and Medina, R. (2010) Coastal setbacks for the Mediterranean: a challenge for ICZM. Journal of Coastal Conservation, 14, 33-39.

Sanyal, J. and Lu, X.X. (2003) Application of GIS in flood hazard mapping: a case study of Gangetic West Bengal, India. Map Asia 2003, Poster Session. Available from: http://tiny.cc/r7zci [Accessed: 21/07/10].

Schwartz, M.L. (2005) Encyclopedia of Coastal Science. The Netherlands: Springer.

Sene, K. (2008) Flood Warning, Forecasting and Emergency Response. Springer.

Sharpe, J., Hirons, G., Kew, J., Pilcher, R., Brooks, W. and Lamberth, C. (2002) Regulated Tidal Exchange: intertidal habitat without the tears. Proceedings of 37th DEFRA Conference of River and Coastal Engineers, Keele.

Sheppard, C.R.C. (2005) Coral reef coasts in Schwartz, M.L. (ed.). Encyclopedia of Coastal Science. The Netherlands: Springer, 339-342.

Shows, E.W. (1978) Florida's coastal setback line – an effort to regulate beachfront development. Coastal Management, 4 (1), 151-164.

Smith Warner International (1999) Storm Surge Mapping for Montego Bay, Jamaica. Kingston: Smith Warner International. Available from: www.oas.org.cdmp/documents/kma/mobay/mobay.htm [Accessed: 26/09/10].

Sterr, H. (2008) Assessment of Vulnerability and Adaptation to Sea-Level Rise for the Coastal Zone of Germany. Journal of Coastal Research, 24 (2), 380-393.

Stive, M.J.F., Cowell, P. and Nicholls, R. J. (2009) Beaches, cliffs and deltas in Slaymaker, O., Spencer, T. and Embleton-Hamann, C. (eds.). Geomorphology and Global Environmental Change. Cambridge: Cambridge University Press, 158-179.

Sunday, O.A. and John, T.O. (2006) Lagos shoreline change pattern: 1986-2002. American-Eurasian Journal of Scientific Research, 1 (1), 25-30.

Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L. and Nicholls, R. J. (2009) Sinking Deltas. Nature Geoscience, 2, 681-689.

Thorne, C., Evans, E. and Penning-Rowsell, E., (eds.) (2007) Future flooding and coastal erosion risks. London: Thomas Telford.

Tol, R.S.J., Klein, R.J.T. and Nicholls, R.J. (2008) Towards successful adaptation to sea level rise along Europe's coasts. Journal of Coastal Research, 24 (2), 432-442.

Tompkins, E.L., Nicholson-Cole, S.A, Hurlston, L.A., Boyd, E., Hodge, G.B., Clarke, J., Gray, G., Trotz, N. and Verlack, L. (2005) Surviving Climate Change in Small Islands: A Guidebook. Norwich: Tyndall Centre for Climate Change Research.

Townend, I. and Burgess, K. (2004) Methodology for assessing the impact of climate change upon coastal defence structures in McKee Smith, J. International Coastal Engineering Conference 2004, Lisbon, 19-24 Sept 2004. London: World Scientific.

Tri, N.H., Adger, W.N. and Kelly, P.M. (1998) Natural resource management in mitigating climate impacts: the example of mangrove restoration in Vietnam. Global Environmental Change, 8 (1), 49-61.

Turner, N. (1994) Recycling of capital dredging arisings – the Bournemouth Experience. In Papers and Proceedings, SCOPAC Conference. Inshore Dredging for Beach Replenishment? Lymington, Hampshire, October 1994.

UK POST (Parliamentary Office of Science and Technology) (2005) Postnote: Early Warnings for Natural Disasters. London: Parliamentary Office of Science and Technology. Available from: www.parliament.uk/documents/post/postpn239.pdf [Accessed: 24/08/10].

UK POST (Parliamentary Office of Science and Technology) (2009) Postnote: Coastal Management. London: Parliamentary Office of Science and Technology. Available from: www.parliament.uk/documents/post/postpn342.pdf [Accessed: 02/07/10].

UNFCCC (United Nations Framework Convention on Climate Change) (1999) Coastal Adaptation Technologies. Bonn: UNFCCC. Available from: http://unfccc.int/resource/docs/tp/tp0199.pdf [Accessed 01/07/10].

UNFCCC (United Nations Framework Convention on Climate Change) (2002) Annotated Guidelines for the Preparation of National Adaptation Plans of Action. Bonn: UNFCCC. Available from: http://unfccc.int/files/cooperation_and_support/ldc/application/pdf/annguide.pdf [Accessed: 02/10/10].

UNFCCC (United Nations Framework Convention on Climate Change) (2008) National Adaptation Programmes of Action: Summary of Projects on Coastal Zones and Marine Ecosystems Identified in Submitted NAPA as of September 2008. Bonn: UNFCCC. Available from: http://unfccc.int/files/adaptation/application/pdf/coastal_marine_e.pdf [Accessed: 08/10/10].

USACE (United States Army Corps of Engineers) (1989) Environmental Engineering for Coastal Shore Protection. Washington DC: USACE. Available from: http://140.194.76.129/publications/eng-manuals/em1110-2-1100/PartI/PartI.htm [Accessed: 29/08/10].

USACE (United States Army Corps of Engineers) (2002) Coastal Engineering Manual – Part I. Washington DC: USACE. Available from: http://140.194.76.129/publications/eng-manuals/em1110-2-1100/PartI/PartI.htm [Accessed: 27/08/10].

USACE (United States Army Corps of Engineers) (2003) Coastal Engineering Manual – Part V. Washington DC: USACE. Available from: http://140.194.76.129/publications/eng-manuals/em1110-2-1100/PartI/PartI.htm [Accessed: 27/08/10].

USAID (2009) Adapting to Coastal Climate Change: A Guidebook for Development Planners. Rhode Island: USAID. Available from: www.crc.uri.edu/download/CoastalAdaptationGuide.pdf [Accessed: 07/10/10].

van der Meer, J. (1998) Geometrical design of coastal structures in Pilarczyk, K.W. (ed.). Dikes and Revetments: Design, Maintenance and Safety Assessment. Rotterdam: A.A. Balkema, 161-176.

van Houweninge, G. and de Graauw, A. (1982) The closure of tidal basins. Coastal Engineering, 6, 331-360.

VanKoningsveld, M., Mulder, J.P.M., Stive, M.J.F., VanDerValk, L. And VanDerWeck, A.W. (2008) Living with sea level rise and climate change: A case study of the Netherlands. Journal of Coastal Research, 24 (2), 367-379.

Vellinga, P. (1983) Predictive Computational Model for Beach and Dune Erosion during Storm Surges. Delft Hydraulics Laboratory, Publication No. 294.

Vera-Cruz, D. (1972) Artificial Nourishment at Copacabana Beach. Proceedings 13th Coastal Engineering Conference. New York: ASCE, 141-163.

Walkden, M. and Dickson, M. (2008) Equilibrium erosion of soft rock shores with a shallow or absent beach under increased sea level rise. Marine Geology, 251 (1-2), 75-84.

Walkden, M.J.A. and Hall, J.W. (2005) A predictive Mesoscale model of the erosion and profile development of soft rock shores. Coastal Engineering, 52 (6), 535-563.

Water Science and Technology Board (2009) Mapping the Zone: Improving Flood Map Accuracy. Washington DC: National Academies Press.

Watson, C.C. and Johnson, M.E. (1999) Design, Implementation and Operation of a Modular Integrated Tropical Cyclone Hazard Model. AMS 23rd Conference on Hurricanes and Tropical Meteorology, Dallas, 10-15 Jan., 1999.

White, P.C.L., Godbold, J.A., Solan, M., Wiegand, J. and Holt, A.R. (2010) Ecosystem services and policy: A review of coastal wetland ecosystem services and an efficiency based framework for implementing the ecosystem approach in Harrison, R.M. and Hester, R.E. (eds.). Ecosystem Services. Cambridge: the Royal Society of Chemistry.

Williams, A. and Micallef, A. (2009) Beach Management: Principles and Practice. London: Earthscan.

Wong, P.P. and Pask, R. (2008) Atlas: Singapore and the World, 2nd ed. South Asia: Pearson Education.

Woodroffe, C. (2004) Mangrove swamp in Goudie, A.S. (ed.). Encyclopedia of Geomorphology. Volume 2. London: Routledge, 639-641.

Yim, W.W.S. (1995). Implications of Sea Level Rise for Victoria Harbour, Hong Kong. Journal of Coastal Research, Special Issue 14, 167-189.

Appendix I: Glossary

Adaptation approach	Pursuance of a protect, accommodate or retreat coastal management strategy
Adaptation technologies	The individual adaptive measures which can be applied, either on their own or as part of a portfolio of measures, to achieve an adaptation approach
Adaptation	Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (Parry et al., 2007)
Backwater effect	A rise in surface elevation of flowing water upstream from and as a result of an obstruction to flow (NALMS, 2008)
Bathymetric mapping	Surveying method which measures water depth and the shape of the seabed
Bathymetric survey	Survey of the seabed in the nearshore zone
Bathymetry	The measurement of the depth of the sea
Beach profile	Surveyed section lines perpendicular to the shoreline (CIRIA, 1996). Profiles describe beach cross-sectional shape including the area above the waterline and the underwater portion
Borrow site	A source of beach grade sediment from which, sediment is removed in order to perform beach nourishment
Coastal cell	A stretch of coastline within which beach-grade sediment movement is self-contained. Beach-grade sediment within one coastal cell is not transported or shared with adjacent cells
Coastal Squeeze	The decline of intertidal habitat quantity or quality caused when these habitats become trapped between a fixed, landward boundary such as a seawall and rising sea levels
Coral Bleaching	Stress-induced loss of the coloured algae which live within corals. This is problematic because corals depend upon these algae for nutrition and energy, and hence for growth and survival
Delta	A landform formed by the deposition of sediment at the mouth of a river where it flows into the sea
Depth of closure	The seaward limit of significant depth change along a beach profile although not the absolute limit to cross-shore transport (Nicholls et al., 1996)
Differential GPS (dGPS)	Global Positioning System with enhanced positional accuracy due to fixed control
Downdrift	A position on the shoreline which is ‘downstream’ of sediment transport caused by longshore drift

Ecological monitoring	Survey focussing on processes and indicators that show ecosystem dynamics and structures – the aim is to increase knowledge of how ecosystems work
Eco-tourism	Tourism focused on appreciation of nature rather than on built environments
Equilibrium beach profile	The preferred cross-sectional shape that a beach will assume if conditions such as the wave climate remain constant for long enough
Footprint	The area occupied by coastal infrastructure, such as a dike
Hindcast	Retrospective forecasting using proxy data
Hydrostatic pressure	The pressure which results from the weight of water; deeper waters cause greater hydrostatic pressure
Intertidal zone	The part of the shoreline between tidal extremes; intertidal areas are exposed at low tides and submerged at high tide
Longshore drift	The movement of beach-grade sediments along a coast parallel to the shoreline. It is caused by waves obliquely approaching the shore
Longshore transport	See longshore drift
Mitigation	A human intervention to either reduce the impacts of an activity or to enhance our ability to cope with those impacts
Native beach material	The sediment present on a beach before beach nourishment
Nowcasting techniques	A technique for very short-range forecasting that maps the current weather and then uses an estimate of its speed and direction of movement to forecast the weather a short period ahead (Met Office, 2010)
Propagule	A structure, such as a cutting, seed or spore that propagates a plant
Regulated tidal exchange	The use of pipes, culverts or sluice gates to allow regular tidal flushing of land situated behind a defence. The method facilitates the creation of saline or brackish habitats behind maintained sea walls (Sharpe et al., 2002)
Relative Sea Level Rise (RSLR)	Sea level rise measured with respect to the land upon which it is situated. As such, both adjustments in absolute sea level and movements of the land have the capacity to affect relative sea level. Tide gauges measure RSLR (and fall where this occurs)
Remote sensing	The science of observation without touching. Often used to refer to Earth observation from satellite platforms using electromagnetic sensors (Heywood et al., 2006)
Residual risk	The risk that remains after adaptation has been undertaken, as risk is only reduced to zero by a complete landward retreat. For example, this may refer to the risk of a storm arriving which is larger than the defence can cope with or the risk of the defence failing
Return period	An estimate of the average interval of time between events such as a flood. Longer return periods are associated with larger events
Rip-rap	Wide-graded quarry stone normally used as a protective layer to prevent erosion (Coastal Research, 2010)

Sediment budget	An accounting of gains and losses of sediment within defined boundaries over a period of time (Kana, 1995)
Side-scan sonar	Surveying method which creates a 3D image of the seafloor
Significant wave height (Hs)	The average wave height of the highest one third of waves
Sub-bottom profiling	Surveying method which identifies and measures the sediment layers that exist below the topmost seabed
Topographic survey	A survey which measures the elevation of certain points on an area of land
Total Station	A survey instrument which combines an electronic theodolite with an electronic distance meter to read the distances and angles to a certain point
Updrift	A position on the shoreline which is 'upstream' of sediment transport caused by longshore drift
Vulnerability	The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes (Parry et al., 2007)
Wetland (re)creation	As opposed to wetland restoration, which refers to the rehabilitation of previously existing wetland functions, wetland (re)creation is the practice of creating wetlands in one of two locations: (i) where they once existed, but no longer do; or (ii) where they have not existed before, but conditions are suitable for wetland creation

Appendix II: Recommended Sources for Additional Information

ABPMER (2010) OMReG: The Online Managed Realignment Guide. Southampton: ABPMER. Available from: www.abpmer.net/omreg/ [Accessed: 28/09/10].

Beca International Consultants (2010) Shore Protection Guidelines Prepared for the Government of Kiribati. Wellington: Beca International Consultants.

CIRIA (Construction Industry Research and Information Association) (1996) Beach Management Manual. CIRIA Report 153. London: Construction Industry Research and Information Association.

CIRIA (Construction Industry Research and Information Association) (2010) Beach Management Manual (2nd ed.). London: Construction Industry Research and Information Association.

Dean, R.G. (2002) Beach Nourishment Theory and Practice. Singapore: World Scientific Publishing.

FEMA (Federal Emergency Management Agency) (2003) Guidelines and specifications for flood hazard mapping partners. Washington DC: US Dept. of Homeland Security. Available from: www.fema.gov/library/viewRecord.do?id=2206 [Accessed: 28/09/10].

French, P.W. (2001) Coastal defences: Processes, Problems and Solutions. London: Routledge.

Kamphuis, J.W. (2000) Introduction to Coastal Engineering and Management. Singapore: World Scientific Publishing.

Leggett, D.J., Cooper, N. and Harvey, R. (2004) Coastal and Estuarine Managed Realignment – Design Issues. London: CIRIA.

Maharaj, R.J. (1999) Coastal Adaptation Technologies. Response to Sea Level Change. London: Commonwealth Fund for Technical Co-operation. Available from: www.sopac.org/data/virlib/NR/NR0079.pdf [Accessed: 05/07/10].

Maharaj, R.J. (2000) Guidelines for Monitoring and Evaluating Beach Erosion and Shoreline Dynamics. Report of a Training Workshop, Tarawa, Kiribati, 14-16 March 2000. Fiji: SOPAC.

Parry, M.L. Canziani, O.F. Palutikof, J.P. van der Linden P.J. and Hanson, C.E. (eds.) (2007) Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Pilarczyk, K.W. (1990) Coastal Protection. Rotterdam: A.A. Balkema.

Tompkins, E.L., Nicholson-Cole, S.A, Hurlston, L.A., Boyd, E., Hodge, G.B., Clarke, J., Gray, G., Trotz, N. and Verlack, L. (2005) Surviving Climate Change in Small Islands: A Guidebook. Norwich: Tyndall Centre for Climate Change Research.

UNFCCC (United Nations Framework Convention on Climate Change) (2002) Annotated Guideline for the Preparation of National Adaptation Plans of Action. Bonn: UNFCCC. Available from: http://unfccc.int/files/cooperation_and_support/ldc/application/pdf/annguide.pdf [Accessed: 02/10/10].

USACE (United States Army Corps of Engineers) (1989) Environmental Engineering for Coastal Shore Protection. Washington DC: USACE. Available from: http://140.194.76.129/publications/eng-manuals/em1110-2-1100/PartI/PartI.htm [Accessed: 29/08/10].

USACE (United States Army Corps of Engineers) (2008) Coastal Engineering Manual (Parts I to V). Washington DC: USACE. Available from: http://140.194.76.129/publications/eng-manuals/ [Accessed: 28/08/10].

USAID (2009) Adapting to Coastal Climate Change: A Guidebook for Development Planners. Rhode Island: USAID. Available from: www.crc.uri.edu/download/CoastalAdaptationGuide.pdf [Accessed: 07/10/10].

Sea level rise, more intense storm surges, and other climate change impacts will pose serious threats to large number of people living along the world's coasts. This guidebook covers thirteen main adaptation technologies for coastal erosion and flooding due to climate change. For each technology, the authors present a technology description, its advantages and disadvantages, costs and benefits, institutional organisation requirements and detailed examples about its application.

This guidebook is co-authored by Matthew M. Linham and Robert J. Nicholls from the University of Southampton. Professor Nicholls is one of the top international experts on coastal impacts and adaptation to climate change, with an emphasis on seal level rise. This guidebook will be a useful handbook for policy makers and coastal zone project planners.

This publication is one of the adaptation and mitigation technology guidebooks produced as part of the GEF-funded Technology Needs Assessment (TNA) project. This project is undertaken by UNEP and URC in 36 developing countries.

UNEP Risø Centre
Risø DTU National Laboratory for Sustainable Energy
http://www.uneprisoe.org/
http://tech-action.org/