Dynamic Assessment of Coastal Vulnerability and Adaptation to Sea Level Rise: An Integrated Spatial-Temporal Decision Making Approach

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DECLARATION

This work has not been previously submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

Oz Sahin
June 2011
There are so many people I need to thank for their guidance and support in conducting this research study. The completion of my PhD would not have been possible without them. I appreciate everyone’s help and encouragement given along the way.

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The following peer reviewed publications were produced to disseminate the concept and results of the research presented in this thesis:

**International Conference Publications**


International Journal Publications

KEY TERMS AND ABBREVIATIONS

KEY TERMS

The most commonly used key terms throughout this thesis have been defined, briefly, below, in alphabetical order, to aid the reader in better understanding the context of the subject matter. While most definitions have been taken from the IPCC Glossary (Parry et al., 2007), a full list of the key terms and their definitions is presented in Appendix 1.

Adaptation: All those responses to climate change that may be used to reduce vulnerability or to actions designed to take advantage of new opportunities that may arise as a result of climate change.

Analytic Hierarchy Process (AHP) - An MCDA technique, developed by Thomas Saaty. The AHP provides the objective mathematics to process the inescapably subjective and personal preferences of an individual or a group in making decision (Saaty, 2001).

Climate: In a narrow sense, the terms describe the "average weather," or more rigorously, it is the statistical description (in terms of the mean and variability) of relevant quantities over a period of time, ranging from months to thousands of years.

Climate Change: A term to describe any change in climate over time, whether due to natural variability or as a result of human activity.

Exposure: The nature and degree to which a system is exposed to significant climatic variations.

Exposure Unit: An activity, group, region, or resource that is subjected to climatic stimuli.

Flooding: A term to describe the temporary submergence of land from which either partial, or total, recovery may occur.
**Geographical Information Systems:** A Geographic Information System (GIS) is mapping software that provides spatial information by linking locations with information about that location. It provides the functions and tools needed to efficiently capture, store, manipulate, analyse, and display the information about places and things (Geoscience Australia, 2008).

**Impacts:** The consequences of climate change on natural and human systems.

**Inundation:** Permanent loss of land or flooding that is so frequent that no recovery is likely. A flood frequency of greater than once per year is often a good threshold value, to distinguish frequent flooding from inundation, but site-specific judgements based on the likely response may be necessary.

**Model:** In its broadest sense, a representation of how a system works, or responds to inputs, and may be used as a basis of risk assessment, analysis or management by decision-makers. A model may be anything from a conceptual framework through to a fully parameterised and validated numerical representation of a system implemented on a computer.

**Scenario:** A coherent, internally consistent and plausible description of a possible future state of the world, usually based on specific assumptions.

**Sensitivity analysis:** A structured approach to investigate how a system, model or assessment responds to small changes in input values, parameter values or other assumptions. Sensitivity analysis is used to identify those input values, parameters or model assumptions that have the most significant impact on the outputs or responses.

**Sensitivity:** The degree to which a system is affected, either adversely or beneficially, by climate-related stimuli (change or extremes).

**Storm surge:** A region of elevated sea level at the coast caused by the combined influence of low pressure and high winds associated with a severe storm such as a tropical cyclone.

**System:** The social, economic and physical domain within which risks arise, produce consequences, and in which risks are managed.
System Dynamics: a method for studying the world around us. It deals with understanding how complex systems change over time. Internal feedback loops within the structure of the system influence the entire system behaviour (SDEP, 2010).

Uncertainty: A characteristic of a system or decision where the probabilities that certain states or outcomes have occurred or may occur is not precisely known. It refers to a concept that reflects a lack of confidence about something, including forecasts. Decision-makers may have more or less certain knowledge of a risk.

Vulnerability Assessment (VA): An analysis of the scope and severity of the potential effects of climate change impact (generally sea level rise).

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. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.
ABBREVIATIONS


CR: Consistency Ratio

CSIRO: Commonwealth Scientific and Industrial Research Organisation

DM: Decision maker

DSM: Dynamic Spatial Model

GIS: Geographical Information Systems

IPCC: Intergovernmental Panel on Climate Change

MCDA: Multiple-Criteria Decision Aid

SD: System Dynamics

SLR: Sea Level Rise

ABSTRACT

As the globe continues to warm, coastal communities across the world will increasingly be faced with rising sea levels, as well as changes in storm surge frequency and magnitude. Significantly, most infrastructure, settlements and facilities are located near the coast. While coastal communities have benefitted from the many advantages of living and working in these areas, inevitably they also face the threat of natural disasters. With concern for the consequences of sea level rise (SLR) and associated storm surge (SS), the primary, and most urgent topics for decision makers are the assessment of vulnerability and the evaluation of adaptation measures. However, due to uncertainty in climate change predictions, many vulnerability and adaptation assessments and most town planning activities, which are based on an the assumption that the sea level will remain stable in the future, are in a state of flux. Added to the dilemma is the realisation that the impacts of SLR will, most likely, be spatially non-uniform across the world. It is therefore essential for decision-makers to consider the dynamic and spatial characteristics of these changes in assessing the impacts of SLR when making decisions about future infrastructure and community life.

With the acknowledgement of the uncertain and dynamic nature of coastal systems, as well as to address these dilemmas, the aim of this PhD research is to provide an integrated approach, incorporating Geographic Information System (GIS), System Dynamics (SD), and Multiple Criteria Decision Aid (MCDA) approaches.

The primary objectives of the research, divided into two segments, are: 1) To develop a dynamic model to assess the present and future vulnerability of coastal populations and properties to SLR and SS, based on various SLR scenarios; and 2) To identify and evaluate adaptation options for coastal areas in order to cope with altering climatic condition scenarios using an MCDA model. The secondary objective is to implement the proposed models for a coastal area.
The research focuses on the development of the conceptual framework for inundation, which is later used as the fundamental structure for the Dynamic Spatial Model (DSM) design. The DSM design comprises three separate models; (1) the temporal component; (2) the spatial model component; and (3) the file monitor and data convertor. The technical focus centres on demonstrating one of the practical ways in which the functionalities of GIS and SD can be enhanced through their integration for building a hybrid DSM. This outcome is achieved by integrating, through a loose coupling, the ArcInfo® GIS software with the Vensim DSS® simulation software. The coupling requires the transfer of data between the GIS and SD models. For this purpose, data convertor software is written in C++ under Visual Studio 2008, using the Microsoft.NET version 2.0. Thus, the format transition between the ArcGIS and SD data formats was automated using the data converter.

Finally, the output from the DSM is used to inform the decision making process using the MCDA. To prioritise the adaption alternatives, three stakeholders’ groups (Residents, Experts, and Politicians) are identified and consulted.

The development of the DSM achieved the first primary research objective, while the MCDA based decision model achieved the second objective. The DSM model is tested, and then the sensitivity analyses are performed for the decision model. The results show that the behaviour of the simulation model is stable and consistent with its conceptual design. Thus, the model is robust and capable of reflecting, accurately, the coastal inundation process.

In summary, this thesis presents an integrated approach that has the capability to: 1) generate important spatial-temporal information required by decision makers (DMs); 2) provide new insights into complex coastal systems; 3) address multi-criteria decision problems involving multiple stakeholders; 4) enable DMs to examine decision alternatives through the use of the Dynamic Spatial Model (DSM); and 5) address uncertainties and generate alternative scenarios, based on different user inputs.
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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Modern societies are becoming more complex and are changing faster than ever. Additionally, it is increasingly unclear what the future world will look like under changing climatic conditions. Indeed, there is overwhelming scientific consensus that global climate change is occurring, as identified in the four International Panel on Climate Change (IPCC) reports published in 1990, 1995, 2001 and 2007, respectively. In its 2007 report, the IPCC states that the warming of the climate system is unequivocal. Three years earlier, a study by Naomi Oreskes (2004) demonstrated that the scientific consensus on global warming was commanding. Oreskes’ paper reviewed 928 studies published in refereed scientific journals between 1993 and 2003. The authors of all papers were in agreement with the IPCC, the National Academy of Sciences (NAS), and public statements issued by their professional (Oreskes, 2004).

Despite this wide-ranging consensus, there are still climate change uncertainties that require further scientific and technical study as stated by the IPCC in its 2007 report. Regrettably, such work may take decades. Thus, the question arises, “Do we have to wait to dot every scientific i and cross every technical t?”, especially when the scientific community has, overwhelmingly, accepted that there is ample information and data currently available to justify taking action now, without further delay.

While the scientific community may be cognisant of all the climate change (CC) information; there is a need, however, for communities to have more accessible and accurate information so that they can improve their understanding of how changing climate is likely affect where they live, their environment and their surroundings. It is only with such knowledge can more effective adaptation strategies be developed. Currently, researchers infer assumptions about how communities would make what
choices under various climate change scenarios. From these suppositions, the researchers develop tools and models to assist communities to make informed decisions. However, the assumptions and, hence, the tools and models, may fail to reflect the true process used by communities to make their decisions or choices.

For this reason, the current research aims to provide an integrated five dimensional decision making approach that will ensure a more appropriate procedure by which to assess the communities’ vulnerability and adaption to rising sea levels. The study will incorporate the use of Geographic Information System (GIS), System Dynamics (SD) simulation, and multiple criteria decision aid (MCDA) modelling approaches. The outcome will provide decision makers with a powerful methodology to assist in acquiring better data that will inform the development and selection of appropriate adaptation strategies.
1.2 RESEARCH RATIONALE

It is broadly accepted that sea level rise (SLR) due to CC will intensify the stress on many coastal zones, particularly those where human activities have diminished natural and socio-economic adaptive capacities (Nicholls et al., 2007). For example, as will be discussed in Chapter II, the IPCC projected that the global mean sea level may rise between 0.18 and 0.59 m by 2090–2099 from the level recorded from 1980–1999 (Meehl et al., 2007). However, these projections do not include the possible contributions from the melting of the Greenland and Antarctica Ice Sheets. If these contributions are taken into account, then the upper ranges of SLR for SRES (The Special Report on Emissions) scenarios will further increase by 10 to 20 cm. A new empirical analysis, published after the conclusion of the IPCC 4th Assessment Report (4AR) suggests a even higher SLR range, namely: 0.50 to 1.40 m for 2100, above the 1990 level (Rahmstorf, 2007).

Furthermore, the SLR is expected to continue to rise for many centuries, even if the atmospheric greenhouse gas concentrations are stabilised at relatively low levels (Nicholls and Lowe, 2004, Church et al., 2001). As a consequence, SLR will exacerbate the vulnerability of coastal populations and ecosystems via the permanent inundation of low-lying regions, the extension of inland episodic flooding, increased beach erosion, and saline intrusion of aquifers (McLean et al., 2001).

Sea level change, however, is a very complex and dynamic process, which reflects the interaction between the local, regional and global contributions arising from both land and ocean processes (Cooper et al., 2008). As noted in the IPCC 4AR, changes in relative sea level can take place if there is a local increase in the level of the ocean relative to the land; such an increase may occur from either a rise in the ocean and/or a subsidence from the land into the ocean.

Nevertheless, no matter what the source of the rise in ocean level, a SLR is a reality that affects coastal areas exposed to a range of physical effects related to the SLR. These effects include: coastal erosion, inundation and displacement of wetlands and lowlands, increased coastal storm flooding and damage, increased salinity of estuaries and aquifers, and increased sea surface temperature. As a consequence, the ripple
effect from the physical impacts may result in socioeconomic impacts on the coastal zone, such as loss of properties and coastal habitats, as well as the loss of tourism, recreation and transportation functions (Figure 1-1).

![Conceptual model of CC effects on coastal regions due to SLR and storm tides](image)

Figure 1-1 Conceptual model of CC effects on coastal regions due to SLR and storm tides

However, SLR is not the only pressure that affects the coastal systems. Non-climatic drivers, such as a growing population and land use changes, can also amplify the SLR related impacts on coastal areas. For this reason, non-climatic factors should be included in any impact assessments of SLR on coastal systems.

More recently, significant human activities and population growth have taken, and are taking, place in coastal areas. According to Brooks et al., (2006) it is widely known that SLR will have profound implications for many existing coastal populations and the systems on which they depend. Indeed, the land areas bordering the shorelines are...
associated with large and growing concentrations of human populations, settlements and socio-economic activities. Such growth has a significant effect on the strategies required to manage the rise in sea level. For example, worldwide, the near-coastal population (within 100 km of a shoreline and 100 m of the sea level) has been estimated at 1.2 billion people, with an average density nearly three times higher than the global average density (Small and Nicholls, 2003). Further, Chen and McAneney (2006) postulate that about half of Australia’s population lives within 7 km of the coast, with as many as 30% of the population, or about six million people, living within 2 km of the coast.

While the SLR, at the currently estimated rate, will not pose an immediate threat to coastal areas, a higher sea level will provide a higher base from which storm surges can build and cause considerable damage. The higher mean sea levels will enable storm surges to inundate and penetrate further inland, with damaging waves, that will increase the frequency and extent of flooding and erosion, as well as subsequent destructive impacts on the built infrastructure and natural ecosystems (Pearce et al., 2007).

![Figure 1-2 Relationships between SLR and storm events.](image)

With a rising sea level, the current 1:100 year storm events are expected could occur more frequently (McInnes et al., 2000). For instance, a flood plain, currently subjected to 1:100 year storm events, may become subject to 1-in-10 year storm events, with only a 1 m sea level rise, as shown in Figure 1-2. Further, properties, which are
currently above of the existing floodplain, would become inundated with 1:100 storm on top of a 1-m sea level rise. Therefore, it is imperative that coastal communities take into account future sea level rises when planning for the future, especially in terms of infrastructure development.

Present community, scientific and administrative concerns about the consequences of SLR, and related storm events, indicate the urgent need to develop and implement methodologies that will accurately assess the vulnerability of coastal systems to climate change. The data collected from such assessments will support the creation of effective policy responses to reduce climate-change-related risks (McFadden et al., 2006).

However, as Klein and Nicholls (1998) note, there is a difficulty with developing an overarching policy, as the effects of SLR will be spatially non-uniform. This problem arises because of the difference in the regional oceanographic responses to global warming, as well as differences in the regional uplift or subsidence of the land surface. Thus, while some regions may experience larger local SLRs earlier than the global mean, the SLR elsewhere may be well below the global mean, or may record a fall (Yin et al., 2010). Even neighbouring coastal areas may record differing levels, a result of widely varying geographical, socioeconomic and environmental factors. As a consequence, vulnerability and adaptation issues must be addressed, at local level, according to regional characteristics. Therefore, each coastal community will have the responsibility to assess their own conditions related to SLR and, in response to the assessment results, develop suitable response strategies that will reduce or eliminate most, if not all, adverse impacts from changes in the local climatic conditions.

Numerous studies have focused on assessing coastal vulnerability to climate change on a national and global scale. However availability of regional scale comprehensive vulnerability assessments studies, which are required by local stakeholders to design adaptation strategies at a local level, are limited (Torresan et al., 2008, Cooper et al., 2008). A case study in Germany in 2003 showed that county level (macro-scale) vulnerability assessments are neither specific, nor conclusive, enough for local authorities to use as a base from which to design area-specific adaptation strategies; more detailed community based (micro scale) analyses, therefore, are required to
provide the desired information (Sterr et al., 2003). Consequently, decisions of how to respond to a given threat, for example by building a seawall or enhancing beach nourishment activities, must be based on community-based assessments of flooding or erosion risks.

According to the IPCC Third Assessment Report (TAR), low-lying coastal settlements in Australia and New Zealand are regarded as highly vulnerable to high sea level and storm events (Pittock and Wratt, 2001). The TAR, confirmed by the IPCC 4AR, concludes that coastal communities will face enormous risks, with far reaching consequences, due to the occurrence of greater coastal inundation and erosion, especially in regions exposed to cyclones and storm surges (Hennessy et al., 2007). It is for this reason that the IPCC 4AR has recommended that communities undertake comprehensive assessments of their vulnerability and adaptation options, especially coastal communities, to provide improved guidance for planning and hazard management. Additionally, such locally based research and community engagement is a crucial step in the process, as each community will hold different attitudes and display different behaviours that will influence the decisions made in relation to the new adaptation policies. Therefore, it is essential to develop a flexible and well-structured method that will enable the collection of relevant information needed to design the most effective adaptation options and the best management plans to reduce the adverse effects of SLR.

In light of the above observations and studies and in line with the need of regional scale analysis, this PhD study focuses on developing a dynamic model to assess present and future vulnerability of coastal areas to SLR and storm events. It will subsequently examine and evaluate adaptation alternatives for reducing the adverse effects of SLR in coastal areas. The concepts of vulnerability and dynamic model will be discussed later in this thesis.
1.3 APPROACH

Figure 1-3, below, presents the input, research activity and expected output for each step of the research. The research constitutes a systematic assessment of coastal vulnerability to SLR and associated storm events. Further, the study evaluates alternatives for an anticipatory response strategy by utilising the following approach:

1. Compilation of knowledge from extensive literature review: Gain understanding of global climate change theories, and focus on three projected physical and socio-economic impacts of global climate change most likely to be experienced in coastal areas at the local level: change in shoreline position, accelerated inundation of land areas, and people at risk.

2. Conceptual model development: Identify the problem and understand the modelling process.

3. Data gathering: Collection information for vulnerability and adaptation assessments.

4. Assess vulnerability: Use of a range of SLR scenarios to assess vulnerability by employing a modular (put in full, DSM), which consists of a spatial model (GIS) and a temporal model (system dynamics, SD). Vulnerability in this study is defined as both people-at-risk and the loss of property due to the exposure to SLR and related storm surges. Therefore, the research focuses on natural and socio-economic systems that are already vulnerable to climate variability. The study analyses their current conditions and, then, the systems are analysed under various scenarios to identify how a rise in sea level will affect the already distressed systems, over time.

5. Alternatives assessed: Using the findings from the vulnerability assessments, the identification and evaluation of various adaption alternatives are assessed using multi-actor multiple-criteria decision analysis (MCDA) to develop strategies that will mitigate the impacts of accelerated sea level rise.

6. Refine and evaluate the approach: The approach is refined and evaluated by modifying the model to test and compare the findings of the DSM with the results of the MCDA, and so discern if the preferred adaptation strategies provide an adequate and effective solution.
7. Providing conclusion based on the research findings.

Figure 1-3 Flowchart for research activities and expected outcomes

The realisation of the research objective relies on successful completion of each step.
1.4 LAYOUT OF THESIS

The thesis comprises eight chapters, grouped into three main parts. It also has an accompanying CD-ROM, which contains PowerPoint files showing the simulation results, the file monitor and data convertor software (developed as part of this research), and sample SD and GIS datasets.

Figure 1-4 illustrates the research stages, organised as subsequent chapters of the thesis. The research, typically a cyclical process, links both theory and practice. This approach suits environmental research, where situations are complex and require the introduction of changes into the research agenda, the observation of the effects, and the revision of the process, when necessary.

![Diagram of thesis layout](image-url)
Following the introduction to the research study **Chapter 1**, an extensive review of the relevant literature was undertaken to gain a fuller understanding of climate change, response strategies, and modelling approaches used to assess the impact of a changing climate. These constitute the first part of thesis (Chapters 2 and 3).

**Chapter 2** is divided into 2 parts. Part A provides an overview of climate change science, including: the causes of the observed changes in the climate, the projection of future climate change under different scenarios, and related impacts, as well as the causes of the sea level rise and related implications. Part B discusses response strategies to climate change. It also provides an up-to-date overview of mitigation and adaptation strategies, and their interactions, and the vulnerability assessment approaches.

**Chapter 3** presents a discussion for the nature of the environmental problems of climate change and SLR; it also provides detailed information about the environmental modelling and decision making approaches.

The second part of the thesis (Chapters 4 to 5) focuses on the research itself, namely, research objectives, design and methodology.

**Chapter 4** defines the research objectives and identifies the research questions, based on previous chapters.

**Chapter 5** discusses the research methodology in detail. First, the general research approach is explained; second, the treatment of uncertainties surrounding vulnerability and decision analyses are described; third, the Dynamic Spatial Modelling (DSM) concept for vulnerability assessment, and the Multiple Criteria Decision Analysis (MCDA) technique for assessing adaption strategies, presented in detail.

The third part of the thesis presents the application of the approach, and model refinement and evaluation (Chapters 6 and 7).

**Chapter 6** is devoted to testing the approach in a coastal area. The implementation of the model provides insight into the practical application of the model in a real world context.
Chapter 7, based on the results of model testing in previous chapter, refines the model by comparing the modified simulation results with the results from the first model and the decision model. A model evaluation is also presented.

Chapter 8 summarises the thesis conclusions and contributions, identifies the limitations of the research, and provides recommendations for future study.
CHAPTER 2

LITERATURE REVIEW - A: CLIMATE CHANGE OVERVIEW

2.1 INTRODUCTION

The overwhelming majority of climate scientists accept that climate change is occurring. Indeed, the scientific understanding of climate change is now sufficiently clear and documented to rationalize that communities should take action, without delay, to mitigate or reduce impacts from such change (The National Academies, 2005). However, there are still a range of uncertainties related to the rate of change and the negative impacts in terms of scale, timing and spatial distribution. As a consequence, there is much scientific and technical work to be undertaken to determine how and when to overcome such uncertainties. Hence, this chapter (Chapter 2) aims to provide a context for climate change, its effects and response strategies, based on the available relevant scientific literature. The chapter does not attempt to shed further light on the physical science of climate change, nor does it cover all the issues incorporated within the term climate science.

The literature has been divided into two sections. Section one provides an overview of the drivers for climate change, lists the observed changes to the climate, projects future changes, and their consequences in the light of recent scientific findings. Specifically, the review will report on the observed climate changes, and the implications of a rise in sea level. The second section focuses on climate change response strategies, especially those related to the impacts on natural and human systems, and vulnerability and adaptation assessments.

2.2 UNDERSTANDING CLIMATE CHANGE

Climate plays an important role in shaping the environment, natural resources, infrastructure, and the economy, as well as other aspects of life in all countries around
the world. Therefore, any variations or changes in the climate can have substantial environmental and socioeconomic implications. Additionally, the climate change processes encompass both human affairs and the climate system in a complex interplay on time scales ranging from the instantaneous to millennia (Aldy et al., 2003). For this reason, climate change and its negative impacts are among the most serious problems to have faced humanity and global sustainable development. Perhaps this is why there are many international, regional and national organizations and institutions that focused on these issues.

In 2007, the Intergovernmental Panel on Climate Change (IPCC) reported that most of the observed increases in global average temperatures, since the mid-20th century, are, very likely, due to the observed increase in anthropogenic (man-made) greenhouse gas concentrations (Solomon et al., 2007b). Using simple energy-balance calculations, Stern (2006) posited that the direct warming effect of the doubling of CO² concentrations would be greater than the 1°C surface warming estimation posed at that time. The change in estimation simply reflects the interaction between the feedbacks in the atmosphere that act to amplify or dampen the direct warming, as illustrated in Figure 2-1.

![Figure 2-1 The link between GHG and climate change (Stern, 2006)](image)

Changes in the atmospheric abundance of greenhouse gases and aerosols, as well as changes in solar radiation and in land surface properties, alter the energy balance of the climate system (Forster et al., 2007). These changes, expressed in terms of
radiative forcing are used to compare how a range of human and natural factors affect the global average temperature.

Figure 2-2 shows the principal components of the radiative forcing (RF) of climate change together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The RF is a measure of the influence of a driving factor. RF is a measure of the influence of a driving factor. The RF value is for the year 2005, relative to the pre-industrial conditions in the year 1750; it is expressed in watts per square (W m²). Changes in RF values associated with human activities appear to be far greater than natural factors.

Unquestionably, human activities have been changing the atmospheric composition and surface properties of the Earth. Concerned that these human-made alterations would substantially alter the Earth’s climate, the United Nations Framework Convention on Climate Change Human activities have been changing atmospheric composition and surface properties of the Earth. Concerned that these human-made alterations could substantially alter the Earth’s climate, the United Nations Framework Convention on Climate Change, under the Article 2, declared (UNFCCC, 1992) that;
“The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.”

To obtain a deeper knowledge of the climate change issues, first, it is necessary to understand the difference between climate and weather. Smit et al., (2000) explain that, while weather consists of the short-term (minutes to about 15 days) variations of the atmosphere, climate, on the other hand, describes the weather averaged over long periods, and consisting of patterns, such as the frequency and intensity of storms, cold outbreaks, and heat waves. The distinction between weather and climate is, however, insufficient to capture the array of climate stimuli and temporal scales pertinent for the analysis of the impacts and adaptations (Smit et al., 2000).

Climate change, as defined by the IPCC, refers to any change in climate over time, due to either natural variability or as a result of human activity (Parry et al., 2007). This usage differs from that of the United Nations Framework Convention on Climate Change (UNFCC). The UNFCC Article 1 defines climate change as (UNFCCC, 1992);

“a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods’.

The UNFCCC makes a distinction between “climate change” attributable to human activities that alter the atmospheric composition, and “climate variability” that is attributable to natural causes. As described in the IPCC’s Fourth Assessment Report (4AR), Climate Variability refers to the variations in the mean state, and other statistics (such as standard deviations, statistics of extremes, etc.), of the climate on all temporal and spatial scales beyond that of individual weather events (Parry et al., 2007).
The key stages of the climate change cycle, attributed to human activities, and that generate GHGs (greenhouse gases), which impact upon human and natural systems, are shown in Figure 2-3. The cycle has five stages (Aldy et al., 2003);

Stage 1- The cycle begins with human activities.

Stage 2 - Total global emissions increase as a result of human activities.

Stage 3 - Rapid emissions growth leads to a rise in the concentrations of GHGs in the atmosphere.

Stage 4 - Rising concentrations enhance the natural greenhouse effect that warms the planet, leading to rising average temperatures.

Stage 5 - Rising global temperatures, in turn, have impacts on human and natural systems.

Figure 2-3 The Physical processes and causal links in the climate change cycle (Reproduced from Aldy et al., 2003)

The climate system is a dynamic and interactive system influenced by various external and internal mechanisms, as shown in Figure 2-4. The external factors include variations between incoming solar radiation and outgoing infrared radiation, long period changes in the Earth’s orbital elements and human activities changing radiative
balance through anthropogenic emissions of greenhouse gases. While the Sun is the most important external mechanism, the direct effect of human activities on the climate system is also considered as an external force (Le Treut et al., 2007). The internal factors include interactions among the components of the climate system and natural internal processes such as the El Nino southern oscillation.

The Earth’s global mean climate is determined by incoming energy from the Sun and by the properties of the Earth and its atmosphere, namely the reflection, absorption and emission of energy, within the atmosphere and at the surface (Solomon et al., 2007a). Thus the Earth’s climate is the result of dynamic balances in the flows of energy, when averaged over sufficiently large time and space scales. This energy exchange between the Earth and space occurs through thermal radiation.

![Figure 2-4 Schematic view of the components the climate system, their processes and interactions (Moss et al., 2010)](image)

The atmospheric trace gases that keep the Earth warm are known as greenhouse gases (GHG), such as carbon dioxide, water vapour, and methane. GHGs are able to change the energy balance of the planet by absorbing long-wave radiation emitted from the Earth's surface. Higher concentrations of GHGs in the Earth's atmosphere lead to the
increased trapping of infrared radiation. As a result, the lower atmosphere is likely to warm, changing both the weather and the climate (Holper, 2001).

As shown in Figure 2-5, GHGs absorb and emit infrared radiation over the long term. However, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing long-wave radiation. (Le Treut et al., 2007)

Anthropogenic GHGs, which are well-measured, cause a strong positive forcing (warming) (Hansen et al., 1998). Additionally, rising levels of GHG are expected to cause climate change by absorbing infrared radiation, these gases control the flow of natural energy through the climate system (UNFCCC, 2002).

The recent completion of drilling at the Vostok station in East Antarctica in 1998 shows that present-day levels of CO₂ (approx 360 p.p.m.v. and approx 1,700 p.p.b.v., respectively) are unprecedented over the past 420,000 years (Petit et al., 1999). Indeed, the Fourth Assessment Report (4AR) of the IPCC reports that Global atmospheric concentrations of GHGs have increased markedly as a result of human activities over the last 10,000 years (large panels) and since 1750 (inset panels) and now far exceed the pre-industrial values determined from ice cores spanning many thousands of years, as shown in Figure 2-6.
A wide range of direct and indirect measurements confirm that the atmospheric mixing ratio of CO\textsubscript{2} has increased globally by about 100 ppm (36\%) over the last 250 years, from a range of 275 to 285 ppm in the pre-industrial era (AD 1000–1750) to 379 ppm in 2005 (Forster et al., 2007). The current rate of atmospheric CO\textsubscript{2} accumulation (~1.8 ppm/year) is about 2–3 times that of the early 1960s (Preston and Jones, 2006).

Figure 2-6 Atmospheric concentrations of GHGs (Solomon et al., 2007b)

Although the ultimate objective of UNFCCC (1992) is expressed as “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference (DAI)”, the UNFCC does not define the thresholds for CO\textsubscript{2} that would be considered dangerous. However, in order to stabilise the concentration of GHGs in the atmosphere, emissions would need to peak and decline thereafter. The lower the stabilisation level, the more quickly this peak and decline would need to occur (Figure 2-7 and Table 2-1).

Figure 2-7 CO\textsubscript{2} emissions and equilibrium temperature increases for a range of stabilisation levels (IPCC Synthesis Report 2007)
Various climate institutions and scientists have defined the global thresholds for dangerous CO$_2$ levels in the atmosphere ranging from 375 - 550 ppm (parts per million). Nevertheless, it has been suggested that a value nearer to 350 ppm should be adopted, until it can be proven that a higher value is safe (Azar and Rodhe, 1997). Further, the Royal Commission on Environmental Pollution UK proposes that an atmospheric carbon dioxide concentration of 550 parts per million by volume (ppm) – approximately double the pre-industrial level – should be regarded as a limit which should not be exceeded (Royal Commission on Environmental Pollution, 2000).

Another study (Hansen et al., 2007a), ten years later, indicates that a CO$_2$ level exceeding ~450 ppm is almost surely dangerous, and the ceiling may be even lower. Exceeding this dangerous level - 450 ppm CO$_2$ in the atmosphere (a greenhouse gas) will trigger dangerous climate change with potentially irreversible glacial melt and rapid sea level rise. With GHGs continuing to increase, the planetary energy imbalance provides ample energy to melt ice corresponding to several metres of sea level per century (Hansen et al., 2007b). According to data taken from the National Oceanic and

Table 2-1 The required emission levels for different groups of stabilisation concentrations (IPCC Synthesis Report 2007)

<table>
<thead>
<tr>
<th>Category</th>
<th>CO$_2$ concentration at stabilisation (2005=379)</th>
<th>CO$_2$ equivalent at stabilisation including GHGs and aerosols (2005=379)</th>
<th>Peaking year for CO$_2$ emissions</th>
<th>Change in CO$_2$ emissions in 2050 (per cent of 2000 emissions)</th>
<th>Global average temperature increase above pre-industrial at equilibrium, using best estimate climate sensitivity</th>
<th>Global average SLR above pre-industrial at equilibrium from thermal expansion only</th>
<th>Number of assessed scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>350-400</td>
<td>445-490</td>
<td>2000-2015</td>
<td>-85 to -50</td>
<td>2.0 – 2.4</td>
<td>0.14 – 1.4</td>
<td>6</td>
</tr>
<tr>
<td>II</td>
<td>400-440</td>
<td>490-535</td>
<td>2000-2020</td>
<td>-60 to -30</td>
<td>2.4 – 2.8</td>
<td>0.5 – 1.7</td>
<td>18</td>
</tr>
<tr>
<td>III</td>
<td>440-485</td>
<td>535-590</td>
<td>2010-2030</td>
<td>-30 to +5</td>
<td>2.8 – 3.2</td>
<td>0.6 – 1.9</td>
<td>21</td>
</tr>
<tr>
<td>IV</td>
<td>485-570</td>
<td>590-710</td>
<td>2020-2060</td>
<td>+10 to +60</td>
<td>3.2 – 4.0</td>
<td>0.6 – 2.4</td>
<td>118</td>
</tr>
<tr>
<td>V</td>
<td>570-660</td>
<td>710-855</td>
<td>2050-2080</td>
<td>+25 to +85</td>
<td>4.0 – 4.9</td>
<td>0.8 – 2.9</td>
<td>9</td>
</tr>
<tr>
<td>VI</td>
<td>660-790</td>
<td>855-1130</td>
<td>2060-2090</td>
<td>+90 to +140</td>
<td>4.9 – 6.1</td>
<td>1.0 – 3.7</td>
<td>5</td>
</tr>
</tbody>
</table>
Atmospheric Administration Earth System Research Laboratory in September 2010, the CO₂ concentration level has already reached 386.3 ppm (Tans, 2010).

Cao and Caldeira (2008) examined the consequences of stabilizing atmospheric CO₂ at different levels for ocean chemistry. They estimated that the potential for major damage to at least some ocean ecosystems, at atmospheric CO₂ stabilization levels is as low as 450 ppm (Cao and Caldeira, 2008). Furthermore, the addition of greenhouse gases and aerosols to the atmosphere has changed its composition. These changes appear to be influenced by temperature, precipitation, storms and sea level (Solomon et al., 2007b). Clearly, therefore, the international community requires strong political commitment to limit global warming by stabilising radiative forcing from CO₂ and other GHGs in the atmosphere.

### 2.3 Observed Changes in Climate

As noted by Forster et al. (2007), composition of atmosphere has been changed by GHGs. The changes in the atmosphere have likely influenced temperature, precipitation, storms and sea level (Forster et al., 2007). Long-term changes in climate have been observed such as changes in arctic temperatures and ice, surface temperature, sea level rise (SLR) and associated extreme events. According to (Hegerl et al., 2007), many of the observed changes in surface, free atmospheric, and ocean temperatures, and sea ice extent, as well as some large-scale changes in the atmospheric circulation over the 20th century, are distinct from internal variability changes, but they are consistent with the expected response to anthropogenic forcing.

There is a general consensus among scientists and decision-makers that the climate is significantly and inevitably changing. Some key climate change evidence and related aspects, reported in the IPCC–4AR WG1, are the following summary (Trenberth et al., 2007, Lemke et al., 2007, Bindoff et al., 2007):

- The rate of warming over the last 50 years is almost double that over the last 100 years \((0.13°C ± 0.03°C) vs. (0.07°C ± 0.02°C) per decade\).
- Average arctic temperatures have increased at almost twice the global average rate in the past 100 years
Over the period 1961 to 2003, global ocean temperatures have risen by 0.10°C from the surface to a depth of 700 m.

The global mean sea level has been rising; thus, for the period 1993 to 2003, the rate of SLR is estimated (from observations with satellite altimetry) as 3.1 ± 0.7 mm yr⁻¹, significantly higher than the average rate.

Substantial increases have been found in heavy precipitation events.

Intense tropical cyclone activity has increased from about 1970.

Snow cover has decreased in most regions, especially in Spring and Summer.

2.3.1 CHANGES IN SURFACE TEMPERATURE

The IPCC concluded, in 2007, that the warming of the climate system is now "unequivocal", based on observations of increases in global average air and ocean temperatures, the widespread melting of snow and ice, and rising global average sea levels (Solomon et al., 2007b). Since the start of the industrial era (about 1750), the overall effect of human impact on the climate greatly exceeds that expected from known changes in natural processes, such as solar changes and volcanic eruptions (Forster et al., 2007). Therefore, it can be posited that human activity has significantly added to the amount of heat-trapping greenhouse gases in the atmosphere (Figure 2-8). As a consequence, human activity is ‘forcing’ the system in a new way. Hence, the current concentrations of key greenhouse gases, and their rates of change, are unprecedented.

Figure 2-8 Atmospheric concentrations of GHG between 0 – 2005 (Forster et al., 2007)
According to Trenberth et al. (2007), between 1906 and 2005, the global average surface temperature has increased by about 0.74°C (Figure 2-9). Further, while there was not much overall change from 1850 to approximately 1915, an increase (0.35°C) did occur in the global average temperature from the 1910s to the 1940s, followed by a slight cooling (0.1°C), and then a rapid warming (0.55°C) up to the end of 2006. Significantly, the warmest years of the series are 1998 and 2005, and 11 of the 12 warmest years have occurred in the last 12 years between 1995 to 2006 (Trenberth et al., 2007).

In Figure 2-9, Black dots show changes in annual global mean temperatures. The left hand axis shows anomalies relative to the 1961 to 1990 average and the right hand axis shows the estimated actual temperature (Trenberth et al., 2007).

The rate of annual warming for global land areas over the 1901–2000 period is estimated by least squares to be 0.07 °C per decade (being significant at better than the 99.9% level) (Jones and Moberg, 2003). The National Oceanic and Atmospheric Administration's (NOAA) 2007 “State of the Climate Report” confirms Jones and Moberg’s calculation. Further, NOAA concluded that, during the past century, global surface temperatures have increased at a rate near 0.05°C/decade; however, this trend has increased to a rate of approximately 0.15°C/decade during the past 25 to 30
years. As shown in Figure 2-10 below, seven of the eight warmest years on record have occurred since 2001, with a rise in temperature of more than 0.6°C since 1900.

![Figure 2-10 Annual average global surface temperature anomalies 1880-2006 (NOAA, 2007).](image)

Figure 2-10 Annual average global surface temperature anomalies 1880-2006 (NOAA, 2007).

Observed changes relative to 1961-1990 in temperature, sea level and Northern Hemisphere snow cover are shown in Figure 2-11: (a) global average surface temperature, (b) global average sea level from tide gauge (blue) satellite data (red) and (c) Northern Hemisphere snow cover for March-April.

![Figure 2-11 Changes in temperature, sea level and northern snow cover (IPCC-WG1-AR4).](image)
2.3.2 CHANGES IN GLACIERS AND ICE CAPS

There are a number of recent studies showing increased contribution of ice sheets. A result of this increase, in the longer term, will be a rise in the sea level, possibly as much as several meters, unless there are significant reductions in greenhouse gas emissions.

At continental, regional and ocean basin scales, a range of long-term changes have been observed in arctic temperatures and ice, as well as precipitation levels and storm frequency (Solomon et al., 2007a, NOAA, 2007, Hansen, 2008). Further, it appears that recent decreases in ice mass are correlated with rising surface air temperatures. This is especially true for the region north of 65°N, where temperatures have increased by about twice the global average from 1965 to 2005 (Lemke et al., 2007).

Indeed, such changes in glaciers and ice caps provide some of the clearest evidence of climate change and, as such, they constitute key variables for the early detection strategies in global climate-related observations. These climatic changes have impacts on global sea level fluctuations, from the regional to the local natural hazard situation, as well as on societies that are dependent on glacier melt water (Zemp et al., 2008). Importantly, terrestrial glaciers are shrinking all over the world and, together with the Greenland and Antarctic ice sheets, have the potential to raise global sea level many metres. According to the latest findings from the World Glacier Monitoring Service (WGMS) in Switzerland, as Zemp et al., (2008) report, the world’s glaciers are continuing to melt. The data, from nearly 30 reference glaciers, in nine mountain ranges, indicate that, between the years 2004-2005 and 2005-2006, the average rate of melting and thinning more than doubled.

The geologic evidence of the retreat of these ancient ice sheets indicates that it increased global sea levels by around 1.3 cm/year, significantly faster than the current projections from the IPCC (which have not yet fully accounted for ice sheet melt) (LeGrande, 2008). Further, the Greenland and Antarctic ice sheets, overall, contain enough water to raise the sea level about 70 m; Greenland and West Antarctica each contain about 10%, while East Antarctica holds the remaining 80% (Hansen et al., 2007a).
According to scientists at the University of Colorado, the total area of surface melt on the Greenland Ice Sheet has broken all known records for the island. An analysis of the extent of the melt, using passive microwave satellite data, has shown a very dramatic increase in the melt trend; For example, the 2005 melt extent exceeded the previous record of 2002 (Steffen and Huff, 2005). Figure 2-12 shows the melt extent for 1992 (minimum extent) and for 2005 (maximum extent), displayed in the same 3-D view of Greenland in light red (1992) and dark red (2005) colour, respectively.

Figure 2-12 Extent of ice melt from the Greenland ice sheet in 1992 and 2005 (Steffen and Huff, 2005).

Similarly, Greenland’s largest outlet glacier, the Jakobshavn Isbrae, located on the west coast of Greenland at Latitude 69 N, receded more than 40 km between 1850 and 2006 (Figure 2-13). The ice front retreated at a steady rate of about 0.3 km/yr. After 1964, it occupied approximately the same location until 2001, when the ice front began to recede again, but far more rapidly at about 3 km/yr (Weidick and Bennike, 2006). The result is that, as more ice moves from the glaciers on land into the ocean, the sea level rises. Further, the ice stream’s speed-up, nearly doubling the ice flow into the sea. Hence, the rate of SLR has risen by about .06 millis per year, or roughly 4 per cent of the 20th century rate of sea level increase(Thomas et al., 2006).

Based on compilation of local sea level indicators, and a statistical approach for estimating global and local sea levels, and ice sheet volumes and their associated
uncertainties, (Kopp et al., 2009) found a 95% probability that global sea levels peaked, during the last interglacial sea level, at least 6.6 m higher than they are today.

![Jakobshavn glacier calving front recession from 1850 to 2006](image)

**Figure 2-13** Jakobshavn glacier calving front recession from 1850 to 2006 (Weidick and Bennike, 2006).

### 2.3.3 CHANGES IN SEA LEVEL AND EXTREME EVENTS

Along with sea level changes, there are also changes in the occurrence of extreme events. For example, the global mean sea level is rising as a result of the increased concentration of greenhouse gases in the atmosphere. Tide gauge measurements and satellite altimetry suggest that the sea level has risen, worldwide, approximately 12-22 cm during the 20th century. Also, it is predicted that SLR will also influence changes in the intensity and frequency of extreme events and, thus, contribute to coastal erosion and the inundation of low-lying coastal regions, particularly during extreme sea level events (Parry et al., 2007). Therefore, decision makers and the community in general need to understand the potential impact that changes in sea level will have on people living in coastal areas.

Briefly, then, global sea level is controlled by the climate, the Earth’s movements, and the gravitational effects of the rotation of the Earth. These factors, combined with local changes, produce a change in sea level relative to the local land level (Figure 2-14).
Such sea level changes will occur on a range of temporal and spatial scales. According to Bindoff et al., (2007), two major processes, related to the recent changes in climate (namely, global average sea level on decadal and longer time scales) are: i) thermal expansion, and ii) the exchange of water between the oceans and the other reservoirs (glaciers and ice caps, ice sheets, and other land water reservoirs, including anthropogenic changes in land hydrology, and the atmosphere). Additionally, the Earth’s movements and the gravitational effect of the rotation of the Earth also cause a rise in global mean sea level; however, oceanographic factors, such as changes in ocean circulation or atmospheric pressure, influence the sea level at the regional scale, although only by a small contribution to the global mean (Figure 2-14 and Figure 2-15). Rahmstorf’s (2007) analysis confirms these findings by demonstrating that, over the last century, observed global SLR is linked to global mean surface air temperature.

As highlighted in Figure 2-14 and Figure 2-15, the climate influences the ocean’s water volume via changes in its density, which is reduced by thermal expansion as the ocean warms. Further, it is anticipated that the exchanges of water between the oceans and
the other water reservoirs will also alter the mass of the ocean and, consequently, will change the total volume of the ocean.

According to the IPCC 4AR Report (2007), observations since 1961 show that: the average temperature of the world’s ocean has increased to a depth of at least 3000 m, the ocean has been absorbing more than 80% of the heat added to the climate system, and such warming causes seawater to expand, and so contribute to SLR (see Table 2-2). Consistent with the IPCC assessments, (Miller and Douglas, 2004) concluded that SLR in the second half of the 20th century was mostly due to water mass added to the oceans. For this reason, ocean warming, and thus the melting of the ice shelves, will continue even if CO₂ levels are stabilised; this continuation will occur because the ocean response time is long and the temperature, at depth, is far from its equilibrium for current forcing (Hansen, 2007a). Additionally, because of the large heat capacity of the ocean, even when the climate stabilises, SLR will persist for centuries. Indeed, thermal expansion is considered the largest contributor to sea level rise.

The widespread decrease in the size of the glaciers and ice caps, even excluding the contributions from the Greenland and Antarctic Ice Sheets, have contributed to a rise in sea level (Lemke et al., 2007). These contributions account for 0.5 mm/year for the period of 1961 – 2003 (See Table 2-2). Further, the 4AR report clearly shows that the contribution made to SLR from the ice sheets of Greenland and Antarctica increased

Figure 2-15 Causes to global mean sea level to change (Bindoff et al., 2007).
between 1993 and 2003 (0.42 mm/year), especially when compare to the period 1961 to 2003 (0.19 mm/year) (See Table 2-2).

Domingues et al., (2008) calculated that SLR for the 1961 to 2003 period was about 1.5 ± 0.4 mm/year. This estimate is in contrast to the IPCC assessment (2007), which indicates a higher increase, as shown in Table 2-2; the average rate of SLR was 1.8 mm/year for this period. After 1993, more accurate data were collected through satellite observations. The data show the sea level rising at a rate of around 3.1 mm/year, significantly higher than the average during the previous half century. It is unclear, however, whether the faster rate for the 1993 to 2003 period reflects a short-term variation or an increase in the long-term trend.

Nevertheless, most of the observed SLR can be attributed to thermal expansion of the ocean and the melting of the glaciers and ice caps, as shown in Table 2-2 (Bindoff et al., 2007). The contributions from the various sources to the budget of sea level change are shown for 1961 to 2003 and 1993 to 2003 (Table 2-2 and Figure 2-16). From 1961 to 2003, thermal expansion accounts for only 23% of the observed rate of SLR (0.42 mm), while, from 1993 to 2003, it accounts for 51.6% (1.6 mm). The difference indicates a sharp increase in the SLR rate due to thermal expansion.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Expansion</td>
<td>0.42 ± 0.12</td>
<td>1.6 ± 0.5</td>
</tr>
<tr>
<td>Glaciers and Ice Caps</td>
<td>0.50 ± 0.18</td>
<td>0.77 ± 0.22</td>
</tr>
<tr>
<td>Greenland Ice Sheet</td>
<td>0.05 ± 0.12</td>
<td>0.21 ± 0.07</td>
</tr>
<tr>
<td>Antarctic Ice Sheet</td>
<td>0.14 ± 0.41</td>
<td>0.21 ± 0.35</td>
</tr>
<tr>
<td>Sum</td>
<td>1.1 ± 0.5</td>
<td>2.8 ± 0.7</td>
</tr>
<tr>
<td>Observed</td>
<td>1.8 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>Difference (Observed - Sum)</td>
<td>0.7 ± 0.7</td>
<td>0.3 ± 1.0</td>
</tr>
</tbody>
</table>

Table 2-2 Estimates of the various contributions to the budget of global mean sea level change (Bindoff et al., 2007).
The IPCC's Third (TAR) and Fourth (4AR) Assessment Reports are consistent in calculation of global mean sea level rise. The 4AR average rate for the 20th century was calculated as $1.7 \pm 0.5$ mm/yr in 4AR, consistent with the TAR calculation of 1 to 2 mm/yr (Bindoff et al., 2007, Church et al., 2001). The changes in global averaged sea level since 1993 are estimated from satellite altimeter data (red in Figure 2-16) and since 1870 by combining in situ sea level data from coastal tide gauges and the spatial patterns of variability determined from satellite altimeter data (blue in Figure 2-16).

The observed changes in the ocean state are summarised in Figure 2-17; the changes include those for ocean temperatures, ocean salinity, sea level, sea ice and biogeochemical cycles. The legend identifies the direction of the changes in these variables. In addition to the changes in ocean mass and the expansion of the ocean water on longer time scales, other processes are also at play, such as high tides, storm surges and surface waves. According to White (2008a), these drive the short term changes in sea level.
The interaction of these various processes is significant, as illustrated in Figure 2-18. Thus, the severe winds and falling atmospheric pressures, associated with storm events, generate higher-than-normal-sea levels at the coast, which are known as storm surges or, in combination with the astronomical tides, as storm tides (McInnes et al., 2005). The societal impacts of sea level change primarily occur via extreme levels (mainly storm surges), rather than as a direct consequence of mean sea level changes (Bindoff et al., 2007).

Many studies, e.g. (Lowe et al., 2001, Church et al., 2001, Cubasch et al., 2001, Woodworth and Blackman, 2004, Emanuel, 2005, Meehl et al., 2007, Hemer et al., 2007, Cayan et al., 2008), have addressed the issue of changes in the global frequency and intensity of tropical cyclones in an environment of increasing sea surface temperature. These studies of extreme sea levels, conducted in many locations around
the world, indicate that, globally, the relative frequency of very strong tropical cyclones may be increasing, with sea level rise being generally regarded as the dominant cause of the increases in the frequency of extreme sea level events.

Lowe et al. (2001) used a regional climate model to argue that the alteration of the frequency of extreme coastal storm surge events, due to climate change, will be of more concern than the slow inundation of coastal areas by century scale changes in mean sea level. The authors also suggest that there is a reduction in the return period of extreme events. Further, they observe that increases in surge height are driven by meteorological forcing, as well as increases in sea level, with the relative importance of these factors varying with location. At Immingham, on the east of England, a storm surge model, driven by the Hadley Centre regional climate model, predicts that the return period of an extreme water height of 1.9 m (relative to mean sea level and the tide) will be reduced from 500 years, in the control case, to 120 years, due to meteorological forcing alone, and to 12 years due to a combination of meteorological forcing and a SLR of 0.5 m by 2100. The 500 year water level is postulated to increase to 2.2 m from meteorological forcing alone, and to 2.7 m when the SLR is taken into account (Lowe et al., 2001).

There will be impacts from any changes in the highest sea levels at a given locality; thus, it is important to understand why these changes may occur. Most changes will arise from two effects. Firstly, if the mean sea level rises, the present extreme levels will be attained more frequently, all else being equal. Secondly, increases in storm surge heights will result from alterations to the occurrence of strong winds and low pressures (Church et al., 2001). Woodworth and Blackman (2004) posit a link between SLR and storm surges. They note that: (a) there is evidence of a general worldwide increase in extreme high-water levels since 1975; and (b) the variations in the extremes during this period are closely related to changes in regional climate.

In their study, Webster et al. (2005) examined the number of tropical cyclones and cyclone days, as well as tropical cyclone intensity. While they could not find any increase in the global trend in relation to the number of tropical storms and hurricanes, they did identify a substantial change in the intensity distribution of
tropical cyclones globally. (Webster et al., 2005). Hemer et al. (2007), the effects of sea level rise will be observed most severely in response to the magnitude and frequency of storm driven (wave and storm surge) events. As a result, there will be greater wave-induced erosion of coastal landforms (Hemer et al., 2007).

The IPCC 4AR, consistent with the previous Third Assessment Report (TAR), highlights an increase in the average number of Category 4 and 5 hurricanes per year, over the last 30 years. Further, it is expected that the intensities of tropical storms will increase, and that there will be a continued pole-ward movement of extra-tropical storm tracks (Cubasch et al., 2001, Meehl et al., 2007). Similar observations were made in a study by Cayan et al. (2008), namely, that as the sea level rises, there will be an increased rate of extreme high sea level events occurring during high tides. These events will occur when accompanied by winter storms; sometimes the events will be exacerbated by the El Nino.

The term cyclone will be used when referring to tropical cyclones, hurricanes (a term used in the USA), and typhoons (a term used in Asia). The Saffir-Simpson Hurricane Scale is used to measure the intensity of tropical cyclones and storm surge elevations. The severity of a tropical cyclone is generally categorised from 1 to 5, as shown in Table 2-3. The relationship between each category is important as storm surge elevations differ by approximately 0.3 m. In Australia, the Australian Bureau of Meteorology uses the five-category system for classifying tropical cyclone intensity, as shown in Table 2-3.

<table>
<thead>
<tr>
<th>Category</th>
<th>Wind Speed (km/h)</th>
<th>Storm Surge (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>119 – 153</td>
<td>1.2 – 1.5</td>
</tr>
<tr>
<td>2</td>
<td>154 – 177</td>
<td>1.8 – 2.4</td>
</tr>
<tr>
<td>3</td>
<td>178 – 209</td>
<td>2.7 – 3.7</td>
</tr>
<tr>
<td>4</td>
<td>210 – 249</td>
<td>4.0 – 5.5</td>
</tr>
<tr>
<td>5</td>
<td>≥ 250</td>
<td>&gt; 5.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category</th>
<th>Wind G st (km/h)</th>
<th>Potential Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 &lt;125</td>
<td>minor</td>
</tr>
<tr>
<td>2</td>
<td>125-170</td>
<td>moderate</td>
</tr>
<tr>
<td>3</td>
<td>170-225</td>
<td>major</td>
</tr>
<tr>
<td>4</td>
<td>225-280</td>
<td>devastating</td>
</tr>
<tr>
<td></td>
<td>&gt;280</td>
<td>extreme</td>
</tr>
</tbody>
</table>

a) Saffir - Simpson Scale (adapted from (National Hurricane Center, 2007)
b) The Australian Bureau of Meteorology Five-Category System (Harper et al., 2000)

Table 2-3 Tropical cyclone scaling systems
If the global sea level rises 0.6 m by 2100, as projected by the IPCC A1F1 scenario (Meehl et al., 2007), then the increase in sea level would be 0.3 m by 2050. Further, a rise in sea level would also result in a rapid increase in the scale of a storm surge, along with an increase in the resultant damage. As a consequence, for example, the damaging impact of a category-1 storm then would be approximately equivalent to a category-2 storm (Table 2-3). Additionally, the occurrence of stronger storms would become more frequent. Indeed, as the mean sea level rises (red arrow), current extreme events of a given size/height (dark red) will tend to become more frequent (purple) as illustrated in Figure 2-19. This scenario will be discussed in more detail in Chapters 5 and 6.

Figure 2-19 Relationship between SLR and extreme events of a given height (White, 2008b).

Occurrence of extreme events is quantified by the Return Period or Average Recurrence Interval (ARI), which is the average time between events of particular heights. Church et al. (2006) examined changes in the frequency of extreme events at Fremantle and Fort Denison in Australia (Figure 2-20). They found that, for both locations, there was a decrease in the average recurrence interval (ARI) by a factor of about three for extreme sea levels, from the pre-1950 period to the post-1950 period. (Church et al., 2006).

As seen in Figure 2-20, for the second half of the 20th century (red line), the ARI for a sea level height of a given value is less than half the value for the first half of the 20th century (blue line) - (Graphic: Hugo Ahlenius, UNEP/GRID-Arendal), (Church et al., 2006).
2.3.4 REGIONAL TRENDS

It is widely accepted that the climate varies from region to region. Further, it is acknowledged that this variation is driven by the uneven distribution of solar heating, and the individual responses of the atmosphere, oceans and land surface, as well as the interactions between these, and the physical characteristics of the region (Christensen et al., 2007).

Observational data reveals significant climate change in and surrounding Australia over the last century. In this island continent, the climate is strongly influenced by the surrounding oceans. These observed changes around have been summarised in CSIRO’s “Climate Change in Australia Technical Report 2007” (Pearce et al., 2007). Briefly, these changes include:

- **Surface Temperature**: Australian average temperatures have increased by 0.9 °C since 1910, with significant regional variations (Figure 2-21).

- **Tropical cyclones**: Although it is difficult to determine trends in the frequency and intensity of tropical cyclones in the Australian region due to inherent multi-decadal variability in tropical cyclone frequencies and intensities, and the varying quality of historical records, limited observations have suggested that there was a substantial increase in tropical cyclone numbers on the east coast since the 1950s, followed by a reduction since the 1970s. On the other hand, on
the west coast, the proportion of severe tropical cyclones (i.e. ‘category 3 or 4’ cyclones) was larger (41%) from 1989 to 1998, than from 1974 to 1988 (29%). Further, as a general, there are also fewer tropical cyclones in Australia during El Nino events than during La Nina.

- For the period 1950 to 2000, the sea level rose at all of the Australian coastal study sites; additionally, there was substantial variability in the trends from location to location (Figure 2-22). Over the period 1920 to 2000, the observed average relative SLR around Australia was 1.2 mm per year.

![Figure 2-21 Australian annual mean temperature anomalies, 1900–2007. The data shows temperature difference from the 1961–90 mean. The black line shows the 10-year trailing average (Pearce et al., 2007)](image1)

![Figure 2-22 Observed rates of relative mean SLR (mm/year), 1990-2007 (Pearce et al., 2007)](image2)
Data used in this map are from the Australian Baseline Sea Level Monitoring Array (white figures) and the South Pacific Sea Level and Climate Monitoring Project (yellow figures) (Pearce et al., 2007).

From the records, the sea level has been rising along the Australian Coast (Hunter et al., 2003). The observations of sea level at Port Arthur, Tasmania indicate an average rate of SLR of 0.8 ± 0.2 mm/year from 1841 to 2002 relative to the land, or about 1.0 ± 0.3 mm/year when combined with estimates of land uplift over the same period. This value is consistent with the estimate of global sea levels from 1870 to 2001 presented in Figure 2-23.

![Figure 2-23 Observed and projected changes in sea levels from 1800 to 2100 (Hunter et al., 2003).](image)

### 2.4 PROJECTION OF FUTURE CLIMATE CHANGE

Future greenhouse gas (GHG) emissions are the product of very complex dynamic systems, determined by driving forces such as demographic development, socio-economic development, and technological change (Nakicenovic et al., 2000). Since the Third Assessment Report, confidence in global atmospheric or Earth system models has increased and they now provide credible quantitative estimates of future climate change, particularly at the continental scale (Solomon et al., 2007a).
One difficulty that such statistics as ‘SLR of 0.8 ± 0.2 mm/year’ is that society may be lulled into a false sense of security by smooth annual projections of global change. Indeed, it is unlikely that such a progressive increase will occur. Instead, it is likely that the climate will experience a “tipping point”, that is, a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system. Lenton et al. (2008) suggest that large-scale components of the Earth’s system may pass a tipping point and, thus, reach their critical point within this century, especially under anthropogenic climate change. The authors conclude that the greatest tipping threats are the Arctic sea-ice, and the perched Greenland and Antarctic ice sheets. Additionally, at least another five elements could unexpectedly exhibit a tipping point (Lenton et al., 2008).

2.4.1 CLIMATE CHANGE SCENARIOS

A scenario is a description of potential future conditions, which are developed to inform decision-makers operating under uncertain climatic conditions (Parson et al., 2007). Scenarios can help illustrate how key drivers, such as economic and population growth, or policy options, lead to particular levels of GHG emissions. Hence, a computer model of the Earth’s climate is used to estimate future climate change, with the aim of providing policy-relevant advice on the consequences of human-induced climate change in the 21st century.

The most significant projections used in climate change analysis are the Special Report on Emissions Scenarios (SRES) of the IPCC. The IPCC employed a range of scenarios of GHG and aerosol emissions up to the year 2100. These emission scenarios were developed by a panel of authors, with wide consultation, and an open process of review and comment by experts and governments, followed by subsequent revisions and reported in SRES (Nakicenovic et al., 2000). As shown in Figure 2-24 the IPCC developed 40 different future emissions scenarios, which fell within four narrative storylines (A1, A2, B1 and B2). Each storyline visualizes a different future, with different levels of technological development and global economic integration (for a detailed description of these scenarios see Appendix 1). To estimate the magnitude of climate change in the future, a number of assumptions about the future level of global
emissions of GHG and other relevant gases have been made. Due to the uncertainties involved in predictions, the projections of future climate change are presented as ranges, rather than a single value.

As can be seen from the above figure, the four qualitative storylines yield four sets of scenarios (called families): A1, A2, B1, and B2. Altogether, 40 SRES scenarios have been developed by six modelling teams. All scenarios are equally valid, with no assigned probabilities of occurrence. A set of scenarios consist of six scenario groups, drawn from the four families, namely, three groups within the A1 family, and one group each in families A2, B1, and B2. A1 family group is characterized by alternative developments of energy technologies: A1F1 (fossil fuel intensive), A1B (balanced), and A1T (predominantly non-fossil fuel). Within each family and group of scenarios, some share “harmonized” assumptions on global population, gross world product, and final energy. The assumptions are marked as; “HS” for harmonized scenarios; And “OS” which denotes scenarios that explore uncertainties in the driving forces beyond those of the harmonized scenarios.

Figure 2-24 Schematic illustration of SRES scenarios (Reproduced from Nakicenovic et al., 200)
Key future projections from the 4AR are also summarised in the IPCC (2007) ‘Summary for Policymakers’ (Table 2-4). They include:

- A rise in the global average temperature of 0.6ºC (0.3–0.9ºC) by 2090–2099 relative to the average for 1980–1999 if emissions did not exceed 2000 levels.
- A best estimate of global average temperature rise of between 1.8 and 4.0ºC (the full range of emission scenarios, including all uncertainties, suggest 1.1–6.4ºC) by 2090–2099 relative to the average global temperature for 1980–1999.

For a mid-range emissions scenario (A1B), the best estimate is a 2.8ºC (1.7–4.4ºC) rise in temperature by 2090–2099 relative to the average for 1980–1999.

<table>
<thead>
<tr>
<th>Case</th>
<th>Temperature Change (°C at 2090-99 relative to 1980-99)</th>
<th>Sea Level Rise (m at 2090-2099 relative to 1980-1999)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Best estimate</td>
<td>Likely Range</td>
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<tr>
<td>Constant Year 2000 concentrations</td>
<td>0.6</td>
<td>0.3 - 0.9</td>
</tr>
<tr>
<td>B1 Scenario</td>
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<td>1.1 - 2.9</td>
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<tr>
<td>A1T Scenario</td>
<td>2.4</td>
<td>1.4 - 3.8</td>
</tr>
<tr>
<td>B2 Scenario</td>
<td>2.4</td>
<td>1.4 - 3.8</td>
</tr>
<tr>
<td>A1B1 Scenario</td>
<td>2.8</td>
<td>1.7 - 4.4</td>
</tr>
<tr>
<td>A2 Scenario</td>
<td>3.4</td>
<td>2.0 - 5.4</td>
</tr>
<tr>
<td>A1F1 Scenario</td>
<td>4.0</td>
<td>2.4 - 6.4</td>
</tr>
</tbody>
</table>

Table 2-4 Projected global average surface warming and SLR (IPCC Synthesis Report 2007).

Specific criticism of the SRES scenarios, in the literature, has been that the climate change believing scientists have overstated the emissions growth. The sceptics believe that the more rapid emission growth SRES scenarios are inconsistent with long-term or recent trends in emissions (Hansen et al., 2000, van Vuuren and O’Neill, 2006). However, a study in 2008, by Garnaut et al.(2008), has projected that annual emissions will almost double current volumes by 2030. This finding is 11 % higher than in the most pessimistic scenario developed by the IPCC, and at the level to be reached in 2050, if the business-as-usual scenario, as used by Stern (2006) in the Stern Review, is accurate (Garnaut et al., 2008).

The IPCC SRES scenarios had no mitigation. In contrast, the Garnaut (2008) Review shows a range of possible outcomes with different levels of mitigation: no mitigation,
Ad hoc mitigation, strong global mitigation, and ambitious mitigation (these outcomes are illustrated in Figure 2-25). The four levels of mitigation are described as:

- **No-mitigation case**: This scenario recognises recent high trends in the emission of CO$_2$ and other GHG; these will continue to increase throughout the 21$^{st}$ century.
- **Ad hoc mitigation case**: This scenario, which recognises current emission commitments, postulates that high emissions growth will continue early in the century; however, as developing countries accept mitigation targets, emissions will peak and then decline, very gradually.
- **Strong global mitigation case**: This scenario recognises the restrictions of GHG concentrations to 550 ppm CO$_2$-e; these emissions will peak before 2030 and decline, steadily, through the remainder of the century.
- **Ambitious mitigation case**: This scenario recognises a stabilisation of the concentration of 450 ppm CO$_2$-e; an overshoot to 500 ppm CO$_2$-e. CO$_2$ emissions will peak before 2020 and decline, steadily, throughout the century.

![Figure 2-25 CO$_2$ Emissions and concentrations of GHG for the four emissions cases, 1990–2100 (Garnaut, 2008).](image)

The annual mean temperature in Australia is expected to rise in parallel with rises in global mean temperature; however, with significant regional variations across the continent. Figure 2-26 shows the best estimate (50$^{th}$ percentile) for Australian annual mean temperature change in 2030, 2070 and 2070 under six SRES emission scenarios. A summary of these temperatures is shown below (Pearce et al., 2007, Garnaut, 2008):
By 2030, the annual temperature for Australia will be around 1°C above the 1990 levels. The best estimate of the global mean temperature for 2030 does not vary much among the emission scenarios, ranging from about 0.75°C (for B1) to 1.0°C (for A1T). By 2050, the best estimate for annual temperature for Australia ranges from around 1.2°C for the B1 scenario to 2.2°C for the A1FI scenario. By 2070, the best estimate for the annual temperature over inland Australia ranges from around 1.8°C for the B1 scenario to around 3.4°C for the A1FI.

2.4.2 PROJECTION OF FUTURE SEA LEVEL CHANGE - SLR SCENARIOS

The IPCC-4AR indicates that there would be up to a 59 cm of SLR over the next century, primarily a result of the expansion of the oceans due to warming (Solomon et al., 2007b). However, these projections do not include uncertainties in carbon cycle feedbacks and possible contribution resulting from the faster-than-expected ice melt from the Greenland and Antarctica Ice Sheets (G&IC). If this contribution were to grow

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Figure 2-26 Projection of Australian annual mean temperature under six SRES scenarios (Pearce et al., 2007).
linearly with global average temperature change, the upper ranges of SLR for the SRES scenarios (Table 2-5) would increase by 10 to 20 cm.

<table>
<thead>
<tr>
<th></th>
<th>B1</th>
<th>B2</th>
<th>A1B</th>
<th>A1T</th>
<th>A2</th>
<th>A1F1</th>
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Table 2-5 Global average SLR projection for the 21st century and its components under SRES scenarios.

In the above table the upper row in each pair gives the 5 to 95% range (m) of the rise in sea level between 1980 to 1999 and 2090 to 2099. The lower row in each pair gives the range of the rate of SLR (mm yr$^{-1}$) from 2090 to 2099. The land ice sum comprises the G&IC and ice sheets, including dynamics, but excludes the scaled-up ice sheet discharge. The SLR is comprised by the thermal expansion and the land ice sum. Note that, for each scenario, the lower/upper bounds for SLR is larger/smaller than the total of the lower/upper bounds of the contributions, since the uncertainties of the contributions are largely independent (Meehl et al., 2007).

Indeed, the sea level rise will be greater than was projected by the IPCC if the average temperature increases are larger than expected. Although estimating the rapid disintegration of the ice sheets is still very difficult, recent publications (Hansen, 2007b, Rahmstorf, 2007, Horton et al., 2008, Carlson et al., 2008, Smith et al., 2009, Grinsted et al., 2009), since the IPCC 4AR in 2007, suggest that future SLR will be much

45
more than the IPCC’s projections. These recent publications, as discussed below, add more information for future SLR assessment.

James Hansen argues that the IPCC scenarios underestimate future sea level rise. According to the author, the IPCC’s linear approximation fits well the past sea level change for the past century; this is only because the two terms contributing significantly to the SLR were: (1) the thermal expansion of the ocean water; and (2) the melting of the alpine glaciers. However, the SLR will be dominated by a third (3) term, the perched ice sheet disintegration during the 21st century, which may, in fact, result in several metres rise in sea level. Hansen further suggests that a rise of over 5 metres over this century is not implausible.

In the same year, Rahmstorf (2007) presented a semi-empirical relation between global SLR and global mean surface temperature; the rate of SLR is roughly proportional to the magnitude of the warming above the temperatures of the pre–Industrial Age, for time scales relevant to anthropogenic warming. According to the author, this holds to a good approximation for the temperature and sea level changes during the 20th century, with proportionality constant 3.4 mm/year per °C. When applied to the future warming scenarios of the Intergovernmental Panel on Climate Change, this relationship results in a projected sea level rise, in 2100, of 0.5 to 1.4 metres above the 1990 level. Thus the study shows that the projections by the IPCC have not been exaggerated; on the contrary, they appear to have underestimated the change to the sea level. Thus the study shows that the projections by the IPCC have not been exaggerated; on the contrary, they appear to have underestimated the change to the sea level.

Horton et al (2008), using the method developed by Rahmstorf (2007) assessed the semi-empirical relationship between the global surface air temperature and the mean sea level to estimate future sea levels. The authors strongly contend that both the IPCC AR4 (2007) and the semi-empirical SLR projections are likely to underestimate the future SLR, especially if recent melt trends in the Polar Regions accelerate.

Another analysis, by Carlson et al. (2008), suggests that the pressures on the perched Laurentide Ice Sheet (LIS), 9000 years ago, were similar to those that Greenland will
face by the year 2100, particularly in terms of the temperature increase. Worryingly, the geologic evidence of the retreat of this ancient ice sheet indicates that it increased global sea levels by around 1.3 cm/year. This increase in SLR is significantly faster than the current SLR projections from the IPCC.

Since the publication of the TAR in 2001, new findings by Smith et al., (2009) have highlighted the risk posed by additional contributions to sea level rise from the melting of both the Greenland and Antarctic perched ice sheets may be larger than projected by ice sheet models assessed in the AR4 (2007). The conclusion is that several metres of additional sea level rise could occur on a century time scale.

Consistent with the findings from these previous studies, Grinsted et al. (2009) estimates that the sea level rise, by the end of the 21st Century, would be 0.9 to 1.3 m for the A1B scenario, with a low probability of the rise being within IPCC confidence limits. In their analysis the authors used used the physically plausible four parameter linear response equations to analyse 2,000 years of global temperatures and sea levels.

In summary, the warmer the globe becomes the faster the sea level will rise. Several factors are in play for this to occur, namely: ocean warming and expansion, glacier melt, and perched ice sheet melt. The range of these changes in global sea level rise projections are much greater than the IPCC (2007) projection ranges, for example, from 0.5 to 1.5 m by 2100, 1.5 to 3.5 m by 2200, and 2.5 to 5.1 m by 2300 (Rahmstorf, 2007, Domingues et al., 2008, WBGU, 2006, WBGU, 2009).
2.4.3 PROJECTIONS FOR THE AUSTRALIAN REGION

As an overview, the IPCC–4AR (2007) indicates a SLR up to 59 cm over the next century, primarily a result of the expansion of the oceans due to warming. However, as shown in Figure 2-27, the distribution of the SLR varies spatially, a result of ocean circulation, local temperature differences, land movements, and the salt content of the ocean (Meehl et al., 2007, Pearce et al., 2007, Christensen et al., 2007, Garnaut, 2008).

In the above figure, positive values indicate greater local sea level change than global during the 21st century, based on the SRES A1B scenario (Meehl et al., 2007).

The 2007 technical report on climate change by CSIRO provides reasonable regional climate change projections for Australia. CSIRO’s projections are based upon the latest international climate change research, including the conclusions from the IPCC Fourth Assessment Report in 2007. According to CSIRO, the regional SLR variability of the oceans surrounding Australia is influenced, in the main, by two climate variations: the El Niño – Southern Oscillation (ENSO), and the Southern Annular Mode (SAM) (Pearce et al., 2007). These regional variations can be quite significant, with the highest rates being recorded in the eastern non-Equatorial Pacific (2 to 3 mm/year), and the lowest along the Equator in the western Pacific and eastern Indian Oceans (0 to 1 mm/year) (Macaulay, 2008).
For the Australian region, and in terms of the spatial pattern of sea level rise by 2070, a number of the climate models have been developed, as shown in Figure 2-28. For example, the projected sea level on the east coast of Australia may be higher, by about 10 cm, than the global average SLR (Church et al., 2008). The calculations used were based on the sub-set of the AR4 models that provided sea level data to the PCMDI. The units were metres, while the simulations used the IPCC Scenario SRES A1B.

Figure 2-28 Projected regional contribution of thermal expansion to sea level by 2070 (Pearce et al., 2007)

Calculations in the above figure are based on 17 CMIP3 models for the A1B emission scenario, relative to the globally averaged value for each model (in metres) (Pearce et al., 2007).

From the regional climate change scenarios prepared by CSIRO for the Australian Greenhouse Office (AGO), a projected average increase in sea level in ten regions was estimated to be between +3 cm to +17 cm (0.75 mm/yr and 4.25 mm/yr) by 2030. In the report, two scenarios were presented for each climate variable: (i) a low global warming scenario (0.54˚C by 2030), which assumes the lowest SRES emission scenario
and the lowest climate sensitivity; and (ii) a high global warming scenario (1.24°C by 2030), which assumes the highest SRES emission scenario, and the highest climate sensitivity (Hennessy et al., 2006). Importantly, the CSIRO projection is consistent with the observed SLR data, which shows substantial variability in SLR trends from location to location (Figure 2-29).

![Figure 2-29 Observed rates of relative mean SLR (mm/yr), 1990 - 2007 (Pearce et al., 2007).](image)

The regional SLR variations on the Australian coast also include local effects that differ for each coastline. In addition to local thermal expansion in the ocean, the sea level at the coast is also impacted upon by short term extreme events, such as storm surges and wave regimes. Both are predicted to increase in severity with a warming climate change. Indeed, SLR during a storm surge is caused by the combined effect of falling atmospheric pressure and intense winds of severe weather events, such as tropical cyclones. The rise in sea level, due to falling pressure, is about 1 cm per hectopascal fall in pressure, although the larger contribution is due to wind, which pushes the water against the coast (Pearce et al., 2007).

### 2.4.4 OTHER EXTREMES

In addition to SLR, other aspects of the climate are expected to change because of anthropogenic warming. Unlike the sea level, however, the direction of that change is often uncertain. Importantly, a SLR at the estimated rate will not pose an immediate threat to coastal areas; nevertheless, a higher sea level will provide a higher base for storm surges to build upon. Thus, storm surges occurring in conditions of higher mean
sea levels will enable inundation and damaging waves to penetrate further inland, increasing flooding, erosion, and the subsequent impacts on the built infrastructure and natural ecosystems (Pearce et al., 2007). As indicated earlier, if the variability of the sea level about the mean does not change, then the sea level rise will lead to an increase in the frequency of extreme sea level events at a given height. The result is expected to impact on the size of the hazards, such as storm surges, namely, their increase during a coastal storm.

A study by McInnes et al. (2000) estimated storm tides’ return periods for sea level heights under present and enhanced GHG conditions in 2050 in Cairns, Australia. They calculated that the current 1:100 year event is about 2.3 m (±0.1) in height under present conditions, while under the enhanced GHG conditions it would increase to about 2.6 m (±0.1). With an additional 20 cm SLR by 2050, the 1:100-year event would be about 2.8 m (+0.3/-0.2) (McInnes et al., 2000).

![Figure 2-30 Storm tide return periods for Cairns, Australia (McInnes et al., 2000).](image)

As noted above, climate change alters the frequency of high sea level extremes. In his study, Hunter (2008) estimates the increase in frequency for a given amount of SLR by using the logarithmic relationship between the return period and the extreme level. Thus, if a sea level rise of \( h \) increases the frequency of occurrence by a factor \( r \), then a sea level rise of \( H \) increases the frequency of occurrence by a factor \( r^{H/h} \), which can become very large, even for modest increases in sea level (Hunter, 2008). Figure 2-31 shows the estimated increase in the frequency of occurrence of extreme high levels,
caused by a sea level rise of 0.1 metre, using the 29 Australian sea level records that are longer than 30 years. By using the formula for a mid-range increase in sea level $H=0.5$, the multiplying factor for Australia can be calculated as:

\[
\begin{align*}
H &= 0.5 \text{ m} \\
h &= 0.1 \text{ m} \\
r &= 3.1
\end{align*}
\]

Multiplying factor for Australia = \(3.1^{0.5/0.1} = 286\)

This figure indicates by the diameter of the discs that events which now happen every few years would happen every few days in 2100.

\[\text{Figure 2-31 Multiplying factor for the increase in the frequency of occurrence of high sea level events (Hunter, 2008).}\]

**2.4.5 COASTAL POPULATION AT RISK**

The world’s richest and most diverse environments are found in coastal zones. From the polar regions to equatorial areas, the coastline is a dynamic interface where land, sea and air interact on scales ranging from pebbles to continents, and from seconds to centuries. Indeed, sea level change dictates the long-term evolution of coastal systems, ecologically and geologically. Therefore, coastal systems are projected to be increasingly at risk, through the 21st century and beyond, due to global climate change. The IPCC 4AR (2007) identifies coastal systems as the interacting low-lying areas and the shallow coastal waters, including their human components. While,
climate change will not create any new coastal hazards, SLR will have a number of effects on coastal regions, such as: inundation, flood and storm damage, loss of wetlands, erosion, and saltwater intrusion.

The main drivers of climate change that will impact on the coastal regions are shown in Figure 2-32, including both external marine and terrestrial influences.

The IPCC (2007) anticipates that coasts will be exposed to increasing risks from climate change, SLR and climate-related changes. The resulting impacts are anticipated to be overwhelmingly negative. As reported in both the TAR (2001) and 4AR (2007), the biophysical effects of climate change and SLR will have direct and indirect socio-economic impacts on tourism, human settlements, agriculture, freshwater supply and quality, fisheries, financial services, and human health in those coastal zones (Nicholls et al., 2007, McLean et al., 2001). Potential biophysical and related socio-economic impacts on coastal systems are summarised in Table 2-6.

Importantly, for the community and decision makers, sea level rise differs from other climate change factors due to the physical constraint of the ocean’s high heat capacity; there is a ‘commitment to sea level rise’ which will persist for hundreds, if not thousands of years, even given a stabilised future climate (Nicholls and Lowe, 2004). In the future, with continued global warming, the effects of extreme events, with the associated SLR, are very likely to further increase in frequency and intensity; consequently, the inundation problems will intensify.
Biophysical impacts | Related socioeconomic impacts
--- | ---
• Increased coastal erosion | • Increased loss of property and coastal habitats
• Inhibition of primary production processes | • Increased flood risk and potential loss of life
• More extensive coastal inundation | • Damage to coastal protection works and other infrastructure
• Higher storm-surge flooding | • Increased disease risk
• Landward intrusion of seawater in estuaries and aquifers | • Loss of renewable and subsistence resources
• Changes in surface water quality and groundwater characteristics | • Loss of tourism, recreation, and transportation functions
• Changes in the distribution of pathogenic microorganisms | • Loss of nonmonetary cultural resources and values
• Higher SS | • Impacts on agriculture and aquaculture through decline in soil and water quality
• Reduced sea-ice cover.

Table 2.6: Potential impacts of climate change and SLR on coastal systems (McLean et al., 2001).

The IPCC (2007) posits that the intensity of tropical cyclones will increase; if this outcome does occur, it will make the combined power of SLR and cyclones potentially even more destructive than today’s cyclones (Solomon et al., 2007b). In the tidal reaches of rivers, relative SLR will raise the base level for river floods. However, under climate change, there could also be an increase in river flow. The interactions of these two factors would amplify an increase in flood risk.

Future impacts, which depend on various factors (as shown in the Figure 2-32), are not always easy to predict, due, mainly, to the great diversity of both natural and socioeconomic coastal systems and their dynamic response to changes. Thus, the consequences of SLR for a given population in a particular locality will depend on the following factors (Brooks et al., 2006):

- the amount of SLR locally (termed relative sea level rise)
- the effects of this SLR on hazards such as storm surges
- the interaction of SLR with other climate change hazards such as changes in the frequency and severity of storms
- the geomorphological response of coasts to SLR, which will in turn depend upon natural geomorphological processes and human interventions in the coastal system
- the physical exposure of the population and associated systems to the immediate impacts of SLR and related coastal hazards
- the ability of the population and related systems to cope with these impacts

Exacerbating the problems related to climate change and SLR is that coastal areas are home to one third of the world’s population. In recent decades, urban development, agriculture, industry, transportation, and tourism have all grown rapidly in coastal zones worldwide. In general, coastal regions tend to be densely populated, economically productive, and environmentally sensitive (Yin, 2001). Hence, even small rises in mean sea level, when associated with storm surges and major coastal populations, can be devastating (Garnaut, 2008).

Many people prefer to live on low-lying coastlines. Cohen et al., (1997) estimated that in 1994 approximately 37% (2.07 billion) of the 1994 population (5.62 billion) lived within 100 km of a coastline, and approximately 44% (2.45 billion) within 150 km of a coastline (Cohen et al., 1997). According to Small and Nicholls (2003), the near-coastal population within 100 km of a shoreline and 100 m of the sea level was estimated to be 1.2 billion people, with average densities nearly 3 times higher than the global average density; further, it is estimated that 50% of the world’s population will live within 100 km of the coast by 2030. According to the authors, the average population density, within the near coastal-zone, diminishes more rapidly with elevation than with distance; the opposite is true of lighted settlements, which are concentrated within 5 km of coastlines worldwide, whereas the average population densities are higher at elevations below 20 m throughout the 100 km width of the near-coastal zone (Figure 2 33).
Distributions of population (bar graph) and integrated population density (IPD) (line graph) as functions of coastal proximity and elevation (Small and Nicholls, 2003).

Research by McGranahan et al., (2007) suggests that, as shown in Table 2-7, low elevation coastal zone, less than 10 metres above sea level, covers 2 % of the world’s land area but contains 10 % of the world’s population (about 634 million people) and 13 % of the world’s urban population.

<table>
<thead>
<tr>
<th>Region</th>
<th>Population (million)</th>
<th>Land ('000 km²)</th>
<th>Share of population and land area in LECZ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Urban</td>
<td>Total</td>
</tr>
<tr>
<td>Africa</td>
<td>56</td>
<td>31</td>
<td>191</td>
</tr>
<tr>
<td>Asia</td>
<td>466</td>
<td>238</td>
<td>881</td>
</tr>
<tr>
<td>Europe</td>
<td>50</td>
<td>40</td>
<td>490</td>
</tr>
<tr>
<td>Latin America</td>
<td>29</td>
<td>23</td>
<td>397</td>
</tr>
<tr>
<td>Australia and New Zealand</td>
<td>3</td>
<td>3</td>
<td>131</td>
</tr>
<tr>
<td>North America</td>
<td>24</td>
<td>21</td>
<td>553</td>
</tr>
<tr>
<td>Small Island States</td>
<td>6</td>
<td>4</td>
<td>58</td>
</tr>
<tr>
<td>World</td>
<td>634</td>
<td>360</td>
<td>2,700</td>
</tr>
</tbody>
</table>

Table 2-7 Population and land area in the low elevation coastal zone by region, 2000 (McGranahan et al., 2007)
Consistent with McGranahan et al.’s (2007) finding, most Australians live near the sea, with all state capitals being located on the coastline. Chen and McAneney (2006) quantified the Australian coastal population at a spatial resolution of 1 km, as a function of distance to shoreline and elevation above mean sea level. Their results, which produced a similar distribution to the global population distribution, show that about 50% of Australian addresses (or populations) are located within 7 km of the shore, with as many as 30% (about six million people) within 2 km of the coast, and that population decreases very rapidly with increasing distance from the shoreline. The same study also indicates that about 6.0% of Australian addresses are situated within 3 km of shorelines in areas with elevations below 5 m (Chen and McAneney, 2006). The Australian Department of Climate Change (2008) estimates that Queensland, with almost 250,000 vulnerable coastal buildings, is at the highest risk of all Australian states, as estimated from the projected SLR associated extreme (The Department of Climate Change, 2008).

Clearly, if the sea level rise reaches 1.5 m by the end of the 21st century, as projected by the many researchers cited above, the outcome will be the inundation of many low lying coastal areas, the submergence of the barrier islands, the loss of the deltas, and the relocation of millions of people who reside in these low lying coastal areas.
LITERATURE REVIEW – B: RESPONDING TO CLIMATE CHANGE

2.5 OVERVIEW

The available scientific evidence overwhelmingly indicates that climate change is happening, and that it is a serious global threat that demands an urgent response (Stern, 2006). Any climate change response, therefore, needs to address the following questions:

- What can/should be done to prevent, or reduce these impacts?
- When and how should these actions be undertaken?

The United Nations Framework Convention on Climate Change (1992) has identified two responses to climate change: (1) the mitigation of climate change by reducing GHG emissions and enhancing sinks; and (2) adaptation to overcome the impacts of climate change.

The IPCC 4AR (2007) states that the warming of the climate system from anthropogenic greenhouse-gas concentrations is unequivocal (Parry et al., 2007). The report also suggests that a reduction in the climate impacts can be accomplished through the two processes of mitigation and adaptation.

Importantly, the IPCC’s (2007) definition of mitigation refers to limiting global climate change through reducing the emissions of greenhouse gases (GHGs), as well as enhancing their sinks. On the other hand, the IPCC’s definition of adaptation refers to initiatives and measures taken to reduce the vulnerability of natural and human systems against actual or expected climate change effects.

A schematic framework (Figure 2-34) representing the anthropogenic drivers, the impacts of and responses to climate change, and their linkages, is defined in the Synthesis report of the IPCC (Allali et al., 2007). This schematic framework also illustrates the differences between the Third Assessment Report (TAR, 2001) and the IPCC-4AR (2007), in terms of the available knowledge. However, due to the limited information available at the time of the TAR, only clockwise linkages were described,
i.e. the link between climatic change and the impacts from socio-economic information and emissions. Today, with our increased understanding of these linkages, it is now possible to assess the linkages counter clockwise, i.e. to evaluate the possible development pathways and global emissions constraints that would help reduce the risk of future impacts, especially those the community may wish to avoid.

Figure 2-34 Anthropogenic drivers, impacts of and responses to climate change, and their linkages (Allali et al., 2007).

While climate change adaptation and mitigation are closely interrelated, there are some distinct differences. For example, Preston and Jones (2006) perceive adaptation as measures that are generally implemented at the local level and reduce risk from the bottom-up. Unlike adaptation, they perceive mitigation as reducing the magnitude of climate change by decreasing GHG emissions; further, mitigation would work best if it were implemented from top-down at the global level.

From another perspective, Fussel and Klein (2006) identify the key differences between mitigation and adaptation policy (Table 2-8). Mitigation and adaptation policies are formulated largely independently of each other, owing to the divergent,
though typical, temporal and spatial scales at which mitigation and adaptation take place, in addition to their respective information requirements.

<table>
<thead>
<tr>
<th>Characteristics of Mitigation and Adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefited systems</td>
</tr>
<tr>
<td>Scale of effect</td>
</tr>
<tr>
<td>Life time</td>
</tr>
<tr>
<td>Lead time</td>
</tr>
<tr>
<td>Effectiveness</td>
</tr>
<tr>
<td>Ancillary benefits</td>
</tr>
<tr>
<td>Polluter pays</td>
</tr>
<tr>
<td>Payer benefits</td>
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<tr>
<td>Monitoring</td>
</tr>
</tbody>
</table>

Table 2-8 The key differences between mitigation and adaptation policies (Fussel and Klein, 2006).

Although adaptation is considered a complementary approach to mitigation, mitigation has been the primary focus of public attention and policy efforts on climate change. Fussel and Klein (2006), while explaining the underlying reasons for the focus on mitigation, argue that adaptation should also be taken into consideration as a response measure. Their comparison highlights the following;

- Mitigating climate change helps to reduce impacts on all climate-sensitive systems, whereas the potential of adaptation measures is limited for many systems.
- Reducing GHG emissions applies the “polluter-pays” principle whereas the need for adaptation measures will be greatest in developing countries, which have contributed relatively little to climate change.
- GHG emission reductions are relatively easy to monitor quantitatively, both in terms of their absolute amount and as deviation from an established baseline. It is much more difficult to measure the effectiveness of adaptation in terms of impacts avoided, or to ensure that international assistance to facilitate adaptation would be fully additional to existing development aid budgets.

Nevertheless, the following reasons are given in support of a more comprehensive consideration of adaptation as a response measure:
- Given the amount of past GHG emissions and the inertia of the climate system, we are already bound to some level of climate change, which can no longer be prevented even by the most ambitious emission reductions.
- The effect of emission reductions takes several decades to fully manifest, whereas most adaptation measures have more immediate benefits.
- Adaptations can be effectively implemented on a local or regional scale such that their efficacy is less dependent on the actions of others, whereas mitigation of climate change requires international cooperation.
- Most adaptations to climate change also reduce the risks associated with current climate variability, which is a significant hazard in many world regions.

The United Nations Environment Programme (UNEP) posits that only mitigation can prevent climate change and its consequences. While this may be so, societies have to be prepared for such outcomes, rather than leave it to future generations to live or attempt to fix. This is especially so as climate changes are reality, and the reduction of greenhouse gas emissions will, most likely, be insufficient to prevent climate change (Feenstra et al., 1998). The IPCC 4AR (2007) describes adaptation and mitigation as complementary, substitutable or independent of each other. Irrespective of the scale of the mitigation measures that are implemented over the next 10–20 years, adaptation measures will still be required due to the inertia of the climate system. Therefore, an effective climate policy needs to be aimed at reducing the risks of climate change to natural and human systems; as such, it involves a portfolio of diverse adaptation and mitigation actions (Klein et al., 2007).

### 2.6 MITIGATION OVERVIEW

Mitigation, as per the IPCC definition (Parry et al., 2007), refers to an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases. To eliminate or reduce the risk of climate change to human life and property, both policy instruments and technology must be used in the context of sustainable development. This direction could include approaches devised to reduce emissions of GHG into the atmosphere; to enhance their removal from the atmosphere through storage in
geological formations, soils, biomass, or the ocean; or to alter incoming solar radiation through several “geo-engineering” options.

Since GHG emissions are a global problem, the reduction of GHG emissions requires effective international cooperation. The UNFCCC is a primary policy tool for facilitating a global response to protect the climate system for present and future generations. Although legally binding targets and timetables for greenhouse gas mitigation could not be agreed to at the 1992 UN Framework Convention on Climate Change, they became the centrepiece of the Kyoto Protocol in 1997 which was entered into force in February 2005. The Kyoto Protocol is an international agreement which builds on the UNFCCC; it sets legally binding targets and timetables for cutting the greenhouse-gas emissions of industrialised countries. Thus, while the UNFCCC has encouraged developed countries to stabilise GHG emissions, the Kyoto Protocol commits them to do so (UNFCCC, 2008).

In the United Nations Framework Convention on Climate Change (UNFCCC) three conditions are made explicit when working towards the goal of GHG stabilisation in the atmosphere, namely:

1. That it should take place within a time-frame sufficient to allow ecosystems to adapt naturally to climate change;
2. That food production is not threatened and;
3. That economic development should proceed in a sustainable manner.

The 2007 report of The IPCC Working Group III, specifically deals with strategies for mitigating the effects of climate change; it recommends greater use of renewable energies (e.g. solar or wind power), as well as the exploration of more efficient methods of using energy. The report also promotes the use of carbon emissions tariffs and other economic measures to promote the application of renewable energies. Further, the report discusses mechanisms that could help compensate for the production of greenhouse gases, such as geo-sequestration (Metz et al., 2001).

A broad range of GHG mitigation options exist; these options can be grouped under three categories:
1. reduction
2. sequestration
3. capture/use

Reductions refer to the options that involve substituting GHG-producing activities with non-GHG producing activities, such as reductions through improvements in energy efficiency and the prevention of deforestation. Unlike the reduction options, all other approaches begin with the capturing of GHGs that have already been produced. Thus, sequestration is the storage of captured gases in a sink, other than the atmosphere (Metz et al., 2001). The scope of sequestration is specifically limited to (long-term) storage of carbon in forests, soil, the ocean, and other carbon sinks (Pew Center, 2008). Capture/use occurs when GHG are captured or absorbed, and then processed and/or used, in some form (Fernandez et al., 2005).

According to Fernandez et al., 2005, reduction involves: Industrial process modifications; fuel switching and efficiency improvements; renewable energy transitions; and demand side efficiency improvements (reductions in energy use by end-users). Sequestration involves: Forest sequestration; agricultural sequestration; CO2 injection into geological formations; mineral carbonation; and ocean sequestration. On the other hand, capture/use involves: Methane capture and use; biomass to energy; and biomass to product.

Nichols and Lowe, (2004) assessed the possible benefits of mitigation of climate change for coastal regions, especially, the possible impact of sea level changes on coastal populations under mitigated and unmitigated SRES scenarios. Their findings show that unmitigated impacts could be significant; however, they can be reduced, to varying degrees, by mitigation after the middle of the 21st century. Further, they conclude that the largest benefits occur long into the future.

The Stern Review (Stern, 2006), which examined the economics of mitigation, identified the benefits that accrue from strong, early action on climate change. These benefits are seen as far outweighing the costs; therefore mitigation must be viewed as an investment in the future, not as a liability.
The estimation of mitigation costs and potentials is a complex task. It depends on the assumptions made about future socio-economic growth, technological change and consumption patterns. Adger et al. (2005a) addressed the economic issues. They suggest that the cost of mitigation policies would rise from a low level today to a range of 0-2% of world GDP by 2050. In terms of GDP output lost, this figure represents a maximum loss of one year’s growth, i.e. the modelled output in 2050 would not be reached until 2051, within a context where the GDP is likely to have risen by two to three hundred per cent in most economies by this date (Adger et al., 2005a).

Although several social, economic and technological policies would produce an emission reduction, an assessment, by the IPCC 4AR – Working Group III (AR4WGIII) (AR4WGIII) (Barker et al., 2007), of the current mitigation efforts shows that the current commitments would not lead to a stabilisation of atmospheric GHG concentrations. In fact, according to the IPCC AR4 – Working Group I (WGIAR4), the lag times in the global climate system mean that no mitigation effort, no matter how rigorous and relentless, will prevent climate change from happening within the next few decades (Christensen et al., 2007, Meehl et al., 2007)

2.7 ADAPTATION

The climate has changed, is changing, and will continue to change, regardless of what, if any, investments in mitigation are made. Further, regardless of the source of change, those systems, that are sensitive to changes in climatic conditions, will be affected (Scheraga and Grambsch, 1998). Hence, adaptation needs to be considered in any strategic options.

Thus, adaptation is an important approach for the protection of human and natural systems from the risks posed by climate variability and change, as well as for the exploitation of beneficial opportunities that may be provided by a changing climate. Additionally, adaptation measures or processes can offer a means of coping with climate change impacts, especially as individuals and communities try to cope with the consequences of climate change.
The process of adaptation to environmental change, however, is not a new concept. Throughout history societies have been adapting to changing climatic conditions (Smit and Wandel, 2006, Lim et al., 2004, Easterling et al., 2004). Indeed, the continued viability and sustainability of many of these systems will be dependent on their ability to successfully adapt to future climate changes (Willows and Connell, 2003).

The U.S. Climate Change Science Program’s (2008) primary goals for adaptation to climate variability and change are summarised as (Ebi et al., 2008):

1. To avoid maladaptive responses;
2. To establish protocols to detect and measure risks and to manage risks proactively when possible;
3. To leverage technical and institutional capacity;
4. To reduce current vulnerabilities to climate change;
5. To develop adaptive capacity to address new climate risks that exceed conventional adaptive responses; and,
6. To recognize and respond to impacts which play out across time.

The following section outlines a number of terms that provide background information to the adaptation approach. The definitions for the key terms adopted by the IPCC (2007) presented below (Parry et al., 2007):

**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.

**Adaptive Capacity:** The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

**Exposure:** The nature and degree to which a system is exposed to significant climatic variations. For example, the more people move to low-lying coastal areas, the greater is the population’s exposure to SLR and increased coastal storms.
Resilience: The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change.

Sensitivity: Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).

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. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

2.7.1.1 ADAPTATION OPTIONS

Many types of adaptation come in a wide variety of forms, that are classified by their timing, goal, function and motive of implementation. Table 2-9 illustrates the types of adaption and the general differentiating concepts. Compared to other concepts, purposefulness and timing are used more commonly.

Further, adaptation can be either reactive or anticipatory and, depending on their degree of spontaneity, they can be autonomous or planned (Smit et al., 2000). Reactive adaptation occurs after the initial impacts of climate change have been felt; anticipatory (or proactive) adaptation takes place before the impacts are observed. Both anticipatory and reactive adaptations can be planned (for example, building sea walls in anticipation of a rise in sea level). However, reactive adaptation can also occur autonomously (for instance, the purchase of air conditioning), while, in most circumstances, anticipatory planned adaptations will incur lower long-term costs, and be more effective than reactive adaptations (Lemmen et al., 2008).
### Differentiating Concepts

<table>
<thead>
<tr>
<th>Purposefulness</th>
<th>Examples of Terms Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autonomous</td>
<td>Planned</td>
</tr>
<tr>
<td>Spontaneous</td>
<td>Purposeful</td>
</tr>
<tr>
<td>Automatic</td>
<td>Intentional</td>
</tr>
<tr>
<td>Natural</td>
<td>Policy</td>
</tr>
<tr>
<td>Passive</td>
<td>Active Strategic</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Timing</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Anticipatory</td>
<td>Reactive</td>
</tr>
<tr>
<td>Proactive</td>
<td>Reactive</td>
</tr>
<tr>
<td>Ex ante</td>
<td>Ex post</td>
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</table>

<table>
<thead>
<tr>
<th>Temporal Scope</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Short term</td>
<td>Long term</td>
</tr>
<tr>
<td>Tactical</td>
<td>Strategic</td>
</tr>
<tr>
<td>Instantaneous</td>
<td>Cumulative</td>
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</table>

<table>
<thead>
<tr>
<th>Spatial Scope</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Localized</td>
<td>Wide spread</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Function/Effects</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Retreat - Accommodate - Protect</td>
<td>Prevent – Tolerate – Spread – Change - Restore</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Form</th>
<th></th>
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</thead>
</table>

<table>
<thead>
<tr>
<th>Performance</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost – Effectiveness – Efficiency – Implementability – Equity</td>
<td></td>
</tr>
</tbody>
</table>

Table 2-9 Bases for characterising and differentiating adaptation to climate change (Smit et al., 2001)

Another type of classification can be based on the system in which the adaptation takes place: the natural system (in which adaptation is, by definition, reactive) or the human system (in which both reactive and anticipatory adaptations are observed). Adaptation in human systems can be of private or public interest, depending on who adapts. Table 2-10 presents examples of adaptation activities for each of the five types of adaptation that have been defined.

The increasing interest in adaptation to climate change is reflected in the evolution of the theory and practice of climate change vulnerability assessments. Fussel and Klein (2006) argue that effective adaptation to climate change is contingent on the availability of two important prerequisites: information on what to adapt to and how to adapt, and resources to implement the adaptation measures.
Adger et al. (2005b) examined the criteria for the definition of “successful” adaptation. The authors showed how the criteria varied with spatial scale, and how they were interpreted and weighted differently, by different interest groups. They also argue that the elements of effectiveness, efficiency, equity, and legitimacy are important when judging success, especially in terms of the sustainability of the development pathways into an uncertain future (Adger et al., 2005b).

The factors that affect adaptive capacity, at the national scale, include a set of calibrated indicators of adaptive capacity. Such adaptive capacity is associated primarily with indicators of governance, civil and political rights, and literacy, rather than with measures of wealth. Additionally, since adaptation does not occur instantaneously, the relationship between adaptive capacity and vulnerability depend on timescales and hazards. The vulnerability, or potential vulnerability, of a system to climate change, that is associated with anticipated hazards in the medium- to long-term, will depend on that system’s success at anticipatory adaptation (Brooks et al., 2005).

Smit and Wandel (2006) reviewed the concept of adaptation in the context of adaptive capacity, and the vulnerability of human systems to global changes. Thus, adaptations, which are changes in the system to better deal with problematic exposure and

<table>
<thead>
<tr>
<th>Natural Systems</th>
<th>Anticipatory</th>
<th>Reactive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Changes in length of growing season</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Changes in ecosystem composition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wetland migration</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Human Systems</th>
<th>Anticipatory</th>
<th>Reactive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Private</td>
<td></td>
<td>Purchase of Insurance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Changes in farm practises</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Changes in insurance premiums</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Purchase of air conditioning</td>
</tr>
<tr>
<td>Public</td>
<td>Early warning systems</td>
<td></td>
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<tr>
<td></td>
<td>New building codes, design standards</td>
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<tr>
<td></td>
<td>Incentives for relocation</td>
<td></td>
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<tr>
<td></td>
<td>Subsidies</td>
<td></td>
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<tr>
<td></td>
<td>Enforcement of building codes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Beach nourishment</td>
<td></td>
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</tbody>
</table>

Table 2-10 Types of adaptation and the examples of adaptation activities (Klein et al., 2006)
sensitivities, are manifestations of adaptive capacity. While, the authors conclude that there have been considerable scholarship in the climate change context, and on calculating indices of vulnerability and adaptive capacities, as well as on evaluating hypothetical adaptations, the practical applications of this work (in reducing the vulnerabilities of people) are not readily apparent. Further, it appears that adaptations can be considered as either local or community based adjustments. These adjustments are developed to manage the changing conditions within the constraints of the broader economic, social and political arrangements. Where those constraints are binding, then the adaptation may be considered as attempting to change those broad economic, social and political structures (Smit and Wandel, 2006).

The adaptation process to climate change, in both the human and natural systems, is highly complex and dynamic. Such a process often entails much feedback and many dependencies on the existing local and temporal conditions (Easterling et al., 2004). The process includes information development, awareness raising, planning, design, implementation, and monitoring. Each part of the adaptation process requires mechanisms to be in place, along with technologies, expertise and other resources available. The availability of appropriate technologies may vary at the country and local level, as may the implementation of the adaptation process. In addition, any adaptation policies must have the potential to contribute to the existing problem that communities face. One example is the building and operating of desalination plants, without a renewable energy supply to provide potable water; such a plant will require higher energy usage, and so contradict any mitigation policies.

2.7.1.2 ADAPTIVE CAPACITY

By definition, adaptive capacity is the ability or potential of a system to respond successfully to climate variability and change; it includes adjustments in both behaviour, and in resources and technologies. Brooks and Adger (2005) view adaptive capacity as a prerequisite for the design and implementation of effective adaptation strategies that will reduce the likelihood, and the magnitude, of harmful outcomes resulting from climate change. The authors suggest that the adaptation process also
requires the capacity to learn from previous experiences; hence, they are better able to cope with the current climate, by applying these lessons to manage future climate impacts, including surprises (Brooks and Adger, 2005).

According to Dessai et al. (2005), the past has informed responsive adaptations to either climate variability (or change), mainly driven by record-breaking extreme weather events. However, as awareness about the potential impacts of human-induced climate change has grown (at different levels throughout countries and sectors), so has the desire to plan (in advance) for the impacts of climate change and, so, mitigate any negative hazards and enhance the benefits (Dessai et al., 2005).

Easterling et al. (2004) postulate that the availability of, and accessibility to, adjustment opportunities serve as the foundation for understanding and defining a system’s adaptive capacity. The authors argue that, in managed systems, wealth, availability of technology, appropriate decision-making capabilities, human capital, social capital, risk spreading, the ability to manage information, and the perceived attribution of the source of stress, all contribute significantly to adaptive capacity and the capability of such systems to actively and adequately respond to changing environments.

However, as reported in the IPCC 4AR report (2007), the adaptive capacities of societies are not always the same, and vary from country to country, community to community, among groups and individuals, and over time. Further, some individuals and groups within all societies have insufficient capacity to adapt to climate change. For this reason, both, human and social capital, are the key determinants of adaptive capacity at all scales. Indeed, they are as important as the level of income and the technological capacity (Adger et al., 2007). Adaptive capacity is not a static element. Smit and Wandel (2006) report that adaptive capacity has been analysed in various ways, via thresholds and coping ranges; it has also been defined by the conditions that a system can deal with, accommodate, adapt to, and recover from.
The relationship between climate change and the exceeding threshold, and how adaptation can establish a new critical threshold to reduce vulnerability to climate change, is illustrated in Figure 2-35. The climate variable shows an upward trend, representing a change in climate that starts at the mid-point of the time series. The coping range represents the tolerable climate; the coping range boundaries (critical thresholds) may lie above and/or below the average value of the climate variable. Adaptation aims to reduce vulnerability by increasing the critical threshold, and countering the increased risk that the un-adapted threshold will exceed, due to climate change. The figure illustrates the relationship between the management of the critical threshold, and the time taken to plan and implement adaptation measures, as well as the time available to plan and implement adaptation measures from a given starting point.

2.7.1.3 VULNERABILITY AND ADAPTATION ASSESSMENTS

Vulnerability is not a straightforward concept; it is defined in many ways, with little agreement about its meaning. Further, different disciplines use different meanings and concepts of vulnerability; these, in turn, have led to diverse methods for measuring vulnerability. These varying approaches to vulnerability can be explained by the tendency of different disciplines to focus on diverse components of risk.

The IPCC defined vulnerability, in the context of climate change, as:

“...the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and...
extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.” (Parry et al., 2007)

A selection of climate related vulnerability definitions are presented below:

'Human vulnerability is a function of the costs and benefits of inhabiting areas at risk from natural disaster.' (Alexander, 1993)

'By vulnerability we mean the characteristics of a person or group in terms of their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard. It involves a combination of factors that determine the degree to which someone's life and livelihood are put at risk by a discrete and identifiable event in nature or in society.' (Blaikie et al., 1994)

'Vulnerability is best described as an aggregate measure of human welfare that integrates environmental, social, economic and political exposure to a range of potential harmful perturbations. Vulnerability is a multilayered and multidimensional social space defined by the determinate, political, economic and institutional capabilities of people in specific places at specific times.' (Bohle et al., 1994)

'Vulnerability is a measure of the degree and type of exposure to risk generated by different societies in relation to hazards. Vulnerability is the a characteristic of individuals and groups of people who inhabit a given natural, social and economic space, within which they are differentiated according to their varying position in society into more or less vulnerable individuals and groups.' (Cannon, 1994)

'Vulnerability refers to exposure to contingencies and stress, and difficulty in coping with them. Vulnerability has thus two sides: an external side of risks, shocks, and stress to which an individual or household is subject: and an internal side which is defencelessness, meaning a lack of means to cope without damaging loss.' (Chambers, 1989)
'Vulnerability is the likelihood that an individual or group will be exposed to and adversely affected by a hazard. It is the interaction of the hazards of place (risk and mitigation) with the social profile of communities.' (Cutter, 1993)

'Vulnerability is the differential susceptibility of circumstances contributing to Vulnerability. Biophysical, demographic, economic, social and technological factors such as population ages, economic dependency, racism and age of infrastructure are some factors which have been examined in association with natural hazards.' (Dow and Downing, 1995)

'Vulnerability is the threat (from hazardous materials) to which people are exposed (including chemical agents and the ecological situation of the communities and their level of emergency preparedness). Vulnerability is the risk context.' (Gabor and Griffith, 1980)

'Distinguishes between vulnerability as a biophysical condition and vulnerability as defined by political, social and economic conditions of society... vulnerability is defined both in geographic space (where vulnerable people and places are located) and in social space (who in that place is vulnerable).' (Liverman, 1990)

'Vulnerability is the threat or interaction between risk and preparedness. It is the degree to which hazardous materials threaten a particular population (risk) and the capacity of the community to reduce the risk or adverse consequences of hazardous materials releases.' (Pijawka et al., 1985)

'Risk from a specific hazard varies through time and according to changes in either (or both) physical exposure or human vulnerability (the breadth of social and economic tolerance available at the same site).' (Smith, 1992)

'Vulnerability is the degree to which different classes of society are differentially at risk.' (Susman et al., 1983)

'Vulnerability is the degree to which a system acts adversely to the occurrence of a hazardous event. The degree and quality of the adverse reaction are
conditioned by a system's resilience (a measure of the system's capacity to absorb and recover from the event). (Timmerman, 1981)

‘Vulnerability is defined in terms of exposure, capacity and potentiality. Accordingly, the prescriptive and normative response to vulnerability is to reduce exposure, enhance coping capacity, strengthen recovery potential and bolster damage control (i.e., minimize destructive consequences) via private and public means. (Watts and Bohle, 1993)

‘Vulnerability is a measure of a system’s susceptibility to climate change, which is a function of the system’s exposure, sensitivity, and adaptive capacity.’ (Easterling et al., 2004)

‘Vulnerability is susceptibility to harm or damage potential. It considers such factors as the ability of a system to cope or absorb stress or impacts and to “bounce back” or recover.’ (Richards and Nicholls, 2005)

‘Vulnerability refers to the magnitude of harm that would result from a particular hazardous event. The concept recognises, for example, that different sub-types of a receptor may differ in their sensitivity to a particular level of hazard. Therefore climate vulnerability defines the extent to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. It depends not only on a system’s sensitivity but also on its adaptive capacity.’ (Willows and Connell, 2003)

The IPCC definition incorporates three main variables;

1. exposure to climatic variations,
2. sensitivity, and
3. adaptive capacity of a system to various stressors.

While these variables determine the vulnerabilities, the responses to the threats are also influential. The concepts of adaptation, adaptive capacity, vulnerability, resilience, exposure and sensitivity are interrelated. Further, they have a wide range of applications within global change science (Smit and Wandel, 2006). The differences in
exposure to the various direct effects of climate change, and the different sensitivities to these direct effects, can lead to a variety of potential impacts on the system of interest. It is the system’s adaptive capacity, then, that determines its vulnerability to these potential impacts. These relationships are shown in Figure 2-36.

![Figure 2-36 Conceptualisation of vulnerability to climate change (Ionescu et al., 2005)](image)

Importantly, the nature of vulnerability is dynamic and complex due to the constantly evolving natural and socio-economic conditions. However, certain factors are more likely to influence vulnerability to a wide variety of hazards in different geographical and socio-political contexts. A common argument is that countries, regions, economic sectors and social groups differ in their degree of vulnerability to climate change. Indeed, (Sperling et al., 2003) posits that climate change is generally superimposed on existing vulnerabilities.

Climate change vulnerability assessments examine the underlying socio-economic, institutional, and political and cultural factors that influence vulnerability. Additionally, the assessments identify the processes that shape the consequences of the climate related factors, along with the conditions that increase or reduce vulnerability to adverse outcomes. Brooks et al. (2005) developed a shortlist of 46 variables representing generic vulnerability, economic well-being and inequality, health and nutritional status, education, physical infrastructure, governance, geographic and demographic factors, agriculture, ecosystems and technological capacity. A summary of these variables is presented in Table 2-11.
<table>
<thead>
<tr>
<th>Category</th>
<th>Variable</th>
<th>Proxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economy</td>
<td>National wealth</td>
<td>GDP per capita (US$ PPP)</td>
</tr>
<tr>
<td></td>
<td>Inequality</td>
<td>GINI coefficient</td>
</tr>
<tr>
<td></td>
<td>National wealth</td>
<td>GNI (total, PPP)</td>
</tr>
<tr>
<td>Health and nutrition</td>
<td>General health</td>
<td>Life expectancy at birth</td>
</tr>
<tr>
<td></td>
<td>State support for health</td>
<td>Public health expenditure (% of GDP)</td>
</tr>
<tr>
<td>Education</td>
<td>Educational commitment</td>
<td>Education expenditure as % of GNP</td>
</tr>
<tr>
<td></td>
<td>Entitlement to information</td>
<td>Literacy rate</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Quality of basic infrastructure</td>
<td>Population with access to sanitation (%)</td>
</tr>
<tr>
<td>Governance</td>
<td>Ability to deliver services</td>
<td>Government effectiveness</td>
</tr>
<tr>
<td></td>
<td>Effectiveness of policies</td>
<td>Control of corruption</td>
</tr>
<tr>
<td>Geography and demography</td>
<td>Coastal risk</td>
<td>km of coastline (scale by land area)</td>
</tr>
<tr>
<td></td>
<td>Coastal risk</td>
<td>Population within 100km of coastline (%)</td>
</tr>
<tr>
<td></td>
<td>Resource pressure</td>
<td>Population density</td>
</tr>
<tr>
<td>Agriculture</td>
<td>Dependence on agriculture</td>
<td>Agricultural employees (% of total population)</td>
</tr>
<tr>
<td></td>
<td>Agricultural self-sufficiency</td>
<td>Agricultural production index</td>
</tr>
<tr>
<td>Ecology</td>
<td>Environmental stress</td>
<td>Protected land area (%)</td>
</tr>
<tr>
<td></td>
<td>Sustainability of water resources</td>
<td>Groundwater recharge per capita</td>
</tr>
<tr>
<td>Technology</td>
<td>Commitment to and resources for research</td>
<td>R&amp;D investment (% GNP)</td>
</tr>
</tbody>
</table>

Table 2-11 Selected potential proxies for national-level vulnerability to climate change (Brooks et al., 2005)

Many studies have addressed how climate change might affect a range of natural and human systems, as well as identifying and evaluating options to respond to these effects. Such analyses of adaptations to climate change have been undertaken for a variety of purposes. The characteristics identified by the adaptation analyses have been comprehensively reviewed by Smit and Wandel (2006), and grouped under four categories (Table 2-12).
<table>
<thead>
<tr>
<th>Purpose</th>
<th>Addressed to</th>
<th>Methods/Tools</th>
<th>Characteristics</th>
<th>Study Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>To estimate impact of climate change, and to estimate the difference adaptation could make</td>
<td>Article 2 UNFCCC which commits countries to mitigate greenhouse emissions in order to avoid “dangerous” anthropogenic changes in climate</td>
<td>Uses assumed or hypothetical adaptations and then estimates the effects they would have on the calculated impacts of conditions captured in specified scenarios</td>
<td>Examine the actual processes of adaptation or adaptive capacity, explore the conditions or drivers that facilitate or constrain adaptations</td>
<td>(Mendelsohn et al., 2000a, Parry, 2002, Mendelsohn et al., 2000b)</td>
</tr>
<tr>
<td>To assess the relative merit or utility of alternative adaptations, in order to identify the best or better ones</td>
<td>Article 4.1-UNFCCC that commit countries to “formulate and implement... measures to facilitate adequate adaptation to climate change”</td>
<td>Uses a set of adaptations, chosen by the experts. These adaptations are considered to be distinct and discrete, in order that they can be subjected to evaluation according to some common principles or criteria.</td>
<td>Ranks the relative merit of adaptations by using benefit-cost, cost effectiveness and multiple-criteria procedures. Common variables employed are benefits, effectiveness, implementability, costs, efficiency, and equity</td>
<td>(Adger et al., 2005b, Klein and 1999)</td>
</tr>
<tr>
<td>To provide an evaluation of the relative vulnerability (and/or relative adaptive capacity) of the countries or regions, usually using some kind of indicator, scoring, rating or ranking procedure.</td>
<td>UNFCCC Article 4.4, which commits developed country parties to “assist developing country parties that are particularly vulnerable to the adverse effects of climate change”.</td>
<td>Vulnerability is taken as the “starting point” rather than the residual or “end point” and it is assumed to be measurable based on attributes or determinants selected a priori.</td>
<td>The processes, determinants or drivers of adaptive capacity and vulnerability as they function in each system are taken as given, and used as the basis for the rating or ranking analysis.</td>
<td>(Van der Veen and Logtmeijer, 2005, O’Brien et al., 2004, Kelly and Adger, 2000, Adger et al., 2004, Brooks et al., 2005)</td>
</tr>
<tr>
<td>To contribute to practical adaptation initiatives and investigate the adaptive capacity and adaptive needs in a particular region or community in order to identify means of implementing adaptation initiatives or enhancing adaptive capacity.</td>
<td>-----</td>
<td>The variables that represent exposures, sensitivities, or aspects of adaptive capacity, are identified empirically from the community. It is sometimes called a “bottom-up” approach in contrast to the scenario-based “top-down” approaches.</td>
<td>The focus is to document the ways in which the system or community experiences changing conditions and the processes of decision-making in this system that may accommodate adaptations or provide means of improving adaptive capacity</td>
<td>(Keskitalo, 2004, Ford and Smit, 2004, Sutherland et al., 2005, Vasquez-Leon et al., 2003)</td>
</tr>
</tbody>
</table>

Table 2-12 Climate change adaptation research (Smit and Wandel, 2006)
Two main assessment approaches are described in the literature (Adger et al., 2004, Dessai and Hulme, 2004, Richards and Nicholls, 2005, Carter et al., 2007):

1. Vulnerability led approaches, and
2. Impact led approaches.

Vulnerability led approaches are usually categorised as bottom-up or second-generation approaches. They have been designed to focus on adaptation, involve stakeholders, and commence with the local scale by addressing socio-economic responses to climate, which tend to be related to the location (Carter et al., 2007).

The frameworks for the impact (top-down) and vulnerability (bottom-up) approaches are summarized in Table 2-13 (See Appendix 3 for more detailed information).

<table>
<thead>
<tr>
<th>Type</th>
<th>Framework</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Down</td>
<td>IPCC Seven Steps: It was the first attempt to define a process for assessing vulnerability to climate change.</td>
<td>(Carter et al., 1994, Parry and Carter, 1998)</td>
</tr>
<tr>
<td></td>
<td>U.S. Country Studies Program: The program provides technical assistance to countries through workshops, guidance documents and analytical tools, and consultations with technical experts</td>
<td><a href="http://www.gcrio.org/CSP/uscsdp.html">www.gcrio.org/CSP/uscsdp.html</a></td>
</tr>
<tr>
<td></td>
<td>UNEP Handbook: It provides information about a number of methods for users to compare. Unlike the USCSP guidance, it does not provide details on how to apply individual methods.</td>
<td>(Feenstra et al., 1998)</td>
</tr>
<tr>
<td>Bottom Up</td>
<td>UNDP Adaptation Policy Frameworks: Focuses on assessing current vulnerability, involving stakeholders and addressing adaptation.</td>
<td>(Lim et al., 2004)</td>
</tr>
<tr>
<td></td>
<td>The United Kingdom Climate Impacts Programme (UKCIP): A comprehensive national program in Britain addressing climate change impacts and adaptation with close stakeholders’ involvement.</td>
<td><a href="http://www.ukcip.org.uk/">www.ukcip.org.uk/</a></td>
</tr>
</tbody>
</table>

Table 2-13 Commonly used impact and adaptation frameworks
Impact led approaches, also known as top-down or first-generation approaches, combine scenarios downscaled from global climate models to the local scale, with a sequence of analytical steps. These steps begin with the climate system and move through the biophysical impacts towards a socio-economic assessment. In the main, they focus on the potential long-term impacts of climate change (Dessai and Hulme, 2004).

Dessai and Hulme (2004) point out the differences between the bottom up (adaptation) and the top down (impacts) approaches (see Figure 2-37).

![Figure 2-37 Attributes of top-down and bottom-up approaches to assessing vulnerability and adaptation (Dessai and Hulme, 2004)](image)

These differences can be summarised under three heading: focus, scale and time horizon, as described below (Dessai and Hulme, 2004):

- **Focus.** The bottom up approaches tend to focus on social vulnerabilities; the top down approaches tend to start with an analysis of the biophysical impacts, e.g., change in crop yields, runoff, or sea level rise.
LITERATURE REVIEW – B: RESPONDING TO CLIMATE CHANGE

- Scale. The bottom up approaches tend to focus on smaller geographic scale impacts; whereas the top down approaches tend to focus on larger geographic scale impacts.

Time Horizon. The bottom up approaches tend to address the past and near term risks or concerns; while top down approaches tend to address the longer term risks, e.g., fifty to one hundred years into the future.

Fussel and Klein (2006) also reviewed the evolution of approaches for assessing vulnerability to climate change. They identified four assessment stages that address different research and policy questions, namely: climate impact assessments, first, and second generation vulnerability assessments, and adaptation policy assessments (Figure 2-38).

The evolution of these assessment stages and their relations can be illustrated in a conceptual framework diagram (Figure 2-38). The different coloured graphical elements represent the various assessment stages: blue represents the impact assessment stage; green is used for the first generation vulnerability assessment stage; orange stands for the second generation vulnerability assessment stage; and pink signifies the adaptation policy assessment stage. The characteristics of these four stages are summarised in Table 2-14.
Evolution of these assessment stages and their relations are illustrated in a conceptual framework diagram (Figure 2-38). The graphical elements with different colours in the conceptual frameworks diagram represent assessment stages; blue represents the impact assessment stage, green is used for the first generation vulnerability assessment stage, orange is for the second generation vulnerability assessment stage and pink is for the adaptation policy assessment stage. Characteristics of these four stages are summarised in Table 2-14.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Impact assessment</th>
<th>Vulnerability assessment</th>
<th>Adaptation policy assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>First generation</td>
<td>Second generation</td>
</tr>
<tr>
<td>Main policy focus</td>
<td>Mitigation policy</td>
<td>Mitigation policy</td>
<td>Resource allocation</td>
</tr>
<tr>
<td>Analytical approach</td>
<td>Positive</td>
<td>Mainly positive</td>
<td>Mainly positive</td>
</tr>
<tr>
<td>Main result</td>
<td>Potential impacts</td>
<td>Pre-adaptation vulnerability</td>
<td>Post-adaptation vulnerability</td>
</tr>
<tr>
<td>Time horizon</td>
<td>Long-term</td>
<td>Long-term</td>
<td>Mid-to-long-term</td>
</tr>
<tr>
<td>Spatial scale</td>
<td>National to global</td>
<td>National to global</td>
<td>Local to global</td>
</tr>
<tr>
<td>Consideration of climate variability, non-climatic factors, and adaptation</td>
<td>Little</td>
<td>Partial</td>
<td>Full</td>
</tr>
<tr>
<td>Consideration of uncertainty</td>
<td>Little</td>
<td>Partial</td>
<td>Partial</td>
</tr>
<tr>
<td>Integration of natural and social sciences</td>
<td>Low</td>
<td>Low to medium</td>
<td>Medium to high</td>
</tr>
<tr>
<td>Degree of stakeholder involvement</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Illustrative research question</td>
<td>What are potential biophysical impacts of climate change?</td>
<td>Which socioeconomic impacts are likely to result from climate change?</td>
<td>What is the vulnerability to climate change, considering feasible adaptations?</td>
</tr>
</tbody>
</table>

Table 2-14 Characteristics of four different stages of vulnerability assessment

2.7.1.4 COMMON APPROACHES FOR ASSESSING COASTAL VULNERABILITY

Sea level rise can cause a number of direct and indirect impacts on coastal systems. From a societal perspective, there are six important natural system effects, as described earlier (Klein and Nicholls, 1999, Klein and Nicholls, 1998), namely:
increasing flood-frequency probabilities, erosion, inundation, rising water tables, saltwater intrusion, and biological effects. The potential socio economic impacts of SLR can be grouped, according to definition, into the following three categories:

- direct loss of economic, ecological, cultural and subsistence values through loss of land, infrastructure and coastal habitats;
- increased flood risk of people, land and infrastructure and the above-mentioned values; and,
- other impacts related to changes in water management, salinity and biological activity.

Due to the variation of natural coastal systems and regional differences in relative sea level rise, coastal vulnerability assessments (VA) have specific drivers; however, the overall frameworks are the same as for the general vulnerability assessments studies.

Klein and Nicholls (1999) developed a conceptual framework for assessing vulnerability to SLR. As shown in Figure 2-39, natural system and socio-economic system vulnerability to climate change are separated, but also related and interdependent. According to their framework, the analysis of coastal vulnerability starts with the natural system and continues with a socio-economic vulnerability analysis. Other climatic and non-climatic stresses are also taken into consideration within the framework, indicating that SLR depends on other processes and, further, that the coastal system will evolve due to factors other than sea level rise.

The advantages and disadvantages of the above mentioned methods in terms of coastal vulnerability assessment are summarised in Table 2-15.
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Figure 2-39 A conceptual framework for coastal vulnerability assessment (Reproduced from Klein and Nicholls, 1999)

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPCC Seven Steps</td>
<td>Logical prescribed structure. Lends itself to producing consistent results – useful for global aggregation. Widely used.</td>
<td>Inflexible, stressing exposure and sensitivity assessment, but not full vulnerability assessment. VA tools not discussed. Adaptation options insufficiently developed.</td>
</tr>
<tr>
<td>UNEP Handbook Methodology</td>
<td>Good conceptual basis. All impacts considered. Guidance on possible assessment tools provided.</td>
<td>Remains to be widely tested.</td>
</tr>
</tbody>
</table>

Table 2-15 An assessment of the different methods for vulnerability
The UNEP Handbook Methodology is viewed as flexible and a broadly applicable vulnerability and adaptation assessment method compared to the other methodologies (Richards and Nicholls, 2005).

### 2.8 SUMMARY

In this chapter, the existing climate change literature was reviewed to gain a better understanding of: the human and natural drivers of climate change; the observed changes in climate, with a focus on rising sea level; and projected future climate change and its impacts.

The available scientific evidence provided by the IPCC and other researchers shows: that, over the past century, land and sea temperatures across the globe have increased, on average; that, overall permanent snow cover has decreased; and that average sea level has increased for the duration of the human measurement period. Based on this information, the IPCC stated, in their 2007 report, that **warming of the climate system is unequivocal**.

A review of the current scientific understanding of the impacts of climate change on natural and human systems also suggests that the magnitude and timing of the impacts will vary with the amount and timing of the climate change, and the capacity of these systems to adapt to these changes.

If the world is, indeed, warming, then it behoves us all to identify what can be done to prevent and/or reduce the impacts of a changing climate? The second part of this chapter sought to provide answers to this question. Hence, the current knowledge related to responding to climate change, namely, mitigation and adaptation, was reviewed in the literature. To provide a more comprehensive overview of the topic, vulnerability and adaptation assessment strategies were also examined.
CHAPTER 3

LITERATURE REVIEW – MODELLING APPROACHES

3.1 INTRODUCTION

The context for the environmental modelling and decision making techniques are presented here as a review of the existing literature. Following a brief discussion around environmental problems, Section 1 focuses on two spatial and temporal modelling techniques commonly used in environmental studies. Firstly, System Dynamics (SD) and Agent-Based Modelling (ABM), two major non-linear modelling approaches, are reviewed. Their similarities and differences are also examined. Secondly, Geographic Information Systems (GIS) used for geospatial data management and analysis is reviewed.

Section 2 discusses the Multiple Criteria Decision Aiding (MCDA) techniques, also known as Multiple Criteria Decision Analysis, or Multiple Criteria Decision Making (MCDM). MCDA techniques are suitable for comparing multiple criteria simultaneously, while providing a solution to a given problem. An examination of the potentials for the assessment of different adaptation alternatives is given in Section 2 and a concise review of the major MCDA techniques (ELECTRE, PROMETHEE, MAUT, and AHP) is provided.

3.2 ENVIRONMENTAL PROBLEMS

Most environmental systems are complex and highly dynamic with many feedbacks. These complexities arise from the interactions and interdependencies of a large number of elements. Such complex environmental problems do not exist in isolation nor are they explained with one-way causal relations. In contrast, complex problems are linked to each other and, in their interactions, they are driven by multi-causality. Indeed, these complex systems are characterized by feedbacks, interdependencies,
and chaotic and discontinuous non-linear relations of their elements (Kauffman, 1993, Patten and Jørgensen, 1995). To address such environmental problems effectively, it is important and necessary that the dynamic character and complexity of these systems are taken into account, in both time and space.

Several definitions of dynamic systems exist. Within the current research, the term dynamic systems refer to highly complex systems changing over time and space, and containing many interconnected and interacting components. This definition implies that the notion of time, unlike static systems, exists as dynamical systems. That is, the state of a system at initial time \( t_0 \) evolves to the next state at a later time \( t_1 \). Therefore, it can be considered an evolution of a system in time.

To gain a better understanding of the concept, it is important to define what is meant by a system. Hence, a system is a structure presumed to exist in the real world, which possesses characteristic properties and consists of interconnected components (Huggett, 1993). The components are meaningfully arranged, in that they function together as a whole. The concept of a system was defined by Ludwig von Bertalanffy (1950) as, ‘complexes of interacting parts’, which incorporate some general conceptions and viewpoints, such as wholeness, isomorphism, and organization. Hence, ‘the whole is more than the sum of its parts’, etc. Thus, the transfer of understanding across spatial, temporal and complexity is a difficult problem; however, it is also a core problem in understanding the complex systems (O’Neill et al., 1989, Ehleringer and Field, 1993, Costanza and Voinov, 2004).

Bertalanffy (1950) also formulated a theory of open systems, as distinguished from closed systems. A system is open if there is an inflow and an outflow, therefore, changing the component materials; in a closed system no materials enter or leave it. Nevertheless, an open system reaches a state of equilibrium through a continuous flow of materials between the system and its environment. The theory of open systems has been widely adopted by researchers in a variety of fields.

The input, output and storage are three fundamental attributes of environmental systems. The matter, or energy, is stored in the system element by entering into it as an input; it leaves the system as an output of another system element, after passing
through the interrelated system elements. A cascade of matter is observed in most environmental systems, e.g. the input, storage and output of marine sediments in a coastal system.

The rate and direction of the matter transfer between the components of environmental systems are determined by two basic laws: the laws of conservation, and the laws of flow/transport. However, as Hugget (1993) explains, these rules apply to outputs which pass into the environment, but not usually apply to inputs from the environment. The Law of conservation of mass (or matter) was discovered by Antoine Lavoisier. His *Traité Élémentaire de Chimie* (Lavoisier et al., 1789) was the first modern chemical textbook, and presented a unified view of new theories of chemistry, contained a clear statement of the Law of Conservation of Mass (Weisstein, 1996). The law of conservation states that matter can be transformed from one form to another, but it cannot be created or destroyed, hence, the law can be applied only to a closed system. In nature, however, no system is totally isolated from the outside environment. Environmental systems act as a network of many compartments connected through the exchange of materials and energy. Thus, energy or matter is allowed into, or out of, the system; it can be changed from one form to another, but never destroyed.

The law of flow / transport defines the input and output that appears in the storage equations (Hugget, 1993). For this reason, the transfer of matter (flow) between the components of a system can be expressed using differential equations.

Environmental systems are dynamic and, in these systems, the behaviour of the process in space is of major importance, along with time. The spatial and temporal variables are represented by the Cartesian co-ordinates (x, y, and z) and t, respectively. For example, as shown below (Fig 3-1), the difference between the matter inflow and outflow equals the sum of the matter accumulation within the system.
This can be expressed in the equation:

\[ M(t+1) = M(t) + (F_{in} - F_{out}) \, dt \]

Equation 3-1

Where:

\[ dt = (t+1) - t = \text{duration of time interval} \]

\[ M(t) = \text{Matter at start of time interval, time } t \]

\[ M(t+1) = \text{Matter at the end of time interval, time } (t+1) \]

\[ F_{in} = \text{matter inflow} \]

\[ F_{out} = \text{matter outflow} \]

In summary, dynamic complex environmental systems consist of components that influence each other through causal relationships. These components form feedback loops that are linked with other feedback loops. Feedback is a process whereby an initial cause ripples through a chain of causation, ultimately to re-affect itself (Roberts, 1983). The interaction between these feedback loops is not linear. That is, an identical change in one component may not always cause the same system behaviour as there may be a change in the state of the system, over time. For this reason, studies of complex systems require the detailed analysis of the causal relationships of their components, in time and space.
The ultimate goal of such analyses is to provide information to improve the decision making process, particularly an improvement in our ability to understand and evaluate environmental problems. Consequently, the complexity of time, space, and decision-making needs to be addressed within the process of environmental modelling (Agarwal et al., 2002). Further, important interactions exist between the temporal complexity and decision making processes, which are made during varying time intervals. For example; while decisions of infrastructure are made to meet the needs over 50 years or more, other decisions are made on a daily basis, such as traffic flow via the timing of traffic lights.

According to Saaty and Kearns (1985), to be effective, the system theory approach must draw on our inherent abilities to deconstruct complex phenomena into component elements, while, simultaneously, conceptualizing and identifying the relations (of varying intensity) among the elements of the system. Thus, it is essential that a decision making method considers the human elements of complex problems and accommodates multiple and conflicting goals and objectives, especially those held by people whose interests are affected by the performance of the system. Therefore, the results from the system analyses need to be integrated into a rational choice about what to do, as well as where and when to do it (Schmoldt, 2001). With such integration, realistic decision making processes, in a dynamic complex environment, are enabled.

The above discourse on environmental problems leads onto the following sections, where environmental modelling and decision making techniques are discussed.

3.3 MODELLING THE ENVIRONMENT

Reflecting on how people make decisions and and take actions, (Sterman, 1991) observes that few are based on the real world; rather, most are made from information from our mental images of that world, of the relationships among its parts, and of the influence that our actions have on it. This mental model: is flexible; can take into account a wider range of information than just numerical data; be adapted to new situations; and be modified as new information becomes available.
Despite having such versatility, mental models are rarely suitable for fuzzy, incomplete, inaccurate knowledge, and filled with unknown assumptions and goals. To overcome such shortcomings, and to understand all elements and their interrelations with the environment, real world problems must be reduced to simple, manageable proportions. This process model-building is used to analyse complex, real world problems to envisage what might occur with a series of action. According to Hugget (1993), modelling is a simplified representation of aspects of the real world; modelling helps to predict and analyse environmental issues. Hugget (1993) classified these models into three major categories: hardware, conceptual and mathematical, as shown in Figure 3-2.

**Hardware models** can be grouped as **scale** and **analogue** models. A **scale model** would include a scaled down replica of a physical system (e.g. a bridge structure), and displays a strong physical similarity to the systems. **Analogue models** are a more simplified form of scale models, where the topographic features are scaled and represented by various symbols. **Conceptual models** (or mental models), as Hugget (1993) described, provide a statement of how a system’s components are connected by using various tools, such as flow charts, pictures, words, and block diagrams.

![Figure 3-2 Types of model](image)

A **mathematical model** is an interpretation of a conceptual model, which uses mathematical language to describe the behaviour of a system. These models can be either **probabilistic** (or stochastic) or **deterministic**, depending on the behaviour of the system to be modelled. Further, system behaviour would be **probabilistic** if any randomness exists, otherwise it would be considered to be **deterministic**. **Probabilistic**
models consist of unpredictable random components, e.g. the rainfall pattern in an area. In contrast, deterministic models depend on the initial conditions; they do not contain any random effects (Hugget, 1993).

Further, according to Hugget (1993), mathematical models can be described as either static or dynamic. A static model does not take into account time factors, whereas a dynamic model, which considers variations in time in its structure, are regarded as a very useful modelling approach for analysing environmental systems.

Importantly, as discussed above, spatial and temporal dimensions are two fundamental characteristics of environmental problems that have to be considered together in modelling environmental systems. Spatial models represent a system as a set of interacting components, and take spatial variations into account. These models have long been used within environmental and social science research. In spatial models, the spatial domain is divided into subregions, such as two dimensional grid-cells. The models use the location and configuration of the system components to analyse the system. The locations of the grid cells are defined in Cartesian coordinates (horizontally x, y and vertically z).

However, to solve a problem by modelling the initial state of a system, the system parameters, and the values of the driving variables are required. Indeed, it is usually possible to develop an analytical solution, for a simple system, by using a deterministic model. In more complex real world cases, with many interacting variables and non-linear relationships, an analytical solution will not suffice. In such cases, a numerical computer model is the alternative method to be used to solve the problem.

Importantly, the advent of the new generation computers has increased the modellers’ abilities to model more complex problems using simulations. A simulation model enables complex environmental systems to be analysed realistically and in detail, through its mathematical simplicity and versatility. Therefore, computer simulations are valuable techniques for solving problems and decision making, especially if the problem is too difficult, time consuming and costly. For example, spatial dynamic modelling enables the analysis of large-scale ecosystems (Costanza and Voinov, 2004). With the use of simulation models and Geographic Information Systems (GIS) together
makes possible to model environment in time and space. Understanding and modelling the spatial and temporal changes in environmental systems is crucial for effective management. Therefore, to develop and implement effective adaptation strategies, dynamic modelling allows the establishment of a linkage between the spatial and temporal characteristics in an environmental system, to support decision making and environmental management.

Fussel and Klein (2006) argue that vulnerability assessment of climate change combines natural and social science perspectives, which follow different approaches in the study of human-nature system interactions. These perspectives have important implications for the visual representation of the system under consideration. In this respect, the primary goal of System Dynamics (SD), as applied in the natural sciences, is to clarify the behaviour of complex systems.

Gharib (2008) emphasises that the more sophisticated environmental models need a SD approach to manage the temporal dimension, the feedback loops, and the overall dynamics and complexity of environmental systems. Furthermore, these systems also need a GIS approach to represent the spatial dimension. Hence, simulation, spatial distribution, increased dimensionality, and resolution provide a straightforward way of "improving" the environmental modelling domain.

In light of the above discussion, the current research considers the use of two major approaches to address environmental problems: System Dynamics (SD) and GIS. The next section provides a concise review of these approaches.

3.3.1 SIMULATION MODELLING TECHNIQUES

Simulation, as defined by Borschchev and Filippov (2004), is the process of model execution that takes the model through (discrete or continuous) state changes, over time. Therefore, simulation modelling is a better answer for complex problems where time dynamics are important.

Various simulation modelling concepts can be used for dynamic modelling, including System Dynamics (SD) and Agent-Based Modelling (ABM), two major non-linear modelling approaches. Underlying these approaches are control theory and the
complexity theory (Scholl, 2001b, Scholl, 2001a). In general, simulation models are based on two techniques; continuous and discrete event simulation.

In a continuous model, the state variables change in a continuous way, rather than abruptly from one state to another (infinite number of states). The system state is traced through infinitesimally small time steps denoted as $dt$. Thus, data given for some time-spans are specified as a continuous function, over time. This function is also differentiable, so that changes of the state variable, can be modelled as the first derivative of the state function.

In discrete models, the state variables change only at a countable number of points in time. These points in time are those at which the event occurs/changes state. Thus, the time axis is divided into a number of adjacent time-segments; the specified number of time intervals and time points are finite; and the system state is captured in jumps between the finite time steps, denoted as $\Delta t$.

Frenkel and Goodall (1978) identified the relationships between major simulation techniques. Accordingly, a discrete-event simulation is often appropriate for situations where the system being studied contains a number of separate items, and each item has its own characteristics and period of existence within the system. In a discrete-event technique, changes in the state of the system are conceptualized as taking place in discrete jumps, corresponding to the arrivals, departures, or other critical changes in the status of the individual items (Frenkel and Goodall, 1978). In contrast, changes occur continuously and smoothly in the continuous simulation technique.

SD, a continuous simulation technique, is well suited to studying systems which contain a complex web of feedback loops; discrete ABM is preferred when the system contains a high degree of uncertainty (Wakeland et al., 2004).

A major difference between these two approaches, as posited by Scholl (2001a), is that the SD approach is deductive in nature, while the ABM approach is inductive. Models are deductive when they use a logical procedure to derive some very specific results from basic and unquestioned assumptions. Inductive methods, in contrast, filter patterns from empirical data to identify some general laws behind them.
The levels of abstraction in simulation modelling approaches can vary. Borshchev and Filippov (2004) identified a range of problems addressed with simulation modelling (Figure 3-3), as well as with major simulation modelling approaches (Figure 3-4), arranging the problems and major approaches on a scale with respect to the typical level of abstraction of the corresponding models. As shown in Figure 3-4, the major approaches are divided into four broad categories: System Dynamics (SD), Discrete Event (DE), Agent Based (AB) and Dynamic Systems (DS). Technically, SD and DS are mostly involved with continuous processes, whereas DE and AB work mostly in discrete time (i.e. jump from one event to another). Further, DS, stays a little aside, as it is used to model “physical” systems.
Based on how the approaches correspond to abstraction, Dynamic Systems or “physical” modelling is located at the bottom of the chart, while System Dynamics (dealing with aggregates) is located at the highest abstraction level. Discrete Event modelling is located at the middle-low abstraction, while Agent Based modelling is located across all abstraction levels.

Schieritz and Milling (2003) compared and identified the major differences between the primary conceptual predispositions underlying the SD (continuous) and AB (discrete) approaches (presented in Table 3-1).

<table>
<thead>
<tr>
<th></th>
<th>System Dynamics</th>
<th>Agent-Based Modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic building blocks</td>
<td>Feedback loop</td>
<td>Agent</td>
</tr>
<tr>
<td>Unit of analysis</td>
<td>Structure</td>
<td>Rules</td>
</tr>
<tr>
<td>Level of modelling</td>
<td>Macro</td>
<td>Micro</td>
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<tr>
<td>Perspective</td>
<td>Top-down</td>
<td>Bottom-up</td>
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<tr>
<td>Adaptation</td>
<td>Change of dominant structure</td>
<td>Change of structure</td>
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<tr>
<td>Handling of time</td>
<td>Continuous</td>
<td>Discrete</td>
</tr>
<tr>
<td>Mathematical formulation</td>
<td>Integral equations</td>
<td>Logic</td>
</tr>
<tr>
<td>Origin of dynamics</td>
<td>Levels</td>
<td>Events</td>
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</tbody>
</table>

Table 3-1 Major differences between the continuous SD and discreet ABM (Adapted from Schieritz and Milling, 2003)

Despite the many differences between the SD and ABM approaches, there are also similarities; for example, both focus on social systems (with local, that is, decentralised, decision making), and both have the same aim (the search for principles underlying the dynamics of complex systems) (Phelan, 1999, Schieritz and Milling, 2003).

To provide a greater understanding of the two approaches (SD and ABM), the procedures and futures of these approaches are discussed, in detail, below.
3.3.1.1 SYSTEM DYNAMICS MODELLING (SD)

3.3.1.1.1 SD INTRODUCTION

System Dynamics (SD) is a powerful methodology and computer simulation modelling technique that helps us to better understand the dynamics of complex systems.

Further, System Dynamics, created by Jay W. Forrester (Forrester, 1961), was initially rooted in the management and engineering sciences. Gradually it spread into other fields, including social, economic, physical, chemical, biological, and ecological systems. SD related to the internal feedback loops and time delays that affect the behaviour of an entire system. Feedback loops are the basic structural elements of systems. Forrester argues that we live in a complex of nested feedback loops; therefore, every action, every change in nature, is set within a network of feedback loops. Hence, feedback loops are the structures within which all changes occur.

Additionally, feedback loops are building blocks of dynamic systems that reflect a chain of causal relations among the interacting components of a system. More formally, a feedback loop is a closed sequence of causes and effects, or, a closed path of action and information (Kirkwood, 1998). These loops are often linked together and display nonlinear relationships that often cause counterintuitive behaviour (Forrester, 1996). Indeed, Forrester argues that people seldom realize the pervasive existence of feedback loops, which drive everything that changes through time; most people think in linear, non-feedback terms.

In SD modelling, causal loop diagrams (CLD) are used to describe positive and negative feedback process. The CLD diagrams illustrate relationships of cause and effect between the individual system variables that, when linked, form closed loops. Hence, feedback loops can be positive and negative. The overall polarity of a feedback loop is indicated by a symbol in its centre (Figure 3-5). The arrows show the direction of the causal links between the variables. The polarity marks at the end of the arrows show if the variables at the two ends of an arrow move in the same direction (+), or opposite direction (-). Thus, the feedback loop on the left is considered to be a positive loop (having a large plus sign) if an increase in a variable, after a delay, leads to a further
increase in the same variable (Figure 3-5). The feedback loop on the right (Figure 3-5) is considered to be a negative loop (having a large minus sign) if an increase in a variable eventually leads to a decrease in the variable. As a consequence, a negative feedback loop yields oscillatory behaviour in a system.

![Causal Loop Diagram](image)

**Figure 3-5 Causal Loop Diagram**

CLDs are an important tool in the field of SD modelling. However, CLD has its limitations, especially their inability to capture the level (stock) and rate (flow) structure of systems, which are the two central concepts of dynamic systems theory (Sterman, 2000). CLDs are not clear enough to communicate the system behaviour, and so can make only vague direct causal relationships between rates and levels. Furthermore, in cases involving rate-to-level links, the polarities of a system’s feedback loops are not enough to identify the behaviour of that system; this, then, becomes a dramatic disadvantage (Richardson, 1981).

### 3.3.1.1.2 SYSTEM STRUCTURE

However, one feature is common to all systems, namely, that a system’s structure determines the system’s behaviour. In the field of System Dynamics, the underlying relationships and connections between the components of a system is called the structure of the system. In understanding a system, or problem, a critical step is to identify its behavioural structures. These structures consist of a set of physical and information interconnections generating behaviour of a series of events connected together, over time. SD can be used to analyse how the structure of a physical,
biological, or literary system can lead to the behaviour that the system exhibits (Martin, 1997).

The systems approach gains much of its power as a problem solving method from the fact that similar patterns of behaviour show up in a variety of different situations, and that the underlying system structures, that cause these characteristic patterns, are known (Kirkwood, 1998). Therefore, identifying a pattern of behaviour causing a problem is the initial step to eliminating the behaviour; this involves finding and modifying the system structure which causes the problem pattern. There are four characteristic patterns of behaviour: list one, two, three and four (as shown in Figure 3-6). They often appear in systems, either individually or in combinations.

![System Behaviours](image)

Figure 3-6 Four patterns of system behaviour

An S-shaped behaviour, observed in many different systems, describes a system in which the initial exponential growth eventually becomes zero. This zero growth happens because the system has more than a single feedback loop, and is, at the outset, dominated by positive feedback, which then shifts to a dominant negative feedback.

Exponential growth, the simplest dynamic behaviour, is generated by a simple positive feedback. An initial quantity (of something) starts to develop exponentially at a growth rate (percentage/unit time). This behavior reflects an unconstrained growth. In contrast, oscillation occurs in a system if there is a delay in a negative feedback loop.
Any changes in the time delay will change the period of oscillation. As seen in Figure 3-6, the oscillation initially displays exponential growth behaviour, and then it changes to become an s-shaped growth, before reversing direction.

On the other hand, goal seeking behaviour is caused by negative feedback. That is, the difference between the current state of the system and its goal drives the system towards its goal. Until the system reaches its goal, the rate of change gradually becomes smaller as the state of the system comes near to its goal as shown in Figure 3-6.

3.3.1.1.3 STOCK AND FLOW DIAGRAM

As with CLDs, in SD, the stock and flow (or level and rate) potentially changing over time; Figure 3-7 shows the relationships among variables. However, unlike a CLD, a stock and flow is distinguished between the different types of variables. Therefore, they provide more detailed information than CLDs. A simple stock and flow structure consists of three different types of elements: stocks, flows and information. The stock, which produces the behaviour in a system, accumulates or depletes, over time. Thus, the Stock collects whatever Flows into them, net whatever flows out. The flow is the rate of change in a stock; it is measured over a certain interval of time. The flows fill and drain the accumulations. The information link moves from the Stock to the Flow, as shown by the curved arrow from the Stock symbol to the Flow symbol.

Figure 3-7 A graphical notation of a simple stock and flow structure

The distinction between Stocks and Flows is important for understanding the source of dynamics. As shown in Figure 3-7, the stock and flow structure has two flows, Flow-in and Flow-out, and one Stock. The two flows (into and out of the stock) cause the dynamic behaviour of the system. The difference between the Flow-in and Flow-out is: when greater than zero, the value of the stock will increase; when less than zero, the
value of the stock will decrease; and when equal to zero, the stock will remain the same, indicating the state of dynamic equilibrium within the system.

In order to identify stocks and flows, it is necessary to determine which variables in the system experiencing the problem define its state (Stocks), and which variables define the changes in its state (Flows) (Sterman, 2000). Sterman (2000) suggests the following guideline for identifying stocks and flows:

- Stocks usually represent nouns and flows usually represent verbs.
- If a snapshot were taken of the system, Stocks do not disappear; on the other hand flows disappear if time is hypothetically stopped.
- Stocks send out information about the state of the system to the rest of the system.

Fussel and Klein (2006) argue that a vulnerability assessment of climate change combines the natural and social science perspectives; further, they follow different approaches in the study of human-nature system interactions. The different views of human and nature systems have important implications for the visual representation of the system under consideration. In this respect, the primary goal of System Dynamics diagrams, as applied in natural sciences, is to clarify the behaviour of complex systems (Fussel and Klein, 2006).

3.3.1.1.4 MATHEMATICAL FOUNDATION

SD models use differential and difference equations (see Equations 3-2 to 3-5) to represent the interconnections in a system. The flows are the functions of the stock and other variables and parameters. A mathematical representation of a Stocks and Flows diagram (Figure 3-8) is shown below:

Equation 3-2
Stocks integrate flows (rates of change). That is:

Equation 3-3

\[ \text{Equation 3-4} \]

Where:

- \( SL(t) \): Sea level at time \( t \),
- \( SL(t-dt) \): Sea level at time \( (t-dt) \),
- \( V(t) \): Vulnerability at time \( t \),
- \( V(t-dt) \): Vulnerability at time \( (t-dt) \)
- \( R_{Rate} \): Sea level rise rate
- \( I \): Increase
- \( D \): Decrease

As shown by the above equations, the stocks (Vulnerability and Sea Level) accumulate or deplete depending how the flows rate over a certain interval of a time \( (dt) \). The net flow into the stock is the rate of change of the stock.

Figure 3-8 A simple stock and flow diagram for vulnerability and sea level
3.3.1.1.5 SPATIAL DIMENSION IN SD

The spatial dimension plays a key role in environmental phenomena; that is because environmental systems’ components are unequally distributed through space, creating spatial differentiation, segregation, and discontinuities. Accordingly, spatial dimension must be considered as a structural component of an environmental system. In a model, spatial dimension refers to the space-component of a system. Agarwal et al. (2002) grouped spatial models into two broad types: spatially representative models, which handle data in two or three spatial dimensions (x, y, and z); and, spatially interactive models, which explicitly define spatial relationships and their interactions over time. However, spatially representative models may not explicitly model topological relationships and interactions among geographic features. In these cases, the value of each cell might change over time, but are independent of the adjacent cells. Spatially explicit interactive models include the impact of the variations, across space and time, of different factors on land-use change (Agarwal et al., 2002). Thus, spatial interactions reflect relations of complementarity and/or competition between the locations; they act as a driving force in the transformation and the dynamics of spatial systems (Sanders, 2007).

To understand the environmental processes, and the relationship between the structure and the behaviour, the spatial dimension should be considered explicitly. Hence, SD models provide insight into the dynamic feedback processes inherent in the evolution of a system (Ruth and Pieper, 1994). While the temporal dimension is adequately represented in SD models, the spatial dimension is not. Thus, SD models can be used for the analysis of different flood management policies and the estimation of flood damages (as a function of time). However, SD modelling provides no easy way to map these damages in space (Ahmad and Simonovic, 2004).

Nevertheless, Grossmann and Eberhardt, (1992) argue that dynamics models can successfully deal with spatial variables if these are either structurally simple models, or they use structurally simple spatial data. Models that are suitable to predict changes in complex systems, in particular feedback models, are not adequate to process numerous spatial details (Grossmann and Eberhardt, 1992).
These authors emphasize the importance of spatial dimension for environmental modelling. However SD modellers mainly focus on the behaviour of the system and neglect spatial dimension. The reason for that might be the lack of a mechanism that represents the spatial dimension explicitly, properly and efficiently in System Dynamics, and creating such a mechanism is a major challenge (Gharib, 2008).

3.3.1.2 AGENT-BASED MODELLING (ABM)

Agent-based modelling is a simulation methodology originating from the field of complexity science. As opposed to the concept of feedback and circular causality in SD modelling, the basic building block of the ABM is the individual agent. One fundamental premise of complexity theory is that much of the apparently complex aggregate behaviour, in any system, arises from the relatively simple and localized activities of its agents (Phelan, 1999). Thus the dynamics of the system arises from the interactions of agents, whereby the behaviour of an agent is determined by its cognitive structure, its schema.

Further, ABM is discrete in space, state, and time. Thus, space is a grid (a one, two, or three dimensional area), while an individual grid cell (agent) has a finite number of states. The rules, which define the spatial relationships and indicate how the agents are to change, regulate the behaviour of the system.

A typical agent-based model consists of the following three elements (Macal and North, 2010):

1. A set of agents, their attributes and behaviours.
3. The agents’ environment: agents interact with their environment in addition to other agents.

Agent-based models are usually implemented as multi-agent systems. Modellers assign individual parameters, which impact the state variables, causing state transitions, by identifying, modelling, and programming these elements to create an agent-based model (Epstein and Axtell, 1996). As illustrated in Figure 3-9, ABM contain
interacting agents sited within a model (a system), where relationships among the agents are defined to link the agents to other agents and/or other entities within a system.

![Agents Interacting in Agent Space (Grid Topology)](image)

**Figure 3-9** Structure of a typical ABM (Epstein and Axtell, 1996)

Macal and North (2010) argue that the single most important defining characteristic of an agent is its capability to act autonomously, that is, to act on its own, without external direction, in response to situations it encounters. Thus, agents are endowed with behaviours that allow them to make independent decisions. Typically, agents are active, initiating their actions to achieve their internal goals, rather than being merely passive, reactively responding to other agents and the environment.

However, the concept of an agent is meant to be a tool for analysing a system, not an absolute classification, where the entities can be defined as agents or non-agents (Russell and Norvig, 2010). Furthermore, the agent-based concept is a mindset more than a technology, which consists of describing a system from the perspective of its constituent units (Bonabeau, 2002).

The term topology (also called connectedness) in ABM refers to how agents are connected to each other; these connections include a spatial grid of agents and their relationships. The agents’ spaces are defined in the model, based on a neighbourhood
concept. Typically, a topology defines how the information is transferred from one agent to another.

In order to show how an ABM model can be modelled from an existing SD model, and to compare their results, Borshchev and Filippov (2004) used a classic SD model, the Bass Diffusion. This model describes the process of how new products get adopted as an interaction between users and potential users. For their study, the authors created two states of an agent: the *Potential Adopter* and the *Adopter*. As shown in Figure 3-10, smaller sample groups (100 agents) create the discrete nature of an ABM simulation. However, if the sample groups are large enough (10,000 agents), as shown in Figure 3-11, the ABM simulation generates results similar to continuous SD simulation results (Figure 3-12), as presented below.

![Figure 3-10 Simulation results of a small group of agent (adapted from Borshchev and Filippov, 2004)](image1)

![Figure 3-11 Simulation results of a larger group of agent (adapted from Borshchev and Filippov, 2004)](image2)
Borshchev (2004) identified three the advantages of ABM as follow:

1. It is more general and powerful because it enables us to capture more complex structures and dynamics.
2. It provides for the construction of models in the absence of knowledge about global interdependencies.
3. It is easier to maintain. Model refinements normally result in very local, rather than global changes.

A type of spatial agent based model involving grids, designated as Cellular Automata (CA), was first introduced by John Von Neumann in the late forties (Von Neumann and Burks, 1966). The Cellular Automata represents agent interaction patterns and available local information via an $n \times n$ grid. Each cell can be interpreted as an agent that interacts with a fixed set of neighbouring cells that are directly to the north, east, south, and west of the site. These neighbours, together with the cell, are called the von Neumann Neighbourhood of the site (Figure 3-13). Each cell in the grid contains a value representing a characteristic of a corresponding location. The CA concept gained popularity three decades later through John Conway's Game of Life (et al., 1987).
Significantly, the states of agents change at each simulation iteration, depending on the surrounding agent’s condition. That is, the grid becomes an agent’s environment, in which the agents interact with other agents, distributed spatially across the grid. Further, the transition rules simply specify that the state of the site, at the time \((t+\Delta t)\), depends on its current condition and its neighbours’ states. Additionally, in the CA model, agents move from cell to cell on the grid, and no more than a single agent occupies a cell at one time.

Although ABM is becoming the dominant paradigm, due to a world view that complex systems: emerge from the bottom-up: are highly decentralised:, and are composed of a multitude of heterogeneous objects, called agents.

However, according to Crooks et al. (2008), ABM raises many challenges and limitations, namely, their arbitrariness due to the perceived need to represent the world in as rich a manner as possible. While, the assumptions behind ABM may be quite plausible, the scale of parameterisation, needed to make such models operational, means that their testing will be mostly cursory. An important criterion for both ABM and SD modelling is the aspect of time (Crooks et al., 2008). This issue is discussed in the following section in terms of the discrete ABM and the continuous SD modelling approaches.
3.3.1.3 DISCRETE VERSUS CONTINUOUS TIME

As noted earlier, there are two different modes for dealing modelling changes over time, which are categorised into distinct concepts of seeing and modelling time: discrete time and continuous time. The discrete concept of time is based upon the distinction between time-points and finite time intervals. In contrast, the continuous concept deals with changes over time, based on infinitesimal mathematics. Mathematically, continuous changes in a SD model are modelled by differential equations or mathematical integration over time.

In theory, any system can be modelled by using a set of rules about the behaviour of its constituent elements. For instance, the behaviour of a crowd can be modelled through rules likely to characterise the behaviour of every individual, as in SD models. However, depending on the size of the crowd and the purpose of the model, this may not be practical or even useful. Continuous-field models manage this problem by replacing individual objects with continuously varying estimates of abstracted properties, for example, the density of people in a crowd (Goodchild, 2005). Alternatively, individual objects can be aggregated into larger wholes, modelling the behaviour of the system through these aggregates.

Borshchev (2004) identified two important points in SD modelling: (1) as long as the model works only with aggregates, the items in that same state variable are indistinguishable; they do not have individuality; and (2) the modeller has to think in terms of global structural dependencies, and has to provide accurate quantitative data for them. In contrast, agent based models are essentially decentralized. Compared to SD, there is no such place in an AB model where the global system behaviour (dynamics) would be defined. Instead, the modeller defines behaviour at an individual level, and the global behaviour emerges as a result of many (tens, hundreds, thousands, millions) individuals, each following their own behaviour rules, living together in the same environment, and communicating with each other and with the environment.

Ossimitz and Mrotzek (2008) argue that, although the core idea of SD modelling is the accumulation of flows over finite time intervals, System Dynamics is considered mostly
a modelling technique based on continuous time. By using Sterman’s (Sterman, 2000) bathtub metaphor, Ossimitz and Mrotzek demonstrated that accumulation in a bathtub can be achieved through both continuous and non-continuous flows. For example, there might be other ways of providing inflow, other than just continuous inflow through the faucet, such as pouring a bucket of water for a moment. This inflow would give the stock of water in the bathtub an instant rise, which cannot be modelled, precisely, with infinitesimal changes over time. The SD approach, in contrast, has the advantage of a capability of attaching several inflows and outflows to the same state variables.

Consequently, they concluded that although SD is generally considered to be a methodology based on continuous time, it is compatible both with the continuous and the discrete concept of time (Ossimitz and Mrotzek, 2008). This conclusion is similar to one by Huggett (1993), who found that, although continuous aggregated models of environmental systems have their uses, more complex discrete disaggregated models are usually preferred. Nevertheless, in aggregated models, any of the four permutations of continuous and discrete time and state-space formats may be used.

For this reason, SD can be considered as a hybrid methodology. Hence, this “hybrid” potential makes System Dynamics a superior technique for modelling time, as it combines the advantages of continuous and discrete time concepts.
3.3.2 GEOGRAPHIC INFORMATION SYSTEM (GIS)

3.3.2.1 INTRODUCTION

Historically, geographical models have been used in the form of maps and globes. The Canada Geographic Information System (CGIS), conceptualised in the early 1960s and operationalised in 1971, has been generally recognised as the first GIS ever produced (Tomlinson, 1972). Further, while GIS has, for many years, been considered to be too difficult, expensive and proprietary, recently, it has emerged as a powerful means to manage voluminous geographic data. Since the 1990s, the advent of powerful and affordable hardware and software, and the availability of public digital data, has broadened the range of GIS applications and has brought GIS to mainstream use (Chang, 2006).

Interestingly, GIS has developed into the language of geography, thus allowing people to communicate with each other. This is an important feature, as geography encompasses both the physical and cultural; also, it is both descriptive and process oriented. GIS has enlarged its scope from dealing primarily with the descriptive aspects of geography. The expansion has been achieved through content automation, which now can address geographic processes. As a consequence, new concepts and methods have been introduced for complex data modelling, interactive mapping, reprocessing, integrating data, visualization, and modelling (ESRI, 2010). Additionally, GIS is used for geospatial data management and analysis, image processing, graphics/maps production, spatial modelling, and visualization. Thus, geospatial data describes both locations and characteristics of spatial features, such as roads, land parcels, and vegetation stands, on the Earth’s surface.

Many definitions have attempted to describe GIS; however, there is no absolute agreement on the definition. Some authors perceive GIS as a branch of IT (e.g. refs), while others see it as computer assisted mapping or a set of spatial analytical tools (e.g. ref). The variety of GIS definitions depend on who is giving it, their background and viewpoint, and the likelihood that the technology and applications will change quickly and develop further (Heywood et al., 2002). However, three definitions of GIS that are credible have been given by Geoscience Australia, U.S. Geological Survey...
(USGS) and ESRI (one of the leading companies in designing and developing GIS technology). These definitions are given below:

GIS is “...a mapping software that provides spatial information by linking locations with information about that location. It provides the functions and tools needed to efficiently capture, store, manipulate, analyse, and display the information about places and things” (Geoscience Australia, 2008)

GIS is “…a computer system capable of capturing, storing, analysing, and displaying geographically referenced information; that is, data identified according to location” (USGS, 2007)

GIS is “...an integrated collection of computer software and data used to view and manage information about geographic places, analyse spatial relationships, and model spatial processes. A GIS provides a framework for gathering and organizing spatial data and related information so that it can be displayed and analysed” (ESRI, 2008a)

These definitions have three key components, namely:

- spatial location,
- information, and
- system.

The data collected by GIS usually refers to a collection of facts and figures related to places, people, events, and concepts. However, the data is then transformed into a meaningful form for a user; this data becomes information. While all the data are constituents of information, not all the data yield functional information. However, the data can inform this transformation via structuring, formatting, conversion and modelling.
As illustrated in Figure 3-14, the function of an *information system* is to convert data into information through (Yeung, 2000):

- **Conversion**: transforming data from one format to another, from one unit of measurement to another, and/or from one feature classification to another,
- **Organisation**: organising or re-organising data according to database management rules and procedures so that they can be accessed cost-effectively,
- **Structuring**: formatting or re-formatting data so that they can be acceptable to a particular software application or information system, and
- **Modelling**: including statistical analysis and visualization of data that will improve user's knowledge base and intelligence in decision making.

![Figure 3-14 Transforming data into information (Yeung, 2000)](image)

Information systems, of which GIS is one form, are a special class of systems that can be understood with respect to the general characteristics of a system, as discussed in detail in Section 3.2. Lo and Yeung (2007) define information systems from various perspectives, such as functionally, structurally, and operationally (see Figure 3-15). These definitions are given below:

*Functionally, an information system is set up to achieve the specific objectives of collecting, storing, analysing, and presenting information in a systematic manner.*
Structurally; an information system is made up of interrelated components that include a combination of data and technical and human resources.

Operationally, it can be perceived as being input, processing and output subsystems working according to a well-defined set of procedure and protocols.

These individual information systems can be operated independently; at the same time, they can be linked with other information systems, through standard communication protocols, to form an information system network (Lo and Yeung, 2007).

![Perspectives of an information systems](image)

Figure 3-15 Perspectives of an information systems (Lo and Yeung, 2007)

GIS is a special class of information systems in which all data is related to the Earth’s features and resources, including human activities. Further, GIS is distinguished from other information systems by its focus on geospatial data for spatial problem solving. Thus, the use of geographically referenced data is the defining characteristic of GIS.

3.3.2.2 GIS COMPONENTS

There are four components of GIS: geographically referenced data, a computer system, software, and people (Chang, 2006, Lo and Yeung, 2007, Grinderud, 2009). It is the interactions of these components that provide the capability to process, analyse and visualise the geospatial data.
Geographically referenced data describes the locations and characteristics of natural features and related human activities. Spatial and attribute data are two components of geographically referenced data. The location represents spatial data, while characteristics are attribute data, in the form of a map, attribute data, or images.

A computer system refers to hardware, which includes, but is not limited to, computers, operating systems, digitisers and scanners for spatial data input, printers and plotters, GPS receivers and mobile devices.

GIS software includes the programs and the user interface for driving the hardware. Software is required to perform some basic functions, such as: displaying, updating, modifying, converting, and measuring distances and areas (Grinderud, 2009). GIS software is supplied by a range of suppliers. A comprehensive list of these products is provided in Appendix 8.

Today, people are as important as any of the other components of GIS. In its earlier formats, GIS was only accessible to a small number of people due to its complex structure, which required expertise to use the technology and to assess the accuracy and integrity of the basic data. Furthermore, as Lo and Yeung (200y) explain, there was no direct interaction between the users and the computer, because data processing was done in a batch mode. However, the rapid growth of GIS led to a growing interest in the human factor within the GIS application. The changes in GIS have seen the establishment of a very large user community, which can be grouped into three categories: viewers, general users, and GIS experts. Each user group has a different level of requirements. These requirements, and the acceptance or rejection of the technology has had an impact on the development of GIS. Hence, people define the purpose and the objectives, and then provide the reason and justification, for using GIS (Chang, 2006).

3.3.2.3 GIS MODELS AND MODELLING

Addressing and analysing a problem using GIS requires a structured approach. As discussed earlier (Section 3.2), a model is a simplified representation of a system. Thus, modelling, in GIS, refers to the use of a GIS and its functionalities related
Ott and Swiaczny (2001) identified the three characteristics of a model: Illustration; simplification; and subjective pragmatism.

Illustration implies that the model may represent either natural or artificial objects, which can be models themselves. Simplification refers to a model building process that intends to create a reduction in complexity by identifying relevant and irrelevant features. Subjective pragmatism means that the reduction and simplification of the real world underlies subjective decisions. Depending on the variety of persons, situations and subjects, a system may be transferred into differing models. The simplification can be described as a shared understanding of how one real world is translated into a model that can be used in a GIS. Hence, these models require simplifying and transforming real objects into features that can be stored in databases.

Lo and Yeung (2007) define digital geospatial data as numerical representations, which describe real world features and phenomena, coded in specific ways to support GIS and mapping applications using the computer; data models are the way of representing the data. Therefore, GIS data is a model of features and phenomena that exist on, or near, the Earth’s surface. Thus, GIS models describe the various real objects, broken down into features, attributes and the relationships between them. Further, geospatial data consists of geometry (e.g. points, lines and polygons) and related attributes (properties of geometric features, e.g. the length of a road, the size of a building, etc.). Two commonalities of these geographic entities are that: they all have a location that can be captured and stored; and they all have properties (Lo and Yeung, 2007).

For this reason, a data model is required to store the data in a database. Two common ways to represent this variety of geographic entities are vector models, and raster models, as described below (Goodchild et al., 1993):

1. Vector models are coordinate-based data models that represent geographic entities as points, lines and polygons (geometric shapes) (Figure 3-16). This modelling approach views features as discrete objects and stores them as coordinate pairs (points) that reference locations on the Earth’s surface, while
line and polygon features are represented as ordered lists of vertices, as shown in Table 3-2. This type of data representation is termed vector data.

2. Raster (or grid) models represent geometric entities as cell values. In the raster model, a discrete or rectangular grid of cells is draped over geographic features and every cell is coded on the basis of what the grid represents. For instance, a cell code in a land use raster represents the land use type in each particular cell.

<table>
<thead>
<tr>
<th>Feature</th>
<th>ID</th>
<th>Attributes</th>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polygon</td>
<td>a</td>
<td>m^2</td>
<td>(9,9), (9,10), (10,10), (10,9)</td>
</tr>
<tr>
<td>Line</td>
<td>b</td>
<td>length</td>
<td>(7,10), (7,6), (6,4), (2,2)</td>
</tr>
<tr>
<td>Point</td>
<td>c</td>
<td>colour</td>
<td>(3,2)</td>
</tr>
</tbody>
</table>

Table 3-2 Vector model property table

In the vector models, attributes are associated with each vector feature, as opposed to a raster data model, which associates attributes with grid cells. The raster model is particularly applicable where remotely sensed images are used; it is considered the most appropriate choice for modelling continuous geographic phenomena, such as snow depth. In contrast, the vector model is considered more appropriate for mapping...
discrete geographic entities, such as road and river networks (Heywood et al., 2002). Arguments about which data model is better have been commonplace since the earliest systems were created. Their advantages and disadvantages are summarised in Table 3-3 below (Escobar et al., 2008):

<table>
<thead>
<tr>
<th></th>
<th>Raster</th>
<th>Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision in graphics</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Traditional cartography</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Data volume</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Topology</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Computation</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Update</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Continuous space</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Integration</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Discontinuous</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 3-3 Advantages and disadvantages of raster and vector data models

Raster models, as show in Table 3-3, are appealing, especially for simplicity of organization, speed of computation, and for many operations in continuous space; whereas vector models are appealing for graphical precision and efficient data storage, are suitable for most usage, and are compatible with data. Therefore, rather than asking “Which one is best?” one must question, “Which one is more suitable?” on a case by case basis. While the data can be converted between the raster and vector models, one will lose data in the conversion process. However, the conversion from vector data to raster data is easier than vice versa. Further, this conversion involves a grid being laid over the polygons in the vector map. Then, each cell is coded as belonging to the given polygon and assigned an attribute value that describes this information. As a result, the data quality is lower, given that the resolution is poorer than in a vector model (Escobar et al., 2008).

The modelling process is cyclic, with all steps interrelated with each other. The development and implementation of a GIS model, therefore, includes the following steps (Goodchild, 2000, Ott and Swiaczny, 2001):
1. Problem definition: The problem has to be identified and the goal must be defined.

2. Conceptualising and developing a model: This stage involves conceptualising of the real world which requires a considerable amount of experience and knowledge on the nature of real world phenomena.

3. Gathering data: This stage is the most costly part of the GIS building process. All required data must be acquired. This is also the most critical point in the process. Depending on data quality and availability, the previous steps must be re-evaluated.

4. Creating a database: To store the relevant information, the data structures must be developed.

5. Implementing the model: The analysis is performed. Errors made at previous stages will impact on the performance of this stage.

6. Presenting and visualising the result: The results of the analysis are interpreted and visualised.

In GIS, the concepts are closely linked to maps and their contents. Homogeneous collections of geographic objects are organized into a series of data themes, or layers, that cover a given map extent. Figure 3-7 illustrates how geographical elements, such as roads, land use, boundaries, hydrography, parcels, elevation, and imagery, are portrayed in maps through a series of map layers (ESRI, 2008b).

![Figure 3-17 Thematic representations of geographic information (ESRI, 2008b).](image)
The spatial relationships between the layers, that is, groups of maps of the same portion of a territory, can be easily derived through their common geographic location. These locations have the same coordinates in all the maps included in the system. Thus, it is possible to analyse its thematic and spatial characteristics to obtain a better knowledge of the particular zone (Escobar et al., 2008).

3.3.2.4 FIELD OF GIS APPLICATIONS

GIS is used in many different fields for a variety of applications, including agriculture, business, utility companies, forestry, geology, hydrology, environment, mapping, risk management, planning and the like. Indeed, GIS provides a powerful tool for spatial analysis, and is widely used for (Escobar et al., 2008, ESRI, 2008c);

- Mapping locations: GIS can be used to map locations, allowing the creation of maps through automated mapping, data capture, and surveying analysis tools.
- Mapping quantities: People map quantities, like where the most and least are, to find places that meet their criteria and take action, or to see the relationships between the places. This ability gives an additional level of information beyond simply mapping the locations of features.
- Mapping densities: While concentrations can be identified by simply mapping the locations of features, in areas with many features it may be difficult to see which areas have a higher concentration than others. A density map measures the number of features using a uniform areal unit, such as acres or square miles, so the distribution can be seen clearly.
- Finding distances: GIS can be used to find out what's occurring within a set distance of a feature.
- Mapping and monitoring change: GIS can be used to: map the change in an area to anticipated future conditions; decide on a course of action; or to evaluate the results of an action or policy.

Chang (2006) emphasises that, since the beginning, GIS has been important in natural resource management, including land-use planning, natural hazard assessment, wildlife habitat analysis, riparian zone monitoring, and timber management. In more
recent years, it has been used for crime analysis, emergency planning, land records management, market analysis, and transportation applications.

Owing to its capacity analyse spatial data within the environmental modelling domain, the GIS approach has been used broadly in vulnerability and impact analyses. A number of researchers have recently used GIS in coastal vulnerability assessments (Al-Jeneid et al., 2008, Gravelle and Mimura, 2008, Lathrop and Love, 2007, Szlafsztein and Sterr, 2007, Hennecke and Cowell, 2000, Poulter and Halpin, 2008). Thus, GIS provides a crucial support to environmental modellers in the areas of data visualisation, database management, and data exploration.

3.3.2.5 TEMPORAL DIMENSION IN GIS

GIS are spatial data processing systems with efficient mechanisms for data storage, retrieval, and display. Thanks to the availability of powerful GIS software packages, in recent years, GIS has gained widespread popularity in many fields other than geography. However, according to Ott and Swiazcny (2001), commercial GIS packages appear to lack the ability to perform temporal analysis of spatial data. As a result, users face great difficulties in finding an answer to questions such as: “What will happen?” or “When did it happen?”

Traditional GIS data models give emphasis to static representations of reality. Hence, the representation of time has been missing since the formative years of GIS (Shaw et al., 2008). This omission, however, has created few problems for geographic information, which is relatively static because natural features, and many features of human origin, do not change rapidly; only static information can be portrayed on a static paper map (Goodchild, 2000).

This outcome is acceptable as geographic information for a location is disintegrated into a set of single-theme layers, as either raster or vector models. However, these layers constrain GIS capabilities to represent dynamic information, such as transitions and motion. Raster cells encode attribute values at every given location with no considerations of the spatial characteristics of the theme they represent. Geometrically indexed vector objects, on the other hand, force a segmentation of the
entities being represented into separate layers whenever they interact in time or space; adopting this representational method forces compromises on most environmental modelling applications (Raper and Livingstone, 1995, Yuan, 1996). Similarly, Shaw et al (2008) argue that mainstream GIS have focused on the representation and analysis of static geographic phenomena due to the heavy influence of cartography on GIS development.

The lack of temporal data representation in GIS models is considered to be a major drawback in GIS modelling. Although the temporal aspect of the world is widely recognized, GIS has lagged in their ability to represent the temporal dimension. Time integration, therefore, is gaining more attention now.

The development of temporal data modelling in GIS corresponds to the progress of dynamic modelling in computer science. Temporal modelling commenced with the integration of time in relational databases; it then extended into object oriented modelling, as shown in Figure 3-18 (Nadi and Delavar, 2003). Parallel to this evolutionary process, temporal modelling in GIS started with time stamping layers; next, it was included in event or process-based modelling. Many researchers incorporated temporal information into spatial databases. Yuan (1996) and Ott and Swiaczny (2001) provide an overview of different approaches to the conceptualising of time related to spatial objects in a GIS. In general, temporal information has been incorporated into GIS spatial data models by time-stamping single layers, attributes and spatial objects.

\[
\begin{array}{c|c|c}
\text{Computer Science} & \text{GIS} \\
\hline
\text{Relational} & \text{Time stamping layer} \\
\text{Object - oriented} & \text{Time stamping event or process} \\
\end{array}
\]

Figure 3-18 Trend of evolution in temporal modelling (adapted from Nadi and Delavar (2003))
Their general framework give little consideration to the data needs for space-time modelling, as they use a set of geometry-based spatial objects to represent reality. The thematic characteristics are represented as attributes of spatial objects, while the temporal information is associated with either time stamped individual layers, such as the Snapshot Model, as shown in Figure 3-19, (Armstrong, 1988), or individual spatial objects, such as the Space-Time Composite Model (STC), as presented in Figure 3-20 (Langran and Chrisman, 1988).

![Figure 3-19 The snapshot model (adapted from Renolen (1997))](image)

![Figure 3-20 The Space time composite data model (adapted from Renolen (1997))](image)

The snapshot model is one of the simplest spatio-temporal models (Renolen, 1997), as the time information is stored as separate, but temporally homogenous, spatial data (Armstrong, 1988). When an event occurs, a new layer is constructed and the occurrence time is stamped to the layer. This model is useful for a continuous interpolation of temporal data, however, any assessment of the past is complicated by the fact that past conditions have been influenced in ways not detectable with snapshot data alone.

In the STC models, time is integrated into the topology of spatial objects (Langran and Chrisman, 1988). The real world is a collection of spatially homogeneous units in a 2D space that changes over time from one unit to another. Each STC has its unique period
of change, which and can be obtained from temporal overlaying of snapshot layers. Thus, a STC can only represent changes in one spatial object over time. Nevertheless, the model is useful for discrete event driven and temporal representation.

Significant data redundancy is a major disadvantage of the STC approach, which requires the re-construction of thematic and temporal attribute tables whenever operations involve any changes in spatial objects.

Events and processes based spatio-temporal models are grouped under two categories (Yuan, 1996, Renolen, 1997): event oriented spatio-temporal data models (ESTDM); and object oriented data models.

The ESTDM model is a raster based model that uses a collection of time stamped layers to represent temporal information from an event; however, in this model, unlike the snapshot model, only changes with respect to how the previous state are stored. In this model, the first base map is stored and then, when an event occurs, changes are discovered and stored in an event map. The relation between these event maps and the base maps are used in a header file. The advantage with the event-oriented model is that it is well suited for queries such as: “what has happened in the area in this period?” Another advantage is its consistency and redundancy (Yuan, 1996, Renolen, 1997).

While object-oriented data models are based on an object-oriented paradigm (which includes objects, classes, encapsulation, inheritance, and polymorphism), most object-oriented approaches to a spatiotemporal system are based on building an abstract structure in 3D or 4D space (where time is one dimension). In the model spatial, as Nadi and Delavar, (2003) describe, temporal and semantic objects are defined in three separate domains. Therefore, time is stored as an individual concept, instead of being considered as an attribute of location, such as in a snapshot model, or as an integral part of the spatial objects, as in the STC and spatio-temporal object models.

With the advancement of computer technology and science, inclusion of a temporal component in GIS models has been increasingly considered by researchers (Shaw and Xin, 2003, Ott and Swiaczny, 2001, Yu and Shaw, 2008, Gharib, 2008, Chen et al., 2011)
However, the creation of a truly spatial-temporal GIS remains an unmet challenge. Furthermore, representation and visualization of space-time paths require the support of an integrated space-time system in GIS. Conventional GIS design falls short in providing such support (Shaw et al., 2008).

Thus, although great progress has been made in developing time-space integration in GIS, there is no generally accepted model which can satisfy all temporal GIS requirements due, mainly, to its database structure. As a consequence, to handle time in GIS, it is necessary to decide how to organize such dynamic information (Nadi and Delavar, 2005). Additionally, existing limitations in the basic understanding of temporal datasets continue to obstruct the development of completely functional temporal GIS data models. As Gharib (2008) argues, it is not just a matter of collecting time-based data within a GIS, but also developing: a new way of thinking about time in a spatial sense; a new way of thinking about feedback loops and delays; and a new vision to the cause and effect (causality relationships) that draw changes in geographic processes.
3.3.3 MULTIPLE-CRITERIA DECISION AID (MCDA)

“Nothing is more difficult, and therefore more precious, than to be able to decide.”

Napoleon Bonaparte

Decision analysis lies at the core of the environmental policy making process. Decision making occurs when a problem requires the action of making choices, among various options, to generate a solution. There are many definitions for “decision” and “decision making”; all vary slightly, depending on the discipline. Two samples of definitions for decisions are provided below:

Definitions of Decision:

“Something somebody has chosen: something that somebody chooses or makes up his or her mind about, after considering it and other possible choices” (Encarta, 2009).

“Choice made between alternative courses of action in a situation of uncertainty” (BusinessDictionary, 2010).

The following are two definitions of decision making:

“Deciding on important matters: the process of making choices or reaching conclusions, especially on important political or business matters” (Encarta, 2009).

“The thought process of select a logical choice from among the available options” (BusinessDictionary, 2010).

According to these definitions, “Choice” and “Alternatives” are the two defining key elements in the decision process. In addition, the “Criteria”, upon which a decision would be made, is another important aspect of the decision making process.

Based on the above discussion, the decision making process occurs where:

“A decision can be seen as a process of selecting from among several alternatives based on various (usually conflicting) criteria.”
Most decision processes regarding the environment are usually complex and involve multiple criteria. Thus, an environmental decision, based on a single criterion, would be an oversimplification of the characteristics of the problem and, therefore, would lead to an unrealistic decision. According to pioneers in the MCDA fields, a problem can be considered as a decision problem if there are at least two criteria (in some cases conflicting) to deal with, otherwise it would be a problem of getting the right information, not a decision problem (Roy, 1968, Keeney and Raiffa, 1976).

Despite the fact that most environmental decisions involve the consideration of multiple-criteria problems, they tend not to be handled accordingly. From a traditional point of view, a decision problem is considered to be the definition of a single criterion, which amalgamates the multidimensional aspects of the decision situation into a single scale of measure. Based on this definition, the solution to a decision problem must define the goal first, which must then be maximised or minimised. This approach is very reductive and, in some sense, also an unnatural way to look at a decision problem (Figueira et al., 2005d).

However, contrary to the above approach, almost all complex decisions are multiple-criteria problems. That is, the decision is strongly related to the comparison of different points of view, and making a choice among them is based on some criteria to satisfy the goal. Some goals can be in favour, and some against, a certain decision, which indicates that the decision is essentially related to differentiating the criteria. Therefore, trade-offs are inevitable in the decision making process (Keeney and Raiffa, 1976, Harrison and Qureshi, 2000, Geldermann and Rentz, 2005).

MCDA is an effective technique, with the goal of providing a general ranking of alternatives, from the most preferred to the least preferred, based on a set of criteria. Further, the alternatives may vary in the extent to which they satisfy several criteria, with no one option being the obviously best in satisfying all the criteria. In addition, some trade-off is usually evident amongst the criteria in order to reach an agreement on the solution (the most preferred alternative). MCDA’s origins exist in the fields of mathematics and operations research (Proctor and Drechsler, 2006).
Five prominent scholars, working in the field of MCDA, revealed their thoughts in a manifesto (French, 1993). They argued that, MCDA always claimed that real-world decision problems are affected by conflicting information, uncertain or imprecise knowledge, and ambiguity in the actors’ positions. In the face of such indecisive data, preference modelling, therefore, requires the use of specific tools, techniques and concepts which make it possible to model and exploit the preference information. Hence, MCDA can be seen as:

1. An attitude towards providing decision aid to actors involved in a decision process,
2. A methodology for providing such decision aid,
3. A collection of methods, and
4. A corpus of experience obtained after many real-world applications.

As a consequence, MCDA constitutes an advanced field of operations research. Its objective is to aid DMs in making realistic decisions by taking into consideration multiple criteria, uncertain information and multiple participants in the decision analytical process. That is, MCDA is capable enough to consider many aspects of the complex real world decision problems (Keeney and Raiffa, 1976).

MCDA techniques provide a powerful modelling framework for aiding complex decision-making processes involving multiple criteria, goals, or objectives of conflicting nature. All MCDA techniques require alternatives, criteria and judgement. That is, alternatives and their performance against the different criteria clearly measured through making a judgement. Further, MCDA techniques usually provide a clear relative weighting system for the different criteria. These techniques are able of handling both quantitative and qualitative criteria, and are well-suited to the concept of compromise solution (Saaty et al., 1991, Vaidya and Kumar, 2006, Tan et al., 2008, Sanga and Venter, 2009).

The main function of the MCDA technique is that it concentrates on decision analysis within a finite set of alternatives. Additionally, it offers techniques to assist individual DMs in making decisions by eliciting and aggregating their preferences (Chen et al., 2009). The aggregation procedure and the data handling are two important features of
the MCDA techniques. However, they vary in how they aggregate the data. Mostly, MCDA techniques are based on a mathematically explicit aggregation procedure, which, for any pair of potential actions, gives a clear answer to the aggregation procedure (Figueira et al., 2005d). This approach is necessary in order to give a numerical value to the inter-criteria parameters. However, a decision problem is not addressed in the same way by all DMs. Each DM has his / her own preferences and experiences.

Roy (1968) suggests that there are three fundamental problems (problématiques) in the MCDA field: choice, ranking, and sorting problems. DMs also have different goals for each problem. In choice, the goal is to choose the best alternative from among a set of alternatives, A. In ranking, the aim is to find the best alternative by ranking the alternatives of A from best to worst. Finally, in sorting, the goal is to sort the alternatives of A to find which alternatives belong to each class of a predefined set of classes. The question then arises as to, “What makes MCDA different from other operational research techniques?”

MCDA is not just a compilation of techniques, but a particular view of how to handle decision problems. The techniques utilise iterative processes to analyse the preferences of the DMs rather than using a straightforward sequential process. Thus, iterative and interactive preference modelling is one of the basic distinguishing characteristics of the MCDA techniques, when compared to statistical and optimization decision-making techniques.

A review of the existing literature shows a variety of MCDA techniques with a broad range of applications. These techniques can be grouped into two main categories (Tan et al., 2008): outranking techniques, e.g. ELECTRE and PROMETHEE; and value measurement techniques, e.g. MAUT and AHP.

The two outranking methods, ELECTRE and PROMETHEE, represent ‘the European school’ of multi-criteria decision making (MCDM), as opposed to the AHP method which represents ‘the American school’ The outranking approach, which was first developed in France, namely, ELECTRE by Bernard Roy (1968), is based on a
fundamental partial comparability axiom where incomparability is a key concept (Climaco, 1997).

The multi-attribute utility theory (MAUT) (Keeney and Raiffa, 1976) and the analytical hierarchy process (AHP) (Saaty, 1980) have many similarities. Geldermann and Rentz (2005) argue that both MAUT and AHP have the same basic principle of preference measurement, that is, the establishment of a value function based on an additive aggregation of scores representing goal achievement for each criterion, multiplied by the particular weights.

These techniques are suitable for comparing multiple criteria simultaneously, while providing a solution to a given problem. An examination of the potentials for the assessment of different adaptation alternatives is given in the following concise review the major MCDA techniques, which include, but are not limited to: ELECTRE, PROMETHEE, MAUT, and Analytic Hierarchy Process (AHP). For further details, the interested readers are referred to “Multiple Criteria Decision Analysis: State of the Art Surveys” by Figueira et al., (2005a), which is one of the most comprehensive works available on MCDA to date. A discussion to identify the best technique, for the current research, from the available MCDA techniques, including their similarities and differences, is provided in Chapter 5.

3.3.3.1 ELECTRE

The term ELECTRE stands for “ELimination Et Choix Traduisant la REalité”, translated as Elimination and Choice Expressing Reality. The ELECTRE method was first presented in Roy’s work in 1968; the method has continued evolving (ELECTRE I, ELECTRE II, ELECTRE III, ELECTRE IV, ELECTRE ELECTRE IS and ELECTRE TRI). Each refinement has addressed different aspects of multi-criteria problems. For example, ELECTRE I and IS were designed for selection problems, while ELECTRE II, III, and IV are used for ranking problems (Roy, 1991, Kangas et al., 2001).

The following section provides an overview for ELECTRE I. (For more detailed information on ELECTRE techniques, readers are referred to the article “Ranking and Choice in Pace of Multiple Points of View (ELECTRE Method)” by (Roy, 1968), and the
book “Multiple Criteria Decision Analysis” by (Figueira et al., 2005c). The underlying idea for the outranking technique, ELECTRE, involves the identification of relations between options to show which option outranks another, often called the “dominance relations”. Further, ELECTRE seeks to reduce the set of non-dominated alternatives. To reflect the relative importance, the DM provides a set of weights for alternatives; those alternatives, which are dominated by other alternatives, are eliminated.

Thus, the main purpose of the ELECTRE techniques is to establish binary outranking relations, $S$, on the alternative set, $A$. The binary outranking relation is the fundamental building block of ELECTRE. The preferences in the ELECTRE methods are modelled by using binary outranking relations, $S$, whose meaning is “at least as good as” (Figueira et al., 2005d). For example; if there are two actions, a and b, then four situations may occur:

1. $aSb$ and not $bSa$, then $aPb$ (a is strictly preferred to b)
2. $bSa$ and not $aSb$, then $bPa$ (b is strictly preferred to a)
3. $aSb$ and $bSa$, then $aIb$ (a is indifferent to b)
4. Not $aSb$ and not $bSa$ then $aRb$ (a is incomparable to b)

They describe that the outranking relation is based on two major concepts:

1. Concordance: For an outranking $aSb$ to be validated, a sufficient majority of criteria should be in favour of this assertion.
2. Non-discordance: When the concordance condition holds, none of the criteria in the minority should oppose too strongly to the assertion $aSb$.

The use of a concordance and a discordance index to measure the relative advantage and relative disadvantage of an alternative, over all other alternatives, is the defining characteristic of the ELECTRE family. An outranking relation of $a \rightarrow b$ (also denoted as $aSb$) shows that $a$ is preferred to $b$, if there are enough arguments to conclude that “$a$ is at least as good as $b$”, while there is no essential reason to refuse this statement. That is, the concordance of alternative $a$ outranking alternative $b$, $C(a, b)$, is a number representing the weight of evidence for the assertion that “$a$ outranks $b$”. Similarly, discordance, $D (a, b)$ represents the weight of evidence for the assertion that $a$ does
not outrank \( b \). Typical MCDA problems to be handled by ELECTRE consist of \( n \) alternatives \( a_i \), \( m \) criteria \( c_j \) and \( m \) weighting factors \( w_j \). The main steps of the ELECTRE techniques are summarised in the following section (Roy, 1991, Kangas et al., 2001, Figueira et al., 2005a, Milani et al., 2006, Zhang and Xu, 2006).

The first step in the technique is to define the concordance and discordance. To do this, the concordance and discordance index sets are defined for every pair of alternatives \( a_i \) and \( b_j \) \((i, j = 1, 2, ..., n; i \neq j)\).

Concordance index set:

Discordance index set:

Where;

\( r_{ij} \) refers to an element of decision matrix \((i_{th} \text{ alternative and } j_{th} \text{ criterion}),\)

represents the set of criteria showing sufficiently strong evidence to accept that \( a_i \) at least as good as \( b_j \), and

represents the existence of a significant opposition to veto this proposition.

Following Roy (1991) example, the concordance index can be calculated for every ordered pair of alternatives \((a_i, a_k)\); hence the concordance index \( C_{ik} \) is:

\[
\text{Equation 3-6}
\]

\[
(0 \leq C_{ik} \leq 1)
\]

Where:

\( w_j \) is the relative importance of attribute \( j \).  

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The concordance index reflects the strength of the support, given the available evidence, that $a_i$ is at least as good as $b_j$ considering all criteria. The successive values of the concordance indices $C_{ik}(i, j=1,2,...,n; i\neq j)$ from the concordance matrix $C$ of $n \times n$ are:

As Roy (1991) explained, the concordance index describes the strength of the positive arguments able to validate the assertion $aSb$. The discordance index, $D_{ik}$, is a little more complex than the concordance index. The discordance index measures the strength of the evidence against the above hypothesis. If alternative $i$ performs better than alternative $k$ on all criteria, the concordance index is zero. If not, then for each criterion where $k$ outperforms $i$, the ratio is from the difference in the performance levels between $k$ and $l$, and the maximum observed difference in the score on the criterion concerned, between any pair of options in the set being considered. This ratio between zero and one is the discordance index. For a decision problem with real number attribute values, the discordance index can be calculated with the formula:

\begin{equation}
0 \leq D_{ik} \leq 1
\end{equation}

After calculating the discordance index for all alternatives based on the above formula, the discordance matrix $D$ can be established as:

The second phase of the technique combines the concordance and the discordance.
To bring the two sets of $n(n-1)$ indices together for all $n$ options being considered, a relatively large concordance threshold ($c'$) and a relatively small discordance threshold ($d'$) have to be defined by the DM or by calculating the average value of the indices.

Using both the concordance and discordance threshold or set, the outranking relation $S$ can be defined. If its concordance index is greater than the chosen threshold value $c'$, and its discordance index is smaller than the threshold value $d'$, then, an option, $a_i$, outranks another option, $b_j$, overall.

Therefore,

Equation 3-8

Once the two tests are completed for all pairs of alternatives, the preferred alternatives are those that outrank more than being outranked.

The set of all alternatives that outrank at least one other alternative, and are themselves not outranked, contains the promising alternatives for this problem. The outranking methods are, thus, distinguished from other MCDA techniques. While an MCDA approach makes relatively strong assumptions about the underlying circumstances of the problem, as an outranking technique, ELECTRE seeks to make fewer assumptions about the nature of the underlying process that produces the preferences. It is a more interactive process between the DMs and the model, while the MCDA has a relatively strong axiomatic basis. Indeed, Loken (2007) concluded that the family of ELECTRE techniques can be seen as an alternative to the utility function and value function methods.

However, according to Gelderman and Rentz (2005), its complexity, which stems from nuances in the comparisons, is also its disadvantage. Thus, due to the underlying assumptions for the algorithm, the method is rather difficult to explain to DMs in industry or in politics, especially since the introduced thresholds do not have a realistic meaning (Geldermann and Rentz, 2005).
3.3.3.2 PROMETHEE - PRIORITY RANKING ORGANISATIONAL METHOD FOR ENRICHING EVALUATIONS

The term PROMETHEE stands for “Preference Ranking Organization METHOD for Enrichment Evaluation”. Several versions of PROMETHEE have been created to handle various decision making scenarios. PROMETHEE I and PROMETHEE II, developed by J.P. Brans, were presented at a conference for the first time in 1982 (Figueira et al., 2005b). Other members of the PROMETHEE family, PROMETHEE III through to PROMETHEE VI, were introduced by J.P. Brans and B. Mareschal between 1988 and 1994. Further, PROMETHEE-I provides a partial pre-order, and PROMETHEE II provides a total pre-order on the set of possible actions (Brans and Vincke, 1985).

PROMETHEE belongs to the class of outranking methods, which is based on building outranking relations and the exploitation of outranking relations. However, they do not follow the definition of outranking relation, as being based on concordance and non-discordance. Instead, PROMETHEE uses the concept of preference intensity functions for valued outranking (Tan et al., 2008). While PROMETHEE I and II allow direct outranking of alternatives, both in part and in full, PROMETHEEs III through to VI group decision making and pictorial output so that they cater for situations with specific and complex attributes (Behzadian et al., 2010).

In PROMETHEE, the preference is based on pair-wise comparisons of alternatives for each criterion. This comparison is performed through a preference function for each criterion in order to calculate partial binary relations denoting the strength of the preference of an alternative over another alternative. A starting point in these methods is to establish an evaluation table, in which alternatives are evaluated on the different criteria. In order to implement the methods, two types of information are needed, namely, the weights of the criteria and the DM preference function.

The weight factors can be determined by using various techniques, such as the DM’s previous experience, their insights and knowledge. The DM chooses a generalised criterion and fixes the necessary parameters related to the selected criterion; a preference function is defined for each attribute. The basic process for PROMETHEE is
described in the following two steps (Dias et al., 1998, Mergias et al., 2007, Behzadian et al., 2010, Brans and Vincke, 1985):

Two main steps of the PROMETHEE methods are:

1. To build the outranking relations, and
2. To exploit the outranking relation with respect to the chosen statement of the problem.

Preference function, $P_k$, is defined separately for each criterion, whose value ranges from 0 to 1. This can be expressed as:

$$P_k (a_i, a_j) = (G_j[f_k(a_i) - f_k(a_j)])$$

Equation 3-9

To facilitate the selection of a particular preference function, $P_k$, six basic types have been described (Type 1: Usual criterion, Type 2: Quasi criterion, Type 3: Criterion with linear preference, Type 4: Level criterion, Type 5: Criterion with indifference area, and Type 6: Gaussian criterion). These functions, as discussed below, can be used to cover most cases occurring in practical applications.

*Type 1: Usual criterion*

Where:

$$d = a_i - a_j$$

In this case, indifference exists between these two values only when $a_i = a_j$. Immediately when these values differ, the DM can act to make a preference for the greatest value. Preference function $P_k$ equals 1 as seen in Figure 3-21.

*Type 2: Quasi criterion*
Here, the DM has to define \( q_k \) first. If the difference, \( d \), does not exceed \( q_k \), for a particular criterion, \( a_i \) and \( a_j \) are indifferent. Otherwise the preference becomes strict (see Figure 3-21).

*Type 3: Criterion with linear preference*

Equation 3-12

In this case, the DM prefers progressively \( a_i \) to \( a_j \) for progressively larger deviations between these two values. The intensity of the preference increases linearly until this deviation equals \( p_k \); after this value the preference is strict (see Figure 3-21).

*Type 4: Level criterion*

Equation 3-13

If the deviation between \( a_i \) and \( a_j \) does not exceed \( q_k \), in this case, then they are considered indifferent. If \( d \) is between \( q_k \) and \( p_k \) then the preference is weak (0.5); after this value the preference becomes strict (see Figure 3-21).

*Type 5: Criterion with indifference area*

Equation 3-14

In this case, the DM assumes that \( a_i \) and \( a_j \) are completely indifferent as long as the deviation between \( a_i \) and \( a_j \) does not exceed \( d \). Above this value the preference grows progressively until this deviation equals \( p_k \) (see Figure 3-21).
**Type 6: Gaussian criterion**

The Gaussian type is considered for a particular criterion; the DM’s preference still grows with the deviation $d$. The value of $\beta$ is the distance between the origin and the point of the inflexion of the curve. In this particular case only the value of $\beta$ has to be defined by the decision-maker (see Figure 3-21).

Equation 3-15

To exploit the outranking relation, preference indices and outranking flows should be defined. An aggregated multi-attribute preference index is determined as follows:
Equation 3-16

Here, $\pi(a_i,a_j)$ expresses a measure of preference of $a_i$ over $a_j$ over all the criteria. That is, the closer the preference index to 1, the greater the preference.

When faced with different kinds of problems, if the DM needs to rank the actions of $A$ from the best to weakest, then it is a *ranking problem*. However, if the DM needs to select the best option, then, it is a *choice problem*.

Two *complete preorders* are built by ranking the alternatives following the decreasing order of leaving flows (Equation 3-17), or ranking the alternatives following the increasing order of entering flows (Equation 3-18). The intersection of the preorders yields a *partial preorder*. A unique *complete preorder* is built by ranking the alternatives following the decreasing order of net flows (Equation 3-19). From these flows, the PROMETHEE-I provides partial outranking of alternatives. In a number of cases, this ranking may be incomplete, which occurs when some alternatives cannot be included in a complete ranking, due to incomparable alternatives. The PROMETHEE-II provides a complete ranking of the alternatives by using the net flow.

Leaving flow:

Equation 3-20

Entering flow:

Equation 3-21

The larger $+ (a_i)$ the more $a_i$ dominates the other actions of $A$. The smaller $- (a_i)$, the less $a_i$ is dominated.
Athawale and Chakraborty (2010) identified the following advantages of PROMETHEE over the other MCDM techniques, such as MAUT and AHP. Firstly, the PROMETHEE method can classify the alternatives, which are difficult to be compared because of the trade-off relation of the evaluation standards as non-comparable alternatives. That is, it is quite different from the AHP, in that there is no need to perform a pair-wise comparison again when comparative alternatives are added or deleted (Athawale and Chakraborty, 2010).

Secondly, the PROMETHEE method makes easy to understand the concepts and parameters inherent in the method, which makes the preference modelling simpler and, consequently, increases the effectiveness of applying the methods. This characteristic is especially useful in the case of social decisions, in which DMs usually have different skills (Silva and Morais, 2010).

Various consequences of the model assumptions of PROMETHEE have been formulated (De Keyser and Peeters, 1996). Hence, the methods can be applied if the following considerations are taken into account:

1. The DM can express his/her preferences between two actions on all the criteria on a ratio scale.
2. The DM can express the importance s/he attaches to the criteria on a ratio scale.
3. The DM wants to take all criteria into account and is aware of the fact that the weights are representing the trade-offs.
4. For all criteria the differences between evaluations must be meaningful.
5. The DM knows exactly what can happen if one or more actions are added or deleted, and is fully aware of the influences on the final decision.
Although many advantages are provided in the literature, PROMETHEE, like any other method, has its shortcomings resulting from assumptions in the building models when the technique is employed. These shortcomings are summarised as follows (Anand and Kodali, 2008).

- Due to outranking principles, the PROMETHEE techniques only produce rankings, they do not produce independent ratings. Moreover, the inclusion of new alternatives and criteria requires the repetition of pair-wise comparisons for re-establishing a ranking order (Waeyenbergh et al., 2004).
- PROMETHEE is very powerful in communicating results, and it is easy to use; however it lacks structural features. Further, these outranking models are rather uncommunicative and tend to behave as a black-box to the non-professional user (Wolfslehner, 2006).
- There are various uncertainty sources in the application of MCDA. such as the definition of criteria weights and the assignment of criteria performance values. Despite the inclusion of the generalized criterion functions, potential sources of considerable uncertainty remain when utilizing PROMETHEE to analyse decision problems, which may be the result of a lack of consensus between the actors and reduced confidence in the outcomes of the decision analysis by the DMs (Hyde et al., 2003).
- Outranking methods, such as PROMETHEE, and ELECTRE, are subject to computational limitations with respect to the number of decision alternatives (Marinoni, 2006).

3.3.3.3 MAUT - MULTI-ATTRIBUTE UTILITY THEORY

The acronym MAUT stands for Multi-Attribute Utility Theory (Keeney and Raiffa, 1976). The concept is based on the utility theory of von Neumann and Morgenstern first published in their 1944 publication *Theory of Games and Economic Behavior*. Utility can be defined as a measure of the satisfaction or reward from which an individual could benefit or suffer, after receiving a service or good. Additionally, utilities reflect relative preferences by using a set of assumptions and techniques.
MAUT, a mathematical theory, is concerned mainly with the decomposition of multi-attribute utility functions, into a set of simple single-attribute utility functions, that can actually be assessed (Botter, 1985). In MAUT, the essential idea is to measure the individual’s preferences through a utility function $U(g)$, based on an additive aggregation of scores representing the goal achievement for each criterion, multiplied by the particular weights. A decision matrix is utilised to organise the data in rows (alternatives) and columns (criteria), as shown in Figure 3-22.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>$g_1$</th>
<th>$g_j$</th>
<th>$g_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1$</td>
<td>$e_{11}$</td>
<td>$e_{1j}$</td>
<td>$e_{1n}$</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>$a_i$</td>
<td>$e_{i1}$</td>
<td>$e_{ij}$</td>
<td>$e_{in}$</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>$a_m$</td>
<td>$e_{m1}$</td>
<td>$e_{mj}$</td>
<td>$e_{mn}$</td>
</tr>
</tbody>
</table>

Figure 3-22 Decision matrix

Its aim is to represent an individual’s preferences by using a utility function $u(g)$ to aggregate the evaluation criteria:

$$u(g) = u(g_1, g_2, ..., g_n)$$  \hspace{1cm} \text{Equation 3-23}$$

Where:

- $u(g)$ : Utility function
- $g$: vector of the evaluation criteria ($g_1, g_2, ..., g_n$)

The multi-criteria utility function $u(g)$ can be decomposed to obtain marginal utility functions for each alternative;

$$u(g) = u_1(g_1) + u_2(g_2) + ... + u_n(g_n)$$  \hspace{1cm} \text{Equation 3-24}$$

Where:

\[ u_1, u_2, ..., u_n \] are the marginal utilities.

The marginal utilities are defined on the scales of the criteria. Once the basis of the utilities of the alternatives are calculated using the utility functions, the alternatives can be ranked from the best (alternatives with the higher utility) to the worst (alternatives with the lower utility). Different models for function \( U \) exist in Equation 3-23, depending on the different expressions. Thus, the simplest model in MAUT is an additive function, which can be expressed mathematically as:

\[
U_k = \sum_{i=1}^{m} c_k \cdot U_k
\]

Where:

\( U_k \): Utility function of criterion \( k \)

\( c_k \): criterion \( k \)

\( m \): number of criteria

MAUT also supports a multi-level analysis of the criteria, where the criteria are broken down into sub-criteria. However, simple additive functions will not be sufficient if interdependencies exist between the criteria. In this case, a multiplicative model will be more appropriate to model the interactions between the criteria (Figueira et al., 2005d). This can be expressed as:

\[
U_k = \prod_{i=1}^{m} c_k \cdot U_k
\]

Where:

\( U_k \): Utility function of criterion \( k \)
The MAUT process involves nine steps when performing a multi-attribute utility analysis:

1. Identify the primary decision to be made
2. Identify the decision alternatives
3. Identify the criteria (attributes) of the alternatives that impact the decision.
4. Define performance measures for each attribute – done by expert reviewers.
5. For each attribute; Evaluate how well each alternative performs on the attribute (score).
6. For a particular application; determine the weight (importance) of each criteria (attribute).
7. Calculate the single-attribute utility of each criteria (attribute):
   \[ \text{Single-attribute utility} = \text{attribute weight} \times \text{criteria score} \]
8. Calculate the multi-attribute utility of each alternative:
   \[ \text{Multi-Attribute Utility} = \sum(\text{single-attribute utilities}) \]
9. Select alternative with highest multi-attribute utility.

Buehring et al, (1978) emphasized that the MAUT process in itself has many benefits for the DMs. For example, the process of assessing utility functions will help the DMs to identify the most important issues, generate and evaluate alternatives, resolve judgment and preference conflicts among the DMs, and identify improvements to the impact (Buehring et al., 1978).

Other researchers, however, have raised concerns about the drawbacks of MAUT (Haustein and Weber, 1983, Siskos and Hubert, 1983, Figueira et al., 2005d, Kim and Song, 2009), some of which are summarised below:
• Contrary to most practical situations, MAUT assumes that complete and definite information about the DM’s preference is available at the beginning of the decision-making process.
• MAUT is based on rather strong assumptions about the rational behaviour of economists. However, everyday decisions are not made by maximizing utility functions, but rather, they are made by establishing certain reference levels.
• The most important concerns of MAUT are not real decision-making problems; they are considerations of the form of the disaggregation rule for the overall utility function.
• MAUT is best suited for repetitive choice situations.
• It is extremely difficult to derive single utility functions for attributes.
• The procedures for assessing utilities are clumsy, complicated, difficult to understand, and time consuming; they do not allow for mistakes; and they sometimes require answers to somewhat nebulous hypothetical questions.

3.3.3.4 AHP - ANALYTICAL HIERARCHY PROCESS

The acronym AHP stands for “Analytical Hierarchy Process”, a technique originally developed by Saaty (1980). Since then, AHP has proven to be one of best known, and the most widely used, MCDA techniques. The method was initially created to aid an individual DM to choose an alternative among many alternatives. Subsequently, its applications have been stretched to a group decision making process, where several people are involved in the decision making. Hence, judgements are obtained from a group of N people; these are combined by using a geometric mean, namely, the mathematical equivalent of consensus, if all the members are considered equal. Otherwise the weighted geometric mean (Saaty and Vargas, 2007), would be used to synthesise the reciprocal judgements in AHP, as it is the only mathematically valid way to preserve the reciprocal conditions (Aczél and Saaty, 1983).

Further, the AHP provides the objective mathematics to process the inescapably subjective and personal preferences of an individual or a group involved in making a decision (Saaty, 2001). The underlying concept of the AHP technique is to convert
subjective assessments, of relative importance, to a set of overall scores and weights. Saaty (1990) describes the AHP technique in the following quote:

> Basically, the AHP is a method of breaking down a complex, unstructured situation into its component parts, or variables, into a hierarchic order; assigning numerical values to subjective judgments on the relative importance of each variable, and synthesizing the judgments to determine which variables have the highest priority and should be acted upon to influence the outcome of the situation (Saaty, 1990).

The AHP, based on the three principles of decomposition, evaluation and synthesis, defined by Saaty, is an eigenvalue approach to the pair-wise comparison (Schmoldt, 2001, Anderson et al., 2003, Vaidya and Kumar, 2006, Render et al., 2006). The principles are defined as:

1. Decomposition, which enables DMs to structure a problem into a hierarchy consisting of a goal and subordinate features.
2. Evaluation, which allows pair-wise comparisons between elements at each level to enable a preferential ordering of decision elements.
3. Synthesis, which involves matrix algebra that propagates level specific, local priorities to global priorities.

Eigen values are a special set of scalars associated with a linear system of equations (i.e., a matrix equation) that are sometimes also known as characteristic roots, characteristic values (Hoffman and Kunze 1971). AHP builds upon complete aggregation and is designed to determine priorities through pair-wise comparisons between all alternatives with each other with respect to each criterion. The paired comparison judgments are arranged in a matrix. The priorities are derived from this matrix as its principal eigenvector, which defines an absolute scale. The eigenvector, therefore, is an inherent concept of a prioritization process. The technique also allows for the measurement of inconsistency in judgment. The basic steps of Saaty’s (1980) AHP technique are summarised below:

**Step 1:** Structuring of the problem as a hierarchy.

The AHP process starts with decomposing a decision problem into a hierarchy of criteria, which allows for an easy analyse and comparison, by listing the overall goal,
criteria, and decision alternatives (Figure 3-23). The hierarchy is an efficient way to manage complex systems. In the hierarchy, the topmost level is the goal followed by the intermediate levels, which correspond to the criteria and sub criteria. The lowest level contains the alternatives.

![A simple analytic hierarchy](image)

**Figure 3-23 A simple analytic hierarchy**

**Step 2:** Develop a pair-wise comparison matrix

After building the hierarchy, the DMs determine the relative priorities of each element in the hierarchy by comparing them in a pair-wise manner, with respect to each criterion. The DM uses a pair-wise comparison mechanism to assess the pair-wise comparisons by using Saaty’s nine point intensity scale of importance between the two elements (scale and verbal judgements) as shown in Table 3-4.

The verbal judgements range from equal to extreme, and correspond to the numerical judgements from 1 to 9. To make plausible distinctions among the ratings, generally odd numbers are used. Hence, the even numbers can only be assigned as the negotiated solution when a consensus cannot be reached. A reciprocal rating (i.e. 1/9, 1/8, etc.) is assigned when the second alternative is preferred to the first. The value of 1 is always assigned when comparing an alternative with itself.
The comparison matrix, constructed from the Saaty scale, lists the alternatives horizontally and vertically. The numerical ratings compare the horizontal (first) alternative with the vertical (second) alternative. The DM’s answers to a series of questions are the input of this matrix, i.e. “the importance of the alternative A relative to alternative B with respect to criterion k”. When a set of elements of a decision problem are compared with each other a square decision matrix is created, as shown below:

This matrix is a reciprocal matrix and can be expressed as:

\[
\begin{array}{cccc}
1 & 1 & & \\
1 & 1 & & \\
& & & \\
& & & \\
& & & \\
& & & \\
& & & \\
& & & \\
& & & \\
& & & \\
\end{array}
\]

Equation 3-27

Where; \( i \) refers to the row and \( j \) refers to the column and \( i, j = 1, 2, ..., n \).

If it is assumed that there are \( n \) alternatives, \( A_1, A_2, ..., A_n \), with their corresponding \( n \) weights, \( w_1, w_2, ..., w_n \),
Then a matrix of pair-wise comparison can be created, in which the rows show the ratios of the importance of each element, with respect to all other elements. This can be expressed as follows:

If the relative importance of the alternative $A$ over the alternative $B$ is expressed as a ratio scale, then, it is entered in the matrix $W_A/W_B$. The reciprocal, $W_B/W_A$, is entered in the matrix for the relative importance of the alternative $B$ over the alternative $A$.

The required number of judgements for a matrix of order $n$ would be:

$$\text{Equation 3-28}$$

**Step 3:** Determine local priorities

The relative contribution of each element on an element in the level immediately above can be determined by using the priority vector (or eigenvector).

Saaty (1987) asserts that the eigenvector method derives benefit from the information provided in the matrix whatever the inconsistency may be and derives priorities based on the information without conducting arithmetic improvements on the data. Accordingly, the idea is to let DMs decide whether they want to change their judgement, rather than being the function or responsibility of a sophisticated mathematician to improve on what the individual DM may not want to change (Holloway, 1987). Although there are several methods for calculating the eigenvector values, Saaty (1980) uses the geometric mean method to obtain a good approximation, instead of using other time consuming methods.

The geometric mean of a row can be calculated by multiplying $n$ elements in each row and taking the $n_{th}$ root. That is:
The resulting numbers yield the eigenvector. To analyse and give relative weight to each element, the eigenvector has to be normalised by dividing each number by the sum of the $n$ eigenvector elements. That is,

\[
\text{Equation 3-29}
\]

\[
\text{Equation 3-30}
\]

Where, $a_i$ ($a_1, a_2, ..., a_n$) is a set of eigenvector components, and $w_i$ ($w_1, w_2, ..., w_n$) is a set of normalised eigenvector components. Then, the multiplication of comparison matrix by $w_i$ yields:

The matrix is the ratio of the weights $W$, which, as Saaty explains, is generally inconsistent. To be consistent, the rank can be transitive, but the values of judgment are not necessarily forced to the multiplication formula. Hence,

$$A(a_{ij}) \text{ is consistent if } a_{ij}a_{jk} = a_{ik}, \text{ and } i, j, k = 1, 2, ..., n$$
In a consistent reciprocal matrix, as proved by Saaty, the largest Eigen value is equal to the size of the comparison matrix. That is,

$$A = \left( \frac{w_i}{w_j} \right), \quad A' = (a_{ij}) \quad \text{and} \quad \lambda_{max} \text{ is the largest eigenvalue of the judgement matrix } A.$$  

Equation 3-31

The consistent problem then involves solving,

$$\text{Equation 3-32}$$

while the general one with reciprocal judgements involves solving;

$$\text{Equation 3-33}$$

Step 4: Consistency Ratio

The consistency ratio step looks for any data inconsistencies. In a decision analysis, it is important to know how good the decision makers’ consistency is. Although a certain degree of consistency is desirable, too much consistency is not desirable because human judgements often require changes when new information is received about the problem. As the AHP technique allows a certain degree of inconsistency, according to Saaty (1991), the inconsistency must be large enough to allow for change in our consistent understanding, but be small enough to make it possible to adapt our old beliefs to new information.

The consistency of the subjective input in a pair-wise comparison matrix can be measured by calculating a consistency ratio. The purpose of such a consistency check is to determine whether the DMs have been consistent in their judgements, because it is undesirable to have judgements with a low consistency. The consistency index (CI) for a $n \times n$ reciprocal matrix, as proposed by Saaty, is calculated from the eigenvalue $\lambda_{max}$ as:
Where, $n$ is the number of elements being compared and $\lambda_{\text{max}} \geq n$.

The consistency index is compared to a value derived by generating random reciprocal matrices of the same size (called the random consistency index ($RCI$)) to give a consistency ratio ($CR$). Then, the $CR$ of $(nxn)$ matrix can be expressed as the ratio of its $CI$:

\begin{equation}
\text{Equation 3-34}
\end{equation}

\begin{equation}
\text{Equation 3-35}
\end{equation}

The $RCI$ values are generated randomly from the scale ($1/9, 1/8, 1/7, \ldots, 1/2, 1, 2, 3, \ldots, 9$). A sample RCI table created by Saaty shown below:

<table>
<thead>
<tr>
<th>Number of Alternative ($n$)</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random Index ($RCI$)</td>
<td>0.58</td>
<td>0.90</td>
<td>1.12</td>
<td>1.24</td>
<td>1.32</td>
<td>1.41</td>
</tr>
</tbody>
</table>

Thus, if the CR is less than 10%, then the matrix is considered as having an acceptable consistency. In some cases, 20% CR can be tolerated, but never more (Saaty et al., 1991). If the CR is not within the acceptable range, then the DMs need to review the problem and revise their judgements.

Once the local priorities of the elements at the different levels are calculated, they are synthesised across various levels to determine the final priorities of alternatives. This process can be achieved by synthesising the priorities from the second level down, by multiplying the local priorities by the priority of their corresponding criterion in the level above, and adding them for each element in the level, according to criteria it affects.

Readers are encouraged to refer to Appendix 7 in which a step-by-step AHP example is provided and solved, numerically. The example demonstrates how the AHP technique can be implemented; here, the goal is determined as the Reducing Vulnerability, with the criteria being Flexibility, Sustainability and Efficiency, while the alternatives are Retreat, Accommodate, and Protect.
When there are dependencies among the hierarchy elements, the Analytic Network Process (ANP) is considered the most suitable decision analysis technique. The ANP (Saaty, 2004) is a generalization of the AHP, which dissolves the structural boundaries towards a network structure covering the interdependencies and the feedbacks between the elements of different clusters. Further, the ANP synthesizes the outcome of the dependence and the feedback within and between the clusters of elements through its super matrix (Saaty, 2004). The priorities are determined through a threestep super matrix calculation:

- The unweighted super matrix is built by ratio scales of pair-wise comparison inputs on the preferences among interconnected elements,
- The weighted super matrix is gained by multiplying those values with their affiliated cluster weights, and
- The limit super matrix is the convergent matrix raised to powers which displays single indicator priorities and overall priorities for alternatives.

In conclusion, the AHP is a powerful technique for differentiating between alternatives in the light of the multiple criteria to be met. Additionally, the application of the technique is not complex. However, like all modelling methods, the AHP has a number of strengths and weaknesses. Despite these its empirical successes, the AHP has received many criticisms, as evidenced by the existence of several alternative procedures (Hummel et al., 1998).

The strengths, as well as the criticisms, of the AHP technique are summarised below (Hummel et al., 1998, Zahir, 1999, Forman and Gass, 2001, Ramanathan, 2001, Macharis et al., 2004, Tan et al., 2008, Qureshi and Harrison, 2003):

The AHP strengths include:

- Formal structuring of the problem; it decomposes a decision problem into its constituent parts and builds hierarchies of criteria;
- Simplicity of pair-wise comparisons that DMs can easily understand;
- Flexibility and redundancy allows consistency to be checked;
- Both subjective and objective evaluation measures can be captured;
- Fast and a low cost approach; and,
- Versatile technique in which scientific judgement can be combined with individual judgements in the evaluation of alternatives.

Criticisms of the AHP include:

- Difficulty of conversion from verbal to numeric scale;
- Inconsistencies imposed by the 1 to 9 scale;
- Lack of meaningfulness of responses to questions;
- Impossible to rank reverse when a multiplicative variant of the AHP is used;
- Number of comparisons required may be large;
- Detailed, and often important, information can be lost due to its complete aggregation method; and,
- If the number of hierarchy elements \( n \) is big, the number of pair-wise comparisons to be made \( (n(n-1)/2) \) may become very large.
3.4 SUMMARY

Global warming and climate change are serious environmental issues that threaten societies across the world. Any long term planning for the future, for example, the development of adaptation strategies, require reliable information so that decision makers can make the most appropriate decision. Thus, the prediction and analysis of environmental problems is of great importance to decision and policy makers.

Within the arena of climate change, environmental processes occur, and so must be understood. These processes occur in four dimensions of time and space, thus, must be considered when making decisions. However, as discussed in Section 3.2.1, both the GIS and dynamic modelling approaches fail to provide enough capability to handle both temporal and spatial variations (Figure 3-24). Hence, combining simulation models with GIS can be considered as a plausible solution to overcoming the shortcomings of each approach. While GIS, as reviewed above, provides spatial modelling power, a dynamic simulation approach introduces strength for temporal analysis. As a result, such an integrated modelling approach would provide the potential to analyse environmental processes in space and time.

Thus, incorporating space into a dynamic modelling framework is a must to extend the capability of dynamic models in order to conduct a spatial analysis of the system and to assess the characteristics and relationships of the system components under study.
Furthermore, the environmental problems will not be the same everywhere. Thus, every society and geographical location might face different sets of environmental problems; additionally, even if the problems are the same, the time of occurrence may be different in each location. Consequently, the spatial and temporal distributions of environmental problems are not even. Therefore, it is extremely difficult, if not sometimes impossible, to develop generic solutions that are applicable to each and every society and location.

It is important to address and analyse an environmental problem by using an integrated dynamic spatial model (DSM); such an approach will provide relevant information for the decision making Process. The information obtained from these analyses will improve the general understanding of environmental problems. **Therefore, interactions of time, space and decision-making should be considered and addressed in the process of environmental modelling.**

The implication for this commendation is that the decision making process must include the human aspects of complex environmental problems, which will include multiple and conflicting goals and objectives. Consequently, the spatio-temporal analysis information should be integrated into the decision making process to achieve realistic solutions that address dynamic complex environmental problems. Additionally, it is apparent that preferences for alternative solutions cannot be gathered for a single decision maker, instead, they need to be built on societal consensus. For this reason, the MCDA methods are appropriate for conducting participatory decision making processes.
CHAPTER 4

“Forewarned is forearmed.”
Miguel de Cervantes

RESEARCH DESIGN AND OBJECTIVES

4.1 MOTIVATION FOR THE RESEARCH

Coastal communities have been adapting to changing climatic conditions throughout history. However, faced with increased threats, due to accelerated sea level rise and changes in tropical storm frequency and intensity, coastal communities must act faster to develop more effective management policies. Developing such policies requires accurate and up-to-date information from which a greater understanding can be gained about the impacts of changing climate on coastal communities, as well as assessing how vulnerable they are.

Overall, vulnerability is a dynamic process; hence, its assessment requires a good knowledge of the current situation, along with a thorough knowledge of the evolution and trends of the problems faced by the vulnerable areas/communities. For this reason, a vulnerability assessment is a continual process that identifies the weaknesses of the current situation; additionally, the process identifies the methods that can be used to support the decision-making process for the selection, exploration and monitoring of the best adaptation strategies and measures.

Nevertheless, identifying and applying correct adaptation options is a difficult process due especially to the uncertainties in future climate change projections. For example, hazardous events can come in many different forms, and may be devastating for a community or location if they are not managed well. However, while devastating events cannot always be predicted or prevented, plans can be made for their
eventuality. Preparing for uncertainty is possible. It merely requires some foresight, some initiative, and flexibility.

A basic dilemma confronting today’s society is how to address climate related problems and uncertainties. Additionally, DMs are expected to develop and implement solutions to short-term problems. However, uncertainties in climate change projections, and the extent of spatial and temporal impacts from climate change prevent DMs from acting promptly and effectively to reduce the vulnerability to these threats. Nevertheless, it is essential that many of the problems be assessed and addressed over a longer period of time. This task is made more difficult as was mentioned previously, environmental systems are complex and circumstances change quickly.

The future is, therefore, uncertain and societies need a high degree of flexibility in order to adapt to the changing conditions. Designing and applying a robust and flexible method to assess present and future vulnerabilities to SLR, and to identify and analyse adaptation options for reducing vulnerabilities, are challenging issues in vulnerability and adaptation research.

The first step in this process involves assessing vulnerability to SLR, which needs to precede the establishment of appropriate adaptation strategies. This process becomes more complex as the word vulnerability has many definitions by scholars from different backgrounds and in a wide range of fields. For conceptual works and terminology of vulnerability, the reader is referred to a number of references (Füssel, 2005, Metzger et al., 2006, Füssel, 2009, Ionescu et al., 2009). Additionally, climate related definitions of vulnerability are also presented in Chapter 2 above. The IPCC definition of vulnerability is quoted below:

“...the degree to which a system is susceptible to, or unable to cope with the adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity”(Parry et al., 2007).

This definition incorporates three main variables: (1) exposure to climatic variations; (2) sensitivity; and (3) adaptive capacity of a system to various stressors. All variable
are interrelated. Thus, vulnerability is a function of the exposure, sensitivity and adaptive capacity of a system. Based on the IPCC definition, many researchers (Rosenzweig and Tubiello, 2006, Yusuf and Francisco, 2009, Dongmei and Bin, 2009, Webersik et al., 2010, Eriyagama et al., 2010) present vulnerability in the form of the following equation:

\[
V = V(t,s) = E \cdot S \cdot AC
\]

Where, \(V\)=Vulnerability, \(E\)=Exposure, \(S\)=Sensitivity, and \(AC\)=Adaptive Capacity.

In Equation 4-1, time is not taken into account. As \(V\), \(E\), \(S\) and \(AC\) do not change with time in Equation 4-1, they are considered constant. Hence, vulnerability assessments, based on the above definition, have assumed that vulnerability is a static process and, so, have been conducted with reference to a target year (i.e. 2100) and sea level rise prediction (i.e. 1m) (The Department of Climate Change, 2009, Wu et al., 2009, Wang et al., 2010). However, the assessments did not account for the element of time. This omission is important as vulnerability is not a static process; it is a dynamic process. Indeed, it should be considered as a dynamic continuum. Further, as the three elements constituting vulnerability interact with, and change in time and space, so does the vulnerability. Thus, as well as spatial characteristics and dimensions, temporal dimensions should be taken into account in vulnerability assessment studies in order to capture changes dynamically. To include the dynamic and spatial aspects of vulnerability, by considering the time and space dependency, vulnerability in the current research is expressed as:

\[
V(t,s) = E(t,s) \cdot S(t,s) \cdot AC(t,s)
\]

Where:

- \(t\): Temporal dimension
- \(s\): Three spatial dimensions (x,y,z)
- \(V(t,s)\): Vulnerability at any given time and location.
The function, $V(t,s)$ represents four dimensions in describing the vulnerability of a particular system, region or group with respect to time and space; it changes as time passes.

Causal relationships among these variables are illustrated by the causal loop diagram (CLD) in Figure 4-1.

The above CLD diagram can be interpreted as follows: The climatic drivers trigger sensitivity and exposure, which cause an increase in impacts; increased impacts cause higher vulnerability. This part of the loop is called the positive feedback. The adaptation is a function of the adaptive capacity and the vulnerability. The higher the adaptation is, the less the vulnerability. However, higher vulnerability will increase the need for adaptation. This part of the loop is called the negative feedback loop. The polarity (+ or -) attached to the head of the arrows indicates positive or negative causality between variables.

Conceptually, any change in the state of a system has to occur over a period of time. While exposure may depend upon geography, both sensitivity and adaptive capacity are closely linked to pre-existing conditions. As shown in Figure 4-2, depending on the changes in the climatic and non-climatic drivers, a system’s vulnerability will increase or decrease over a certain interval of a time (dt). In other words, the greater the exposure or sensitivity, the greater is the vulnerability. However, adaptive capacity is inversely related to vulnerability. So, the greater the adaptive capacity, the lesser is the vulnerability. Therefore, reducing the vulnerability would involve reducing exposure and sensitivity through increasing adaptive capacity.
The ultimate goal of vulnerability assessment is to predict the vulnerability, as well as to provide information and guidance to DMs, thus, enabling them to take concrete action towards adaptation to climate change. The use of an appropriate assessment approach, therefore, would strengthen the DMs’ abilities to take appropriate action with speed and accuracy. Thus, incorporating vulnerability assessments into the decision making required to develop adaptation strategies would constitute the fifth dimension of vulnerability and adaptation analyses.

4.2 RESEARCH OBJECTIVES AND QUESTIONS

As argued above, changes, including climate changes, occur in time and space. Thus, vulnerability assessment studies have to take both temporal and spatial aspects into account and, subsequently, integrate those findings into rational choices that to seek answers the questions, where, when, and what should be done.

Furthermore, to improve DMs’ ability to understand and evaluate environmental management problems, a range of analytical tools are available, including; simulation models, GIS, experts systems, econometric models, and optimisation techniques under the umbrella of decision support. However, although these tools provide invaluable information for decision making, each tool addresses only one aspect of a management problem. Therefore, effective decision making, in a dynamic complex environment, requires the expansion of the mental modelling boundaries and the
development of additional tools to help DMs better understand how complex systems behave. Thus, DMs need to integrate each tools’ analytical results into a rational choice about what to do, where to do it, and when to do it (Schmoldt, 2001). Such an approach, integrating analytical results into a rational choice, will help with realistic decision making processes, particularly under conditions of uncertainty, and where the availability of appropriate information for problem solving is limited.

**Clearly, dealing with environmental problems requires an approach that can take into account human decision making processes, as well as time and space.**

This conclusion gives rise to the idea of employing a dynamic approach, and choosing suitable methods and tools to manage these dynamic environmental management problems, in both time and space. However, since there is no single tool to effectively address all aspects, it is necessary to develop an alternate way to manage the issue.

With this is in mind, three objectives (two primaries and one secondary) were developed to guide the current research. The primary objectives are:

1. Firstly, to develop a dynamic model to assess the present and future vulnerability of coastal populations and properties to sea-level rise and storm surges, based on various SLR scenarios and projections; and
2. Secondly, to identify and evaluate adaptation options for coastal areas in order to cope with altering climatic conditions scenarios using an MCDA model.

The secondary objective is to test the proposed models through their implementation in a coastal area in order to address the following four questions:

1. What is the present vulnerability in the study area in terms of the number of residential properties and the population within the 1/100 year flood level?
2. How vulnerable is the study area to future SLR and associated storm surges (number of residential properties, their value and people at risk)?
3. What are the potential physical (inundation, flood and storm surge damage) and socio-economic (people at risk and properties, loss of properties) impacts of SLR and storm surges on the study area?
4. What are the desirable adaptation options to reduce adverse impacts of future climate change?

The secondary objective represents a proof-of-concept to demonstrate that the proposed model is viable and capable of solving this particular problem.

The framework for the current research study is presented in Figure 4-3.
CHAPTER 5

RESEARCH METHODOLOGY

5.1 INTRODUCTION AND OVERVIEW

Many projects in the field of environmental science are increasingly interdisciplinary, involving many fields, such as geography, mathematics, physics, engineering, system and computer science, and social sciences. Further, a large number of these projects use traditional environmental modelling approaches, more specifically, the reductionist approaches. As the name suggests the reductionist approach breaks down geographic phenomena into their elementary components. Additionally, it is assumed that the characteristics of these components remain unchanged, whether they are examined in isolation or as a whole.

This approach is suitable for some situations where the whole is the sum of many small parts (Benenson and Torrens, 2004). However, in reality it is not possible to fully understand the complex system by examining its individual elements. According to Steven Levy (1992):

*A complex system is one whose component parts interact with sufficient intricacy that they cannot be predicted by standard linear equations; so many variables are at work in the system that its overall behaviour can only be understood as an emergent consequence of the holistic sum of all the myriad behaviours embedded within. Reductionism does not work with complex systems, and it is now clear that a purely reductionist approach cannot be applied when studying life: in living systems, the whole is more than the sum of its parts* (Levy, 1992).

Hence, the general system theory highlights that the whole is not a simple summation of the elementary units; rather, it is governed by dynamic laws. Thus, the whole is more than the sum of its parts’ and the like (Bertalanffy, 1950). That is, the whole is more than the simple aggregation of individual parts. The individual parts are like
building blocks of a machine, interrelated and interdependent and, importantly, their features cannot be explained simply by their individual characteristics. For this reason, to obtain a comprehensive overview, the current study investigates the individual units, as well as the relations and interactions of these units with the whole.

At the outset, it is imperative that the reader realise that environmental problems are neither static nor do they exist in isolation; indeed, they are in a series of continual dynamic interactions, driven by multi-causality. As such, the complexity and interdependencies of their elements define the characteristics of the environmental problems. Consequently, as the environment changes in time and space, so do its problems and the solutions to these problems. As a result, the dynamic characteristics of the environmental problems must be fully considered to enable them to be addressed effectively.

When addressing these problems, it is essential to use an approach that elicits a variety of relevant information. With this in mind, the research has chosen the system concept as the research approach to be applied in the development of a dynamic model that assesses the whole situation and the many interacting components. Further, the research uses modelling to analyse these complex, real world problems in order to evaluate the impact of rising sea level on coastal areas. However, as it is not possible to model all the components or elements and their interactions, a degree of abstraction has been selected to distinguish the components and interrelations; thus, the reality has been reduced to a more manageable size.

Generally speaking, a model is a representation of how a system works, or how it responds to inputs; a model may be used as the basis of a risk assessment, an analysis, or management judgments by decision-makers. In other words, a model can be defined as a simplified representation of the real world used to analyse complex real world problems in order to predict what could happen in various scenarios. When considering a meaningful way of putting System, Model, and Simulation into an appropriate perspective, the following distinctions can be made between the three terms (Bellinger, 2004):

A system exists and operates in time and space.
A **model** is a simplified representation of a system, at some particular point in time or space, intended to promote understanding of the real system.

A **simulation** is the manipulation of a model in such a way that it operates on time or space to compress it; thus enabling one to perceive the interactions that would not otherwise be apparent because of their separation in time or space.

This chapter, therefore, introduces an integrated approach that is used to assess vulnerability and adaptation to sea level rise (SLR); the approach combines many disciplines that assist in better understanding complex coastal systems. Further, the chapter is divided into two main sections: (1) developing a spatial-temporal model for vulnerability assessments; and (2) developing a MCDA model for evaluating adaptation alternatives. The first section describes the method used for the development of the hybrid spatio-temporal model, a combination of the Geographic Information System (GIS) and the System Dynamics (SD) modelling approaches. The hybrid model structure then discussed in detail. The second section provides an insight into a multi criteria decision model assessing adaptation alternatives. Further the goals, criteria and alternatives are identified and described in the hierarchical structure.

### 5.2 GENERAL APPROACH

The world’s coastal areas have been a particular focus when considering adaptation strategies for SLR. Importantly, the specific goal of vulnerability assessment is to produce recommendations on actions to reduce that vulnerability in terms of SLR (Sahin and Mohamed, 2009). The assessment includes both present and future vulnerability appraisals and adaptation alternatives. Identifying such SLR vulnerabilities requires a clear conceptual framework. As discussed in Chapter 2, a range of approaches have been developed as assessment tools, or models, for use in coastal areas. Two general approaches, impact-led and vulnerability-led, have been identified by the literature review (Adger et al., 2004, Dessai and Hulme, 2004, Carter et al., 2007, Richards and Nicholls, 2005). Impact-led approaches begin with climate system scenarios; they then move through biophysical impacts towards socio-economic
assessments; in the main, they focus on the potential long-term impacts of climate change. In contrast, vulnerability-led approaches commence at the local scale by addressing socio-economic responses to the climate; they then focus on adaptation alternatives, with stakeholder involvement.

To address both the short and long-term risks posed by SLR, it seems desirable to merge these two approaches. Thus, the current study seeks to merge both approaches, so as to provide a flexible model that addresses both short and long term vulnerability assessment issues, by focussing on two aspects of vulnerability and adaptation modelling essential to local decision-making, namely:

- the information generated through vulnerability assessments by using a hybrid spatial-temporal model, and
- the link between this information and the decision-making process using an Analytical Hierarchy Process (AHP) model.

The term vulnerability, in this study, refers to people-at-risk and the loss of property due to exposure to SLR and related storm surges. Therefore, the focus is on natural and socio-economic systems that are already vulnerable to climate variability. The current conditions are analysed; next, these systems are analysed further, under various scenarios, so as to identify how SLR will affect the already distressed systems, over time.

The current study uses a range of SLR scenarios and sensitivity analyses to address the uncertainty issues associated with the projections of sea-level rise. The research addresses the systematic assessment of coastal vulnerability to SLR, and the associated storm events. Further, it evaluates the alternatives for an anticipatory response strategy using the following steps, which is also illustrated in Figure 5-1:

1. Begin identification of the problem by understanding historic sea level events.
2. Use a range of SLR scenarios to assess vulnerability, e.g. employ a modular DSM, which consists of a spatial model (GIS) and a temporal model (SD) (rather than limiting the analysis to a single sea level projection).
3. Evaluate potential adaptation strategies by using an MCDA approach, based on information obtained from the previous step.

4. Test the solution using the dynamic simulation model to see if the preferred adaptation strategies are adequate enough to provide an effective solution.

5. Refine the model to eliminate or reduce any weakness in the solution.

![Five dimensional (x, y, z, t, h) spatio-temporal decision modelling framework](image)

Importantly, this approach facilitates the use of creativity and experience to clearly structure the complex problems and pursue their solution within a systematic framework. The modelling steps for each module are explained further in the section 5.4.

### 5.3 UNDERSTANDING AND TREATMENT OF UNCERTAINTIES

There are a range of uncertainty types, often resulting from incomplete scientific understanding of the various processes. Indeed, some uncertainties are caused by the processes themselves, which function in space and time, and so cannot be captured by the models. As a consequence, the uncertainties cannot be reduced. The adequate treatment of uncertainties is a crucial aspect in the development and application of integrated assessment models. Uncertainty about the future stems from three sources (Robinson, 2003):
• The lack of knowledge about system conditions and underlying dynamics

• The prospects for innovation and surprise; and

• The intentional nature of human decision-making.

From a positivist perspective, the first two sources of uncertainty can be overcome and reduced by progressively improving the models and including more variables (Mannermaa, 1991). However, system theorists question the validity of the positivist approach, arguing that it is theoretically impossible to pre-state all possible future outcomes for most real systems. They contend that the behaviour of complex systems, including ecosystems and human systems, is non-linear, chaotic, and sensitively dependent on the initial conditions and contexts, which are not fully known (Kay et al., 1999). Further, these complex systems exhibit unpredictable emergent phenomena as they evolve.

Swart et al., (2009) provide a useful review of how uncertainty has been treated in the assessments of the IPCC, and how this treatment has evolved over time. Firstly, uncertainty, as described in IPCC TAR, occurs as a result of problems with:

• The data, i.e. missing components or errors in the data, random sampling errors, and biases, and

• The models, i.e. the processes are known, but the functional relationships or errors in the structure of the model are unknown; the structure is known, but the values of some important parameters are unknown or are erroneous; the historical data and model structure are known, however, the reasons for believing in the parameters or the model structure will change over time.

• Other sources of data or information, such as the use of inappropriate spatial/temporal units, uncertainty due to projections related to human behaviour, and the ambiguously defined concepts and terminology, etc.

The IPCC AR4 relates to objective types of uncertainty, as well as subjective type of uncertainty, indicative examples of sources, and typical approaches and considerations (IPCC, 2005), as shown in Table 5-1. The human dimensions of uncertainty play the biggest role as a cause of unpredictability (Swart et al., 2009).
The research model recognises the potentially critical influence of such uncertainties. Therefore, it seeks to develop a holistic understanding of a complex reality through the simplification of a number of steps, such as through sensitivity analyses and scenarios. Additionally, for the decision-making process, the sound communication of uncertainties and participation is crucial. Further, participation and consensus building around scenarios can help to deal with uncertainty.

Another important aspect to the analysis is to differentiate between the reducible and the irreducible uncertainties. For irreducible uncertainties, the model has to make explicit assumptions that explore the usage of alternative scenarios. Therefore, it is important that the model is to build so that it avoids the results being determined by the uncertain elements. Where possible, the model should present different scenarios to illustrate the importance of specific uncertainties.

It is also important that the models are neither transparent nor susceptible to deliberate manipulation, a criticism that has been levelled at the Multiple Criteria Decision Aid (MCDA) techniques (Vasant et al., 2005, Pérez et al., 2006, Lee and Chan, 2007).
These two aspects are of particular importance in decisions regarding environmental planning and management issues. For example, stakeholders often have contrasting views on the relevance and weights of decision criteria. These contrasting views are the result of two levels of uncertainty: lateral uncertainty (which refers to a lack of knowledge about the present relationships, and the interactions between the decision criteria), and temporal uncertainty (which refers to difficulties associated with predicting future trends).

In the current study, various approaches have been used to manage these uncertainties in a two phase step.

In the first phase, uncertainties surrounding the model’s vulnerability assessment have been addressed through use of scenarios, sensitivity analysis, and performance tests, using a range of diagnostic processes including: calibrating and validating the model against independent datasets (measured or modelled).

In the climate change context, scenarios are widely used to improve our understanding of the complex interactions of the climate system, the ecosystems, and human activities. These scenarios provide plausible descriptions of how the future might unfold under changing climatic conditions (Moss et al., 2010).

Although uncertainties are an important aspect in the policy debate, a formal treatment of uncertainty is difficult achieve. Hence, the current research considers uncertainty management as an important guiding principle. Consequently, it has adopted a variety of measures in designing the model, such as the use of scenarios and sensitivity analyses to systematically minimize the potential influence of uncertainties in the model output. For example, rather than relying on a single point prediction in relation to future sea levels, a range of SLR scenarios are preferred, within which the model is proven to work, with sufficient accuracy.

In addition, sensitivity analyses are performed to explore the sensitivity of the model results to changes in important model input. The results identify any systematic bias in the model’s calculations, and provide information about whether the model needs to
be revised, in light of this new information. Further, the sensitivity analyses also suggest whether the model structure and assumptions are robust.

In the second phase, to address the temporal and spatial uncertainties surrounding the decision process, the current research incorporates the model output of vulnerability analysis into the MCDA analysis; then a sensitivity analysis is conducted to further minimise the uncertainties.

The scenarios and sensitivity analyses used in this research are discussed in detail in Chapter 6.

5.4 MODEL DEVELOPMENT

As discussed in Chapter 4, the primary objective of the current study is to develop a dynamic model for the assessment of vulnerability and adaptation to SLR. Two underlying challenges for the research are: (1) how to build a robust methodology that provides detailed guidance on the development of the model; and (2) to discern which techniques are more suitable for the eventual development of the model.

When designing a suitable purpose-specific model, it is necessary to select the most suitable assessment and decision making techniques from those that have been critically reviewed. The techniques reviewed in Chapter 3 were assessed and combined so that the current research could be provided with the most effective analysis techniques. To assess coastal vulnerability, and the adaptation alternatives, to rising sea level, the research developed a spatial-temporal decision-modelling framework (Figure 5-1), as presented in Section 5.2. The framework is based on five dimensions of the decision process for environmental dynamics. Space \((x,y,z)\) and time \((t)\) constitute the first four dimensions, and provide a common base where all natural and human processes occur. That is, the modelling approach takes into account natural and human processes in both the temporal and spatial contexts. This approach is crucial in generating adequate information from which decision makers can devise realistic adaptation strategies. For this reason, it is essential to incorporate the first four dimensions into the fifth dimension, the element of human decision making.
The developed framework provides a working strategy for the current study. It also contains and presents a number of general concepts and their interrelations, in addition to the components and the relationships used in the modelling and analyses. According to the framework underpinning general system theory and hierarchy theory (as discussed in Section 5.1), to develop the 5D model, it is necessary to address the whole, as well as the parts, and then apply the system concepts.

In developing the current model, the following generic steps of the modelling process were adopted:

1. Problem definition: It is fundamental to analyse the situation and understand the problem clearly. Identifying and classifying the objectives provides a basis upon which to build a model and solve a problem using mathematical solutions.

2. Model development: The model is formulated, and an abstraction of the system under question is made. Additionally, the required data about the system is collected. As it is impossible to assess every aspect of a complex, real world problem, the model formulation requires some simplification and some assumptions. While some aspects affecting the system are simplified, other, less important elements are excluded from the model. Further, all the variables in the model are identified, and processed. To aid the simplification process some variables are ignored; at the same time, other variables are aggregated or treated as constant variables.

The relationships among the variables are also established, with some assumptions being made for the sake of simplification. Finally, the equations and functions needed to explain the relationships among these variables are determined.

3. Implement the model: Through the implementation of the model the solution for the situation is depicted. If necessary, the model can be reformulated by additional simplification.
4. Verify and optimise the model: After obtaining a solution, the results are examined to determine whether the model works effectively and satisfies the problem objectives. If the model is not robust enough, then it should be refined by returning to the previous modelling steps.

5. Interpret the model results: Once the previous steps are completed, the results are interpreted to provide a conclusion and recommendations, as well as suggestions for future work.

It is extremely important that vulnerability assessment techniques are able to address the spatial and temporal aspects of modelling. Likewise, decision making techniques need to be able to manage the complex multiple criteria decision problem. Additionally, these techniques are used, in conjunction with each other, to meet the current research objective in an efficient and effective way.

After completing the above steps, the researcher developed a spatial-temporal inundation model to assess the impacts of SLR. While the temporal component of the model was used to capture changes over time, the spatial component was used to determine the spatially distributed changes.

Finally, the human decision making model, for evaluating various adaptation strategies, was developed and incorporated into the spatial-temporal components to form the 5D model. Sometimes the cyclic modelling process requires the revisiting of an earlier step, the repetition of the step, and the continuation of the process from that point. The following sections address the use of various approaches to enable the integration of the different dimensions into the 5D model.

5.4.1 CONCEPTUAL FRAMEWORK FOR INUNDATION ANALYSIS

It is unequivocal that SLR will cause an increase in the level of the hazard zones. However, depending on the rate of the SLR, an area that is now subject to a 1 in 100 year flood risk may, in time, and with a high enough SLR, face more frequent flood events, or become permanently inundated. As a result, the boundary of the coastal flood plain will shift inland over time.
Thus, the ability to identify low-lying areas is a crucial factor in any coastal region vulnerability assessment. Further, the degree of risk of flooding from storm surges is determined by a number of morphological and meteorological factors, including coastal slope, wind and wave characteristics (Klein and Nicholls, 1998). Additionally, spatial dependency is a key concept that aids in a better understanding, and a more comprehensive analysis, of spatial events. This assumption reflects Waldo Tobler’s (Tobler, 1970) “first law of geography”, which states that, everything is related to everything else, but near things are more related than distant things (Tobler, 1970). From this premise, then, most of the occurrences, natural or social, maintain a relationship that depends on distance. The relevance of this principle, in the current study, implies that as the proximity (that is, distance) of an area to the coast increases, or decreases, so too does the location’s risk of being exposed to SLR.

In addition to proximity, the elevation of coastal areas is also a critical variable when assessing the vulnerability of the area to inundation. Therefore, these models require the use of elevation and proximity data to identify low-lying areas in coastal regions that would be subject to the spread of flood water. Further, the identification of the impacts of projected SLR, on vulnerable areas and populations, is critical information that assists coastal communities to plan and implement adaptation strategies, and so reduce the effects of natural disasters.

Impacts from extreme SLR, resulting from storm surges of 2 or more metres, already causes widespread coastal flooding. While less extreme SLR, where the physical processes are more complex, will not flood the coastal landscape below a given elevation contour; however, the SLR will modify the landscape, as the sea level rises, with changes in the waves and currents (Gesch et al., 2009). The ability to distinguish and quantify the individual contributions, from inundation and erosion, are made more difficult by the complex and interrelated processes of erosion and sediment redistribution (Pilkey and Cooper, 2004).

Despite this challenge, the need remains to quantify the various effects of sea-level rise, as well as to identify the areas along the coast where inundation will be the dominant coastal change process. One factor is known, the potential extent of
inundation, which is controlled by the slope of the land. Hence, areas with mild gradients will be subject to a greater degree of inundation than areas with step gradients. Therefore, inundation is an important component of coastal change (Leatherman, 2001). Further, coastal inundation and flooding, stemming from SLR and associated extreme events, can be modelled by establishing the interactions between time and space to capture the changes in a coastal system.

Often, within the literature, as well as within the general community, the terms *inundation* and *flooding* are used interchangeably. The current study distinguishes between the two terms using the following IPCC (2007) definitions:

*Flooding* refers to temporary submergence of the land from which either partial or total recovery may occur.

*Inundation* connotes permanent submergence (loss) of land or flooding that is so frequent that no recovery is likely.

The IPCC, (2007) also suggests a threshold to distinguish frequent flooding from inundation. *Threshold* (for inundation) equals a flood frequency of more than once per year (Thresholds = flood frequency of > once per year).

Inundation risk is best expressed as the likelihood of exceeding a given level of tide, surge and flood height, over a particular time horizon. Thus, inundation events vary in frequency and magnitude. Frequency is measured as the average recurrence interval of events, e.g. a 1:100 year flood, or a flood height that is expected to be exceeded, on average, once every 100 years. Magnitude refers to a given level of flood height; additionally, the less frequent the event the larger in size or magnitude it generally is.

Traditionally, coastal risks have been assessed using the assumption that the mean sea level will remain constant. However, this is no longer the case; the sea level is changing (Solomon et al., 2007a). Consequently, the baseline upon which current inundation risks are calculated is also changing, as seen in Figure 5-2. Thus, depending on the rate of SLR, an area that is now subject to a 1 in 100 year flood risk, in the not too distant future, may face more frequent flood events, possibly annually. As a result, the
problem of planning for longer horizons becomes more difficult as the baseline continually changes.

As discussed in Chapter 4, vulnerability changes over time and space. Consequently, to assess the vulnerability of coastal areas, spatial inundation modelling needs to take time into consideration. Accordingly, the extent and impact of the dynamic inundation process, as a function of time, must be modelled to ensure the establishment of a baseline for the assessment of coastal vulnerability and adaptation. The coastal inundation is modelled to analyse this dynamic and complex real-world problem to assist with credible predictions about what might happen with various actions, under a range of scenarios.

The inundation modelling used in this research is not a simple bucket-fill modelling approach wherein sea level is raised by defining the area at and below a specified land elevation to create the inundation zone. Therefore, unlike the model presented here, the bucket-fill approach does not take into account the physical processes occurring in the real world and changing over time. The physical processes such as overland flow, and proximity to and connectivity of the area with neighbouring areas are important for modelling inundation caused by storm events and rising sea level.
According to Gesch et al. (2009), the minimum rate of SLR, to be used for inundation modelling, should not be smaller than the range of statistical uncertainty of the elevation data. For example, a 0.5 m SLR can be reliably modelled with elevation data having a vertical accuracy of ±0.25 m at a 95-percent confidence level. Thus, the reliability of a delineation of a given SLR scenario will be more accurate if the inherent vertical uncertainty of the elevation data is much less than the modelled SLR. (Data accuracy is presented in more detailed in Chapter 6).

A time-driven inundation modelling illustrates the state in a cell on a square grid. At any time step, the state can change if it satisfies certain criteria. The modelled space is portrayed as a three dimensional grid (x, y, z). The transition rules, which describe the relationships between the cells and the criteria (showing how the states of a cell are to change), regulate the behaviour of the system.

The area under consideration is modelled with an \((i \times j)\) grid, as shown in Figure 5-3. Each cell in the grid contains an attribute value representing a characteristic of a corresponding location. For example, in a simulation for inundation, a cell can contain a value of 1 (Sea), 2 (Waterway), 3 (Pond), or 4 (Land) indicating the cell’s state at each time step.

\[
\begin{array}{cccccc}
X_{1,1} & X_{1,2} & \ldots & \ldots & X_{1,m-1} & X_{1,m} \\
X_{2,1} & X_{2,2} & \ldots & \ldots & X_{2,m-1} & X_{2,m} \\
\vdots & \vdots & \ddots & \ddots & \vdots & \vdots \\
X_{n,1} & X_{n,2} & \ldots & \ldots & X_{n,m-1} & X_{n,m} \\
\end{array}
\]

Figure 5-3 The \(i \times j\) grid for a modelled area

To simulate this system, using the attribute values assigned for each cell, the current research employed the following logic: A cell at a location \((X_{ij})\) will be flooded if the following two conditions are satisfied (Figure 5-4).
1. The cell cover type, $CT(X_{i,j}) = L$ (not inundated) and the cover type of at least one of the adjacent cells, $CT(X_{n,m}) = W$ (a sea cell or inundated cell); and
2. The elevation of the cell, $CE(X_{i,j}) \leq$ the adjacent cell, $CE(X_{n,m})$.

![Figure 5-4 Adjacent cells that determine the state of the Cell $(X_{i,j})$](image)

The following equation describes how the model predicts flood water diffusion from one cell to another:

**Equation 5-1**

Where:

- $F$ is, either flooded (1) or not flooded (0),
- $CE$ represents the cell elevation,
- $CT (X_{i,j})$ represents the cover type, either inundated $L$ or not inundated $W$
- $CT (X_{n,m})$ represents the adjacent cells cover types, either $L$ land (or other cover types other than sea) or $W$ sea (or became sea due to inundation)
- $(n,m)$ refers to all adjacent cells to $i,j$ (i.e.: $i,j-1, i,j+1, i+1,j$ and $i-1,j$).

Importantly, the direction of the flooding, between the adjacent grid-cells, depends on the difference in elevation between them. Further, as the sea level rise is simulated, the flood water spreads from one cell to another, with the total number of inundated cells increasing accordingly. Subsequently, for each incremental sea level rise, the total inundated surface area is computed by summing the number of inundated cells.

**5.4.2 DYNAMIC SPATIAL MODELLING**
As with all reality, sea level rise is dynamic; therefore, the space-time integration is useful only in so far as it can be help us understand and predict reality. Indeed, the accumulative nature of sensing and knowing our world arises through spatio-temporal experiences and interpretations (Yuan, 2008). However, dynamic systems, as mentioned earlier, often require an interdisciplinary approach to aid understanding. Different disciplines provide models that can be adapted to suit another research field.

A variety of models and techniques are available that can assist with complex and dynamic process of problem solving as discussed in Chapter 3. The first part of the process involves understanding what is likely to happen (vulnerability assessment); the second part relates to how to choose and implement the best solution options to address the situation (evaluation of adaptation alternatives).

Effective decision making, especially in an environment of growing dynamic complexity, requires the development of tools to facilitate an understanding of how the structure of complex systems interact. A System Dynamics approach allows us to model, describe, and understand the behaviour of complex systems; thus, improving the capacity of an individual or an organization to identify and manage the information related to these systems.

Grossmann and Eberhardt (1992) outlined the advantages and disadvantages of dynamic models. Comparing three dynamic modelling techniques (complex aggregated dynamic feedback models; simple generic dynamic models; and models of physics based on partial differential equations), they argued that the coupling between the dynamics and spatial details is a translation process that exists in reality.
5.4.2.1 THE NEED FOR COUPLING GIS AND SD

To model and simulate changes in coastal zones, it is necessary to take into account the spatial and temporal dimensions of rising sea-level, as any single approach is deficient in one feature or other. Therefore, an integrated approach is the most appropriate way of dealing with various complex problems. GIS and SD originated in, and still represent, substantially different domains of expertise, as discussed in Chapter 3. Combining the SD and GIS approaches provide the power to meet these requirements as emphasised by several authors (Grossmann and Eberhardt, 1992, Ruth and Pieper, 1994, Ahmad and Simonovic, 2004, Gahrib, 2008).

The GIS approach, as discussed in the section 3.3.2, has a powerful database management structure; hence, it is able to provide user-friendly interfaces, interactive and intuitive methods, as well as support for multiple concurrent data accesses and inquiries. However, GIS is designed for spatial components only. On the other hand, the dynamic modelling approaches have strong temporal components, hundreds of thousands of ready-to-use embedded codes, and complex data structures to expedite the modelling of environmental dynamics. However they do not provide spatial components as detailed the section 3.3.1.

As a consequence, there is a need for models that can merge the two approaches, and so provide a technique that can enable coastal process in time and space to be understood. Further, the need for such coupling is driven by the need to effectively address environmental issues. Such models have the ability to represent changes in coastal systems over time, while also tracking the spatial distribution of those changes. It would appear that the end result would be a greater understanding of the dynamics of environmental processes.

Modelling coastal processes would provide a critical tool for obtaining quantitative information for managing and planning coastal areas. Parks, (1993) argues that research to increase knowledge can inform the act of making choices, with hopes of producing good decisions. But according to him, the co-adaption of GIS and the dynamic (environmental) modelling to support practical decision processes can
simultaneously, without self-contradiction, and with little extra effort, be made to support research needs as well (Parks, 1993).

While GIS modelling is the key to spatial data management, it lacks problem domain modelling capacity. Thus, additional processing or analytical capabilities are needed to extend the functionality for decision making (Pelizaro and McDonald, 2006). On the other hand, the spatial details of dynamic models, based on difference equations, are defined as state variables. Grossman and Eberhard (1992) affirm that large nonlinear systems of difference equations are theoretically capable of exhibiting whatever dynamics are desired. However, there is general agreement that small models are useful for prediction, and can be validated; in contrast, large models are seen as useless for prediction; additionally, they not even good in supporting our understanding of the system which was modelled. Therefore, an attempt to include spatial details into a model would only be appropriate if the model environment also provides all the capabilities of a GIS.

Although many dynamic models deal with spatial information, generally these are either structurally simple models (such as transport models of physics), or they use structurally simple spatial data (such as grids). Therefore, as Grossman and Eberhardt (1992) contend, models that are suitable to predict the future development of complex systems, in particular, feedback models, are not adequate to process numerous spatial details. As a result, dynamic models have difficulty in predicting spatial changes over time, because: (1) multi-loop feedback models are inadequate to handle voluminous spatial data; and, (2) the availability of spatial data is uneven; in some areas much good data is available, while in others little data exists.

To address this problem, a number of researchers have proposed the use of a versatile approach, which considers many aspects of the problem by combining GIS with dynamic models. In this approach, the GIS and dynamic model assesses different aspect of the complex problem. While GIS handles spatial data, dynamic modelling processes the dynamics of the complex system, revealing its causal structure and the relations of the system components. The use of these two methods is appropriate for to tackling different environmental problems (both spatial and temporal). This
versatile method, firstly, allows the processing of details separately; and, secondly, then, combines the results of the different methods. Therefore, the coupling of these two approaches provides immeasurable potential to solve problems. It would appear that success in creating a hybrid approach provides an enormous benefit, especially if the results are made available to users working in a wide range of domains.

Three primary reasons, according to Parks, (1993), for combining these approaches are:

1. Spatial representation is critical to environmental problem solving, but GIS currently lacks the predictive and related analytical capabilities to examine complex problems.
2. Modelling tools typically are sufficiently flexible GIS-like spatial analytic components. They, however, are often inaccessible to potential users who are less expert than their makers.
3. Modelling and GIS technology can both be made more robust by their linkage and co-evolution.

System Dynamics simulation modelling is becoming increasingly popular in addressing complex natural processes, such as flood policy analyses (Deegan, 2006), and evaluating adaptation options for responding to coastal flooding. Further, GIS and SD approaches have their own strengths, but also their own weaknesses. For example, GIS's spatial features are not made for analysing systems which show changes over time, thus they require repetitive computation; on the other hand, System Dynamics is not made for managing spatial relationships. Hence, there is a gap between the two approaches. As a result, our understanding of the complex system falling inside this gap is limited. Therefore, the coupling of GIS and SD would overcome this limitation.

Given the strength of SD in representing the temporal processes, especially with restricted spatial modelling capabilities, and the competency of GIS for spatial modelling, with limited representation of temporal aspects, the association of SD and GIS produces a synergy effect. Additionally, using GIS as a pre-processing tool of the SD model will significantly reduce the data preparation and processing workloads, enhance the spatial data display capabilities, and reveal hidden space relationships.
Meanwhile, the SD model can extend the spatial analysis functions of GIS, realize the dynamic simulation, and trend the prediction of system behaviour. By the integration of GIS and SD, the feedback based dynamic processes can be modelled in time and space (Ahmad and Simonovic, 2004, Zhang, 2008).

In summary, it is easy to envisage the synergy achieved by combining the spatial dimension through GIS and the temporal dimension through SD. The synthesis provides extra dimensional modelling power, as well as enhanced abilities. To effectively address pressing environmental problems, GIS and SD need to be integrated into a flexible and intelligent process that expands their versatility and ease of use.

5.4.2.2 COMBINING SD AND GIS: SPATIAL-TEMPORAL ASSESSMENT TOOL

There exist a range of strategies for coupling dynamic models and complex analytical tools with GIS. These strategies span a range from low to high integration: isolated with data exchange, loose coupling, tight coupling, and full integration. The three common approaches for coupling GIS and dynamic simulation models are (Maguire et al., 2005, Gimblett, 2002):

1. Loose coupling: employs common file structures, file translators and more recently, Web services messaging.
2. Moderate integration: uses techniques such as remote procedure calls and shared database access.
3. Tight integration: achieved by, for example, object-component calls, or function calls.

Loose coupling employs common file structures. The GIS is used to retrieve and preprocess the spatial data into the form required by the SD model structure. The data are written to files that are then used as input to the model. The model computes the results and returns them as files of data that are then displayed in the GIS. The easiest approach is to couple GIS with a dynamic model by exchanging files (Goodchild, 2005). Moderate level coupling is characterised by an automated and transparent procedure
for exchanging data, mainly through the use of a common database, and allowing the model to address this database directly.

In a tight coupling (full integration) approach, the model is developed using the analytical engine of the GIS (API, scripting tools, map algebra), or a GIS model is added to a complex modelling system to display the results and provide interactive control. The model has its own data structures with the automatic exchange of data, between the model and the GIS, being hidden from the user. That is, data is exported from the GIS to the model with the results being returned for display. This approach requires considerable investment in programming and data management.

Each approach has its own weaknesses and strengths. A number of advantages and disadvantages for each coupling approach are summarised by Maguire et al., (2005) as shown below (Table 5-2 ). Needless to say, there are trade-offs that are unique to each of the coupling strategies, since each approach has its advantages and disadvantages.

<table>
<thead>
<tr>
<th></th>
<th>Loose</th>
<th>Moderate</th>
<th>Tight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to integrate</td>
<td>Fast</td>
<td>Medium</td>
<td>Slow</td>
</tr>
<tr>
<td>Programmer expertise</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Execution speed</td>
<td>Slow</td>
<td>Medium</td>
<td>Fast</td>
</tr>
<tr>
<td>Simultaneous execution capability</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Debugging</td>
<td>Easy</td>
<td>Moderate</td>
<td>Hard</td>
</tr>
</tbody>
</table>

Table 5-2 Approaches for coupling GIS and SD

Modelling is a creative activity to provide a new and better formulation of the workings of a part of the complex real world. To build a good model, a proper balance is required between the model’s complexity and accuracy. That is, a model should not be more complex than necessary, and should not attempt predictions for situations that are more accurate than can be measured (Bennett, 1991).

However, it is difficult to determine the optimum level of complexity for an acceptable level of accuracy, especially as the complexity and accuracy are dictated by the amount of available data for the model building, the number of subsystems, and the state variables, as well as the mathematical equations of the processes in the model. Given these difficulties, model complexity involves a trade-off between the simplicity and the
accuracy of the model. Therefore, pragmatic choices have to be made regarding the appropriate level of model complexity and the consequences of those choices (Grayson and Bloschl, 2001). Figure 5-5 illustrates the relationship between the model complexity, the availability of data for model testing, and the predictive performance of the model. The term “data availability” means the amount, quality and “information content” of the data available for model testing. The term “model complexity” defines the detail of the process representation. According to them, complex models simulate more physical processes and so are likely to have more parameters. “Predictive performance” describes how much confidence we can have in the model outputs when used to predict future events.

![Figure 5-5 Relationship between model complexity, data availability and predictive performance (Grayson and Bloschl, 2001)](image)

A more complex model is able to account more accurately for the complexity of the real system; however, this is not often true. Grayson and Bloschl (2001) argue that, ultimately, the answer to “what model complexity is warranted” depends on the objectives of the modelling exercise, and the knowledge of the system being modelled. As increasing numbers of parameters are added to the model there will be an increase in uncertainty (Bendoricchio and Jorgensen, 2001). Notably, more complexity should not be added to the model, if there is no possibility to test whether the addition improves the model or makes it worse. Therefore, it is more efficient to start with a
simple model and, thus, gain initial insights quickly, making it easier to determine how much additional complexity is warranted.

Essentially, the simpler models can offer several advantages. For example, without going into too much detail they can still be robust enough to provide adequate information, easier data availability, and be quick and inexpensive to execute simulation. On the other hand, there is always a risk of oversimplification, and a loss of fine spatial and temporal detail. In general, however, simpler models will enable the user to analyse the system to detect where, and if, problems will occur. Based on the first analysis, users can construct and run more complex models as needed.

Four principles should guide model development (Hillel, 1986)

- Parsimony: It should not be any more complex than necessary and its parameters should be derived from data;
- Modesty: It should not pretend to do too much;
- Accuracy: It should not attempt predictions for situations that are more accurate than can be measured; and
- Testability: The results should be open to objective testing and the limits of its validity.

5.4.2.3 PREVIOUS WORKS

Over the last two decades, a discourse has revolved around the various perspective related to the concept of coupling spatial and system dynamics, with different levels of integration, within a variety of fields. Some examples are listed in chronological order in Table 5-3, below.

Singhasaneh et al. (1991) defined the gap between the GIS and the SD software as one that limits the study and in-depth understanding of any system falling within this gap. To fill this gap, they developed a system to demonstrate the integration of SD with GiS. Three SD models were used to test the performance of the system, and to demonstrate the importance of the integration through the development of a complete system for the prediction of the land use changes.
### Previous works coupling GIS and SD approaches

<table>
<thead>
<tr>
<th>Authors</th>
<th>Research Field</th>
<th>Type of Coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singhasaneh et al., 1991</td>
<td>Tourism, economy, and agriculture policies</td>
<td>Conceptual level</td>
</tr>
<tr>
<td>Grossmann and Eberhardt, 1992</td>
<td>Landscape changes in coastal areas</td>
<td>Loose coupling, using MS Excel for data management</td>
</tr>
<tr>
<td>Ruth and Pieper, 1994</td>
<td>SimArc software enabling to interface SD and GIS</td>
<td>Tight coupling using both DDE and DLL approaches for data exchange</td>
</tr>
<tr>
<td>Mazzoleni et al., 2003</td>
<td>Spatial Modelling Environment (SME) for ecosystems, watersheds, populations, and landscapes modelling</td>
<td>Tight coupling using modular modelling language (MML) based integration developed by the authors</td>
</tr>
<tr>
<td>Maxwell and Costanza, 1997, Costanza and Voinov, 2004</td>
<td>Simulation of Emerald Ash Borer spreads based on tree information and land use data</td>
<td>SME based application</td>
</tr>
<tr>
<td>Ahmad and Simonovic, 2004</td>
<td>Water resource systems</td>
<td>Tight coupling, Dynamic Data Exchange (DDE)</td>
</tr>
<tr>
<td>BenDor et al., 2006</td>
<td>Irrigation system</td>
<td>Tight coupling vector based GIS with SD</td>
</tr>
<tr>
<td>Gharib, 2008</td>
<td>One dimension simulation model for water quality simulation in water pollution accident</td>
<td>Tight coupling using DDE through MS Excel and universal development environment for integration</td>
</tr>
<tr>
<td>Zhang, 2008</td>
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</tr>
</tbody>
</table>

Table 5-3 Previous works coupling GIS and SD approaches

A number of dynamic modelling techniques were reviewed by Grossmann and Eberhardt (1993). For example, the integration of the dynamic models, and the GIS, was applied in the context of “tourism and its interactions with the regional economy and the new agricultural strategies”. The integration was on a conceptual level, while the dynamic model was used to describe the mechanism of attractiveness, and the resulting deterioration of an area. The GIS used several base maps to portray the areas where the infrastructure was likely to be built and the tourists likely to reside.

A study by Ruth and Pieper (1994) coupled SD and GIS to simulate changes in the physical landscape of coastal zones by building a base model, which defined the coastal area. The model was developed by loosely coupling Stella simulation software with GRASS, a raster based GIS software. For the data exchange, MS Excel was employed. The model took into account the effects of erosion on the land surface, resulting from sea-level rise over time. However, the vertical and horizontal accuracy of the spatial data was too coarse to reflect realistic changes.
Further, Thomas Maxwell and Robert Costanza (1997) assessed the conceptual and computational complexity barriers to spatio-temporal model development. They developed a spatial modelling environment (SME), which linked dynamic modelling to GIS, using SD software, STELLA, to model a single patch. Next, they exported the equations to produce a program that was coupled to the GIS (Muetzelfeldt, 2007). The SME was built upon common modelling software to create, run, analyse, and present spatial models of ecosystems, watersheds, populations, and landscapes. The main purpose of the SME was to translate a set of difference equations to describe an ecosystem model, generated by STELLA into parallel-C++ (Costanza and Maxwell, 1991, Straaten et al., 1994, Maxwell and Costanza, 1995, Maxwell and Costanza, 1997).

Mazzoleni et al. (2003) developed the SimARC software to interface models created by Simile simulation environments with ArcView GIS environments. Simile is a visual modelling environment that combines the familiar System Dynamics paradigm with an object-based paradigm (Muetzelfeldt and Massheder, 2003). SimARC enables users to link a model to input data from the GIS database, creating new GIS layers from any selected output variable of the Simile model. The SD model and GIS can be linked through data file sharing, Dynamic Data Exchange (DDE), compiled model library (DLL), or COM Automation. However, the custom software tool was developed to specifically link Simile and ArcView with limited computational capability.

Importantly, the SD and GIS approaches were tightly coupled to capture the space-time interaction in overland flood modelling; the model was named SSD, for Spatial System Dynamics (Ahmad and Simonovic, 2004). The SSD approach, which offers single modelling frameworks for developing conceptually different models, runs both programs separately. However, it also incorporates a two-way dynamic data and information exchange between the SD and the GIS. Due to a dynamic data exchange (DDE) requirement for their frameworks, they employed a tight coupling approach, since the DDE is not possible with loose coupling. In their approach, SD modelling was utilised as the main model development environment because of its ability to build models using graphical icons, whereas tight embedded coupling does not provide this modelling ability. A limitation of the SSD is its restricted portability; it can only be used with the GIS package for which the application is developed.
An integrated SD approach with vector based GIS, using a tight coupling method, was developed by Gharib (2008). The Object Oriented Paradigm (OOP) was employed as a common platform for the integration process. Microsoft Visual Basic was used to tightly couple the SD model components with their counterparts in the GIS model. The emphasis of Gahrib's work was on the analysis of the irrigation system within the context of policy design and strategy development for water scarcity problems in the Nile delta. However, the approach has the common disadvantages of any embedded tight coupling approach, such as, a lack of specialist insight (which may yield invalid model concepts and formulations); inflexibility (meaning that the user is fully responsible for the model formulation), a long integration time period, and the need for a high degree expertise.

In that same year, Zhang (2008) created a one dimensional river quality SD model for applying to water quality simulations; a conceptual GIS-SD framework was also constructed. Based on the GIS component and the SD model, an experimental system of water quality simulation was developed for water pollution accidents. MS Excel was used for the data association, and the universal development environments used the DLL model to integrate the SD and GIS. The model, developed in Windows system environment, was based on GIS, a SD embedded software development kit, and API technology. The main drawback of this approach was that it only takes one dimension into account in analysing spatial changes. Additionally, the embedded tight coupling restricts the modellers’ ability to modify and tweak the models when needed.

The above applications, which link GIS to some form of environmental modelling, highlight the importance of coupling the dynamic modelling approach with the GIS. The capabilities of the GIS to analyse relational and spatial data makes this type of technology ideal for coupling with environmental simulation models. The GIS, then, is used as a visual spatial analytical tool, as well as to develop input parameters for the simulation model. Such linkage greatly reduces the time needed to develop input data for simulation models, while, at the same time, simplifies the input process.
5.4.3 HYBRID SD-GIS MODEL ARCHITECTURE

Spatial and temporal dimensions are indivisible components of environmental problems. These complex processes and relationships involve many interacting elements with multiple attributes, and a dynamic behaviour. These characteristics go well beyond the analytical capabilities of most commercial GIS software and so require an alternative approach of GIS (Fedra, 2006), particularly one that links and integrates GIS with the specialised tools for complex and dynamic analysis. The outcome would be a clear solution for the spatial information system requirements, namely:

- Dynamics including real-time aspects
- Complex behaviour (simulation) and multiple attributes, stochastic variables
- Decision support orientation, optimisation.

A range of strategies exist for coupling dynamic models with GIS, ranging from low to tight integration (as discussed, along with their drawback, in the previous sections). Although loose coupling is the simplest approach when using separate GIS and SD and exchanging files, the approach has a number of advantages, such as (Fedra, 2006):

- it is straightforward,
- data structures do not have to be matched,
- data can be transformed to each other’s formats through a converter,
- it is fast and portable; the SD model can be used with different GISs.
- Users are able to make on-the-fly changes more rapidly.
- Ease of use, both in GIS and SD can be modified and run without any complication, and
- It is easy and cheap to develop.

As the current research objective is to build a flexible model, the loose coupling approach will be adopted as the most appropriate method to link SD and GIS. The fast integration time, easy debugging facility, and the low programming expertise requirements are expected to provide a flexible model at the cost of execution speed. These are important trade-offs to consider when determining the coupling approach.
Importantly, the coupling of SD and GIS provides a hybrid model which can address temporal and spatial aspects of dynamic processes. The approach requires at least five steps:

1. Spatially distributed data input through GIS;
2. Export of GIS data and conversion into the variables and parameters used in the SD;
3. Running the SD simulation model;
4. Importing the results of the SD model into GIS as GIS input; and
5. Analysis of the model results and creating final maps (GIS) and graphs (SD).

The main emphasis of the current study is the introduction of a method that provides a fast and an efficient predictive capability in assessing the impacts of SLR and associated storm events. Thus, the proposed hybrid model consists of three components: GIS model, SD model, and the data monitor and convertor, as shown in Figure 5-6.

![Figure 5-6 Hybrid GIS-SD architecture](image-url)
Further, the hybrid model is concerned with modelling behaviour over space, as well as in time. The advantages of both the spatial and temporal modelling approaches are combined in the hybrid model, while their shortcomings are eliminated. As a result, the new model dynamically captures the changes in time and space by obtaining and processing the temporal data from the SD and the spatial data from the GIS through dynamic data exchange.

To build an effective model, a proper balance needs to be achieved between the model’s complexity and accuracy. Hence, the model should not be more complex than is necessary, nor more accurate than can be measured. Therefore, in approaching the problem, the level of abstraction in the model should be determined. Abstraction is defined as the process of identifying the first important aspects or properties of the phenomenon being modelled. Using a more abstract level, one can concentrate on the relevant aspects, or properties, of the phenomenon, and ignore the irrelevant ones. The level of abstraction determines the number of subsystems and state variables, and the mathematical equations of the processes in the model that are necessary for a certain complex analysis (Jennings, 1999, Abbott, 2006, Fisher et al., 2010).

In undertaking this process, some degree of simplification has to be made to reduce the reality to manageable proportions, since the real world is too rich for all components and relationships to be considered. The stock (level) and flow (rate) diagram of the SD component expresses ideas about the variables assumed to be important in a coastal system, and their interactions (Figure 5-7). The diagram provides an abstraction of the pure picture of a system. The condition of the system is described by the state variables, which are the measures of the system’s components, whose values vary with time. In the model below, the system comprises three state variables; **Cell Cover, Elevation and Sea Level**. The Sea Level is an exogenous or driving variable, causing changes in both the Elevation and Cover variables, over time. Additionally, a change in one state variable effects a change in the others, if they are connected. Thus, the modelled system acts as a single unit through the interrelations among its components.
However, in environmental systems (as discussed above), modelling the behaviour of the process in space is just as important as modelling it in time. That is, conceptually, any change in the state of a system has to occur over some time. The model, shown in Figure 5-7, is a non-spatial model that includes a spatial component. The modification can be done by linking the GIS to the SD model through a data exchange (Figure 5-8). As a result, temporal and spatial changes in the system can be captured.

The spatial and temporal data are processed and exchanged between the GIS and SD through dynamic data exchange. The model calculates the potential inundated areas, based on elevation, the states of adjacent cells states (inundated or not inundated), and their proximity to the inundated cells. Thus, the initial elevation value and the cover type of each cell are determined in GIS and transferred to the SD module. Then, in the SD, the elevation and cover type value of each cell is recalculated, depending on the sea level in the next time step.

Figure 5-7 SD Model for Inundation
The second aspect of the coupling of GIS and SD is the selection of the data model. Two basic spatial data model types, raster and vector, are commonly used in spatial modelling. The vector data models represent the geographic entities as geometric shapes (feature classes), such as points, lines, and polygons; the raster data models represent the geographic features by dividing the world into discrete square or rectangular cells, laid out in a grid.
The use of the raster data structure allows for sophisticated mathematical modelling processes, while the vector based systems are often constrained by the capabilities and language of relational database management systems (DBMS). This difference is the major distinguishing factor between vector and raster based GIS software. For this reason, the selection of a vector or a raster data model is dependent on the source and type of the data, as well as on the intended use of the data. Certain analytical procedures require raster data, while others are better suited to vector data. For example, the raster data model is more ideally suited for continuous data, e.g. elevation, while the vector data model does not handle this very well (Gopi et al., 2007).

However, as Lo and Yeung (2007) report, the raster data model has been the most widely used for the following practical reasons:

1. It is compatible with different types of hardware devices for data capture and output;
2. It is compatible with concepts and methods of bit-mapped images in computer graphics; and
3. It is compatible with grid-oriented coordinate systems.

Furthermore, in the raster data model spatial relationships are implicit. Therefore, explicitly storing spatial relationships is unnecessary; in the vector data model it is essential. Also, since grid-cells can be handled as two-dimensional arrays in computer encoding many analytical operations are easy to program. For the above reasons, and to be consistent with the inundation model discussed in Section 5.4.1, which is based on a grid-based model, the raster data model is incorporated into the hybrid model composition used in the current study.

As already discussed in Section 3.3.1, System Dynamics is considered a hybrid methodology; it is compatible with the both continuous and discrete concept of time. Consequently, any of the four permutations of continuous and discrete time and state-space formats may be used. This “hybrid” potential makes SD a superior technique for temporal modelling when compared with other simulation techniques.
Therefore, for modelling the temporal process, the SD technique is included in the hybrid model architecture.

The data monitor and convertor, the third component of the hybrid model, is a special program developed using C++, for data conversion and exchange between SD and GIS. Each component of the model is described in more detail in the following three sections.

5.4.3.1 TEMPORAL MODEL COMPONENT

5.4.3.1.1 APPROACH

The temporal modelling segment consists of the building, integration and running of two types of models: an inundation model due to SLR and storm surge and a vulnerability model.

The power of the SD approach stems from its simplicity and flexibility. According to Forrester (1971), it may be enough to make use of only a few variables to capture the dynamics of a large system, as he demonstrated skilfully with only a few state variables to build his enormous model, *World Dynamics*. The model mapped the important interrelationships between the world population, industrial production, pollution, resources, and food (Forrester, 1971).

Before discussing the model in detail, its overall structure is presented, along with a definition of the basics of SD convention, boundary, time bounds, and the main variables used in the temporal model. Firstly, the model adopts a System Dynamics approach using differential equations, simulated numerically (Sterman, 2000). Figure 5-9 illustrates the overall model structure and its sub-models. These sub-models of the temporal components interact with each other through feedback links. Each sub-model is described individually in the following three sections. Secondly, there are two sets of variables (exogenous and endogenous) that drive the model behaviour. The basic exogenous and endogenous variables used in the current research are summarised in Table 5-4.
The Sea level and Population variables, contained within the red boxes in Figure 5-10, are the two exogenous drivers used in the temporal model component. They are important independent drivers affecting inundation, vulnerability, and storm events models.

The Sea level is the main driver causing an increase in storm surge frequency and inundation and, therefore, puts people and properties at risk. For this reason, population growth rate is likely to be adversely affected by frequent flooding and inundation. A comprehensive population growth analysis, while desirable, is beyond the scope of the current project; however, a range of population growth projections is included in the model.

In modelling the temporal component, the SD stock-flow diagram conventions are used to exhibit system structure (Figure 5-10). Stocks (X) are the system state variables, illustrated by boxes. The dynamics of a system is defined by its state variables (Stocks); the flow in a system represents the rates of change, and is signified
by the pipes (dX). The stocks integrate flows. The auxiliary variables (Y) are used to break the flow equations into manageable segments, with a clear meaning (Fiddaman, 1997).

![Figure 5-10 Stock and Flow diagramming convention (Adapted from Fiddaman, 1997)](image)

The following equations show the basic mathematical form of the SD modelling language.

**Equation 5-2**

**Equation 5-3**

**Equation 5-4**

In these equations g and f are arbitrary, nonlinear, potentially time varying, vector-valued functions. Equation 5-2 represents the change of the stock over time, Equation 5-3 the computation of the rates determining that change, Equation 5-4 the intermediate results necessary to compute the rates.

Time boundaries for the model are listed briefly below:

A hundred year time horizon is considered as from the present (2011) through to 2110; this scale is consistent with most SLR scenarios developed by the IPCC (Meehl et al., 2007).

Initial time is the time at which simulation begins: \( t_0 = 2010 \)

Final time is the time at which simulation ends: \( t_{100} = 2110 \)
Time Step is the time interval for the simulation: \( dt = 1/32 \)

Units for time are the unit of measure of time: Year

Regardless of the integration technique used, Time Step remains important in determining when to compute exogenous values, and when to compare the model to the data. Furthermore, the error made in using the Euler integration is proportional to the square of the Time Step in an integration step, and proportional to the Time Step over the whole simulation. To make the integration more accurate and to prevent serious integration errors, the Time Step is deliberately minimal.

When building the temporal model, the Vensim DSS (Decision Support System) software was chosen. It is flexible when representing continuous or discrete time, a graphical interface, or performing causal tracing, optimization, and sensitivity analysis (Ventana Systems, 2009). Further, the software provides users with a highly developed model, including the construction of an interface that allows other users easy access to the developed model.
5.4.3.1.2 INUNDATION MODEL

A temporal simulation model also captures the fundamental dynamic processes of inundation. The development of an inundation model is based on the conceptual framework discussed in Section 5.4.1. Its purpose is to examine the timing and extent of inundation from rising sea level, over time. Currently, our understanding and prediction of the timing and magnitude of this process is limited, specifically due to the uncertainties in sea level rise projections. Thus, as discussed in Section 5.3, a range of SLR scenarios and a sensitivity analysis are used to address the uncertainty issues.

Sea level rise scenarios, ranging from 0.5 m to 1.5 m, are used in the current study; these levels are the IPCC’s lower and upper range projections (including the 10-20 cm icesheet contribution) and Rahmstorf’s (2007) estimation, together with additional local adjustment (Figure 5-11). Further, the model contains a range of variables, three of which are state variables: Sea Level, Elevation, and Cell Cover (which were discussed above). Sea Level is an exogenous variable; it refers to the level of the surface of the sea with respect to the adjacent land. Sea Level changes include both global sea-level rise and local subsidence, based on a range of sea level rise projections Table 5-5.

Figure 5-11 A range of SLR scenarios used in the model
<table>
<thead>
<tr>
<th>Variables</th>
<th>Type</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Sea Level</td>
<td>Constant – exogenous variable</td>
<td>The sea level when simulation begins</td>
</tr>
<tr>
<td>Sea Level</td>
<td>Stock – State variable</td>
<td>Exogenous variable</td>
</tr>
<tr>
<td>Initial Elevation</td>
<td>Constant – exogenous variable</td>
<td>Exogenous variable describing cell’s initial elevation</td>
</tr>
<tr>
<td>Elevation</td>
<td>Stock – State variable</td>
<td>Defining changes in cell elevation if cell cover type is Sea or Water, or when it changes to Water or Sea</td>
</tr>
<tr>
<td>Initial Cover</td>
<td>Constant – exogenous variable</td>
<td>The cell’s cover type when simulation begins</td>
</tr>
<tr>
<td>Cell Cover</td>
<td>Stock – State variable</td>
<td>Defining Cell Cover types, which change over time</td>
</tr>
<tr>
<td>Rise</td>
<td>Flow</td>
<td>Defines the rate of change in Sea Level</td>
</tr>
<tr>
<td>Increase</td>
<td>Flow</td>
<td>Defines the rate of increase in Elevation</td>
</tr>
<tr>
<td>Decrease</td>
<td>Flow</td>
<td>Defines the rate of decrease in Elevation</td>
</tr>
<tr>
<td>Change</td>
<td>Flow</td>
<td>Defines the change in Cell Cover at each time step</td>
</tr>
<tr>
<td>Change Previous</td>
<td>Flow</td>
<td>If there is any change in Cell Cover at each time step, this variable removes the previous cover type value from the stock</td>
</tr>
<tr>
<td>Time Step</td>
<td>Simulation control parameter</td>
<td>Defines the time interval for the simulation</td>
</tr>
<tr>
<td>Adjacent Cells’ Elevation</td>
<td>Constant</td>
<td>Defines elevation of four adjacent cells of each cell at each time step</td>
</tr>
<tr>
<td>Adjacent Cells’ Cover</td>
<td>Constant</td>
<td>Defines cover type of four adjacent cells of each cell at each time step</td>
</tr>
</tbody>
</table>

Table 5.5 Main variables used in the temporal model

The current model assumes a linear increase in the sea level over time. The SLR, at a given time, is calculated by:
Where:

\[ SL_t \text{ is the linear Sea Level at time } t \]

\[ dR \text{ is the rate of rise at each time step } dt \]

\[ SL_0 \text{ is the initial Sea Level at beginning of simulation.} \]

Figure 5-12 shows the model structure using the variables listed in Table 5-5. The SLR scenarios, which drive other model components, can be altered to test the impact of varying rates of sea level rise on the other model elements.

As noted above, for modelling purposes, the study area is subdivided into a cellular grid to simulate how flood water spreads between adjacent cells, based on the conceptual framework for inundation. This grid is then superimposed over the coastal area.

For coastal areas that are vulnerable to inundation by sea level rise, along with SLR rate, *Elevation* and *Cell Cover* are the most critical factors in assessing the potential impacts. For this reason, the model shows the temporal changes in the *Cell Cover* and...
cell *Elevation*. Each cell represents a specific area corresponding to one of four cover types: *Sea, Waterways, Pond, or Land*. At each simulation step, the state of each cell is determined by the condition of its neighbours to the north, east, south, and west (Figure 5-13).

Thus, the model uses five parameters (the cell itself and its four neighbours in four cardinal directions) to simulate the inundation from SLR. For simplicity, each cell is assumed to have four neighbours, and the state of a diagonal cell (to the northeast, southeast, northwest, or south west) does not have an impact on the cell’s value at the next time step. These four neighbours, along with the cell itself, are called the *Von Neumann neighbourhood* of a site (Von Neumann and Burks, 1966). In the layout of the grid-cells, the diagonal cells are only connected to the four corners of the cell at one point. On the other hand, the four neighbours, in the cardinal directions, are connected to the four sides of the cell. Further, it is assumed that the water movement would occur mainly between a cell and its four neighbours. For this reason, contributions from diagonal neighbouring cells are neglected. However, if necessary, the model can be modified easily to include all eight neighbours.

At each simulation step, as the sea level rises, the elevation of a cell is determined by its condition at the previous time step, its border conditions with its neighbours, and the cover type of its neighbours (Land, Waterways, Sea, or Pond). The elevation of a cell is determined by adjusting the elevation, at previous time steps, by the flow-in (increase) and the flow-out (decrease) of the cell, according to the properties of the adjacent cells.
The *Elevation* is the integral of the net flow of *Increase* and *Decrease*, which is mathematically represented by the following equation:

\[
E_t(x,y) = \int (\text{Incr Increase} + \text{Decrease Increase}) \, dt
\]

Where:

- \( E_t(x,y) \): Cell elevation at location \( (x,y) \) at a given time
- \( E_0(x,y) \): Initial cell elevation at location \( (x,y) \)
- \( I_t(x,y) \): Rate of elevation increase at location \( (x,y) \)
- \( D_t(x,y) \): Rate of elevation decrease at location \( (x,y) \)

The changes in cell elevation occur when only the *Cover Type* of a cell is *Land*, *Waterways*, or *Pond*, at time step \( t_n \), and it is transformed into *Sea* at the next time step, \( t_{n+1} \). Here, the cell is assumed to be inundated from the rising sea level and, therefore, the elevation of the cell is updated, and said to be equal to the *Sea Level* at the time period \( t_{n+1} \).

The following logical equations are formulated to capture the changes in each cell’s *Elevation*:

\[
\text{Increase}[X,Y] = ( \text{IF THEN ELSE ( Cell Cover}[X,Y] = 1
\]

:OR: ( Cell Cover[X,Y] = 4 :AND: ( CTRight[X,Y] = 1


:OR: ( Cell Cover[X,Y] = 3 :AND: ( CTRight[X,Y] = 1 :OR: CTTop[X,Y] = 1

:OR: CTBottom[X,Y]= 1 :OR: CLeft[X,Y] = 1 ) )

:OR: ( Cell Cover[X,Y] = 2 :AND: ( CTRight[X,Y] = 1 :OR: CTTop[X,Y] = 1

:OR: CTBottom[X,Y]= 1 :OR: CLeft[X,Y] = 1 ) )

\]
MAX (Sea Level - Elevation[X,Y], 0), 0) ) / TIME STEP

Decrease[X,Y] = IF THEN ELSE ( Elevation[X,Y] > Sea Level,

Elevation[X,Y] - MAX ( Sea Level, Elevation[X,Y], 0) / TIME STEP

Where:

Increase(X,Y): Flow into the cell (X,Y)

Decrease(X,Y): Flow out of the cell (X,Y)

Cell cover type value can be Sea (1), Waterway (2), Pond (3), or Land (4)

CTTop(X,Y), CTBottom(X,Y), CLeft(X,Y), and CRight(X,Y) represent four neighbouring cells’ cover types of the cell(X,Y).

Elevation(X,Y): Cell Elevation at location (X,Y) at a given time.

The Cell Cover is the integral of the net flow of Change and Change Previous. Based on the following equation, the type of Cell Cover in any given time is determined.

Equation 5-6

Where:

\( CT_1(x,y) \) : Cell Cover type at location (x,y) at a given time

\( CT_0(x,y) \) : Initial Cell Cover type at location (x,y)

\( C_t(x,y) \) : Rate of cell cover type change at location (x,y)

\( CP_t(x,y) \) : Rate of previous cell cover type change at location (x,y)

As the model runs, the state of the each cell is assessed simultaneously. The change flows into the cell (Stock) and updates the Cover Type of the cell for the present time step (i.e. \( t_1 \)). Subsequently, Change Previous removes the Cover Type of the cell at previous time step (i.e. \( t_0 \)). This is necessary to assign only one Cover Type value to the
cell for each time step. For example, if the Change alters the Cover Type of a cell from Land to Water at time step (t_1), then Change Previous discards the previous cover type value (Land) from the cell.

Further, the model simulates the transformation process in Cell Cover type at a given time using the following logical equations:

\[
\text{Change}[X,Y] = \begin{cases} 
\text{IF THEN ELSE} & \left( \text{Cell Cover}[X,Y] = 4 \land \text{Elevation}[X,Y] \leq \text{ERight}[X,Y] \land \text{CTRight}[X,Y] = 1 \lor \text{Cell Cover}[X,Y] = 4 \land \text{Elevation}[X,Y] < \text{ELeft}[X,Y] \land \text{CTLeft}[X,Y] = 1 \lor \text{Cell Cover}[X,Y] = 4 \land \text{Elevation}[X,Y] \leq \text{ETop}[X,Y] \land \text{CTTop}[X,Y] = 1 \lor \text{Cell Cover}[X,Y] = 3 \land \text{Elevation}[X,Y] \leq \text{EBottom}[X,Y] \land \text{CTBottom}[X,Y] = 1 \lor \text{Cell Cover}[X,Y] = 2 \land \text{Elevation}[X,Y] \leq \text{ERight}[X,Y] \land \text{CTRight}[X,Y] = 1 
\end{cases}
\]
RESEARCH METHODOLOGY

:OR: Cell Cover[X,Y] = 2 :AND: Elevation[X,Y] <= ELeft[X,Y]

:AND: CTLeft[X,Y] = 1

:OR: Cell Cover[X,Y] = 2 :AND: Elevation[X,Y] <= ETop[X,Y]

:AND: CTTop[X,Y] = 1

:OR: Cell Cover[X,Y] = 2 :AND: Elevation[X,Y] <= EBottom[X,Y]

:AND: CTBottom[X,Y] = 1, 1,


Change Previous[X,Y] = Cell Cover[X,Y]

Where:

Change (X,Y): Flow into the cell(X,Y).

Change previous (X,Y): Flow out of the cell (X,Y).

Cell cover type value can be Sea (1), Waterway (2), Pond (3), or Land (4)

ETop(X,Y), EBottom(X,Y), ELeft(X,Y), and ERight(X,Y) represent four neighbouring cells’ elevations of the cell(X,Y).

Cell Cover (X,Y): Cell Cover Type at the location (X,Y) at a given time.

Initial Cover(X,Y): The cover type of the cell (X,Y) when simulation begins.

Once a cell is modelled by using above equations, these modelling rules can be extended to every grid cell covering the study area in question.

5.4.3.1.3 STORM SURGE MODEL
Rising sea level and the associated stronger storm events pose an increasing threat to coastal cities, residential communities, infrastructure, beaches, wetlands, and ecosystems. As discussed in Section 2.4, with a rising sea level, the current 1:100 year storm event is expected to occur more frequently. Indeed, there is a logarithmic relationship between the return period and the sea level, for example, the flood plain, subject to current 1:100 year storm events, will become subject to 1-in-10 year storm events with 1 m sea level rise, as shown in Figure 5-14. Although the storms will occur at irregular intervals, they will have long-term physical and socio-economic impacts on the coastal region. Thus, in addition to higher sea levels, coastal storm surges from cyclones could become higher and cause more damaging flooding. Although the storms will occur at irregular intervals, they will have long-term physical and socio-economic impacts on the coastal region. Thus, in addition to higher sea levels, coastal storm surges from cyclones could become higher and cause more damaging flooding.

According to Hunter (2008), if a sea-level rise of $h$ increases the frequency of the occurrence by a factor $r$, then a sea-level rise of $H$ increases the frequency of occurrence by a factor $r^{H/h}$. The resulting SLR could very large, even for a modest increase in sea level.

Similarly, McInnes et al. (2000) estimated that the current 1:100 year event, which is about 2.3 m in height under present conditions, would increase to about 2.6 m under
the enhanced GHG conditions. With an additional 20 cm SLR by 2050, the 1:100 year event would be about 2.8 m.

The purpose of this model, therefore, is to determine how rising sea level would affect the average recurrence interval (ARI), as well as identify the height of current and future 1:100 year storm surges, over time. The Storm Surge model, developed in the light of the previous discussion, is illustrated in Figure 5-15.

![Storm Surge Model](image)

To calculate the increase in current in the 1:100 year storm events, the following equation is used, based on the work of Hunter (2008):

\[
\text{Equation 5-7}
\]
Where:

CSSF: Increase in current 1 in-100 year storm surge frequency

\[ H \] Predicted sea level rise

\[ r \]: 3.1, average multiplying factor for Australia calculated by Hunter (2008)

\[ h \]: observed sea level rise in a given time (0.1 m for Australia observed over 30 years).

This equation can be interpreted as follows: if a sea-level rise of \( h \) increases the frequency of the occurrence by a factor \( r \), then a sea-level rise of \( H \) increases the frequency of the occurrence by a factor \( r^{H/h} \). The outcome can be very large, even for a modest increase in sea level.

Harper et al. (2000) provided estimates of various storm tide levels within Moreton Bay, Queensland, Australia. Moreton Bay is the site where the proposed model was implemented. The highest projected storm tide levels (relative to the Australian Height Datum – AHD) for 50, 100, 500 and 1000 year storm events are 2.3m, 2.5m, 3.2m and 3.5m, respectively. By applying their data, the current storm event is plotted (Figure 5-16) in Excel. Using the trend-line in the chart, Equation 5-8 and 5-9 which generate the trend-line coefficients were created. Then, by using use these equations, for the current conditions, the average recurrence interval (ARI) and the height of a given event were calculated in the model:

Height:

Equation 5-8

ARI:

Equation 5-9
Depending on the SLR rate, the model determines the changes in storm events, over time. The new future ARI and SS height values are used by the vulnerability model to assess the impact of the storm events at each time step.

### 5.4.3.1.4 VULNERABILITY MODEL

Coastal areas are intrinsically dynamic, so the impacts of SLR are more complex than a simple inundation. Further, vulnerability to SLR results from a combination of various factors, such as: high population density along the coast, and the susceptibility of coastal regions to coastal storms, as well as other effects of climate change. However, our understanding of the magnitude and timing of these processes is limited, in the main, because of uncertainties in global SLR predictions.

Further, coastal systems, such as beaches, barrier islands, wetlands, and estuarine systems, are closely linked to sea level. Therefore, an accelerated SLR could fundamentally change the state of the coast and, as a result, coastal environments and human populations will be affected significantly. Additionally, movement to the coast and coastal development continues despite the growing vulnerability to coastal hazards. Thus, an increasing population, further developments and infrastructure resulting from the increase in population, will place extra stress on the ability of governments and administrators to manage the areas.
The most obvious potential impacts of rising sea level are the loss of lives and the loss or damage of properties as the coastal areas are inundated. The timing and extent of these impacts are strongly related to both the physical aspects (shape and composition) of the coastal landscape and its ecological setting. Given the large potential impacts to human and natural environments, it is imperative that our ability to conduct long-term projections is improved.

In the final building step of the temporal model component, the Vulnerability model is developed to estimate the potential impacts of SLR in terms of people and properties and how they will be affected (Figure 5-17). The critical vulnerability of coastal areas to coastal storms (in the short term) and SLR (in the long term) relates to flooding. Therefore, the vulnerability assessment (VA) needs to focus on people and residential properties in the study area already facing flood risks. Hence, two VA indicators are selected:

1. Population at risk over time due to coastal flooding
2. Property at risk due to inundation and coastal flooding

Figure 5-17 Vulnerability model for people and property at risk
The vulnerable land area and population are estimated using several datasets from several resources. For example, to calculate the land area under inundation threat, changes in land cover type, over time, are captured and used in the vulnerability model.

Initial population data, acquired exogenously, is simulated, based on population projections. In the current study, the following data is used to predict the vulnerable population, namely: the Australian Bureau of Statistic (ABS) 2001 data on dwellings, and the Digital Cadastral Database (DCDB) spatially representing every parcel of land and providing land related information. Further, the vulnerable land and population are calculated by using the mathematical equations below.

First, the number of people who live in the area is calculated based on two stocks in the model: The Population \( P_0 \) that resides in the area at the beginning of simulation, and the Residents \( R_t \), which is the integral factor of the Population Increase \( P_t \). The model determines the changes in population living in the area using the following equation:

\[
R_t(x,y) = R_0(x,y) + \int P_t(x,y) \, dx \, dy
\]

Where:

\( R_t(x,y) \) : People reside at location \((x,y)\) at a given time

\( P_0(x,y) \) : Initial number of people reside at location \((x,y)\)

\( P_t(x,y) \) : Rate of population increase at location \((x,y)\)

Then, People at Risk are calculated by multiplying the sum of Flooded Cells with the Cell Size:

\[
\text{People at Risk} = \sum \text{Flooded Cells} \times \text{Cell Size}
\]

Equation 5-10

Equation 5-11
Where:

\( VP_t(x,y) \) : Vulnerable people at a given time

\( R_t(x,y) \) : People residing at location \((x,y)\) at a given time

\( Cs \) : A constant value showing size of each grid cell.

\( FC_t(x,y) \) : Flooded Cells at location \((x,y)\)

To calculate the vulnerable land area over time, the model identifies the *Flooded Cells* by using the following logical expressions:

\[
\text{Flooded Cells}[X,Y] = \text{IF THEN ELSE}((\text{Cell Cover}[X,Y] = 1: \text{AND: Initial Cover}[X,Y] = 4) \\
: \text{OR: ( Cell Cover}[X,Y] = 2 : \text{AND: Initial Cover}[X,Y] = 4) \\
: \text{OR: ( Cell Cover}[X,Y] = 3 : \text{AND: Initial Cover}[X,Y] = 4) , 1, 0)
\]

Then, the *Area at Risk* is calculated by multiplying the sum of the *Flooded Cells* with the *Cell Size*:

Where:

\( A_t(x,y) \) : Vulnerable area at a given time

\( Cs \) : A constant value showing size of each grid cell.

\( FC_t(x,y) \) : Flooded Cells at location \((x,y)\)

5.4.3.2 SPATIAL MODEL COMPONENT

5.4.3.2.1 APPROACH

The spatial model component building phase involves a spatial analysis. The aim of the spatial model is to derive a meaningful representation of events, occurrences or processes, by making use of the power of spatial analysis. Spatial analysis is a set of
methods whose results change when the locations of the objects being analysed change (Longley, 2005). Importantly, spatial analysis derives information from the data using the spatial context of the problem and the data. That is, it deals with space.

Hence, spatial relationships are the associations or connections between different real world features, and are crucial in vulnerability assessments and modelling. The synthesis of data, and the essential mapping of the spatial relationships between environmental phenomena and the vulnerability of people and properties, requires the use of spatial tools. GIS is a key tool used in the model construction and calibration, and plays a critical role when the predictions are distributed and reproduced for other areas. Further, GIS allows an enormous amount of information to be visualised in a spatial situation. Thus, incorporating a spatial model into temporal modelling provides a powerful tool that permits scenario modelling in space and time.

Real world features exist in two basics forms: objects and phenomena. While objects are discrete and definite (such as buildings, highways, cities, etc.), phenomena are distributed continuously over a large area (such as terrain, temperature, rainfall, etc.). Geospatial data depicts the real world in these two forms, which leads to two distinct approaches: the object-based model, and the field-based model (Goodchild, 1992).

The object-based method uses contour lines; it is usually suitable for a very rapid and simple risk assessment over large areas. However, it does not take into account the presence of intervening topographic ridges or other features (e.g. man-made defences) that can separate a low-lying area from the source of flooding (Brown, 2006). This situation is particularly true for coastal floodplains where a series of dune ridges and embankments prevent the lower hinterland from flooding in most sea conditions.

The Raster model, as Lo and Yeung, (2007) define it, is one of the variants of the field based models of geospatial data modelling. It is best employed to represent spatial phenomena that are continuous over a large area. For example, the Raster data model uses a regular grid to cover the space; the value in each cell represents, the characteristic of a spatial phenomenon at the cell location. In computing algorithms, a raster can be treated as a matrix with rows (y-coordinates) and columns (x-
coordinates), and its values can be stored into a 2D array. These characteristics hence make integration of GIS and SD easier, especially since SD can easily use array variables for data manipulation, aggregation, and analysis. Therefore, the raster data model was selected for spatial modelling. The basic elements of a raster model include the cell value, cell size, raster bands, and spatial reference (Chang, 2006).

Each cell in a raster has a value representing the characteristic of a spatial phenomenon at the location denoted by its column and row \((x,y)\). This value can be an integer or floating-point raster. The integer value has no decimal digits, whereas the floating-point value has decimal digits. Therefore, depending on the data type, both are used in the current research. For example; the research considers a sea level rise of 0.5-1.5 cm and. Thus, a floating-point raster is more suitable for the elevation data, as it represents continuous numeric data with decimal digits, i.e. 10.125 m, 10.124, and so forth. However, the integer values are used for land cover rasters, i.e. 1 for Sea, 2 for Waterways, 3 for Pond, and 4 for Land.

Importantly, the cell size determines the resolution of the raster model. For example; a cell size of 5 m refers to an area measuring 5x5 = 25 m\(^2\). On the other hand, a cell size of 100 meters means that each cell represents an area of 100x100 = 10,000 m\(^2\). As a larger raster cannot provide the precise location of the spatial features, the model result may not be satisfactory. Nevertheless, the smaller cell size can address these problems; although their use increases the data volume and data processing time, considerably. There are always trade-offs between the quality of the model outcomes and the processing time. In the current study, a 5 m cell size is used for the modelling.

The Raster data are organised into layers, also called bands, themes, or overlays (Lo and Yeung, 2007). If a raster has multiple layers, such as satellite images, it is associated with more than one cell value. On the other hand, in a single-layer raster, each cell has only one value, such as in an elevation raster. Rasters are used in the current research as they have a single-layer, except for the satellite images.

Essentially, the raster layers must be geo-referenced to a common map coordinate system in order to align the raster datasets, spatially, with each other. The GDA_1994 Transverse Mercator coordinate system is used in this research.
The GDA 1994: Geodetic Datum of Australia is the latest Australian coordinate system (Geoscience Australia, 2011). The GDA_1994 specifications are shown below:

- **Datum**: Geocentric Datum of Australia (GDA)
- **Geographical coordinate set**: Geocentric Datum of Australia 1994 (GDA94) (latitude and longitude)
- **Grid coordinates**: (Universal Transverse Mercator, using the GRS80 ellipsoid) Map Grid of Australia 1994 (MGA94)
- **Reference Frame**: ITRF92 (International Terrestrial Reference Frame 1992)
- **Epoch**: 1994.0
- **Ellipsoid**: GRS80
- **Semi-major axis (a)**: 6,378,137.0 metres
- **Inverse flattening (1/f)**: 298.257222101

The current study uses the ArcInfo 9.3.1 to develop the spatial model (ESRI, 2009), which is connected to the simulation model through the data convertor and file monitor application developed by the researcher.

The following section covers the modelling process using GIS.

### 5.4.3.2.2 SPATIAL MODEL

The process of building new GIS products from existing products is known as GIS Modelling. However, the use of GIS in the process of building models with spatial data is not, typically, modelling as in a simulation model, because the GIS provides a template for implementing the GIS projects. In other words, an empty geo-database is used to start a project by adding data layers into this blank template.

The development of a model follows a series of six steps (Figure 5-18). This approach is important as modelling and analysing a problem using GIS requires a structured approach. In the current research, these steps (described in the following sections) are used to define the GIS workflow and procedure:
Problem/Goal

The purpose of this study was to develop and implement a spatial-temporal decision model to assess coastal vulnerability and coastal adaptation to SLR. Developing a spatial model is one of the essential components of the hybrid spatial-temporal model, which was created to handle the initial data required for whole assessment process. It was developed to:

- Determine the study area;
- Store, manipulate, and convert data into ASCII format suitable for use in the temporal model; and
- Data visualisation.

Deliverables:

The most critical step in model development is to determine what the deliverables of the modelling process should be. The main outputs of the spatial model are:

- Storing the required data;
Combining various related datasets of the same kind to create a new layer;

- Converting dataset vector data to raster;
- Exporting data to, and importing data from, temporal model;
- Creating maps showing elevation of the study area with types of land cover, waterways, and population density; and

Creating maps showing the extent of inundation under various SLR and storm surge scenarios.

**Data Gathering:**

Coastal processes and vulnerability are strongly determined by local, regional and, sometimes, global conditions. As a consequence, it is important that we comprehend and understand the data of related to the physical and social system characteristics. Hence, it is essential that the data (and information) are referenced to a location on the Earth's surface, using precise scientific coordinates, such as maps, charts, air photos, satellite images, and land and water surveys. As a result, the data are defined as geospatial data. In the current study, the spatial data on land cover, elevation, Digital Cadastral Database DCDB, study area boundaries and waterways were acquired from public sources (referenced when used) and processed into GIS format. Geospatial datasets needed to develop and apply the spatial model are listed in Table 5-6:

<table>
<thead>
<tr>
<th>Layer</th>
<th>Data Type</th>
<th>Spatial Coordinate System</th>
<th>Resolution for Rasters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>Raster</td>
<td>GDA_1994 Transverse Mercator</td>
<td>5 m</td>
</tr>
<tr>
<td>Land use/cover</td>
<td>Raster</td>
<td>GDA_1994 Transverse Mercator</td>
<td>5 m</td>
</tr>
<tr>
<td>Digital Cadastral Database (DCDB)</td>
<td>Raster</td>
<td>GDA_1994 Transverse Mercator</td>
<td>n/a</td>
</tr>
<tr>
<td>Census data</td>
<td>Text</td>
<td></td>
<td>n/a</td>
</tr>
<tr>
<td>Waterways</td>
<td>Raster</td>
<td>GDA_1994 Transverse Mercator</td>
<td>5 m</td>
</tr>
<tr>
<td>Satellite image</td>
<td>Raster</td>
<td>GDA_1994 Transverse Mercator</td>
<td>0.15 m</td>
</tr>
</tbody>
</table>

Table 5-6 Geo-spatial datasets required for the spatial modelling

The elevation data are the most critical elements in assessing the potential impacts of rising sea level. The two main types of elevation data commonly used are: Digital Elevation Model (DEM) and Light Detection and Ranging (LIDAR) data. Major
discrepancies between the DEMs and LIDAR occur in places where there are man-made structures (mainly buildings). The discrepancies occur because the DEMs always depict ground elevation, whereas the LIDAR data show the top-of-building elevations. In most inundation analyses a place is deemed as flooded when the ground is flooded, even if the top of the building remains above water. For this reason, areas covered by buildings should be eliminated from the comparison (Wu et al., 2009).

The uncertainty of the elevation data affects the delineation of the coastal elevation zones. Most elevation datasets have vertical accuracies of several meters or even tens of meters (at the 95 percent confidence level). Following the example of Gesch (2009), the graphical representation of the DEM vertical accuracy was plotted using error bars around a specified elevation (Figure 5-19).

![Figure 5-19 A graphical representation of DEM vertical accuracy using error bars around a specified elevation (Adapted from Gesch 2009)](image)

In this example, a hypothetical sea-level rise of 1 meter is to be mapped onto the land surface; three elevation datasets are available for map production. On a topographic profile diagram, the elevation datasets, with differing vertical accuracies, can be shown with error bars around the 1 meter elevation. The first dataset has a LIDAR elevation
(LE) of ±0.1 meter at a 95% confidence level; the second dataset has an LE of ±0.3 meters at a 95% confidence level; while the third dataset has an LE of ±2.2 meters at a 95% confidence level. By adding the LE to the projected 1 meter sea-level rise, more area is added to the inundation zone delineation. This additional area is a spatial representation of the uncertainty. The additional area is interpreted as the region in which the 1 meter elevation may actually fall, given the statistical uncertainty of the original elevation measurements. Gesch (2009) argues that the mapping of sub-meter increments of sea-level rise is highly questionable, especially if the elevation data used have a vertical accuracy of a meter or more (at the 95-percent confidence level).

As illustrated in Figure 5-19, the additional area representing the elevation uncertainty is much smaller for the more accurate elevation data. To keep the analysis reasonably manageable, the current study has ignored the horizontal error; instead, it has focused entirely on the vertical errors. Therefore, to acquire more accurate results, the research used 5 m DEM with 0.1 m vertical accuracy.

**Data Preparation:**

A variety of data from different sources was used in the current research (as shown in Table 5-6). As the original raw forms of the data are not often suitable for use, it is necessary to create new special sets in which the raw data are assembled, corrected, transformed, summarized and aggregated into more consistent useful formats. Therefore, for the present research it was necessary to transform the data into a compatible raster format.

Several GIS layers were required as inputs to the spatial model. All the data layers needed to be in grid (raster) format, with a resolution of 5 x 5 m cell size. By working at a high spatial resolution, the model was able to reflect, accurately, the spatial changes in inundation resulting from the SLR. Further, within the taxonomy of GIS functions, procedures in geo-processing can be classified into three categories (Giordano et al., 1994):

1. Input functions: include functions that prepare, and structure raster data for use in GIS, such as restructuring, compilation, and editing.
2. Analysis domain: includes all functions that will derive spatial relationships implicit in the source data, such as logical operations, overlay operations, and geometric operations.

3. Output functions: present the results of the analysis functions in a suitable form for communication and spatial problem solving, such as maps, graphs, and statistical reports.

This approach provides a convenient way for describing the geo-processing procedure in GIS. Hence, based on this approach, the researched began by converting the shape-files to the raster format, then reclassifying, and correcting their projection and, finally, unifying the coordinate system, according to the general process shown in Figure 5-20.

![Flowchart](image)

**Figure 5-20 General processing approach**

First, the data was clipped to the extent of the study area boundary, as determined by the study area-specific layer. Next, the attribute data conversion was classified, to create a new layer (by changing the attribute values of the input layer), as seen in Figure 5-21. This operation was useful for simplifying the data analysis for the land use change.
The conversion process generated a new attribute file that contains the descriptive properties of the polygons on the vector layers. The existing attributes of every polygon in the land use data were assigned new attributes values, such as Sea=1, Waterways=2, Pond=3, and Land=4 (Figure 5-22). The protection data was then converted from a vector format to a raster (grid-based) format, with a cell size of 5 meters, to match the resolution of the elevation data.

The ArcGIS Model Builder was the main tool used for the data processing. The Model Builder is a graphical tool for automating a model through the use of a work flow. Thus, different components can be linked together to create a new tool. The model builder allowed a new Land use layer to be created by combining data from several source layers, as shown in Figure 5-23.
The vector data were, consequently, converted to a raster format using the model builder (Figure 5-24). Spatially, the size of the raster cell generated was based on the minimum mapping unit (5x5m) to match the DEM data. The attribute assignments were based on the centroid of the cell. Australian Bureau of Statistic (ABS) 2001 data on dwellings, and the Digital Cadastral Database (DCDB), represented, spatially, every parcel of land and provided land related information that was converted to a raster format.

Uncertainty, however, exists regarding where the population resides within the census parcel. Additionally, the relationship between the portion of a parcel’s area that is lost to SLR and the portion of the population residing in the vulnerable area is also
uncertain. Further, homes are not necessarily distributed uniformly within a census parcel. Therefore, in the current study, the vulnerable population was estimated as a percentage of the census population, based on the inundated parcels. The clipped elevation, land use, population density, and population attribute tables are shown below (Figure 5-25, Figure 5-26 and Figure 5-27), respectively.
5.4.3.3 DATA CONVERTOR

The loose coupling approach involves the transfer of data between the GIS and SD. Hence, it is necessary to establish, create and manipulate data files, so that they can be exported or imported between the spatial and temporal components of the hybrid model. The data in the files can be stored in several file formats. Different file formats have different characteristics, depending on a range of factors, such as the source of the data, and the software architecture.

In GIS, raster file formats can be grouped into five categories, as defined by Lo and Yeung, (2007):

1. Generic file formats,
2. Data interchange formats,
3. Data compression formats,
4. Remote sensing image formats, and
5. Proprietary formats of GIS software

A generic raster file format is a simple format that is closest to the conceptual raster model of data representation. Two generic file formats (ASCII and binary) are the most suitable for integrating GIS and other modelling platforms. Vensim is also binary-compatible across platforms. In SD various data formats are used, such as binary formats (.vmf), text formats (.cin, .mdl, .vgd, .dat, tab delimited, and others), and spreadsheet formats (.xls, and Lotus123).
The Constant Input file (.cin) is a text file. In this format, model variables are written to a .cin format changes file. This process is a convenient way of saving all constants in a model in a format that can be edited and used to make simulations. In the .dat format for data, each individual data time-series begins with the variable name associated with it. Following the variable name, the data is listed in two columns. The first column contains the time for the data value; the second column contains the data value itself (Ventana Systems, 2009). The use of data from Tab delimited files, which is just a series of numbers separated by Tabs (ASCII 08), and spreadsheet formats (i.e. Excel and Lotus 123) are also supported by SD software.

As the hybrid model combines two different modelling approaches, it is useful to choose a device independent file format which can be usable by both applications, regardless of their hardware or software platforms. Therefore, in the current study, the device independent ASCII file format for GIS, and the .cin and tab text file formats for SD were chosen for the cross-platform exchange of data.

When exchanging data between two applications, it is necessary to convert the data formats into the right file format, as used by the applications (i.e., ASCII → .cin, and/or .cin → ASCII). To assist with this process, a converter program was developed. The converter program involves two separate applications: the data converter and the file monitor. The program converts the formats between two SD and ArcGIS file formats, as illustrated in Figure 5-28.

![Figure 5-28 The Conversion process](image_url)
5.4.3.3.1 THE DATA CONVERTOR

The data converter software automates the format transition between the ArcGIS and SD data formats. First, it converts the ArcGIS text (ASCII) files to SD text files (.cin), then it converts the files from the SD .tab files back to the ArcGIS .txt files. All code for the data converter was written in C++ under Visual Studio 2008, using the Microsoft.NET framework version 2.0. As a console application, it takes its commands via program arguments. That is, the program can be shelled to give command line arguments of the file to be converted. As a result, it’s also possible to drag and drop a file into the executable (.Exe file), then, the program will use them for the conversion. The conversion process is accomplished through the following steps outlined below.

A conversion process begins with an ArcGIS file, which is read into the program all set for the processing. First, the program detects if it is viewing a GIS or SD file; it looks at the first word of the file passed to it.

If it is a GIS file, then:

- It reads the first six lines of the text (header information), and uses the column and row data within to read the rest of the file (Figure 5-29). This header contains metadata used by ArcGIS so that it can display the data correctly. The converter uses some of this information to determine the length of the file.

- A variable name, input from the user, is required for the data to appear in SD. The resulting filename is then given the variable name. The program asks for a variable name, taken via command line in manual mode, or the program argument in automatic mode.

- The header information is then saved, using the variable name as a filename, and ‘hdr’ as an extension.

- After saving the header and setting the variable name, the body of the file is read, line by line, into an array. The column and row metadata from the header is then used to iterate through the file, and store all the information into arrays.
Once the converter has finished reading, and has reached the end of the file, the program writes the data into a file in a format readable by SD (Figure 5-30). The SD reads data in the following format:

\[
\text{VariableName} [x_n, y_n] = \text{data value}
\]

Where; the VariableName is the user chosen variable name. \(x_n\) and \(y_n\) are the current x and y coordinates, with \(n\) specifying the value (i.e. \(x_1, y_{12}\)). And the data value is the value at that point.

- This file is saved with the variable name as a filename, with ‘.cin’ as an extension.

After the simulations have been run in SD, the output files are created; they now contain the recently processed spatial data, with increments of time, if applicable.
Next, this information is reconverted to be displayed in ArcGIS. In the case of time steps, a separate file is created for each step. The reconversion process is the same process as was undertaken before, with the exception that the previously removed header is re-added to the file. In this way, the spatial information can be passed to, and from, the SD and ArcGIS.

SD file format to the ArcGIS conversions are conducted as follows (Figure 5-31):

- The last line of the file is read, and the variable name, X (row) and Y (column) data is taken out.
- The first line is then read, and the number of time steps in the data is found.
- The variable name is then used to open the header file created during the GIS to SD conversion. Nothing in the header file is processed during this operation.
- The X, Y, and time step data are used to iterate through the file, saving all values into a 3D array. A 1D for each time step, and then the X and Y dimensions.
- For each time step, a new file is created. The first thing to be written into this file is the header information.
- All the data for a particular time step are written into the file, in the GIS form (Figure 5-29); the columns are written sequentially, with a line break at the end of each.
- The file is saved, using the filename of the original SD file, with the value of the time step at the end of the name.
- This process is repeated for each time step in the data.
5.4.3.3.2 THE FILE MONITOR

The second program in the Solution is the file monitor (5-32). It does not work itself, instead relying on the data converter application to undertake all the converting. The file monitor facilitates the easier operation of the converter by monitoring two project folders, one for the SD and one for the ArcGIS. When a file is output from the ArcGIS, the monitor detects this, and begins creating the file used for the SD, again prompting the user for a Variable name. Likewise, when the SD outputs the simulation data, it is automatically converted and placed into the GIS folder.

![File Monitor](image)

Figure 5-32 File monitor

This process works through the use of a `FileSystemWatcher`, which is a class contained within the .net framework. The `FileSystemWatcher` is created, with the folder to monitor, and the file type(s) to monitor; these are passed as arguments to its constructor. In the case of the ArcGIS folder, it listens for the creation of .txt files. For the SD Folder, it monitors for the creation of .tab files. Any other file type created in these folders will not be noticed by the application. While monitoring for file changes, there is a waiting period, during which the file is completely written; once completed the file is loaded up for conversion. This process is accomplished by checking if the file is currently in use, waiting, and then checking again, etc., until the file is free. The `File Monitor`, written in VB.NET, is a Windows form application that monitors the creation of files in two specified folders (Figure 5-32).

The file monitoring process is performed using the following steps:

- The file takes two folder locations via a standard browse dialogue.
It hides itself in the tray, and waits for the creation of a txt or tab file. It will not notice an update or rename operation.

Once it detects a file has been created, it waits to make sure that the file is not still being written to (as may be the case with large files).

It passes this filename, the location of the folder it needs to be output to, the location of the header directory, and a variable name, if one was necessary, to the converter application.

As soon as this begins, the monitor halts monitoring until the operation is completed.

The converter will return a value, indicating success or error. If there is an error, it will be displayed in the tray area. If there is no error, then the monitor resumes its task, and waits for the next file creation.
5.4.4 Decision Model

Faced with increased threats from accelerated SLR and associated storm surge events, there is an urgent need for coastal communities to act faster to adapt to SLR, to reduce any potential destructive impacts, and to develop more effective policies. Developing effective policies requires more accurate information to strengthen the decision makers’ (DMs) ability to make more effective decisions, with greater speed and accuracy.

However, due to the uncertainty of the precise behaviour of complex environmental systems, two dilemmas confronting DMs: how and when to adapt to SLR. Some concern has been raised regarding which proposed adaptation alternative should be implemented (Sahin and Mohamed, 2009), in the short term and in the long term. Determining how and when specific actions should be taken, however, is not a simple decision. Therefore, the decision making process inevitably involves making choices regarding the appropriate forms of adaptation response. The process is always complex and rarely straightforward, often including many stakeholders, with different goals, and numerous adaptation alternatives. Despite this confusion and complexity, one or more adaptation responses to climate change must be chosen, so that the outcomes are effective in managing the wide range of impacts from SLR.

The critical question, then, is: Who would make the decision? While climate change is a global problem that affects everyone, some people and some communities are more affected than others, depending on their location as well as their ability to adapt. Therefore, the decision making process has to include all stakeholders directly or indirectly affected by changing climate. Into this mix will be disagreements about which objectives should be achieved, and which criteria or definitions should be used. This process is a particularly delicate endeavour in democratic systems with limited resources, especially where many stakeholders have to be satisfied. The public’s support of the DM’s efforts to reduce the impacts of changing climatic conditions depends on the dissemination of robustly debated information from the Experts across a range of disciplines to the community.
Undoubtedly, a robust and flexible adaptation alternative selection technique would be ideal for the decision making process. This process would include multiple stakeholders (as DMs), who prioritise adaptation alternatives, and provide a clear identification of the sequence of the alternatives to be implemented. Decision making on local levels in the coastal areas can be better supported by an improved understanding of the vulnerabilities and risks resulting from the SLR impacts. A wide range of approaches can be used to model the effects of a changing climate with respect to SLR (as discussed in previous sections). Although these approaches can provide invaluable information, they are not sufficient when decision makers (DMs) are making decisions that identify adaptation alternatives to SLR. The situation is made more difficult for decision makers as they are required to take into account the levels of uncertainty surrounding climate change and the related future impacts. Nevertheless, it is crucial to link the vulnerability assessments with the decision making processes.

Decision making is a process of selecting from among several alternatives, based on various (usually conflicting) criteria. A decision, based on a single criterion, reflects the oversimplification of the characteristics of the problem under consideration; the result may be an unrealistic decision. According to research pioneers in the multiple criteria decision aid (MCDA) fields, a problem can be considered as a decision problem if there are at least two criteria (in some cases conflicting) to deal with, otherwise the problem would only be an issue related to getting the right information; it would not be a decision problem (Keeney and Raiffa, 1976, Roy, 1968).

MCDA techniques provide a powerful modelling framework for aiding complex decision-making processes, especially involving multiple criteria, goals, or objectives of a conflicting nature. MCDA techniques concentrate on a decision analysis within a finite set of alternatives; it offers techniques to assist individual DMs in making decisions by eliciting and aggregating their preferences (Chen et al., 2009).

5.4.4.1 SELECTION OF MCDA MODELLING TECHNIQUE

The current study will use the MCDA technique because it is the most suitable approach by which to identify the priority of adaptation alternatives. Information on
priority alternatives is vital in aiding DMs to design more effective adaptation options and better management plans to reduce the adverse effects of SLR.

Several multi-criteria decision aid techniques are suitable for comparing multiple criteria, simultaneously, and for providing a solution to a given problem. While there are no better or worse techniques, some techniques are better suited to a particular decision problem (Haralambopoulos and Polatidis, 2003). Thus, depending on the decision problem, an appropriate method will be available for DMs to use. To help identify the best MCDA, the similarities between the four techniques (MAUT, AHP, ELECTRE, and PROMETHEE) are briefly outlined below, in Table 5-7 (Zhang, 2004 cited in Geldermann and Rentz, 2005). A more detailed discussion is presented in Chapter 3; what follows will then be an outline of the differences between these techniques.

<table>
<thead>
<tr>
<th></th>
<th>MAUT</th>
<th>AHP</th>
<th>ELECTRE</th>
<th>PROMETHEE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Foundation</strong></td>
<td>Classical MADM Approach</td>
<td>Saaty’s Eigenvector Approach</td>
<td>Outranking Approach</td>
<td>Outranking Approach</td>
</tr>
<tr>
<td><strong>Basis</strong></td>
<td>Utility Function additive model</td>
<td>Pair-wise Comparison matrix by means of 9 point scale Evaluation according to weighted eigenvector</td>
<td>Pair-wise Comparison by means of concordance analysis</td>
<td>Pair-wise Comparison by means of Preference Function</td>
</tr>
<tr>
<td><strong>Approaches to determine criteria weights</strong></td>
<td>Trade-off Swing Direct-ratio Eigenvector approach</td>
<td>Saaty’s Eigenvector approach</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Result</strong></td>
<td>Relative preference order</td>
<td>Relative preference order</td>
<td>A set of non dominated alternatives</td>
<td>Partial and complete ranking order</td>
</tr>
</tbody>
</table>

Table 5-7 An overview of selected MCDA approaches

The AHP and PROMETHEE approaches are similar as each provides the user with useful output of the best alternative from a list of options or choices, after judgments have
been made. However, these methods are only a means to determine which alternative is preferred; they do not provide a means by which to implement that alternative. Additionally, group decision-making is fundamentally supported the methods (Kasperczyk and Knickel, 2005), whereas various extensions must be implemented for some other MCDA techniques (such as TOPSIS) to be applied within this environment (Shih et al., 2007, Fu et al., 2007, Lee and Chen, 2008, Wei, 2010).

However, both AHP and PROMETHEE can be subject the rank reversal phenomenon (Macharis et al., 2004). As they draw upon, and take into account, multiple criteria concurrently, compromises can occur when combining ranking and judgment scores. This may happen when aggregating results that may be large (relatively) and, therefore, dominate, or small (relatively) and, hence, become insignificant (Macharis et al., 2004).

The PROMETHEE approach has no formal weights scale assigned to their methods (Macharis et al., 2004, Chamodrakas et al., 2011), whereas AHP has a specific judgment scale to propose and implement (Saaty and Kearns, 1985).

Further, AHP uses a fundamental scale of absolute numbers that has been proven in practice and validated by physical and decision problem experiments. The fundamental scale has been shown to be a scale that captures individual preferences with respect to quantitative and qualitative attributes just as well, or better than, other scales (Saaty, 1980). AHP also uses ratio scale measures, whereas earlier decision making methodologies relied on lower levels of measurement. For example; ELECTRE uses ordinal measurement, and MAUT an interval measurement. According to Forman and Gass (2001), measurement is one of the three primary functions of AHP, along with structuring complexity and synthesis. Ratio scale measures, a cornerstone of AHP, convey more information than interval or ordinal measures, and are required for some applications where interval measures are not adequate. The authors argue that AHP is superior to other methods in terms of its flexibility, ease of understanding and simplicity, and use of ratio scales (Forman and Gass, 2001). The authors argue that AHP is superior to other methods in terms of its flexibility, ease of understanding and simplicity, and use of ratio scales.
Correspondingly, AHP, owing to its flexibility to be integrated with different techniques, enables the user to extract benefits from all the combined methods and, hence, achieve the desired goal in a better way (Vaidya and Kumar, 2006). An additional unique feature of AHP is its ability to structure a problem with a hierarchy, whereas PROMETHEE does not support this kind of approach. The hierarchic structure is slightly different in AHP, as alternatives are located at the last level of the hierarchy; however, they are accounted for in the exact same way as the elements, at all other levels, by means of pair wise comparisons (Martel, 1999).

These MCDA methods also vary in the way that judgments are made and recorded. AHP requires pair wise comparisons for each alternative with respect to each criterion; PROMETHEE uses a ranking of each alternative for each criterion; TOPSIS, unlike the other two, begins with a normalised decision matrix (Chamodrakas et al., 2011).

Importantly, AHP has a unique utilisation in its hierarchy structure that allows it to represent a problem in the form of a goal, criteria and alternatives, and so, it is set apart from the other MCDA techniques (see discussion in Chapter 4) (Saaty & Kearns 1985). As a consequence, the problem can be broken into various parts for pair wise comparisons, which use a single judgement scale. Further, AHP is a mathematical technique originally developed by Thomas L. Saaty (1980). Since its invention, it has been an effective tool in the hands of DMs and researchers; it is one of the most widely used multiple criteria decision-making tools (Vaidya and Kumar, 2006).

Kangas et al. (2001) posit that the AHP has several advantages, especially from the viewpoint of multiple use and participatory planning. Hence, it is possible to utilise objective value information, expert knowledge and subjective preferences. In addition, qualitative criteria can be applied in the evaluation of alternative plans (Kangas et al., 2001).

The AHP technique, despite some criticisms, has been selected for the current study because of a number of desirable attributes, such as:

- Its unique utilisation of an hierarchy structure to represent a problem in the form of a goal, criteria and alternatives (Saaty & Kearns 1985);
• Its ability to utilise both, objective value information, expert knowledge and subjective preferences (Kangas et al., 2001);
• Its flexibility to be integrated with different techniques (Vaidya and Kumar, 2006);
• Its simplicity, ease of understanding and use of ratio scales (Forman and Gass, 2001);
• Its suitability for incorporating multiple stakeholders in group decision making (Kasperczyk and Knickel, 2005); and,
• The availability of commercial and educational software as well as documentations.

5.4.4.2 MODEL ARCHITECTURE

AHP has proven to be one of the best known and most widely used MCDA techniques today. It provides the objective mathematics to process the inescapably subjective and personal preferences of an individual or a group in making decisions (Saaty, 2001). The AHP is set apart from other MCDA techniques because of the unique utilisation of a hierarchy structure to represent a problem in the form of a goal, criteria and alternatives (Saaty and Kearns, 1985). This allows for breakdown of the problem into various parts for pair wise comparisons, which uses a single judgement scale. The underlying concept of the AHP technique is to convert subjective assessments of relative importance to a set of overall scores or weights (Saaty, 1980).

The broad steps involved in executing the AHP are given below:

1. Determining a goal;
2. Determining the stakeholders or groups that will take part in the decision making process;
3. Identifying various objectives of the stakeholders, which can then be formed into a list of criteria;
4. Listing proposed alternatives as solutions of the goal;
5. Creating a hierarchy with levels. This includes the goal at the top, levels of criteria underneath and alternatives in another level. Note: intermediate levels may be required to further break down the problem; this may occur if one or more of the levels in the hierarchy become overcrowded with too many elements (e.g. >7);
6. Inviting stakeholders to make judgements based upon the various levels in the hierarchy. In practice, each of the alternatives should be judged with respect to each of the criterion in the level above, using an appropriate scale and judgements stored in the matrix form, using Saaty’s nine point (1, 2, ..., 9) intensity scale of importance (Saaty, 1980); and

7. Using consistency calculations and sensitivity analysis should be performed to verify the stability of the results.

The specific goal used in the AHP structure is to reduce SLR vulnerability. To clarify further, this goal implies the identification and evaluation of adaptation alternatives in an attempt to reduce the negative impacts from SLR. It encompasses the idea behind the entire effort to reduce the negative impacts from climate change, specifically SLR. After determining the goal for decision making processes, the stakeholders are classified into three groups: Residents, Experts, and Politicians.

The platform on which to formulate the goal, criteria and alternatives for the evaluation in the study area is derived, and based upon, the adaptation programs, the existing adaptation works by local government, and an extensive literature review, including articles, reports and studies regarding adaptation techniques (e.g. GCCC, 2001, Willows and Connell, 2003, The Allen Consulting Group, 2005, EPA, 2006, Adger et al., 2007, The Department of Climate Change, 2009, Wang et al., 2010). These hierarchical elements are then finalised, after further consultation, with local stakeholders in the study area.

The AHP requires participants to make judgements based upon the various levels in the hierarchy. This process can be executed in several ways:

- Focus meetings with members from only a particular stakeholder group. At this meeting, the group would discuss the goal, criteria and alternatives and, then, make decisions based upon their opinions.
- A variation of the above focus group scenario, including all participants from multiple stakeholder groups.
Individual contact with stakeholders (in person, via email or phone calls) to identify if they would be willing to complete a survey questionnaire to obtain their responses.

Several consequences regarding the possible processes of decision making are given below in the following paragraphs. During the focus group meetings (with all members from a stakeholder group), the possibility exists of particular participants being intimidated by the opinions of other participants; in turn, this will influence their decisions. For some people, group environments can be very confronting, especially when they are asked to voice their opinions aloud; inaccurate decisions may result from such an environment, which is clearly not a favourable outcome (Antunes et al., 2006).

Additionally, the ideals of individuals or cliques can dominate the discussions and provide a warped outcome from the decision making process. Once again, quiet members of the focus groups can have their ideals and opinions silenced. Further, it is virtually impossible to gather all the required members of stakeholder groups, at the same time, in one place, for a meeting. In contrast, individual contact only relies on the researcher handing out survey questionnaires to stakeholders. The participants are able to give their honest opinions, without the influence from the opinions of other stakeholders, as well as at a time suited to their schedule. As a consequence, the current study used a survey questionnaire (Schmoldt, 1995). The survey questionnaire is presented in Appendix 6.

5.5 SUMMARY

In this chapter, an integrated five dimensional spatial-temporal decision modelling approach was introduced that assessed vulnerability and adaptation to SLR. The approach was based on three major modelling and decision making approaches: SD, GIS, and AHP. The dynamic-spatial model was defined to address environmental problems in time and space. The study examined the common strategies used to incorporate dynamic modelling predictive functionality into spatial data analysis. (The chapter provides an explanation of previous work conducted by a range of
researchers.) The strategy of the adopted approach was to use the loose coupling approach by which a spatial model component is transparently incorporated into an SD model component. The fundamentals of the DSM process were outlined in detail, using sample figures drawn from the case study, which is discussed in the following chapter.

As discussed in Chapter 3, the nonlinearities, and spatial and temporal lags, are common in many environmental systems. Thus, without considering these characteristics the ability of the models to produce insights into complex environmental systems may be considerably diminished.

Further, unlike statistical approaches, which use historical or cross-sectional data to quantify the relationships among the components of human-environmental systems, the dynamic modelling approaches are built into the representation of a phenomenon. These aspects of the system are known to exist. Additionally, the approach describes the input-output relationships in industrial and biological processes (Hannon and Ruth, 2001). Importantly, dynamic modelling does not require historical or cross-sectional data to reveal those relationships; therefore it has an advantage over the purely statistical approach. Moreover, dynamic models can be transferable to new applications (in most cases), because the basic concepts on which they are built are present in many other systems (Agarwal et al., 2002).

The chapter also presented a discussion on the coupling process, and introduced the data convertor, developed by the researcher, to link the SD and GIS. The chapter plays a significant role in the study as it provided an insight into the multi criteria decision modelling approach used (in the current research) to establish the most effective adaptation strategies. Further, the goal, criteria and alternatives for the decision making process were also presented in detail.
CHAPTER 6

IMPLEMENTING THE APPROACH: PROOF OF CONCEPT

6.1 INTRODUCTION

This chapter, initiated as a proof-of-concept, shows that the approach introduced in this research is worthwhile and has a reasonable prospect of applicability. In this chapter, the proposed approach is tested through its implementation in a number of major cities along the Australian coast line. The implementation addresses the four research questions:

1. What is the present vulnerability in the study area in terms of the number of residential properties and the population within the 1/100 year flood level?
2. How vulnerable is the study area to future SLR and associated storm surges (number of residential properties, their value and people at risk)?
3. What are the potential physical (inundation, flood and storm surge damage) and socio-economic (people at risk and properties, loss of properties) impacts of SLR and storm surges on the study area?
4. What are the desirable adaptation options to reduce adverse impacts of future climate change?

The chapter presents a discussion of the general study areas that were chosen as the best locations where the model could assess the impact of predicted SLR, and evaluate the adaptation alternatives. Then, an explanation was given of the scenarios that were developed to be analysed. As part of this analysis, the hybrid dynamic spatial model was implemented to identify the most vulnerable area and population. Based on the information obtained from the preceding vulnerability assessment, the adaptation strategies were evaluated the MCDA approach.
6.2 STUDY AREA

In Australia, most major cities, situated along the coastline, are threatened by natural hazards, mainly storm tides. Many rapidly growing coastal areas, such as in Queensland, have already been experiencing substantial impacts from storm related floods. It is expected that the projected sea-level rise and increased storm frequencies will increase these risks, particularly to urban infrastructure (The Allen Consulting Group, 2005).

According to a study by Geoscience Australia (2002), storm tides are the major problem for coastal areas, while storm events contribute about 29% of the total damage cost from natural hazards. In 1999 prices, this cost amounts to about $40 billion during the period 1967 to 1999, including the cost of deaths and injuries (Geoscience Australia, 2002).

One area that is vulnerable is the Gold Coast City, located in south-east Queensland. The city spans across 1402 km², featuring more than 270 km of navigable waterways, and 70 km of coastline from the Queensland-New South Wales border, in the south, to the Logan River and southern Moreton Bay, in the north, and from the coastal beaches in the east to the crest of the McPherson and Darlington Ranges in the west (GCC, 2008a).
The population of the Gold Coast grew from 214,949 in 1986 to 524,667 persons in 2007; it is expected to increase to 886,700 residents in the year 2031 (Queensland Government, 2008, ABS, 2008). The annual average population growth rate during the period of 1997 to 2002 was 3.46%, significantly higher than the Queensland and Australian population growth rates of 1.8% and 1.2%, respectively.

The Gold Coast region is an important economic centre. The Gross Regional Product (GRP) increased from $9.7 billion in 2001 to $15.6 Billion in 2008; it is projected to further increase to $17.3 billion in 2011 ( ). An important element of this GRP is tourism. The area is an extremely popular tourist destination, which attracts, on average, 82,000 tourists with $12.1 million expenditure daily (GCCC, 2008b).

![Gross Regional Product](GCCC, 2008b)

Figure 6-2 Gross Regional Product [Adapted from (GCCC, 2008b)].

In the region, the annual temperature is predicted to rise between 0.4°C and 2°C by 2030, and between 1°C and 6°C by 2070. A mid-range increase in sea-level is expected for the Gold Coast region: 11 cm by 2030, 18 cm by 2050, and 27 cm by 2070 (EPA, 2006). The coastal area for the Gold Coast encompasses a diverse range of features, including a barrier island (South Stradbroke Island), beaches and dunes, river deltas, bays, estuaries and wetlands, rolling foothills and low mountain ranges. Additionally, much of the eastern portion of the City is less than 10m above sea level (GCCC, 2007, Granger and Leiba, 2000). The maximum tidal range is 1.8m and on average the coast is affected by 1.5 cyclones each year (Boak et al., 2001).

Harper et al. (2000) estimated a number of various storm tide levels within Moreton Bay, between Cape Moreton and Point Danger. These numbers consider the combined
effects of tides, storm surges and wave setups. Relative to Australian Height Datum (AHD), the highest projected storm tide levels for the 50, 100, 500, and 1000 year events are 2.3 m, 2.5 m, 3.2 m and 3.5 m, respectively (Harper et al., 2000). As seen in Table 6-1, the heights of the storm events can vary even within a region, depending on the conditions in the area under question. For example; components of storm tides and storm tide level predictions (Figure 6-3) for three locations (Surfers Paradise, the Gold Coast Seaway, and the Coomera River Mouth) are shown in Table 6-1, In the current research, the vulnerability analyses were based on the highest storm surge estimation rather than on a figure that underestimated the impact of future events. The indicated storm tide level considers the combined effects of tide, storm surge and wave setup. The levels are given relative to the AHD; the highest expected tidal level (HAT) is also indicated (Harper et al., 2000).

![Figure 6-3 Components of a storm tide](Harper et al., 2000).

<table>
<thead>
<tr>
<th>Site</th>
<th>HAT</th>
<th>Average Recurrence Interval (ARI) years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m above AHD</td>
</tr>
<tr>
<td>Surfers Paradise</td>
<td>1.13</td>
<td>2.0</td>
</tr>
<tr>
<td>Gold Coast Seaway</td>
<td>1.13</td>
<td>1.9</td>
</tr>
<tr>
<td>Coomera River Mouth</td>
<td>1.03</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 6-1 Predicted storm tide levels for 3 locations on the Gold Coast (Harper et al., 2000)
Abbs et al., (2000) assessed the flood levels and damage estimates for the Gold Coast region by applying an atmospheric model of storm events, coupled with a non-linear flood event model (flooding by Cyclone Wanda, in 1974) region. They estimated that, if the same event happened in 2050, with a 10 to 40 cm rise in mean sea level, the number of dwellings and people affected would be likely to increase by 3% to 18% (Abbs et al., 2000).

Importantly, many of the residential areas in this low-lying coastal city are filled to the 1:100 year flood level. Consequently, if this level is exceeded, many thousands of dwellings will become affected by above floor flooding (Betts, 2002). In recognition of these threats, both the Queensland Government and the Gold Coast City Council have been developing short, medium and long term strategies. These strategies are based on various studies conducted in the region, and relate to: building and sharing knowledge, including climate change in decisions, and reducing vulnerability and increasing resilience to climate change (The Department of Natural Resources and Water, 2007, GCCC, 2001).

The area at the north of the Gold Coast was selected for the case study analyses (Figure 6-4). The area encompasses a diverse range of features, including sandy beaches, estuaries, coastal lagoons, and artificial waterways. As such it is suitable location for capturing the immediate impacts of the SLR and storm surges, due to their close proximity to the waterways. Further, the area is highly vulnerable to SLR due to its diverse topographic nature, as illustrated in (Figure 6-4).

In any planning scenario, it seems unwise to rely on the lower projections of the storm events in assessing vulnerability. It is always preferable to err on the side of caution, especially when developing strategies for the impact of future events. Therefore, the vulnerability analyses used the highest storm surge estimation provided by Harper et al., (2000).
6.3 SCENARIOS FOR VULNERABILITY ASSESSMENTS

6.3.1 SLR SCENARIOS

According to Nicholls et al., (2007), regional sea-level change will depart significantly from the global mean trends. Thus, while global sea-level rise scenarios are important, when assessing impacts, it is the local change in relative sea level that matters, not the global average (Feenstra et al., 1998). Nevertheless, due to our limited understanding and ability to develop regional SLR scenarios, Hulme et al. (2002) used only global mean SLR as the basis for their studies in the UK. They recommended that, to assess the full range of possible change, the scenarios should contain an additional sea-level rise of ±50% of the amount of global mean rise, plus uplift/subsidence, (Hulme et al., 2002). Since their studies, there have been significant improvements in understanding uncertainty, although there are still a large number of uncertainties associated with the regional sea level predictions.
The 2100 global SLR projections are in the range of 0.28 - 1.4 m, which includes 10-20 cm additional contributions from the potential icesheet process (Meehl et al., 2007, Rahmstorf, 2007).

A CSIRO projection, based on the IPCC Scenario SRES A1B (mid-range), for 2007, for the east coast of Australia, south of 30ºS, was a 10 cm (1.4 mm/year) additional rise above the global average change (Pearce et al., 2007). Importantly, geographically, the Gold Coast region is in close proximity to the area indicated in the CSIRO report. The same figure was to be used to calculate the relative sea level of the Gold Coast region. In light of the above information, a range of SLR scenarios, ranging from 0.5 m to 1.5 m, were used in this research (Figure 6-5).

The scenarios take into account the IPCC lower and upper range projections (including a 10-20 cm icesheet contribution), and Rahmstorf’s (2007) estimation, together with additional local adjustments. Thus, while the lower (0.5 m) and mid-range (1.0 m) scenarios match, approximately, to the relative SLR projections (the IPCC projection for global SLR added with CSIRO projection for local subsidence), the higher range (1.5 m) scenario combines the local subsidence with the global SLR projection proposed by Rahmstorf (2007). A one-hundred year time horizon is considered from the present through to 2110, which is consistent with most SLR scenarios developed by the IPCC.
6.3.2 STORM SURGE SCENARIOS

As discussed in detail in Chapter 2, a broad review of the literature indicates that frequency of sea level extremes of a given height are expected to increase due to SLR, even if the variability of the sea level about the mean does not change (Church et al., 2006, Meehl et al., 2007, Hunter, 2008, Cayan et al., 2008).

The 2007 CSIRO technical report estimates that about 10 per cent of the population, and 2.9 per cent of residential buildings, in south-east Queensland may be currently at risk from inundation associated with a ‘current climate’ 1-in-100 year storm surge event. Under climate change, this could increase, by 2030, to 14 per cent of the south-east Queensland population and 5.2 per cent of residential buildings, without factoring in population growth (Pearce et al., 2007).

As shown in Table 6-1 above, the storm tide height estimations, by Harper et al. (2000), for the region (including the study area) are 2.3 m, 2.5 m and 3.2 m for 50, 100 and 500 year Average Recurrence Intervals (ARI), respectively.

Mindful of this, and assuming that the sea level rises linearly through to 2100, with a total 1 m increase, the 50 year storm surge elevation, in 2100 (3.3 m), would be higher than the 500 year storm surge elevation today (estimated at 3.2 m).

Using the above data, and based on three SLR scenarios, a range of storm events were plotted for Moreton Bay, Australia (Figure 6-6) in Excel. Using the trend-line in the chart, Equation 6-1 and 6-2 which generate the trend-line coefficients were created. By using these equations, for the current conditions, the ARI and the height of a given event were calculated.

Height:

Equation 6-1

ARI:

Equation 6-2

The lowest line (blue) represents the current condition, while the other three lines
show future conditions under three SLR scenarios, 0.5 m (red line), 1 m (green line), and 1.5 m (purple line), respectively.

Future conditions were also calculated by adding 0.5 m, 1 m and 1.5 m sea level rise to the equations. As seen in Table 6-2, given a 1 m SLR by the end of the century, a current 1-in-100 year storm event would eventually become a 1-in-10 year event. In other words, with 1 m SLR, future 1-in-100 year storm event heights would reach 3.50 m.

<table>
<thead>
<tr>
<th>ARI (Years)</th>
<th>Storm Surge Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current</td>
</tr>
<tr>
<td>10</td>
<td>1.6</td>
</tr>
<tr>
<td>50</td>
<td>2.3</td>
</tr>
<tr>
<td>100</td>
<td>2.5</td>
</tr>
<tr>
<td>500</td>
<td>3.2</td>
</tr>
<tr>
<td>1000</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Table 6-2 Changing ARI with changing SLR conditions
For assessing the impact of 1:100 year Storm Surge (SS), the research utilises the following approaches:

1. Firstly, it calculates the changes in the ARI of the current 1:100 year storm event, and its impact on population and properties; and
2. Then, the future SS heights values are calculated, by the vulnerability model, using the above equations, to assess the impact of storm events over time.

6.3.3 POPULATION SCENARIOS

The size of community and its population growth depends on a number of factors, such as: the birth and death rates, employment opportunities, housing, infrastructure, climate, etc. Thus, a population model should cover all the essential factors to predict the future population; these factors need to be incorporated into the DSM for a more realistic vulnerability analysis. Regrettably, this scope is beyond the current focus of this research.

Therefore, the population scenario used as the foundation for this research is taken from the Queensland Government’s own projection (Queensland Government, 2008). According to the projection, the Gold Coast population is anticipated to increase by 2.2% (by 2031). However, rather than limiting the users to a single growth rate projection, the research here has employed a range of population growth scenarios ranging from -4% to 4%. This approach enables users to modify the population growth rate in order to accurately assess the vulnerable population by applying various scenarios.

6.4 VULNERABILITY ASSESSMENT

6.4.1 INPUT DATA

The fundamental starting point for any assessment study is the acquisition of basic data for a number of important parameters that characterise the study area (Feenstra et al., 1998). Since SLR is a fact, with long-term implications, it is important that any research on vulnerability and adaptation assessment to SLR be based on the most relevant information at hand In the present study, such information includes high
resolution LIDAR data, accurate land use data, census data, and regional projections of SLR. Hence, it is important to obtain the most accurate data available to reduce the uncertainty of climate models, as well as to improve our understanding of the ongoing changes. Thus, gathering information on a particular area is possibly the most significant challenge for coastal modelling and analyses.

Supporting data for these analyses often spread across multiple datasets. Therefore, coastal modelling also requires that gathered information be linked across these multiple datasets. Additionally, the availability of datasets also determines the extent of the model and vice versa. For example, if the purpose of modelling is to assess vulnerability in a particular area, then high resolution DEM is required, so that greater levels of detail are reflected. A major problem occurs because most data is held by government departments and are often classified as sensitive information. Therefore, frequently the data are incomplete, unavailable, or difficult to access.

This hurdle was also experienced when acquiring data for the current study. Nevertheless, obtaining specific datasets (such as DEM, land use and flood surface) were crucial for the research. As the researcher was aware of these difficulties and sensitivities in obtaining such datasets, the government sources were approached at the very earliest stages of the research.

However, despite obtaining some datasets within a reasonable time frame, it took a considerably longer time to obtain the DEM, flood surface, and land use datasets. Furthermore, the owner of the required datasets would only share the datasets for a specific, and much smaller, geographical area, instead of for the greater city as a whole. Consequently, obtaining the data acquisition took much longer than expected, and the original study area was reduced to a much smaller size. Nonetheless, the quality of the datasets was ample to carry out a detailed vulnerability analysis.

As any analysis, performed using a GIS, relies heavily on the accuracy of the data. The current data needed to be able to be used in confidence. This is especially so, as the GIS, is used as a visual spatial analytical tool, to process the data, and to develop input parameters for the temporal model. For this reason, and in order to obtain more
complete datasets, the researcher obtained a number of datasets from different sources. A summary of the datasets are shown in Table 6-3:

<table>
<thead>
<tr>
<th>Required Datasets</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 m DEM with 0.1 m vertical accuracy</td>
<td>Gold Coast City Council (GCCC)</td>
</tr>
<tr>
<td>Land use shape file</td>
<td>GCCC</td>
</tr>
<tr>
<td>Flood surface shape file</td>
<td>GCCC</td>
</tr>
<tr>
<td>Canal &amp; Lakes shape file</td>
<td>GCCC</td>
</tr>
<tr>
<td>Creek &amp; rivers shape file</td>
<td>GCCC</td>
</tr>
<tr>
<td>Wetland shape file</td>
<td>GCCC</td>
</tr>
<tr>
<td>Waterways shape file</td>
<td>GCCC</td>
</tr>
<tr>
<td>DCDB - Digital Cadastral Database</td>
<td>Queensland Government - Department of Natural Resources and Water</td>
</tr>
<tr>
<td>Census Data</td>
<td>Australian Bureau of Statistics</td>
</tr>
</tbody>
</table>

Table 6-3 Fundamental datasets used for the vulnerability assessment.

Within the current study, the coastal elevation data was a critical factor in determining the area’s vulnerability to inundation. Therefore, the inherent accuracy of the underlying data, and its effects on any vulnerability assessments, were important features required authentication. As discussed in section 5.4.3.2.2, using high-resolution, high-accuracy elevation data ensures the development of improved capabilities for any vulnerability assessment.

The elevation data used in the present research for the study area supports an assessment using a SLR increment of 0.1 m. This small increment is particularly important for narrowing down the uncertainty range of the elevation dataset resulting from the level of data accuracy. Thus, the use of such elevation data improves the researcher’s ability to conduct detailed assessments, as well as the user’s understanding of the technical issues to properly apply the information in local decision making setting.

6.4.2 IMPLEMENTATION OF SPATIAL-TEMPORAL ASSESSMENT TOOL

Vulnerability analyses report metrics are important for the decision making process. As discussed in Chapter 5, the analyses of vulnerable land, and the population living there, can be conducted using a number of steps. Figure 6-7 shows the process of vulnerability assessment using the hybrid DSM.
For automating the current work flows within the GIS based spatial model, the Model Builder (a part of the ArcGIS geo-processing framework (ESRI, 2009)) linked the data input, the ArcGIS tools and functions, and the data output. The main advantage of using the model builder for GIS work is that the processes can be automated without the use of any code. Its robust and flexible data management capability provides a seamless integration between the spatial model and the temporal model, through the data convertor. A number of models within the model builder were created to process the following datasets and to view the data output. The first exogenous data obtained from the various sources were entered into the GIS based spatial model and clipped to the study area extent, as seen in Figure 6-8.
Next, the natural waterways, the creeks and rivers, and the waterways layers were combined with the land use layer; the new land use layer was reclassified to generate a composite new layer with attributes from each source dataset (e.g. Sea, Waterways, Pond, and Land). This process was done using the union tool in the model builder as, shown in Figure 6-9, to create a new coverage by overlaying the four polygon coverages. The Output Coverage contains the combined polygons and attributes of all coverages.

Then, to encapsulate the data by elevation, the vector formats were converted into raster formats to match the DEM data. The conversion took into consideration the
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DEM accuracy; thus, the size of all the generated raster cells was based on a 5-m cell size to match the DEM data (Figure 6-10).

Following this process, the raster data were formatted into ASCII format (Figure 6-11). ASCII, a device independent file format, is used by both SD and GIS applications, regardless of the hardware and software platforms. Consequently, a suitable file format was used in the case of integration of GIS and SD, while the ASCII files were exported to the temporal model component through the data converter. Using the initial spatial input data, imported from the GIS, the SD model (Figure 6-12) simulated the effect of sea level rise on Elevation, and Cover Type, over a period of 100 years.
As discussed in Chapter 5, the structure of the SD model is, in the main, defined by equations, and stock and flow, diagrams. Other settings, such as Time Bounds and Units Equivalents are made using the Model Setting dialog box. All SD models have the Initial and Final Times over which the simulation occurs, as well as the Time Step for integrating, and the Saveper for saving results (Ventana Systems, 2009). A summary of the SD model settings for the current study is provided below:

- **Initial Time**: 2010
- **Final Time**: 2110
- **Time Step**: 1/32 year
- **Saveper**: 10
- **Units for time**: Year

The SD model used for vulnerability analyses, here, had 2,997,414 variables, including all model variables, after fully expanding all subscripted variables.

In the present study, the changes in these variables were captured, then stored in a tab file with a 10 yearly interval, and exported to the spatial model for visualisation through the data converter. As illustrated in Figure 6-13, the time interval (Saveper) was set to 10 years because it was not possible to capture the changes that were less than 0.1 m in Elevation (and, therefore, the changes in Cover Type), since the vertical accuracy of the elevation data was limited to 0.1 m.

Subsequently, the file was exported using the setting, and the values run from 0 to 100 years by 10, thus, indicating that the model would export values for the selected variables at every 10 years, and ignore the intermediate values. This result, in the output file, appears as:

<table>
<thead>
<tr>
<th>Time</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>...</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation [x1,y1]</td>
<td>1.10</td>
<td>1.10</td>
<td>1.20</td>
<td>...</td>
<td>2.00</td>
</tr>
<tr>
<td>Elevation [x1,y2]</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>...</td>
<td>1.60</td>
</tr>
<tr>
<td>Elevation [x1,y3]</td>
<td>0.80</td>
<td>0.90</td>
<td>1.00</td>
<td></td>
<td>1.80</td>
</tr>
</tbody>
</table>
Next the dataset in tab format was converted into an ASCII format for use in the GIS. Based on the time interval setting, the converter created a new file for each time step, then, the files were transferred into the GIS for visualisation. Upon receiving the new files, the GIS converted each ASCII file into a raster file through use of the model builder (Figure 6-14).

Finally, the spatial model generated the time series maps that showed changes in the study area; at the same time the temporal model calculated the vulnerable Population and Area over time, and produced related graphs and tables. Figure 6-15 provides sample output figures that show three different stages of an area’s inundation, over time, under a 1 m sea level rise scenario.
The results of these processes are further discussed in the following section.

6.4.3 RESULTS

A SLR increases the risk of flooding in low-lying areas. Hence, the decision to live or build in a low-lying coastal area is one of the most important decisions that people make in relation to SLR. For the current study, the inundation risks were considered as a consequence of SLR and coastal flooding caused by storm surge events.

Firstly, due to diminishing drainage capacity, rising sea levels would result in the flooding of nearby waterways. Further, an increased water elevation at the mouth of waterway would bring about the overflow and cause upstream inundation. (Flooding caused by rainfall and its impacts are not evaluated here.)

Therefore, to assess the impact of SLR in the study area, especially in terms of land area being at risk of inundation, and the population being exposed to the consequences of this risk, the SLR was calculated for a given scenario and model, over a period of one hundred years. Based on these values in SLR, the DSM was then used to estimate the area that would be inundated. Next, the possible impacts of SLR were estimated in terms of the population to be affected.

The study also assessed the impact of storm events in the area. To undertake this portion of the study, the height of a 1:100 year storm surge was added on top of the SLR estimation to project future storm surge levels. An apparent hypothesis was that some areas would become flood prone, even if not permanently submerged. Further, the population and the properties within theses area would also be affected by SLR and storm activities.
Using the values calculated for future storm surge levels, the DSM was used to predict the extent of the flood prone areas that would be affected by storm events. The results of the model, presented here, were generated using three SLR scenarios (ranging from 0.5 cm to 1.5 cm per year).

6.4.3.1 CURRENT VULNERABILITY ASSESSMENT

In any given area, changes in sea level, due to extreme conditions (such as a storm surge), pose a threat to coastal systems, including people and properties. Inevitably, increased coastal flooding, resulting from these extreme conditions, will lead to evacuations, the destruction of homes and property and, possibly, the loss of lives.

To determine the populations and land areas at risk in the present study area, the current vulnerability conditions were assessed. The 100-year flood levels (a measurement standard widely used for planning) were used to evaluate the area’s vulnerability to coastal flooding. Based on the 1:100 year storm surge conditions (approx. a 2.5 m event), the vulnerable area and population were identified. The results indicate that the study area is already highly vulnerable to extreme conditions, such as 1:100 year storm events.

Using the DSM, with an assumption of zero SLR, currently 86% of the land area, and 83% of the population, are susceptible to 1:100 year storm events (Figure 6-16). However, for a 1:10 storm event (approx. a 1.6 m event), 56% per cent of the land would be under threat of flooding, while only 7% of the population would be affected.

<table>
<thead>
<tr>
<th>Current condition in the study area</th>
<th>56%</th>
<th>86%</th>
<th>83%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vulnerable Area (1/10 yr SS)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vulnerable Area (1/100 yr SS)</td>
<td>56%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vulnerable Population (1/10 yr SS)</td>
<td></td>
<td>86%</td>
<td></td>
</tr>
<tr>
<td>Vulnerable Population (1/100 yr SS)</td>
<td></td>
<td></td>
<td>83%</td>
</tr>
</tbody>
</table>

Figure 6-16 Vulnerable area and population to 1:100 SS in the study area
This analysis implies that a 0.9 m increase in storm surge height would cause a 76% increase in the vulnerable population, and an increase (though relatively smaller, at 30%) in the vulnerable land area. Further, the assessment highlights that a 100 year storm event would have devastating impacts on the people residing in the inundated area.

Importantly, the nature of flooding is that it is a random event; hence, there is the chance of a flood in any year, independent of past events. However, the probabilities that a 1:100 year storm event will occur during a given period can be calculated using exceedance probability (Mansell, 2003). Thus, based on exceedance probability theory, the likelihood of a storm event that will not happen over a 50 year period can be calculated for a study area, using the following variable definitions:

- **P**: Exceedance probability that an event level will be exceeded during a one year interval, which is defined as $1/T$
- **$P_0$**: General exceedence probability that exceeded during a $n$ year interval
- **T**: return period (ARI) is defined as $1/P$

Therefore, if an event has a $P$ percent exceedance probability in a given year, then,

The chance that the event will not occur in a given year is:

$$= 1 - P$$

The chance that an event will not occur in $T$ successive years is

$$= (1-P)^T$$

Then, the chance that a 100-year storm event will not occur over 50 years:

$$= (1-1/100)^{50}$$

$$= 0.61$$

The probability that it will be exceeded during the $T$-year return period is:

$$= 1 - (1-P)^T$$
Thus, it can be assume that, in the study area, there is a 61% chance that a 100-year storm will not occur over a 50-year period; and a 39% chance that it will occur. Similarly, there is a 63% probability that an event, with a 100-year return period, will be exceeded during a 100-year period, and a 37% chance that it will not be exceeded. From these results, the location of the susceptible areas to flooding were mapped; they are included in the accompanying CD-ROM (PresentationCD.ppsx).

6.4.3.2 FUTURE VULNERABILITY ASSESSMENT

To determine the effect of changes in vulnerable populations and land areas over time, the Cover Type and Elevation data were simulated under a number of SLR and SS scenarios. The changes were captured in a SD model and exported to a GIS model for visualisation. The inundation layer was overlayed with the 2001 ABS census data, which was aggregated by census parcel for the area.

The population was assumed to be distributed evenly within a parcel boundary (as discussed in Chapter 5). Further, the estimates of populations at risk were based on the current population data and the projected populations. However, the DSM allows the users to change the population projections so that they can better understand the impacts of the changing conditions. Within the future vulnerability assessments, the major land cover categories were: Sea, Waterways, Pond, and Land. The storm surge heights were assumed to increase by the same amount as the SLR (this assumption, however, may not always be true).

Figure 6-17 presents a series of flood maps generated by the model. It shows the extent of the areas at risk due to rising sea level, over a period of 100 years. (A complete range of the maps created to quantify risk in the area under various scenarios can be found in the accompanying CD-ROM).
<table>
<thead>
<tr>
<th>Year</th>
<th>Scn1</th>
<th>Scn2</th>
<th>Scn3</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td><img src="image" alt="Map for 2010 Scn1" /></td>
<td><img src="image" alt="Map for 2010 Scn2" /></td>
<td><img src="image" alt="Map for 2010 Scn3" /></td>
</tr>
<tr>
<td>2020</td>
<td><img src="image" alt="Map for 2020 Scn1" /></td>
<td><img src="image" alt="Map for 2020 Scn2" /></td>
<td><img src="image" alt="Map for 2020 Scn3" /></td>
</tr>
<tr>
<td>2030</td>
<td><img src="image" alt="Map for 2030 Scn1" /></td>
<td><img src="image" alt="Map for 2030 Scn2" /></td>
<td><img src="image" alt="Map for 2030 Scn3" /></td>
</tr>
<tr>
<td>2040</td>
<td><img src="image" alt="Map for 2040 Scn1" /></td>
<td><img src="image" alt="Map for 2040 Scn2" /></td>
<td><img src="image" alt="Map for 2040 Scn3" /></td>
</tr>
<tr>
<td>2050</td>
<td><img src="image" alt="Map for 2050 Scn1" /></td>
<td><img src="image" alt="Map for 2050 Scn2" /></td>
<td><img src="image" alt="Map for 2050 Scn3" /></td>
</tr>
<tr>
<td>2060</td>
<td><img src="image" alt="Map for 2060 Scn1" /></td>
<td><img src="image" alt="Map for 2060 Scn2" /></td>
<td><img src="image" alt="Map for 2060 Scn3" /></td>
</tr>
</tbody>
</table>
Figure 6-17 Flood maps generated by the model
SLR Scenarios: Scn1 = 0.5 cm/year, Scn2 = 1 cm/year and Scn3 = 1.5 cm/year.
Figure 6-18, and Figure 6-19 show the vulnerable population and land area to a 0.5 m, 1.0 m, and 1.5 m SLR. As seen from the figures and tables, as the sea levels rise, the area and the number of people vulnerable to flooding also rises.

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
<th>2060</th>
<th>2070</th>
<th>2080</th>
<th>2090</th>
<th>2100</th>
<th>2110</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scn1</td>
<td>0.138</td>
<td>1.54</td>
<td>1.72</td>
<td>1.87</td>
<td>2.09</td>
<td>3.63</td>
<td>4.07</td>
<td>4.40</td>
<td>4.97</td>
<td>5.99</td>
<td></td>
</tr>
<tr>
<td>Scn2</td>
<td>0.148</td>
<td>1.87</td>
<td>3.63</td>
<td>4.40</td>
<td>5.95</td>
<td>9.39</td>
<td>13.75</td>
<td>19.24</td>
<td>26.90</td>
<td>33.89</td>
<td></td>
</tr>
<tr>
<td>Scn3</td>
<td>0.160</td>
<td>3.63</td>
<td>4.89</td>
<td>9.39</td>
<td>15.89</td>
<td>26.65</td>
<td>35.78</td>
<td>42.90</td>
<td>47.99</td>
<td>55.70</td>
<td></td>
</tr>
</tbody>
</table>

Table 6-4 Area at risk under three SLR scenarios

Figure 6-18 Graphical representation of area at risk

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
<th>2060</th>
<th>2070</th>
<th>2080</th>
<th>2090</th>
<th>2100</th>
<th>2110</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scn1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Scn2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
<td>0.07</td>
<td>0.13</td>
<td>0.18</td>
<td>0.33</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>Scn3</td>
<td>0.00</td>
<td>0.01</td>
<td>0.03</td>
<td>0.07</td>
<td>0.15</td>
<td>0.33</td>
<td>0.54</td>
<td>0.92</td>
<td>1.48</td>
<td>7.06</td>
<td></td>
</tr>
</tbody>
</table>

Table 6-5 Population at risk under three SLR scenarios
The results of the assessment indicate that, at the end of a 100 year simulation period, approximately 6% of the landscape in the study area will be gradually inundated over time, with 0.5 cm SLR per year. Importantly, a 0.5 m SLR does not pose any significant threats to the local population. However, this situation dramatically changes with scenarios 2 and 3, which represent 1 cm and 1.5 cm SLR per year. Indeed, the percentage of the vulnerable area leapt to about 34% for Scenario 2, and 56% for Scenario 3 (Table 6-4, Figure 6-18, Table 6-5 and Figure 6-19). The most noticeable changes occur after the first 25 years. Further, the rate of inundation becomes much higher after the first 50 years of the simulation period for both scenario 2 (1 m SLR) and scenario 3 (1.5 m SLR).

Although a substantial fraction of the landscape is threatened by the rising SLR, the percentage of the population that can be classes as vulnerable is relatively low for Scn2 and Scn3 scenarios, only 0.5% and 7%, respectively. The answer lies with most of the population residing at high altitudes. Nevertheless, the population located near waterways and coastal strips was especially vulnerable.

Further, as inundation occurs at the water – land interface, the land area in close proximity to the sea, and around water bodies, were identified as the most vulnerable...
areas. The rising sea quickly penetrates inland through waterways and submerges the vulnerable areas around them, thus, putting the people currently living in those areas at risk.

From Figure 6-18 and 6-19 it can be seen that the areas inundated show a nonlinear response to SLR (which reflects the distribution of the elevations of the area). Indeed, about 6% of the study area landscape will be submerged if the sea level rises a 0.5 m by 2110 (Table 6-4). Hence, the area at significant risk will be increased, up to 34% and 56% with a 1 m and 1.5 m rise in sea level, respectively. However, the inundation will, generally, be restricted to fringing shorelines and finger waterways margins (Figure 6-17). Additionally, although, up to 56% percent of the land area will be facing the risk of inundation, the impacts of the same SLR scenarios on the residential areas are much smaller, as shown in Figure 6-19 and Table 6-5.

The simulation results predict that the residents in the area are safe from a sea level rise of up to 1 m. Nonetheless, about 7% of residents face the risk of inundation with a 1.5 m rise in sea level within 100 years (Table 6-5). It appears that the year 2100 is a critical point; the analysis shows that the threat posed by a 1.5 m SLR demonstrates a sharp increase, jumping from about 1.5 % to 7 %. Thus a 1.5 m SLR may be the tipping point that leads to a rapid and irreversible change in the inundation area.

The current assessment also addressed the SLR impacts, the combined effects of the predicted sea level rise and storm surge events. Figure 6-20 and Figure 6-21 present a summary of the predicted changes for the vulnerable populations and land areas for a 100 year simulation period, based upon a combination of SLR and SS scenarios. The results of the combined impacts show that a 0.5 m SLR, combined with a 100 year storm event will increase the vulnerable population from 83% to 90%. With a greater SLR of 1 m and 1.5 m, the vulnerable population increases from 83% to 92%, and 83 % to 93%, respectively.
Figure 6-20 Vulnerable population under 3 SLR and SS scenarios

Perhaps not unexpectedly, the impacts on the land area show similar trends (Figure 6-21). Therefore, a 0.5 m SLR combined with a 100 year storm event increases the vulnerable area 3%, from 86% to 89%. However, with 1 m and 1.5 m SLR, the vulnerable population increases from 83% to 92 percent, and 83% to 93%, respectively.

Figure 6-21 Vulnerable area under 3 SLR and SS scenarios
6.4.3.3 POTENTIAL PHYSICAL AND SOCIO-ECONOMIC IMPACT

The resolution of the model used in the current research appears to be sufficient to detect areas that have the potential to be inundated by SLR and the associated storm surges. This detailed analysis of storm surge behaviour, which included the use of high-resolution data and a socio-economic analysis, has provided important information on the potential impacts of SLR.

The following range of parameters were used to describe the exposure to, and risk of, flooding for the coastal population and land area: a 100 year storm surge event, increased over time; an increase in storm surge frequency; and changes in the 100 year SS height over time. The analysis also identified new flood prone areas and populations due to changes in the frequencies of 1:100 year SS over time.

In the literature, coastal flooding is often described by its average recurrence interval (ARI), which is the period of time between floods of a particular intensity, based on historic conditions for a given area. The terminology used to define the 1:100 year flood ARI refers to a flood that has a 1% probability of occurring in any year.

For the study area, the potential future flood impact was calculated by adding the SLR projections to the height of a current 1:100 year flood event. That is, the current 1:100 year flood level was increased by 0.5 m, 1m and 1.5 m, to correspond to the three sea level rise scenarios, respectively (Figure 6-22). Thus, an increase in SLR would also increase the frequency and intensity of flood events. As seen in Figure 6-23 and Table 6-6, a 1:100 year flood event could become a 1:3 year, even if the sea level rises 1.5 m during the next 100 years.

At present, the 100 year storm event projected for the study area, when combined with SLR, will reach up to 3 m, 3.5 m, and 4 m for the three scenarios of 0.5 m, 1 m and 1.5 m SLR, respectively. Hence, depending on the SLR scenarios, the ARI of the current SS events could be significantly reduced.
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Figure 6-22 Changes in future SS elevations due to SLR

Figure 6-23 Changes in 100 year flood ARI

Table 6-6 Changes in 100 year ARI under three SLR scenarios
For example, given a 0.5 m SLR over a period of 100 years, a 100 year SS event would become a 30 year event in 2110, while it becomes a 9 year event with 1 m SLR, and a 3 year event with 1.5 m SLR. Therefore, the people living in the area would experience more frequent extreme events in the future.

To compute the potential impacts of a rising sea level on already highly vulnerable populations and land areas, along with a 1:100 year storm event, the current 1:100 year SS height was gradually increased by 0.5 cm, 1 cm and 1.5 cm per year, over a hundred year period. This adjustment was based upon the three SLR scenarios previously used. As shown in Table 6-7, a rising sea level will further increase the cumulative percentage of the vulnerable population and land area. As a result, and depending on the SLR scenario, vulnerabilities from a 100 year SS will increase from 4% to 7% for the population, and between 8% and 11% for the land area. This outcome indicates only a small increase, as the area is already highly vulnerable to a current 100 year SS event. Nevertheless, this small increase, combined with the increase in ARI, would be devastating. Specifically, the impact will be more frequent and more damaging floods that increase the size of the coastal floodplain, placing new areas at risk for the first time.

<table>
<thead>
<tr>
<th>Year</th>
<th>People at Risk of 1:100 yr SS (%)</th>
<th>Area at Risk of 1:100 yr SS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLR= 0.5 m</td>
<td>SLR= 1 m</td>
</tr>
<tr>
<td>2010</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>2020</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td>2030</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td>2040</td>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>2050</td>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>2060</td>
<td>2%</td>
<td>4%</td>
</tr>
<tr>
<td>2070</td>
<td>3%</td>
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<td>2080</td>
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<td>3%</td>
<td>5%</td>
</tr>
<tr>
<td>2110</td>
<td>4%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Table 6-7 Increase in Area and Population at risk of 1:100 yr SS due to SLR
6.5 MULTI-CRITERIA DECISION ANALYSIS FOR ADAPTATION OPTIONS

The findings from the vulnerability analysis provide the data for an evaluation of the adaptation alternatives, using a Multi Actor – Multi Criteria Decision Aid (MA-MCDA) technique. This process is important as there is a need for a new approach that can evaluate alternative adaptation strategies, which many of the available vulnerability assessment methods cannot do (as discussed in Chapter 5). According to (Carter et al., 2007), adaptation assessment accommodates a wide range of methods used in mainstream policy and planning. To narrow the gaps in vulnerability and adaptation research, they suggest the creation of a list of research high priorities, namely: the integration of scientific information on impacts, vulnerability, and adaptation in decision making processes. In this respect, the fifth component of the current framework focuses on linking vulnerability assessment with the evaluation of adaptation alternatives through the use of multi-criteria analysis and multi-stakeholder consultation.

Generally, most environmental problems are regarded as an MCDA problem, which involves various stakeholders with conflicting interests. Nevertheless, stakeholder involvement is one of the most important aspects of the decision making process in democratic societies. Such involvement will often improve the community’s understanding and increase the likelihood of more applicable decision making.

The large body of the literature emphasises the importance of stakeholder participation in the decision making process on environmental issues, which are complex, uncertain, and vary in time and space (van den Hove, 2000, Willows and Connell, 2003, Lim et al., 2004, Adger et al., 2007). Additionally, such involvement is a crucial in refining the methodologies, disseminating the vulnerability information, and successful implementing the adaptation strategies.

Although there are many definitions, in the literature, for the term stakeholder, in the current study, the following IPCC definition is used as it refers to (Parry et al., 2007): ‘people or organisations, who have an investment, financial or otherwise, in the consequences of any decisions taken’. Here, along with the expert DMs, two other
important stakeholder groups, within the Gold Coast region, were also included in the decision making process: the Residents, and the Politicians.

To achieve and facilitate a workable process to reduce the vulnerability of an area and a population to SLR, a hierarchical (AHP) structure was developed. The goal, criteria and adaptation alternatives were derived, and based upon, adaptation programs, existing adaptation works by local governments, and an extensive literature review (including articles, reports and studies on adaptation techniques). The final structure was developed after further consultations with the local stakeholders (Figure 6-24).

The goal used in the AHP structure was: To Reduce Vulnerability to SLR. This goal encompasses the idea behind the entire effort to reduce the negative impacts from climate change, specifically SLR, on the Gold Coast. This goal, however, is not specific to any particular stakeholder group; rather, the goal was specifically designed with the differences of each stakeholder group in mind. The Applicability of this goal across the three stakeholder groups was identified as helping to unify the wider community in their attempts to tackle the climate change issues in a holistic approach.

The criteria used in the decision making process to evaluate the alternatives, with respect to the goal, were: Applicability, Effectiveness, Sustainability, Flexibility, and Cost. The definitions for these criteria are:
• **Applicability:** the level of ability for adaptation alternatives to be implemented and integrated into current and future systems that deal with the negative impacts climate change, including sea level rise. It implies that the adaptation alternative will be able to cater for the varying circumstances of the stakeholders it will affect.

• **Effectiveness:** how successful an adaptation alternative is at achieving its intended purpose.

• **Sustainability:** how a particular adaptation alternative will change over time with respect to the negative effects from a changing climate, such as sea level rise and whether the success is continual for a sustained period of climate change.

• **Flexibility:** from an adaptation alternative perspective, means that any alternative to be applied must be able to change with a changing environmental climate. Flexibility also implies that any applied alternative must be modifiable for a particular region’s characteristics.

• **Cost:** It refers to the price of designing, implementing and maintaining an adapation action. This involves the consideration of monetary cost (as opposed to emotional, physical or social cost for example). The action should be economically feasible.

The five chosen adaptation alternatives, aimed at reducing SLR vulnerability, were: **Retreat, Improve Building Design, Improve Public Awareness, Build Protective Structures, and Take No Action.** The definitions of these hierarchical elements are:

• **Retreat:** the conscious decision of residents and policy-makers to abandon or relocate from property and land that is under threat from damage due to sea level rise or possible flooding. It may be necessary for governments to intervene to ensure the safety and well-being of the public in high risk areas.

• **Improve Building Design:** the necessary changes to the planning, design and construction phase of buildings are applied with the aim of preventing flood damage. Practical changes include ensuring that the base of new homes is above the projected future flood level and for any parts under this level flood resistant materials are used.
• **Improve Public Awareness:** the main focus is to keep members of all stakeholder groups informed about the impacts and negative consequences of flooding and sea level rise. Public discussion forums within these relevant groups will lead to the education of the wider community.

• **Build Protective Structures:** building physical structures that will actively prevent the encroaching sea level. These include sea walls, embankments and dykes.

• **Take No Action:** the acceptance of the risk, rather than bearing the costs of adaptation.

As seen in Figure 6-24 above, the hierarchical structure contains the goal, criteria and adaptation alternatives, but not stakeholders. The stakeholders were purposely excluded from having a dedicated level within the hierarchy, so that a uniform format of responses could be obtained from each of the three stakeholder groups. If the stakeholders had been included in their own level, within the hierarchy structure, then the overall solution to the goal would be influenced by the priority assigned to each of the stakeholder groups in that level (i.e. the stakeholder groups would be weighted).

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While several multiple criteria analysis case studies, concerning resource management, involve multiple stakeholders, Harrison and Qureshi (2000) posit that, aside from a few exceptions, that weights were not strategically assigned to stakeholder groups, or no weights were assigned. It appears, then, that the clear identification of stakeholder groups within the Gold Coast region, combined with a decision to avoid assigning weights to the stakeholders, is a unique application of the AHP.
The same hierarchy structure (and hence, the same objectives), were used for all participating stakeholders, which allowed them all to respond to a uniform set of questions. Consequently, a comparison and identification of the differences between the stakeholder groups allowed for a preferred solution to be specific for a particular stakeholder group. As a result, the three datasets (the same types of data for each the stakeholder group) allowed for a comparison and identification of the differences between the stakeholder groups. The use of the AHP in this way allows for flexibility when combining the participants' responses.

6.5.1 SURVEY QUESTIONNAIRE DESIGN AND DATA COLLECTION

The AHP process requires participant stakeholders to make judgements based upon the various levels in the hierarchy. This process can be executed in several ways (as discussed in section 5.4.4.2), namely:

- Focus meetings with members from only a particular stakeholder group. At this meeting, the group would discuss the goal, criteria and alternatives and, then, make decisions based upon their opinions.
- A variation of the above focus group scenario, including all participants from multiple stakeholder groups.
- Individual contact with stakeholders (in person, via email or phone calls) to identify if they would be willing to complete a survey questionnaire to obtain their responses.

The advantage of individually handing out survey questionnaires to stakeholders, allows for: honest opinions to be conveyed without influence from other stakeholders; and the participants to complete their survey at a time suited to their schedule. Therefore, the survey questionnaire was chosen as the best method for obtaining stakeholders’ opinions. A sample page from the survey questionnaire is given in Figure 6-25. The complete survey questionnaire is also provided in Appendix 5.
The participants (local residents, experts, and politicians) were recruited by:

- Door knocking local residents living near or on waterfront properties, and asking for verbal consent to participate in the survey via hard copy or via email;
- Networking the Experts (including scientists, researchers and other academics) via professional forums; and
- Directly contacting politicians (the regional politicians, including Members of Parliament, and local councillors).

The completed questionnaires contained the participants’ opinions of the relative importance of the decision alternatives (pair-wise), with respect to the research goal and criteria.

### 6.5.2 DATA ANALYSIS

Thirty-three questionnaire responses were received between June and November 2010. The final sample size for each stakeholder group was: 19 for Residents, 10 for Experts, and 4 for Politicians (out of the 16 approached)
Disappointingly, only a quarter of the politicians surveyed responded. There may be several reasons for this. For example, the surveyed Politicians:

- Do not believe in the issue of climate change and the predicted negative impacts to the environment;
- Did not have time to take part in the survey to identify the adaptation alternatives for high risk areas in the Gold Coast region; and
- Do believe in climate change, but refused to acknowledge that there may be looming problems regarding sea level rise.

These explanations confirm the findings of a survey of Australian politicians conducted in 2010 (Hoegh-Guldberg et al., 2010), which showed that a clear majority of Politicians believed climate change was happening; however, many appear unsure about some of its consequences. Of the greatest concern, however, is that a large number of Australian political leaders do not feel compelled by the overwhelming scientific case for climate change.

In terms of the current study, an important issue for disquiet is the size of the sample of each stakeholder group. Especially in the case of the four political participants; therefore, the sample size is considered too small for the generalisation of the results to the overall population of Experts and Residents. On the other hand, the AHP is not a statistical technique. As clearly attested to in a recent study, AHP is a subjective method, and so it is not necessary to involve a large sample (Wong and Li, 2008), and additionally, the survey process may be impractical with a large ‘cold-called’ sample, as the participants may have a tendency to provide arbitrary answers, resulting in a very high degree of inconsistency (Cheng and Li, 2002).

Further, the importance of sample size for probability sampling in multiple criteria analysis is questionable (Harrison and Qureshi, 2000). Hence, AHP is a decision making technique that provides the objective mathematics to solve complex decision making problems. Consequently, a smaller sample size is adequate for implementing the AHP technique. The important concern relates to whether these few responses accurately represent the stakeholder groups to which they belong. The following discourse provides the answer for the case in question.
The AHP was initially created to assist a single DM in finding a solution to a problem with multiple and, possibly, conflicting criteria. Therefore, when the AHP is implemented with multiple actors (or participants), the geometric mean is used to aggregate the participants’ responses into single values (which represents the collective decision of all participants). This notion can be extended to the practice of aggregating participants responses from different stakeholder groups, i.e. all responses from Residents compared to all responses from Experts as compared to all responses from Politicians. The issue does not revolve around whether enough participant responses were obtained to implement the AHP, but whether the sample size truly reflects the opinions of all members belonging to the current Residents, Experts and Politicians stakeholder groups within the Gold Coast region. Using the work of (Duke and Aull-Hyde, 2002, Cheng and Li, 2006), it can be inferred that, for the current study, there exists an accurate representation of stakeholders’ opinions regarding the reduction of the impacts of sea level rise on the Gold Coast.

Aside from the above explanation, however, the responses obtained from the Politicians don’t count for nothing. To further confirm that the responses obtained from the surveyed Politicians are in fact quite relevant and useful, the context of the Politicians’ circumstances and professional relationships was considered. The 4 Politicians who responded to the survey questionnaire are considered to represent the views of Gold Coast City Council. This fact can be asserted because the City Councillors most certainly work in close contact with each other regarding policies and programs which are to be implemented. The Politicians have been elected to be in charge of the local region; these local members will meet often to discuss policy options and consider city-wide matters. Hence, when only considering local Politicians (i.e. no other stakeholder group), the views of a few will most certainly represent the views of all the councillors.

Overall, the responses from the three stakeholder groups provided important insights into the preferences and priorities of the local population regarding sea level rise adaptation alternatives and the criteria upon which these preferences were based. The results were obtained through the use of Expert Choice-11, a commercial software package for AHP used for computing relative weights, consistency ratio and local and
global priorities (Expert Choice, 2008). The package was also used to determine the rankings of the five adaptation alternatives for the stakeholder groups. Additionally, the MS Excel 2007 was also been employed for some calculations and data plotting.

6.5.2.1 CONSISTENCY

One of the strengths of the AHP is its ability to carry out a consistency check of the participants’ pair wise judgements. Here consistency refers to acting or thinking in the same way throughout an entire activity. Additionally, it implies an expected and identifiable result, based upon a known standard or set of parameters. Thus, to achieve the research goal of reducing the vulnerability of the population and land areas to sea level rise, it is expected that, in the majority of cases, the participants’ judgements will be reasonably consistent, with respect to each criterion. This outcome contrasts with the more general circumstances of life, where people usually produce a low consistency in successive judgements, implying a high rate of inconsistency.

For example, in a football game play-off between teams A, B and C the following outcomes could occur. Team A beats team B, and team B beats team C. Therefore, it could be logically inferred that the results would be A > B > C. However, in another football game (on a different week), team C may beat team A. This result would be inconsistent with the earlier expected results for A > B > C.

The concept of inconsistency can also apply to decision making processes; hence, there is a level of inconsistency that may need to be considered (Qureshi and Harrison, 2003). This is a natural occurrence in decision making, particularly when the criteria being considered is diverse (Banai, 2006).

The AHP methodology is a valuable tool because it allows the inconsistency of every participant’s responses to be represented by the consistency ratio (CR). A low CR implies that the inconsistency of participant judgements is also low. A high CR implies that the judgements have a high level of inconsistency. In most cases the CR should be ≤0.10 to be acceptable, which implies that the judgements have a 10% inconsistency rating, and a 90% consistency rating; nevertheless, a CR ≤ 0.20 could be tolerated (Saaty and Kearns, 1985). The CR is calculated from the pair wise judgement matrices from each stakeholder group. In the present study, the CRs are quite low (Table 6-8),
ranging from: 2% for the Residents, 2% for the Experts, to 6% for the Politicians; all results are less than the 10% limit. Hence, all groups have a consistency rating of 98%, 98%, and 94%, respectively.

| CR for Residents (geometric mean) | 0.02 |
| CR for Experts (geometric mean)  | 0.02 |
| CR for Politicians (geometric mean) | 0.06 |

Table 6-8 Participant Consistency Ratios

The result indicates that the judgements of the stakeholder groups, with respect to each criterion and the study’s goal of reducing the population and land area to SLR vulnerability are highly consistent.

6.5.2.2 GLOBAL ALTERNATIVE PRIORITIES

The survey questionnaire results and discourse for the adaptation alternatives are given below for each stakeholder group (Figure 6-26). To identify the priorities of the adaptation alternatives for a particular stakeholder group (with respect to a particular criteria) the individual participant’s judgements were aggregated. A vector was obtained, which described the corresponding ranking importance of the adaptation alternatives: the higher the numerical value, the greater the priority. The numerical values in Figure 6-26 are referred to as priorities. Thus, each alternative has a particular priority, which defines its importance in comparison to each of the other alternatives.

When prioritising the five adaptation alternatives, the Residents stakeholder group gave the highest priority to Improve Building Design (Figure 6-26) (0.325 priority), followed closely by Build Protective Structures (0.285 priority). Their least preferred alternative was Take No Action, followed by Retreat, with priorities of 0.061 and 0.102, respectively (Refer to the Residents’ row in Figure 6-26.)

In contrast, the Experts gave their highest priority to Improve Public Awareness with priority of 0.289, while Improve Building Design and Retreat were deemed the next most important alternatives with priorities of 0.278 and 0.203, respectively. (Refer to the experts’ row in Figure 6-26). While in accord with the Residents judgements for
their least preferred alternative (Take No Action had a 0.089), the experts next least preferred alternative was Build Protective Structures (0.141 priority).

The Politicians top two preferred adaptation alternatives were Improve Building Design with a priority of 0.457 (the Residents had this alternative as their top priority, while the Experts rated it as their second priority), and Retreat with a priority of 0.254 (which was one of the Residents least preferred alternatives, but the Experts third top priority). (Refer to the Politicians’ row in Figure 6-26.) Once again, the least preferred option for all three groups was Take No Action; However, the Politicians rated, as second to last, the alternative to Build Protective Structures, which disagreed with the Residents judgement, but agreed with the Experts judgement.

6.5.2.3 GLOBAL CRITERIA PRIORITIES

The survey questionnaire results for the global criteria priorities are discussed below, and presented in Figure 6-27. The priorities of the criteria (with respect to the goal of reducing negative impacts from SLR) were calculated by aggregating the individual participant’s judgements. A vector was obtained; it described the corresponding ranking importance of the criteria: the higher the numerical value, the greater the
priority. The term numerical value and priority are synonymous. Therefore, each criterion has a particular priority, defining its importance in relation to each of the other criteria.

From the combined results for each stakeholder group, the two most important criteria to consider when making a judgement to reduce the negative impacts of SLR are **Effectiveness** and **Sustainability**. It appears that the three stakeholder groups uniformly agree about the importance of the criteria. For example, **Applicability** and **Flexibility** generally rank next highest (with **Politicians** the exception), while **Cost** ranks the lowest (with **Politicians** the exception ranking **Flexibility** last).

![Global Criteria Priorities for Stakeholders](image)

6.5.2.4 DISCUSSION

The current research has focused on the identification and evaluation of adaptation alternatives which would reduce the vulnerability to SLR on the Gold Coast, Australia. Overall, the AHP technique was particularly suited for the decision making process regarding the adaptation alternatives to SLR for the Gold Coast. The ability of the AHP to incorporate the decisions of multiple members, from multiple stakeholder groups, was highly favourable for use in this scenario. Further, the method allowed a fast and
efficient outcome, with reliable results; the attributes permitted favourable project management decisions and the appropriate allocation of project resources.

To the best of the authors’ knowledge, the current research is unique. It is the first study to utilise the AHP method in such a context for the Gold Coast region. Indeed, this research has shown that AHP is well suited to evaluating adaptation alternatives. The main reason for its aptness in the present context is the richness of its hierarchical structure, which allows stakeholders to easily identify and evaluate various options by considering multiple criteria.

The results from the AHP analysis demonstrated that, for all stakeholder groups, there is a clear and unanimous agreement that the least preferred alternative is ‘prolonging adaptation action’. However, the correct adaptation alternatives and strategies to implement are not altogether clear. The stakeholders have a variety of preferences; nevertheless, what is clear is that the implementation of any adaptation strategies will occur in a number of step by step processes, and that not all strategies will be implemented at one time.

The following discourse seeks to provide background information that will help develop an understanding of why each stakeholder group chose their adaptation alternative preference priority and their criterion priority.

For example, the Residents most preferred adaptation alternative was Improve Building Design, and their second preference was Build Protective Structures (Figure 6-26). These two alternatives are related to the Residents wish to stay in their current homes and not relocate, but maintain their current style of living. Importantly, they do not wish to ignore SLR and so have chosen to take structural action to protect their current homes, and the other properties within their community. Not unexpectedly, their least preferred adaptation alternative was the Take no Action, which would see their home and community partially or completely destroyed.

With respect to Residents, the reasons behind their first and second preference for action against SLR may be understandable due to Residents being content in their current homes and their unwillingness to relocate to different properties. It could be inferred that Residents with established properties that are under threat from SLR will
be reluctant to make decisions to move away. The Residents who were surveyed are the owners of properties that are prone to flooding due to SLR. From the perspective of these Residents, some will probably believe that moving away from the coast (Retreat) or making efforts to better understanding the problems (Improve Public Awareness) will not be the most beneficial ways (for them) to adapt to SLR.

From their responses, it can be inferred that the Residents wish to remain where they are and maintain their current style of living. It is clear to see that the Residents of such properties believe that ignoring SLR is not desirable; however taking a structural action to accommodate and protect them in their current situations is most important.

The underlying reasons for the Experts’ preferences (first, Improve Public Awareness; second, Improve Building Design, see Figure 6-26) may involve their recognition that SLR is an almost intractable problem, and that the sea level will continue to rise for many centuries. Hence, from their perspective, the best way to manage the impacts of SLR to coastal regions is a combination of adaptation and mitigation (Nicholls et al., 2007). The ranked priorities show their possible intention to embrace change in the form of innovative buildings, as well as their hope for increased public knowledge regarding the impacts of climate change, and the risks, effects, and consequences of SLR. As with the Residents, the Experts’ least preferred alternative was the Take no Action option. Once again, it is inconceivable that an Expert would be able to resist the imperative to fix or find solutions to the impacts of SLR.

The alternatives chosen by the Experts show their technical perspective, especially in relation to their choice of adaptation alternatives, which require expertise and specialised knowledge. Interestingly, a survey of Experts by (Hamin and Gurran, 2009) confirm the validity of the current findings, although the phrases are not identical, the intention is similar, namely: ‘revise building codes for altered climate scenarios, and to invest in civic education and engagement’. Additionally, their knowledge of the impacts of SLR places them in a more informed position than that of the Residents or Politicians.

The adaptation alternative priorities advocated by the Politicians were, first, Improve Building Design and, second, Retreat. Their first priority agrees with the first priority of
the Residents, and the second priority of the Experts. However, the Politicians’ second priority (Retreat) was the Residents second last alternative, and the Experts third last alternative. Further, it is interesting to note the large difference in magnitude of these two priorities, when compared to the priority given to the other three alternatives. Perhaps, not unexpectedly, the Politicians distribution of priorities highly favours an adaptation / planning approach, which focuses on future circumstances. This preference implies that any future construction should be able to withstand any impacts of SLR and climatic change (planning for adaptation), or if this scenario is not possible then the all or certain parts of the community must Retreat (adapting to a new plan). However, Politicians also agreed with the Residents and the Experts that the least preferred alternative was Take no Action.

A number of general comments regarding criteria preferences between stakeholder groups can also be made. With respect to Politicians, it seems highly suspect that the criterion of Flexibility ranks the lowest, considering that the adaptation alternatives to be implemented on the Gold Coast will have a high probability of being applied over multiple sites, with varying geographical features, and diverse populations. In such circumstances, the approach requires a high degree of flexibility. Interestingly, the high ranking of Sustainability (highest for Residents and second highest for Experts and Politicians) seems to focus on the mindset that climate change, and its related impacts, will remain an issue for many years into the future.

There are two facets of Sustainability to consider: (1) any form of adaptation that is implemented must continue to function as originally intended over an extended period of time; and (2) each successive generation will have to bear the consequences of the choices and decisions made by the preceding generation (Howarth, 2007). Thus, the policy options of Sustainability (including adaptation) must maintain a sufficient level of effectiveness for future generations. It appears that the surveyed participants have identified with the importance of long term, sustainable adaptation options.

However, the stakeholders varied in their view of how to resolve adaptation problems, depending on the role they played. For example, Politicians gave their main attention to those adaptation problems that are most prominent in the mind of their voters. Consequently, the time-scale for Politicians was too often limited by the timing of next
the election. On the other hand, the Experts tend to hold longer-term views of such problems, especially if they are required to work on the same (or similar) issues over a long period of time. As result, the Experts may be regarded as the main driving force behind the decision making on adaptation and implementation.

From the current context, a comparison between the stakeholder groups with respect to the adaptation alternatives is of most interest. For instance, the alternatives advocated by each group differ significantly from those of the other groups. The major difference, however, relates to their knowledge, and their perspective, which is based upon their positions within society. As a consequence, disagreements even exist between stakeholder groups. The following paragraphs address these two trends among the priorities of adaptation alternatives.

For the first trend, within a particular stakeholder group, there appears to be a distinct gap between significantly higher ranking priorities and the remaining, lower ranking priorities. Importantly, this trend exists loosely in all three groups, with the proviso that the high and low ranked adaptation alternatives vary according to group, and a clear alternative can be identified as the most preferred. However, there exists a cluster of a few options which are significantly preferred (higher ranked) over the cluster of the remaining alternatives (lower ranked). This result seems to imply the occurrence of a possible confusion when identifying a clear alternative option to implement. Such confusion could have either negative consequences (delays in implementation) or positive consequences (several adaptation strategies implemented simultaneously).

The second observed trend focuses on the percentage differences between the highest and lowest priorities for the stakeholder groups. (Figure 6-28 provides an illustrated clarification of these results.) The alternative showing the greatest percentage difference in magnitude of priority, between the stakeholder groups, was Improve Building Design (17.9%) (i.e. highest priority given (0.457) minus lowest priority given (0.278)). Thus, the adaptation alternative Improve Building Design has the widest range of priority approval.
Overall, the percentage difference between the highest priority and the lowest priority for each adaptation alternative was greater than 15%, except for Take No Action, which was uniformly identified as the least preferred adaptation alternative. Clearly, when a number of stakeholders are involved, and there are other adaptation alternatives, sizable differences occur among the stakeholder groups.

One reason for the priority difference might be that some Experts and Politicians have additional, undisclosed knowledge, or insights, regarding this adaptation alternative. For example, the surveyed Residents may or may not be aware of the scope of the implementation of the protective structures. Further, they may only be concerned with their own properties, whereas the Experts and Politicians must consider the wider community situation, and the complex interactions between the different Gold Coast systems.
Similarly, for the adaptation alternative *Improve Public Awareness*, the *Politicians* gave a priority of 0.125, while the *Experts* a priority of 0.289; the difference being 16.4%. In this case, the *Politicians* appear to downplay the importance of ensuring that the members of high-risk areas (particularly *Residents*) are well informed of the negative impacts of SLR. Hence, a number of parallels exist between the stakeholder groups in relation to the adaptation alternative *Improve Building Design*. For *Politicians*, the majority of the weighting is spread between *Retreat* and *Improve Building Design*; for *Experts*, the higher priority distributions are spread over three adaptation alternatives; *Retreat, Improve Building Design, and Improve Public Awareness*; and for *Residents*, three most preferred alternatives spread over *Improve Building Design, Build Protective Structures* and *Improve Public Awareness*.

These variations highlight the discrepancies and resemblances between the stakeholder groups. Such disagreements provide the arena for robust discussions about which adaptation alternative(s) should be implemented. Furthermore, several important conclusions can be drawn regarding the similarities and differences between the stakeholder groups' preferences of adaptation alternatives to SLR.

To begin, the surveyed *Experts* have placed emphasis on making a conscience effort to *Improve Public Awareness*. Interestingly, *Experts* are often held in high esteem, by the wider community, simply due to society’s stereotyping, namely, their being responsible to all stakeholders for ensuring that adequate, accurate and reliable information is available on climate change, and SLR, in this current context. The advocating of the *Improve Public Awareness* adaptation alternative implies two issues. First, the surveyed *Experts* have recognised the crucial importance of maintaining the flow of information to the public, the majority of who happen to be *Residents*, so that their inclusion in the entire process of adaptation is preserved. Second, the *Experts* have an understanding that there is a certain level of uncertainty surrounding how the SLR will affect the Gold Coast in the long term and, due to that uncertainty, the wider population needs to remain educated and well informed.

Importantly, there exists a mutual priority for *Residents* and *Politicians* with respect to *Improve Building Design*. Their agreement represents an important understanding between these two stakeholder groups, highlighting the considerations they have
made. From the **Politicians** perspective, making efforts to accommodate the **Residents**, without imposing a requirement to **Retreat**, is a significant realisation, especially as their next highest priority was to **Retreat**. From the **Resident** perspective, making efforts to understand the environmental threat posed to their land has led to a natural realisation that there are options available to ensure safety, security and wellbeing.

Finally, the unanimous decision, by each stakeholder group, to rank **Take No Action** with the lowest priority is explained with respect to each of the criteria. During the decision making process, each participant pair-wise judged the alternatives with respect to each criterion. The final ranking of **Take No Action** implies that, under each criterion, all other alternatives had a higher preference for implementation.

Overall, the participants from the three stakeholder groups agreed that adaptation alternatives should be **Effective** and **Sustainable**, while **Cost** is not a major concern. The **Applicability** and **Flexibility** of the adaptation alternatives are of medium importance. Further, there was a unanimous agreement that any form of adaptation should be **Effective** and **Sustainable**. Thus, there exist clear differences about which adaptation alternatives should be implemented, there is unanimous agreement that action should be taken.

### 6.6 SUMMARY

In this chapter, the approach detailed in Chapter 5 was implemented. Hence, the vulnerability of the population and the land area to present-day storm-surge flooding, resulting from future SLR, was assessed by using the DSM. To model the potential hazard posed by future SLR and SS, the potential inundation and flood prone areas were simulated and mapped for a 100-year storm event under a range SLR scenarios.

The assessments demonstrated that those areas of the region vulnerable to a 100 year flood event, today, are the same areas where the most vulnerable portions of the population reside, that is, the areas in close proximity to the tidal waters, which are heavily impacted upon, will be vulnerable to future sea level rise.

The model used here provides a straightforward approach to the simulation of the effects of SLR on the spatial dynamics of a coastal area, as well as the subsequent
evaluation of the adaptation of alternatives from multi stakeholders’ perspectives. Among the primary advantages of this model are: its flexibility in accommodating separate models for subsets of the dynamic processes; its versatility in application to coastal processes; and its inclusion of the multiple stakeholder in the decision making process.
CHAPTER 7

MODEL REFINEMENT AND EVALUATION

7.1 INTRODUCTION

In Chapter 6, the proposed approach was implemented for vulnerability and decision analyses, specifically for SLR and climate change. The IPCC (2007) recognises that the changing climate poses a significant threat to many activities, and emphasises the need to make decisions that could reduce any related negative impacts. For this reason the DMs have to identify local community and land area vulnerabilities, and make decisions accordingly. These decisions need to be made with reference to the objectives and criteria established by the DMs and other stakeholders.

As there is a strong intersection between human decision making and environmental stresses, due to uncertainties, the decision-making may lead to decisions being taken that are less than ideal. While it is desirable to avoid or minimise the risk of making decision errors, and most decisions are flawed to some degree, the decisions still have to be made. Hence, a robust process is required that considers the range of risks and associated uncertainties, and so increase the chance of producing better decisions.

Using the decision modelling framework introduced in Chapter 5, some of the adaptation strategies (identified by stakeholders in Chapter 6) were tested. The outcomes are presented in this chapter (Chapter 7). Additionally, the DSM was modified by adding a few new variables. Further, this chapter looks at the general aspects of the model evaluation procedures, including calibrating and validating the model against independent modelled datasets.

Moreover, sensitivity analyses of the DSM and MCDA models were conducted: (1) To explore how the models respond to small changes in input values, parameter values or other assumptions; (2) To minimise the temporal and spatial uncertainties surrounding the decision making process; (3) To test the robustness of the model structures and
assumptions by identifying biases in model calculations; and (4) To provide information about whether the model needed to be revised.

7.2 MODEL REFINEMENT

The temporal model, introduced in Section 5.4, takes into account key variables that predict the extent and timing of coastal inundation. However, no variable was available to represent the adaptation alternatives discussed in Section 6.5. Thus, the model simulations were conducted under the *Take No Action* strategy. By modifying the model, 14 successive simulations were performed, with various values, to explore the impact of the *Build Protective Structure* and *Improve Building Design* adaptation options on vulnerable people and areas.

First, to test the efficiencies of *Build Protective Structure*, the model was modified by adding a variable to represent an imaginary protective structure along the shoreline. The heights of the protective structure varied from 0 to 2.5 m to estimate the most effective height that provided the best protection (Figure 7-1). The imaginary wall was built by altering the initial elevations of the border cells whose initial cover types were *Land* and adjacent to cells with *Sea*.

![Figure 7-1 Modified temporal model with protective structure variable](image)

The term “*Build Protective Structure*” refers to coastal engineering activities that reduce the risk of flooding and inundation. In Figure 7-2, the simulation results of
Scenario 3 were compared to the results obtained in Scenario 3 with a 2 m protective structure using vulnerability map series over a 100 year period. The findings show that building protective structures along the coastline does not have any effect on reducing the extent of the inundation under Scenario 3, and, therefore, does not reduce the vulnerability.

Figure 7-2 Vulnerable area to SLR, with and without Protective Structure
A comparison was made of the usefulness of building a 1m or 2m high protective structure to reduce vulnerable areas to a 1.5 cm SLR per year (3) (Figure 7-3). The results can be seen from the two graphs (Figures 7-3 and 7-4). The solid blue line represents vulnerabilities under a 1.5 cm/year SLR (Scenario 3), while the solid red and green lines represent vulnerabilities under two scenarios, Scenario 3 with 1 m and 2 m Protective Structure, respectively.

Figure 7-3 Vulnerable area to SLR, with and without Protective Structure

Figure 7-4 Vulnerable people to SLR, with and without Protective Structure
The comparison shows that the protective structures have no effect on vulnerable areas or populations. At the beginning of the simulation period, it seemed that the adaption alternatives, *Protective Structures* (1m and 2m), would be effective in reducing vulnerability (Figure 7-3). However, after the first 25 years, all three lines on the graph (representing an SLR of 0.5m, 1m, and 1.5m) overlapped, indicating that the effectiveness of these adaption alternatives were completely diminished. Therefore, building a 1m or 2m protective structures will not change the vulnerability, which, with or without protective structures, remains the same (56% during the simulation period).

Similarly, the overlapping lines also indicate that *Protective Structures* (both, 1m and 2m) will not provide any safeguard for the vulnerable population from rising sea level (Figure 7-4). The 7% prediction for the vulnerable population, without any adaptation measure, remains the same over the simulation horizon (2010 to 2110).

However, compared to a gradually rising sea level, the impact of SS in the short term is expected to be more devastating, with a greater magnitude. The impact of SS using Scenario 3 (1.5 cm per year) was simulated to determine the efficiency of 1m and 2m *Protective Structures*. In both graphs (Figures 7-4 and 7-5) the solid blue line represents vulnerabilities under the 1:100 year SS with a 1.5 cm/year SLR (Scenario 3); the solid red and green lines represent vulnerabilities under two scenarios: 1:100 year SS plus Scenario 3 with 1 m and 2 m *Protective Structure*, respectively.

As illustrated in Figure 7-5, the impact of SS, without any protection, is enormous, causing 92% of the area to be affected. However, the presence of the *Protective Structures* (both 1m and 2m) will not reduce the vulnerability of the flood affected areas, where the results remain the same (92%).

Similar results were obtained for the vulnerable population. As shown in Figure 7-6, the percentages of the vulnerable population remained the same (93%). Additionally, because there were no differences between the simulation results, the solid lines in both graphs, representing the three scenarios, overlapped and looked as if they were showing only one simulation result.
Secondly, to test the efficiency of the *Improve Building Design* option, the model was further modified by adding another variable (*Improve Building Design*), as seen in Figure 7-7.
The **Improve Building Design** option covers a wide range of adaptation measures, including (but not limited to) flood proofing, elevated building design, and minimum flood level. As it was not possible to test each adaptation measure under this category, the focus was specifically on two measures: *elevated building design* and *minimum flood level*. Further, it was assumed that new building regulations would be introduced, and that all existing and new buildings would be modified and/or designed accordingly. Based on these assumptions, the initial elevation of each cell with a *Land cover type* was increased by 1 m, and then 2 m.

The simulations were carried out by setting initial values for three variables, then changing these values to test this adaptation alternative under a range of scenario conditions. For this simulation, the values of the variables *Rise Rate* (min 0.005 m/y and max 0.015 m/y), *Current 100 year SS Height* (min 0 and max 2.5 m), and *Improve Building Design* (min 1m and max 2m) were altered within the range shown in brackets. Fourteen successive simulations, with various values, were performed to explore the impact of the new adaptation variables on vulnerable people and areas.
The simulation results (Figure 7-8) predicted that, with a 1.5 m SLR over a 100 year period, 56% of the land area would be submerged. However, implementing the option *Improved Building Design* reduced the vulnerability down to 6.5%, and 0.1 % for a 1 m and 2m building elevation, respectively.

![Graph](https://via.placeholder.com/150)

*Figure 7-8 Vulnerable area to SLR with and without Improved Building Design*

In contrast, the *Improved Building Design* adaption option provided the vulnerable population with 100 percent protection (Figure 7-9). The results demonstrate that elevating structures by the amount of the SLR, or more, would keep these structures at the same elevation relative to the sea and, thereby, prevent their becoming more vulnerable as the sea level rises.

Using the simulation results, the impacts of the three adaptation options were compared. The outcomes on vulnerable people and areas are shown in Table 7-1. Firstly, the *Build Protective Structure* adaptation option was not an effective strategy in reducing vulnerability to SLR and associated SS. Secondly, the presence of rivers and canals in the study area nullified the effectiveness of any protective structures against SS and SLR, especially when combined with heavy rainfall and flash flooding. Thirdly, as the sea level rises, flooding penetrates into the same places it has occurred before.
However, the *Improve Building Design* option offers a much better option against SS with a 1.5 cm/year SLR. As demonstrated above, this option has the potential to reduce, significantly, the vulnerabilities to a 1.5 m SLR. On the other hand, its shielding power diminishes against a 1.5 m SLR combined with SS.

Thus, it can be concluded that the findings of the simulation are consistent with the MCDA findings, that is, the *Improve Building Design* was ranked as the most preferred option by the *Residents* and *Politician*, while the *Experts* voted it the second most preferred option. However, the *Politicians* and *Experts* voted the *Build Protective*...
Structures as the fourth most preferred option, while the Residents ranked it as the second most preferred option.

The information generated by the DSM appears to provide very useful data for designing and implementing efficient and cost effective adaptation policies.
7.3 MODEL EVALUATION

7.3.1 CALIBRATION, VALIDATION AND VERIFICATION PROCEDURES

The research approach has an underlying conceptual model implemented as the DSM model. This model represents a coastal system that concerns vulnerable people and land areas due to inundation.

As discussed earlier, the environmental models are approximations of reality and, therefore, are all subject to varying degrees of uncertainty. In general, uncertainty sources in environmental modelling include parameter, data, and model structure. Hence, the model needs to be calibrated, verified and validated before it is run. Before describing this process, called a model evaluation, these three process components are defined.

 Calibration is the process of adjusting the variable values to reproduce the response of reality, within the range of accuracy specified in performance criteria (Refsgaard and Henriksen, 2004). It involves fine-tuning the model to a particular context by establishing a unique set of parameters that measure the model to its data (Crooks et al., 2008). Oreskes et al. (1994) have defined this process as the manipulation of the independent variables to obtain a match between the observed and simulated distributions of dependent variables. However, as they argue, even if the model is consistent with present and past observational data, this does not mean that the model would perform at an equal level for predicting the future. As natural systems are dynamic and change unpredictably, the future conditions may differ greatly from the present conditions.

 Verification literally means assessing the truth, to ensure that the system is internally complete, coherent, and logical (from a modelling and programming perspective). The process ensures that an implemented model matches its design, that is, the model is checked to confirm that it does exactly what the developer intended. This code verification tests and debugs the computer program (Refsgaard and Henriksen, 2004, Sojda, 2007).
Hence, the truth is limited to the technical description or conceptual model; whether or not this description is a truthful resemblance of the real world cannot be ascertained (Marchand, 2009).

Validation, according to Sojda (2007), is involves examining whether the system is realistic and useful to the user; it should answer the question: “Was the system successful at addressing its intended purpose?” In other words, validation is the process ensuring that an implemented model matches the real-world. In contrast to the term verification, validation does not necessarily denote an establishment of the truth. According to Oreskes et al. (1994), validation denotes the establishment of legitimacy, typically given in terms of contracts, arguments, and methods. Thus, a valid contract is one that has not been nullified by action or inaction; and a valid argument is one that does not contain obvious errors of logic (Oreskes et al., 1994). Therefore, validation requires an agreement about the use of common standards, such as juridical, scientific or otherwise. In this way, a valid model is accepted by all parties to play a role in the decision making process. Nguyen and de Kok, (2007) formulated this concept as the validity of an integrated systems model being the equivalent to the user’s confidence in the model’s usefulness.

Clearly, the evaluation requires the use of multiple, complementary methods to identify any shortfalls in the data, the theory, and the methodology. However, there is no consensus among modellers as to what the methodologically correct guidelines or procedures for evaluating simulation models should be.

Furthermore, a number of researchers have raised concerns regarding calibration, verification and validation. For example, Oreskes et al .(1994) states that:

*Verification and validation of numerical models of natural systems is impossible. This is because natural systems are never closed and because model results are always non-unique. Models can be confirmed by the demonstration of agreement between observation and prediction, but confirmation is inherently partial. Complete confirmation is logically precluded by the fallacy of affirming the consequent and by incomplete access to natural phenomena. Models can only be evaluated in relative terms, and their predictive value is always open to question. The primary value of models is heuristic.*

Similarly, the following researchers have expressed similar concerns:
The models cannot be proven or validated, but only tested and invalidated. However, model testing and the evaluation of predictive errors lead to improved models and a better understanding of the problem at hand (Konikow and Bredehoeft, 1992).

Ecological simulation models often develop in an ad hoc fashion rather than as highly structured software development projects, therefore, in contrast to industry and government, no structured reporting requirement for the verification and validation processes exists in ecological modelling (Rykiel, 1996);

Process models, like any scientific hypothesis, cannot be validated in the absolute sense, they can only be invalidated (Zheng, 2002).

Then why do we use models? To answer this question, Bankes, (1993), asserts that the models are explorative and play a role in the science-policy interface, they should comply to the criteria which are used both by stakeholders and scientists If these statements are correct, why do we use models? To answer this question, Bankes, (1993) asserts that models are explorative, and that they play a role in the science-policy interface, by complying with the criteria which are used by stakeholders and scientists. Oreskes et al, (1994) confirmed the usefulness of models when they are used to challenge existing formulations, rather than to validate or verify them. Furthermore, the models can also be used for sensitivity analysis by exploring the ‘what if’ questions to highlight which aspects of the system are most in need of further study, and where more empirical data are most needed.

Decision support systems use a combination of models, analytical techniques, and information retrieval to help develop and evaluate the appropriate alternatives. However, because such systems handle complex and poorly structured problems, they are difficult to empirically evaluate (Sojda, 2007). Nevertheless, the evaluation of all decision support systems is important.

Rykiel (1996) identified and discussed a number of the tests that are used for model validation, specifically to compare other models, or for internal validity, historical data.
validation, sensitivity analysis, extreme-condition tests, statistical validation, and predictive validation.

Other model validation testing approaches have been proposed by Sojda (2007), namely:

1. Model performance tested against a preselected standard;
2. Real-time and historic datasets used for comparison with simulated output;
3. Panels of experts judiciously used, but often are not an option in some ecological domains;
4. Sensitivity analysis of system outputs in relation to inputs can be informative; and
5. Examining major components when the validation of a complete system is impossible to recognize potential pitfalls.

Outlined below are the definitions for the scientific criteria, usability criteria, and transparency criteria, composed by Marchand (2009) from the work of a range of researchers. Indeed, the following approach was used for the evaluation of the current model.

7.3.1.1 CALIBRATION

The DSM model uses the initial value for each constant variable; however, the model allows the users to alter these initial values to best represent the changes in the coastal inundation process. In the current study, as past, observational real world data was unavailable for the study area (as discussed earlier), the calibration process was carried out by adjusting and fine-tuning the model parameters, and manipulating the independent model variables to reflect, realistically, the inundation conditions.

To achieve adequate reliability of the simulation model, a total of 18 models were developed, tested, and modified before the final model was confirmed. Most of the calibration efforts were performed to achieve a reasonable correspondence between the data representing the current conditions in the study area and the output of the simulation model.
This process involved: (1) a simulation model setup, including a model boundary selection, program coding, data collection for the study area, and modelling scope and purpose; (2) initial testing by comparing the model to the data collected for the study area, with and without changing the model parameters, to test the model behaviours. Once the model behaviours were close enough to represent the system, it was deemed appropriate for use in further analyses. Then, the key calibration parameters, within the simulation model, were identified. Next, the acceptable ranges of the selected calibration parameters were determined, and modified as needed.

7.3.1.2 VERIFICATION

As explained above, the process of verification ensures that the model design (conceptual model) has been transformed into a computer model with sufficient accuracy. This process requires testing the model to see whether it satisfies the intended purpose of the model. Various aspects of the model were checked during the model development by: (1) ensuring that the right data and logic had been entered through reading the code; (2) by running the model to visual the display of the model output, and observing whether the behaviour satisfies the logic of the model; and (3) inspecting the output of the simulation by comparing the actual and expected results.

7.3.1.3 VALIDATION

At the outset, it is acknowledging that a complete scientific validation is impossible (Oreskes et al., 1994). Nevertheless, the researcher sought to achieve an open, transparent, and objective validation procedure, which would lead to its acceptance by the users. Deterministic models, such as the one used in the current research, are conceptual models expressed mathematically; they contain no random components. Hence, they are derived from the physical principles of the coastal process, rather than from further experiments. As Hugget (1993) posits, it is sound practice to test the validity of a deterministic model by comparing its prediction with independent observations made in the field or laboratory. Thus, in the current study, the DSM model was used as the validation model to compare a hydraulic model (described below) obtained from the GCCC, and for the sensitivity analyses of the model outputs by changing the input values, parameter values or other assumptions.
The Gold Coast City Council (GCCC) generously allowed the researcher access to a 40 m flood surface raster data, derived using a hydraulic model. The flood surface represents the 1 in 100 year flood. After the data was clipped to the extent of the study area boundary, a 40 m raster was changed to a 5 m raster to match the other data layers used in the spatial analyses (Figure 7-10). The pink colour gradient represents the 1:100 year flood extent in the study area, overlayed with satellite imagery. Then, using the DSM, another 1:100 year flood map was created (Figure 7-11); the flood extent was marked with the blue colour gradient.

Figure 7-10 A 100 year flood extent generated by a hydraulic model
To compare the results from both models, the DSM flood map was overlayed with the 1:100 year map (Figure 7-12), obtained from the GCCC, and created by using the hydraulic model.
As seen in Figure 7-12, the DSM model result (blue) differs slightly from the hydraulic model result (pink). Further, the DSM result indicates that the impact of the 100 year SS and, therefore, the vulnerability of the land area, especially around residential areas, is slightly higher than the model used by the GCCC. The variation can be attributed to the accuracy differences between the datasets used in these models. As discussed in Section 5.4.32, the attribute assignment was based on the centroid of the cell when the 5-m grid cells were created to match the digital elevation model (DEM) data. The DEM refers to the actual set of elevation data points.

The dataset used in the DMS has one elevation data point for each 5-m cell (25 sqm), whereas, there is only one elevation data point for each 40-m cell (1,600 sqm) the grid
cell of hydraulic model. When the 40-m grids were changed to 5-m grids to match the other data layers used in spatial analyses, the new 5-m cells used the same elevation data point as the 40-m grid, from which they were created. That is, while the hydraulic model calculation was based on only one elevation data point (for a 1600 sqm area divided equally into 64 cells), the DSM analyses was based on 64 elevation data points for the same geographical area. In other words, the use of high resolution, high accuracy data elevation points enabled the DSM to conduct more accurate vulnerability analyses.

Furthermore, the model also enabled the quantification of vulnerability, adding further transparency to the conclusions, as well as increasing the complexity to beyond what most people can manage. Importantly, the model shows a direct link connecting the SLR, SS and vulnerability. Therefore, the DSM provides a useful tool, to aid DMs decision making, through its ability to calculate a whole range of scenarios and measures, as well as assess the impacts on vulnerability. Thus, this model has made a most useful contribution to the wider scientific, disaster and coastal management community.
7.3.2 SENSITIVITY ANALYSIS

Sensitivity analysis, as defined by the IPCC (2007), is a structured approach that investigates how a system, model or assessment responds to small changes in the input values, parameter values, or other assumptions. The purpose of a sensitivity analysis is to identify the input values, variables or model assumptions that have the most significant impact on the outputs or responses. For this reason, the current study used sensitivity analyses to assess the changes to the model by modifying the parameters. First, the DSM model was tested, and then the sensitivity analyses were performed for the MCDA model. The details of these analyses are described in the following sections.

7.3.2.1 SENSITIVITY ANALYSIS – DYNAMIC SPATIAL MODEL

As discussed in Chapter 2, the rate of the SLR has a major effect on the timing of the changes. The storm surge events also have a significant effect on both the long term and short term changes. As a result, changing the values of these variables directly affects the extent and magnitude of the inundation (permanent submergence) and flooding (temporary submergence).

To gain more confidence in the behaviour of the DSM, a sensitivity analysis was performed using Vensim software, which required changing the assumptions about the value of the constant variables, as well as examining the resulting output. The temporal component of the DSM contains a range of constant variables. To examine their effects on the simulation output, the values of three constants variables (Figure 7-13) were chosen and modified: Rise Rate, SS Height, and Protective Structure. These uncertain variables have the potential to directly affect two static variables: Area at Risk and People at Risk.

The following maximum and minimum values were assigned to these variables for the sensitivity simulation:

Rise Rate : 0.5 – 1.5 cm/year

SS Heights : 0 – 2.5 m
The sensitivity simulations required the definition of the kind of probability distribution values from which each variable would be drawn. Hence, the Vector distribution was selected, as it generates a sequence of incremental numbers from the minimum to the maximum. Although this sequence increases uniformly, it is not random. A Vector distribution is especially useful in performing an exhaustive grid search (Ventana Systems, 2009).

![Figure 7-13 Sensitivity simulation setup](image)

Rather than using randomly selected values, the researcher preferred to methodically search out all possible parameter combinations in an $N$ dimensional grid. This approach allowed the researcher to observe what happened when: a Rise Rate takes on the values from 0.005 m to 0.015 m, by 0.005 increments; a Protective Structure takes on the values 0, 1 and 2 m; the Improve Building Design takes on the values 0, 1 and 2; and the SS Height takes on the values from 0 to 2.5 m. Fifty-four combinations of values were checked for each static variable under investigation.
By selecting the *Multivariate* search and *Vector* distribution approach, the model performed a methodical analysis by conducting a total of 108 simulations, which assessed every combination of the four variables. Table 7-2 presents a sample (20) of combinations of the sensitivity simulation results for the vulnerable areas and populations (Appendix 4 provides the detailed results of the sensitivity simulations showing the vulnerable areas and populations for each combination).

<table>
<thead>
<tr>
<th>Sim. Run</th>
<th>Rise Rate (m/yr)</th>
<th>SS Height (m)</th>
<th>Protective Structure (m)</th>
<th>Improve Building Design (m)</th>
<th>Area at Risk (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.005</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.3% 1.5% 1.7% 1.8% 2.1% 3.6% 4.1% 4.4% 5.0% 6.0%</td>
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<tr>
<td>2</td>
<td>0.01</td>
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<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>3</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>1.6% 3.6% 9.4% 16.5% 26.7% 35.8% 42.9% 47.9% 55.7%</td>
</tr>
<tr>
<td>4</td>
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<td>1</td>
<td>0</td>
<td>0</td>
<td>0.8% 0.9% 1.1% 1.4% 1.6% 3.1% 3.5% 4.1% 4.7% 5.7%</td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.9% 1.4% 3.1% 4.1% 5.7% 9.1% 13.5% 19.0% 26.6% 33.6%</td>
</tr>
<tr>
<td>6</td>
<td>0.015</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1.0% 3.1% 4.6% 9.1% 16.2% 26.4% 35.8% 42.9% 47.9% 55.7%</td>
</tr>
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<td>0</td>
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</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>0.9% 1.4% 3.1% 4.1% 5.7% 9.1% 13.5% 19.0% 26.6% 33.6%</td>
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<tr>
<td>9</td>
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<td>1.0% 3.1% 4.6% 9.1% 16.2% 26.4% 35.5% 42.6% 47.6% 55.4%</td>
</tr>
<tr>
<td>10</td>
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<td>0</td>
<td>0</td>
<td>1</td>
<td>0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.1% 0.1% 0.1% 0.2%</td>
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</table>

<table>
<thead>
<tr>
<th>Sim. Run</th>
<th>Rise Rate (m/yr)</th>
<th>SS Height (m)</th>
<th>Protective Structure (m)</th>
<th>Improve Building Design (m)</th>
<th>Population at Risk (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.005</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0%</td>
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<tr>
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</tr>
<tr>
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<tr>
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<tr>
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<tr>
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<tr>
<td>9</td>
<td>0.015</td>
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</tr>
<tr>
<td>10</td>
<td>0.005</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0%</td>
</tr>
</tbody>
</table>

Table 7-2 Sample sensitivity simulation results

A comparison was made of the range of scenarios in the model to the sensitivity analyses (Figure 7-14: area at risk; and Figure 7-15: people at risk). The yellow shaded area indicates the range of outcomes for the 108 sensitivity simulations, while the solid black line is the median outcome. The sensitivity simulations were based on the *Rise Rate*, *SS Height*, *Improve Building Design*, and *Protective Structure* variables; the reference simulations, represented by the solid lines, were based on the *Rise Rate*, and 1:100 year SS, and only reflected the changes in these particular variables.
The reference scenarios combined: the 1:100 year SS with the 1.5 cm/year SLR (worst case); the current 1:100 year SS without the SLR; and the 0.5 cm SLR without the SS. The reference scenarios served as a comparison for the sensitivity and adaptation scenarios. In both the graphs depicting these scenarios (Figures 7-14 and 7-15), the top line (green colour) illustrates the worst case scenario, and represents the 1:100 year SS combined with a 1.5 cm/year SLR; the solid red line, below the green line, shows the impact of the current 1:100 year SS without the SLR; the grey line, at the bottom, represents the vulnerability conditions resulting from the 0.5 cm SLR without the SS; while the black line represents the mean sensitivity value. The areas depicted in yellow colour show the results of the 108 sensitivity simulations.

Figure 7-14 Sensitivity analyses for Area at Risk variable
Figure 7-15 Sensitivity analyses for *People at Risk* variable

The lower bounds of the sensitivity simulations illustrate the vulnerable area and population predicted for a best case scenario (*Rise Rate* 0.005 m/year, *SS Height* 0 m, and *Improve Building Design* 2 m adaptation option representing a 2 m elevation for the buildings and structures). The upper bounds of the sensitivity graphs show the vulnerabilities predicted for a worst case scenario (*Rise Rate* 0.015 m/year, and *SS Height* 2.5 m representing the current 1:100 year flood level, with no *Protective Structure* or *Improve Building Design* adaptation options).

As seen in these graphs, the Scenario 1 line (grey) is slightly higher than the lower bounds of the sensitivity simulations. Thus, if the SLR occurs over a 100-year period it will be equal to or less than 0.5 m; then, the impact on the vulnerable areas and population would be very small. That is, without any adaptation measures, only 6% of the land area would be affected, while the people would remain safe.

A summary of the sensitivity simulation statistics are presented in Table 7-3. The minimum in the table displays the smallest value amongst all the points considered (best-case), while maximum displays the largest value (worst-case). Under the worst case conditions, the percentage of the vulnerable area and the population to SLR, and the associated SS, are almost the same, being 92% and 93%, respectively. The best-
case scenario, however, draws a different picture. The percentage of the vulnerable area and population are equal to zero, which reflects the ultimate adaptation position in a specific adaptation scenario (2 m Improve Building Design).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Area at Risk (%)</th>
<th>People at Risk (%)</th>
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</thead>
<tbody>
<tr>
<td>Number of simulations</td>
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<td>54</td>
</tr>
<tr>
<td>Minimum</td>
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<td>0</td>
</tr>
<tr>
<td>Maximum</td>
<td>91.92</td>
<td>92.65</td>
</tr>
<tr>
<td>Mean</td>
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</tr>
<tr>
<td>Median</td>
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<td>0.93</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>37.72</td>
<td>38.93</td>
</tr>
</tbody>
</table>

Table 7-3 Sensitivity simulation statistics at time end of simulation period

The sensitivity tests show that there is no likelihood of improving the fluctuations in the vulnerability of an area by changing the Build Protective Structure policy parameters in the existing system. However, changing the value of the Improve Building Design option has the potential to substantially reduce vulnerability.

As a general observation, changing the initial values of the variables affected the simulation results within both the best and the worst case scenarios. Further, the model behaviour was stable and consistent with its conceptual design. Therefore, the model behaviour was not sensitive to changes in the input values, which confirms the quality of the model. In other words, the model is robust, with a high capacity to accurately reflect the coastal inundation process.

7.3.2.2 SENSITIVITY ANALYSIS - AHP

One advantage of using the AHP is its ability to perform the sensitivity analysis. A sensitivity analysis is performed to assist with the uncertainty surrounding the decision process, to determine the possible effects of weighing the decision criteria differently, and to ascertain that influence on the outcome. In the current study, to determine the sensitivity of the aggregated stakeholder groups' responses, the criteria percentage priorities were altered slightly to observe any changes in the alternative priorities. The
results show that the alternative priorities did not change by any significant amount, for any of the stakeholder, when one of the criteria priorities were altered.

This behaviour was illustrated when the aggregated judgements for the Residents were changed from the original rankings (Figure 7-16). For example, the percentage priority of Flexibility was increased by 10% (from 17.5% to 19.2%), with no changes in the ranking of the priorities (Figure 7-17).

Figure 7-16 The original rankings the percentage priorities

Figure 7-17 The percentage priority of Flexibility increased by 10%
The percentage priority of Flexibility was increased continuously until the first change in percentage priorities of the adaptation alternatives occurred (Figure 7-18). This first change only occurred when the priority of Flexibility was increased by 130% (from 17.5% to 40.3 %). However, the ranking of the adaptation alternatives remained unchanged. The sensitivity results, confirm the ranking of the adaptation alternatives reported in Figure 7-16. Hence, the results are not particularly sensitive; rather, they are robust.

![Figure 7-18 The percentage priority of Flexibility increased by 130%](image)

### 7.4 SUMMARY

To be consistent with the modelling framework, the refined model tested the findings of the decision analysis. An innovative characteristic of the approach presented in this chapter involved the capacity to evaluate the decision choices prior to their implementation. This outcome was achieved by linking the DSM simulation results with the decision making process and, then, retesting the information, obtained from this process, using the DSM. The model’s ability to pre-evaluate decision choices is an important feature; its legacy is that communities can avoid or minimise their decision error, and increase their chance of obtaining better decisions. Additionally, the chapter addresses and presents an explanation of the evaluation procedures, the model’s
calibration, verification, and validation, as well as the sensitivity analyses for the model’s behaviours.
CHAPTER 8

CONCLUDING REMARKS AND FUTURE RECOMMENDATIONS

8.1 INTRODUCTION

The previous chapters have demonstrated the development and implementation of an integrated vulnerability and adaptation assessment approach. This chapter outlines the research conclusions, and addresses the research objectives (Section 8.2), summarises the thesis contributions (Section 8.3), identifies the limitations of the research (Section 8.4), and provides recommendations for future studies (Section 8.5).

8.2 CONCLUSIONS

As the globe continues to warm, coastal communities across the world will increasingly be faced with rising sea levels, as well as changes in storm surge frequency and magnitude. One result is that people in coastal areas will have to contend with more and more difficult and contentious decisions, which seek to find the best solutions to the social, economic, environmental and political problems created by these changes. The dilemma confronting decision makers is how, and when, to adapt to SLR. Such decisions are not simple, they are fraught with uncertainty, specifically, the timing and magnitude of the SLR impacts (Sahin and Mohamed, 2009). Indeed, the complexity that arises from climate changes, coastal systems, and their interactions in space and time, can easily overwhelm the ability of decision makers to thoroughly investigate the outcomes of adaptation alternatives. To facilitate these decisions, policy makers require credible scientific data and information.

However, environmental systems are complex and the conditions that affect a situation can change quickly. The future is, therefore, uncertain in a number of areas, and so societies and communities need a high degree of flexibility to enable them to adapt to the changing conditions. Designing and applying a robust and flexible method
to assess vulnerabilities and adaptation to SLR have challenged researchers in vulnerability and adaptation field. One difficulty has been that previous coastal vulnerability and adaptation studies have typically over-simplified their vulnerability analysis. The researchers have assumed that vulnerability is a static process; as a consequence, the studies were conducted with reference to a target year (i.e., 2100) and/or a SLR prediction (i.e. 1m) (The Department of Climate Change, 2009, Wu et al., 2009, Wang et al., 2010). However, as discussed in previous chapters, vulnerability is a dynamic process and should be considered as a continuum.

By considering the uncertain and dynamic nature of the projected changes in climate, as well as to address these dilemmas, the aim of the current research was to provide an integrated, five dimensional decision approach, incorporating GIS, SD simulation, and Multiple Criteria Decision Aid Modelling approaches.

Hence, the primary objectives of the research, divided into two segments, were:

1. Firstly, to develop a dynamic model to assess the present and future vulnerability of coastal populations and properties to sea level rise and storm surges, based on various SLR scenarios and projections; and
2. Secondly, to identify and evaluate adaptation options for coastal areas in order to cope with altering climatic condition scenarios using an MCDA model.

The secondary objective was to test the proposed models through implementation simulations in order to address the following four questions:

1. What is the present vulnerability in the study area in terms of the number of residential properties and populations within 1/100 year flood level?
2. How vulnerable is the study area to future SLR and associated storm surges (number of residential properties, their value and people at risk)?
3. What are the potential physical (Inundation, flood and storm surge damage) and socio-economic (people at risk and properties, loss of properties) impacts of SLR and storm surges on the study area?
4. What are the desirable adaptation options to reduce adverse impacts of future climate change?

These objectives have been achieved, and this success is discussed below:
CONCLUDING REMARKS AND FUTURE RECOMMENDATIONS

- Chapter 2 presented the seminal literature review needed to understand climate change, its effects and response strategies for reducing the adverse impacts of climate change. The chapter provided a basis for identifying the gaps in existing vulnerability and adaptation studies, research topics and objectives. It became clear that vulnerability had not been defined previously as a dynamic continuum and, therefore, it was not analysed accordingly. Additionally, no regional scale vulnerability assessment studies were available, nor did any of the studies include local stakeholders in the decision making process to develop adaptation strategies.

- Chapter 3 explored the major modelling approaches for environmental problems, including simulation modelling, spatial modelling and various decision making techniques. The review of the existing literature covered a range of specific topics, namely: environmental problems, and their complex, dynamic, spatial and multi-criteria nature. The models were critically assessed for their weaknesses and strengths in order to provide the foundation for the selection of the major modelling approaches. Thus, the literature review also provided the necessary rationale underpinning this research, as well as serving as a potential basis for future research efforts.

- The research objectives were defined in Chapter 4, being based on the reviewed literature in Chapters 2 and 3.

- Chapter 5 focussed on the adopted research methodology. Following a discussion regarding the general approach used in the current research, a discourse was presented on our understanding, and treatment, of uncertainty surrounding environmental problems and the decision making process.

A great deal of research effort focussed on the development of the conceptual framework for inundation, which was later used as the fundamental structure for the DSM design. The DSM design comprised three separate models; (1) the temporal component; (2) the spatial model component; and (3) the file monitor and data convertor. The technical focus centred on demonstrating one of the practical ways in which the functionalities of GIS and SD can be enhanced through their integration.
building a hybrid Dynamic Spatial Model (DSM). This outcome was achieved by integrating, through a loose coupling, the ArcInfo GIS software with the Vensim DSS simulation software.

The coupling required the transfer of data between the GIS and SD models (as explained in Section 5.4.3.3). However, as the data formats used in these applications were not compatible, it was necessary to establish, create and manipulate the data files to be exported and imported between the spatial and temporal components of the hybrid model. For this purpose, data converter software was written in C++ under Visual Studio 2008, using the Microsoft.NET version 2.0. Thus, the format transition between the ArcGIS and SD data formats was automated using the data converter.

The output from the DSM was used to inform the decision making process using the MCDA. The AHP, one of the best known MCDA techniques, was selected evaluate the adaptation alternatives. Three stakeholders groups (Residents, Experts, and Politicians) were identified and consulted when building the AHP model. Later, they were asked to prioritise their adaption alternatives. The selection of techniques used in this research was also justified. The development of the DSM achieved the first primary research objective, while the MCDA based decision model achieved the second primary research objective. Further, the research aim, to provide an integrated five dimensional decision approach, was accomplished by linking these three modelling approaches.

- In Chapter 6, the empirical focus of the research demonstrated that the proposed approach adequately assessed vulnerabilities, and prioritising the adaptation alternatives. The four research questions, which formed part of the secondary research objective, were answered in a rigorous manner (using the research approach presented in Chapter 5).

First, the boundary of the study area, implemented in the models, was defined from the available data sets. Next, the scenarios, used for the analyses, were explained. Their usage was important in developing a holistic

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understanding of a complex reality, specifically, by simplifying some steps, and addressing the uncertainties around the model for vulnerability assessments. A vital component in a successful decision-making process is the thoughtful communication of the uncertainties and the active participation of the stakeholders. The current approach facilitated both elements.

Within the current study, the acquisition of coastal elevation data provided the fundamental information required for the vulnerability assessment. As discussed in section 5.4.3.2.2, high-resolution, high-accuracy elevation data leads toward the development of improved capabilities for vulnerability assessments. Thus, acknowledging the importance and need for data accuracy in the underlying data, and its effects on any vulnerability assessments, the research obtained and applied 5-m DEM with 0.1 m vertical accuracy, together with a number of other datasets (as outlined in Section 6.4). The high resolution elevation data ensured a much smaller elevation uncertainty.

Empirically, the GIS and SD model components were loosely linked using the data converter to form a hybrid DSM. The GIS became an effective tool for storing, processing, managing, and analysing spatial information, while the SD model provided insights into the dynamic feedback processes inherent in the evolution of the system, scenario development, and the capturing of temporal changes.

The implementation of the MCDM models involved: assigning weights and priorities to the criteria by stakeholders; the normalisation of the raw scores to create a common scale of measurement; and the calculation of the decision scores used to generate the final output from the models. The proposed integrated approach successfully provided a framework for adequately addressing vulnerability and adaptation problems, via the dimensions of space, time and the human element.

- Chapter 7 detailed how the proposed approach was refined and evaluated. Thus, firstly, following the decision modelling framework introduced in Chapter 5, the DSM was modified by adding new variables to test the
efficiency of a number of adaptation alternatives. Next, the results of the DSM simulation were compared to the results from the MCDA model. The comparison enabled the DMs to avoid or minimise the risk of making a decision error, while considering the range of identified risks and associated uncertainties. This process was an important attribute of the proposed approach.

Secondly, the successful implementation of the approach (outlined in Chapter 6) validated the proposed framework, while the general aspects of the model’s calibration, verification and validation were discussed and executed in Chapter 7. Within the model’s validation process, the output of the DMS model was compared to that of the hydraulic model (obtained from the GCCC). Additionally, the sensitivity analyses of the DSM and MCDA models were conducted.

The DSM model was tested, and then the sensitivity analyses were performed for the decision model. The results showed that the behaviour of the simulation model was stable and consistent with its conceptual design. Thus, the model is robust and capable of reflecting, accurately, the coastal inundation process.

- Further, the preference rankings generated by the MCDA models were also tested; their robustness was examined in terms of the validity of the criteria and the weights used in the decision analysis. The results from the sensitivity analyses confirmed that the preference rankings were stable.

### 8.3 RESEARCH IMPACT AND CONTRIBUTION

A PhD thesis is required to make original contributions to knowledge, either by the originality of the approach and / or the interpretation of the findings and, in some cases, the discovery of new facts. According to Phillips and Pugh, (2005), if a PhD dissertation contains one of the following nine characteristics, it is considered as an original contribution, namely.
1. Carrying out empirical work that has not been done before;
2. Making a synthesis that has not been made before;
3. Using already known material, but with a new interpretation;
4. Trying out something in this country that has previously only been done in other countries;
5. Taking a particular technique and applying it in a new area;
6. Bringing new evidence to bear on an old issue;
7. Being cross-disciplinary and using different methodologies;
8. Looking at areas that people in the discipline have not looked at before; and
9. Adding to knowledge in a way that has not been done before.

The research presented here satisfies the five criteria highlighted in bold lettering. It also offers a significant and innovative contribution to the knowledge base in the fields of vulnerability and adaptation studies, particularly from the perspectives of methodological development and empirical application as described below:

**Carrying out empirical work that has not been done before**

The pioneering empirical research, demonstrated in Chapters 6 and 7, involved: The assessment of the current and future vulnerabilities in the study area using the DSM; the evaluation of the adaptation alternatives by linking the DSM with the decision making process; and testing their impacts on reducing vulnerabilities. These processes confirmed that the research offers a powerful new framework for addressing the vulnerability and adaptation issues. Thus, the research is original.

**Making a synthesis that has not been made before**

The innovation emanating from this research lies in the utilisation of three approaches (SD, GIS and MCDA). The approaches were synthesised within the integrated 5D decision making framework; the new approach was then applied to the vulnerability and adaptation assessment in a coastal area of the Gold Coast, Australia. To the best of the researcher’s knowledge, this is the first time that vulnerability assessments have been incorporated into decision making to develop adaptation strategies that result in a cyclical process. Thus, the proposed modelling approach demonstrates a high degree
of scientific rigor and contributes original theoretical insights, as well as technical originality.

**Trying out something in this country that has previously only been done in other countries**

The current research utilising existing techniques but adapts them into the design of a 5D model. This “tried and true” model was the first time in Australia that the SD and GIS modelling techniques were combined for assessing coastal vulnerabilities to SLR. However, different techniques have been combined in research undertaken in other countries (Chapter 3). Thus, the SD and GIS integration used in this research can be considered as both “new” and “tried and true”.

**Taking a particular technique and applying it in a new area**

The research addresses adaptation decision problems in coastal areas by combining spatial (GIS), dynamic (SD), and multi criteria decision modelling approaches in an integrated manner. Individually, each technique is well established and used for modelling and decision making in many different disciplines (Chapter 3). However, the three approaches, and their application in the vulnerability and adaptation fields, is unique to the current research.

**Being cross-disciplinary and using different methodologies**

Designing and implementing a multi-dimensional approach demands that the approach crosses multiple disciplines. As the dimension becomes broader, more disciplines may need to be incorporated. The present research approach incorporated many different fields, namely: system dynamics, geographical information systems, operational research, computer science, mathematics, and geography. The cross-disciplinary / multi-methods approach used here permitted an assessment of this complex disciplinary study. Additionally, different methodologies were used to integrate, and so make more accessible, knowledge about the vulnerability and adaptation domains for the decision making process.
Moreover, the modular approach parallels its cross-disciplinary nature. The modularity provides flexibility by assigning a particular disciplinary aspect of the model to a separate module. Therefore, the other elements affecting the coastal systems can be integrated as needed.

### 8.4 LIMITATIONS AND RECOMMENDATIONS FOR FUTURE WORKS

The following section outlines the general limitations of the current research and, importantly, makes recommendations regarding future research in the area of vulnerability and adaptation assessments:

- One of the limitations of the scope of the current study is that it only addresses the impacts on communities and land area from inundation and coastal flooding (the result of storm surge and sea level rise). Thus, other types of coastal impacts, such as erosion, saltwater intrusion, flooding due to heavy precipitation, are disregarded. Nevertheless, the findings from the vulnerability analyses indicate that a simple inundation scenario provides a satisfactory representation of the impacts from rising seas (Najjar, 2000, Rowley, 2007, Demirkesen et al., 2008).

  Future research could investigate the other types of coastal impacts to determine their relevance to the general topic. Some studies in this area, such as coastal erosion, may need the addition of another module or variable to the existing DSM structure.

- Additionally, non-tidal artificial waterways (including access channels, inland lakes and water bodies), disconnected from the tide by locks and weirs, or that have no connection to the sea, are also excluded due to a lack of information on potential interactions with a sea level rise.

  Future research could concentrate on sourcing such data.

- A simple population growth scenario was included in the simulation model. However, in reality, feedback relations exist that link the population growth with other physical conditions, and so could result in a sharp population drop,
or jump. Nevertheless, these feedback relations with changing environmental conditions are not included in the model. Further, it is asserted that this omission would not affect the model’s results.

Future research could examine the relationships between the impacts of rapid population growth, together with the gradual expansion of the urban area, and the frequency and magnitude of coastal inundations, using a more comprehensive socio-economic scenario linked to the DSM.

- Although the spatial extent of SS is calculated in the model, a number of important SS characteristics were not included, such as the duration of storms, or the speed of response to, and recovery of, coastal flooding. Instead, the SS impacts, and the increase in SS frequency were calculated using a simple relationship between the SLR and SS height (i.e. 1:100 year SS). However, this omission does not influence the simulation results in terms of providing sufficient insights to support the making of informed strategic decisions.

Future research could calculate the spatial extent of the duration of storms, and the speed of response to, and recovery of, coast flooding to expand the data available to DMs.

- Flash flooding, especially during high tides, with SLR, was not considered in the current research did not fit within the scope of the current study. Nevertheless, at these times the natural drainage system may not be able to cope with the sudden volume of water.

Therefore, future research could examine the impacts of flash flooding, focusing specifically on the diminishing drainage capacity of existing natural systems that discharge into tidal water.

- While the present research involved the stakeholders prioritising their options for the decision-making process, the study did not explore the reasons underlying stakeholders’ decisions.
Future research is needed to analyse the relations between the decision making and the stakeholders’ behaviour and attitude.

- The economic and social costs related to SLR and SS were not addressed by the current study, as these areas did not fit within the research scope.

Future research could investigate the cost of adaptation, such as land values, and loss of income, etc.

### 8.5 Closure

Importantly, the current research has made significant contributions to the area of decision making, particularly in the context of coastal vulnerability and adaptation. By introducing a 5D decision making approach spatial and temporal dimensions of environmental problems can be integrated with the human decision making process.

Further, the practical implications of the research encompass the development of a model to assist DMs to: better understand coastal processes; identify vulnerabilities more accurately and effectively; and develop, prioritise, and implement effective adaptation strategies with the participation of stakeholders.

In summary, the proposed approach generates the necessary spatial-temporal information required by decision makers. The work provides insights into the complex coastal systems, while also addressing the multi-criteria decision problems resulting from the involvement of multiple stakeholders. Importantly, the approach enables DMs to critically examine the decision alternatives through the use of the DSM. Significantly, the research outcomes confirm that the DSM is capable of addressing uncertainties and generating alternative scenarios based on different inputs to the models.
APPENDICES

APPENDIX 1 - GLOSSARY

Summarised from the IPCC Glossary (Parry et al., 2007).

This glossary defines the specific terms in a climate change context that are used in the IPCC Reports.

**Accommodation**: All natural system effects are allowed to occur and human impacts are minimised by adjusting human use of the coastal zone. Examples of accommodation policies include flood-proofing or raising buildings, changing agriculture towards more flood-tolerant crops, etc.

**Adaptation**: The adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.

**Adaptive capacity**: The ability of a system to adjust to climate change (including changes in variability and extremes) so as to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

**Anthropogenic**: Resulting from or produced by human activities, in particular, factors that affect the atmosphere due to the burning of fossil fuels, deforestation and other land use change.

**Autonomous Adaptation**: The coastal system’s spontaneous adaptive response to climate change impact (generally sea level rise). This is determined by the natural system’s resilience and resistance, and the socio-economic system’s ability to prevent or cope. Examples include increased wetland accretion, or changes in the price of coastal property.
**Carbon dioxide (CO2):** A colourless, odourless gas that occurs naturally and is also emitted by fossil fuel combustion and land clearing. It is the main anthropogenic-influenced greenhouse gas affecting climate change.

**Carbon sink:** Natural or human activity or mechanism that removes carbon dioxide from the atmosphere, such as the absorption of carbon dioxide by growing trees.

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

**Climate Change:** It, in IPCC usage, refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the Framework Convention on Climate Change, where climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods.

**Climate prediction:** A climate prediction or climate forecast is the result of an attempt to produce a most likely description or estimate of the actual evolution of the climate in the future (e.g., at seasonal, inter-annual, or long-term time scales).

**Climate projection:** A projection of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasise that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on assumptions, concerning, for example, future socioeconomic and technological developments that may or may not be realised and are therefore subject to substantial uncertainty.
Climate scenario: A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships, that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models.

Climate variability: Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

Coping range: The range of variability described by a climate variable, climate-related variable or proxy climate variable whose consequences or outputs can be measured in terms of tolerable levels of harm or risk.

Critical threshold: The point at which an activity faces an unacceptable level of harm, such as a change from profit to loss on a farm due to decreased water availability, or coastal flooding exceeding present planning limits. It occurs when a threshold q.v. Is reached at which ecological or socioeconomic change is damaging and requires a policy response.

Decision objective: The intention put forward by the decision-maker that is to be achieved by implementing a decision or sequence of decisions.

Do nothing: This may also be a response to the problem of climate change impact (generally sea level rise), and may result from an active analysis that there is no problem, and hence nothing to do, or ignorance/lack of understanding about the need to adapt. Therefore, it is important to define why nothing is being done.

Emission Scenario: A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships.
**Evaluation**: The process of examining options and assessing their relative merits.

**Exposure unit**: The system considered to be at risk. The exposure unit will often be defined in terms of geographical extent and the location and distribution of the populations of receptors at risk. In some cases the exposure unit and receptor may be synonymous.

**Extreme event**: An extreme weather event refers to meteorological conditions that are rare for a particular place and/or time, such as an intense storm or heat wave. An extreme climate event is an unusual average over time of a number of weather events, for example heavy rainfall over a season.

**Flooding**: Temporary submergence of the land from which either partial or total recovery may occur.

**Global temperature**: Usually referring to the surface temperature, this is an area-weighted average of temperatures recorded at ground- and sea-surface-based observation sites around the globe, supplemented by satellite-based or model-based records in remote regions.

**Global warming**: An increase in global average surface temperature due to natural or anthropogenic climate change.

**Greenhouse effect**: The natural greenhouse effect is the process where gases in the lower atmosphere such as carbon dioxide, methane and water vapour are warmed by radiation released by the Earth’s surface after it has been warmed by solar energy. These gases then radiate heat back towards the ground—adding to the heat the ground receives from the Sun. Without the natural greenhouse effect the surface of the planet would be about 33 °C colder on average.

**Greenhouse gas emissions**: The release of greenhouse gases and aerosols into the atmosphere. Emissions are usually measured in tonnes. About 25% of carbon dioxide emissions are absorbed by the ocean and another 25% by the terrestrial biosphere, leaving about 50% in the atmosphere.
Greenhouse gases: Natural and anthropogenic gases in the atmosphere that absorb and emit infrared or heat radiation, causing the greenhouse effect. The main greenhouse gases are water vapour, carbon dioxide, nitrous oxide and methane.

Hazard: A situation or event with the potential to cause harm. A hazard does not necessarily cause harm.

Inundation: Permanent loss of land or flooding that is so frequent that no recovery is likely.

Mitigation: Mitigation of climate change refers to those response strategies that reduce the sources of greenhouse gases or enhance their sinks, to subsequently reduce the probability of reaching a given level of climate change. Mitigation reduces the likelihood of exceeding the adaptive capacity of natural systems and human societies.

Model: In its broadest sense, a representation of how a system works, or responds to inputs, and may be used as a basis of risk assessment, analysis or management by decision-makers. A model may be anything from a conceptual framework through to a fully parameterised and validated numerical representation of a system implemented on a computer.

Planned adaptation: The planned responses to climate change impact (generally sea level rise), which usually would involve an informed policy maker and some agreed collective action.

Protection: Natural system effects are controlled by soft or hard engineering, reducing human impacts in the zone that would be impacted without protection. The form of adaptation that most readily springs to mind – sea walls, dikes, beach nourishment, etc.

Risk: Risk is the probability that a situation will produce harm under specified conditions. It is a combination of two factors: the probability that an adverse event will occur; and the consequences of the adverse event. Risk encompasses impacts on human and natural systems, and arises from exposure and hazard. Hazard is
determined by whether a particular situation or event has the potential to cause harmful effects.

**Scenario:** A coherent, internally consistent and plausible description of a possible future state of the world, usually based on specific assumptions.

**Sensitivity analysis:** A structured approach to investigate how a system, model or assessment responds to small changes in input values, parameter values or other assumption. Sensitivity analysis is used to identify those input values, parameters or model assumptions that have the most significant impact on the outputs or response.

**Sensitivity:** Refers to the changes that result (in a system or variable) from a specific perturbation in an input value, parameter value, or other assumption. Therefore climate sensitivity is the degree to which a system would be affected, either adversely or beneficially, by climate-related stimuli.

**Stakeholder:** A person or an organisation that has a legitimate interest in a project or entity, or would be affected by a particular action or policy.

**Storm surge:** A region of elevated sea level at the coast caused by the combined influence of low pressure and high winds associated with a severe storm such as a tropical cyclone.

**System:** The social, economic and physical domain within which risks arise, produce consequences, and in which risks are managed. An understanding of the way in which a system may behave is an essential aspect of understanding and managing risk. In particular it is important to identify mechanisms and thresholds by which the system may fail when loaded, and the processes that provide opportunities for risk management decisions.

**Uncertainty:** A characteristic of a system or decision where the probabilities that certain states or outcomes have occurred or may occur is not precisely known.

**Variable:** Strictly, a fundamental property of a system (or model) that can take a range of possible values, determined by the values of other system variables and parameters,
external inputs or boundary conditions. Driving or forcing variables link internal system variables to influences that are external to the model.

**Vulnerability Assessment (VA):** An analysis of the scope and severity of the potential effects of climate change impact (generally sea level rise).

**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. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, the sensitivity and adaptive capacity of that system.
APPENDIX 2 - IPCC - SRES SCENARIOS – STORYLINES

To provide more consistent projections of greenhouse gas emissions – projections that considered the complex social, economic, and technological relationships that underlie energy use and resulting emissions – the IPCC developed the Special Report on Emission Scenarios (SRES). The SRES approach aims to present a short “history” of possible future development expressed in a combination of key scenario characteristics based upon an underlying consistency of the complex economic relationships that underlay energy use. The result was a set of logical storylines that encompass the social and physical relationships driving greenhouse gas (GHG) emissions (Nakicenovic and Swart, 2000).

At the core of the SRES approach are four poles along two major axes:

- Economic versus environmental
- Global versus regional.

Combinations of these four poles give rise to four primary storylines:

- A1 – Economic growth and liberal globalization
- A2 – Economic growth with greater regional focus
- B1 – Environmentally sensitive with strong global relationships
- B2 – Environmentally sensitive with a highly regional focus.

Each storyline describes a global paradigm based on prevalent social characteristics, values and attitudes that determine, for example, the extent of globalization, economic development patterns and environmental resource quality. The storylines are by their nature highly speculative. Nonetheless, they do provide identifiable starting points that are defined and consistent with available datasets for projecting some variables (most notably population, income, land use, and emissions). They have been used in previous and ongoing assessments and provide a basis for inter-country comparisons. Finally, they illustrate the degree of creative imagination that this scenario building embraces. It is certainly appropriate to consider these storylines as
appropriate or desired, based on national and regional outlooks and goals and plausible futures.

The A1 and B1 scenarios focus on global solutions to economic, social and environmental sustainability, with A1 focusing on economic growth and B1 focusing on environmental sensitivity. A2 and B2 focus on regional solutions with strong emphasis on self-reliance. They differ in that A2 focuses on strong economic growth and B2 focuses on environmental sensitivity. The IPCC describes their differences as follows: “While the A1 and B1 storylines, to different degrees, emphasize successful economic global convergence and social and cultural interactions, A2 and B2 focus on a blossoming of diverse regional development pathways.”

The A1 scenario assumes strong economic growth and liberal globalization characterized by low population growth, very high GDP growth, high-to-very-high energy use, low-to-medium changes in land use, medium-to-high resource availability (of conventional and unconventional oil and gas), and rapid technological advancement. The A1 scenario assumes convergence among regions, including a substantial reduction in regional differences in per capita income in which the current distinctions between “poor” and “rich” countries eventually dissolve; increased capacity building; and increased social and cultural interactions. A1 emphasizes market-based solutions; high savings and investment, especially in education and technology; and international mobility of people, ideas, and technology.

The A2 scenario describes a world with regional economic growth characterized by high population growth, medium GDP growth, high energy use, medium-to-high changes in land use, low resource availability of conventional and unconventional oil and gas, and slow technological advancement. This scenario assumes a very heterogeneous world that focuses on self-reliance and the preservation of local identities, and assumes that per capita economic growth and technological change are more fragmented and slower than in other scenarios.

The B1 scenario describes a convergent world that emphasizes global solutions to economic, social and environmental sustainability. Focusing on environmental sensitivity and strong global relationships, B1 is characterized by low population
growth, high GDP growth, low energy use, high changes in land use, low resource availability of conventional and unconventional oil and gas, and medium technological advancement. The B1 scenario assumes rapid adjustments in the economy in the service and information sectors, decreases in material intensity, and the introduction of clean and resource-efficient technologies. A major theme in the B1 scenario is a high level of environmental and social consciousness combined with a global approach to sustainable development.

The B2 scenario, like the A2 scenario, focuses on regional solutions to economic, social and environmental sustainability. The scenario focuses on environmental protection and social equality and is characterized by medium population and GDP growth, medium energy use, medium changes in land use, medium resource availability, and medium technological advancement.

The four standard SRES scenarios

A1 – Economic growth and liberal globalization

- Utilitarian values, affluence oriented
- Rapid economic growth (3% globally)
- Low population growth, long life, small families
- Rapid introduction and adoption of efficient technologies
- Intermediate GHG emissions
- Personal wealth emphasized over environmental quality
- Reduced differences in regional incomes
- Cultural differences throughout the world converge

A2 – Economic growth with greater regional focus

- Local, community, and family centred values
- Greater regional emphasis both culturally and economically
- Less rapid economic growth (1.5% globally)
- High population growth
- Low per capita incomes
• Technology change and adoption depends on resources and culture
• Highest GHG emissions
• Focus on agricultural productivity to feed rapidly rising populations

B1 – Environmentally sensitive with strong global relationships

• High level of environmental and social concern and value
• Emphasis on globally sustainable and balanced development with investments in social infrastructure and environmental protection
• Moderate economic growth (2% globally)
• Low population growth
• Moderate per capita income, slightly less than A1
• Services emphasized over material goods, quality over quantity
• Mitigation technologies rapidly adopted and rapid decline in use of fossil fuels
• Low GHG emissions

B2 – Environmentally sensitive with highly regional focus

• High level of environmental and social concern and value
• Emphasis on decentralized decision-making and local self-reliance
• Moderate economic growth (1% globally)
• Moderate population growth
• Moderate per capita income, slightly less than A1
• Less technology development and adoption, declining global investment, and less international diffusion
• Regional differences in energy use and innovation, transition out of fossil fuels is gradual
• Moderate GHG emissions
APPENDIX 3 - THE SD MODEL DOCUMENTATION

(01) Area[X,Y] = IF THEN ELSE ( Initial Cover[X,Y] = 4, 1, 0)  
Units: Dmnl

(31) Initial Cover - Sea = 1 Waterway = 2 Pond = 3 Land = 4

Used by:

(51) Total Area -

(02) Area at Risk = SUM ( Flooded Cells[X!,Y!] ) * Cell Size  
Units: sqm

(06) Cell Size –

(25) Flooded Cells -

Used by:

(03) Area at Risk (%)  

(03) "Area at Risk (%)" = Area at Risk / Total Area * 100  
Units: Dmnl

(02) Area at Risk -

(51) Total Area -

(04) Cell Cover[X,Y] = INTEG( ( Change[X,Y] - Change Previous[X,Y] ) / TIME STEP , 
Initial Cover[X,Y] )  
Units: Dmnl
(07) Change - Cell Cover types: Sea=1 Waterway=2 Pond=3 Land=4

(08) Change Previous -

(31) Initial Cover - Sea = 1 Waterway = 2 Pond = 3 Land = 4

(50) TIME STEP - The integration solution interval

Used by:

(07) Change - Cell Cover types: Sea=1 Waterway=2 Pond=3 Land=4

(08) Change Previous -

(12) CBottom - Cell_cover Types: Sea=1, Waterway=2, Pond=3 or Land=4

(13) CLeft - Cell_cover Types: Sea=1, Waterway=2, Pond=3 or Land=4

(14) CRight - Cell_cover Types: Sea=1, Waterway=2, Pond=3 or Land=4

(15) CTop - Cell_cover Types: Sea=1, Waterway=2, Pond=3 or Land=4

(25) Flooded Cells -

(29) Increase –

Cx,y= 1 Cover type is "Sea"

Cx,y= 2 Cover type is "Waterway" Cx,y= 3 Cover type is "Pond"

Cx,y= 4 Cover type is "Land"

(05) Cell Elevation with Protective Structure[X,Y] =

IF THEN ELSE ( Protective Structure <= 0, Initial Elevation[X,Y] ,

IF THEN ELSE ( Initial Cover[X,Y] = 4 :AND: CTTop[X,Y] = 1

:OR: Initial Cover[X,Y] = 4 :AND: CLeft[X,Y] = 1
:OR: Initial Cover\([X,Y]\) = 4 :AND: CTBottom\([X,Y]\) = 1

:OR: Initial Cover\([X,Y]\) = 4 :AND: CTRight\([X,Y]\) = 1,

\[\text{MAX ( ( Initial Elevation}\,[X,Y]\text{) + Protective Structure ), }
\]

Protective Structure , Initial Elevation\([X,Y]\) )

Units: meter

(12)CTBottom - Cell_cover Types: Sea=1, Waterway=2, Pond=3 or Land=4

(13)CTLeft - Cell_cover Types: Sea=1, Waterway=2, Pond=3 or Land=4

(14)CTRight - Cell_cover Types: Sea=1, Waterway=2, Pond=3 or Land=4

(15)CTTop - Cell_cover Types: Sea=1, Waterway=2, Pond=3 or Land=4

(31)Initial Cover - Sea = 1 Waterway = 2 Pond = 3 Land = 4

(32)Initial Elevation -

(41)Protective Structure -

Used by:

(21)Elevation -

(18)Decrease -

(06) Cell Size  = 25

Units: sqm \([25,400]\)

Used by:

(02)Area at Risk -

(35)Number of People in the Area -

(36)People at Flooded Cell -

(51)Total Area -

(07) Change\([X,Y]\) =

\[\text{IF THEN ELSE ( Cell Cover}\,[X,Y]\text{) = 4 :AND: Elevation}\,[X,Y]\text{ <= ERight}\,[X,Y]\text{:AND: CTRight}\,[X,Y]\text{ = 1}\
\]
:OR: Cell Cover\([X,Y] = 4\) \:\AND: Elevation\([X,Y] \leq ELeft\[X,Y]\) \:\AND: CTLeft\[X,Y] = 1

:OR: Cell Cover\([X,Y] = 4\) \:\AND: Elevation\([X,Y] \leq ETop\[X,Y]\) \:\AND: CTTop\[X,Y] = 1

:OR: Cell Cover\([X,Y] = 4\) \:\AND: Elevation\([X,Y] \leq EBottom\[X,Y]\) \:\AND: CTTBottom\[X,Y] = 1

:OR: Cell Cover\([X,Y] = 3\) \:\AND: Elevation\([X,Y] \leq ERight\[X,Y]\) \:\AND: CTRight\[X,Y] = 1

:OR: Cell Cover\([X,Y] = 3\) \:\AND: Elevation\([X,Y] \leq ELeft\[X,Y]\) \:\AND: CTLeft\[X,Y] = 1

:OR: Cell Cover\([X,Y] = 3\) \:\AND: Elevation\([X,Y] \leq ETop\[X,Y]\) \:\AND: CTTop\[X,Y] = 1

:OR: Cell Cover\([X,Y] = 3\) \:\AND: Elevation\([X,Y] \leq EBottom\[X,Y]\) \:\AND: CTTBottom\[X,Y] = 1

:OR: Cell Cover\([X,Y] = 2\) \:\AND: Elevation\([X,Y] \leq ERight\[X,Y]\) \:\AND: CTRight\[X,Y] = 1

:OR: Cell Cover\([X,Y] = 2\) \:\AND: Elevation\([X,Y] \leq ELeft\[X,Y]\) \:\AND: CTLeft\[X,Y] = 1

:OR: Cell Cover\([X,Y] = 2\) \:\AND: Elevation\([X,Y] \leq ETop\[X,Y]\) \:\AND: CTTop\[X,Y] = 1

:OR: Cell Cover\([X,Y] = 2\) \:\AND: Elevation\([X,Y] \leq EBottom\[X,Y]\) \:\AND: CTTBottom\[X,Y] = 1

IF THEN ELSE ( Cell Cover\([X,Y] = 1\) \:AND: ( Initial Cover\[X,Y] = 2

:OR: Initial Cover\([X,Y] = 3\)

:OR: Initial Cover\([X,Y] = 4\) \:AND: ( Elevation\([X,Y] - Sea Level) > 0, Initial Cover\[X,Y] , Cell Cover\([X,Y]\) )

Units: Dmnl

Cell Cover types:

Sea=1

Waterway=2

Pond=3

Land=4

(04)Cell Cover -

(21)Elevation -

(12)CTBottom - Cell_cover Types: Sea=1, Waterway=2, Pond=3 or Land=4

(13)CTLeft - Cell_cover Types: Sea=1, Waterway=2, Pond=3 or Land=4
(14) CTRight - Cell_cover Types: Sea=1, Waterway=2, Pond=3 or Land=4

(15) CTTop - Cell_cover Types: Sea=1, Waterway=2, Pond=3 or Land=4

(19) EBottom -

(20) ELeft -

(22) ERight -

(23) ETop -

(31) Initial Cover - Sea = 1 Waterway = 2 Pond = 3 Land = 4

Used by: (04) Cell Cover -

(08) Change Previous[X,Y] = Cell Cover[X,Y]

Units: Dmnl

(04) Cell Cover -

Used by:

(04) Cell Cover -

(09) Constant = 0.4094

Units: meter

Used by: (27) Future ARI -

(10) convert mt = 1

Units: meter

Used by:

(17) Current ARI -

(11) convert sqm = 1

Units: sqm
Used by:

(35) Number of People in the Area -

(36) People at Flooded Cell -

(12) \[ CT_{\text{Bottom}}[X_{\text{earlier}}, Y] = \text{Cell Cover}[X_{\text{later}}, Y] \]

\[ CT_{\text{Bottom}}[x361, Y] = \text{Cell Cover}[x361, Y] \]

Units: Dmnl

Cell_cover Types:

Sea=1,
Waterway=2,
Pond=3
Land=4

(04) Cell Cover -

Used by:

(05) Cell Elevation with Protective Structure -

(07) Change

(29) Increase

(13) \[ CT_{\text{Left}}[X, Y_{\text{later}}] = \text{Cell Cover}[X, Y_{\text{earlier}}] \]

\[ CT_{\text{Left}}[X, y1] = \text{Cell Cover}[X, y1] \]

Units: Dmnl

04) Cell Cover -

Used by:

(05) Cell Elevation with Protective Structure -

(07) Change - Cell Cover types: Sea=1 Waterway=2 Pond=3 Land=4

(29) Increase

(14) \[ CT_{\text{Right}}[X, Y_{\text{earlier}}] = \text{Cell Cover}[X, Y_{\text{later}}] \]
CTRight\[X,y361\] = Cell Cover\[X,y361\]

Units: Dmnl

(04) Cell Cover -

Used by:

(05) Cell Elevation with Protective Structure -

(07) Change - Cell Cover types: Sea=1 Waterway=2 Pond=3 Land=4

(29) Increase - Cx,y= 1

(15) CTTop\[Xlater,Y\] = Cell Cover\[Xearlier,Y\]

CTTop\[x1,Y\] = Cell Cover\[x1,Y\]

Units: Dmnl

(04) Cell Cover -

Used by:

(05) Cell Elevation with Protective Structure -

(07) Change - Cell Cover types: Sea=1 Waterway=2 Pond=3 Land=4

(29) Increase

(16) Current 100 yr SS Height = 2.50

Units: meter [1.9,5,0.1]

Used by:

(26) Future 100 yr SS Height -

(27) Future ARI -

(17) Current ARI = EXP ( ( ( SS Heights / convert mt ) - 0.6594) / 0.4094)

Units: Year

(10) convert mt -

(48) SS Heights

(18) Decrease\[X,Y\] =
IF THEN ELSE ( Elevation\([X,Y]\) > Cell Elevation with Protective Structure\([X,Y]\) :AND: Elevation\([X,Y]\) > Sea Level, Elevation\([X,Y]\)-MAX (Sea Level, Cell Elevation with Protective Structure\([X,Y]\) ) , 0) / TIME STEP

Units: meter/Year

(21) Elevation -

(47) Sea Level -

(05) Cell Elevation with Protective Structure -

(50) TIME STEP - The integration solution interval

Used by:

(21) Elevation -

(19) EBottom\([xearlier,Y]\) = Elevation\([xlater,Y]\)

EBottom\([x361,Y]\) = Elevation\([x361,Y]\)

Units: meter

(21) Elevation -

Used by:

(07) Change

(20) ELeft\([X,Ylater]\) = Elevation\([X,Yearlier]\)

ELeft\([X,y1]\) = Elevation\([X,y1]\)

Units: meter

(21) Elevation -

Used by:

(07) Change

(21) Elevation\([X,Y]\)=INTEG( Increase\([X,Y]\)-Decrease\([X,Y]\), Cell Elevation with Protective Structure\([X,Y]\))

Units: meter

(05) Cell Elevation with Protective Structure -

(18) Decrease -

(29) Increase - Cx,y= 1
APPENDIX 3

Used by:

(07) Change - Cell Cover types: Sea=1 Waterway=2 Pond=3 Land=4

(18) Decrease -

(19) EBottom -

(20) ELeft -

(22) ERight -

(23) ETop -

(29) Increase

(22) ERight[X,Yearlier] = Elevation[X,Ylater]

ERight[X,y361] = Elevation[X,y361]

Units: meter

(21) Elevation -

Used by: (07) Change

(23) ETop[Xlater,Y] = Elevation[Xearlier,Y]

ETop[x1,Y] = Elevation[x1,Y]

Units: meter

(21) Elevation -

Used by: (07) Change

(24) FINAL TIME = 100

Units: Year


:OR: ( Cell Cover[X,Y]= 2:AND: Initial Cover[X,Y]= 4)

:OR: ( Cell Cover[X,Y]= 3:AND: Initial Cover[X,Y]= 4) , 1, 0)

Units: Dmnl

(04) Cell Cover -

(31) Initial Cover
Used by:

(02) Area at Risk -
(36) People at Flooded Cell

(26) Future 100 yr SS Height = Current 100 yr SS Height + Sea Level

Units: meter

(47) Sea Level

(16) Current 100 yr SS Height

(27) Future ARI = EXP (( Current 100 yr SS Height - (0.6594 + Sea Level)) / Constant )

Units: Dmnl

(47) Sea Level

(09) Constant - constant for Exp function to calculate future ARI

(16) Current 100 yr SS Height

(28) h = 0.1

Units: meter

Observed change in sea level

Used by:

(30) Increase in Current 100 yr SS Frequency

If a sea level rise of \( h \) increases the frequency of occurrence by a factor \( r \), then a sea level rise of \( H \) increases the frequency of occurrence by a factor \( (r^H/h) \)

\( H \): Future sea level rise prediction

\( h \): observed sea level rise in a given location (0.1 m for Australia observed over 30 years)

(29) Increase\([X,Y]\] = ( IF THEN ELSE ( Cell \text{Cover} \[X,Y]\] = 1

:OR: ( Cell \text{Cover} \[X,Y]\] = 4:AND: ( \text{CRight} \[X,Y]\] = 1

:OR: \text{CTop} \[X,Y]\] = 1

:OR: \text{CTBottom} \[X,Y]\] = 1

:OR: \text{CLeft} \[X,Y]\] = 1 ) )
\[ \text{OR: ( Cell Cover}[X,Y] = 3: \text{AND: ( CTRight}[X,Y] = 1} \]
\[ \text{OR: CTTop}[X,Y] = 1 \]
\[ \text{OR: CTBottom}[X,Y] = 1 \]
\[ \text{OR: CLeft}[X,Y] = 1) ) \]
\[ \text{OR: ( Cell Cover}[X,Y] = 2: \text{AND: ( CTRight}[X,Y] = 1} \]
\[ \text{OR: CTTop}[X,Y] = 1 \]
\[ \text{OR: CTBottom}[X,Y] = 1 \]
\[ \text{OR: CLeft}[X,Y] = 1) ) , \]
\[ \text{MAX ( Sea Level - Elevation}[X,Y] , 0) , 0) ) / \text{TIME STEP} \]

Units: meter/Year

(04) Cell Cover -
(21) Elevation -
(47) Sea Level
(12) CTBottom
(13) CLeft
(14) CTRight
(15) CTTop
(50) TIME STEP - The integration solution interval

Used by:
(21) Elevation

(30) Increase in Current 100 yr SS Frequency = \( r \ ^ \ ( \text{Sea Level} / h \ ) \)

Units: Dmnl

(47) Sea Level

(28) h - observed changes in sea level

(42) r - the multiplying factor has a range of 1.8 to 5.8 and a mean of 3.1 for Australia

(31) Initial Cover}[X,Y] = 0
Units: Dmnl
Used by:
(04) Cell Cover -
(01) Area -
(05) Cell Elevation with Protective Structure -
(07) Change - Cell Cover types: Sea=1 Waterway=2 Pond=3 Land=4
(25) Flooded Cells
(32) Initial Elevation\([X,Y]\) = 0
Units: meter
Used by:
(05) Cell Elevation with Protective Structure
(33) Initial Sea Level = 0
Units: meter \([0,2.5,0.1]\)
Initial sea level = 0
Used by:
(47) Sea Level
(34) INITIAL TIME = 0
Units: Year
The initial time for the simulation.
(35) Number of People in the Area=SUM ( Residents\([X!,Y!]\) )\*Cell Size / convert sqm
Units: persons
(43) Residents
(06) Cell Size
(11) convert sqm
Used by:
(37) People at Risk (%)
(36) People at Flooded Cell\(X,Y\) = Residents\(X,Y\)\*Flooded Cells\(X,Y\)\*Cell Size
/convert sqm

Units: persons

(43) Residents

(06) Cell Size

(11) convert sqm -

(25) Flooded Cells -

Used by: (52) Total Number of People at Risk

(37) People at Risk (%) = Total Number of People at Risk/Number of People in the Area * 100

Units: Dmnl

(35) Number of People in the Area

(52) Total Number of People at Risk

(38) Population\(X,Y\) = Initial population

Units: persons

Used by:

(43) Residents -

(39) "Population Growth (%)" = 2

Units: Dmnl [-4,4,0.1]

The growth rate value represents percentage increase in population per year

Used by:

(40) population increase

(40) population increase\(X,Y\) = ( Residents\(X,Y\) * ( "Population Growth (%)" / 100)) / TIME STEP

Units: persons/Year

(43) Residents

(39) Population Growth (%)
(50) TIME STEP
Used by:
(43) Residents -

(41) Protective Structure = 2
Units: meter [0,3,0.25]
Used by:
(05) Cell Elevation with Protective Structure

(42) \[ r = 3.1 \]
Units: Dmnl [1.8,5.8,0.1]
r: the multiplying factor has a range of 1.8 to 5.8 and a mean of 3.1 for Australia,
Used by:
(30) Increase in Current 100 yr SS Frequency

(43) \[ \text{Residents}[X,Y] = \text{INTEG}( \text{population increase}[X,Y], \text{Population}[X,Y]) \]
Units: persons
(38) Population
(40) population increase
Used by:
(35) Number of People in the Area -
(36) People at Flooded Cell -
(40) population increase -

(44) \[ \text{Rise} = \text{Rise Rate} \]
Units: meter/Year
(45) Rise Rate - (m/yr)
Used by:
(47) Sea Level

(45) Rise Rate = 0.015
Units: meter/Year [0,0.06,0.005]
Used by:
(44) Rise

(46) SAVEPER = 10
Units: Year [0,?]
The frequency with which output is stored.

(47) Sea Level = INTEG( Rise , Initial Sea Level )
Units: meter
(33) Initial Sea Level
(44) Rise -
Used by:
(07) Change
(18) Decrease -
(26) Future 100 yr SS Height -
(27) Future ARI -
(29) Increase
(30) Increase in Current 100 yr SS Frequency
(49) SS Heights with Rising Sea Level

(48) SS Heights=IF THEN ELSE(Time=0, ( 0.4094*LN((Time/TIME STEP )+1) + 0.6594),
( 0.4094* LN ( Time /TIME STEP ) + 0.6594) )
Units: meter

IF THEN ELSE (Time=0, (0.4094*LN(TIME STEP)+0.6594),
(0.4094*LN(Time)+0.6594))

(00) Time - Internally defined simulation time.

(50) TIME STEP - The integration solution interval
SS Heights with Rising Sea Level = SS Heights + Sea Level

Units: meter

Sea Level

SS Heights

TIME STEP = 0.03125

Units: Year

The integration solution interval

Total Area = SUM ( Area[X!,Y!] ) * Cell Size

Units: sqm

Area -

Cell Size

Total Number of People at Risk = SUM ( People at Flooded Cell[X!,Y!] )

Units: persons

People at Flooded Cell
(37) People at Risk (%)

(53) $X : (x_1-x_{361})$

(54) $X_{\text{earlier}} : (x_1-x_{360}) \rightarrow X_{\text{later}}$

(55) $X_{\text{later}} : (x_2-x_{361}) \rightarrow X_{\text{earlier}}$

(56) $X_p \leftrightarrow X$

(57) $Y : (y_1-y_{361})$

(58) $Y_{\text{earlier}} : (y_1-y_{360}) \rightarrow Y_{\text{later}}$

(59) $Y_{\text{later}} : (y_2-y_{361}) \rightarrow Y_{\text{earlier}}$

(60) $Y_p \leftrightarrow Y$
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<th>Rise Rate (m/yr)</th>
<th>SS Height (m)</th>
<th>Protective Structure (m)</th>
<th>Improve Building Design (m)</th>
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<tr>
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<td>Rise Rate (m/yr)</td>
<td>SS Height (m)</td>
<td>Protective Structure (m)</td>
<td>Improve Building Design (m)</td>
<td>Population at Risk (%)</td>
</tr>
<tr>
<td>----------</td>
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</table>

**APPENDIX 4**
Dear Participant,

We are currently undertaking a research project into the vulnerability assessment and adaptation options in coastal areas on the Gold Coast.

As part of this research, we are conducting a multi criteria analysis in order to elicit stakeholders’ opinions for evaluating adaptation alternatives to adapt to the impacts of climate change.

Adaptation to climate change is a complex area. It involves, considering the climate change impacts on a range of stakeholders such as governments, organizations and people. Making decisions about adaptation policy involves vulnerability assessment and assessments of various adaptation alternatives. The main goal of such adaptation measures is to ensure that decisions we make today do not compromise the resilience of the Gold Coast in the future.

Mindful of this, the purpose of this study is to identify and evaluate preferred adaptation alternatives which could reduce the vulnerability to SLR and storm surges.

In the following pages we would like to obtain your opinion as an expert/resident/politician through a survey questionnaire, in which you are requested to prioritise five adaptation options with respect to the criteria and the project goal.

If you decide to participate in this research, please complete the survey and return it directly to the researcher using the reply-paid envelope by 30 July 2010.

The information you provide will be of great value for this research, and accordingly, your participation is anticipated and very much appreciated.

We sincerely hope you can assist.

Oz Sahin
PhD Candidate
School of Engineering
Griffith University Qld 4222
0439 799 109

o.sahin@griffith.edu.au
INFORMED CONSENT FORM

Dear Participant,

You are being asked to participate in a research study regarding adaptation policy analysis. Investigator Oz Sahin is conducting this research under the supervision of Prof. Sherif Mohamed.

Please read the information provided in Sections A and B carefully. You should ask Investigator Mr. Oz Sahin to explain any sections that are unclear to you and to answer any questions that you may have. If, after deciding to participate in this study, you find you have more questions, you should contact the investigator at the number given at the end of this form.

If you decide to participate in this research, please complete the survey and return it directly to the researcher using the reply-paid envelope. Please keep a copy of this consent form for your records as it contains important information, including names and telephone numbers that you may wish to have in the future.

By completing and returning the attached survey, you are consenting to participate in this research.

Section-A – Information for Participants

Participants

Residents, local Politicians and Experts are identified as key participants of this study. Residents include any adult, male or female aged 18 or over who is the owner of and/or living in a waterfront property in the City of the Gold Coast.

Politicians include Gold Coast City councillors and local members of State and Federal Parliaments.

Experts include those identified as having an extensive knowledge of, or ability in climate adaptation, coastal management, urban planning as related to the development and implementation of adaptation strategies. Experts are expected to include university academics, professional engineers, planners, etc.

Participants' Right to Decline

Your participation is voluntary and you can withdraw from the survey after having agreed to participate. You are free to refuse to answer any question that is being asked in the questionnaire.

Time to Complete Survey: The survey will take approximately 30 minutes to complete.

Conducting Survey

The survey will be conducted by:

- Delivering the questionnaires in person to the participants, explain the study, and then collect the questionnaires at a date after completion.
- Mailing questionnaires directly to participants (or an electronic survey by email if preferred) and asking the respondent to mail the survey back when completed.
For either method, each interested participant will be provided with a survey pack, including a cover letter, an informed consent form, a project description, a questionnaire, and a reply-paid envelope.

Confidentiality

The information provided by participants will not be disclosed. Participant’s name, address and other personal data are not asked, however, if provided, they will be removed from the questionnaire and not known to others. The answers s/he gives will be only used for research purposes and for writing a report. Care will be taken to report information so as to minimize the readers’ ability to identify the role and hence identity of the source of information.

Use of Information: The information and findings obtained will be used for completing the requirements for the degree of PhD thesis. In addition, they may be used in seminars, conference presentations and research publications.

Risk: The identified potential risk to the participants could be losing their time for completing the questionnaire. The questionnaire is expected to take approximately 30 minutes to complete.

Availability of Results

A summary of the results is expected to be available by December 2010. Participants wanting a copy should forward their request directly to Oz Sahin at Griffith University,

by email to: o.sahin@griffith.edu.au , or by phone: 0439 799 109.

Ethical Statement

Griffith University conducts research in accordance with the National Statement on Ethical Conduct in Human Research. If potential participants have any concerns or complaints about the ethical conduct of the research project they should contact the Manager, Research Ethics on

(07) 3735 5585 or research-ethics@griffith.edu.au .

Contact Numbers

1. For answers to questions about the research or to voice concern or complaint about the research, or to report a study-related problem:

   Oz Sahin
   PhD Candidate
   Griffith School of Engineering
   Griffith University Qld 4222
   0439 799109
   o.sahin@griffith.edu.au

2. For questions, problems, concerns or complaints about the study, or for information about your rights as a research participant:

   The Manager
   Research Ethics
   (07) 3735 5585
   research-ethics@griffith.edu.au.
PARTICIPANT STATEMENT

I have read (or had read to me) this consent form. I have been given the opportunity to ask questions and my questions were answered to my satisfaction.

I understand that I may refuse to participate in this study and that if I refuse to participate; this will not result in the loss of any benefits or services to which I am otherwise entitled. I agree to participate in this study. I also understand that if, for any reason, I wish to stop participating, I will be free to do so, and this will have no effect on my future care or services. I have been given a copy of this consent form for my records.

Date ______________
Section-B – MULTI-CRITERIA ANALYSIS FOR EVALUATING ADAPTATION OPTIONS

Introduction

There is growing evidence that our climate is changing. Sea level rise (SLR) is one of the best known effects of changing climate. SLR and storm surges can cause significant problems for low-lying coastal areas. Millions of people live near sea may be forced to displace due to coastal flooding. The impacts of climatic changes are expected to be hit locally and regionally in different ways. The majority of adaptation actions will therefore need to be decided and to be undertaken at the local and regional level.

In recognition of these threats, both the Queensland Government and the Gold Coast City Council have been developing short, medium and long term strategies based on various studies conducted in the region, such as; building and sharing knowledge, including climate change in decisions and reducing vulnerability and increasing resilience to climate change.

However, the selection and implementation of appropriate adaptation strategies to reduce climate change impacts is a complex problem. The process of prioritisation and selection of adaptations must involve stakeholders so that the process of implementation can be facilitated successfully.

In this context, the purpose of this research project is to identify and evaluate preferred adaptation alternatives which could reduce the vulnerability to SLR and storm surges. With this research, we are therefore exploring stakeholders’ opinions for adaptation alternatives to adapt to the impacts of climate change. As part of exploring options to improve Gold Coast’s resilience to climate change effects we are undertaking a multi-criteria analysis.

Through a survey questionnaire, we intend to evaluate five adaptation options by obtaining the opinions of stakeholders. For a multi-criteria analysis, Analytic Hierarchy Process (AHP) is employed. The AHP is a method designed to help in prioritizing very complex decision alternatives involving multiple stakeholders and multiple goals. Pair-wise comparisons are the fundamental building blocks of AHP.

By using the questionnaire, the participants compare the relative importance of the decision alternatives of pair-wise with respect to criteria and the goal explained below (Figure 1).

Each participant is requested to enter his/her judgments and makes a distinct, identifiable contribution to the issue. Participants do not have to agree on the relative importance of the criteria or the rankings of the alternatives.

As shown in Figure 1, the first level of hierarchy is the ultimate goal of the project; the second level represents the criteria on the basis of which the projects are to be evaluated and, finally, the third level presents the adaptation options.
Goal: To Reduce SLR Vulnerability

Criteria: Five criteria were chosen in the AHP evaluation: These are:

1. **Applicability**: It refers to legal, institutional, technical, human, social and political resources that should exist to implement the actions.
2. **Effectiveness**: It means the capability to produce a desired solution to problems arising from climate change.
3. **Sustainability**: It describes the processes, actions, decisions and strategies by society which should not actually add to SLR impacts or limit the ability of other parts of the natural environment or society to carry out adaptation elsewhere.
4. **Flexibility**: It refers to phased adaptation approach to cope with possible changes in environmental conditions, e.g. sea level rise and storm surge. Adaptation action is taken over time as required, based on more information as it becomes available on the present and future climatic conditions.
5. **Cost of Measure**: It refers to the cost of designing, implementing and maintaining an adaption action. The action should be economically feasible.

Adaptation Options: 5 adaptation options were identified. These are:

1. **Retreat**: involves a decision to withdraw, relocate or abandon assets that are at high risk of being affected by climate change hazards in the coastal zone. It can occur on a range of scales, can involve increased setback provisions, relocation of structures within properties, and rezoning of land (for example, to constrain ribbon development in high risk areas or to provide for horizontal migration of wetlands). It can include buyouts of properties.
2. **Improve Building Design**: refers to planning, designing and constructing the building to minimize any potential flood damage by elevating as much of the building as possible above the projected flood level, designing the building subject to flooding to withstand the projected flood conditions, and using flood-damage-resistant materials for any portions of the building below the projected flood level.
3. **Improve Public Awareness**: refers to improving public awareness and preparedness by informing the public about risks and possible consequences of climate change, and by developing strategies that includes ongoing public training and education programs, and improving psychological preparedness of community members.
4. **Build Protective Structures**: refers to building and maintaining protective structures such as the construction of seawalls, revetments, levees, dykes and other defences. It includes the repeated nourishment of beaches with sand and engineering works, such as tide gates, to constrain flooding.
5. **Take No Action**: refers to acceptance of the risk, rather than bear the costs of adaptation.
In the following sheets, we would like to elicit your opinion in order to select amongst the alternatives. The pair-wise comparison scale is used to express the importance of one element over another (Table 1).

<table>
<thead>
<tr>
<th>Explanation</th>
<th>Numeric Values</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1</td>
</tr>
<tr>
<td>if Option A is moderately more important than Option B : Mark/Insert</td>
<td>3</td>
</tr>
<tr>
<td>if Option A is strongly more important than Option B : Mark/Insert</td>
<td>5</td>
</tr>
<tr>
<td>if Option A is very strongly more important than Option B : Mark/Insert</td>
<td>7</td>
</tr>
<tr>
<td>if Option A is extremely more important than Option B : Mark/Insert</td>
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</tr>
<tr>
<td>Use even numbers for intermediate judgements</td>
<td>2, 4, 6, 8</td>
</tr>
</tbody>
</table>

Table 1—Saaty Comparison Scale

Example:

Given Options A & B, you can judge their relative importance as shown below example:

if you think the option ‘Build Protective Structures’ in column A is strongly more important than the option ‘Improve Building Design’ in column B, then you mark 5 with (X) on the left hand side.

if you think the option ‘Retreat’ in column B is extremely more important than the option ‘Improve Building Design’ in column A, then you mark 9 with (X) on the right hand side.
With respect to **APPLICABILITY**, 
Using the scale from 1 to 9 (where 9 is extremely and 1 is equally important), please indicate (x) the relative importance of options A (left column) to options B (right column).

<table>
<thead>
<tr>
<th>A Options</th>
<th>Extremely</th>
<th>Very Strong</th>
<th>Strongly</th>
<th>Moderately</th>
<th>Equally</th>
<th>Moderately</th>
<th>Strongly</th>
<th>Very Strong</th>
<th>Extremely</th>
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</thead>
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<td>Build Protective Structures</td>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
<td>Improve Building Design</td>
<td></td>
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<tr>
<td>Build Protective Structures</td>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
<td>Retreat</td>
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</tr>
<tr>
<td>Build Protective Structures</td>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
<td>Improve Public Awareness</td>
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</tr>
<tr>
<td>Build Protective Structures</td>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
<td>Take No Action</td>
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<tr>
<td>Improve Building Design</td>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
<td>Retreat</td>
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<td>Improve Building Design</td>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
<td>Improve Public Awareness</td>
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<td>Improve Building Design</td>
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<td>Retreat</td>
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<tr>
<td>Improve Public Awareness</td>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
<td>Take No Action</td>
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</table>

With respect to **EFFECTIVENESS**, 
Using the scale from 1 to 9 (where 9 is extremely and 1 is equally important), please indicate (x) the relative importance of options A (left column) to options B (right column).

<table>
<thead>
<tr>
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<th>Extremely</th>
<th>Very Strong</th>
<th>Strongly</th>
<th>Moderately</th>
<th>Equally</th>
<th>Moderately</th>
<th>Strongly</th>
<th>Very Strong</th>
<th>Extremely</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build Protective Structures</td>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
<td>Improve Building Design</td>
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<tr>
<td>Build Protective Structures</td>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
<td>Retreat</td>
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<tr>
<td>Build Protective Structures</td>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
<td>Improve Public Awareness</td>
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<tr>
<td>Build Protective Structures</td>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
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<td>Improve Building Design</td>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
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<tr>
<td>Improve Building Design</td>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
<td>Improve Public Awareness</td>
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<tr>
<td>Retreat</td>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
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With respect to **FLEXIBILITY**, using the scale from 1 to 9 (where 9 is extremely and 1 is equally important), please indicate (X) the relative importance of options A (left column) to options B (right column).

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### APPENDIX 5

#### With respect to COST,
Using the scale from 1 to 9 (where 9 is extremely important and 1 is equally important), please indicate (X) the relative importance of options A (left column) to options B (right column).

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#### With respect to Goal: TO REDUCE SLR VULNERABILITY,
Using the scale from 1 to 9 (where 9 is extremely important and 1 is equally important), please indicate (X) the relative importance of options A (left column) to options B (right column).

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Dear Mr Sahin

I write further to the additional information provided in relation to the provisional approval granted to your application for ethical clearance for your project "NR: Vulnerability Assessment of gold Coast Waterfront Properties to Climate Change: A Dynamic Model for Adaptation Policy Analysis" (GU Ref No: ENG/08/08/HREC).

The additional information was considered by Office for Research.

This is to confirm that this response has addressed the comments and concerns of the HREC.

Please provide us with a copy of the updated informed consent materials for our records. In the case of the politician and expert stakeholders, the materials must discuss the measures to conceal their identity.

Consequently, you are authorised to immediately commence this research on this basis.

The standard conditions of approval attached to our previous correspondence about this protocol continue to apply.

Regards

Dr Gary Allen
Manager, Research Ethics
Office for Research
Bray Centre, Nathan Campus
Griffith University
ph: 3735 5585
fax: 3735 7994
email: g.allen@griffith.edu.au
web:

Cc:

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You can find further information, resources and a link to the University's Code by visiting http://www62.gu.edu.au/policylibrary.nsf/xupdatemonth/e7852d226231d2b44a25750c0062f457?opendocument

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APPENDIX 6 - A Sample AHP Case

Scenario: A local government must decide which of the three adaptation options is suitable to reduce vulnerability of water-front properties to SLR. Three criteria are determined for assessment of adaptation options. Criteria:

1. *Flexibility*
2. *Sustainability*
3. *Efficiency*

Three adaptation options are considered:

1. *Retreat*
2. *Accommodate*
3. *Protect*

These criteria and alternatives can be structured into a hierarchy, as shown below.

The judgment scale for ranking alternatives as proposed by Saaty & Kearns (1985): With respect to *Flexibility* (the first criteria), we assume that *Accommodate* is moderately preferred to *Retreat* and very strongly preferred to *Protect*. In turn *Retreat* is (strongly to very strongly) preferred to *Protect*.

**Forming the Pair-wise Comparison Matrix for *Flexibility***
Since Accommodate is moderately preferred to Retreat, Retreat’s entry in the Accommodate row is 3 and Accommodate’s entry in the Retreat row is 1/3.

Since Accommodate is very strongly preferred to Protect, Protect’s entry in the Accommodate row is 7 and Accommodate’s entry in the Protect row is 1/7.

Since Retreat is strongly to very strongly preferred to Protect, Protect’s entry in the Retreat row is 6 and Retreat’s entry in the Protect row is 1/6.

**Pair-wise Comparison Matrix for Flexibility**

<table>
<thead>
<tr>
<th></th>
<th>Retreat</th>
<th>Accommodate</th>
<th>Protect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retreat</td>
<td>1</td>
<td>1/3</td>
<td>6</td>
</tr>
<tr>
<td>Accommodate</td>
<td>3</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Protect</td>
<td>1/6</td>
<td>1/7</td>
<td>1</td>
</tr>
</tbody>
</table>

**Normalized Matrix for Flexibility**

Divide each entry in the pair-wise comparison matrix by its corresponding column sum. For example, for Retreat the column sum = 1 + 3 + 1/6 = 25/6. This gives:

<table>
<thead>
<tr>
<th></th>
<th>Retreat</th>
<th>Accommodate</th>
<th>Protect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retreat</td>
<td>6/25</td>
<td>7/31</td>
<td>6/14</td>
</tr>
<tr>
<td>Accommodate</td>
<td>18/25</td>
<td>21/31</td>
<td>7/14</td>
</tr>
<tr>
<td>Protect</td>
<td>1/25</td>
<td>3/31</td>
<td>1/14</td>
</tr>
</tbody>
</table>

**Priority Vector for Flexibility**

The priority vector is determined by averaging the row entries in the normalized matrix. Converting to decimals we get:
\[
\text{Retreat} = \frac{6/25 + 7/31 + 6/14}{3} = 0.298
\]
\[
\text{Accommodate} = \frac{18/25 + 21/31 + 7/14}{3} = 0.632
\]
\[
\text{Protect} = \frac{1/25 + 3/31 + 1/14}{3} = 0.069
\]

**Checking Consistency**

Multiply each column of the pair-wise comparison matrix by its priority:

\[
\begin{array}{ccc|c}
1 & 1/3 & 6 & 0.923 \\
0.298 & 3 & + 0.632 & 1 & + 0.069 & 7 & = 2.009 \\
1/6 & 1/7 & 1 & 0.209
\end{array}
\]

Divide these numbers by their priorities:

\[
\frac{0.923}{0.298} = 3.097
\]
\[
\frac{2.009}{0.632} = 3.179
\]
\[
\frac{0.209}{0.069} = 3.029
\]

Average the above results to get \( \lambda_{\text{max}} \).

\[
\lambda_{\text{max}} = \frac{3.097 + 3.179 + 3.029}{3} = 3.102
\]

Compute the consistence index, CI, for two terms.

\[
\text{CI} = \frac{(\lambda_{\text{max}} - n)}{(n - 1)} = \frac{(3.102 - 3)}{2} = 0.051
\]

Compute the consistency ratio (CR) by CI/RI, where RI = 0.58 for 3 factors:

\[
\text{CR} = \frac{\text{CI}}{\text{RI}} = \frac{0.051}{0.58} = 0.088
\]

Since the consistency ratio (CR) is less than 0.10, this is well within the acceptable range for consistency.

For *Sustainability*, *Retreat* is very strongly preferable to *Accommodate* and equally preferable to *Protect*. Also, *Protect* is strongly preferable to *Accommodate.*
Pair-wise Comparison Matrix for **Sustainability**

<table>
<thead>
<tr>
<th></th>
<th>Retreat</th>
<th>Accommodate</th>
<th>Protect</th>
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</thead>
<tbody>
<tr>
<td>Retreat</td>
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<tr>
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<td>5</td>
</tr>
<tr>
<td>Protect</td>
<td>1/2</td>
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</table>

Normalized Matrix for **Sustainability**

Divide each entry in the pair-wise comparison matrix by its corresponding column sum. For example, for *Retreat* the column sum = $1 + 1/7 + 1/2 = 23/14$. This gives:

<table>
<thead>
<tr>
<th></th>
<th>Retreat</th>
<th>Accommodate</th>
<th>Protect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retreat</td>
<td>14/23</td>
<td>35/41</td>
<td>2/8</td>
</tr>
<tr>
<td>Accommodate</td>
<td>2/23</td>
<td>5/41</td>
<td>5/8</td>
</tr>
<tr>
<td>Protect</td>
<td>7/23</td>
<td>1/41</td>
<td>1/8</td>
</tr>
</tbody>
</table>

Priority Vector for **Sustainability**

The priority vector is determined by averaging the row entries in the normalized matrix. Converting to decimals we get:

- $Retreat = \frac{(14/23 + 35/41 + 2/8)}{3} = 0.571$
- $Accommodate = \frac{(2/23 + 5/41 + 5/8)}{3} = 0.278$
- $Protect = \frac{(7/23 + 1/41 + 1/8)}{3} = 0.151$

Consistency for **Sustainability** could be checked in the same manner as was **Flexibility**.
For Efficiency, *Retreat* is equally preferable to Protect. Both *Retreat* and Protect are very strongly to extremely preferable to Accommodate.

**Pair-wise Comparison Matrix for Efficiency**

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<tr>
<th></th>
<th>Retreat</th>
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<th>Protect</th>
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</thead>
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<td>Retreat</td>
<td>1</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>Accommodate</td>
<td>1/8</td>
<td>1</td>
<td>1/8</td>
</tr>
<tr>
<td>Protect</td>
<td>1</td>
<td>8</td>
<td>1</td>
</tr>
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</table>

**Normalized Matrix for Efficiency**

Divide each entry in the pair-wise comparison matrix by its corresponding column sum.

<table>
<thead>
<tr>
<th></th>
<th>Retreat</th>
<th>Accommodate</th>
<th>Protect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retreat</td>
<td>8/17</td>
<td>8/17</td>
<td>8/17</td>
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<tr>
<td>Accommodate</td>
<td>1/17</td>
<td>1/17</td>
<td>1/17</td>
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<tr>
<td>Protect</td>
<td>8/17</td>
<td>8/17</td>
<td>8/17</td>
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</tbody>
</table>

**Priority Vector for Efficiency**

The priority vector is determined by averaging the row entries in the normalized matrix. Converting to decimals we get:

*Retreat* = \(\frac{8/17 + 8/17 + 8/17}{3} = 0.471\)

*Accommodate* = \(\frac{1/17 + 1/17 + 1/17}{3} = 0.059\)

*Protect* = \(\frac{8/17 + 8/17 + 8/17}{3} = 0.471\)
Consistency for Efficiency could be checked in the same manner as was *Flexibility*.

It is assumed that in terms of criteria, *Flexibility* is extremely preferable to Efficiency and very strongly preferable to *Sustainability*, and that *Sustainability* is very strongly preferable to Efficiency.

**Pair-wise Comparison Matrix for Criteria**

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<th>Efficiency</th>
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<td>7</td>
<td>9</td>
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<tr>
<td>Sustainability</td>
<td>1/7</td>
<td>1</td>
<td>7</td>
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<tr>
<td>Efficiency</td>
<td>1/9</td>
<td>1/7</td>
<td>1</td>
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</table>

**Normalized Matrix for Criteria**

Divide each entry in the pair-wise comparison matrix by its corresponding column sum.

<table>
<thead>
<tr>
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<th>Sustainability</th>
<th>Efficiency</th>
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</thead>
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<tr>
<td>Flexibility</td>
<td>63/79</td>
<td>49/57</td>
<td>9/17</td>
</tr>
<tr>
<td>Sustainability</td>
<td>9/79</td>
<td>7/57</td>
<td>7/17</td>
</tr>
<tr>
<td>Efficiency</td>
<td>7/79</td>
<td>1/57</td>
<td>1/17</td>
</tr>
</tbody>
</table>

**Priority Vector for Criteria**

The priority vector is determined by averaging the row entries in the normalized matrix. Converting to decimals we get:

\[
\text{Flexibility} = \frac{(63/79 + 49/57 + 9/17)}{3} = 0.729
\]

\[
\text{Sustainability} = \frac{(9/79 + 7/57 + 7/17)}{3} = 0.216
\]
\[ \text{Efficiency} = \frac{7/79 + 1/57 + 1/17}{3} = 0.055 \]

**Overall Priority Vector**

The overall priorities are determined by multiplying the priority vector of the criteria by the priorities for each decision alternative for each objective.

Priority Vector for Criteria \([0.729 \ 0.216 \ 0.055]\)

<table>
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<th>Efficiency</th>
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<tbody>
<tr>
<td>Retreat</td>
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<td>0.571</td>
<td>0.471</td>
</tr>
<tr>
<td>Accommodate</td>
<td>0.632</td>
<td>0.278</td>
<td>0.059</td>
</tr>
<tr>
<td>Protect</td>
<td>0.069</td>
<td>0.151</td>
<td>0.471</td>
</tr>
</tbody>
</table>

Thus, the overall priority vector is:

- \[ \text{Retreat} = (0.729)(0.298) + (0.216)(0.571) + (0.055)(0.471) = 0.366 \]
- \[ \text{Accommodate} = (0.729)(0.632) + (0.216)(0.278) + (0.055)(0.059) = 0.524 \]
- \[ \text{Protect} = (0.729)(0.069) + (0.216)(0.151) + (0.055)(0.471) = 0.109 \]

Accommodate appears to be the overall recommendation.
# APPENDIX 7 - GIS SOFTWARE AND SUPPLIERS

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