FUZZY VULNERABILITY ASSESSMENT MODEL OF COASTAL AREAS TO SEA LEVEL RISE

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

GÜLİZAR ÖZYURT

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY
IN
CIVIL ENGINEERING

SEPTEMBER 2010

Approval of the thesis:

FUZZY VULNERABILITY ASSESSMENT MODEL OF COASTAL AREAS TO SEA LEVEL RISE

submitted by **GÜLİZAR öZYURT** in partial fulfillment of the requirements for the degree of **Doctor of Philosophy in Civil Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen ____________________
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Güney Özcebe ____________________
Head of Department, **Civil Engineering**

Prof. Dr. Ayşen Ergin ____________________
Supervisor, **Civil Engineering Dept., METU**

Examining Committee Members:

Prof. Dr. Halil Önder ____________________
Civil Engineering Dept., METU

Prof. Dr. Ayşen Ergin ____________________
Civil Engineering Dept., METU

Prof. Dr. Ahmet Cevdet Yalçıner ____________________
Civil Engineering Dept., METU

Prof. Dr. Aysel Atımtay ____________________
Environmental Engineering Dept., METU

Prof. Dr. Can Balas ____________________
Civil Engineering Dept., Gazi University

Date : 23/09/2010

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Gülizar Özyurt

Signature:

ABSTRACT

FUZZY VULNERABILITY ASSESSMENT MODEL OF COASTAL AREAS TO SEA LEVEL RISE

Özyurt, Gülizar
Ph.D., Department of Civil Engineering
Supervisor: Prof. Dr. Ayşen Ergin
September 2010, 283 pages

Climate change and anticipated impacts of sea level rise such as increased coastal erosion, inundation, flooding due to storm surges and salt water intrusion to freshwater resources will affect all the countries but mostly small island countries of oceans and low-lying lands along coastlines. Turkey having 8333 km of coastline including physically, ecologically and socio-economically important low-lying deltas should also prepare for the impacts of sea level rise as well as other impacts of climate change while participating in adaptation and mitigation efforts. Thus, a coastal vulnerability assessment of Turkey to sea level rise is needed both as a part of coastal zone management policies for sustainable development and as a guideline for resource allocation for preparation of adaptation options for upcoming problems due to sea level rise.

In this study, a fuzzy coastal vulnerability assessment model (FCVI) of a region to sea level rise using physical and human activity indicators of impacts of sea level rise which use commonly available data are developed. The results enable decision makers to compare and rank different regions according to their vulnerabilities to sea level rise, to prioritize impacts of sea level rise on the region according to the vulnerability of the region to each impact and to determine the most vulnerable parameters for planning of adaptation measures to sea level rise.

The sensitivity and uncertainty analysis performed for the results of the model (FCVI) is the first time application of a fuzzy uncertainty analysis model to coastal vulnerability assessments. These analysis ensure that the decision makers could be able to interpret the results of such vulnerability assessments based primarily on expert perceptions accurately enough. This in turn, would increase the confidence levels of adaptation measures and as well as accelerate implementation of adaptation of coastal areas to climate change.

The developed coastal vulnerability assessment model is applied successfully to determine the vulnerability of Göksu, Göcek and Amasra regions of Turkey that have different geological, ecological and socio-economical properties. The results of the site studies show that Göksu has high vulnerability, Göcek has moderate vulnerability and Amasra shows low vulnerability to sea level rise. These results are in accordance with the general literature on impacts of sea level rise at different geomorphological coastal areas thus the applicability of fuzzy vulnerability assessment model (FCVI) to coastal areas is validated.

Keywords: Vulnerability Assessment, Fuzzy Theory, Uncertainty Analysis, Sea Level Rise, Coastal Zone Management

ÖZ

KIYI ALANLARININ DENİZ SUYU SEVİYESİ YÜKSELMESİNE OLAN KIRILGANLIĞININ BULANIK MANTIK YÖNTEMİYLE MODELLENMESİ

Özyurt, Gülizar
Doktora, İnşaat Mühendisliği
Tez Yöneticisi: Prof. Dr. Ayşen Ergin

Eylül 2010, 283 sayfa

İklim değişikliği ve buna bağlı olarak yükselen deniz seviyesinin yaratacağı artan kıyı erozyonu, fırtına kabarma dalgalarına bağlı su baskınları, kıyıların daimi olarak su altında kalması, tatlı su kaynaklarında tuzluluk artışı gibi etkiler bütün ülkelerde sorunlara yol açacaktır. Yine de bu etkilerden en çok zararı okyanuslardaki küçük adalar ile deniz seviyesine yakın alçak rakımlı kıyı alanları görecektir.

Türkiye, 8333 km'lik kıyı şeridi ve bu şerit üzerinde bulunan oldukça büyük jeolojik, ekolojik ve sosyoekonomik önemi olan kıyı alanları ile deniz seviyesi yükselmesi ve de iklim değişikliğinin diğer etkilerine karşı, hem iklim değişikliğini önlemek hem de uyumluluğunu sağlamak için çalışmalar yapmalıdır. Kıyılardaki kalkınmanın sürdürülebilirliğini ve de deniz seviyesi yükselmesine karşı yapılacak uyum çalışmalarına kaynak aktarımının en uygun şekilde düzenlenebilmesi için Türkiye kıyılarının deniz seviyesi yükselmesine karşı kırılganlık(etkilenebilirlik) analizinin yapılması geremektedir.

Bu çalışmada, deniz seviyesi yükselmesinin yaratacağı olumsuz etkilerin faktörleri kullanılarak, deniz seviyesi yükselmesine karşı kıyı alanlarının kırılganlığını bulanık mantık yöntemiyle ölçen bir kıyı alanları kırılganlık modeli geliştirilmiştir. Bu model; farklı kıyı alanlarının deniz seviyesi yükselmesine olan

kırılganlıklarını göz önüne alarak bu alanlara uyumda öncelik verilmesini; herhangi bir kıyı alanında yaşanacak etkilerin o bölge için önem sırasına dizilmesini ve de herhangi bir etki için kritik olan parametrelerin anlaşılmasını sağlamaktadır. Böylece uygulanabilecek uyumluluk stratejilerinin planlaması ve de uygun kaynak aktarımı doğrulukla yapılacaktır. Model sonuçlarının doğru yorumlanabilmesi için ayrıntılı duyarlılık ve belirsizlik analizleri yapılmıştır. Karar verme sürecinde engel teşkil eden, model sonuçlarının belirsizliklerinin karar vericilerce anlaşılamaması sorunu bu konuda ilk defa uygulanan yöntemle aşılmaya çalışılmıştır.

Bu çalışmada geliştirilen "kıyı alanlarının deniz seviyesi yükselmesine karşı kırılganlık analiz modeli", farklı fiziksel özelliklere ve insan aktiviteleri bulunan Göksu, Göcek ve Amasra kıyı alanlarına başarı ile uygulanmıştır. Model sonuçları Göksu için yüksek, Göcek için orta ve Amasra için düşük düzeyde kırılganlık değeri vermektedir. Model sonuçlarının literatürde bulunan farklı kıyı alanlarında değerlendirilen deniz seviyesi yükselmesi etkileri ile uyumlu olması geliştirilen modelin uygulanabilirliğini desteklemektedir.

Anahtar kelimeler: Kırılganlık Analizi, Bulanık Mantık, Belirsizlik Analizleri, Deniz Seviyesi Yükselmesi, Kıyı Alanları Yönetimi

"The fundamental imperfection of knowledge is the essence of uncertainty."

Shackle

Dedicated to my family.

ACKNOWLEDGEMENTS

"Büyük olmak için hiç kimseye dalkavukluk etmeyeceksin, hiç kimseyi aldatmayacaksın. Memleket için gerçek ülkü ne ise onu görecek, o hedefe yürüyeceksin. Herkes sana karşı çıkacaktır, herkes seni yolundan çevirmeye çalışacaktır, fakat sen buna dayanıklı olacaksın. Önüne sonu gelmeyen engeller çıkacaktır. Kendini büyük değil; küçük, zayıf, kimsesiz ve araçsız kabul edecek, kimseden yardım gelmeyeceğine inanmış olarak bu engelleri aşacaksın. Bundan sonra da sana "Büyüksün" derlerse bunu söyleyenlere güleceksin."

Mustafa Kemal ATATÜRK

I would like to mention the above words of Atatürk which keep me carry on during the distressed moments.

I would like to express my gratitude to Prof. Dr. Ayşen Ergin for not letting me walk through this path alone and for encouraging me to challenge each and every day with the same energy and ethusiasm. The time she had devoted and the guidance she had provided has helped me overcome the obstacles of both academic and daily life.

I would like to attend my thanks to every member of my family for all the support they have given. The last months would not be bearable if it were not for you.

I would like to thank all my friends for keeping me sane throughout this chapter of my life. Thank you for all the support you have given during all those lunches and "Uptown"s.

Finally, I would like to acknowledge that this study was partially supported by the TUBITAK Research Grant No: 108M589, "Kıyılarda İklim Değişikliğine Karşı Kumlanma Modeli Destekli Kırılganlık Analizi Projesi – KIDEKA" (Coastal vulenrability assessment to climate change supported with a numerical sedimentation model).

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

CHAPTER I

INTRODUCTION

Predicting the future conditions of the land and sea resources that the coastal areas offer to human population has become one of the main problems that concern both national and local decision makers. "These are the resources that attract millions of people to the coastal areas, increasing the population densities to almost three times the global mean" (Small and Nicholls 2003). The dynamic and complex physical processes such as sediment transport or coastal flooding derive changes in coastal areas. These processes can only be predicted up to a certain level even with recent scientific developments. This fact is underlined by the latest assessment of IPCC (2007) by stating that "While knowledge is not adequate in any aspect, uncertainty increases from the natural sub-system to the human sub-system, with the largest uncertainties concerning their interaction."

The concept of coastal zone management to ensure sustainable development of coastal areas was initiated by the high demand and the uncontrolled use of these resources by various stakeholders. There are many problems that the decision makers have to face when implementing coastal zone management practices due to the fact that the outcomes of the decisions regarding the complex physical processes will not happen as expected. On top of all the uncertainties and conflicts that are present at coastal areas, impacts of climate change, associated with high uncertainty, turn decision making into a risk management process.

Global warming and climate change has become one the major problems of this century that will continue to pose a major threat for all major systems of the earth. The projections on the impacts of climate change in addition to the observations all around the world strongly underlines the fact that both mitigation and adaptation measures are needed to be taken immediately. Although there are many systems and sectors to be affected by different impacts of climate change, for the reasons already mentioned in the previous paragraphs, coastal zones are especially under threat due to the additional impact of global sea level rise due to climate change.

The need for management of the risks associated with global sea level rise has initiated many research around the world for a variety of sub-systems in coastal areas such as ecological assessments, assessments of physical problems such as coastal erosion that can be triggered by sea level rise, engineering solutions and adaptation of present coastal protection measures, and recently socio-economic systems including the response and perception of coastal communities. Although research on different sub-systems are ongoing, they are most of the time stand-alone researches that ignores interaction between the sub-systems. In fact, integrated assessment is not a new concept in coastal system modelling through the implementation of many coastal zone management studies. In the context of climate change it has a fairly new application mostly due to many inherent uncertainties related to the interactions between earth systems and human systems and the climate change itself. On the other hand, importance of integration of earth and human systems has been highlighted as more research is undertaken which show that main actors of the framework of climate change are parts of forward and backward feeding cycles.

Several research initiatives were stated by ‘Intergovernmental Panel on Climate Change,(IPCC 2007a)’ which strongly agrees with the understanding that limitations of available data, limitations of knowledge on especially interaction and integration of human and natural subsystems as well as limitations of integration of uncertainty by decision makers to actual policy making processes (adaptation options) are the key sources of problems that need to be overcome by the scientific approaches when coastal zones are considered.

The limitation on available data is especially an important problem for Turkey where long term coastal data, for most locations, does not exist. The quality of available data is another uncertainty due to many other factors such as the location of meteorological stations, calibration of the measuring devices and the duration of measurements including availability of human and budget capacity. Focusing on the limitation of data problem and underlining the fact that coastal areas are under threat due to many driving factors such as high urbanization rates and unsustainable use of available resources including the threat of climate change, a preliminary coastal vulnerability assessment model was developed by Ozyurt, 2007. The objective of this preliminary model was to present the current vulnerability of a coastal area by comparing and ranking the impacts of sea level rise (which already exist or might be triggered in the future) by integrating physical characteristics and human activities. This objective was effectively achieved by using parameters that govern the physical processes and integrating data classification in a matrix format. Thus, with limited local data integrated with expert knowledge, the model calculates the vulnerability of a coastal area to impacts of sea level rise using the idea of integrated coastal zone management.

Although the preliminary model (Ozyurt 2007) achieved its objectives, there were some short comings of the model. Equal weighting of parameters, crisp boundaries of ranges of parameters, not integrating stake holder or expert perceptions and 'ignorance' of the uncertainty concept, limit the accuracy of the model to represent the real system. On the other hand, vulnerability assessments showed that "sea-level rise is usually not the most critical issue when the existing problems are considered" (IPCC 1994). Thus coastal managers do not act proactively to implement adaptation measures related to sea-level rise. The uncertainty associated with the level of the expected rise is high and this fact decreases the motivation for making active responses. Other factors that affect proactive and effective implementation of adaptation measures at coastal areas are the limitations on local resources in terms of time, money, and manpower. While the complex and dynamic interaction between many parameters of the system increased the uncertainties and the complexity of models, the increased observations of damages and threat calls for efficient, accurate tools for decision making which do not drive away local experts/decision makers due to model complexity.

In light of the discussions, it was decided to focus on one of the research initiatives underlined by IPCC (2007) as a scope of this thesis:

> **"Improving impact and vulnerability assessments within an integrated assessment framework that includes natural - human sub-system interactions which requires a strong inter-disciplinary approach.** Limited understanding of how development planners incorporate information about climate variability and change into their decisions is one the major obstacles of integrated assessment of

vulnerability. Therefore, improving systems of coastal planning and zoning and institutions that can enforce regulations for clearer coastal governance is required in many countries."

In light of this research initiative, it is the main objective of this study;

1. to upgrade the preliminary vulnerability assessment model (Ozyurt, 2007) by
    - increasing the strength of the preliminary model on integration of natural and human subsystems through reassessment of model parameters
    - developing and integrating a weighting system for accurate representation of real system
    - involving perception of coastal experts on sea level rise and its impacts on physical processes along coastal areas
    - developing a database that covers different coastal areas with various human activities
2. to integrate uncertainty concept into new vulnerability assessment model that could be easily understandable and interpreted by end-users to achieve clearer and efficient coastal governance through accurate and effective decision making by
    - determining the most suitable uncertainty model to built the coastal vulnerability assessment by using an uncertainty taxonomy and profile vectors proposed by (Zimmermann 2000)
    - highlighting the main sources of uncertainties related to coastal vulnerability assessment within an uncertainty framework
    - defining conceptual and quantifiable uncertainties related to coastal vulnerability assessment using an uncertainty framework proposed by (Walker et al. 2003)
    - determining the impact of quality of available data on the application of vulnerability assessments using different sets of analysis

The new fuzzy vulnerability assessment model (Fuzzy Coastal Vulnerability Index - FCVI) is built to act as a bridge between earth and human systems well aware of the fact that the interactions between vulnerability, adaptation and mitigation are one of the important components of the climate change research that need to be analyzed in an integrated framework.

The proposed fuzzy vulnerability assessment model (FCVI) has been applied and validated at three selected sites (Goksu, low-lying land with high human activity; Gocek, indented coast with high human activity and Amasra, high cliffs with low human activity) in Turkey and the uncertainty framework of the model has been analyzed by using different uncertainty methodologies.

In Chapter 2, processes that have an impact on sea level trends including climate change, observations up to present and projections of the future of sea level rise are explained. Future impacts on coastal areas, research and measures taken to mitigate and adapt to these impacts highlighting the key vulnerabilities, needs of decision makers, key relationships between vulnerability, adaptation, integrated coastal zone management and sustainable development are summarized. Key uncertainties and research agenda proposed by Intergovernmental Panel on Climate Change (IPCC, 2007) is given to act as a guideline for this study. Finally, brief summary of the methodology of the preliminary vulnerability assessment model proposed by Ozyurt (2007) is included highlighting the physical processes of sea level rise and the objectives for the proposed methodology.

In Chapter 3, research methodology and results for the work undertaken to overcome the shortcomings of the preliminary vulnerability assessment model (Ozyurt, 2007) were presented including reassessment of the model parameters.

In Chapter 4, detailed information on the contents and methodology of building the model database were given which was the basis of the membership functions of the fuzzy vulnerability assessment model (FCVI).

In Chapter 5, an in depth presentation of the analytical hierarchy process procedure integrating expert perception to the resultant weights to be used in the fuzzy vulnerability assessment model were presented.

In Chapter 6, fuzzy vulnerability assessment model methodology is given in detail focusing on the concept of uncertainty in model construction, modeling the uncertainty itself and the uncertainty models. Experts systems combined with fuzzy logic theory are given to justify the use of fuzzy set theory as the mathematical model to build the coastal vulnerability assessment model. Main building blocks of the fuzzy vulnerability assessment model, including the modular structure, membership functions, rule bases and fuzzy operators are explained in detail. The developed graphical user interface is given, highlighting the efficient use of output graphs. The application and validation of the model is performed by comparing the results of both the fuzzy and preliminary model (Ozyurt, 2007) on three selected coastal areas in Turkey; Goksu (low-lying land with high human activity), Gocek (indented coast with high human activity) and Amasra (high cliffs with low human activity).

In chapter 7, sensitivity and uncertainty of the fuzzy vulnerability model is given through a set of different methods (sensitivity analysis, scenario analysis, Monte Carlo analysis) applied. The data of the validation studies are used as base results for any comparison. The uncertainty framework of the fuzzy vulnerability model is given in detail with references to chapter 6 to comply with the objectives of the study and detailed discussions are also included to increase the reliability of implementation of the fuzzy vulnerability model by decision makers/local experts.

In chapter 8, conclusions and future research agenda are discussed highlighting the main advantages of the fuzzy vulnerability model, uncertainty modeling and with references for future development of the model.

CHAPTER II

LITERATURE REVIEW

Climate change has been accepted as one of the global problems which is not easy to tackle. The causes, impacts, solutions, adaptation options and the consequences of the implementations of different solutions are all individually challenging problems. On the other hand, they are all interconnected and related to each and every other systems of earth, human and environment. Figure 2.1 schematically shows these relations and the subcomponents of the main actors of the framework of climate change.

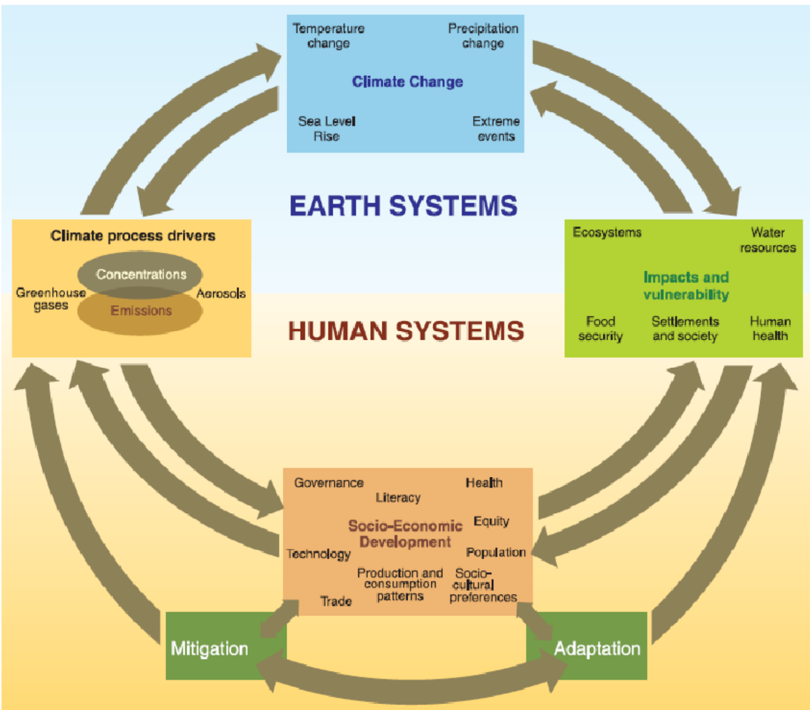


Figure 2.1 Schematic framework representing the relations between drivers, impacts and adaptation components of climate change (IPCC, 2007)

The climate showed variations throughout the history of the earth. These variations are mostly natural, periodic occurrences. The natural variability of earth's climate is the research area of paleoclimatology. However the term 'climate change' recently took another meaning, variation of climate throughout the earth due to anthropogenic forcing. Thus it is important to define the context of climate change as a reference to the study to clarify the extent of this term. Climate change in IPCC usage refers to "a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity"(IPCC 2007a). On the other hand, United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as "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".

Although long term natural variations and anthropogenic climate change can not be differentiated at the moment, this study focuses on the definition of UNFCCC; change of climate that is attributed directly or indirectly to human activity. Whether the change in climate results from anthropogenic drivers or natural variations; the observations show that "warming of the climate system is unequivocal, as is now evident from observations (Figure 2.2) of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level"(IPCC 2007a).

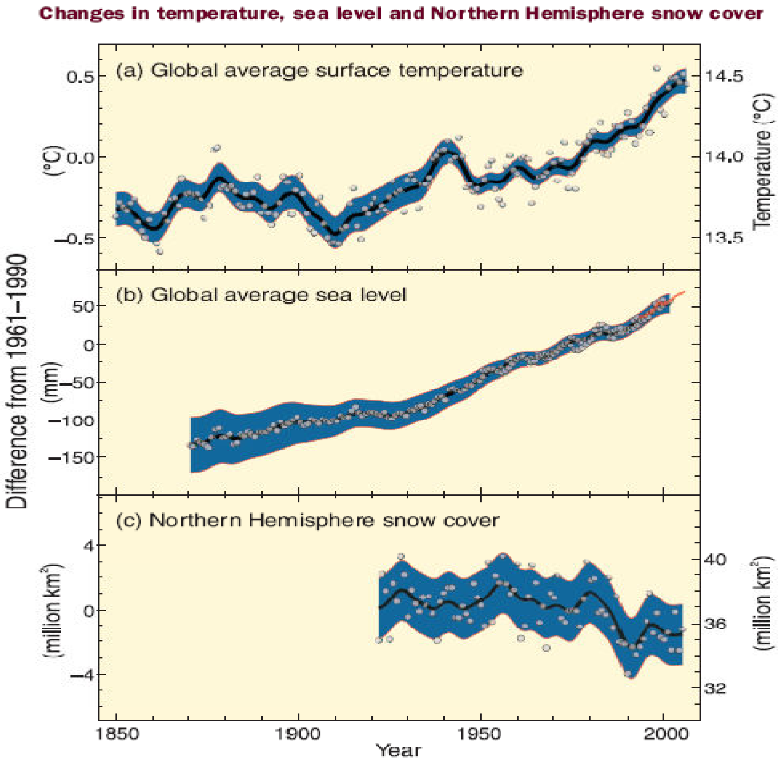


Figure 2.2 Observed changes in temperature, sea level and Northern Hemisphere snow cover (IPCC 2007aa)

The observed changes and the corresponding impacts experienced across the world are affecting various geographic regions, sectors, communities and ecologies differently. What is common is that as long as climate change continues, these changes and the impacts will continue to affect much more significantly. One of the systems which will be significantly affected by climate change is the coastal systems and low-lying areas along coasts. In addition to changes in temperatures and precipitation which are the driving forces of all the expected impacts of climate change, coastal systems are faced with another threat; sea level rise.

2.1 Sea-level Trends

The volume of ocean water, the volume of the ocean basins, and the distribution of the ocean water are the parameters that control the sea level. Crustal deformation and sediment compaction cause vertical land movements which additionally affect coastal sea level. Many other elements influence sea level as well. Some of these elements affect sea level in shorter durations while some operate globally and locally over longer timescales: tides, storms (days to weeks); thermosteric changes, weather (seasonal); climate, tectonic (10^0–10^4 years); and ocean basin evolution (up to millions of years). However, recent sea level rise (SLR) triggered by global warming is dictated by two primary factors: "thermal expansion due to heat uptake by ocean surface waters and water input caused by the transfer of water from the land to the oceans"(IPCC 2007b); which are long term changes.

2.1.1. Longer Term Changes

On larger time scales (months and longer), sea level changes due to changes in ocean mass such as addition of water to the ocean from the land and expansion/contraction of the ocean water as it warms/cools.

"Exchange of water with other "reservoirs" is an important contribution to sea level change. A significant part of this is through the hydrological cycle (Figure 2.3). There are both annual variations as well as longer-term variations. For example, extraction of water from underground aquifers can increase the mass of the ocean whereas the storage of water in dams can decrease the mass of the ocean."(IPCC 2007aa)

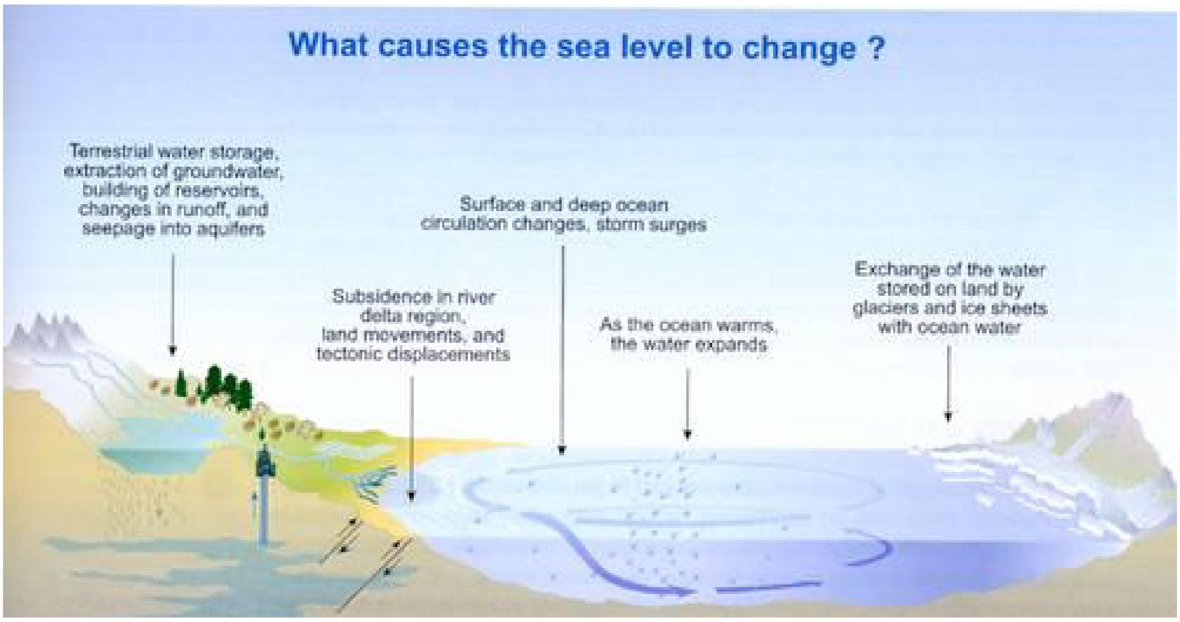


Figure 2.3 Causes of sea level change (IPCC 2001)

A major contribution to sea level change is from the changing mass of glaciers, and the ice sheets. Thermal expansion is another contributor to long-term sea level change. As shown in Figure 2.4 observations show that "the upper depths of oceans are absorbing large amounts of heat and expanding in an accelerated rate".(CSIRO 2010)

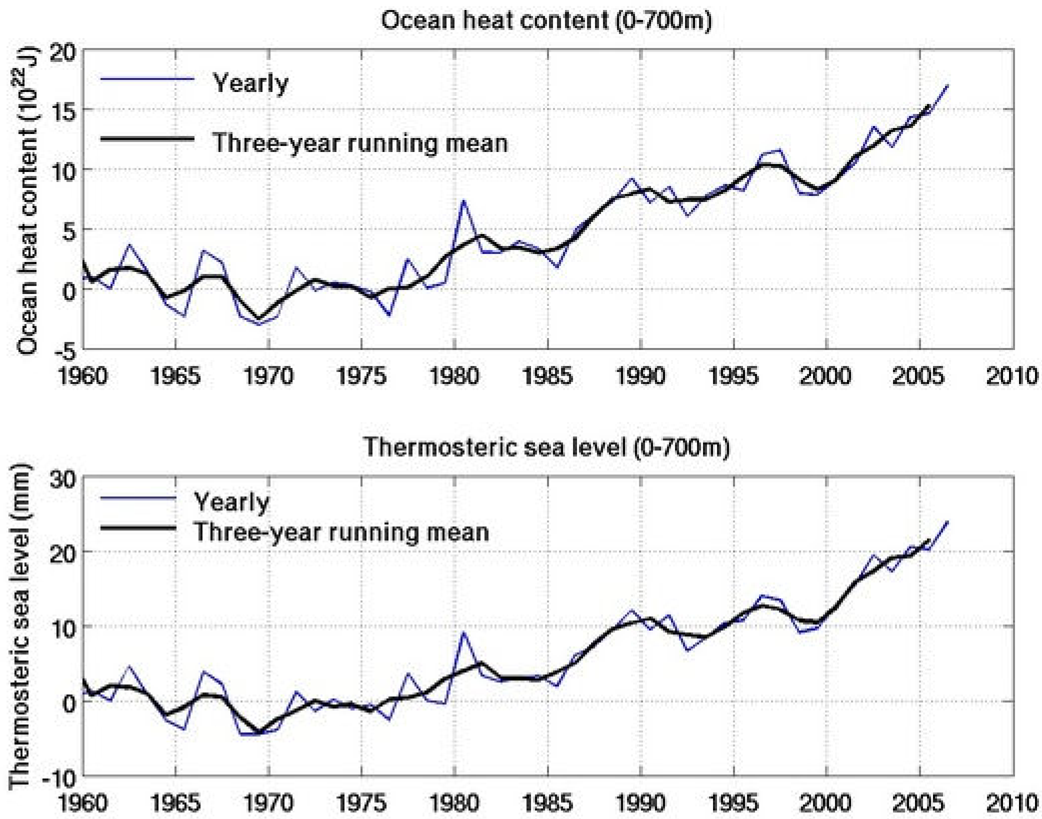


Figure 2.4 The top graph show changes in the heat content and the bottom graph shows the change in thermosteric sea level of the top 700 metres of the ocean from 1960 to 2007. (CSIRO 2010)

Due to natural variations of the climate system, global sea level has risen approximately 120 m since the last glacial maximum approximately 20,000 years ago. The rate slowed down to 0.1 to 0.2 mm year^{-1} 2000 to 3000 years ago. Now, the rate of sea level rise has started to accelerate again due to global warming and climate change.

Estimates of the various contributions of the present and past rates of SLR are presented in Table 2.1 (IPCC, 2007). "Thermal expansion accounts for more than half of the present (1993–2003) SLR trend (1.6 +/− 0.5 mm year^{-1}) caused by warming to a depth of 3000 m. The influx of water by melting glaciers is about half that value (0.77 +/− 0.22 mm year^{-1}). Comparatively, lesser amounts of water come from the Greenland and Antarctic ice sheets, which combined, store enough water to raise sea level by 63.9 m."(FitzGerald et al. 2008)

Table 2.1 Contributions to Sea Level Rise (IPCC 2007aa)

Source of seal level rise	Rate of SLR (mm year^{-1}) 1961–2003	1993–2003
Thermal expansion	0.42 ± 0.12	1.6 ± 0.5
Glaciers and ice caps	0.50 ± 0.18	0.77 ± 0.22
Greenland ice sheet	0.50 ± 0.12	0.21 ± 0.07
Antarctic ice sheet	0.14 ± 0.41	0.21 ± 0.35
Sum of individual climate contributions to SLR	1.1 ± 0.5	2.8 ± 0.7
Observed total SLR	1.8 ± 0.5[a]	3.1 ± 0.7[a]
Difference (observed minus sum of estimated climate contributions)	0.7 ± 0.7	0.3 ± 1.0

[a]Data prior to 1993 are from tide gauges and after 1993 are from satellite altimetry.

2.1.2. Projections for the 21st Century

During the 21st century, sea level will continue to rise due to warming from both past (20th century and earlier) and 21st century greenhouse gas emissions. In its 2007 assessment of global warming, the Intergovernmental Panel on Climate Change (IPCC 2007aa) projected that global mean sea level is expected to rise between 0.18 to 0.59 meters (0.6 and 2 feet) in the next century (Figure 2.5).

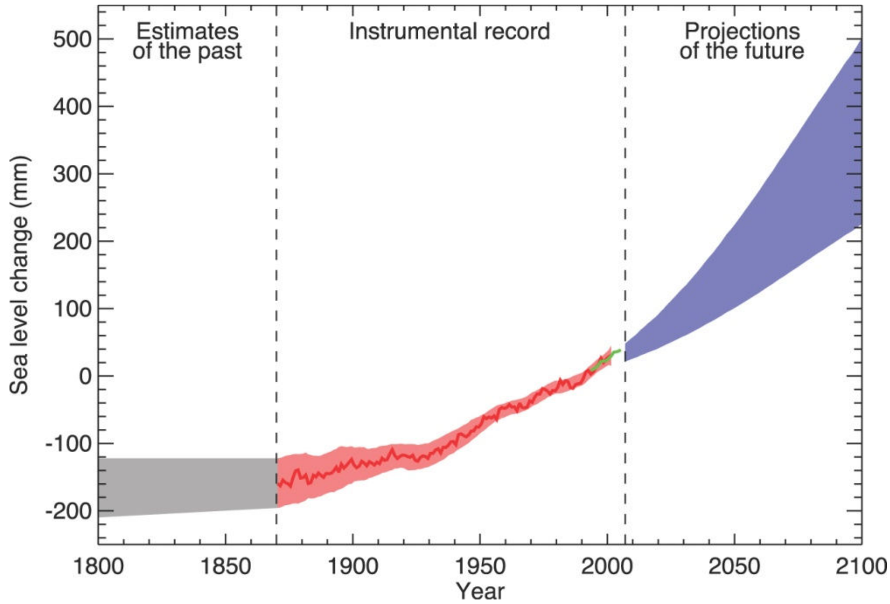


Figure 2.5 Sea Level Change (IPCC, 2007)

Contributions of different sources of sea level rise are estimated individually. The estimates of the ocean thermal expansion are made with coupled climate models for the range of SRES greenhouse gas emission scenarios. "Lemke et al. 2007 states that non-polar glaciers and ice caps are estimated to contain only enough water to raise sea level by 15 to 37 centimetres"(CSIRO 2010). The largest contribution is from large glaciers in regions with heavy precipitation, such as the coastal mountains around the Gulf of Alaska, or Patagonia and Tierra del Fuego in South America.

"For Greenland, both glacier calving and surface melting contribute to mass loss. Over the last few decades surface melting has increased and now dominates over increased snowfall, leading to a positive contribution to sea level during the 21st century. For the majority of Antarctica, present and projected surface temperatures during the 21st century are too cold for significant melting to occur and precipitation is balanced by glacier flow into the ocean (Lemke et al., 2007)"(CSIRO 2010).

In addition to these surface processes, there are suggestions of a potential dynamical response (sliding of the outlet glaciers over the bedrock) of the Greenland and Antarctic ice sheets due to increasing surface melt making its way to the base of the glaciers, lubricating their flow over the bed rock, consistent with increased glacier flow rates. Another effect which may be becoming more important is breaking up of ice shelves around Antarctica and Greenland (e.g. Larsen B) which allow the glaciers behind them to flow faster increasing the flow into the ocean.(IPCC 2007aA)

2.1.3 Global projections

There is no agreed pattern for the longer-term regional distribution of projected sea-level rise. This is because local trends associated with decadal variability will be superimposed on the slowly increasing global-mean sea level. However, several features are common to most model projections; there will be a maximum sea-level rise in the Arctic Ocean and a minimum rise in the Southern Ocean south of the Antarctic Circumpolar current will be observed (Figure 2.6).

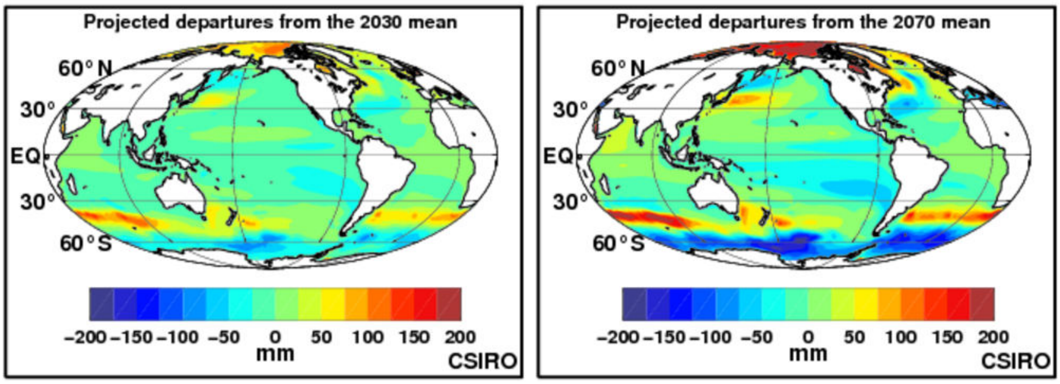


Figure 2.6 The multi-model mean of the departure of the projected regional sea-level rise from the global-averaged (SRES A1B) projections for 2030 and 2970. (CSIRO 2010)

2.1.4 Longer Term

For the near future, the rate of sea-level rise is mostly defined by past emissions. Higher greenhouse gas emmisions will accelerate the processes of ocean thermal expansion and the ice sheets which will contribute metres of sea-level rise closer to and beyond 2100. On the other hand, the contribution from the ice sheets is poorly understood at the moment and is an active area of research.

"In the case of the Greenland Ice Sheet, if global average temperatures cross a point that is estimated to be in the range of 1.9°C to 4.6°C above pre-industrial values, surface melting is likely to exceed precipitation (Gregory and Huybrechts, 2006). The inevitable consequence of this is an ongoing shrinking of the Greenland Ice Sheet over a period of centuries and millennia. Total melting of the Greenland ice sheet alone would increase global mean sea level by around 7 metres. This conclusion is consistent with the observation that global sea level in the last interglacial, when temperatures were in this range, was several metres higher than it is today. This threshold (of melting exceeding precipitation) could potentially be crossed late in the 21st century." (CSIRO 2010)

Model-based projections of global average sea level rise at the end of the 21st century (2090-2099) are shown in Table 2.2. It is important to underline the fact that the best estimate shows an acceleration of up to 2.4 times compared to the 20th century. Because understanding of some important effects driving sea level rise is too limited, predictions of future sea levels do not assess the likelihood, nor provide a best estimate or an upper bound for sea level rise. Improved information about some uncertainties in the projected contributions enabled better predictions. Still the sea level projections do not include many uncertainties such as climate-carbon cycle feedbacks or the full effects of changes in ice sheet flow. Therefore the upper values of the ranges given are not to be considered upper bounds for sea level rise. Also, if the contribution from Greenland and Antarctica were to grow linearly with global average temperature change, the upper ranges of sea level rise for SRES scenarios shown in Table 2.2 would increase by 0.1 to 0.2m. (IPCC 2007aA)

Table 2.2 Projected global average surface warming and sea level rise at the end of the 21st century. (IPCC 2007aA)

Case	Temperature change (°C at 2090-2099 relative to 1980-1999) [a, d]		Sea level rise (m at 2090-2099 relative to 1980-1999)
	Best estimate	*Likely* range	Model-based range excluding future rapid dynamical changes in ice flow
Constant year 2000 concentrations[b]	0.6	0.3 – 0.9	Not available
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

"Importantly, local (or relative) changes in sea level depart from the global mean trend due to regional variations in oceanic level change and geological uplift/subsidence; it is relative sea-level change that drives impacts and is of concern to coastal managers” (Nicholls and Klein 2005).

Not considering the threat of Greenland ice sheet collapse, the expected global sea level rise ranges 20 – 60 cm for the 21st century keeping in mind that the upper boundary is not set. What is the threat which is caused by this ‘mere’ (as is constantly referred by general public) rise of sea level?

2.2 Impacts of Sea Level Rise on Coastal Areas

“It has been estimated that 23% of the world’s population lives both within 100 km distance of the coast and <100 m above sea level, and population densities in coastal regions are about three times higher than the global average” (Small and Nicholls 2003). “Sixty percent of the world’s 39 metropolises with a population of over 5 million are located within 100 km of the coast, including 12 of the world’s 16 cities with populations greater than 10 million” (IPCC 2007aa). Thus, not if but when the impacts of sea level rise become significant, the scale of population and many economic sectors affected is expected to be overwhelming.

Key human vulnerabilities to climate change and sea-level rise exist where the stresses on natural low-lying coastal systems showing low human adaptive capacity and/or high exposure. These areas are stated in IPCC’s 4th Assessment Report as:

- “deltas, especially Asian megadeltas (e.g., the Ganges-Brahmaputra in Bangladesh and West Bengal);

- low-lying coastal urban areas, especially areas prone to natural or human-induced subsidence and tropical storm landfall (e.g., New Orleans, Shanghai);

- small islands, especially low-lying atolls (e.g., the Maldives).”

On the other hand, although corals, salt marshes and mangroves are the most vulnerable coastal ecosystems (IPCC 2007aa), all coastal ecosystems are vulnerable to climate change and sea-level rise.

Six important policy-relevant messages were stated in IPCC’s 4th Assessment Report based on the understanding of the implications of climate change for coastal systems and low-lying areas:(IPCC 2007a)

"Coasts are experiencing the adverse consequences of hazards related to climate and sea level." Coastal flooding in low-lying areas will become a greater risk unless there is significant adaptation. "Without adaptation, more than 100million people could experience coastal flooding each year by the 2080s due to sea-level rise alone"(IPCC 2007a). Other impacts of sea level rise are increased coastal erosion, permanent loss of land due to inundation, salt water intrusion to groundwater resources and rivers.

"Coasts are very likely to be exposed to increasing risks in future decades due to many compounding climate-change factors." These risks are accelerated sea level rise, further rise in sea surface temperatures, more intense tropical and extra-tropical cyclones, larger extreme wave and storm surges, altered precipitation/runoff, and ocean acidification. The risks will vary considerably at regional and local scales.

"The impact of climate change on coasts is exacerbated by increasing human-induced pressures. The direct impacts of human activities on the coastal zone have been more significant over the past century than impacts that can be directly attributed to observed climate change (Scavia et al., 2002; Lotze et al., 2006)"(IPCC 2007a). The major direct impacts include drainage of coastal wetlands, deforestation and reclamation, discharge of contaminants into coastal waters, extractive activities such as sand mining, introductions of invasive species, construction of engineering structures. Ecosystem services on the coast are also often disrupted by human activities such as large-scale ecosystem conversion for agriculture, industrial and urban development, and aquaculture.

"Adaptation for the coasts of developing countries is virtually certain to be more challenging than for coasts of developed countries." Developing countries already experience the most severe impacts from present coastal hazards and have a limited adaptive capacity due to their development status, with. Adaptation in developing countries will be most challenging in the vulnerable 'hotspots'.

"Adaptation costs for vulnerable coasts are much less than the costs of inaction." It is estimated that adaptation costs for climate change are to be much lower than damage costs without adaptation for most developed coasts. Effective adaptation to climate change can be integrated with wider coastal management, reducing implementation costs among other benefits.

"The unavoidability of sea-level rise, even in the longer term, frequently conflicts with present-day human development patterns and trends." Sea-level rise has substantial inertia and will continue beyond 2100 for many centuries. The long-term sustainability of many coastal settlements and infrastructure (e.g., nuclear power stations) and the current trend of increasing human use of the coastal zone, including a significant coastward migration contradicts with the risks associated with sea level rise. This issue presents a challenge for long-term coastal spatial planning.

All these facts collectively analyzed by the researchers of IPCC(2007) showed that, "the most appropriate response to sea-level rise for coastal areas is a combination of adaptation to deal with the inevitable rise, and mitigation to limit the long-term rise to a manageable level". Although mitigation is an important addition to the available responses to sea level rise and the consequent impacts, the key concept of response for coastal areas is adaptation. "Integrated assessment and management of coastal systems, together with a better understanding of their interaction with socio-economic and cultural development are the important components of successful adaptation to climate change (Figure 2.7)".(IPCC 2007a)

However, it is not an easy task to develop or implement tools for integrated assessment and management of coastal systems. Having dynamic and complex characteristics as well as acting as focus for socio-economic activities, coastal areas present unique and multi-dimensional problems.

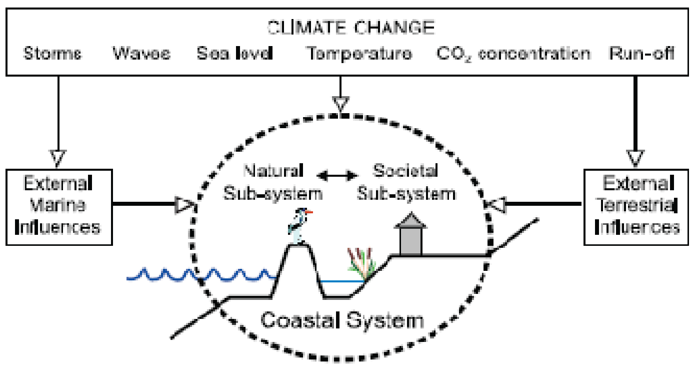


Figure 2.7 Climate change and the coastal system showing major climate change factors (IPPC 2007).

The first complexity arises due to dynamic characteristic of coastal areas. It is a well established fact that although coastal landforms are affected by short-term perturbations such as storms, they generally return to their pre-disturbance morphology, implying a simple, morphodynamic equilibrium(Woodroffe 2003). Thus, this natural variability of coasts can make it difficult to identify the impacts of climate change. For example, most beaches worldwide show evidence of recent erosion but sea-level rise is not necessarily the primary driver. Erosion can result from other factors, such as offshore bathymetric changes or reduced sediment supply or construction of coastal structures. A major challenge is determining whether observed changes have resulted from alteration in external factors (such as climate change) or short-term disturbance within natural climate variability (such as a storm). Although it is important to differentiate the causes of the changes theoretically, it might not be as important in terms of implementation of management and/or adaptation practices since; many of the present problems associated with rising sea level represent the cumulative effects of processes that have been ongoing for many decades and perhaps centuries. Thus, many of the impacts of accelerating SLR can be generalized as worsening widespread existing conditions. For example, flooding lowlands, beach erosion, saltwater intrusion, and wetland loss are all processes that have been ongoing along coasts for centuries and have been widely recognized for many years.

The second complexity arises due to different time-scale of coastal processes and to choose which time-scale should the adaptation be planned for. The various ways that coastlines respond to changes in sea level complicate assessments of the impact of SLR on natural systems. For example, barrier islands can migrate landward for over timescales of 10^3–10^4 years. These areas will have erosion only if the sediment supply rate is less than the rate of SLR. On the other hand, the daily forces associated with SLR do not appear to contribute to the net coastal sediment transport. During decadal- to centennial-scale time periods (10^1–10^2 years), additional processes, such as El Nino, storm surges, or human interaction, can overwhelm the impact of SLR.

Observations on the impacts of climate change on coastal societies underlined the importance of integration of societal subsystem to assessments of coastal areas. "First, significant regional differences in climate change and local variability of the coast, including human development patterns, result in variable impacts and adjustments along the coast, with implications for adaptation responses. Second, human vulnerability to sea-level rise and climate change is strongly influenced by the characteristics of socio-economic development. Third, although the future magnitude of sea-level rise will be reduced by mitigation, the long timescales of ocean response mean that it is unclear what coastal impacts are avoided and what impacts are simply delayed by the stabilisation of greenhouse gas concentration in the atmosphere (Nicholls and Lowe, 2006). Fourth, vulnerability to the impacts of climate change, including the higher socio-economic burden imposed by present climate-related hazards and disasters, is very likely to be greater on coastal communities of developing countries than in developed countries due to inequalities in adaptive capacity”(IPCC 2007a).

“In general, the coastal sciences do not have a holistic model available to make those links reliably in multiple settings” (IPCC 2007a).

2.3 Responding To Climate Change

Responding to climate change can be grouped into two main actions:

- Mitigation: actions aimed at reducing greenhouse gas emmisions
- Adaptation: actions aimed at reducing the vulnerability of the system.

Adaptive capacity is intimately connected to social and economic development, but it is not evenly distributed across and within societies. Recent studies reaffirm that adaptation will be vital and beneficial. However, financial, technological, cognitive, behavioural, political, social, institutional and cultural constraints limit both the implementation and effectiveness of adaptation measures.

2.4 Assessing Key Vulnerabilities and The Risk From Climate Change

IPCC (2007) defines the key concepts related to responses to climate change as follows: “An impact describes a specific change in a system caused by its exposure to climate change. Impacts may be judged to be either harmful or beneficial. Vulnerability to climate change is the degree to which these systems are susceptible to, and unable to cope with, the adverse impacts. Vulnerability to climate change is a function of exposure, sensitivity and adaptive capacity. Adaptation can reduce sensitivity to climate change while mitigation can reduce the exposure to climate change, including its rate and extent. The term 'vulnerability' may therefore refer to the vulnerable system itself, e.g., low-lying islands or coastal cities; the impact to this system, e.g., flooding of coastal cities and agricultural lands or forced migration; or the mechanism causing these impacts, e.g., disintegration of the West Antarctic ice sheet. The concept of risk, which combines the magnitude of the impact with the probability of its occurrence, captures uncertainty in the underlying processes of climate change, exposure, sensitivity and adaptation."

A focus on key vulnerabilities is meant to help policy-makers and stakeholders assess the level of risk and design response strategies. The assessment of key vulnerabilities requires consideration of the response of biophysical and socio-economic systems to changes in climatic and non-climatic conditions over time (e.g., changes in population, economy or technology), important non-climatic developments that affect adaptive capacity, the potential for effective adaptation across regions, sectors and social groupings, value judgements about the acceptability of potential risks, and potential adaptation and mitigation measures.

Assessments of climate change impacts, adaptation and vulnerability (CCIAV) are implemented to inform decision makers in an environment of uncertainty. A major aim of CCIAV assessment approaches is to manage, rather than overcome, uncertainty. "Another important trend has been the move from research-driven agendas to assessments tailored towards decision-making, where decision-makers and stakeholders either participate in or drive the assessment (Wilby et al., 2004a; UNDP, 2005)".(IPCC 2007a)

The standard approach to assessment has been the climate scenario-driven 'impact approach', developed from the seven step assessment framework of IPCC (1994). This approach, which dominated the CCIAV literature, aims to evaluate the likely impacts of climate change under a given scenario and to assess the need for adaptation and/or mitigation to reduce any resulting vulnerability to climate risks. The other approaches are adaptation- and vulnerability-based approaches, integrated assessment, and risk management. Although all these approaches are used in environmental research, the following objectives are required to be fulfilled by these methods (Table 2.3) when incorporated into decision making process:

• “assessing current vulnerabilities and experience in adaptation,

• stakeholder involvement in dealing with extreme events,

• capacity-building needs for future vulnerability and adaptation assessments,

• potential adaptation measures,

• prioritisation and costing of adaptation measures,

• interrelationships between vulnerability and adaptation assessments,

• national development priorities and actions to integrate adaptation options into existing or future sustainable development plans.”(IPCC 2007a)

Table 2.3 Some characteristics of different approaches to CCIAV assessment (IPCC 2007a)

	Approach			
	Impact	**Vulnerability**	**Adaptation**	**Integrated**
Scientific objectives	Impacts and risks under future climate	Processes affecting vulnerability to climate change	Processes affecting adaptation and adaptive capacity	Interactions and feedbacks between multiple drivers and impacts
Practical aims	Actions to reduce risks	Actions to reduce vulnerability	Actions to improve adaptation	Global policy options and costs
Research methods	Standard approach to CCIAV Drivers-pressure-state-impact-response (DPSIR) methods Hazard-driven risk assessment	Vulnerability indicators and profiles Past and present climate risks Livelihood analysis Agent-based methods Narrative methods Risk perception including critical thresholds Development/sustainability policy performance Relationship of adaptive capacity to sustainable development		Integrated assessment modelling Cross-sectoral interactions Integration of climate with other drivers Stakeholder discussions Linking models across types and scales Combining assessment approaches/methods
Spatial domains	Top-down Global → Local	Bottom-up Local → Regional (macro-economic approaches are top-down)		Linking scales Commonly global/regional Often grid-based
Scenario types	Exploratory scenarios of climate and other factors (e.g., SRES) Normative scenarios (e.g., stabilisation)	Socio-economic conditions Scenarios or inverse methods	Baseline adaptation Adaptation analogues from history, other locations, other activities	Exploratory scenarios: exogenous and often endogenous (including feedbacks) Normative pathways
Motivation	Research-driven	Research-/stakeholder-driven	Stakeholder-/research-driven	Research-/stakeholder-driven

2.4.1 Advances in vulnerability assessment

“Vulnerability is highly dependent on context and scale, and care should be taken to clearly describe its derivation and meaning (Downing and Patwardhan, 2005) and to address the uncertainties inherent in vulnerability assessments (Patt et al., 2005). Frameworks should also be able to integrate the social and biophysical dimensions of vulnerability to climate change (Klein and Nicholls, 1999; Polsky et al., 2003; Turner et al., 2003a). Formal methods for vulnerability assessment have also been proposed (Ionescu et al., 2005; Metzger and Schröter, 2006) but are very preliminary" (IPCC 2007a).

"The methods and frameworks for assessing vulnerability must also address the determinants of adaptive capacity (Turner et al., 2003a; Schröter et al., 2005a; O'Brien and Vogel, 2006) in order to examine the potential responses of a system to climate variability and change"(IPCC 2007a). There are many studies that aim to understand the relations between human developments, the underlying causes of vulnerability and adaptive capacity. Some quantitative approaches use indicators related to adaptive capacity, such as national economic capacity. Other use indicators that can provide information related to the conditions, processes and structures that include adaptive capacity.

Although initially, climate change impact, adaptation and vulnerability (CCIAV) assessments were perceived as now speculative, academic endeavour, CCIAV assessments are changing from being an exclusively research-oriented activity towards analytical frameworks that are designed for practical decision-making. "Decision makers are increasingly calling upon the research community to provide:

• good-quality information on what impacts are occurring now, their location and the groups or systems most affected,

• reliable estimates of the impacts to be expected under projected climate change,

• early warning of potentially alarming or irreversible impacts,

• estimation of different risks and opportunities associated with a changing climate,

• effective approaches for identifying and evaluating both existing and prospective adaptation measures and strategies,

• credible methods of costing different outcomes and response measures,

• an adequate basis to compare and prioritise alternative response measures, including both adaptation and mitigation."(IPCC 2007a)

Contrary to the considerable advances in CCIAV assessment (Table 2.4), still the implementation is constrained due to limited availability and access to good-quality data.

Table 2.4 Selected tools that support CCIAV assessments (IPCC 2007a)

Description	Selected examples
Indices of vulnerability to sea-level rise	Thieler and Hammar-Klose, 2000; Kokot et al., 2004
Integrated models and frameworks for knowledge management and adaptation assessment	Warrick et al., 2005; Dinas-Coast Consortium, 2006; Schmidt-Thomé, 2006
Geographic information systems for decision support	Green and King, 2002; Bartlett and Smith, 2005
Scenarios – a tool to facilitate thinking and deciding about the future	DTI, 2002; Ledoux and Turner, 2002
Community vulnerability assessment tool	NOAA Coastal Services Center, 1999; Flak et al., 2002
Flood simulator for flood and coastal defences and other responses	Discovery Software, 2006; Box 6.2
Estimating the socio-economic and environmental effects of disasters	ECLAC, 2003
ICZM process sustainability – a score card	Milne et al., 2003
Monetary economic valuation of the environment	Ledoux et al., 2001; Ohno, 2001
Evaluating and mapping return periods of extreme events	Bernier et al., 2007
Methods and tools to evaluate vulnerability and adaptation	UNFCCC, 2005

"A comprehensive assessment of the potential impacts of climate change must consider at least three components of vulnerability: exposure, sensitivity and adaptive capacity. Significant regional differences in present climate and expected climate change give rise to different exposure among human populations and natural systems to climate stimuli (IPCC 2001). Differences in geological, oceanographic and biological processes can also lead to substantially different impacts on a single coastal system at different locations. Some global patterns and hotspots of vulnerability are evident; deltas/estuaries (especially populated mega deltas), coral reefs (especially atolls), and ice dominated coasts appear most vulnerable to either climate change or associated sea-level rise and changes. Low-lying coastal wetlands, small islands, sand and gravel beaches and soft rock cliffs may also experience significant changes."(IPCC 2007a)

The fact that sea-level rise will not occur uniformly around the world should be underlined when site-specific vulnerability assessments are implemented. Variability of storms and waves, as well as sediment supply and the ability to migrate landward, also influence the vulnerability of coastal areas. Hence, there is an important element of local to regional variation among coastal system types that must be considered

"While physical exposure is an important aspect of the vulnerability for both human populations and natural systems to both present and future climate variability and change, a lack of adaptive capacity is often the most important factor that creates a hotspot of human vulnerability. Societal vulnerability is largely dependent upon development status (Yohe and Tol, 2002).

Recent work has also reconfirmed that (1) any system's vulnerability to climate change and climate variability could be described productively in terms of *its exposure to the impacts of climate and its baseline sensitivity to those impacts* and that (2) both exposure and sensitivity can be influenced by that system's *adaptive capacity* (Smith et al. (2001))"(IPCC 2007a).

However, there is an increasing recognition of the linkages between disaster risk reduction and adaptation to climate change, since climate change alters not only the physical hazard but also vulnerability. Many of the impacts associated with climate change exacerbate or alter existing threats, and adaptation measures can benefit from practical experience in disaster risk reduction. However, when the effects of sea-level rise are considered, there is little experience to rely on. Therefore co-ordinated action to address both existing and new challenges becomes urgent. "Incorporating climate change and its uncertainty into measures to reduce vulnerability to hazard is essential in order for them to be truly sustainable (O'Hare, 2002), and climate change increases the urgency to integrate disaster risk management into development interventions (DFID, 2004)"(IPCC 2007a).

However, many responses to current climatic variability would not be sufficient as a response to climate change. For example, a changing climate could alter the design standard of a physical defence, or the effectiveness of building codes based on designing against specified return period or change the status of an area from safe to risky. Finally, it could introduce hazards previously not experienced in an area. It is an important research priority to assess the success of current adaptation to present-day climate risks and climate variability to predict their performance under changing climate.

2.5 Assessment of Adaptation Practices, Options, Constraints and Capacity

"Adaptation to climate change is already taking place, but on a limited basis."(IPCC 2007a) Actual adjustments or changes in decision environments aiming to enhance resilience or reduce vulnerability are called adaptation practices. Investment in coastal protection infrastructure to reduce vulnerability to storm surges and anticipated sea-level rise is an example of actual adjustments. Development of climate risk screening guidelines, which might make projects more resilient to climate risks, is an example of changes in the policy environment.

"From a temporal perspective, adaptation to climate risks can be viewed at three levels: responses to (a) current variability (which also reflect learning from past adaptations to historical climates); (b) observed medium and long-term trends in climate; (c) anticipatory planning in response to model-based scenarios of long-term climate change. The responses across the three levels are often intertwined, and indeed might form a continuum" (IPCC 2007a).

Adaptive capacity is the ability of a system to evolve in order to accommodate climate changes or to expand the range of variability with which it can cope. Current pressures are likely to adversely affect the integrity of coastal ecosystems and thereby their ability to cope with additional pressures, including climate change and sea-level rise. This is a particularly significant factor in areas where there is a high level of development, large coastal populations and high levels of interference with coastal systems. Natural coastal habitats, such as dunes and wetlands, have a buffering capacity which can help reduce the adverse impacts of climate change. Equally, improving shoreline management for non-climate change reasons will also have benefits in terms of responding to sea-level rise and climate change (Nicholls and Klein 2005). Adopting a static policy approach towards sea-level rise conflicts with sustaining a dynamic coastal system that responds to perturbations via sediment movement and long-term evolution. In the case of coastal megacities, maintaining and enhancing both resilience and adaptive capacity for weather-related hazards are critically important policy and management goals. The dual approach brings benefits in terms of linking analysis of present and future hazardous conditions. It also enhances the capacity for disaster prevention and preparedness, disaster recovery and for adaptation to climate change(Klein et al. 2003).

(Yohe and Tol 2002) assessed the potential contributions of various adaptation options to improving systems' coping capacities. They suggest focusing attention directly on the underlying determinants of adaptive capacity. This highlights the importance of the socio-economic conditions (e.g., institutional capabilities; informed and engaged public) as a fundamental control of impacts with and without climate change. The constraints and limitations on adaptation by coastal systems, both natural and human, highlight the benefits for deeper public discourse on climate risk management, adaptation needs, challenges and allocation and use of resources.

Adaptation will provide immediate and longer-term reductions in risk in the specific area that is adapting. On the other hand, mitigation reduces future risks in the longer term and at the global scale. Identifying the optimal mix is problematic as it requires consensus on many issues, including definitions, indicators and the significance of thresholds. Importantly, mitigation removes resources from adaptation, and benefits are not immediate, so investment in adaptation may appear preferable, especially in developing countries. The opposite view of the need for urgent mitigation has recently been argued. Importantly, the limits to adaptation may mean that the costs of climate change are underestimated, especially in the long term. These findings highlight the need to consider impacts beyond 2100, in order to assess the full implications of different mitigation and adaptation policy mixes.

Adaptation to climate change is seldom undertaken in a stand-alone fashion, but as part of broader social and development initiatives. Adaptation also has limits, some posed by the magnitude and rate of climate change, and others that relate to financial, institutional, technological, cultural and cognitive barriers. The capacities for adaptation, and the processes by which it occurs, vary greatly within and across regions, countries, sectors and communities. Policy and planning processes need to take these aspects into account in the design and implementation of adaptation.

There are significant outstanding research challenges in understanding the processes by which adaptation is occurring and will occur in the future, and in identifying areas for leverage and action by government. Further research is needed to monitor progress on adaptation, and to assess the direct as well as ancillary effects of adaptation measures. In this context there is also a need for research on the synergies and trade-offs between various adaptation measures, and between adaptation and other development priorities. Barriers, limits and costs of adaptation are not fully understood, partly because effective adaptation measures are highly dependent on specific geographical and climate risk factors as well as institutional, political and financial constraints.

Table 2.5 Major impediments to the success of adaptation in the coastal zone (IPCC 2007a)

Impediment	Example Reference
Lack of dynamic predictions of landform migration	Pethick, 2001
Insufficient or inappropriate shoreline protection measures	Finkl, 2002
Data exchange and integration hampered by divergent information management systems	Hale et al., 2003
Lack of definition of key indicators and thresholds relevant to coastal managers	Rice, 2003
Inadequate knowledge of coastal conditions and appropriate management measures	Kay and Adler, 2005
Lack of long-term data for key coastal descriptors	Hall, 2002
Fragmented and ineffective institutional arrangements, and weak governance	Moser, 2000
Societal resistance to change	Tompkins et al., 2005a

"Adaptation (e.g., coastal planning and management) and mitigation (reducing greenhouse gas emissions) are responses to climate change, which can be considered together (King, 2004). The response of sea-level rise to mitigation of greenhouse gas emissions is slower than for other climate factors (Meehl et al., 2007) and mitigation alone will not stop growth in potential impacts (Nicholls and Lowe, 2006). However, mitigation decreases the rate of future rise and the ultimate rise, limiting and slowing the need for adaptation as shown by Hall et al. (2005). Adaptation and mitigation need to be considered together when addressing the consequences of climate change for coastal areas. Collectively these interventions can provide a more robust response to human-induced climate change than consideration of each policy alone (Nicholls and Lowe (2006), Tol (2007))." (IPCC 2007a)

"The literature on costs and benefits of adaptation to sea-level rise is relatively extensive. Fankhauser (1995a) used comparative static optimisation to examine the trade-offs between investment in coastal protection and the value of land loss from sea-level rise. The resulting optimal levels of coastal protection were shown to significantly reduce the total costs of sea-level rise across OECD countries. The results also highlighted that the optimal level of coastal protection would vary considerably both within and across regions, based on the value of land at risk. Nicholls and Tol (2006) estimate optimal levels of coastal protection under IPCC Special Report on Emissions Scenarios (SRES; Nakićenović and Swart, 2000) A1FI, A2, B1, and B2 scenarios. They conclude that, with the exception of certain Pacific Small Island States, coastal protection investments were a very small percentage of gross domestic product (GDP) for the 15 most-affected countries by 2080." (IPCC 2007a)

“Ng and Mendelsohn (2005) use a dynamic framework to optimise for coastal protection, with a decadal reassessment of the protection required. It was estimated that, over the period 2000 to 2100, the present value of coastal protection costs for Singapore would be between US$1 and 3.08 million (a very small share of GDP), for a 0.49 and 0.86 m sea-level rise. A limitation of these studies is that they only look at gradual sealevel rise and do not generally consider issues such as the implications of storm surges on optimal coastal protection. In a study of the Boston metropolitan area Kirshen et al. (2004) include the implications of storm surges on sea-level rise damages and optimal levels of coastal protection under various development and sea-level rise scenarios. Kirshen et al. (2004) conclude that under 60 cm sea-level rise ‘floodproofing’ measures (such as elevation of living spaces) were superior to coastal protection measures (such as seawalls, bulkheads, and revetments). Meanwhile, coastal protection was found to be optimal under one-metre sea-level rise. Another limitation of sea-level rise costing studies is their sensitivity to (land and structural) endowment values which are highly uncertain at more aggregate levels.Aglobal assessment by Darwin and Tol (2001) showed that uncertainties surrounding endowment values could lead to a 17% difference in coastal protection, a 36% difference in amount of land protected, and a 36% difference in direct cost globally. A further factor increasing uncertainty in costs is the social and political acceptability of adaptation options. Tol et al. (2003) show that the benefits of adaptation options for ameliorating increased river flood risk in the Netherlands could be up to US$20 million /yr in 2050. But they conclude that implementation of these options requires significant institutional and political reform, representing a significant barrier to implanting least-cost solutions.” (IPCC 2007a)

2.6 Perspectives on Climate Change and Sustainability

Climate change will interact at all scales with other trends in global environmental and natural resource concerns, including water, soil and air pollution, health hazards, disaster risk, and deforestation. Their combined impacts may be compounded in future in the absence of integrated mitigation and adaptation measures.

Sustainable development can reduce vulnerability to climate change by reducing sensitivities through adaptation and/or exposure through mitigation. However, few projects have included adaptation into sustainability plans. Additionally, changing development paths to promote sustainability enhances mitigation efforts. However these require resources to overcome multiple barriers (Figure 2.8).

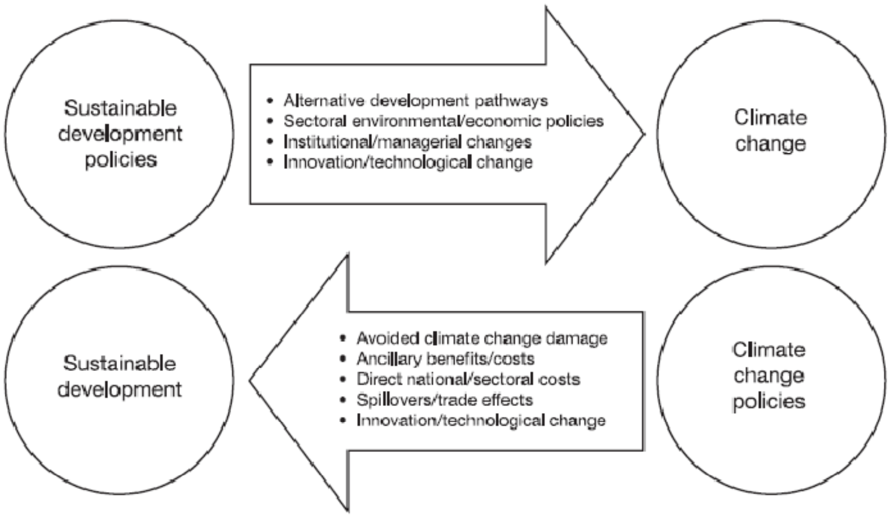


Figure 2.8 Two-way linkages between climate and sustainable development. Source: Swart et al. (2003) taken from IPCC 2007a

While promoting sustainability increases the success of adaptation and mitigation efforts, climate change and sea-level rise increase the challenge of achieving sustainable development in coastal areas, especially in developing countries. Adapting effectively to climate change and sea-level rise will involve investment with resources diverted from other productive uses. Additionally risks will grow for many generations due to long-term sea-level rise. Hence, sustainability for coastal areas appears to depend upon a combination of adaptation and mitigation.

There will be significant benefits if sustainability and climate change concept are integrated into management plans. However, this requires decision makers to move from reactive to more proactive coastal management practices. "As recognised in earlier IPCC assessments (Bijlsma et al., 1996; McLean et al., 2001), a key conclusion is that reactive and standalone efforts to reduce climate-related risks to coastal systems are less effective than responses which are part of integrated coastal zone management (ICZM), including long-term national and community planning" (IPCC 2007a).

"One constraint on successful management of climate-related risks to coastal systems is the limited ability to characterise in appropriate detail how these systems, and their constituent parts, will respond to climate change drivers and to adaptation initiatives (Finkl, 2002)"(IPCC 2007a). Of particular importance is understanding the extent to which natural coastal systems can adapt and therefore continue to provide essential life-supporting services to society. The lack of understanding of the coastal system, including the highly interactive nature and non-linear behaviour, means that failure to take an integrated approach to characterising climate-related risks increases the likelihood that the effectiveness of adaptation will be reduced, and perhaps even negated.

ICZM provides a major opportunity to address the many issues and challenges identified above. ICZM is widely recognised and promoted as the most appropriate process to deal with climate change, sea-level rise and other current and long-term coastal challenges due to its advantages over purely sectoral approaches. (Nicholls and Klein, 2005). Additionally, enhancing adaptive capacity is an important part of ICZM. Responses to sea-level rise and climate change need to be implemented in the broader context and the wider objectives of coastal planning and management. The extent to which climate change and sea-level rise are considered in coastal management plans is one useful measure of commitment to integration and sustainability. "Generation of equitably distributed social and environmental benefits is a key factor in ICZM process sustainability, but is difficult to achieve. Attention is also paid to legal and institutional frameworks that support integrative planning on local and national scales. Different social groups have contrasting, and often conflicting views on the relative priorities to be given to development, the environment and social considerations, as well as short and long-term perspectives (Visser, 2004)"(IPCC 2007a).

2.7 Key uncertainties, research gaps and priorities

IPCC Fourth Assessment report concludes that "the level of knowledge is not consistent with the potential severity of the problem of climate change and coastal zones. While knowledge is not adequate in any aspect, uncertainty increases from the natural sub-system to the human sub-system, with the largest uncertainties concerning their interaction. An understanding of this interaction is critical to a comprehensive understanding of human vulnerability in coastal and low-lying areas and should include the role of institutional adaptation and public participation. In addition, any response to climate change has to address the other non-climate drivers of coastal change in terms of understanding potential impacts and responses, as they will interact with climate change and generally exacerbate the impacts of climate change."

The following research initiatives were proposed by IPCC to reduce the uncertainties and increase the effectiveness and science base of long-term coastal planning and policy development.

1. "Establishing better baselines of actual coastal changes, including local factors and sea-level rise, and the climate and non-climate drivers, through additional observations and expanded monitoring. This would help to better establish the causal links between climate and coastal change which tend to remain inferred rather than observed and support model development.
2. Improving predictive capacity for future coastal change due to climate and other drivers, through field observations, experiments and model development. A particular challenge will be understanding thresholds under multiple drivers of change.
3. Developing a better understanding of the adaptation of the human systems in the coastal zone. At the simplest this could be an inventory of assets at risk, but much more could be done in terms of deepening our understanding of the qualitative trends and issues of adaptive capacity.
4. Improving impact and vulnerability assessments within an integrated assessment framework that includes natural - human sub-system interactions which requires a strong inter-disciplinary approach. Understanding of how development planners incorporate information about climate variability and change into their decisions is limited. This limits the integrated assessment of vulnerability. Improving systems of coastal planning and zoning and institutions that can enforce regulations for clearer coastal governance is required in many countries.
5. Developing methods for identification and prioritisation of coastal adaptation options. The effectiveness and efficiency of adaptation interventions need to be considered, including immediate benefits and the longer term goal of sustainable development.

6. Developing and expanding networks to share knowledge and experience on climate change and coastal management among coastal scientists and practitioners.” (IPCC 2007a)

These issues need to be explored from local to global scale assessments and, given the long timescales of sea-level rise and for different time scales across a broad range of activities from the needs of coastal management and adaptation to global integrated assessments and the benefits of mitigation.

2.8 Preliminary Coastal Vulnerability Assessment Model to Sea Level Rise

“Integration of climate change impacts on coastal areas, especially impacts of sea-level rise, with coastal zone management practices is performed through coastal vulnerability assessments in which vulnerability is defined as the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes (IPCC 2001). There are many levels of vulnerability assessments, which can be classified as strictly quantitative to semiquantitative, nonadaptive to perfectly adaptive, science driven to policy driven, simplistic to sophisticated, *etc.* (Fussel and Klein 2006). Each of these approaches has its shortcomings and requires a different type of data with a different level of accuracy, which in some cases may be indeterminate or simply not exist. Although the option of detailed research of the region, with extensive data collection and the use of mathematical models, will most likely give a more accurate prediction of the outcome of the impacts of sea-level rise on the coastal areas, the limitations mentioned earlier eliminate this option in most cases. However, the relative vulnerability of different coastal environments to sea-level rise may be quantified on a regional to national scale using basic information on coastal geomorphology, rate of sea-level rise, past shoreline evolution, coastal slope, mean tidal range, and mean wave height, as demonstrated by Thieler and Hammar-Klose (2000) in the National Assessment of Coastal Vulnerability to Future Sea- Level Rise for U.S. coasts within U.S. Geological Survey Marine Geology Program’s National Assessment, which produced several reports used as reference for this study as well.

Although their methodology highlights those regions in which the various effects of sea-level rise may be the greatest, the method yields numerical data that cannot be directly equated with particular physical effects (Thieler and Hammar-Klose 2000). Another shortcoming of the model is that the model does not consider the impacts of human manipulation of the coastal environment on the physical processes of the impacts of sea-level rise. Thus, by using the concept of Thieler and Hammar-Klose (2000) as a starting point, a coastal vulnerability matrix and a corresponding coastal vulnerability index (CVI-SLR) of a region to sea-level rise, using indicators of the impacts of sealevel rise that use commonly available data, are developed. The results of the matrix and the index enable decision makers

- to compare and rank regions according to their vulnerabilities to sea-level rise,
- to prioritize the impacts of sea-level rise on the region according to the vulnerability of the region to each impact,
- to determine the most vulnerable parameters for planning adaptation measures to sea-level rise

within the integrated coastal zone management concept (Ozyurt 2007)."(Ozyurt and Ergin 2010)

2.8.1 Methodology

Extensive literature review is summarized to briefly describe and discuss the impacts of sea level rise an the governing physical and anthropogenic parameters. The impacts considered in the model are:

- Inundation
- Coastal erosion
- Flooding due to increased storm surges
- Saltwater intrusion to freshwater resources

2.8.1.1 Coastal Erosion

"Coastal erosion represents the physical removal of sediment by wave and current action"(Klein and Nicholls 1998). The process of coastal erosion depends mostly on the type of shore being eroded that is the geomorphology of the area and the wave climate.

"With a significant rise in sea level, there will be an acceleration of beach erosion in areas already eroding and possibly a start of erosion in areas not previously subject to erosion" (Sorensen et al. 1984) due to higher and deeper water levels changing the sediment sources and bathymetry.

"The best known and most widely applied model to estimate coastal erosion due to sea level rise has been developed by Bruun. Bruun's concept was that beaches adjust to the dominant wave conditions at the site. The basic assumption behind Bruun's model is that with a rise in sea level, the equilibrium profile of the beach and the shallow offshore moves upward and landward" (Klein and Nicholls 1998). The Bruun rule can be expressed schematically as in Figure 2.9.

Bruun Rule;

$$R = \frac{L_*}{B + d_*} S \qquad \text{(Eq.2.1)}$$

Where

R = shoreline retreat
S = increase in sea level
L_* = cross-shore distance to water depth d_*
B = berm height of the eroded area
d_* = depth of closure

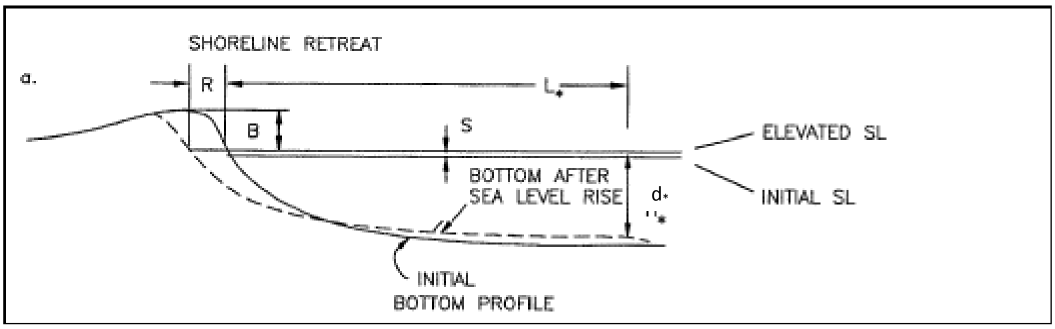


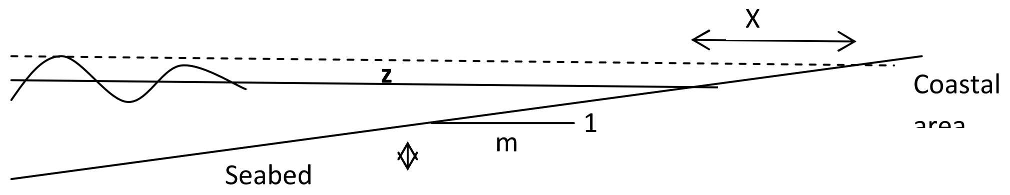
Figure 2.9 Shoreline response to sea level rise by Bruun Rule(CEM 2003).

"One of the strengths of the Bruun concept is that the equations are valid regardless of the shape of the profile" (CEM 2003).

Marshes, wetlands and reefs have the natural ability to adjust to changing sea level as long as they are not damaged by manmade factors like major changes in sediment supply. Other than sediment supply, offshore or long shore transport is an important process for erosion or accretion of these shores.

2.8.1.2 Inundation

"Inundation is the permanent submergence of low-lying land" (Klein and Nicholls 1998). This is an effect, which is difficult to separate from the effect of increased coastal erosion where erosion is occurring. Land loss resulting from inundation depends on the coastal slope of the area. The milder the slope is, the greater the land loss (Figure 2.10).



Where z – rise in sea level

X – inundated distance

Figure 2.10 Inundation Definitions

2.8.1.3 Increased Coastal Flooding due to Storm Surges

"Storm surge is a meteorologically forced long wave motion, which can produce sustained elevations of the water surface above the levels caused by the tides" (Bode and Hardy 1997). Surges are mostly associated with mid-latitude storms or with tropical storms. Figure 2.11 shows the storm surge-flooding concept schematically.

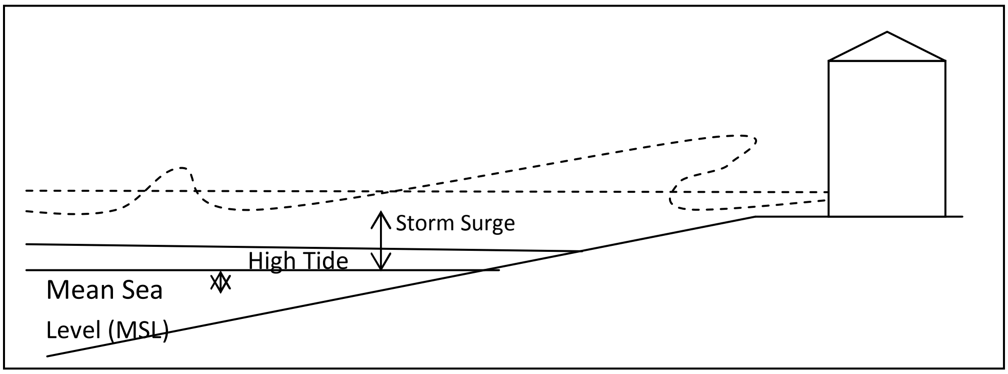


Figure 2.11 Storm surge process

A rise in sea level will increase the flood risk due to storm surges by moving the risk zones upward and seaward.

2.8.1.4 Salinity Intrusion to Groundwater and River

Salinity intrusion can be classified according to the location of intrusion as salinity intrusion in groundwater and salinity intrusion in estuary and rivers since different processes dominates the impact.

"Saltwater intrusion in groundwater can be assessed using analytical methods and mathematical modeling" (Klein and Nicholls 1998). The Ghyben-Herzberg principle provides an initial estimate of the inland extent of saltwater intrusion in a simple unconfined aquifer of infinite depth analytically. According to the principle, a one meter height of water table (WT) above mean sea level ensures 40 m of freshwater below sea level. Likewise, a 50 cm rise in sea level causes a 20 m reduction in the freshwater thickness, as shown in Figure 2.12(Sherif and Singh 1999). When the Ghyben-Herzberg principle is used for artesian aquifers, the piezometric surface above sea level should be considered (Kana et al. 1984).

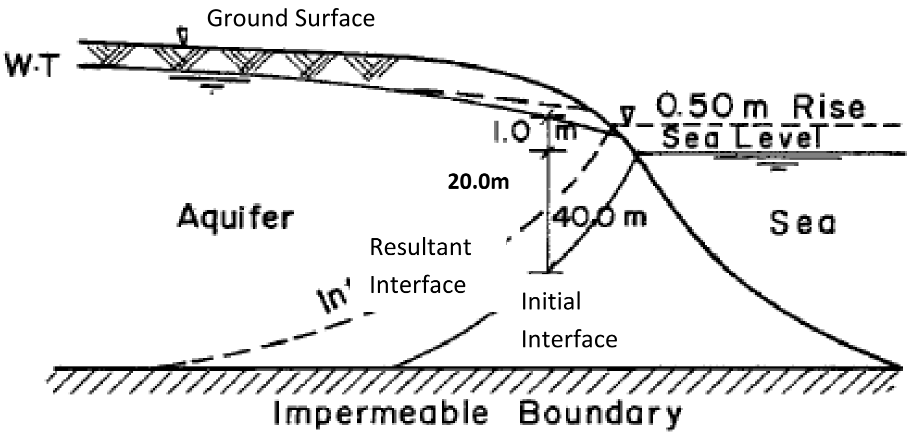


Figure 2.12 Sharp interface and sea level rise (Sherif and Singh 1999)

Although sea level rise puts an additional pressure head at the seaside boundary of the aquifer, the intrusion process is governed by many other parameters such as subsoil characteristics (porosity and conductivity of the aquifer, hydraulic resistance of the aquifer), hydraulic variables(groundwater flow and recharge) and geohydrology(confined, semi-confined or unconfined) (Klein and Nicholls 1998).

On the other hand salt water intrusion to estuary/river depends on dominating processes of the location that can be classified as

1. Wave-dominated, where wave energy acts more on the estuary than tidal influence and the estuary is fully stratified,
2. Tide-dominated estuary where tide current energy is greater than wave energy at the mouth of the river and the estuary is well-mixed (CEM 2003).

The length of the saline interface whether saline wedge or mean salinity will be affected by sea level rise. Several other processes increase or decrease the salt intrusion length such as variation of river flow from dry years to wet years, temporary increase of mean sea level due to landward wind or storm surges. "The salt intrusion may increase considerably during dry season when river discharge drops below a critical value. If the river discharge remains below this critical value for an extended period, the salt intrusion increases steadily" (Bashar and Hossain 2006). A rise in sea level will also cause saltwater to migrate upstream.

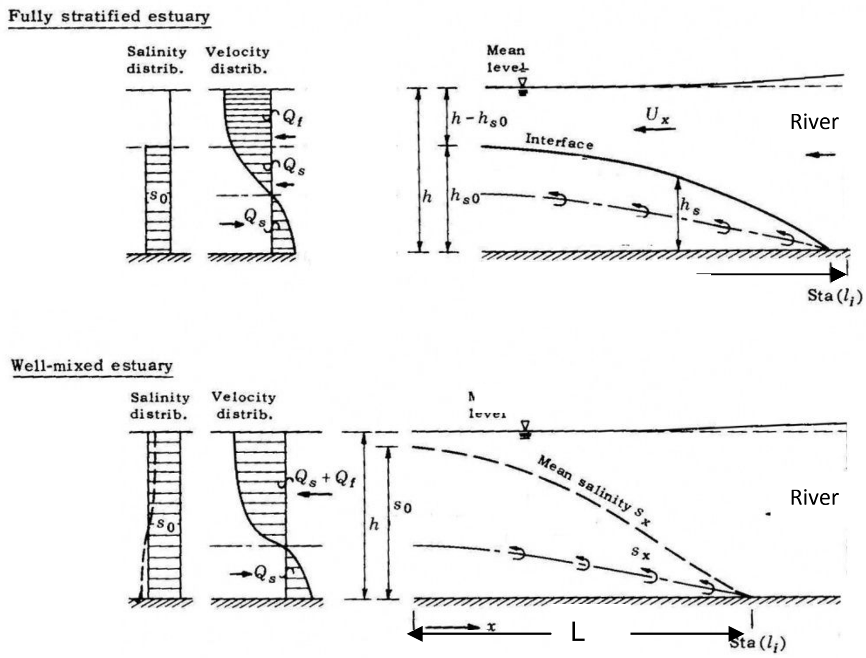


Figure 2.13 Schematic representation of salinity intrusions in estuaries (Ippen 1966)

Quantitative prediction of the expected shift of saline interface can be evaluated accurately by using numerical models and empirical models. The following empirical relations are given in the literature for salt intrusion length (L);

$$L = 4.7\frac{h_0}{f}F_d^{-1}\left(\frac{-\pi Q_f}{1.08A_0 \mathrm{v}_0}\right)$$ tidal effect considered(Rigter 1973) (Eq. 2.2)

$$L = 6.0h_0\left(\frac{V_\Delta h_0}{\upsilon}\right)^{\frac{1}{4}}\left(\frac{2V_r}{V_\Delta}\right)^{\frac{-5}{2}}$$ tide-less sea (Ippen 1966) (Eq.2.3)

Where h_0 = river depth at downstream

F_d = densimetric Froude number = $\frac{\rho \mathrm{v}_0^2}{\Delta\rho g h_0}$

f = Darcy-Weisbach's roughness

Q_f = river discharge for dry season

A_0 = cross sectional area at the mouth

v_0 = tidal velocity amplitude

V_r = velocity of river

V_Δ = densimetric velocity = $\sqrt{\frac{\Delta\rho}{\rho_m} g h_0}$
ρ = density of fresh water
Δρ = density difference between sea water and fresh water
ρ_m = average of density of fresh and sea water
υ = kinematic viscosity of water

Coastal areas are not only under threat due to climate change induces sea level rise but anthropogenic factors also increase the vulnerability of the coastal areas to sea level rise by decreasing the resilience of the area. Thus in order to assess the vulnerability of a coastal area, the present anthropogenic pressures on the coasts should be included in the vulnerability assessment model.

Coastal erosion is determined by sediment budget deficit. In naturally balanced area, human activities can cause erosion by decreasing sediment amount delivered to coast. Main activity responsible for sand transport loss is upstream dam construction on discharging rivers. Since the beginning of 20th century, a dramatic reduction (%25) in sediment supply to the coastal zone has occurred globally following the construction of dams for irrigation and hydroelectric power schemes (Vorosmarty CJ 2003). Dams also eliminate peak flood discharges, which is responsible for flushing lower reaches of rivers and transporting most sediment to coast (Morton 2003). In addition, coastal excavation such as dredging and mining causes the most rapid and direct conversion of land to open water.

Many countries have built coastal protection structures such as groins, seawalls, breakwaters and revetments in order to control erosion and land loss. However, these structures themselves initiated undesirable effects on sedimentary processes at the region or neighbouring regions. Although coastal protection structures may cause negative impacts at the adjacent shores, if properly planned, they do control the erosion by causing accretion within their region. Thus the coastal protection structures can decrease the vulnerability of the region when they keep working properly, achieving the intended results if adapted to sea level rise.

Urbanization and increased agricultural activities through development of irrigation networks on coastal areas increases the vulnerability as well. Both activities consume significant amount of water that will be exploited either from groundwater resources or surface waters. Thus increase in the amount of exploitation of groundwater, will increase the salinity intrusion dropping the pressure head of the aquifer. Also massive consumption of river water for usage will disturb the wetlands which are natural barriers against inundation and flooding due to storm surge, as well as increasing salinity intrusion to rivers and estuaries.

The main impacts of sea level rise summarized above, underline the holistic and coastal zone management point of view for the vulnerability assessment of coastal areas to sea-level rise. It was concluded that 12 physical parameters and 7 human influence parameters presented in Table 2.6 and Table 2.7 would be sufficient to represent the system with regard to vulnerability without reducing the quality of the assessment. A five level scale was selected as vulnerability ranges from very low vulnerability (1) to very high vulnerability (5).

Table 2.6 Physical parameters of coastal vulnerability assessment to sea level rise and the corresponding ranges of vulnerability

				Range		
		Very low	**Low**	**Moderate**	**High**	**Very High**
Parameters		**1**	**2**	**3**	**4**	**5**
Rate of SLR	mm/yr	<1	1-2	2-5	5-7	7-9 and over
Geomorphology		Rocky cliffed coasts Fiords	Medium cliffs Indented coasts	Low cliffs Glacial drift Alluvial plains	Cobble beaches Estuary Lagoon	Barrier beach Sand beach Salt marsh Mudflats Deltas Mangrove Coral reefs
Coastal Slope		>1/10	1/10-1/20	1/20-1/30	1/30-1/50	1/50-1/100
Significant Wave Height	m	<0.5	0.50-3.0	3.0-6.0	6.0-8.0	>8.0
Sediment Budget		More than 50% of the shoreline is in accretion	Between 10-30% of the shoreline is in accretion	Less than 10% of the shoreline is in erosion or in accretion	Between 10-30% of the shoreline is in erosion	More than 50% of the shoreline is in erosion
Tidal range	m	>6.0	4.0-6.0	2.0-4.0	0.5-2.0	<0.5
Proximity to Coast	m	>1000	700-1000	400-700	100-400	<100
Type of Aquifer		leaky confined		confined		unconfined
Hydraulic Conductivity	m/day	0-12	12-28	28-41	41-81	>81
Depth to groundwater level above sea	m	>2.00	1.25-2.0	0.75-1.25	0.0-0.75	≤0.00
River Discharge	m^3/s	>500	250-500	150-250	50-150	0-50
Water Depth at down stream	m	≤1	2	3	4-5	>5

Table 2.7 Parameters of human influence on coastal areas and the corresponding ranges

			Range		
	Very low	**Low**	**Moderate**	**High**	**Very High**
Human Parameters	**1**	**2**	**3**	**4**	**5**
Reduction of sediment supply	>%80	%60-80	%40-60	%20-40	<%20
River flow regulation	Not affected		Moderate affected		Strongly affected
Engineered frontage	<%5	%5-20	%20-30	%30-50	>%50
Groundwater consumption	<%20	%20-30	%30-40	%40-50	>%50
Land use pattern	Protected Area	Unclaimed	Settlement	Industrial	Agricultural
Natural protection degradation	>%80	%60-80	%40-60	%40-20	<%20
Coastal protection structrues	>%50	%30-50	%20-30	%5-20	<%5

The vulnerability ranges were determined based on the distribution of available data related to each parameter at locations around the world to fulfil the aim of developing a vulnerability assessment method that can be used for comparison of any coastal area on earth.

2.8.2 Coastal Vulnerability Index

Two types of CVIs are calculated by the model such that the overall vulnerability index enables decision makers to compare different regions and five subindices show the vulnerability level of a region for each particular impact of sea-level rise. Using available regional data or expert opinion, each parameter is assigned a vulnerability rank of very low to very high vulnerability (1–5) within the developed coastal vulnerability matrix (Table 2.8) to calculate the impact subindices and the overall vulnerability index.

"Physical impact subindices (CVIimpact) are the results of the ratio of the sum of weighted parameters to the least vulnerable case result for the impact studied. The calculated indices range between 1 and 5, indicating the level of vulnerability accordingly" (Ozyurt 2007).

The CVI-SLR is calculated according to the group the region is in, which depends on the likelihood of the existence of types of physical impacts.

Table 2.8 Coastal Vulnerability Matrix of Goksu Delta – case study

Location Göksu Delta

Impact	Physical Parameters							Human Influence Parameters							Impact Total	CVI impact
	Parameter	1	2	3	4	5	Total	Parameter	1	2	3	4	5	Total		
1. Coastal Erosion	P1.1 Rate of Sea Level Rise		1				2	H1.1 Reduction of Sediment Supply			1			3		
	P1.2 Geomorpholgy					1	5	H1.2 River Flow Regulation			1			3		
	P1.3 Coastal Slope					1	5	H1.3 Engineered Frontage		1				2		
	P1.4 $H_{1/3}$				1		4	H1.4 Natural Protection Degradation					1	5		
	P1.5 Sediment Budget				1		4	H1.5 Coastal Protection Structures					1	5		
	P1.6 Tidal Range					1	5									
	TOTAL	0	1	0	2	3	25	TOTAL	0	1	2	0	2	18	21.5	3.909090909
2. Flooding due to Storm Surge	P2.1 Rate of Sea Level Rise		1				2	H2.1 Engineered Frontage		1				2		
	P2.2 Coastal Slope					1	5	H2.2 Natural Protection Degradation					1	5		
	P2.3 $H_{1/3}$				1		4	H2.3 Coastal Protection Structures					1	5		
	P2.4 Tidal Range					1	5									
	TOTAL	0	1	0	1	2	16	TOTAL	0	1	0	0	2	12	14	4
3. Inundation	P3.1 Rate of Sea Level Rise		1				2	H3.1 Natural Protection Degradation	0	0	0	0	1	5		
	P3.2 Coastal Slope					1	5	H3.2 Coastal Protection Structures	0	0	0	0	1	5		
	P3.3 Tidal Range					1	5									
	TOTAL	0	1	0	0	2	12	TOTAL	0	0	0	0	2	10	11	4.4
4. Salt Water Intrusion to Groundwater Resources	P4.1 Rate of Sea Level Rise		1				2	H4.1 Groundwater consumption				1		4		
	P4.2 Proximity to Coast				1		4	H4.2 Land Use Pattern					1	5		
	P4.3 Type of Aquifer			1			3									
	P4.4 Hydraulic Conductivity	1					1									
	P4.5 Depth to Groundwater Level Above Sea		1				2									
	TOTAL	1	2	1	1	0	12	TOTAL	0	0	0	1	1	9	10.5	3
5. Salt Water Intrusion to River/Estuary	P5.1 Rate of Sea Level Rise		1				2	H5.1 River Flow Regulation			1			3		
	P5.2 Tidal Range					1	5	H5.2 Engineered Frontage		1				2		
	P5.3 Water Depth at Downstream		1				2	H5.3 Land Use Pattern					1	5		
	P5.4 Discharge				1		4									
	TOTAL	0	2	0	1	1	13	TOTAL	0	1	1	0	1	10	11.5	3.285714286

CVI(SLR)-1		
CVI(SLR)-2		
CVI(SLR)-3	68.5	3.7027027

One of the main limitations of the model is the weighting system, in which weights of all the parameters are taken as equal to one. To assign accurate weights to model parameters, implementation of the model to several coastal areas is needed. Nevertheless, we underline that the given weights of 1 for the parameters and 0.5 for the effect of physical parameters and human influence parameters on the overall vulnerability can be used as a baseline analysis until further research is available.

This model in a matrix format was successfully applied to different coastal areas of Turkey, each having unique coastal properties, to show the effect of local properties in terms of both physical parameters and human influence parameters. A detailed review of the applicability of the developed model and how it achieves representation of the differences among regions (Amasra on the Black Sea, Gocek on the Aegean Sea, and Goksu on the Mediterranean Sea) in terms of coastal vulnerability to sea-level rise was given in Ozyurt and Ergin (2010).

The initial model does not have a predetermined spatial scale or timescale. Although the need for a spatial scale exists, since no future scenarios of sea-level rise are required for the assessment model the need for a timescale is eliminated. The time factor comes into the framework of the assessment in the accuracy and up-to-date database of the parameters involved in the assessment. To overcome the issue of spatial scale, an initial model was implemented using geographic information systems (GIS) (Figure 2.14). The last step enabled the evaluation of the applicability of the developed model.

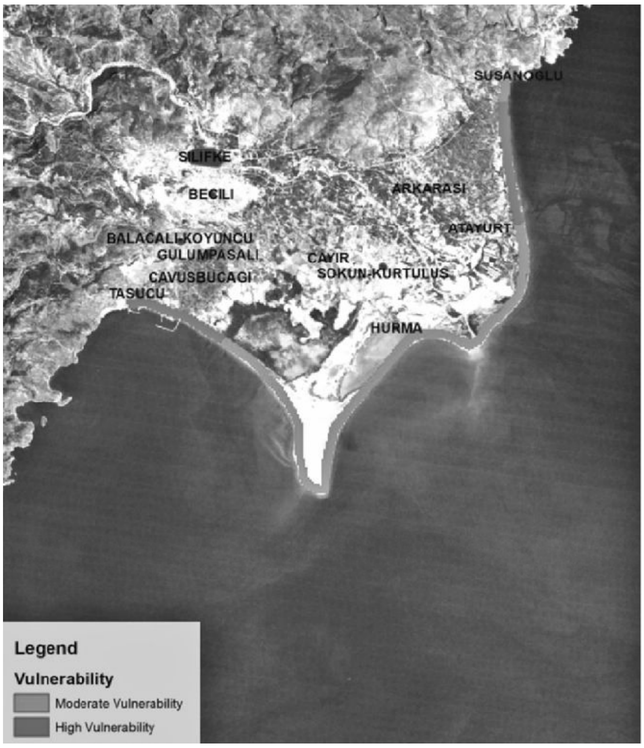


Figure 2.14 Coastal Vulnerability Index of Sea Level

2.8.4 Conclusions

"In light of the need for vulnerability assessments of sea level rise, which will exacerbate the present pressures on coastal areas, different types of assessment methodologies with different levels of requirement to data, resources, and technology are proposed. Most of these assessments require a future sea-level rise scenario and focus only on the sea-level rise impacts on coastal evolution, such as inundation and coastal erosion, and do not include present and future human activities in the coastal areas. On the other hand, implementation of adaptation measures is mostly controlled by national and local decision makers, who generally have limitations on available resources for these types of assessments. Furthermore, the coastal processes are very dynamic and complex, with important socioeconomic consequences making the decision making process much harder. Thus, the need for a quick but informative vulnerability assessment method based on the Thieler and Hammar-Klose (2000) methodology, which uses both physical and human activity parameters, was proposed as an alternative to available assessments.

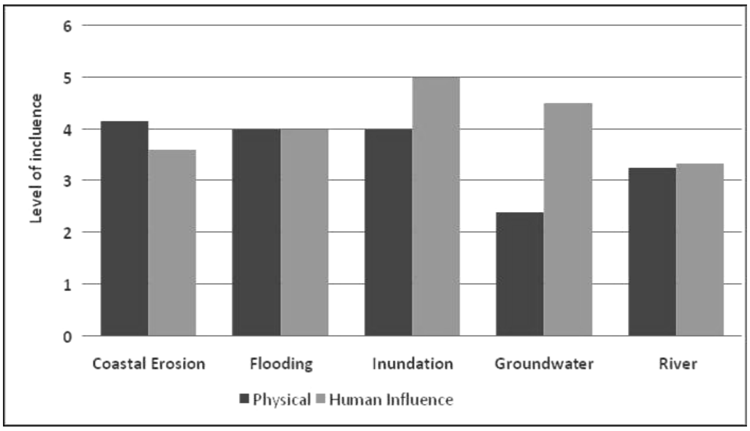


Figure 2.15 Histogram of physcial and human influence parameters with respect to impacts of sea level rise for Göksu Delta.

The developed model uses both physical and human factors on coastal processes affected by sea-level rise. This method yields to quantitative results for regions and particular impact vulnerability ranges using both quantitative and qualitative data. Contrary to the Thieler and Hammar-Klose model, the developed model can rank types of impacts according to the vulnerability level for a region. A histogram of physical parameters and human influence parameters (Figure 2.14) enables decision makers to determine the controllable values. The developed CVI-SLR model can be used as a guideline for adaptation management strategies since it is believed to be easily integrated into present coastal zone management practices."(Ozyurt and Ergin 2010)

CHAPTER III

REVISITING MODEL PARAMETERS

There were 12 physical parameters and 7 human influence parameters included in the initial model which is given in detail in Section 2.8. These parameters (Table 3.1) were chosen to describe the following physical impacts of sea level rise on coastal areas;

- coastal erosion,
- flooding due to storm surges,
- inundation,
- salt water intrusion to groundwater resources
- Salinity intrusion to estuary/rivers.

The aim of the initial model was to define these physical impacts by using governing parameters for which site specific data can be collected or can be classified by local experts easily. For this purpose, extensive literature reviews were performed when determining the governing parameters. However, since the aim of this study was to minimize the uncertainties related to data limitations, scientific knowledge on physical processes and driving forces as well as influence of human activities on the physical processes and vulnerability of coastal area; revisiting the physical processes of the impacts of sea level rise was mandatory when upgrading the initial model. In order to achieve this objective, further literature was reviewed and several discussions are presented below that demonstrates the reasons for keeping each parameter and adding new parameters (when necessary).

Table 3.1 Parameters used to calculate the sub-indices of each impact of sea level rise

Impacts of Sea Level Rise	Physical Parameters	Human Influence Parameters
Coastal Erosion	1. **Rate of Sea Level Rise** 2. Geomorphology 3. Coastal Slope 4. Significant Wave Height 5. Sediment Budget 6. Tidal Range	1. Reduction of Sediment Supply 2. River Flow Regulation 3. Engineered Frontage 4. Natural Protection Degradation 5. Coastal Protection Structures
Flooding due to Storm Surges	1. **Rate of Sea Level Rise** 2. Coastal Slope 3. Significant Wave Height 4. Tidal Range	1. Engineered Frontage 2. Natural Protection Degradation 3. Coastal Protection Structures
Inundation	1. **Rate of Sea Level Rise** 2. Coastal Slope 3. Tidal Range	1. Natural Protection Degradation 2. Coastal Protection Structures
Salt Water Intrusion to Groundwater Resources	1. **Rate of Sea Level Rise** 2. Proximity to Coast 3. Type of Aquifer 4. Hydraulic Conductivity 5. Depth to Groundwater Level Above Sea	1. Groundwater consumption 2. Land Use Pattern
Salt Water Intrusion to Rivers/Estuaries	1. **Rate of Sea Level Rise** 2. Tidal Range 3. Water Depth at Downstream 4. Discharge	1. River Flow Regulation 2. Engineered Frontage 3. Land Use Pattern

3.1 Coastal Erosion

Initial physical and human influence parameters were kept for the upgraded model. However several clarifications were needed when the initial model was applied for several coastal areas such as which wave statistics should significant wave height represent. For coastal erosion, wave climate is one of the basic governing forces. Although single extreme events such as storms contribute significantly in shoreline changes in short durations, the coastal area always tries to establish equilibrium in the longer term. When the time scale of sea level rise is considered, longer trends gain importance which is why historical and present shoreline movements are also considered in assessing the vulnerability of coastal areas to coastal erosion as a separate parameter-sediment budget- as well. In light of these discussions, it must be underlined that significant wave height parameter signifies long term wave statistics of a region, not extreme wave statistics.

When human influence parameters are considered, it was seen that reduction of sediment supply and river flow regulation parameters were considered to be almost same when application of the initial model was performed. "As a consequence of activities outside the coastal zone, natural ecosystems (particularly within the catchments draining to the coast) have been fragmented and the downstream flow of water, sediment and nutrients has been disrupted"(Nilsson et al. 2005). Land-use change, particularly deforestation, and hydrological modifications have had downstream impacts, in addition to localised development on the coast. "Erosion in the catchment has increased river sediment load; for example, suspended loads in the Huanghe (Yellow) River have increased 2 to 10 times over the past 2000 years" (Jiongxin 2004). In contrast, damming and channelization have greatly reduced the supply of sediments to the coast on other rivers through retention of sediment in dams. This effect will likely dominate during the 21st century. In light of this discussion, it could be argued that river flow regulation works such as damming is directly related to reduction of sediment supply of a coastal region; however, what these parameters are defining is essentially different.

Reduction of sediment supply was defined as the ratio of present sediment supply to the region to the natural state sediment supply in Ozyurt 2007. This includes the sediment trapped in dams or reservoirs at the upstream of the river, excavation of coastal zone, mining and changes in land use. This parameter directly defines the sediment particle itself and the abundance of it through different mechanisms, regulation works on rivers that trap sediment included.

On the other hand, river flow regulation parameter shows the amount of impact of any regulative structure on rivers at the down drift in terms of flow rate by using Nilsson et al., 2005 methodology of flow regulation index (Ozyurt 2007). This parameter focuses on the flow rate of the river and how this regulation of river flow either increases or decreases the sediment movement along the river. As is well documented in literature, unregulated rivers carry most sediments partly because sediment is not trapped behind dams but partly because of flushing of river channel during floods or high flow rates which are not controlled by regulatory structures. While regulatory structures enables stable flow rates, this mostly decreases the amount of sediment carried to the coastal area by generating favourable conditions for settlement of sediment particles along river channels.

In light of above discussions, it is important to distinguish the difference between these two parameters and the mechanisms that they represent when the model is applied for a coastal area. If there is no river discharging at a coastal area, reduction of sediment supply parameter is included in the model while river flow regulation is not applied. If there is a river, then sediment trapped at regulative works on a river should be included when reduction of sediment supply parameter is calculated.

3.2 Flooding Due To Storm Surges

Initial model included significant wave height as one of the physical parameters; however this parameter were changed to storm surge height which is predicted to happen in 100 years as a result of literature review. Initially, the significant wave parameter was used to define extreme wave statistics indicating wave height with a return period of 100 years. But the flooding of coastal areas during storms is dominated by surge heights (A. T. Vafeidis et al. 2005; Feenstra JF et al. 1998; Hinkel and Klein 2006). Thus numerical predictions of surge heights with 100 years of return period were used as a new parameter in upgraded model.

On the other hand, flooding is influenced by human activities along coastal areas such as presence of dunes and their present status (in good shape or not), presence of coastal protection structures such as seawalls, flood gates, etc. and the amount of coastal structures such as harbors, jetties, etc. which could alter the surge dynamics and exacerbate the impacts of storm surges (Hinkel and Klein 2006; Morton 2005). All these anthropogenic activities were included in the initial model (Ozyurt 2007) as well as the upgraded vulnerability assessment model.

3.3 Inundation

It is seen that still there is not a universal terminology for permanent loss of land directly due to rising of sea levels. In Ozyurt 2007, inundation was defined as permanent submergence of land due to sea level rise. However many coastal experts use the term inundation associated with periodic flooding of land due to storms or flooding due to tsunamis as well. Although it is hard to distinguish land loss due to direct rising sea levels or coastal erosion triggered by sea level rise and/or other drivers, in the upgraded model study, the definition of inundation was kept as the initial one; the permanent submergence of low-lying land which is also used by (Klein and Nicholls 1998). The parameters defining this impact were kept as they are for the upgraded methodology.

3.4 Salt Water Intrusion to Groundwater

Salt water intrusion to coastal groundwater resources was an important addition to the vulnerability assessment of coastal areas. It was an important step to ensure that vulnerability of a coastal area to sea level rise was considered thoroughly by the initial model.

"There is no question that the use of groundwater has brought many benefits to billions of people through urban water supply and agricultural groundwater use. Although the value of groundwater use is unquestioned, the sustainability of that use is" (Giordano 2009). Groundwater tables are falling very rapidly in many parts of the world. The natural system of groundwater is created by infiltration of precipitation and surface runoff. However, in many regions, the natural system of groundwater recharge and discharge has been greatly altered by human activities in recent decades. An important problem regarding groundwater vulnerability assessments is the problem of data availability and quality. This is due to "lack of regionally sufficient monitoring networks, itself a function of monitoring cost; lack of consistent collection standards across and even within countries; insufficient or nonexistent data archiving standards; and the fact that well design must be planned for both extraction and monitoring—a fact often not considered in construction decisions".(Giordano 2009)

On the other hand, the process of salt water intrusion to coastal aquifers is a complex subject which has not been thoroughly understood. "Early attempts to evaluate the behavior of freshwater encountering sea water in coastal aquifers relied on the classic Ghyben–Herzberg relationship (Badon-Ghyben 1888, Herzberg 1901). This relationship was based on the elevation of the water table and the density difference of fresh and sea water. It predicted the position of the interface between freshwater and sea water in coastal aquifers; mixing of fresh and salt water was not allowed. Later workers recognized that this relationship represented an unrealistic hydrostatic situation, because a truly stable hydrostatic distribution would lead to saline groundwater everywhere below sea level (Burnett et al. 2003). Dupuit (1863) recognized that there must be a dynamic equilibrium supported by freshwater recharge. He approximated the hydrostatic distribution of fresh and salt water by assuming the flow of groundwater was entirely horizontal and the saltwater/freshwater interface was a no-flow boundary, which intersected the shoreline, and the salty groundwater was stationary. The Dupuit– Ghyben–Herzberg relationship led to the awkward conclusion that all the freshwater recharge had to escape exactly at the shoreline (Burnett et al. 2003). Hubbert (1940) introduced the concept of an outflow gap that allowed the interface to intersect the sea floor at some distance from shore, producing a discharge zone of intermediate salinity. Refinements of this concept by Glover (1959) and Henry (1964) led to techniques to calculate the size of this gap and the position of the saltwater/freshwater interface; however, they led to the mistaken impression that SGD is entirely freshwater derived from land (Burnett et al. 2003)."(Moore 2010)

As can be seen from the review by Moore 2010, "the quantification of freshwater/saltwater interface of coastal aquifers made many assumptions that simplified the computations but led to unrealistic situations. There are many areas that more research on this process as well as more detailed data on both the groundwater properties including ocean derived parameters is needed. Aquifer permeability is assumed constant where in reality aquifers consist of various mixtures of layers; freshwater recharge is rarely stable and may lead to considerable lags between recharge and discharge (Michael et al. 2005) and ocean forces were rarely considered in these early studies. Coastal aquifers are responding to sea level rise, groundwater mining, harbor dredging, and changes in coastlines due to the construction of dikes, canals, roads, and structures. The overall effect of these changes on the aquifers and on submarine groundwater discharge is unknown." (Moore 2010)

In light of these discussions, use of parameter based model instead of numerical modeling was fit to achieve the purpose of determining vulnerability of a coastal region with respect to its groundwater resources when assumptions used to simplify the situation gave unreasonable results in numerical calculations. Also parameter based modeling is simple enough to apply using the available data, yet capable of making best use of data in a technically valid and useful way which was the objective of the initial model study. Using an index to define vulnerability of a groundwater to pollution has been used to develop models such as DRASTIC, EPIK, SYNTACS, etc.(Gogu et al. 2003). As stated by Gogu and Dassargues, 2000 groundwater vulnerability predictions are made in a relative, not an absolute, sense. These kinds of methods can reduce the number of areas to be studied in detail by identifying the most vulnerable areas which was also one of the initial objectives of the coastal vulnerability assessment model. In order to determine vulnerability of groundwater to saltwater intrusion, some modifications and/or new parameter based models were presented; e.g., modified DRASTIC model which uses sea level rise parameter and GALDIT model proposed by(Chachadi and Lobo-Ferreira 2001).

The initial vulnerability assessment model used a modified version of GALDIT model. Although initial model included main driving parameters, the use of these parameters also includes many assumptions when real cases are considered as in the case of hydraulic conductivity and depth of water level above sea. Thus an in depth literature review was performed to minimize any uncertainties that may arise when interpreting the parameters used in the vulnerability model.

Aquifer type is the major parameter that defines the vulnerability of coastal groundwater to salt water intrusion. The extent of seawater intrusion is dependent on basic nature of groundwater occurrence. Unconfined aquifer under natural conditions would be more affected since confined aquifer exists under more pressure. Confined aquifers need very long time periods to reestablish the equilibrium needed due to any rise of sea level.(Kana et al. 1984) Thus, human activities related to groundwater use will be more profound during the time scale that this assessment model is concerned. If multiple aquifer system exists, it is advisable to use the highest rating of vulnerability associated with existing aquifer types.

Hydraulic conductivity has dimensions of [$L\ T^{-1}$] and is a measure of the ease of movement of water through a porous material. Values of hydraulic conductivity display a wide range in nature, spanning 13 orders of magnitude. In general, coarse-grained and fractured materials have high values of hydraulic conductivity, while fine-grained silts and clays have low values. (Hiscock 2005) The hydraulic conductivity of geological materials is not only a function of the physical properties of the porous material, but also the properties of the migrating fluid, including specific weight, γ (= ρ*g*, where ρ is the density of the fluid and *g* is the gravitational acceleration), and viscosity, μ such that:

$$K = k_i \frac{\gamma}{\mu} \qquad \text{Eq. 3.1}$$

where the constant of proportionality, k_i, is termed the intrinsic permeability because it is a physical property intrinsic to the porous material alone. The intrinsic permeability is representative of the properties of the porous material alone and is related to the size of the openings through which the fluid moves:

$$k_i = Cd^2 \qquad \text{Eq.3.2}$$

where *d* is equal to the mean pore diameter and *C* represents a dimensionless 'shape factor' assessing the contribution made by the shape of the pore openings, as influenced by the relationship between the pore and grain sizes and their effect on the tortuosity of fluid flow. Intrinsic permeability has the dimensions of $[L^2]$. (Hiscock 2005) This discussion shows that although it is a rough assumption when parameter based modeling is considered using the direct relation between grain size (which in turn signifies geologic material) and hydraulic conductivity can be used interchangeably (Table 3.2) if data on K does not exist.

Table 3.2 Range of values of hydraulic conductivity and porosity for different geological materials (Hiscock 2005)

Geological material	Hydraulic conductivity, K (m s^{-1})	Porosity, n
Fluvial deposits (alluvium)	10^{-5}–10^{-2}	0.05–0.35
Glacial deposits		
Basal till	10^{-11}–10^{-6}	0.30–0.35
Lacustrine silt and clay	10^{-13}–10^{-9}	0.35–0.70
Outwash sand and gravel	10^{-7}–10^{-3}	0.25–0.50
Loess	10^{-11}–10^{-5}	0.35–0.50
Sandstone	10^{-10}–10^{-5}	0.05–0.35
Shales		
Unfractured	10^{-13}–10^{-9}	0–0.10
Fractured	10^{-9}–10^{-5}	0.05–0.50
Mudstone	10^{-12}–10^{-10}	0.35–0.45
Dolomite	10^{-9}–10^{-5}	0.001–0.20
Oolitic limestone	10^{-7}–10^{-6}	0.01–0.25
Chalk		
Primary	10^{-8}–10^{-5}	0.15–0.45
Secondary	10^{-5}–10^{-3}	0.005–0.02
Coral limestones	10^{-3}–10^{-1}	0.30–0.50
Karstified limestones	10^{-6}–10^{0}	0.05–0.50
Marble, fractured	10^{-8}–10^{-5}	0.001–0.02
Volcanic tuff	10^{-7}–10^{-5}	0.15–0.40
Basaltic lava	10^{-13}–10^{-2}	0–0.25
Igneous and metamorphic rocks: unfractured and fractured	10^{-13}–10^{-5}	0–0.10

Proximity to coast determines the magnitude of impact of seawater intrusion which generally decreases as one move inland. If the parameter based model is spatially applied, an assessment of individual groundwater resource could be performed exclusively pointing out the most vulnerable parts of the groundwater resource assessed which is the case in GALDIT model(Chachadi 2005). However, the upgraded coastal vulnerability assessment model aims to assess the vulnerability of a body of groundwater as a whole. Thus the distance from shore parameter acts as the size of groundwater resource available and how far the body extends inland. As the distance increases, the width of groundwater body increases, meaning vulnerability of the groundwater decreases since there exists a large portion of fresh water resource available for future use which will be lowly vulnerable to salt water intrusion. The proximity to coast parameter is calculated as the perpendicular distance between shoreline and midpoint of the groundwater body when the groundwater vulnerability is applied for coastal vulnerability assessment model.

Depth to groundwater level above sea defines the level of groundwater with respect to sea level. This is an important driving parameter which determines the hydraulic pressure availability of groundwater to push the seawater front back (Chachadi and Lobo-Ferreira 2001; Sherif and Singh 1999). In assigning values for this parameter, it is important to consider the long term spatial variations of groundwater levels that show minimum groundwater levels above sea, since this would provide the highest possible vulnerability risk. Although especially in unconfined aquifers, the ocean driven parameters are found to be effective in short time scales, the time scale of sea level rise which is in terms of decades make it possible to eliminate these periodic short term influences as parameters of vulnerability assessment model.

The above discussion holds true when existence of groundwater extraction is profound on the coastal area. In most areas, especially for shallow coastal aquifers, the impact of groundwater extraction and contamination by human activities strongly influences the vulnerability of groundwater resources in higher rates than the impact of sea level rise (Chachadi 2005; Kana et al. 1984). To include the vulnerability exerted by human activities along coastal areas, two human influence parameters were included in the initial vulnerability. However in the upgraded vulnerability assessment model groundwater consumption parameter was modified as water stress index which compares the demand by human activities to recharge (availability of groundwater resource). Land use parameter is kept as it is.

One additional discussion was considered when the parameters for groundwater vulnerability assessment are revisited; the impact of changes on precipitation on the vulnerability of coastal groundwater resources. Recharge of groundwater is strongly dependent on precipitation, surface runoff, or infiltration of water stored in surface bodies to an aquifer; thus changes in these parameters will affect the amount of groundwater which can be measured by water table levels. Since the primary objective is to determine the present vulnerability of the coastal areas to sea level rise, changes in precipitation is not included in the model. However if future vulnerability assessment would be performed by using the upgraded model, the depth to water table above sea parameter could be assessed considering the changes in precipitation and then the vulnerability assessment model could be run to analyze the coastal area. It is important to underline the fact that it is beyond the scope of this study to quantify the changes of freshwater saltwater interface changes due to sea level rise which needs numerical modelling as well as detailed data on hydrogeology properties as well as recharge mechanisms.

2.5 Salt Water Intrusion to Rivers

Salinity intrusion to estuaries/rivers is a key issue for surface water quality when ecosystem modeling and human activities along the river and coastal areas are considered. The initial vulnerability assessment model analyzed two empirical formulas representing fully-stratified and well-mixed estuaries. The analysis led to the conclusion that rate of sea level rise, tidal range, river depth and discharge were the driving physical parameters (Ozyurt 2007). "The prevailing view has been one in which estuarine length adjusts to river flow, whereas the stratification and exchange flow adjust to tidal mixing. The resolution to this contradiction lies in the adjustment time of salt water intrusion length, L. Typically, L adjusts too slowly to change much over the spring-neap cycle (tidal effects), and so the stratification and exchange flow will behave as if L is relatively constant. In contrast, major variation of the river flow is often seasonal, a timescale over which L can fully adjust for many estuaries" (MacCready and Geyer 2010). Although density differences between sea and river is a driving element, when gross features (total discharge through a cross section, range, tidal phase) of estuarine dynamics are of interest, variations of density can be safely neglected (Blumberg 1978).

Recent research on impacts on river basins underlined the fact that many of the changes related to surface runoff, discharge, sediment transport are derived anthropogenic impacts as well as changes in climate. Although it is hard, it is very important to discern the changes induced by climate change from those induced by human activities. Although the impacts of climate change will have a significant influence on the processes, it is the anthropogenic changes that dominate the changes in the physical parameters of salt water intrusion process such as discharge and water depth (Jiongxin 2004; Kundzewicz et al. 2009; Liu et al. 2004; Nilsson et al. 2005). River regulation structures are one of the main parameters that affect the flow regime significantly by decreasing and increasing the amount of flow at the downstream during wet/dry seasons. If the regulation structures are also used as reservoirs for irrigation purposes, then most of the time the river flow is decreased substantially and without proper management of the river flow, salt water intrusion can move to upstream causing negative consequences to adjacent land. On the other hand, proper management of river flow can decrease the vulnerability of coastal area in terms of salinity intrusion by maintaining a stable flow that controls the salinity intrusion length (Hanasaki et al. 2006; Jiongxin 2004; Kundzewicz et al. 2009; Liu et al. 2008).

When changes in discharge is considered, another climate factor should be considered as a driving force; precipitation. Although changes in precipitation regime due to climate change is a secondary driving force when salt water intrusion is considered, a literature review was performed to finalize the discussion of including this parameter to the upgraded vulnerability model. It is a well stated fact that runoff and precipitation are directly related to each other and any change (intense and higher precipitation rates or droughts) in the precipitation regime of a region will affect the discharge significantly which in turn will move the salt water intrusion to upstream or downstream (Arora and Boer 2001; Yaning 2009). Many projections predict different precipitation regimes around the world. One such analysis is performed by (Nohara et al. 2006) including 24 major river basins around the world which states that "Although the spatial distribution of the changes in the precipitation and runoff tends to coincide with that in the river discharge, it should be emphasized that the change of runoff in the upstream region affects the river flow in the downstream region." However the results are best when the rivers are unregulated and the impact of changes at the upstream could affect the downstream river flow. In light of this discussion, it is concluded that in the cases of unregulated rivers, inclusion of precipitation parameter and corresponding changes would be necessary however since most of the rivers around the world have become regulated within the last 50 years, it is more appropriate to use discharge at the downstream after major regulative structures and/or management practices such as abstraction of river water for irrigation purposes (the reason for the land use parameter in the assessment of salt water intrusion to river) as the only parameter. If an unregulated river is assessed then, the user should keep in mind the impact of any changes in precipitation at the upstream and reflect it on the discharge parameter when future vulnerability is considered.

River depth at the downstream is another important factor that was used in the initial model (Ozyurt 2007). Many models and empirical studies concluded that wider and deeper entrances increase the length of salinity intrusion (Bashar and Hossain 2006; Cat and Duong 2006; Pinho and Viera). Although river channel geometry (cross sectional area) as a whole can be considered as a parameter, it is hard to gather data thus, considering the main objectives of the vulnerability assessment model, it was concluded that water depth at downstream will be kept as the only parameter to define channel geometry since most of the time the width is kept constant due to human activities (such as settlements). Thus anthropogenic effects such as coastal works at the river mouth can influence the depth parameter significantly such as jetties or dredging of river bed (increasing the depth) or changing the river bed morphology. In order to consider the human impact on this physical process, engineered frontage parameter was used in the initial model as well as the upgraded model.

In light of in-depth literature review and discussions presented in this section, the input parameters of the upgraded fuzzy vulnerability assessment model is finalized as shown in Table 3.3 below:

Table 3.3 Parameters used to calculate the sub-indices of each impact of sea level rise

Impacts of Sea Level Rise	Physical Parameters	Human Influence Parameters
Coastal Erosion	1. **Rate of Sea Level Rise** 2. Geomorphology 3. Coastal Slope 4. Significant Wave Height 5. Sediment Budget 6. Tidal Range	1. Reduction of Sediment Supply 2. River Flow Regulation 3. Engineered Frontage 4. Natural Protection Degradation 5. Coastal Protection Structures
Flooding due to Storm Surges	1. **Rate of Sea Level Rise** 2. Coastal Slope 3. Storm Surge Height (100years) 4. Tidal Range	1. Engineered Frontage 2. Natural Protection Degradation 3. Coastal Protection Structures
Inundation	1. **Rate of Sea Level Rise** 2. Coastal Slope 3. Tidal Range	1. Natural Protection Degradation 2. Coastal Protection Structures
Salt Water Intrusion to Groundwater Resources	1. **Rate of Sea Level Rise** 2. Proximity to Coast 3. Type of Aquifer 4. Hydraulic Conductivity 5. Depth to Groundwater Level Above Sea	1. Groundwater consumption 2. Land Use Pattern
Salt Water Intrusion to Rivers/Estuaries	1. **Rate of Sea Level Rise** 2. Tidal Range 3. Water Depth at Downstream 4. Discharge	1. River Flow Regulation 2. Engineered Frontage 3. Land Use Pattern

CHAPTER IV

DATABASE DEVELOPMENT

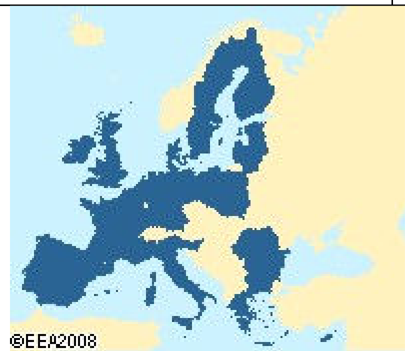
Developing a model requires data to generate, verify and calibrate the model so that the uncertainties are kept at a limiting scale. Including 18 different parameters and aiming to derive information regarding processes having natural uncertainties including sea level rise which is a process related with high uncertainty, it is important to develop a database that can reflect different coastal regions having variety of physical and social characteristics. Such a database was compiled as a component of fuzzy vulnerability assessment model where data on European coastal areas are collected from several sources. This section includes:

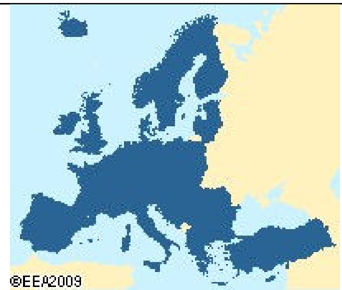
- A description of the data sources that were used to develop the research database
- A description of the data model and the process of coastline segmentation
- Analytical descriptions of the individual parameters contained in the database, including information on the data sources used and on the methodologies employed for attributing the data to the coastline segments.

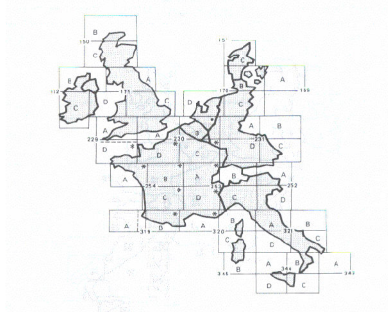
4.1 Data Sources

The database covers most of the European coastlines from Baltic Sea to Atlantic Ocean and Mediterranean Sea including information on 79 major river basins and groundwater resources of 9 EU countries. This variety of coastal properties ensured compilation of a complete dataset enabling the model to be applied to every coastal area around the world. Some of the databases used are themselves collection of other databases that are either publicly or commercially available. However, all the data collected from the databases presented below are available for free for research. It is worth mentioning that although several databases were covered to compile the data for all the parameters of fuzzy vulnerability assessment model, in the end, every parameter was covered to a satisfactory spatial extent (data for areas of different coastal characteristics and different human activities were covered for each parameter although not for every km of EU coastline).

Table 4.1 List of databases used to compile vulnerability model database

Database	Developing Group/Project	Spatial Coverage	Parameters	Properties
DIVA (Dynamic Interactive Vulnerability Assessment)	DINAS-COAST (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea Level Rise) www.dinas-coast.net/	Global	Area Geomorphology Bruun factor(possibility of erosion) River Storm surge height Coastal slope Tidal range Wave climate Uplift/ subsidence River depth River discharge	Attributes of each parameter is integrated to coastal segments of shoreline divided due to morphological and social characteristics. Given in digital format in GIS environment.
EUROSION database	EUROSION project: www.eurosion.org/project/ The main objective of this project is to provide a comprehensive description of the calculation of the EUROSION Indicators (technical and conceptual) which will support the rating of European regions in terms of exposure to coastal erosion.	 %20 of coastal areas of Romania, Bulgaria and Cyprus are included	Geomorphology Wave Climate Tide Climate Rate of sea level rise Present status of coastline (erosion, etc) Coastal structures CORINE land cover	Coastal areas are defined as the land between shoreline and 10 km distance from shore. Data is given in digital format in GIS environment.

WISE database	WISE (Water Information System for EU) http://water.europa.eu/	 Scale: 1:1 000 000	Rivers and lakes	Rivers having basins larger than 50000km2 are given in digital format in GIS environment
Waterbase database	EUROWATERNET http://water.europa.eu/		Surface and groundwater quality parameters, stations, land use, water demand	Given as digital table.
WWDII database	World Water Development Assessment http://www.unesco.org/water/wwap/wwdr/	Global	River discharge, dams and reservoirs water use for irrigation, river flow regulation and fragmentation, sediment trapping efficiency of dams	Given as table, printed map and some layer are digitized in GIS environment

Digital Dataset of European Groundwater Resources	Groundwater resources of the European Community: Synthetical Report. – (1982)		Aquifer locations, types, hydrologic properties, water table, water demand and sectoral demand	Digitized in GIS environment for 9 countries of EU.
Whymap database	WHYMAP project www.whymap.org	Global and country specific	Global groundwater information sheets, hydro-geologic maps of countries	Printed data digitized
GEMS/GLORI database		Global	River discharge, sediment load, water quality	Printed data digitized
RivDIS database	River Discharge Database, Version 1.1 (RivDIS v1.0 supplement) 1998	Europe	River discharge (monthly and annually)	Printed data digitized for rivers of Europe
GISCO administrative boundaries (NUTS) v9	Administrative land accounting units (Land analytical and reporting units, LARU, used in LEAC), zipped shape file format, raster http://www.eea.europa.eu/	Europe	NUTS 3 (province level) to NUTS 0 (country level)	Digitized in GIS environment

In Table 4.2, properties related to data of each parameter are summarized.

Table 4.2 Model Parameter Data Properties

Parameters	Database	Properties
PHYSICAL PARAMETERS		
Rate of sea level rise	EUROSION database PSMSL observations	Predicted sea level rise at the location centers mm/year Rate of relative sea level data from PSMSL stations worldwide
Geomorphology	EUROSION database DIVA database	Morphological coding related to coastal erosion McGill(1958)
Coastal Slope	DIVA database	Degrees
Wave climate	EUROSION database DIVA database	17 year data (m) According to LOICZ classification
Sediment budget	EUROSION database DIVA database	Evolution trend of shoreline Bruun rule factor (possibility of coastal erosion)
Tide range	EUROSION database DIVA database	17 year data (m) According to LOICZ classification
Proximity to coast (groundwater)	Digital Dataset of European Groundwater Resources	Calculated using GIS
Type of aquifer		Unconfined, confined, mixed and karstic
Hydraulic Conductivity		Using the layer type given in the database correlation will be performed
Depth to water table above sea		Piezometric head, water table (long term)
River depth at downstream	DIVA database WWDII database Waterbase database	Water depth (m)
Discharge	DIVA database WWDII database Gems-GLORI database RivDIS database	Annual or mean (m3/s)
Storm surge height	DIVA database	Return periods of 1,10,100 ve 1000 years Calculated storm surge height above Mean Sea Level
HUMAN INFLUENCE PARAMETERS		
Reduction of sediment supply	WWDII database EUROSION database GLORI database	Sediment yield (before and after dams)
River flow regulation	WWDII database EUROSION database GLORI database Rivers of Europe (**Klement Tockner** et al., 2009)	Discharge, river fragmentation and regulation index

Table 4.2 Continued Model Parameter Data Properties		
Engineered frontage	EUROSION database	Harbors, marinas, other coastal structures in terms of coastal segment length
Natural Protection Degradation	EUROSION database	CORINE land cover 1990, 2000 and 2006 comparison of dunes, wetlands and land use changes
Coastal protection structures	EUROSION database	Parallel and perpendicular to shoreline
Land use	CORINE land cover database DIVA database Whymap database	Land use in raster format
Groundwater Resource Abstraction	Whymap database Digital Dataset of European Groundwater Resources	Location of wells, amount of water demand and country specific sectoral use of water

Any study on coastal areas deals with two main limitations; space and time. Duration is important since different coastal processes occur on different time scales driven by different forces of nature (sea level rise in decades, storm surges in hours). It is also important to define the spatial extent of the coastal area to be analyzed since processes along coastal areas are not only driven by near shore dynamics but might include more land area than water area (river basins) or activities on adjacent shorelines might have more impact than the properties of the exact location. Although with the advances in GIS, it is possible to present coastal space as a single entity with varying internal processes, for practicality and accessibility, it is necessary to work with simple schematic representation of the coast on which vulnerability analysis can be conducted(McFadden et al. 2007). Thus it is mandatory to use proper coastal segmentation to define the study area when assessing vulnerability with respect to different impacts such as the fuzzy vulnerability assessment model developed by this study. Although there is no an explicit literature on coastal segmentation, topography, geomorphology, administrative boundaries and socioeconomic properties are used together or individually for coastal segmentation (McFadden et al. 2007). Since coasts are dynamic environments with the nature of coastal change having both spatial and temporal dimension, the complexity increases at large spatial and temporal scales, and it is important that coastal segmentation captures and reflects the behavior of the system both physically and socially.

For fuzzy vulnerability assessment model, coastline layer provided by EUROSION study was used as the base layer that all the attributes were assigned for each coastal segment. The segmentation of EUROSION layer is follows(Lenôtre and Thierry 2002):

A segment should be at least 200 m long, but has no maximum defined length. If a segment has a different value for one of its attributes, then it should be split into 2 different segments, provided that each respects the minimum length of 200 m.

In case segments needed to be generalised to fit to the minimum length requirement, the following rules was followed:

1. The morpho-sedimentology criterion has first priority,

2. Evolutionary trend (erosion/accretion) criterion has second priority,

3. Different geology criterion has third priority,

4. The presence of coastal defence works has last priority.

In the event that there are two different features for an attribute within a 200-m-long segment, the choice will be for the attribute showing the greatest segment length.

Figure 4.1 gives an example of segmentation of coastline. Here, within a single initial segment, characteristics of the 3 attributes change at different places. Thus, the first split is determined by the Morpho-sedimentology change (result A) attribute, and the second split will be at the Evolutionary trend change (result B). Since the new median segment has already reached its minimum 200 m length and it is not further divided on the basis of the Coastline geology change.

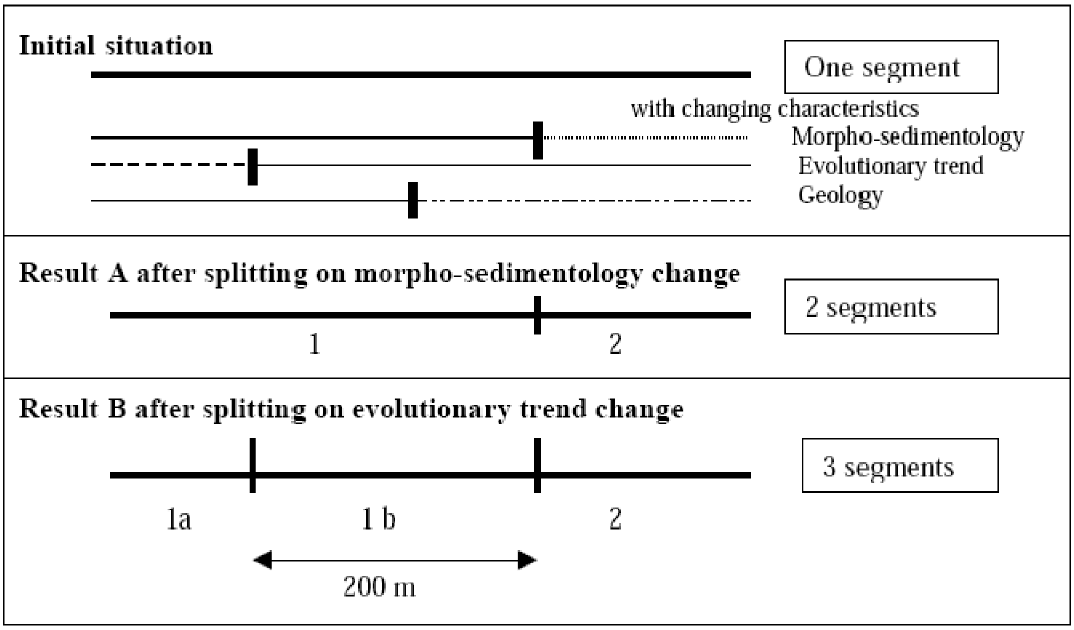


Figure 4.1 Rules to follow for splitting segments

In this case, there are two different features for Geology layer within a segment of 200 m length, the attribute is assigned as the longest represented characteristic.

There are other data sources that could be used as the base layer for the study such as DIVA database however EUROSION database has the highest resolution with the limitation of coastal segmentation as 200m in length. DIVA on the other hand used a different coastal segmentation methodology and being a global database, the resolution is much coarser. Since EUROSION shoreline layer was used as the base layer for this study having geographic coordinate system as WGS 1984, most of the attributes were also used from the same database. Comparisons with other sources of data were performed for verification of the data that was to be used for developing the methodology of this study.

4.2 Descriptions of Parameters

It is important to describe effective metadata information of a database since detailed information about the source of data, such as the content, quality, condition, origin, and other characteristics of data or other pieces of information is essential when the same database is used by other user groups from different disciplines. Metadata for spatial data may describe and document its subject matter; how, when, where, and by whom the data was collected; availability and distribution information; its projection, scale, resolution, and accuracy; and its reliability with regard to some standard. Since most of the analysis of fuzzy vulnerability assessment methodology is structured on the basis of the compiled database, information on each parameter is listed including methodologies employed for generating datasets and methods and techniques used for attributing the data to the coastline segments.

4.2.1 Coastline Segment

a) Rate of sea level rise:

Sources

Relative Sea level rise dataset from EUROSION database (Layer HDEURK100KV1). 237 points of interest located between 30 to 100 km from the coastline and giving an average value of the sea level evolution in a 200 x 200 km square around each point.

Additionally, PSMSL station data is used to increase point data of relative sea level change around the world.

Methodology

Since sea level rise values are given as point layer not attributed to coastal segments, the GIS tool *spatial join* is used to connect the sea level rise value to the nearest segments of the shoreline.

Limitations and recommendations

Main limitations are related to the data calculations themselves, especially considering the Mediterranean sea where "Sea level change in the Mediterranean was limited to 1 mm/year", those values are not really significant since they are mapped on the mean of global accelerated sea level rise value.

Map

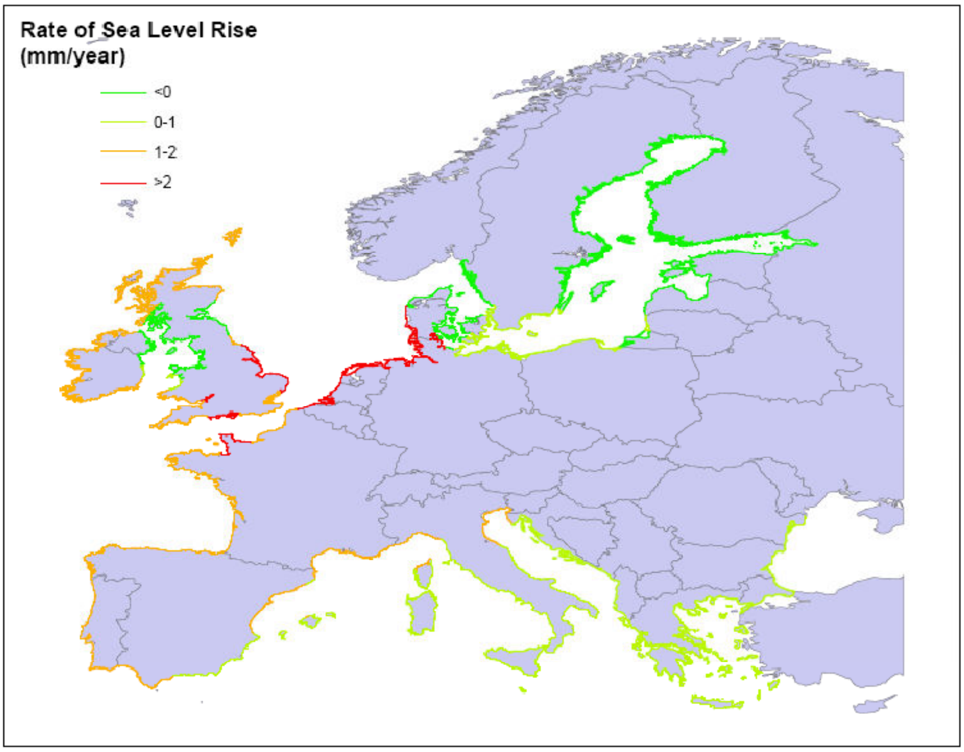


Figure 4.2 Rate of sea level rise map

b) Geomorphology:

Sources

EUROSION Layer: Geomorphologic attribute (CEMOV2) 1 / 100 000 scale

Morpho-sedimentology codes

Rocky coasts

A Rocks and/or cliffs made of hard rocks (little subject to erosion) with eventual presence of a rock platform

B Conglomerates and/or soft-rock cliffs (example : chalk) i.e. subject to erosion: presence of rock waste and sediments (sand or pebbles) on the strand

AC Mainly rocky, little erodible, with pocket beaches (< 200 m long) not localized

Beaches

C Small beaches (200 to 1000 m long) separated by rocky capes (<200m long)

D Developed beaches (> 1 km long) with strands made of coarse sediment: gravel or pebbles

E Developed beaches (<1 km long) with strands fine to coarse sand

F Coastlines made of soft non-cohesive sediments (barriers, spits, tombolos)

P Soft strands with rocky "platforms" (rocky flat) on intertidal strands

R Soft strands with "beach rock" on intertidal strands

N Very narrow and vegetated strands (pond or lake shore type)

S Soft strands made of mine-waste sediments

K Artificial beaches

This code concerns :

- beaches entirely man-made such as found in the Canary Islands

- beaches where the granulometric nature of the sediments changes after installing defense work –e.g. the formation of a sand beach in front of a gravel beach after the defense work has been completed.

- nourished beaches

X Soft strands of heterogeneous grain-size category

Z Soft strands of unknown grain-size category

Muddy coasts

G Strands of muddy sediments : "wadden" and intertidal marshes with "slikkes and shorres"

Artificial coasts

Y Artificial shoreline or shoreline with longitudinal protection works (walls, dikes, quays, rocky strands) without sandy strands

L Coastal embankments for construction purposes (e.g. by emplacement of rocks earth, etc.)

J Harbour areas

Mouth (virtual coastal segment)

H Estuary (virtual line)

Internal coasts of estuaries, rias, fjords, bays and coastal lagoons are excluded from the inventory when the mouth is less than an arbitrary width of 1 km. In these cases and in order to have a continuous coastline, the two sides of the estuary, ria and bay or coastal lagoon are joined by a virtual line.

Methodology

Since these values are direct attributes of each coastal segment of shoreline they are kept as same. However comparison with DIVA database (A. T. Vafeidis et al., 2005) through *Join* tool was performed using cpc (coastal plain characteristics) attribute of DIVA which classifies coastal landforms based on large-scale geomorphology.

Map

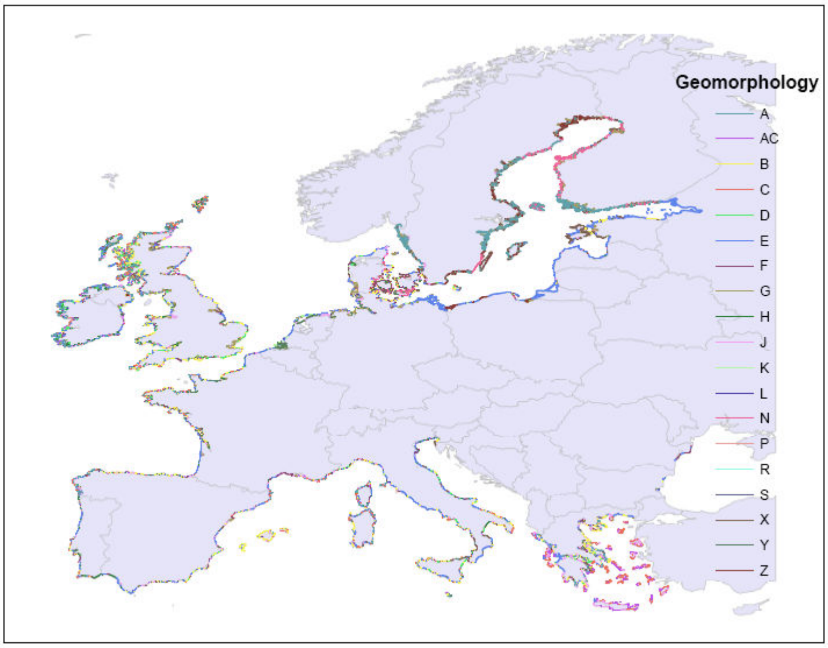


Figure 4.3 Geomorphology map (for explanation of the codes, see methodology section

c) Beach slope

Sources

DIVA database: slopecst attribute; Average topographic slope (in degrees) along the coastal segments of DIVA database (A. T. Vafeidis et al., 2005).

Methodology

Attribute of DIVA database was spatially joined with the base coastline layer of the study.

Limitations and Recommendations

Due to coarser resolution of DIVA database, the values of this attribute in the study database are not unique for each coastal segment.

Map

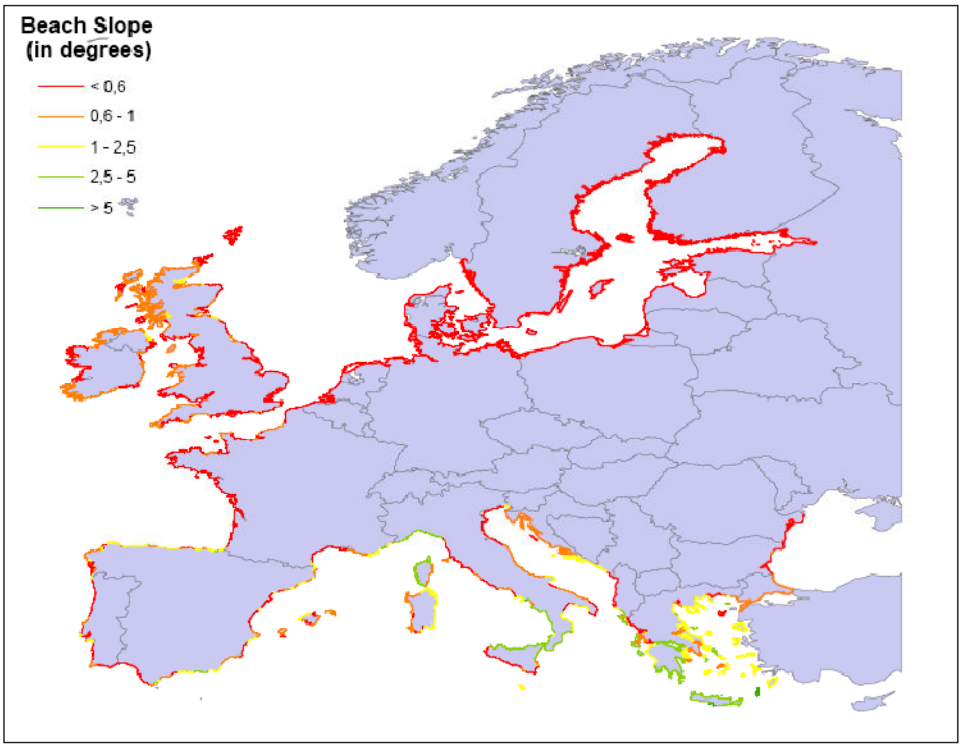


Figure 4.4 Beach slope map

d) Significant Wave Height

Sources

EUROSION Layer: Hydrodynamics layer (HDWAHSAV) 1 / 100 000 scale Mean significant wave height in meters.

Methodology

Since these values are direct attributes of each coastal segment of shoreline they are kept as same. However comparison with DIVA database (A. T. Vafeidis et al., 2005) through *Join* tool was performed using waveclim (wave climate) attribute of DIVA which gives LOICZ wave data in terms of LOICZ classification.

Limitations and Recommendations

Since DIVA data was given in classification form, EUROSION data was also classified according to LOICZ and then comparison was performed. There are some discrepancies along the Atlantic Ocean coastlines. The reason is believed to be due to differences in the definition of significant wave heights and the durations of data.

Map

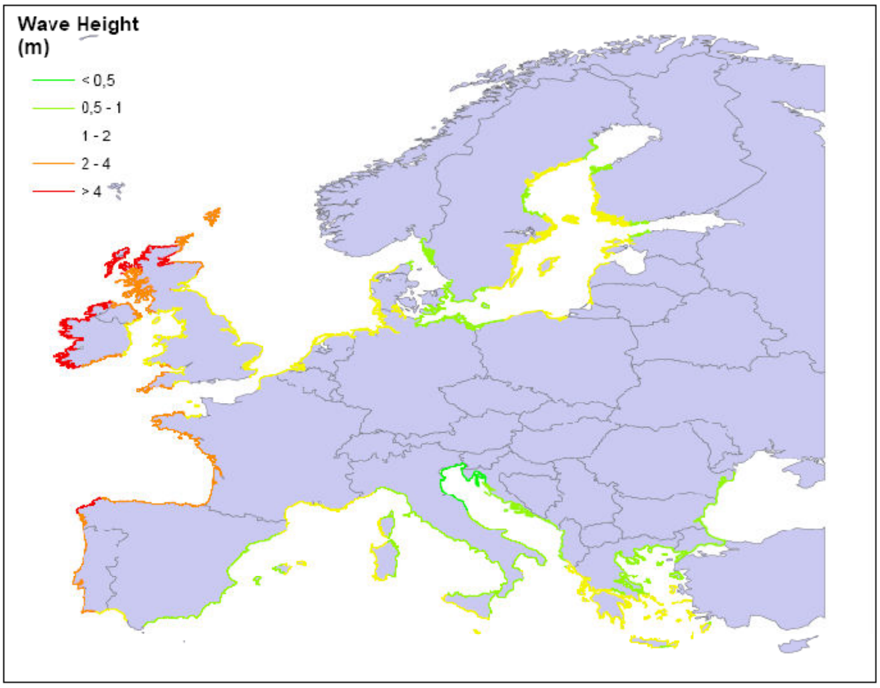


Figure 4.5 Significant wave height map

e) Surge Height

Sources

DIVA database: s1, s10, s100, s1000, smax attributes; 1 in 1, 1 in 10, 1 in 100, 1 in 1000 year surge height (m), height above mean sea level (includes high water level). As input for the calculation of storm surge levels, data on tidal levels, barometric pressures, wind speeds and sea bed slopes were employed (A. T. Vafeidis et al., 2005).

Methodology

Attribute of DIVA database for surge height of 1 in 100 years was spatially joined with the base coastline layer of the study.

Limitations and Recommendations

Due to coarser resolution of DIVA database, the values of this attribute in the study database are not unique for each coastal segment.

Map

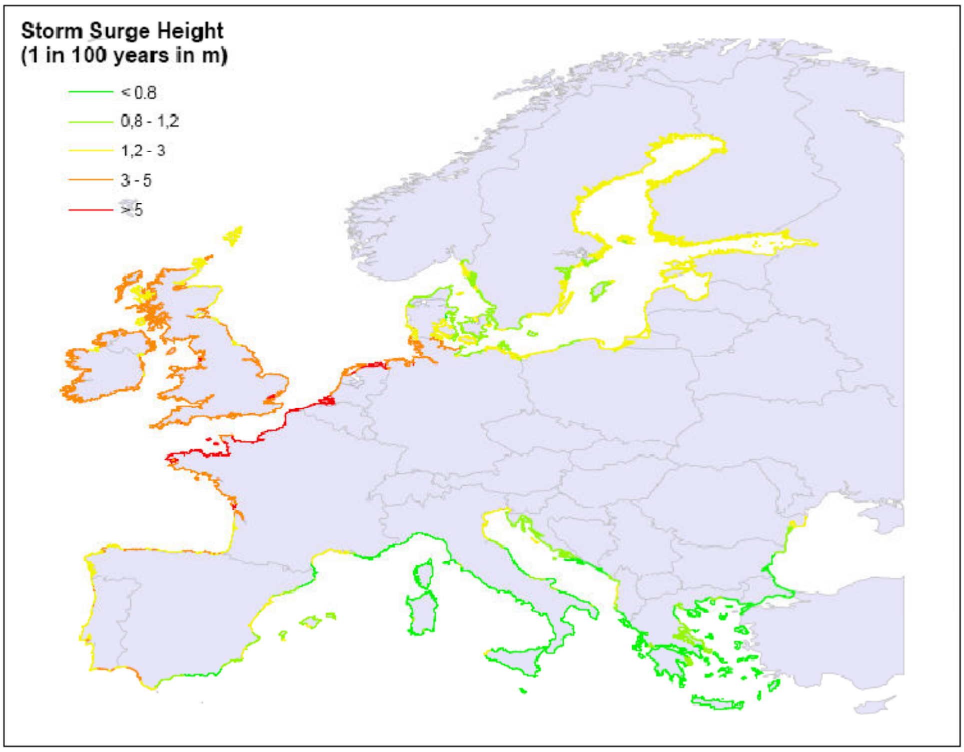


Figure 4.6 Storm surge height (1 in 100 years) map

f) Sediment Budget

Sources

EUROSION database: Geomorphology layer (CEEV) 1 / 100 000 scale Coastal erosion evolutionary trend.

Table 4.3 Geomorphology layer legend explanations (Eurosion_Consortium, 2003)

CEEV CODE	EXPLANATION
0	Out of nomenclature.
1	No information on evolution
2	Stable: Evolution almost not perceptible at human scale
3	Generally stable: small "occasional" variations around a stable position; evolutionary trend is uncertain
4	Erosion probable but not documented
6	Aggradations probable but not documented
50	Erosion confirmed (available data), localised on parts of the segment.
51	Erosion confirmed (available data), generalised to almost the whole segment.
70	Aggradations confirmed (available data), localised on parts of the segment.
71	Aggradations confirmed (available data), generalised to almost the whole segment.

Methodology

Since these values are direct attributes of each coastal segment of shoreline they are kept as same. However new classification was performed to comply with only three classes of evolutionary trend; erosion, stable, accretion. So each segment also were given a new classification code accordingly where

CEEV CODE	NEW CODE	EXPLANATION
0	**0**	Out of nomenclature.
1	**1**	No information on evolution
2	**S**	Stable: Evolution almost not perceptible at human scale
3	**S**	Generally stable: small "occasional" variations around a stable position; evolutionary trend is uncertain
4	**E**	Erosion probable but not documented
6	**A**	Aggradations probable but not documented
50	**E**	Erosion confirmed (available data), localised on parts of the segment.
51	**E**	Erosion confirmed (available data), generalised to almost the whole segment.
70	**A**	Aggradations confirmed (available data), localised on parts of the segment.
71	**A**	Aggradations confirmed (available data), generalised to almost the whole segment.

Map

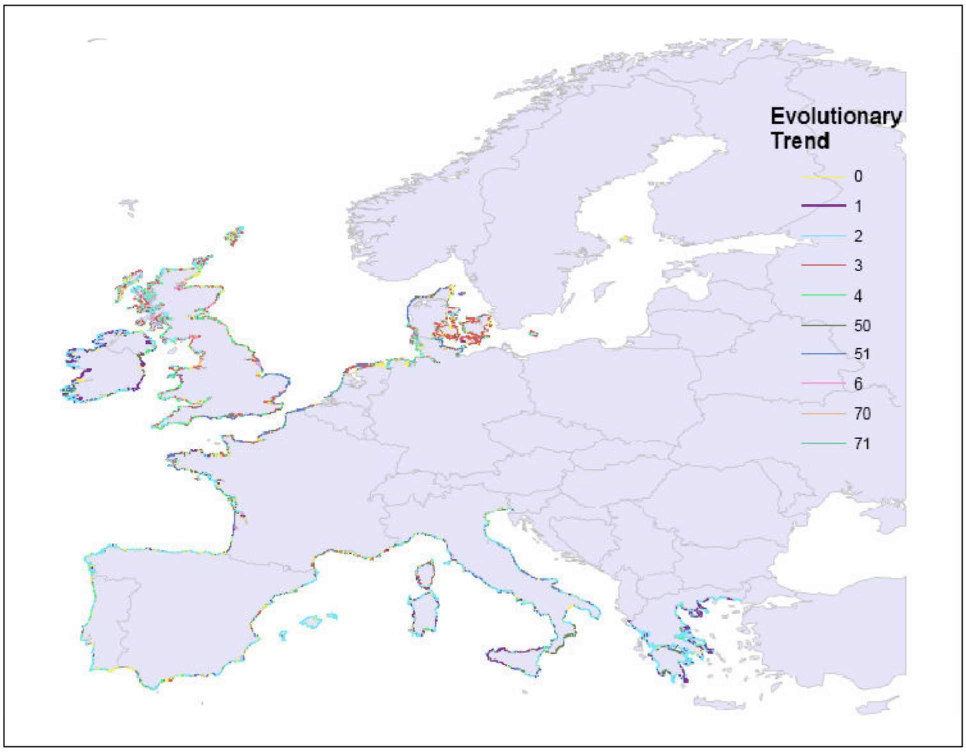


Figure 4.7 Evolutionary trend map (for explanations on codes, see Table)

To calculate changes in coastal evolution trend in percentages (which are used as actual inputs to the fuzzy vulnerability assessment model) coastal segments are grouped with respect to administrative units at NUTS3 (province level) level using GISCO administrative units dataset. Each group was analyzed according to the length of the coastal segments that shows changes in evolutionary trend. This length was then compared to the overall coastal length of the respective NUTS3 group giving changes in percentage.

Map

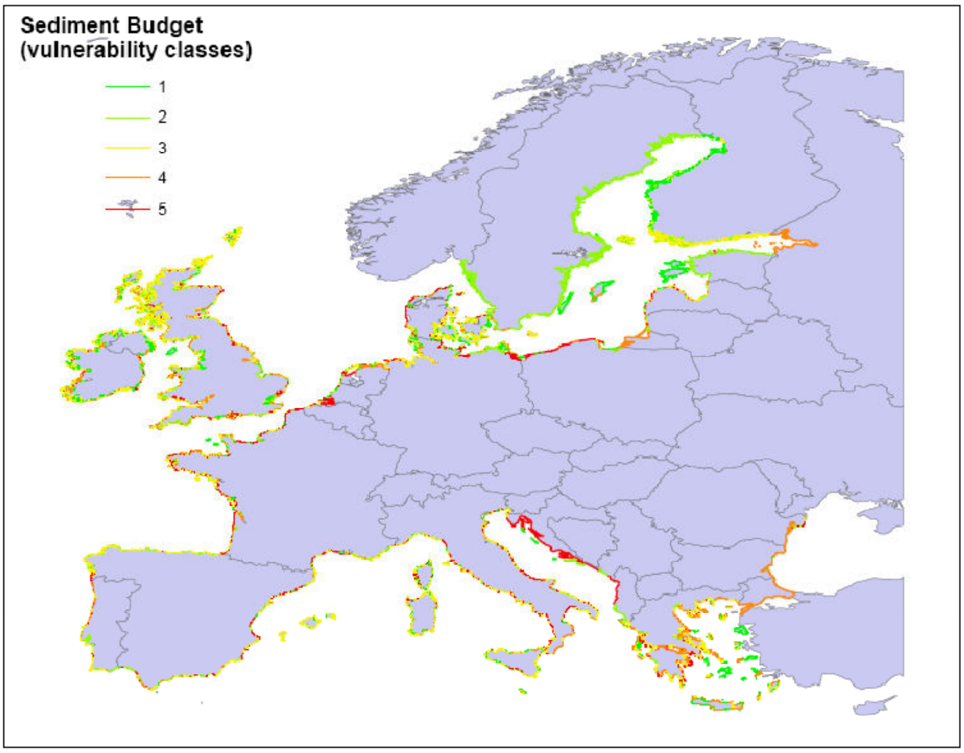


Figure 4.8 Sediment budget map

g) Tidal Range

Sources

EUROSION Layer: Hydrodynamics layer (HDTIMNAM) 1 / 100 000 scale Tidal mean amplitude at the location centers. It is defined as the square root of the sum of squared amplitudes of the harmonics (Lenôtre and Thierry, 2002).

Methodology

Since these values are direct attributes of each coastal segment of shoreline they are kept as same. However comparison with DIVA database (A. T. Vafeidis et al. 2005) through *Join* tool was performed using *tidalrng* (tidal range) attribute of DIVA which gives LOICZ wave data in terms of LOICZ classification.

Map

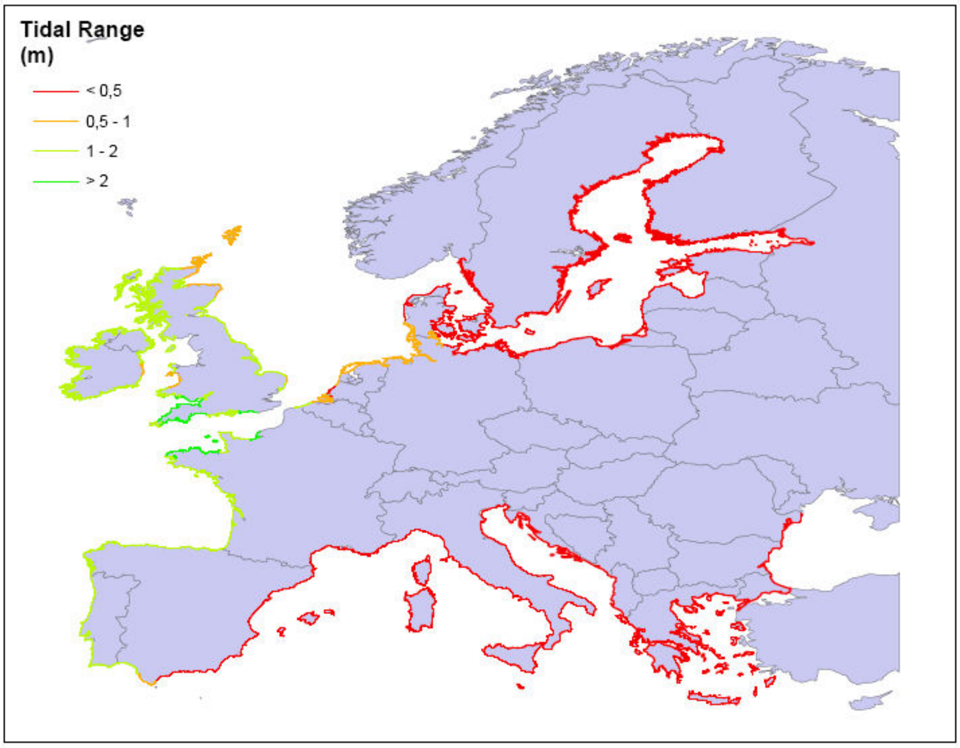


Figure 4.9 Tidal range map

Limitations and Recommendations

Since DIVA data was given in classification form, EUROSION data was also classified according to LOICZ and then comparison was performed. EUROSION data was used for development of the vulnerability assessment model.

h) Engineered Frontage

Sources

EUROSION Database: Geomorphology layer (CEMOV2 and CEDWV2) 1 / 100 000 scale Geomorphologic attribute and presence of defense works attribute

Methodology

The coastal segments with following geomorphologic attributes were selected and assigned a value of 1 (presence of engineering frontage):

K Artificial beaches

Artificial coasts

Y Artificial shoreline or shoreline with longitudinal protection works (walls, dikes, quays, rocky strands) without sandy strands

L Coastal embankments for construction purposes (e.g. by emplacement of rocks earth, etc.)

J Harbour areas

Also coastal segments having defense works are chosen by using CEDWV2 attribute (CEDWV2=Y) and assigned a value of 1.

To calculate engineered frontage in percentages (which are used as actual inputs to the fuzzy vulnerability assessment model) coastal segments are grouped with respect to administrative units at NUTS3 (province level) level using GISCO administrative units dataset. Each group was analyzed according to the length of the coastal segments that have coastal structures. This length was then compared to the overall coastal length of the respective NUTS3 group giving engineered frontage parameter in percentage.

Map

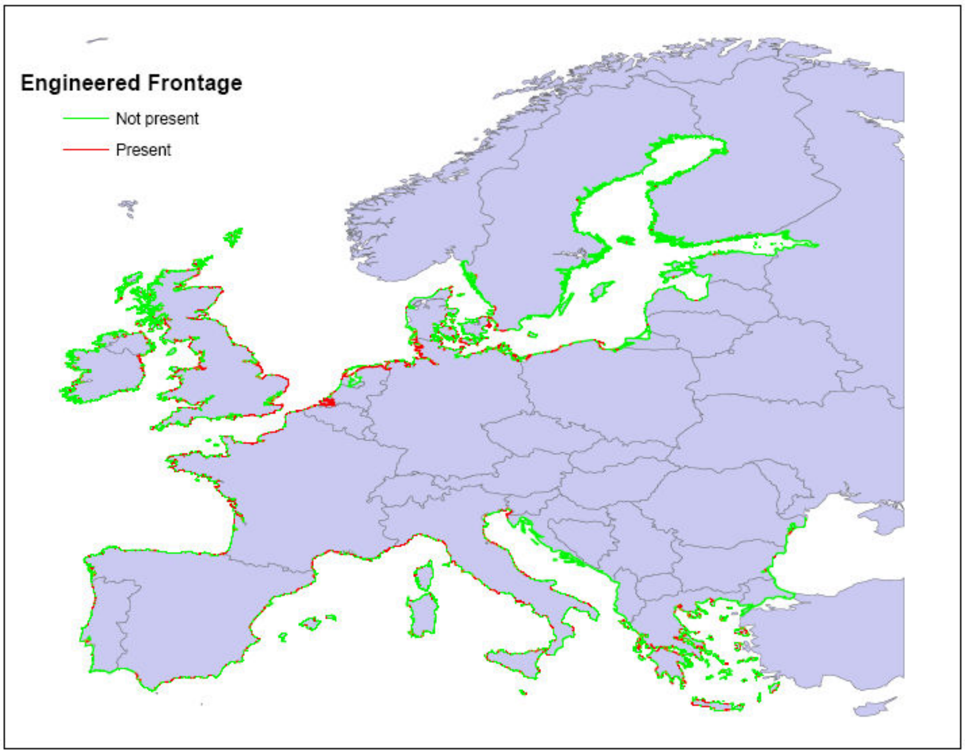


Figure 4.10 Locations of Engineered Frontage

i) Coastal Protection Structures

Sources

EUROSION Database: Geomorphology layer (CEDWV2) 1 / 100 000 scale Presence of defense works attribute

Methodology

Coastal segments having defense works are chosen by using CEDWV2 attribute (CEDWV2=Y) and assigned a value of 1 (presence of coastal protection structure).

To calculate coastal protection structures in percentages (which are used as actual inputs to the fuzzy vulnerability assessment model) coastal segments are grouped with respect to administrative units at NUTS3 (province level) level using GISCO administrative units dataset. Each group was analyzed according to the length of the coastal segments that have coastal protection structures. This length was then compared to the overall coastal length of the respective NUTS3 group giving coastal protection structures parameter in percentage.

Map

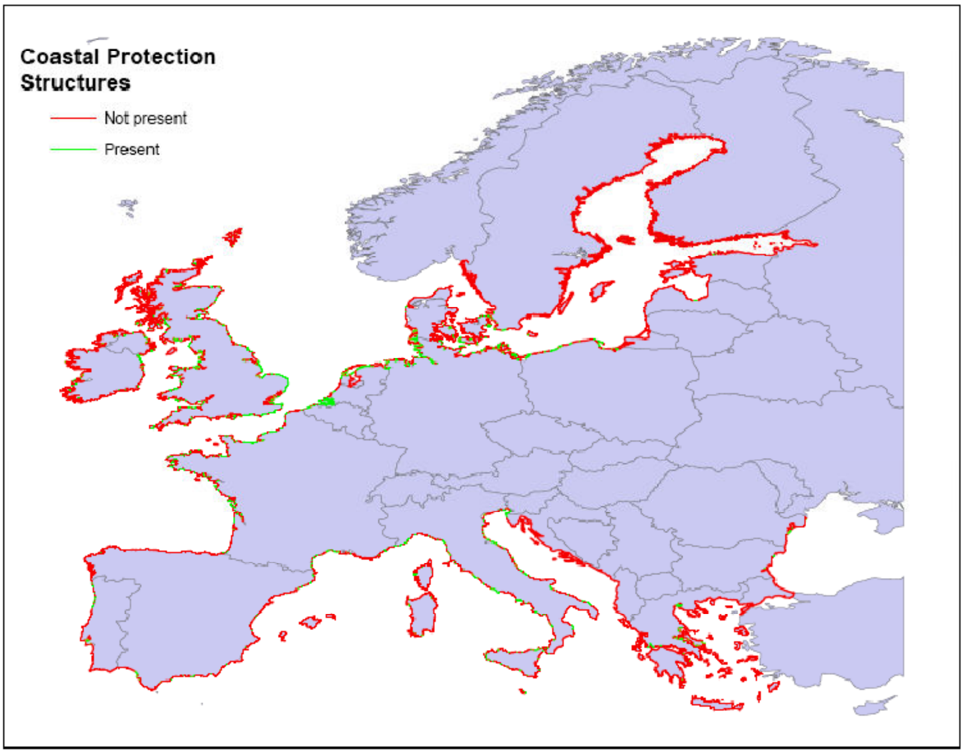


Figure 4.11 Locations of Coastal Protection Structures

j) Land Use

Sources

EUROSION Database: 2000 CORINE land cover layer 1 / 100 000 scale

Land Cover Code	Explanation
111	Continuous urban fabric
112	Discontinuous urban fabric
121	Industrial or commercial units
122	Road and rail networks and associated land
123	Port Areas
124	Airports
131	Mineral extraction sites
132	Dump sites
133	Construction sites
141	Green urban areas
142	Sport and leisure facilities
211	Non-irrigated arable land
212	Permanently irrigated land
213	Rice fields

221	Vineyards
222	Fruit trees and berry plantations
223	Olive groves
231	Pastures
241	Annual crops associated with permanent crops
242	Complex cultivation patterns
243	Land principally occupied by agriculture, with significant areas of natural vegetation
244	Agro-forestry areas
311	Broad-leaved forest
312	Coniferous forest
313	Mixed forest
321	Natural grassland
322	Moors and heathland
323	Sclerophyllous vegetation
324	Transitional woodland-scrub
331	Beaches, dunes, sands
332	Bare rocks
333	Sparsely vegetated areas
334	Burnt areas
335	Glaciers and perpetual snow
411	Inland marshes
412	Peat bogs
421	Salt marshes
422	Salines
423	Intertidal flats
511	Water courses
512	Water bodies
521	Coastal lagoons
522	Estuaries
523	Sea and ocean
950	Ocean
951	European Union
952	Non European union
999	Not Classified

Methodology

The dataset covers land area of Europe thus a 10 km buffer from shoreline was used for classification of coastal area. The land cover codes present at the buffer zone were also reclassified according to the classification of fuzzy vulnerability assessment model as follows:

Agriculture : 211 till 244

Settlement: 111-112-141-142

Industry: 121 till 124 and 131 till 133

Unclaimed: 311 till 335

Protected: Common Database on Designated Areas (CDDA) boundaries were used.

To assign land use codes for each coastal segment, the dominant land cover code within the buffer of the coastal segment is calculated by using statistical analysis tools of GIS.

Map

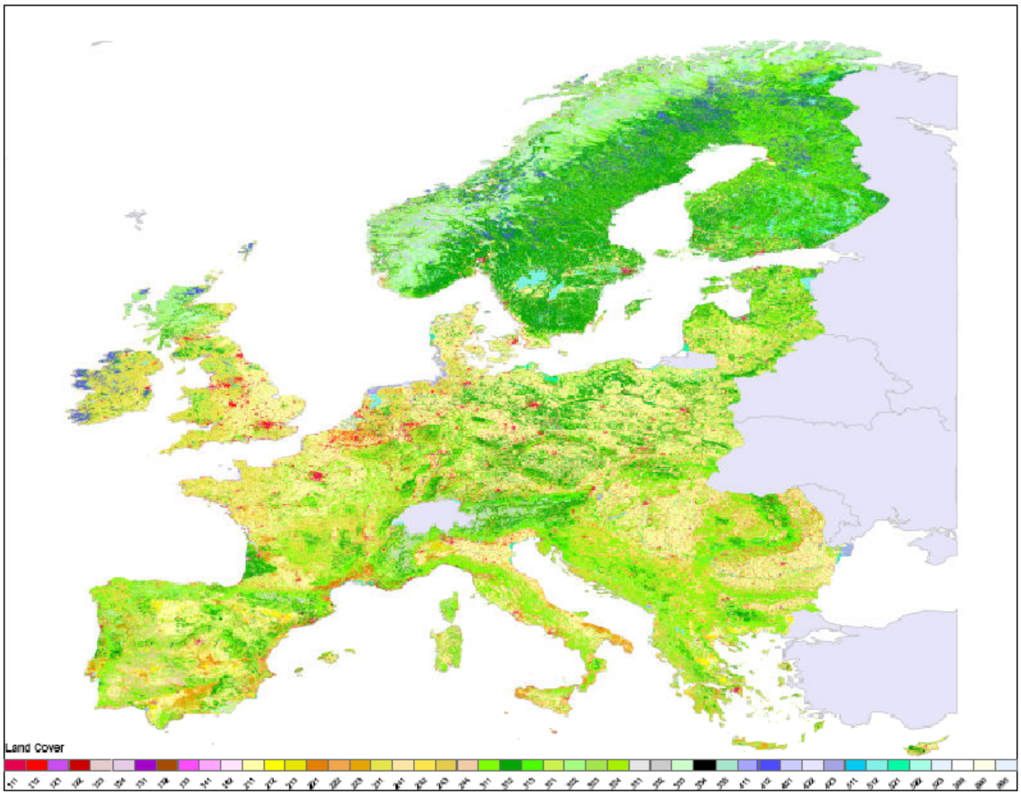


Figure 4.12 Land Cover of Europe

k) Natural Protection Degradation

Sources

CORINE land cover layer 1 / 100 000 scale 3 different datasets were used to derive changes in land cover along coastal areas: 1990, 2000, 2006(partial dataset)

Methodology

Using the following land cover codes, coastal segments with natural protection characteristics are selected and saved as layers from the land use layer that was already generated:

311	Beaches, dunes, sands
411	Inland marshes
412	Peat bogs
421	Salt marshes
422	Salines
423	Intertidal flats

To calculate natural protection degradation in percentages (which are used as actual inputs to the fuzzy vulnerability assessment model) coastal segments are grouped with respect to administrative units at NUTS3 (province level) level using GISCO administrative units dataset. Each group was analyzed according to the area of the coastal segments that contain land cover classes for natural protection for 1990, 2000 and 2006. Then the 1990 results of each segment were compared to the 2000 and 2006 results giving natural protection degradation parameter in percentage.

Limitations and Recommendations

The results of this layer consider only the changes of the given six land cover classes to other land cover classes. In some cases, it might be possible that the land cover changes into the six land cover classes, enhancing the natural protection capacity of the region. However such cases are almost always encountered in protected areas where the natural protection degradation is already minimized.

Map

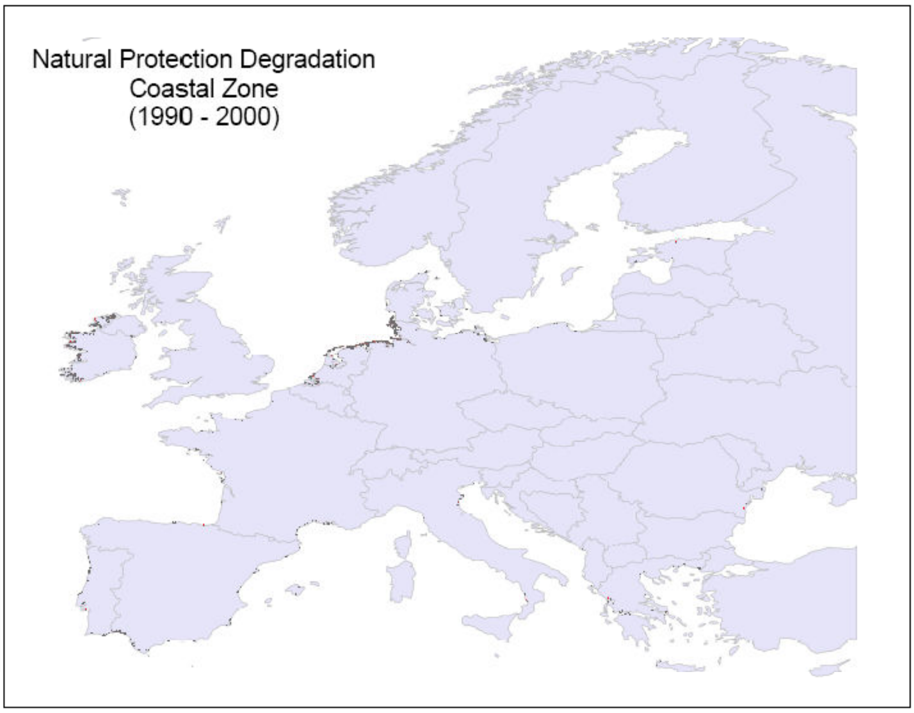


Figure 4.13 Locations where natural protection degraded between 1990 and 2000

4.2.2 River Feature

The river dataset contains 81 rivers European wide. The base layer which shows the locations of the rivers are generated by using the Water Information System for EU dataset (WISE) which compiles spatial information in three separate layers as lakes, major rivers and minor rivers. From the dataset generated from WISE database, 81 rivers for which information related to parameters of the model exist are selected to form base layer for river analysis. Figure 4.14 shows the map of the rivers compiled for the study.

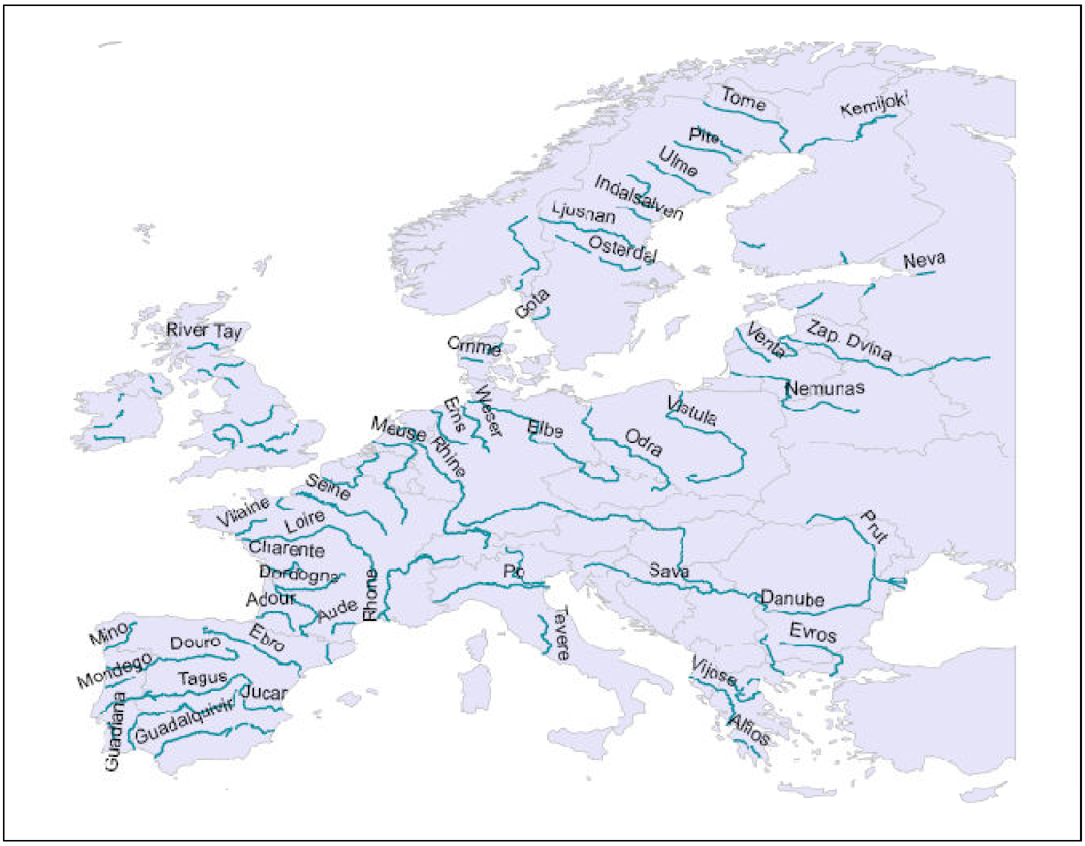


Figure 4.14 Rivers of Europe assessed in the study

a) River Discharge

Source

Several sources are used to compile discharge of the listed rivers: DIVA, Waterbase, WWDII, RivDIS, GEMS/GLORI and Rivers of Europe(Klement Tockner et al. 2009).

Methodology

Each discharge value was assigned to the corresponding river as an attribute manually. When more than one data existed, most recent dataset was used. If the data was in different units of measurement, then it was changed to comply with the parameter definition which is m^3/s (Table 4.4).

Table 4.4 Mean discharge rates of rivers assessed for the database

OBJECTID	NAME	DISCHARGE m3/s	OBJECTID	NAME	DISCHARGE m3/s
1	Adige	219.49	42	Orne	27.50
2	Adour	157.68	43	Osterdal	378.43
3	Akheloos	138.13	44	Pinios	80.42
4	Alfios	66.23	45	Pite	187.01
5	Aliakmon	85.15	46	Po	1532.65
6	Angermanalven	481.00	47	Põrnu	18.08
7	Aude	37.95	48	Prut	66.54
8	Blackwater	622.84	49	Rhine	2283.21
9	Charente	45.00	50	Rhone	1690.64
10	Danube	6464.88	51	River Bann	60.00
11	Dordogne	441.50	52	River Eden	51.82
12	Douro	427.63	53	River Great Ouse	11.80
13	Ebro	422.90	54	River Nith	40.00
14	El Llobregat	19.00	55	River Ouse	50.46
15	Elbe	864.09	56	River Severn	104.07
16	Ems	80.00	57	River Tay	167.14
17	Evros	220.75	58	River Thames	66.23
18	Evrotas	23.97	59	River Trent	28.38
19	Garonne	630.72	60	River Tweed	78.84
20	Glomma	700.10	61	River Wye	72.53
21	Gota	554.00	62	Sado	10.51
22	Guadalquivir	227.69	63	Sava	1564.19
23	Guadiana	194.89	64	Scheldt	110.00
24	Gudena	31.49	65	Segura	25.86
25	Indalsalven	444.66	66	Seine	500.00
26	Jucar	25.54	67	Shannon	220.75
27	Kemijoki	553.00	68	Somme	35.00
28	Kokemaenjoki	223.91	69	Stora-Lule	498.27
29	Kymijoki	315.36	70	Strimon	135.92
30	Lielupe	55.50	71	Suir	50.00
31	Ljusnan	226.00	72	Tagus	313.15
32	Loire	851.47	73	Tevere	265.85
33	Meuse	315.36	74	Torne	372.12
34	Mino	311.00	75	Ulme	428.89
35	Mondego	97.76	76	Venta	65.91
36	Narew	141.00	77	Vijose	52.00
37	Narva	387.89	78	Vilaine	80.00
38	Nemunas	788.40	79	Vistula	1053.30
39	Neva	2516.57	80	Weser	324.82
40	Odra	545.57	81	Zap. Dvina	643.33
41	Omme	36.60			

Limitations and Recommendations

The values compiled in this study are mostly mean discharge values. In some cases annual values were converted in to m^3/s which is a very rough estimate. For a specific case study, site specific and the most recent value should be considered.

b) River depth at downstream

Sources

River depth values were taken from DIVA dataset for 31 rivers.

Methodology

Each depth value was assigned to the corresponding river through a Join operation performed in GIS environment.

Table 4.5 Depth of rivers at the downstream

OBJECTID	NAME	RIVER DEPTH m		OBJECTID	NAME	RIVER DEPTH m
1	Adour	3.60		17	Nemunas	5.50
2	Charente	3.60		18	Neva	7.60
3	Danube	3.70		19	Odra	4.70
4	Douro	3.60		20	Osterdal	6.60
5	Ebro	4.60		21	Po	4.10
6	Elbe	3.10		22	Rhine	4.90
7	Evros	4.70		23	Rhone	5.00
8	Garonne	3.60		24	River Thames	2.20
9	Glomma	3.10		25	Scheldt	2.40
10	Guadalquivir	2.40		26	Segura	1.60
11	Guadiana	2.60		27	Seine	3.80
12	Jucar	2.70		28	Tagus	3.70
13	Kemijoki	3.50		29	Tevere	3.10
14	Loire	3.50		30	Vistula	5.20
15	Mino	2.50		31	Weser	3.50
16	Mondego	4.20				

c) Dams and Reservoirs

Sources

Main source of data is the ICOLD (International Commission on Large Dams) World Register of Dams, but augmented and corrected for apparently erroneous or inconsistent entries by consulting with various ancillary data sources yielding a list of 29,484 named reservoirs with country, nominal capacity and year of completion(Chao et al. 2008)

Methodology

Reservoirs located at Europe was selected and digitized as points using coordinates which were assigned manually. The volumes of the reservoirs were directly assigned from the main data source.

Map

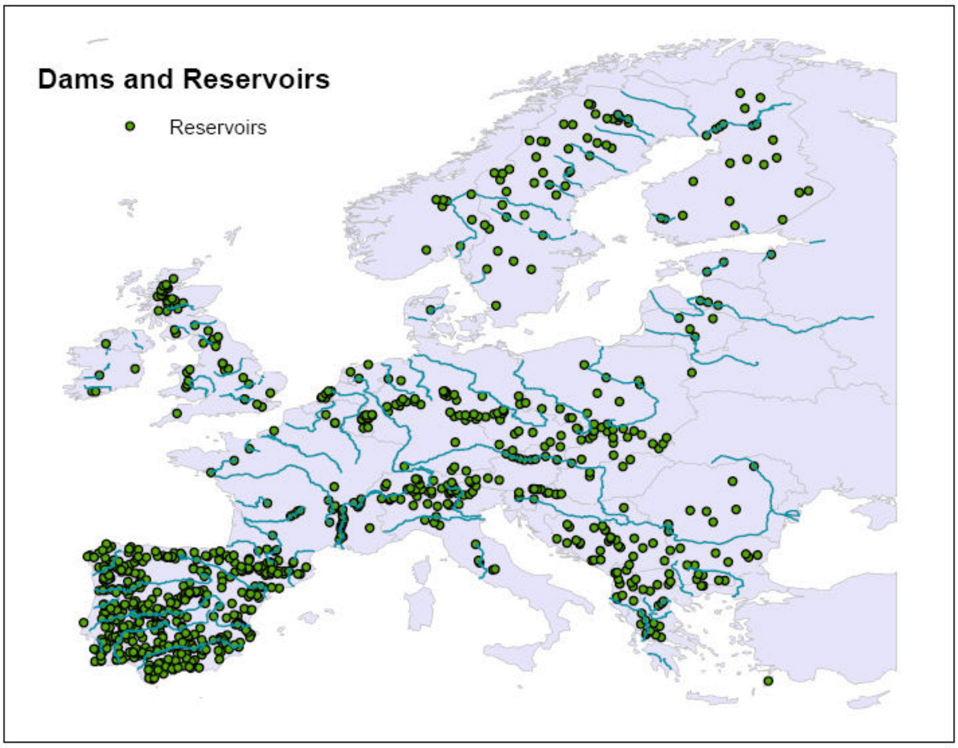


Figure 4.15 Reservoir data collected for the study

d) River Flow Regulation

Sources

Several sources are used to compile parameters necessary for calculation of river flow regulation : DIVA, Waterbase, WWDII, RivDIS, GEMS/GLORI,(Klement Tockner et al. 2009; Nilsson et al. 2005)

Methodology

1. Discharge data for individual river systems is collected.
2. All dams within a river system are located and storage capacities identified.
3. Flow regulation is calculated as the sum of reservoir live storage capacities within the system as a percent of the discharge.
4. Channel fragmentation is ranked into five classes describing the longest main-channel segment without dams (but frequently including reservoir water tables) in relation to the entire main channel (0 = 100%; 1 = 75-99%; 2 = 50-74%; 3 = 25-49%; and 4 = 0-24%). For the tributaries, fragmentation is described by three classes (0 = no dams; 1 = dams only in the catchment of minor tributaries; 2 = dams also in the catchment of the largest tributary).
5. Presented below are the principles for constructing the river flow regulation parameter, comprised of classes of river system impact (not affected, moderately affected, and strongly affected) from the combination of fragmentation and flow regulation assessments.

Table 4.6 Table for assigning flow regulation values (Nilsson et al. 2005)

Fragmentation (Main channel + tributaries)	Flow regulation (%)		
	Not affected	Moderately affected	Strongly affected
0 + 0	0		
0 + 1	≤ 2	> 2	
0 + 2	≤ 1	> 1	
1 + 0		≤ 30	> 30
1 + 1		≤ 25	> 25
1 + 2, 2 + 0		≤ 20	> 20
2 + 1		≤ 15	> 15
2 + 2,3 + 0		≤ 10	> 10
3 + 1		≤ 5	> 5
3 + 2, 4 + 0, 1, 2			≥ 0

Limitations and Recommendations

Data of river flow regulation for 51 rivers were directly taken from Rivers of Europe (Klement Tockner et al. 2009) and assigned as attributes manually. For the rest of 30 rivers, the methodology is applied in GIS environment using the available data. It is important to apply the methodology using detailed assessment of required data when the model is applied for a specific location.

Map

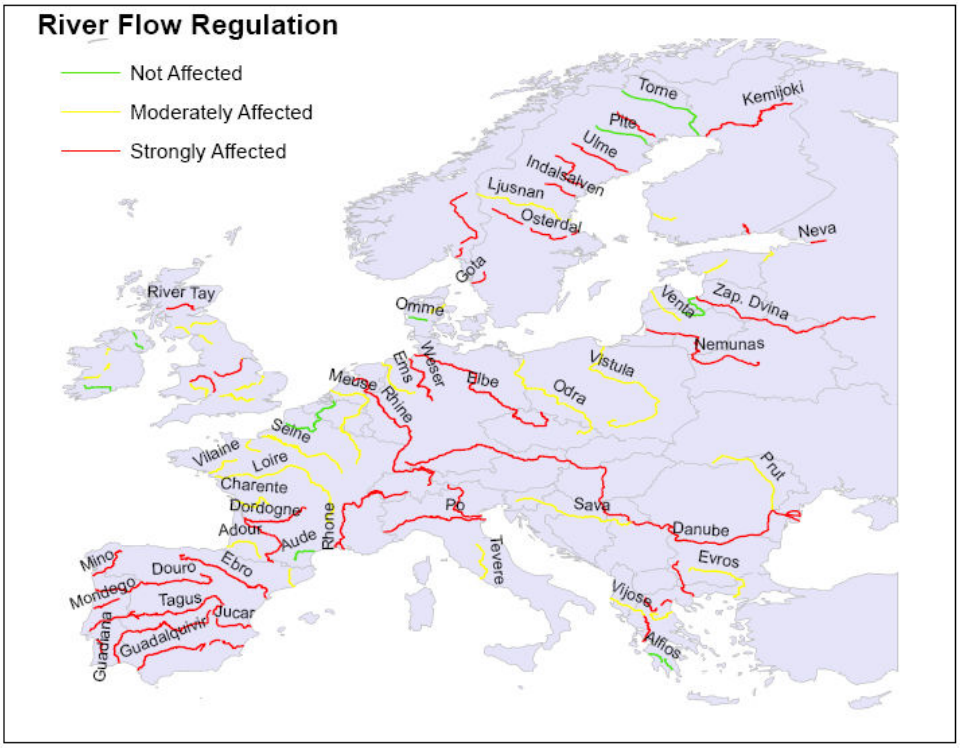


Figure 4.16 River flow regulation scores of rivers

e) Reduction of sediment supply

Sources

CORINE land covers 1990, 2000 and 2006, World Water Development Assessment dataset and (Vorosmarty CJ 2003)

Methodology

Impact of sediment trapping by dams and reservoirs were assigned from WWD2 and (Vorosmarty CJ 2003) datasets. Using CORINE land covers, changes in the beaches, dunes and other sediment resources can be calculated.

Limitations and Recommendations

Site specific data is mandatory to calculate the best realistic result for this parameter. The data of the database are rough estimates based on coarse resolution data.

Map

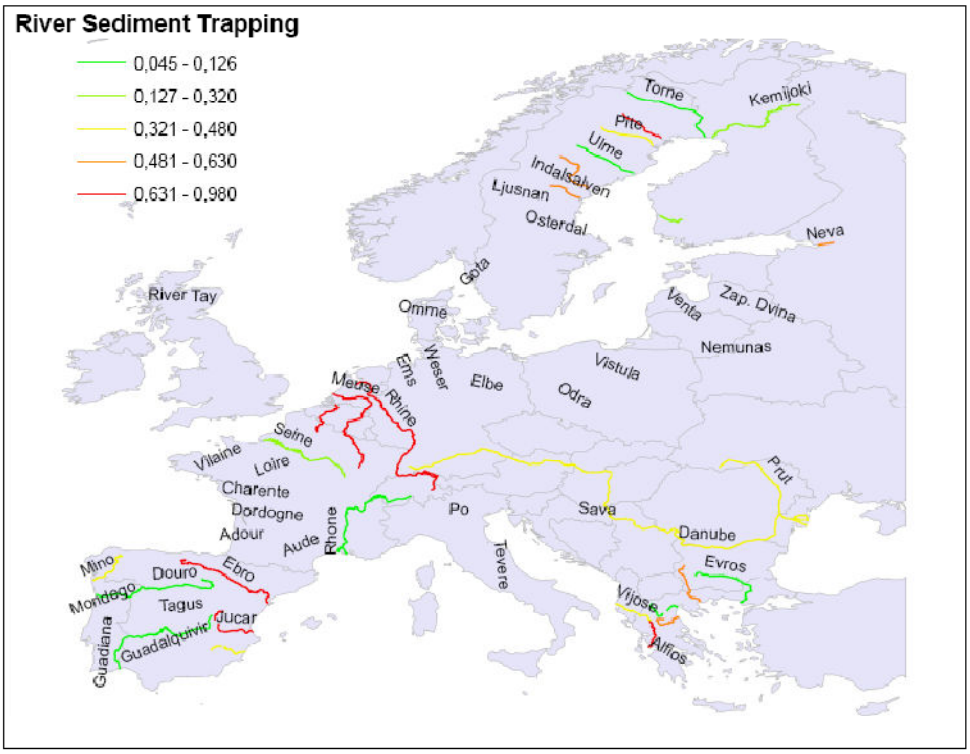


Figure 4.17 River Sediment Trapping efficiency scores

4.2.2 Groundwater Feature

The groundwater database is extracted from Digital Dataset of European Groundwater Resources (2002) which contains digitized information about aquifers located in 9 European countries; Belgium, Denmark, France, Ireland, Italy, Luxembourg, Netherlands, United Kingdom, Western Germany. The scale of maps is 1:500,000. The published paper maps are extremely complex and the information on them is organized into four 'Themes':

1. An inventory of **Aquifers** in terms of their spatial distribution, geological and lithological features, as well as their types (phreatic or confined) and flow characteristics (interstitial, fissured or karstic).

2. The **hydrogeological characteristics** of the aquifers, including contours of the piezometric surface of the groundwater (where available), arrows indicating the direction of groundwater flow and interactions between surface and groundwater and between individual aquifers. Also shown in this theme are the presence of saline groundwater areas and saline intrusions from sea waters.

3. **Abstraction** of groundwater, including the distribution of abstraction sources, the type of source (wells, springs or mine water) and the amount of abstraction classified into three ranges.

4. Potential **Additional Groundwater Resources**, including zones of possible surplus, equilibrium, overdevelopment and where no significant groundwater occurs.

The coastal aquifers were extracted from the main database by selecting those aquifers having a border with sea.

a) Aquifer Type

Methodology

Aquifers are re-classified according to the classification of the fuzzy vulnerability assessment model. The original dataset compiled type of aquifers as unconfined, confined and mixed. However cases of karstic aquifers were also identified.

Map

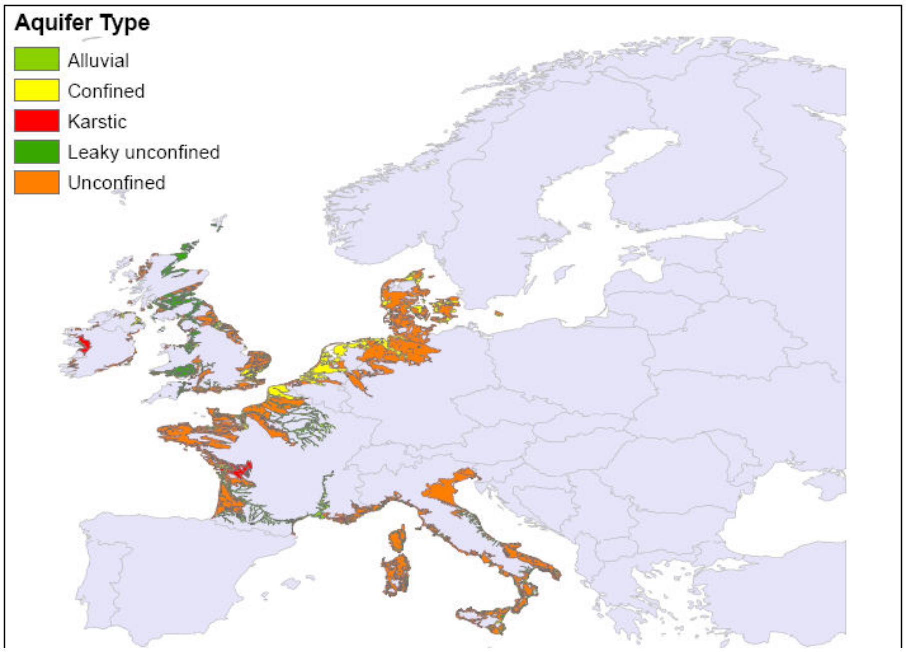


Figure 4.18 Types of coastal aquifers

b) Hydraulic Conductivity

Methodology

Some limited quantitative data were given for hydrogeological properties of the aquifers. These include dominant aquifer lithology which can be used to assign hydraulic conductivity class for an aquifer.

Table 4.7 Codes used to indicate the lithological classes

Lithology	Map code
Alluvium (sands, pebbles, gravels, loam)	A
Sands	S
Alternate strata sands and clay	Sc
Alternate strata alluvia and clay	Ac
Sands and gravels	Sg
Sandstones or calcarenites (sandstones with calcareous cement)	G
Conglomerates	C
Sandstones with conglomerates	Gc
Limestones	L
Chalk	Lh
Marly limestone	Lm
Karst limestone	Lk
Dolomitic limestone	Ld
Dolomites	D
Calcareous sinters	T
Intrusive rocks	I
Extrusive rocks	V
Acid extrusive rocks	Va
Basic extrusive rocks	Vb
Metamorphic rocks	M
Evaporates (sodic, potassic salts, gypsum)	E
Marly-sandstone flysch (alternate marly, sandstones, sand strata)	Fm
Alternate sandstones and shales	Ga
Marl	M
Pierres vertes	p.v.

Map

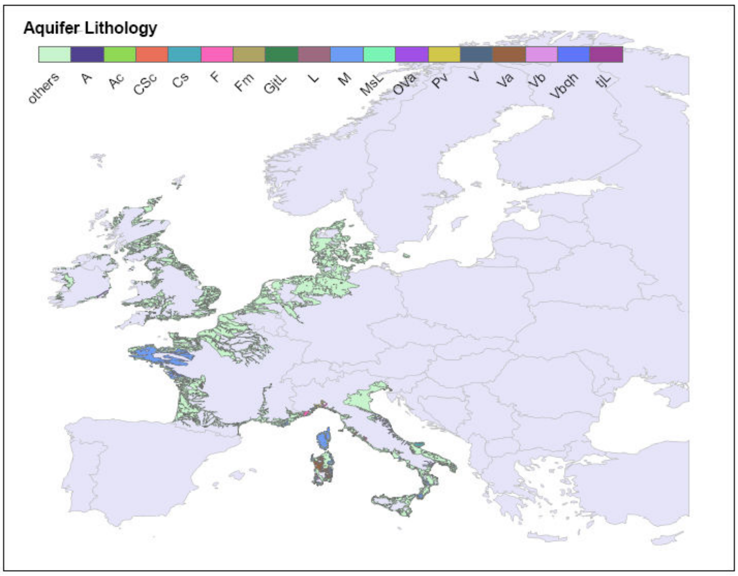


Figure 4.19 Type of lithology data available for coastal aquifers

c) Depth to water table above sea

Methodology

Contours are given for some of the main aquifers showing typical elevations of the water table (in unconfined aquifers) or potentiometric surface (confined aquifers). Contours of the coastal aquifers were extracted and drawn on GIS environment for the groundwater database.

Map

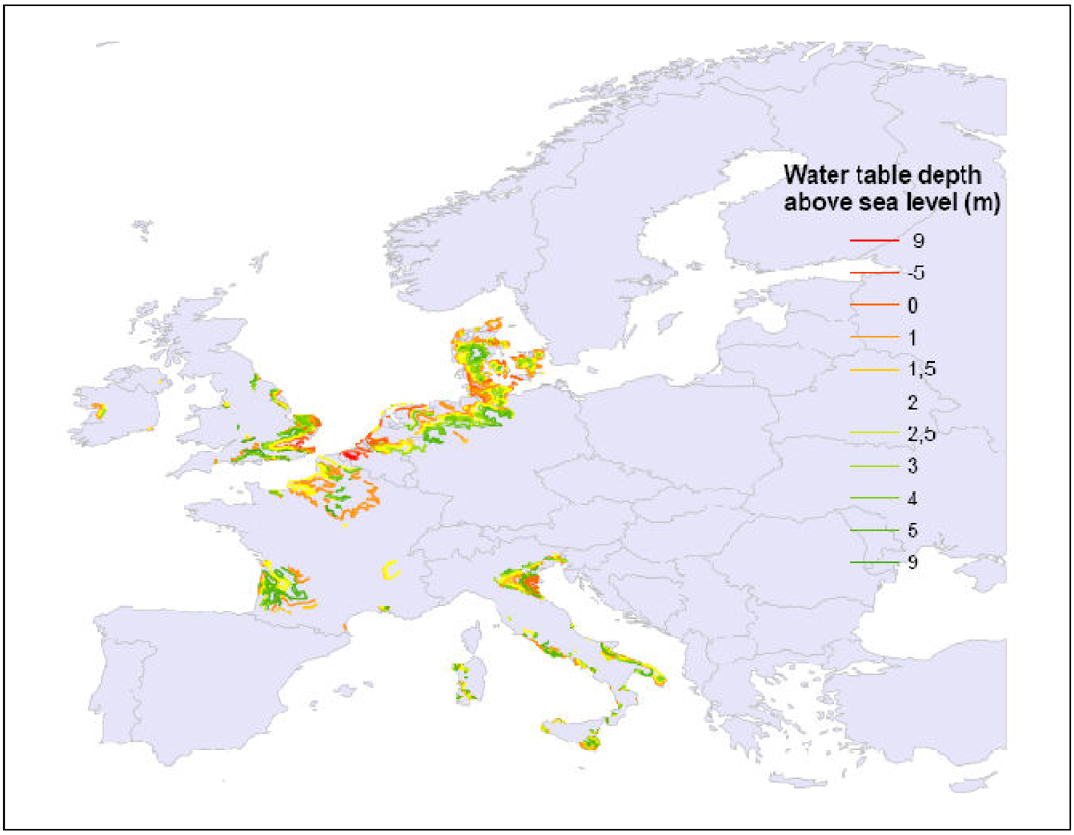


Figure 4.20 Water table contours for coastal aquifers

Limitations and Recommendations

Contours of water table elevation can be used to provide an indication of the depth of the water table below groundwater. Contours of the elevation of the potentiometric surface cannot be used to provide an indication of the depth of groundwater below the land. In the digitized map, contours are not related to aquifer types so caution must be exercised when using the water table elevations.

d) Groundwater abstraction

Sources

Digital Dataset of European Groundwater Resources (2002) and Whymap database

Methodology

Three sets of information are provided by the main dataset (Digital Dataset of European Groundwater Resources (2002)) ; springs, wells and mine drainage. Wells are subdivided according to the size of abstraction (1-2 x10^6 m^3/a, 2-4 x10^6 m^3/a, 4-10 x10^6 m^3/a and >10 x10^6 m^3/a) and digitized as point features. Total amount of abstraction for a coastal aquifer were calculated by aggregating the well abstraction information. On the other hand, Whymap database provided water stress index values which indicate the amount of demand over supply for national assessments. Both values are used to analyze groundwater abstraction parameter.

Map

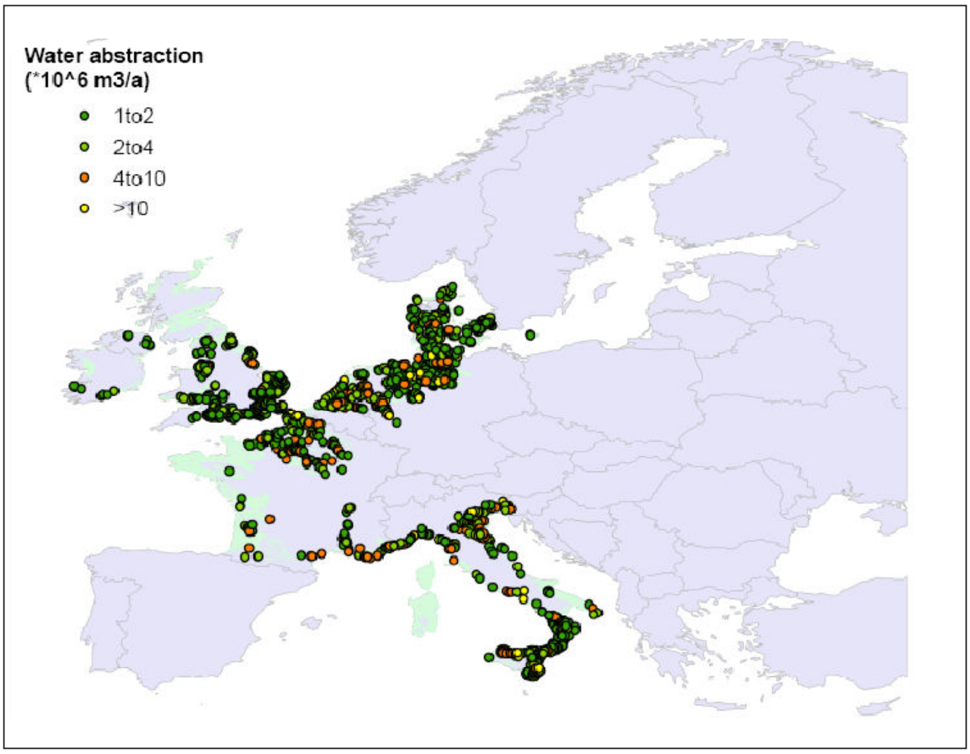


Figure 4.21 Water abstraction rates from wells

e) Proximity to Coast

Methodology

The center coordinates of aquifers from the base layer were calculated using feature to point tool of GIS and then the distances were compiled by using Near tool of GIS. These distances were then assigned to each aquifer indicating the proximity to coast.

Map

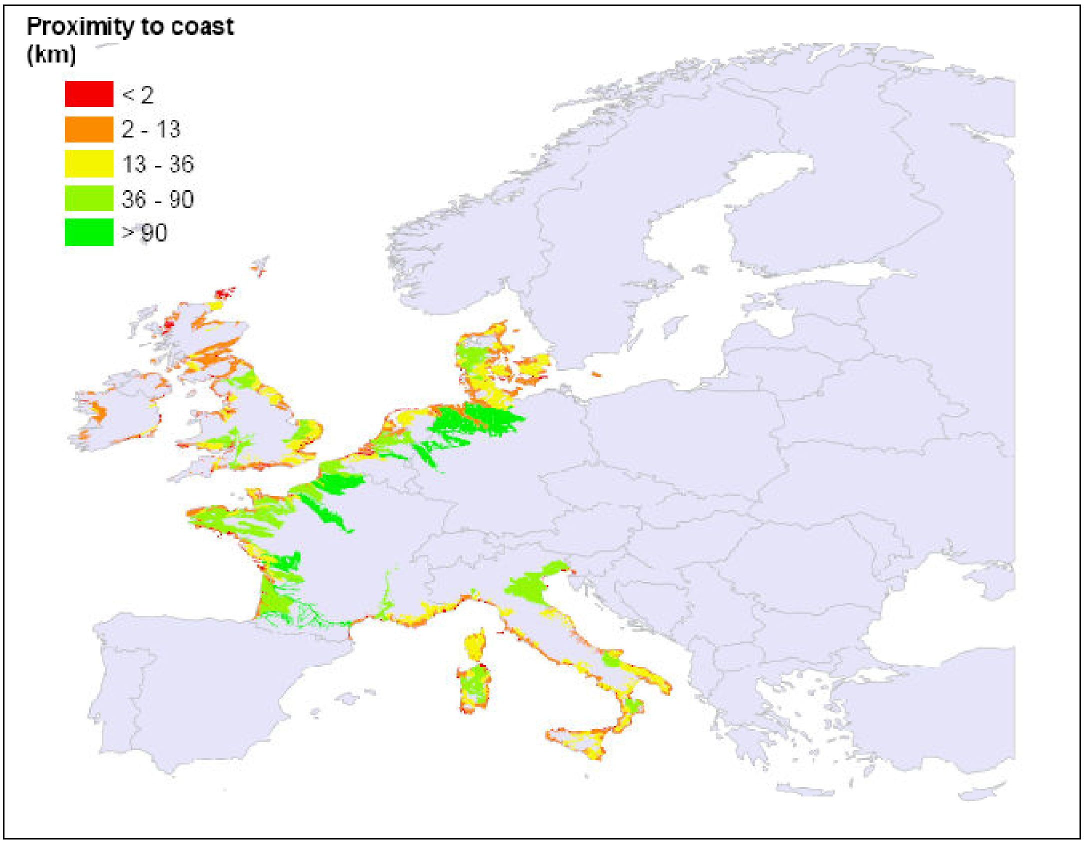


Figure 4.22 Proximity of coastal aquifers (distance from shoreline to center of the aquifer)

CHAPTER V

ANALYTICAL HIERARCHY PROCESS

Although breaking down a problem into its components to analyze a system is a systematic way to solve many problems, when problems involving many disciplines need to be solved, using a pure analytical approach, most of the time, do not give the best solution. The best solution may not be the best technical or best economic or best political or social solution but must consider all of them. This holds true when coastal zone management practices are considered as well. Involving various stakeholders, limitations from different coastal sources, facing a variety of physical problems and considering socio-economic costs and benefits, any decision concerning coastal areas are prime examples of multi-criteria decision making. "What is needed is a method of *synthesis,* to form the whole from the parts. It must enable one to deal with the different values and objectives, prioritizing their relative importance by looking ahead to forge a best compromise answer according to the different parties and influences involved and the values they have"(Saaty 2006).

Causal influences and their effects can be analyzed in two ways; deductive logic beginning with assumptions and deducing an outcome from them or a holistic approach that involves all the factors and criteria in a hierarchy or in a network system that allows for dependencies. All possible outcomes that can be thought of are joined together in these structures. Using both judgment and logic the relative influence is estimated. "This approach generally leads to a sound overall outcome about the real world".(Saaty 2006)

"The Analytic Hierarchy Process (AHP) is a method that can be used to establish measures in both the physical (objective reality outside the individual) and social domains (subjective ideas, feelings, and beliefs of an individual, of a group working together)".(Cheng and Li 2001) It is used to derive relative priorities on absolute scales from both discrete and continuous paired comparisons in multilevel hierarchic structures. AHP combines both qualitative and quantitative approaches into a single empirical inquiry. It uses a qualitative way to decompose an unstructured problem into a systematic decision hierarchy. In the quantitative sense, it employs a pair wise comparison to execute the consistency test to validate the consistency of responses.

In practice, AHP aims at assigning weights to tested elements. Weighting of elements has two major functions; prioritize (rank) elements in order to determine the key elements and to assign weights to key measures to make more accurate decisions.(Cheng and Li 2001; Saaty 1994a)

"AHP is a hierarchical representation of a system. A hierarchy is an abstraction of the structure of the system, consisting of several levels representing the decomposition of the overall objective to a set of clusters, sub-clusters and so on down to the final level" (Cheng and Li 2001). Figure 5.1 shows the step by step methodology for weighting elements of construction information.

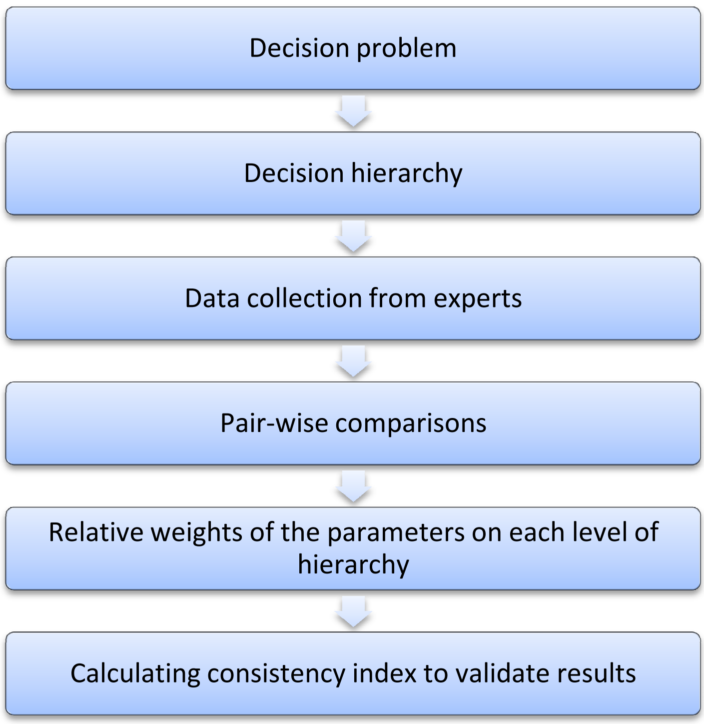


Figure 5.1 Methodology of Analytical Hierarchy Process

“In the absence of a weighting instrument, measuring relative weights of the sources is acceptable”(Saaty 1980). Usually subjective judgments of the decision makers and/or experts are used to assign weights to parameters. A simple method is to guess each element according to an absolute rating scale and use weighted averages to get its relative weight where key elements have heavier weights. However, “the traditional rating method cannot filter out the inconsistency of responses” (Cheng and Li 2001).

In contrast, AHP is a structured method that can extract biased opinions of decision makers in weighting and prioritization. AHP uses a pair-wise comparison process where two objects are compared at one time to form a judgment of their relative weight. A higher level of consistency is achieved since pairwise comparison requires the respondents to think precisely before giving their answers.

Moreover, the AHP method includes the consistency test that can screen out inconsistent responses. “Inconsistency refers to a lack of transitivity of preferences” (Saaty 1980) where those who are responsible of judgments could not build up their judgments logically. The consistency test brings out these results to the implementer’s attention.

The use of AHP for the fuzzy vulnerability assessment model is described step by step in this section.

5.1 Decision Problem

The decision problem should be defined clearly since it drives the whole process. To prioritize coastal areas according to their vulnerability to sea level rise is one of the objectives of the fuzzy vulnerability assessment model which requires ranking of coastal areas. In addition, comparison of individual impacts of sea level rise according to vulnerability as well as selecting the governing parameters for site specific vulnerability requires ranking of impacts and parameters relatively. On the other hand, the physical impacts are complex and continuous processes, which different set of criteria and sub-criteria are necessary to be defined. Not all the parameters have equal influence on the physical process assessed by the model. In some cases, such as salt water intrusion to groundwater resources, one set of criteria (human parameters) are more dominant. To be able to derive most realistic results using different sets of criteria requires assignment of weights to different parameters and criteria with respect to their influence on the impact vulnerability. The objective of integrating physical parameters and human influence parameters as well as the problem structure which is very suitable for hierarchical definition enables the use of AHP to assign weight to the criteria.

5.2 Decision hierarchy

Structuring a decision is achieved by decomposing it into the most general and most easily controlled factors. Then the alternatives can be compared by aggregating the sub criteria into generic higher level criteria until the levels of the two processes are linked in. The formation of the hierarchy is based upon two assumptions, without which a problem cannot be dealt with using AHP(Kuruüzüm and Atsan 2001; Saaty 1994a):

1. "It is expected that each element of a level in the hierarchy would be related to the elements at the adjacent levels. AHP recognizes the interaction between elements of two adjacent levels. (Hierarchic dependent structure)

2. There is no hypothesized relationship between the elements of different groups at the same level. (Homogenous elements)"

Considering the two axioms mentioned above and the problem definition given in Step 1, decision hierarchy model was decided to be built in six different hierarchies; five hierarchies for individual impacts and the sixth one for the overall vulnerability of coastal area. A schematic representation of the decision hierarchy for impacts is shown in Figure 5.2.

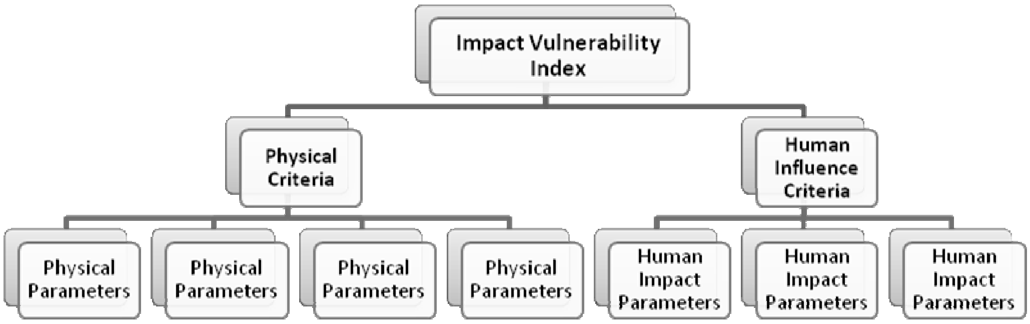


Figure 5.2 Schematic representation of the decision hierarchy of impacts

Overall system is shown in Figure 5.3; such a chain of hierarchy represents the system of the problem.

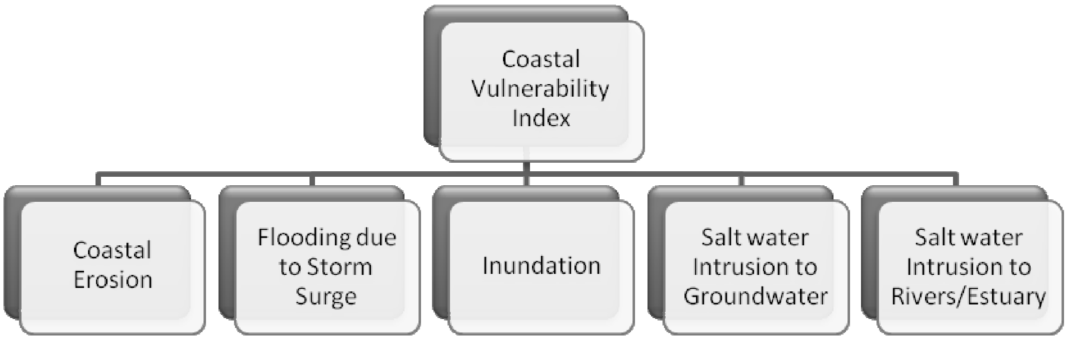


Figure 5.3 Decision hierarchy for overall vulnerability index

Impact hierarchies are composed of three layers of hierarchy where the fourth layer is the actual locations which are compared to each other. However the fourth layer is not shown in the structures since the aim of employing AHP is to determine relative weights of elements of each layer of the hierarchy. The global rates are also not considered in the fuzzy vulnerability assessment model since the actual comparison was aimed to be performed through fuzzy inference systems. Overall vulnerability hierarchy is only composed of one layer where all the impacts are considered. However, it should be underlined that this final structure is highly related to the study sites and participants (especially decision maker groups).

One big hierarchical structure is also possible to design for the vulnerability assessment however, since some of the parameters are used repeatedly for some of the physical impacts, homogeneity axiom would be compromised. In order to comply with the two axioms presented, five individual hierarchical structures are designed. For the case of sixth hierarchy describing the overall vulnerability index, although it is known that there are some relations between the impacts of sea level rise such as storm surges causing coastal erosion, the time scale of the vulnerability assessment model allows to neglect these indirect effects enabling to comply with homogeneity axiom.

With regards to hierarchic dependent structure axiom, all the elements presented in the structures have relations with higher levels and the aggregate impact determines the overall decision problem.

5.3 Data collection

Data are obtained by questioning experts who are actively involved in coastal engineering and coastal zone managmenet research. An online survey (Appendix A) was prepared which asked the participants to compare each parameter in pair-wise manner by first defining the governing (important/influential) one and then the scale of the influence according to the Saaty's scale of measurement (Table 5.1).

The initial survey was first given to a test group to take feedback on survey questions, wording of the questions and to test the overall applicability of the survey. Considering several suggestions from the test group, the survey was upgraded and finalized. The survey link was sent to several coastal experts around the world; UK, Portugal, Brazil, Australia and Turkey. Each participant was asked to answer the questions that belonged to their own expertise area, thus different number of results (3 to 10 answers) was obtained for different impacts. "It should be noted that the AHP approach is a subjective methodology that does not necessarily involve a large number of experts to take part in the AHP process."(Cheng and Li 2001) Certainly, in an academic research, a small sample might only provide a rough picture, however the impacts which are asked about are clearly defined physical processes where opinions from a small group of key experts provided reliable results (as is shown by consistency ratios). Additionally, with reference to coastal zone management practices and the impacts of sea level rise, opinions from a small but spatially varying group of key experts enabled to generate efficient results in terms of the perception of the importance of sea level rise on the overall coastal processes.

Table 5.1 Saaty's scale of measurement for pair-wise comparisons (Saaty 1994b)

Intensity of importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favour one over another
5	Strong importance	Experience and judgement strongly favour one over another
7	Very strong importance	An activity is strongly favoured and its dominance is demonstrated in practice
9	Absolute importance	The importance of one over another affirmed on the highest possible order
2, 4, 6, 8	Intermediate values	Used to represent compromise between the priorities listed above
Reciprocals of above non-zero numbers		If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.

5.4 Pair-wise comparisons

"A judgment or comparison is the numerical representation of a relationship between two elements that share a common parent. The set of all such judgments can be represented in a square matrix in which the set of elements is compared with itself. The judgments matrix (square matrix) reflects the answers to two questions: which of the two elements is more important with respect to a higher level criterion, and how strongly, using the 1-9 scale shown in Table 5.1 for the element on the left over the element at the top. If the element on the left is less important than that on the top of the matrix, then the reciprocal value in the corresponding position is entered to the matrix (reciprocal axiom of AHP). It is important to note that the lesser element is always used as the unit and the greater one is estimated as a multiple of that unit"(Saaty 1994b). (Table 5.2)

Table 5.2 Judgement matrix of group decision for physical parameters of coastal erosion

Erosion	RSL	Geo	Slope	Wave	Sediment	Tide
RSL	1.000	0.455	0.779	0.570	0.309	0.830
Geo	2.196	1.000	1.866	0.789	0.511	1.914
Slope	1.283	0.536	1.000	0.554	0.291	1.701
Wave	1.755	1.268	1.804	1.000	0.427	2.246
Sediment	3.240	1.958	3.442	2.340	1.000	5.284
Tide	1.205	0.523	0.588	0.445	0.189	1.000

For a set of n elements in a matrix, there are n 1's on the diagonal for comparing elements with themselves. Of the remaining judgments, half are reciprocals. Thus there will be (n2-n)/2 judgments to form the judgment matrix.

Additionally, the AHP makes group decision making possible by aggregating judgments in a way that satisfies the reciprocal relation in comparing two elements. It then takes the geometric mean of the judgments. When the group consists of experts, each works out his or her own hierarchy and the AHP combines the outcomes by the geometric mean.(Saaty 1994b) This is how the results of the survey were processed.

From each survey, judgments were combined using geometric mean and the final judgment matrices were formed for each hierarchy level and the impact. When only two elements existed such as the case of second level of impact hierarchy structure (physical and human influence parameters are compared), the weights were assigned such that the sum would always equal to 1.

The final judgment matrices are provided in Appendix B.

5.5 Relative Weights

To determine the relative weights, a vector of priorities (a proper or Eigen vector) in the pair-wise comparison matrix is calculated and is then normalized to sum to 1.0 or 100%. The procedure is as follows:

- Divide the elements of each column of the matrix by the sum of that column (normalizing the column);
- Obtain the Eigen vector by adding the elements in each resulting row
- Divide this sum by the number of elements in the row (to obtain priority or relative weight).

This procedure was automatically performed by each judgment matrix prepared from survey results by means of writing a MATLAB function. The function calculates the relative weights of each parameter and checks for consistency.

5.6 Consistency Ratio

It is known that people are often inconsistent in answering questions, thus inconsistency is inherent in the judgment process. When pair-wise comparisons are performed, it might be possible that A would be more important than B and B than C; however C could be chosen over A. On the other hand, A would contribute 3 times more than B and B would contribute 2 times more than C; but A would not be shown as contributing 6 times more than C. "These types of inconsistencies may be considered a tolerable error in measurement only when it is of a lower order of magnitude (10 percent) than the actual measurement itself; otherwise the inconsistency would bias the result by a sizable error comparable to or exceeding the actual measurement itself and revision of subjective judgments have to be performed."(Teknomo)

Consistency ratio is used to measure the consistency in the pair-wise comparison. Saaty (1994) has set the acceptable CR values for different matrices' sizes; the CR value is:

1. "The CR value is 0.05 for a 3 by 3 matrix;
2. 0.08 for a 4 by 4 matrix;
3. 0.1 for larger matrices."

"If the consistency level falls into the acceptable range, the weight results are valid" (Teknomo).

For consistent reciprocal matrix, the largest Eigen value is equal to the size of comparison matrix, or$\lambda_{max} = n$. Then the measure of consistency, called Consistency Index as deviation or degree of consistency using the following formula is calculated:

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad \text{Eq.5.1}$$

Then, Consistency Ratio, which is a comparison between Consistency Index and Random Consistency Index, is calculated using the Random Consistency Index table developed by Saaty 1994 by using the formula:

$$CR = \frac{CI}{RI} \qquad \text{Eq. 5.2}$$

Table 5.3 Random Consistency Index (RI)

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Random Consistency Index (RI)	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

5.7 Results

The results of AHP hierarchies are shown in Table 5.4 including the consistency ratio when applicable. The weights derived from impact hierarchies are assigned as "default" weights of the parameters of the fuzzy vulnerability assessment model.

These relative weights show that only for inundation process, rate of sea level rise is the major parameter to be considered. Although it is seen that rate of sea level rise is thought as one of the contributors to these impacts, it is not taken as the driving force by the experts contrary to the reports stating that sea level rise will trigger these impacts along coastal areas. This also underlines the general perception on sea level rise of the decision makers who believe that sea level rise is not an urgent threat when present problems are considered. However it should be noted that although sea level rise would not trigger any of the impacts within a short frame of time, it will exacerbate the present coastal problems of erosion, groundwater usage, etc. (Harvey et al. 1999). Thus any coastal zone management plans and implementations should consider the effect of sea level rise on these impacts for the near future and keep in mind that new impacts could be triggered as longer time scales are considered.

In addition to the perception of sea level rise as a minor component in the physical process along coastal areas, the results of the AHP analysis highlighted the fact that for some of the impact processes, anthropogenic parameters are much more dominant. This is a very important fact that needs to be considered seriously. Although the interaction between human and physical parameters is not a simple problem, human activities are easier to control and regulate than the physical properties of a coastal region. Thus when adaptation planning is considered, understanding the influence of human activities on the impact processes as well as the overall vulnerability of a region would increase the options for future implementations. Especially for salt water intrusion to groundwater and rivers, the perception of experts is that human activities are the primary controlling parameters that need to be addressed. On the other hand, flooding due to storm surges and inundation primarily depend on the physical characteristics of the coastal area. Coastal erosion is the most complex process of these impacts where many physical and human parameters need to be considered. Although both parameters contribute to the coastal erosion process, human activities especially any anthropogenic activity leading to reduction of sediment supply significantly state the outcome vulnerability.

The outcome of the AHP analysis shows that integration of anthropogenic activities and physical processes needs to be considered when implementation of any coastal assessment. This is established by fuzzy vulnerability assessment model of coastal areas, a significant addition to coastal vulnerability assessments available in literature.

Table 5.4 Relative weights of elements of each layer of AHP hierarchy for individual impacts

Inundation

Physical	Weights	Human	Weights		Weights
Rate of sea level rise	**0.35**	Natural Protection Degradation	**0.63**	Physical Parameters	**0.56**
Beach Slope	**0.47**	Coastal Protection Structures	**0.36**	Human Influence Parameters	**0.43**
Tidal Range	**0.18**				
CR	0.06				

Flooding due to Storm Surge

Physical	Weights	Human	Weights		Weights
Rate of sea level rise	**0.08**	Engineered Frontage	**0.32**	Physical Parameters	**0.76**
Beach Slope	**0.18**	Natural Protection Degradation	**0.48**	Human Influence Parameters	**0.24**
Surge Height	**0.57**	Coastal Protection Structures	**0.19**		
Tidal Range	**0.16**				
CR	0.03		0.00		

Coastal Erosion

Physical	Weights	Human	Weights		Weights
Rate of sea level rise	**0.09**	Reduction of sediment supply	**0.40**	Physical Parameters	**0.41**
Geomorphology	**0.17**	River flow regulation	**0.13**	Human Influence Parameters	**0.56**
Beach Slope	**0.11**	Engineered Frontage	**0.20**		
Significant Wave Height	**0.18**	Natural Protection Degradation	**0.12**		
Sediment Budget	**0.37**	Coastal Protection Structures	**0.15**		
Tidal Range	**0.08**				
CR	0.010		0.005		

Groundwater

Physical	Weights	Human	Weights		Weights
Rate of sea level rise	**0.04**	Groundwater Abtraction	**0.70**	Physical Parameters	**0.30**
Proximity to coast	**0.09**	Landuse	**0.30**	Human Influence Parameters	**0.70**
Aquifer type	**0.60**				
Hydraulic Conductivity	**0.08**				
Depth to water table from sea	**0.19**				
CR	0.06				

River

Physical	Weights	Human	Weights		Weights
Rate of sea level rise	**0.13**	River flow regulation	**0.71**	Physical Parameters	**0.34**
Tidal Range	**0.09**	Engineered Frontage	**0.14**	Human Influence Parameters	**0.65**
Depth at downstream	**0.34**	Landuse	**0.14**		
Discharge	**0.45**				
CR	0.016		0.016		

In addition, the relative weights calculated from the surveys for the overall vulnerability are also given. However for the fuzzy vulnerability assessment model, each impact is assumed to have the same weight since the relative importance of impacts depends highly on the site and the related decision maker groups. These results (Table 5.5) should be considered as the general perception of the experts participated in the survey on which impacts will be more profound due to sea level rise, thus will be more important in the upcoming future.

Table 5.5 Weights of individual impacts on coastal vulnerability as perception of coastal experts

Impacts	
	Weights
Coastal Erosion	**0.36**
Inundation	**0.13**
Flooding due to Storm Surge	**0.18**
Salt water intrusion to Groundwater	**0.16**
Salt water intrusion to River/Estuary	**0.17**
CR	**0.01**

From the results, it is seen that major concern for the upcoming future is coastal erosion as is the present problem of many coastal areas. Although flooding due to storm surges is a problem that could be significantly exacerbated in the near future, it is considered as a secondary impact along with salt water intrusion to groundwater and rivers. Inundation is the least important impact which is an expected outcome due to the time scale it is expected to occur.

The fuzzy vulnerability assessment model enables the user to assign different weights to each parameter although the results of AHP analysis were used as default values for the fuzzy vulnerability assessment model. Thus it is strongly suggested that AHP analysis be performed when site specific applications are implemented especially regarding the weights of physical and human impact criteria level and the overall vulnerability hierarchy and then, the model should be run.

CHAPTER VI

FUZZY VULNERABILITY ASSESSEMENT MODEL

Uncertainty is involved in many real phenomena. To consider uncertainty explicitly when modelling is one of the modelling decisions depending on the context. The modeller might decide to approximate the uncertainty by a certain (deterministic) model. Alternatively he/she might include some type of factor of safety in the model so that it is `on the safe side' concerning uncertainty. "In either of the above cases the modeller does not have to choose any specific method for modelling uncertainty".(Zimmermann 2000) In terms of applicability of the preliminary vulnerability assessment model(Ozyurt 2007), the results of preliminary vulnerability model were an important addition in coastal zone management. On the other hand, decision makers are not clear on how to implement measures related to sea level rise when the uncertainty of the possibility of the expected impacts is very high decreasing the motivation for active responses. Thus, describing and determining uncertainty related to data, knowledge and procedure of the model was mandatory when the perspectives of decision makers are considered.

6.1 Uncertainty in Theoretical Perspective

"The below given principles are currently widely shared in social sciences, and are getting increasingly accepted in the Integrated Assessment community.

• Science is not a purely objective, value-free activity of discovery: Science is a creative process in which social and individual values interfere with observation, analysis and interpretation.

• Knowledge is not equivalent with truth and certainty.

From this viewpoint, uncertainty is not simply the absence of knowledge."(Asselt and Rotmans 2002) Uncertainty can still exist where a lot of information is available. Additionally, new information can either decrease or increase uncertainty. For example, new knowledge on complex processes may reveal the presence of uncertainties that were previously unknown or were underestimated. This might be due to our understanding being more limited or that the processes are more complex than previously thought. Thus, more knowledge does not imply less uncertainty and vice versa. (Asselt and Rotmans 2002) Or as Shackle (1955) phrased it in his theory of 'unknowledge': "There would be no uncertainty if a question could be answered by seeking additional knowledge. The fundamental imperfection of knowledge is the essence of uncertainty".

6.2 Taxonomy of Sources of Uncertainty

Uncertainty is usually defined through classification due to the difficulty in defining the concept itself. One way to classify uncertainty is by investigating different sources of uncertainty. Asselt and Rotmans 2002 have developed a taxonomy of sources of uncertainty (Figure 6.1), that enables analysts to differentiate between uncertainties and to communicate about uncertainties in a more constructive manner. The taxonomy is meant to be applicable to all contexts.

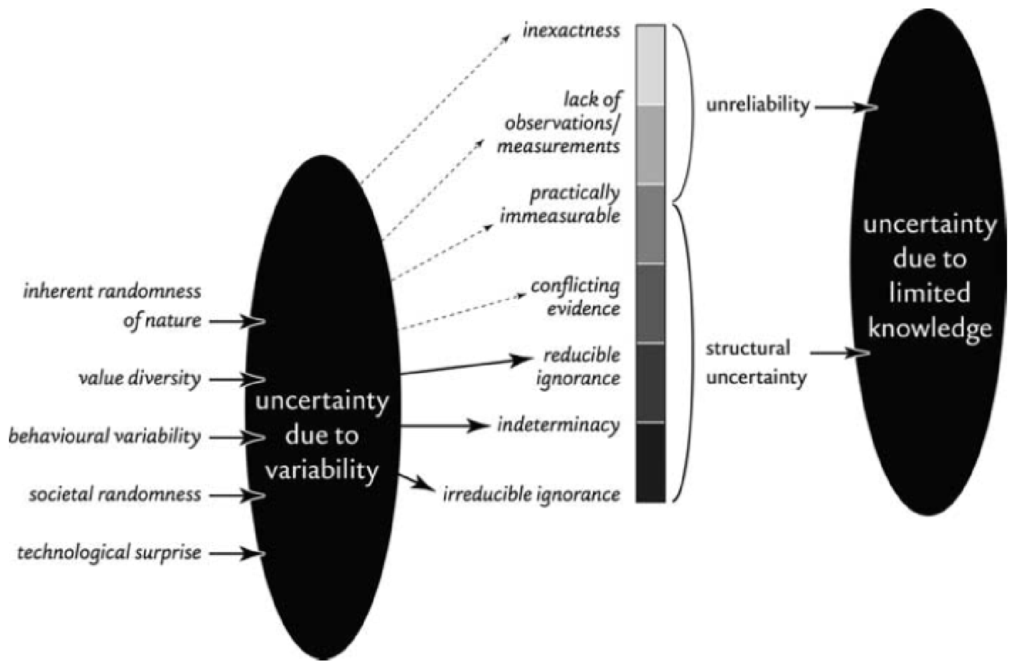


Figure 6.1 Typology of sources of uncertainty (Asselt and Rotmans 2002)

Building upon extensive literature analysis, Asselt and Rotmans 2002 grouped the sources of uncertainty into two at the highest level of aggregation:

• "*Variability*. The system/process under consideration can behave in different ways or is valued differently. Variability is an attribute of reality.

• *Limited knowledge.* Limited knowledge is a property of the analysts performing the study and/or of our state of knowledge."

Accordingly, different sources of variability can be distinguished (Asselt and Rotmans 2002) :

• "Inherent randomness of nature: The non-linear, chaotic and unpredictable nature of natural processes, also referred to as (unobserved) seasonalities (van Vlimmeren et al., 1991 cited in (Asselt and Rotmans 2002)); *examples of uncertainties related to this source pertaining to integrated assessment of climate change:* Ocean dynamics and the behaviour of clouds."

• "Value diversity: Differences in people's mental maps, world views and norms and values, due to which problem perceptions and definitions differ; *examples of uncertainties related to this source pertaining to integrated assessment of climate change:* Climate risk aversive versus economic risk aversive, discounting rate."

• "Human behaviour (behavioural variability): 'Non-rational' behaviour, discrepancies between what people say and what they actually do (cognitive dissonance), or deviations of 'standard' behavioural patterns (micro-level behaviour); *examples of uncertainties related to this source pertaining to integrated assessment of climate change:* Consumption patterns (e.g., related to energy use)."

• "Social, economic and cultural dynamics (societal variability): The non-linear, chaotic and unpredictable nature of societal processes (macro-level behaviour). *Examples of uncertainties related to this source pertaining to integrated assessment of climate change:* Effectiveness of policy agreements (such as Kyoto), institutional conditions for infrastructural changes in energy supply."

• "Technological surprises: New developments or breakthroughs in technology or unexpected consequences ('side-effects') of technologies; *examples of* *uncertainties related to this source pertaining to integrated assessment of climate change:* Renewable energy options, ecological effects of large scale biomass plantation."

Uncertainty and unpredictability exists naturally in reality due to both variability and limited resources to measure and obtain empirical information. Thus, limited knowledge is a subset of variability. However knowledge regarding deterministic processes can also be incomplete and uncertain. Unceratinty associated with deterministic processes can be defined in several levels of exactness from inexactness to irreducible ignorance (Asselt and Rotmans 2002):

• "*Inexactness* (Zimmermann, 1996), also referred to as lack of precision, inaccuracy, metrical uncertainty, measurement errors, or precise uncertainties. 'We roughly know'. *Examples of uncertainties related to this source pertaining to integrated assessment of climate change:* Life-times of greenhouse gases."

• "*Lack of observations/measurements:* Lacking data that could have been collected, but haven't been. 'We could have known'. *Examples of uncertainties related to this source pertaining to integrated assessment of climate change:* Temperature feedbacks."

• "*Practically immeasurable:* Lacking data that in principle can be measured, but not in practise (too expensive, too lengthy, infeasible experiments). 'We know what we do not know'. *Examples of uncertainties related to this source pertaining to integrated assessment of climate change involve:* Indirect effects of aerosols."

• "*Conflicting evidence* (Zimmermann, 1996): Different data sets/observations are available, but allow room for competing interpretations. 'We don't know what we know'. *Examples of uncertainties related to this source pertaining to integrated assessment of climate change involve:* CO2-fertilisation effect."

• "*Reducible ignorance* (Funtowicz and Ravetz, 1990; Wynne, 1992): Processes that we do not observe, nor theoretically imagine at this point in time, but may in the future. 'We don't know what we do not know'. *Examples of uncertainties related to this source pertaining to integrated assessment of climate change involve:* Geophysical feedbacks."

• "*Indeterminacy* (e.g., Wynne, 1992): Processes of which we understand the principles and laws, but which can never be fully predicted or determined. 'We will never know'. *Examples of uncertainties related to this source pertaining to integrated assessment of climate change involve:* Weather dynamics."

• "*Irreducible ignorance:* There may be processes and interactions between processes that cannot be (or not unambiguously) determined by human capacities and capabilities. 'We cannot know'. *Examples of uncertainties related to this source pertaining to integrated assessment of climate change involve:* Role of sun spots."

These levels of uncertainty thus range from unreliability to more fundamental uncertainty (also called as radical, structural or systematic uncertainty). Uncertainties in the category of unreliability are usually measurable, or can be calculated, since they are associated with well-understood systems or processes. "Such measurable processes are also referred to as 'ergodic processes'. This implies that in principle either margins or patterns can be established, so that usually the uncertainty can be described quantitatively (either in terms of a domain or as stochastic equation)". On the other hand, radical uncertainty can at best be roughly estimated. They are generally associated with conflicting evidence, ignorance, indeterminacy and uncertainty due to variability. "It is even likely that the most salient uncertainties in an Integrated Assessment endeavour are radical." (Asselt and Rotmans 2002)

In light of the taxonomy of uncertainty presented by Asselt and Rotmans 2002, uncertainties regarding the preliminary vulnerability assessment model were discussed as;

Variability: When the physical impacts of sea level rise are considered, there are many sources of uncertainties related to variability. Coastal erosion and storm surges are mainly derived by ocean dynamics which show inherent randomness of nature while uncertainties due to value diversity and human behaviour can be seen in integration of human activities and physical processes such as the perception of decision makers/experts on the influence of sea level rise affecting coastal processes vs. existing impacts or implementation of integrated coastal zone management (in which the vulnerability assessment model is aimed to be implemented) vs. actual policy implementations. On the other hand, research on eco-friendly adaptation techniques and soft measures and the possibility of them being implemented can be considered as `technological surprises` which is another source of variability. As also stated by (Asselt and Rotmans 2002) this type of uncertainty (i.e. variability) can be at most roughly estimated. Thus these sources of uncertainties, although should be highlighted, can not be easily quantified, if can be quantified at all.

Limited Knowledge: On the other hand, sources of limited knowledge are also an important part of the vulnerability model's uncertainty as the main objective of the initial model (Ozyurt 2007) was to overcome the data limitation while considering interaction of human activities and physical processes. The driver of the vulnerability assessment which is sea level rise, itself, is a source of uncertainty in the sense of inexactness. Both the projections of sea level rise, as well as the present progress includes much uncertainty both in terms of lack of data as well as lack of knowledge regarding the driving forces such as melting of Greenland, future of ocean cycles, etc. Although many of the impacts of sea level rise can be measured (have been measured) such as shoreline recession rates (although these sets of measurements are either very scarce or their duration not long enough), the uncertainty, whether the results of these measurements are due to ocean dynamics of human alteration or sea level rise, is very high. This makes the direct measurement of impacts due to solely sea level rise practically immeasurable. On the other hand there is the ever persisting problem of lack of data which can actually be measured such as wave climate, tides, groundwater quality and quantity parameters, discharge, land cover changes, etc. These lack of observations and inexactness of the available measurements needs to be included and when necessary quantified in the vulnerability assessment model.

This discussion underlines the fact that although the variability component of uncertainty could not be included in this study, limited knowledge component should be included and since limited knowledge component is basically composed of data uncertainty, the type of available information and the uncertainties related to this information had to be considered.

6.3 Type of available information

"Uncertainty implies that in a certain situation a person does not dispose about information which quantitatively and qualitatively is appropriate to describe, prescribe or predict deterministically and numerically a system, its behavior or other characteristica" (Zimmermann 2000). When uncertainty of system is considered, both sources of uncertainty depend on the quality or quantity of available information. Thus the type of available information with respect to uncertainty has to be considered. This information can be numerical, linguistic, interval-valued or symbolic.

a) Numerical information

The definition of certainty in a study demands that a system can be described numerically. Thus the information about the system should also be available numerically. However the numerical information should also indicate the scale level on which this information is provided since this numerical information can come from quite a variety of sources. A nominal scale level indicates that the information provided (even though in numerical form) only has the function of a name, an ordinal scale level provides information of an ordering type and a cardinal scale level indicates information about the differences between the ordered quantities, i.e. contains a metric.

b) Interval-information

When the information is available, but not as precise in the sense of a real-valued number, the use of interval arithmetic is necessary and the outcome will again be interval-valued information. "It should be clear, however, that this information is also `exact' in the sense that the boundaries of the intervals (no matter how they have been determined) are `crisp' or exact" (Zimmermann 2000).

c) Linguistic information

"By linguistic information it is meant that the information provided is given in a natural language and not in a formal language (Bellman and Zadeh, 1970)" (Zimmermann 2000). The properties of linguistic information are different from numerical information or information in a formal language (e.g. low, medium, high, tall, etc). It is important to distinguish between a word as a label and the meaning of a word. Very often there is no one-to-one relationship between the label and the meaning. Additionally, the meaning of the word is highly context dependent and usually defined as continous functions. "By contrast to numerical information there are also hardly any measures of quality of information for natural languages (e.g. there are no defined scale levels for linguistic information). Linguistic information has developed as a means of communication between human beings and the `inference engines' are the minds of people about which is still much too little known"(Zimmermann 2000).

d) Symbolic information

Very often information is provided in the form of symbols: numbers, letters or pictures (such as pi). The information is as valuable as the definitions of the symbols are. It is important to understand that the type of information processing also has to be symbolic (not numerical or linguistic).

The parameters of vulnerability assessment model use different types of information as inputs and output. The input parameters are all numerical information even though different scales exist such as nominal scale for geomorphology or land use (although in words, these parameters are crisp values) and cardinal scale such as significant wave height in meters or flow rate of rivers in m^3/s. Some of the input parameters can be described both numerical or as interval information such as sediment budget describing the current condition of shoreline or hydraulic conductivity of an aquifer (in terms of range). This is possible since interval information is also extract when the boundaries are considered. On the other hand, the output variable which is vulnerability can be only defined as linguistic information such as the case in preliminary vulnerability model; very low, low, moderate, high and very high. The definition and characteristics of this type of information call for different methods when dealing with uncertainty since there is not an exact numerical and one-to-one correspondence for these values in crisp-mathematical sense.

6.4 Uncertainty methods

Uncertainty methods can be any of the probability theories available in literature such as fuzzy set theory, rough set theory, evidence theory, etc. "These theories build on certain axioms with respect to the uncertainty to be modelled and they propose generally a mathematical framework to arrive at measures of uncertainty (Dubois and Prade, 1989)" (Zimmermann 2000). These mathematical models require a certain scale level of numerical information. Thus when a specific uncertainty method is selected to be used, it is important to check that should not be used if its mathematical operations require a higher scale level than that on which the available information is provided. This is very often neglected when applying uncertainty models. Rather it is assumed that numerical information is available on a cardinal or absolute scale level and all the mathematical operations can be used.

To an increasing degree moreover, uncertain information or information about `uncertainties' is also processed in knowledge-based systems which can either be systems which essentially perform symbol processing or they perform meaning preserving inference. Obviously, for these systems different requirements exist and different types of information are offered at the end.

When the uncertainty methods are considered, it is important to include the type of information required by the end user. When the end user is human, the information has to be provided in a suitable language(type and scale level of information) that the end user can understand('readable') and has to meet additional requirements defined by the end use.

On the other hand, the uncertainty method used to describe the system should not require information on a higher level than provided. Also it should not make any axiomatic assumptions about the cause of uncertainty which are not satisfied by the real situation. "Hence, the theory which is appropriate to model a specific uncertainty situation should be determined by the properties of this situation as specified above and by the requirements of the end user" (Zimmermann 2000). Thus it is important to match uncertainty theory and uncertain phenomena correctly.

"Considering uncertainty as an informational feature of a situation or a phenomenon, it can be described by a 4-component vector. In this vector the four components describe the four dimensions which are roughly sketched in Table 6.1. Essentially each uncertainty theory can also be characterized by such a vector or profile. Optimally the profile of the theory should match the profile of the situation it is applied to. For the most common frequentistic probability theory (Kolmogoroff) it is rather simple to define its profile, which is:

$$\{a; a; c; a\}. \quad \text{Eq. 6.1}$$

For other probability theories it is already more difficult to determine an appropriate profile. For Fuzzy Set Theory the profile vector will certainly depend on the operators used, on the type of membership function assumed, on the scale level of the membership function, etc. Or, putting it the other way around, after the `uncertainty profile' of the uncertain situation has been determined that version of fuzzy set theory that matches the profile of the situation has to be found." (Zimmermann 2000)

Table 6.1 Rough taxonomy of uncertainty properties (Zimmermann 2000)

Rough taxonomy of uncertainty properties

Rough taxonomy of uncertainty models (not exhaustive, not disjunct)
1. *Causes of (subj.) uncertainty*
(a) Lack of information
(b) Abundance of information
(c) Conflicting evidence
(d) Ambiguity (complexity)
(e) Measurement
(f) Belief
2. *Available information (input)*
(a) Numerical
(b) Set-or interval-valued
(c) Linguistic
(d) Symbolic
3. *Scale level of numerical information*
(a) Nominal
(b) Ordinal
(c) Cardinal
4. *Required information (output)*
(a) Numerical
(b) Set- or interval-valued
(c) Linguistic
(d) Symbolic

Each of the available uncertainty theories make assumptions about available information contains a certain calculus (or several) by which these information or data are processed and certain `measures' of uncertainty. However as also mentioned before, it is very seldom that these theories are investigated whether they are adequate to a specific context. Zimmermann 2000 argues that "the modelling of uncertainty should not be done context free, the entire information flow from the phenomenon via the uncertainty theory to the end user has to be consistent with respect to quality and quantity of information".

This discussion of modelling uncertainty considering the context raises the following questions (a) what is the best way to model uncertainty? (b) how should measures of uncertainty be assessed, combined and updated? And (c) how should the measures be used to make inferences and decisions?

Before answering these questions, considering that the context is important when modelling uncertainty, it is mandatory to discuss the context of the coastal vulnerability assessment model to sea level rise. Problem solving is the process of finding a solution when the path leading to that solution is uncertain. Even though there are many problem solving techniques, for some complicated problems such as coastal zone management problems including vulnerability assessment where several complex and dynamic problems exist and interact within a dynamic environment, no straight forward solution technique can be applied.

"Conventional problem-solving computer programs make use of well-structured algorithms, data structures, and crisp reasoning strategies to find solutions. For the difficult problems with which expert systems are concerned, it may be more useful to employ heuristics: strategies that often lead to the correct solution, but that also sometimes fail. For these types of problems heuristic solution techniques may be the only alternative" (Abraham 2005).

Knowledge-based expert systems utilize a knowledge base which collects available human knowhow to reason through a problem, using the knowledge that is appropriate. An important advantage is that, different problems within the domain of the knowledge base can be solved using the same program. Moreover, expert systems could explain the reasoning process and handle levels of confidence and uncertainty, which conventional algorithms do not handle. Abraham 2005 stated some of the important advantages of expert systems as follows:

- "ability to capture and preserve irreplaceable human experience;
- ability to develop a system more consistent than human experts;
- minimize human expertise needed at a number of locations at the same time (especially in a hostile environment that is dangerous to human health);
- solutions can be developed faster than human experts". (Abraham 2005)

Coastal vulnerability assessment model is an expert system where the expert knowledge is integrated with solutions of other algorithms such as Bruun Rule for coastal erosion(Klein and Nicholls 1998), Ghyben-Herzberg for saltwater intrusion to groundwater resources (Sherif and Singh 1999). The use of expert system was mandatory since the complex interaction of human parameters and physical characteristics that define the impacts can not be effectively described by available problem solving techniques. The output of the model, vulnerability, being an linguistic variable that the end user can understand and process was an important limitation to use of classical numerical algorithms. (Zimmermann 2000) stated that context of the problem and context of the uncertainty dictated that the preliminary vulnerability assessment model had to be upgraded to an expert system. To comply with the discussion of Zimmermann 2000 the uncertainty model that was decided to be used in this study– Fuzzy Set Theory or Possibility Measures – and the context of the problem is discussed next, reflecting the taxonomy that Zimmermann 2000 (Table 6.1) provided.

When Table 6.1 is applied to the coastal vulnerability assessment problem which consists of several different physical processes and human activities that can be described in different time and space, it is seen that all causes of certainty defined in the Table is applicable as also stated previously. However when the most dominant ones (which are the reasons for selecting the appropriate uncertainty system at the same time) are considered, it could be ranked such that

1. Causes of uncertainty in this study
    a. Abundance of information: due to many processes and data reflecting the scale but also the climate change process which is itself very complex and has high uncertainty.
    b. Lack of information: in its broadest sense as also stated previously lack of information is the superset of the other uncertainties, however in the sense of taxonomy of Zimmermann, 2000 , information on the scale level of ratio, ordinal or nominal is considered as ‘qualitative lack of information’. In this sense, although some parameters have information of cardinal scale level such as discharge of rivers with corresponding occurring information (probability distributions which could be calculated if necessary), there are also parameters defined in ratio scale level

such as natural protection degradation or engineering frontage and in ordinal scale level such as geomorphology and linguistic information such as the output parameter vulnerability. This distribution of types of information calls for another uncertainty method other than probability.

  c. Ambiguity: the output value vulnerability being a linguistic type of information has ambiguity and adding more information on the context of the words 'high' or 'low' which describe vulnerability would decrease the uncertainty related to ambiguity.
  d. Measurement: in the sense of 'engineering measurements' and the quality of these available measurements are important in the application processes for coastal vulnerability model however due to lack of information being a more dominant source of uncertainty, the importance of measurement can be considered low since one of the aims of the model is to reflect the real world situation using the available data. Thus the model should consider the uncertainty related to measurement but should also be stable in the case of small uncertainties related to measurement.
  e. Conflicting evidence and belief (although both exists) are not considered in the problem of coastal vulnerability assessment.

2. Available information (input): Regarding input parameters used to define the coastal vulnerability in this study (input parameters such as rate of sea level rise, geomorphology, coastal protection structures, etc.), information could be numerical values or interval-valued depending on the parameter definition and level of information available at the study area.
3. Scale level of numerical information: with different scale levels (nominal, cardinal or ratio) depending on the definition of the input parameter of this study and the available information at the study site.
4. Required information (output): Vulnerability is a linguistic variable which do not have an universal definition nor could be only defined numerically without a linguistic context.

Using the context of the problem defined by the uncertainty taxonomy, the profile vector suitable for this context has to be at least:

$$\{[a,b,d,e];[a,b];[a,b,c];[c]\} \qquad \text{Eq.6.2}$$

The output vector being the dominant parameter for selecting the suitable uncertainty model, fuzzy set theory or possibility measures were applied to handle the uncertainty of the coastal vulnerability assessment problem since the concept of linguistic variable plays a pivotal role in all applications of fuzzy logic and the concept of granularity (a granule variable X is a clump of values of X which are drawn together by indistinguishability, equivalence, similarity, proximity or functionality) underlies the concept of a linguistic variable(Zadeh 2005). Additionally, granulation (basis of fuzzy set theory) is rationalized by Zadeh, 2005 for the following reasons:

- Bounded ability of sensory organs and ultimately the brain (complexity or abundance of information) (1-b)
- When numerical information may not be available (lack of information) (1-a&d)
- When an attribute is not quantifiable (linguistic type of information) (2&4-c)
- Where there is a tolerance for imprecision (measurement) (1-e)

This rationalization enables to develop a uncertainty vector for any fuzzy set theory application since any type of information can be used as input at any scale level of numerical information and for output it can be linguistic (Mamdani type) or numerical (Sugeno type). The granulation dictates the general uncertainty profile vector of fuzzy set theory as:

$$\{[a,b,d,e];[a,b,c];[a,b,c];[a,b,c]\} \qquad \text{Eq.6.3}$$

Thus a higher uncertainty vector defined by problem context can be defined for the uncertainty model complying with discussions of Zimmermann 2000. This ensures that the fuzzy set theory will reflect uncertainty accurately.

6.5 Fuzzy decision-making

Probability concept is widely used when vagueness or uncertainty inherent in real-world phenomena are modelled. However, two potential issues arise with using probabilistic models. First, some natural sources of uncertainty may not exist in a form that fits a known probability distribution. Second, the nature of process might not be suitable for the use of probability theory and randomness.

The basic idea that conventional mathematics should be augmented to describe complex systems prompted Lotfi Zadeh to generate an alternative form of mathematics, which began with his theory of fuzzy sets (Zadeh 1965) and later generalized into "soft computing" (encapsulating techniques such as fuzzy systems, neural networks, and genetic algorithms).

Fuzzy set theory and fuzzy logic provide a system of mathematics that maps directly into natural language, thus capturing complex interactions between variables in qualitative descriptions that lend themselves to everyday reasoning. The potential of the fuzzy system approach for modeling human judgment and decision making lies in several critical features. Zadeh (2005) describes these features as:" (a) fuzzy systems as model-free estimators or universal approximators; (b) fuzzy sets as a method to capture the imprecision associated with everyday reasoning; and (c) the representation of human judgment models as fuzzy rules, formed on the basis of fuzzy sets."

Many traditional mathematical and statistical techniques are able to model more complex, nonlinear functions. However, these models require a priori specification of model form such as specification of the type of relation expected. On the other hand, it is unlikely that an a priori identification of model terms can be assessed given the current lack of knowledge about nonlinear, noncompensatory processes in many areas of human performance and decision-making research. Thus, fuzzy systems theoretically enable capturing human judgment strategies of arbitrary complexity.

"The potential of the fuzzy system approach for modeling uncertainty in environmental decision-making lies in several critical features including (i) fuzzy logic as a method to capture the imprecision associated with everyday reasoning; and (ii) the representation of human judgment models as fuzzy rules. Furthermore, fuzzy systems offer opportunities to model environmental processes for which only a linguistic description is available; non-fuzzy techniques (e.g., probabilistic tools and Monte Carlo simulation) cannot handle the imprecision and vagueness of semantic aspects which are inherent in linguistic uncertainty.

The ability to integrate expert knowledge (structured mainly by means of linguistic expressions) concerning environmental and ecological relationships, as well as the availability of qualitative data (e.g., habitat variables), are frequently cited as important reasons to use fuzzy system tools (e.g., fuzzy-rule-based models for decision support and predictive modelling) to deal with uncertainty inherent in ecosystem management. Fuzzy sets and rules have been constructed for implementation in integrated environmental management, sustainable development, threatened species classification, and groundwater management. Fuzzy set theory has also been used to characterise uncertainty in engineering design calculations, wastewater sludge disposal, and solute transport modelling. By addressing areas of uncertainty, ambiguity, and dissent in the decision process, fuzzy set techniques provide the opportunity to improve both immediate short-term decisions and the strategic aspect of environmental management." (Dorsey and Coovert 2003)

Central to applications of fuzzy systems is the concept of a *fuzzy set,* the members of which belong to it to some degree. Fuzzy sets, as opposed to crisp sets, have a gradual transition from membership to non membership in the set. Membership degree in a fuzzy set is specified as a real number on the interval [0, 1], with 0 indicating that the element does not belong to the set and 1 indicating that the element belongs 100%. In essence, the membership function defines the shape of the fuzzy set.

This property of fuzzy sets can be very efficient when classification of parameter is considered, especially parameters that are defined by single crisp values which are also approximations or defined as intervals. One such example can be categorization of winds as given in (Hansen 1997).

"The conventional way of verifying, or measuring the accuracy of a marine forecast is to examine records of forecast and observed winds and check whether the forecast and observed winds are within the same crisp categories. For instance, winds equal to or greater than 34 knots belong to the category of *gales*. Gales imply hazardous conditions for many mariners. When forecasters predict that gales will blow, they issue warnings to that effect. Periodically, the accuracy of the forecasts is examined and tabulated. The case of an accurate forecast is called a "hit." An inaccurate forecast is called a "miss." The membership function of a wind speed in the category of gales is shown in Figure 6.2.

The rules of verification are simple: winds of 33 knots or less are not gales; winds of 34 knots or more are. The implication is that 5 knot winds and 33 knot winds are one type of wind, and 34 knot winds and 50 knot winds are another type of wind. This is absurd; there is hardly any difference between a 33 and a 34 knot wind, yet they fall into opposite categories.

In actual practice, meteorologists avoid the trap of categorizing winds in a simple binary way. Winds in the range of 28 to 33 knots are treated as "near gales" and are regarded separately from those winds under 28 knots and those of 34 knots or more. This is a reasonable practice where linguistic variables are used defined the crossover range from not gales to gales. Additionally, forecasts apply to thousands of square miles of ocean. Over the course of six hours, meteorologists typically receive only several actual wind observations with which to verify a forecast. If one of the reports is of 30 knots, it is not unreasonable to suppose that nearby winds may have reached 34 knots. One cannot be certain that gales blew or that they did not.

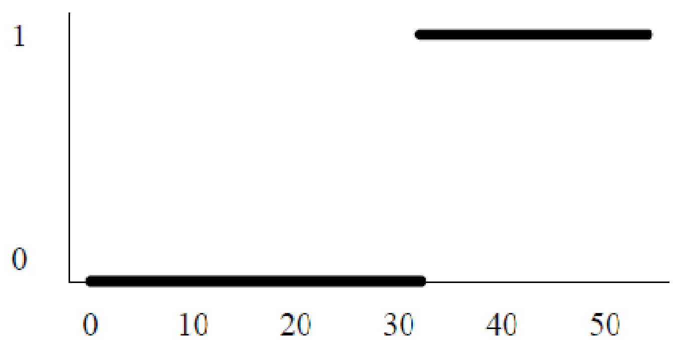


Figure 6.2 The membership function of a wind speed in the category of gales when crisp values are used for classification

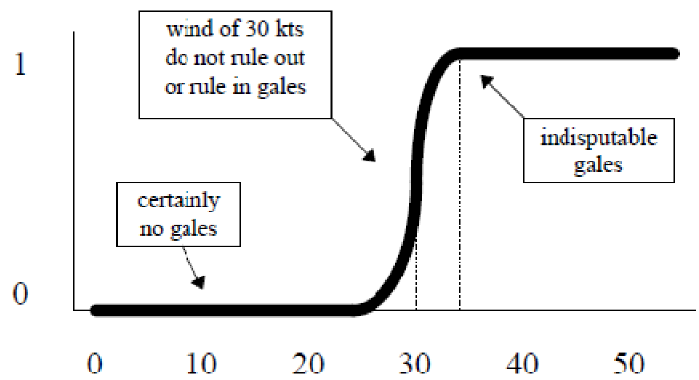


Figure 6.3 The fuzzy membership function of a wind speed in the category of gales

With fuzzy methods enabling advances in a rapidly increasing number of data processing and expert system applications, meteorological data is amenable to treatment with it. For instance, consider the trivalent treatment of winds shown in Figure 6.3. The function shown in Figure 6.3 models the intuitive decision making behavior of a meteorologist. In plain English: A wind measurement of 10 knots very strongly refutes the presence of gales. A wind measurement of 34 knots or more definitively confirms the presence of gales. A wind measurement between 28 and 33 knots is suggestive of gales, and the closer the speed is to 34 knots, the stronger one's belief is in the presence of gales." (Hansen 1997)

The same discussion is true when classification of coastal parameters is considered such as wave climate, tide ranges where crisp boundaries do not reflect real system. Additionally, human parameters included in coastal vulnerability assessment can easily be classified by clustering. The uncertainty of these classifications (classes which are arbitrary initially) can be handles much easily reflecting real system by the use of fuzzy sets or fuzzy membership functions.

Fuzzy systems also use rules, that associate multiple output or consequent fuzzy sets with multiple input or antecedent fuzzy sets. "Fuzzy rules are implemented using a process called *inferencing*. Inference engines perform a series of steps to computationally link inputs to outputs. These steps include the following: (a) inputs are "fuzzified" by comparing input variable values with membership functions in fuzzy sets used to define the input variables; (b) fuzzy logic operators are applied if a rule has more than one part to define a single antecedent for each rule; (c) an "implication" is formed such that an output is generated (based on output fuzzy sets) from a rule's antecedent; (d) outputs across rules are combined; and (e) the output is "defuzzified," yielding a single number" (Gulley & Jang, 1995).

"Given the structure of fuzzy rules and fuzzy systems, it seems plausible that a judgment policy can be represented not only in terms of low-level mathematical/statistical equations (e.g., regression models) but also as structured knowledge, in the form of fuzzy systems."(Dorsey and Coovert 2003)

Two fuzzy inference systems are widely used in various applications. Mamdani's fuzzy inference method is the most commonly seen fuzzy methodology. Mamdani-type inference expects the output membership functions to be fuzzy sets. After the aggregation process, there is a fuzzy set for each output variable that needs defuzzification.

A typical example for IF-THEN rule for Mamdani-type inference system can be given from a study on groundwater pollution vulnerability assessment study by (Afshar et al. 2007)

IF _Depth to water is low_

AND _Vadose zone is high_

AND _Net recharge is high_

AND_Aquifer media is high_

AND _Hydraulic conductivity is high_

AND _Soil media is medium_

AND _Topography slope is low_

THEN _Vulnerability is very high_ Eq.6.4

As can be seen clearly from the example rule, several input parameters with corresponding subdivisions are combined by expert opinion to give an output value of "very high" in terms of vulnerability. Although almost all the input parameters could be explained numerically, the output parameter can only be defined linguistically meaning use of fuzzy sets; thus, the use of Mamdani-type Inference System.

On the other hand, it is possible, and in many cases much more efficient, to use a single value as the output membership function rather than a distributed fuzzy set. This type of output is sometimes known as a singleton output membership function, and it can be thought of as a pre-defuzzified fuzzy set. It enhances the efficiency of the defuzzification process because it greatly simplifies the computation required by the more general Mamdani method, which finds the centroid of a two-dimensional function. Rather than integrating across the two-dimensional function to find the centroid, the weighted average of a few data points are used. These types of systems are called Sugeno-type systems and they can be used to model any inference system in which the output membership functions are either linear or constant.

An example for Sugeno-type systems can be given from another fuzzy expert system which assess the environmental effect of pesticides to field crops by (Roussel et al. 2000);

IF _Rate of Application is Favourable_

AND _DT50 is Unfavourable_

THEN _Environmental Effect equals to 0.5. Eq.6.5

As can be seen from the example, Sugeno-type systems can be used when the experts can assign exact values or when the output needs to be a constant number or linear expression. Most of the time, Sugeno-type systems are used with control systems where input and output parameters can be defined in numerical format and the system requires for a numerical output.

The main difference between Mamdani and Sugeno is that the Sugeno output membership functions are either linear or constant. Also their aggregation and defuzzification procedures differ. Advantages of Sugeno method can be summarized as: it is computationally efficient, it works well with linear techniques as well as optimization and adaptive techniques, it has guaranteed continuity of the output surface and it is well suited to mathematical analysis. Advantages of Mamdani method is that; it is intuitive, it has wide spread acceptance and it is well suited to human input.

6.6 Fuzzy Coastal Vulnerability Assessment Model Structure

Considering the limitations and advantages of the two inference methods, as well as the nature of the research problem which is assessment of vulnerability of coastal areas to sea level rise; Mamdani type method was decided to be applied for this study. Vulnerability has no universal and clear-cut definition. Also there is not a measurable data that can directly quantify vulnerability. Thus the use of Mamdani type method is most suitable for expert system to assess the vulnerability of coastal areas. The fuzzy vulnerability assessment method is described in detail following the main blocks of fuzzy inference system.

6.6.1 Database and fuzzification interface

To derive the fuzzy membership functions of each input parameters, the fuzzy c-means clustering method (MATLAB Fuzzy Logic Toolbox) is used to form clusters of the data gathered from different databases (See Chapter 4). However, the final membership functions were determined by comparing and integrating initial classifications of parameters used in preliminary vulnerability model, i.e. expert judgements (See Chapter 5), with the output of FCM analyses. The results were then used as input membership functions to the fuzzy inference systems which were explained in the next sections.

6.6.1.1 Fuzzy C-Means Clustering

"Fuzzy c-means (FCM) is a data clustering technique wherein each data point belongs to a cluster to some degree that is specified by a membership grade. This technique was originally introduced by Jim Bezdek in 1981 as an improvement on earlier clustering methods. It provides a method that shows how to group data points that populate some multidimensional space into a specific number of different clusters. The algorithm starts with an initial guess for the cluster centers, which are intended to mark the mean location of each cluster. The initial guess for these cluster centers is most likely incorrect. Additionally, it assigns every data point a membership grade for each cluster. By iteratively updating the cluster centers and the membership grades for each data point, the algorithm iteratively moves the cluster centers to the right location within a data set. This iteration is based on minimizing an objective function that represents the distance from any given data point to a cluster center weighted by that data point's membership grade.

The algorithm outputs a list of cluster centers and several membership grades for each data point. This information returned by fuzzy c-means clustering help to build a fuzzy inference system by creating membership functions to represent the fuzzy qualities of each cluster. Membership functions for the fuzzification of the data are generated by projecting the resulting clusters onto the axes of each component of data.

The advantages of the FCM algorithm are: (i) it can be used as an unsupervised algorithm, (ii) it can be used to generate multi-dimensional membership functions, and (iii) the shape of the membership functions can be controlled by using different types of distance measures. However, the number of classes must be provided to run the algorithm. Additionally, the memberships cannot distinguish between a moderate outlier and an extreme outlier. This makes the FCM algorithm sensitive to outliers."(Medasani et al. 1998)

6.6.1.2 Membership Functions

Determining the shapes of the membership functions is an important step of developing any fuzzy system since the accuracy of the membership functions ensure that uncertainty of the represented system is kept at a minimum. Although there are many methods to generate membership functions, most of the time "experts" determine the outcome. This is mainly due to lack of knowledge or data. Most of the time, several membership functions and classes are tried to finalize the model. While it is a highly subjective process, it is also not very efficient.

For fuzzy vulnerability assessment model proposed in this study; the subjectivity related to membership functions are kept at a minimum by using the database that is developed. Fuzzy c-means algorithm analyzed the available data (which almost cover every type of coastal geomorphology) to determine the membership functions of each parameter. The "expert opinion" was used later when approximating the Gaussian shaped FCM outputs to triangular membership functions.

The procedure is shown in detail for some of the parameters below. However, fuzzy c-means clustering plots, preliminary classifications and the final membership function diagrams are presented for each parameter in the Appendix C.

a) Rate of Sea Level Rise

This parameter is used as the basic input parameter for the vulnerability assessment. The initial data used were gathered from 237 measurements along European coasts. This data then, analyzed by using FCM algorithm of MATLAB Fuzzy Logic Toolbox to be classified around 5 center points which were statistically derived by the FCM algorithm as well. The center points, fcm plot are given in Figure .

Centers: -7,356, -3,837, -0,706, 1,003, 1,785

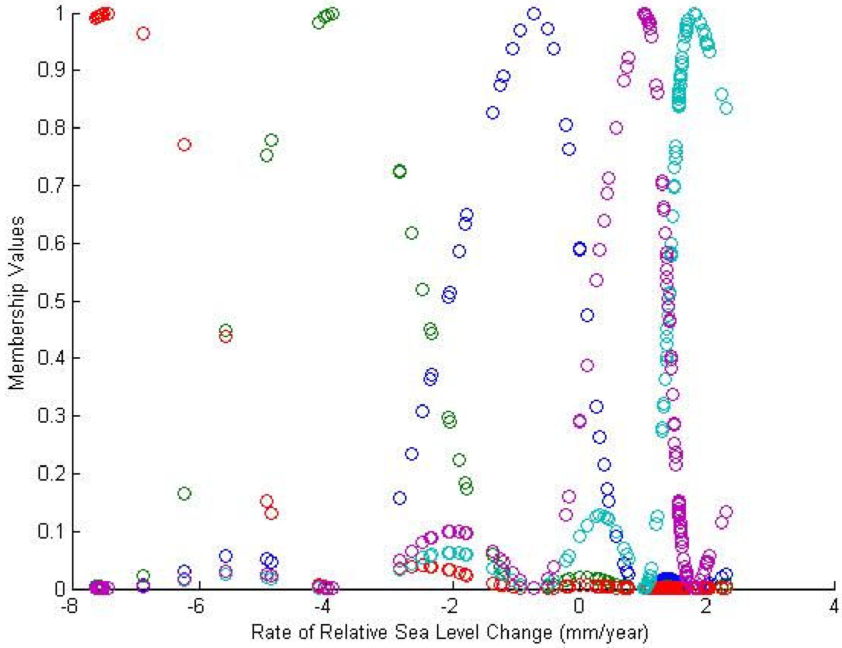


Figure 6.4 FCM results for rate of relate sea level change (mm/year)

As can be seen from the plot (Figure 6.4) the membership values are scattered following normal distribution. It is an accepted practice that to have simple fuzzy membership functions, normal distributions can be approximated to triangular fuzzy functions. Although some information is lost through the process, the simplicity this approximation provides is much more important. However, as also can be seen from the plot, two functions at the both ends can be approximated as trapezoid fuzzy functions both the shape of the plot as well as the fact that there might be observations beyond the scale of the x-axis. These observations would belong to the nearest cluster/function.

Table 6.2 shows the parameter membership values, initial classification from the preliminary vulnerability model and the final membership function values. The final fuzzy functions determined as input for inference systems are shown in MATLAB environment as well.

Table 6.2 Classification values of rate of relative sea level change for the models

Membership function shape	FCM results	Initial Classification	Final Fuzzy Membership Functions
Trapezoid	[-10 -8 -7 -4]	<1	[-18 -11 -1 0]
Triangle	[-7 -4 -0.5]	1-2	[-1 0 1]
Triangle	[-4 -0.5 1]	2-5	[0 1 2]
Triangle	[-0.5 1 2]	5-7	[1 3 5]
Trapezoid	[1 2 4 8]	>7	[3 5 15 20]

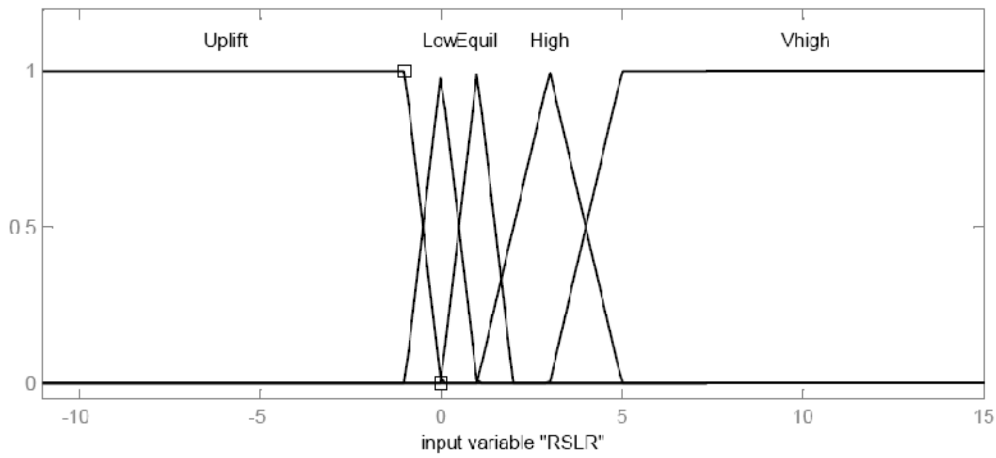


Figure 6.5 Membership function plots for Rate of Sea Level Rise

Although Figure 6.5 was used as the input membership function plot for this parameter, sensitivity analysis showed that the membership function needed to be re-evaluated (See Appendix for the discussions). In order to re-analyze the parameter, additional data was gathered and integrated to the existing database. Then, this new dataset was analyzed using fcm algorithm. In addition to new data, the dataset was reorganized such that only positive values indicating sea level rise were analyzed since any negative values indicate that there is uplift and no sea level rise is observed, thus no impact of sea level rise. For such cases, the rate of sea level rise parameter is automatically assigned as very low vulnerability, and the fuzzy vulnerability assessment model calculates the present vulnerability of the region with respect to possible problems such as coastal erosion or flooding due to storm surges. The resulting fcm plot is shown in Figure 6.6 with centers at 1.0, 3.0, 6.5, 14.0 and 26.5 mm/year. And the new membership function plot is given in Table 6.3 and Figure 6.7.

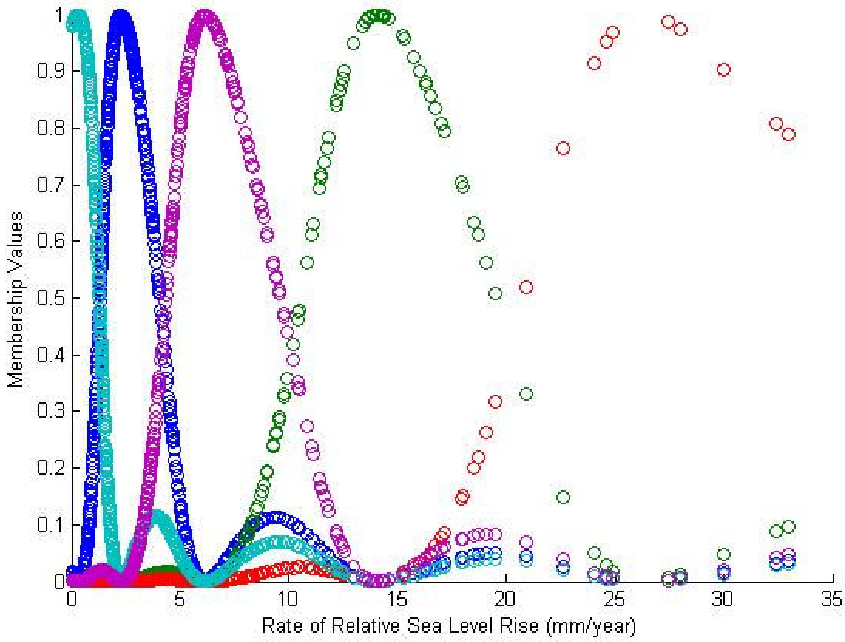


Figure 6.6 FCM results for rate of relate sea level change (mm/year) including additional data

Table 6.3 New classification values of rate of relative sea level change for the models

Membership function shape	FCM results	Initial Classification	Final Fuzzy Membership Functions
Trapezoid	[-10 -8 0 1]	<1	[-18 -11 -1 0]
Triangle	[1 3 6.5]	1-2	[-1 1 3]
Triangle	[3 6.5 14]	2-5	[1 3 6]
Triangle	[6.5 14 26.5]	5-7	[3 6 15]
Trapezoid	[14 26.5 35 45]	>7	[7 15 25 40]

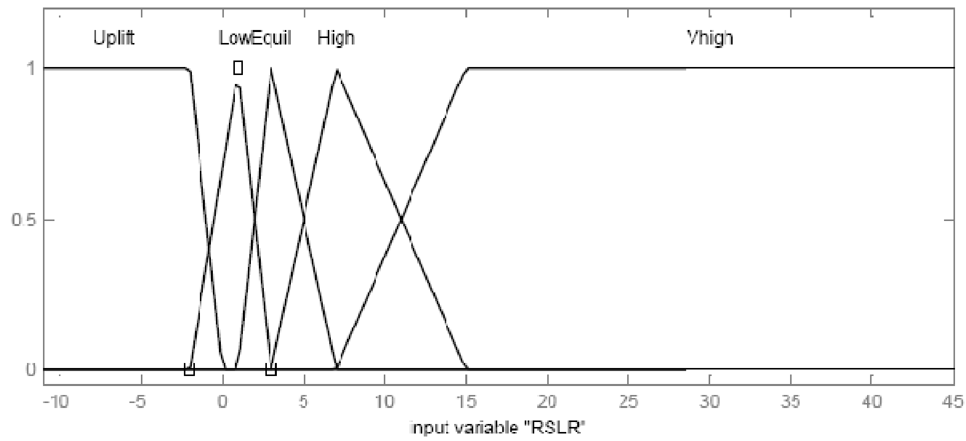


Figure 6.7 New membership function plots for Rate of Sea Level Rise

b) Geomorphology

Geomorphology is a variable that needs to be defined verbally. Initial classification was proposed by (Thieler and Hammar-Klose, 2000) and this was used in the preliminary model. This classification was kept as it is in the fuzzy vulnerability model however in order to integrate this parameter, each classification group was assigned an integer as follows:

Group 1: Rocky cliff coasts, fiords = 1

Group 2: Medium cliffs, indented coasts = 2

Group 3: Low cliffs, glacial drift, alluvial plains = 3

Group 4: Cobble Beaches, estuary, lagoon = 4

Group 5: Barrier beach, sand beach, salt marsh, mudflats, deltas, mangrove, coral reefs = 5

These integers are crisp values that can be used as input of the fuzzy inference system. This is performed by defining these values as straight lines having membership function values as 1 (Figure 6.8).

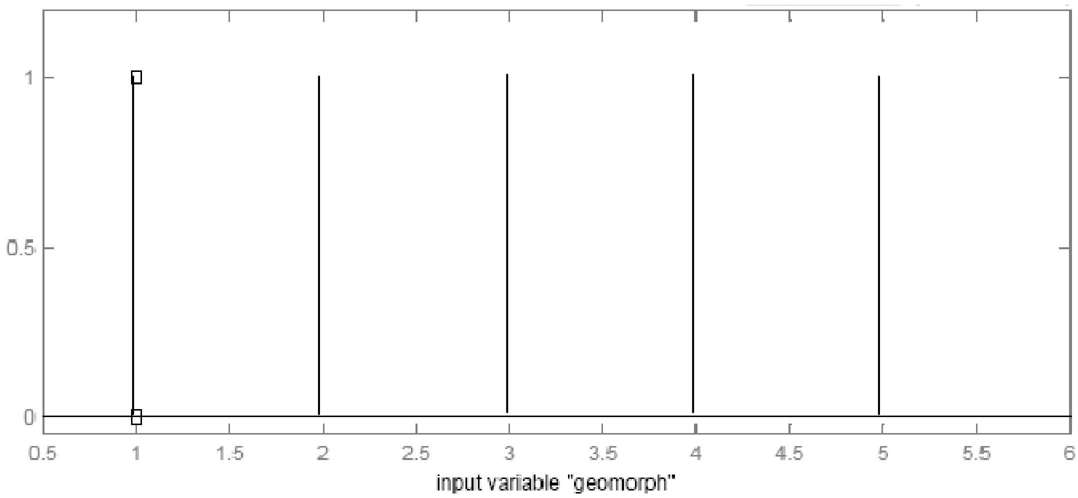


Figure 6.8 Membership function plots for Geomorphology

c) Beach Slope

The data collected was given in degrees. However during implementation beach slope is usually given in fractions which can be easily interpreted in percentages such as m=1:100=%1. So the data was first converted to percentage values and then analyzed by using FCM algorithm of MATLAB Fuzzy Logic Toolbox to be classified around 5 center points which were statistically derived by the FCM algorithm as well. The center points, fcm plot are given in Figure 6.9.

Centers: 0,309 1,122 2,188 4,360 7,560

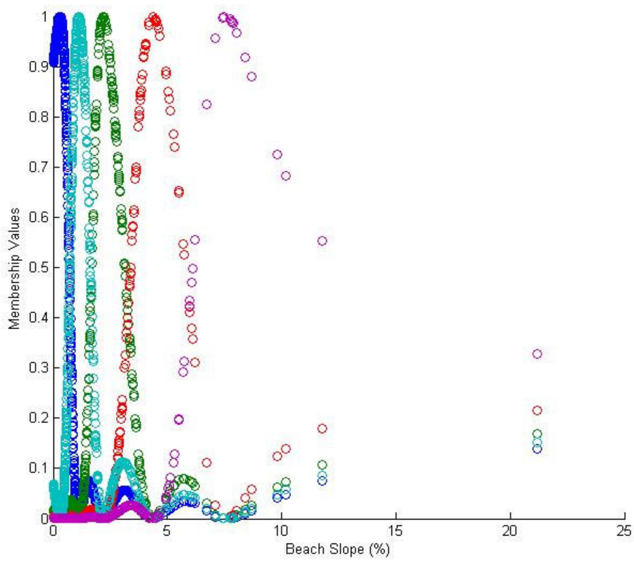


Figure 6.9 FCM result for beach slope

As can be seen from the plot (Figure 6.9) the membership values are scattered following normal distribution. Following the discussion on rate of sea level rise parameter, the end functions were trapezoid fuzzy functions while the middle functions have triangular shape for simplicity. Table 6.4 shows the parameter membership values, initial classification from the preliminary vulnerability model and the final membership function values. The final fuzzy functions determined as input for inference systems are shown in MATLAB environment as well.

Table 6.4 Classification values of beach slope for the models

Membership function shape	FCM results	Initial Classification (%)	Final Fuzzy Membership Functions
Trapezoid	[0 0 0.3 1.1]	1–2	[0 0 0.6 1]
Triangle	[0.3 1.1 2.2]	2-3.3	[0.6 1 2.5]
Triangle	[1.1 2.2 4.4]	3.3-5	[1 2.5 5]
Triangle	[2.2 4.4 7.5]	5-10	[2.5 5 10]
Trapezoid	[4.4 7.5 25 50]	>10	[5 10 25 50]

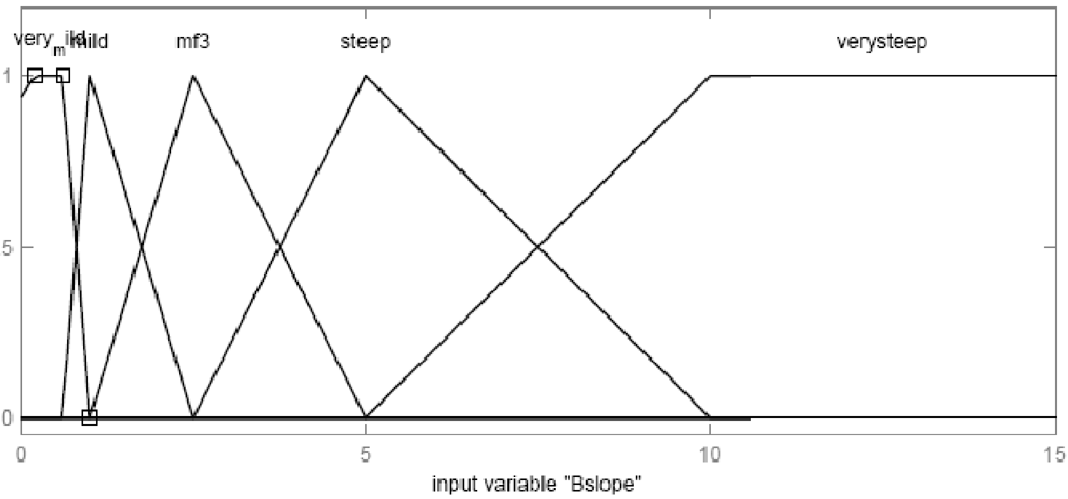


Figure 6.10 Membership function plots for Beach Slope

Although Figure 6.10 was used as the input membership function plot for this parameter, sensitivity analysis showed that the membership function needed to be re-evaluated. (See Appendix for the discussions). It was seen that three fuzzy membership functions are defined within 0-5% range and this causes discrepancies in the outcome since input uncertainties are high due to larger overlapping areas of these fuzzy membership functions. In order to eliminate this problem, another fcm analysis was performed using 4 centers. The resulting fcm plot is shown in Figure 6.11 with centers at 0.38, 1.57, 4.1 and 7.4. And the new membership function plot is given in Table 6.5 and Figure 6.12.

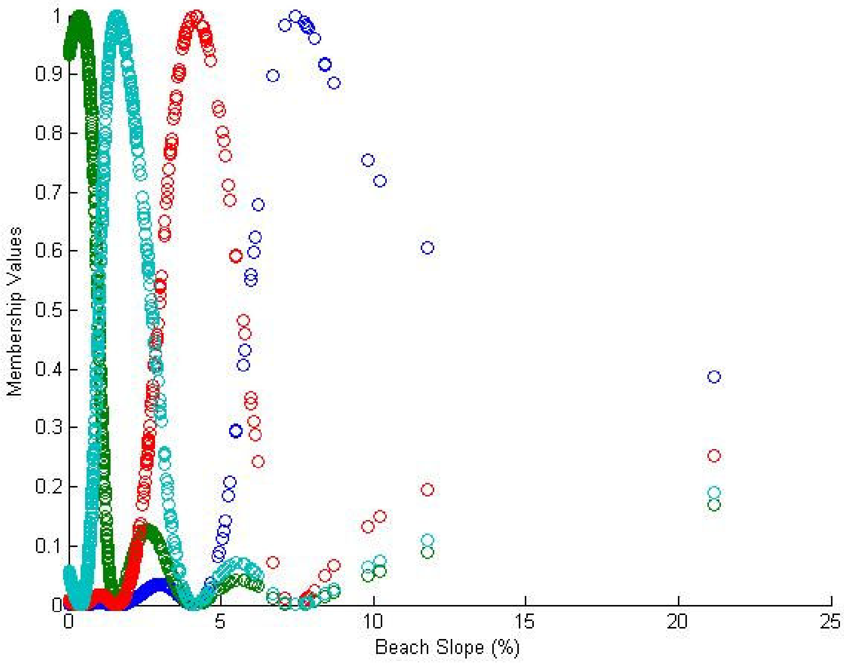


Figure 6.11 FCM results for beach slope – 4 classes

Table 6.5 New classification values of beach slope for the models

Membership function shape	FCM results	Initial Classification (%)	Final Fuzzy Membership Functions
Trapezoid	[0 0 0.4 1.6]	1–2	[0 0 0.5 2]
Triangle	[0.4 1.6 4.1]	2-3.3	[0.5 2 5]
Triangle	[1.6 4.1 7.4]	3.3-5	[3 5 7.5]
Triangle		5-10	[5 7.5 10]
Trapezoid	[4.1 7.5 25 50]	>10	[7.5 10 25 50]

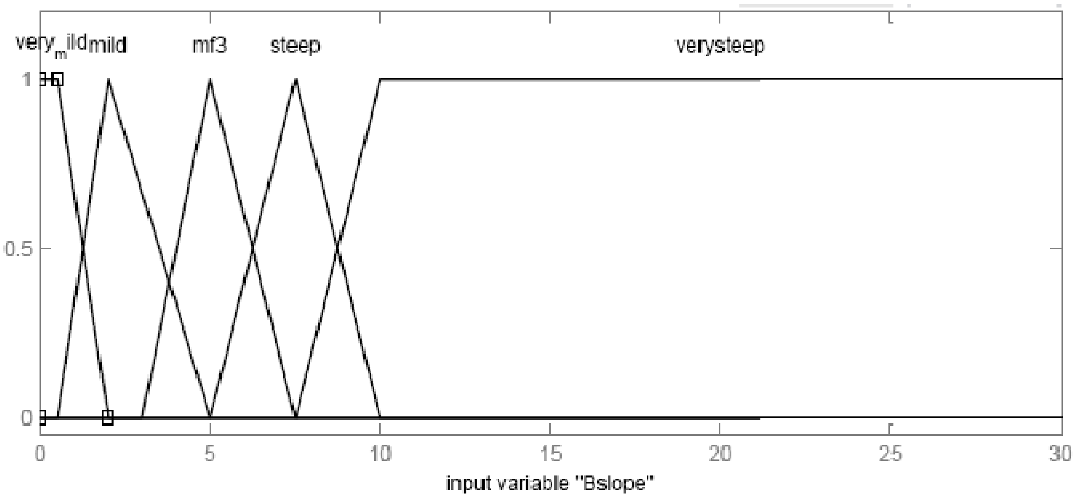


Figure 6.12 New membership function plot of beach slope

d) Sediment Budget

Although there is data that is used to describe sediment budget, the data was also described verbally and this description does not include any numerical information on the classification. It is described such as "erosion confirmed generalized to almost whole segment" or "on parts of segment". On the other hand, the initial classification was taken from (Thieler and Hammar-Klose, 2000) . Thus to eliminate the verbal descriptions of the data such as erosion and accretion, these words are described as – for erosion and + for accretion. The ranges are defined by combining (Thieler and Hammar-Klose, 2000) and expert opinion. Since the ranges could be classified with less uncertainty, trapezoid functions are used to define this parameter. Table 6.6 shows the parameter membership values, initial classification from the preliminary vulnerability model and the final membership function values. The final fuzzy functions determined as input for inference systems are shown in MATLAB environment as well.

Table 6.6 Classification values for sediment budget for the model

Membership function shape	FCM results	Initial Classification	Final Fuzzy Membership Functions
Trapezoid		>50% erosion	[-100 -100 -50 -25]
Trapezoid		10-30% erosion	[-50 -30 -15 0]
Trapezoid		<10% erosion/accretion	[-20 -10 10 25]
Trapezoid		10-30% accretion	[0 20 30 50]
Trapezoid		>50% accretion	[25 50 100 100]

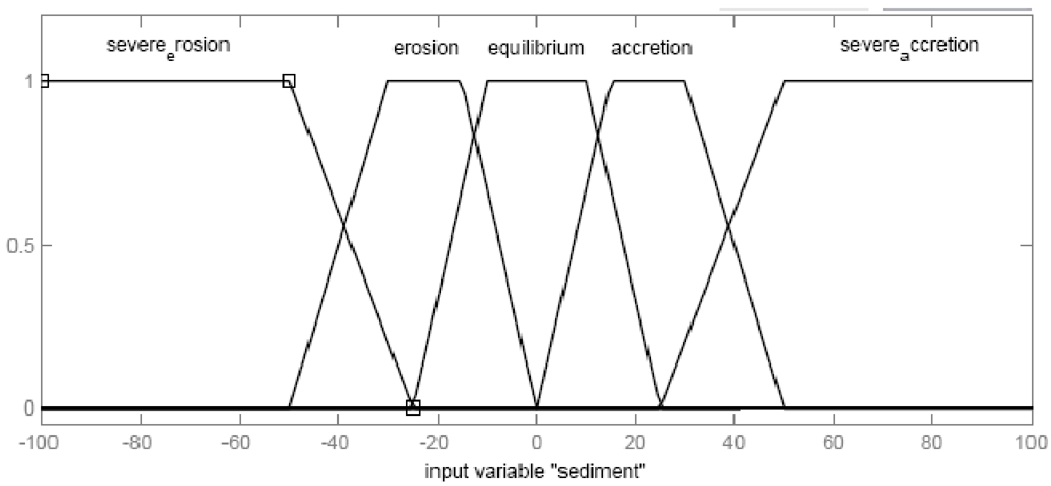


Figure 6.13 Membership function plots for Sediment Budget (%).

e)Vulnerability Membership Function:

Although vulnerability is defined as function of impact, sensitivity and adaptive capacity, there is no universal definition of vulnerability or it is a directly measurable parameter. How it is defined depends on linguistic information such as low, medium, high, etc. Both the quantification of the vulnerability as a parameter as well as quantification of the linguistic information depend on the expert which is the main reason for using fuzzy expert system methodology for the fuzzy coastal vulnerability assessment model to sea level rise. The membership function defining vulnerability depends on expert institution which was also used in the preliminary model. The membership function is composed of 5 trapezoidal functions defining very low, low, moderate, high and very high vulnerability. The boundaries of each trapezoidal function and the membership function plots are given in Table 6.6 and Figure 6.14.

Table 6.6 Classification values of vulnerability

Membership function shape	Fuzzy Membership Functions
Trapezoid	[0 0 1.25 1.75]
Trapezoid	[1.25 1.75 2.25 2.75]
Trapezoid	[2.25 2.75 3.25 3.75]
Trapezoid	[3.25 3.75 4.25 4.75]
Trapezoid	[4.25 4.75 5 5]

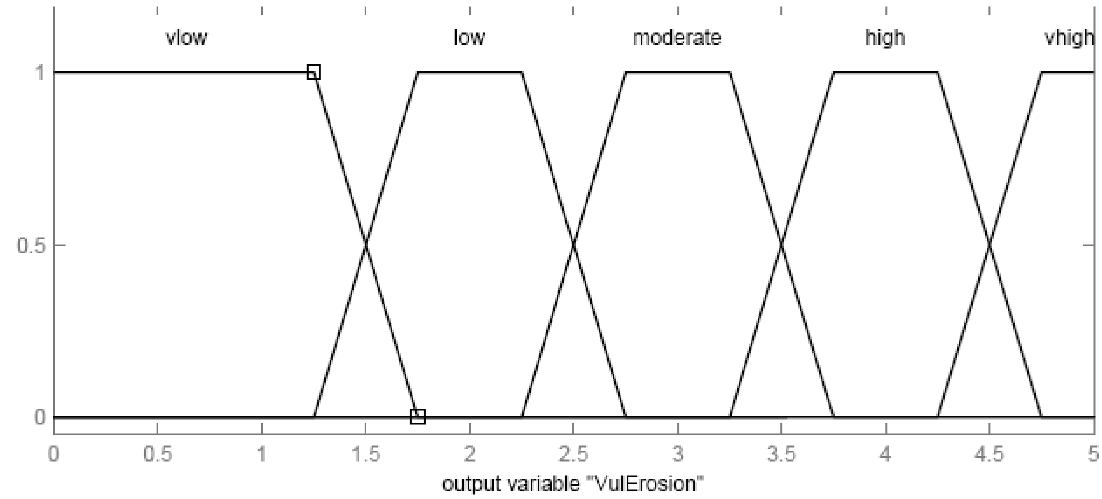


Figure 6.14 Membership function plot for vulnerability

6.6.2 Rule Base

The fuzzy inference system is consisted of a rule base which enables the mapping of inputs to output variable. The objective is to generate necessary IF-THEN rules which will give the accurate output value whatever input value is given by the end user to the system.

It is important that each and every input parameter is mapped to an output value through rule base. This means that if each input variable is divided into 5 domains as is the case of fuzzy vulnerability assessment model, considering 20 parameters, a total of 5^{20} rules mapped to only 5 divisions of the output parameter which is the vulnerability. This could require an extensive amount of rule generation for the rule base which might not be efficient in terms of applicability of the fuzzy expert system such that either some of the rules could be futile or nonexistent in real world.

There are different methods to derive rules from available data such as neural network, genetic algorithm, clustering and expert intuition almost similar to generation of membership functions which eliminate the "don't care" rules that do not change the output if the state of input changes (Afshar et al. 2007). However, not having a measurable output parameter such as vulnerability limits the use of most of these methods especially in rule generation where mapping of input values to output values are used as training sets. Thus, the rule bases for fuzzy vulnerability assessment model are constructed by expert intuition using the preliminary vulnerability model as a basis.

Considering the rule generation process as well as to comply with the initial aims of the preliminary vulnerability assessment model, using Mamdani Inference System, the structure of the fuzzy expert system was such that it was built from several modules. Using a structure based on modules enable the model to consider the components of impact individually which in turn enables comparison between anthropogenic and physical properties of a region; to consider the impacts individually or all of them can be aggregated into an overall indicator of vulnerability which enables ranking of different regions according to their vulnerability to sea level rise. This modular structure has several advantages as mentioned in the overall objective sense and also existing modules can be upgraded or new modules can be integrated as availability of data and understanding the processes and integration of impacts of sea level rise increases. For example, adaptive capacity which mostly depends on socio-economic parameters could be integrated to this model in the future from interdisciplinary research with ease.

The structure of fuzzy vulnerability assessment model is defined as follows (Figure 6.15):

1. Each impact of sea level rise was considered to be composed of two fuzzy inference systems; physical inference system and human inference system.
2. Each physical and human inference system have their own inputs and rule bases. However output parameter is always the vulnerability parameter which has the same membership function throughout the fuzzy vulnerability assessment model. The rule bases were determined by mapping the subdivisions of each input parameter to an appropriate subdivision of the output parameter. When rule bases were formed, no rules are formed which considers the interactions between input parameters (contarary to given example in Section from (Afshar et al. 2007))but rather weights assigned to the parameters and the aggregation operator are used to include the interaction between the individual inputs at the end of the system. The weight of each rule depended on the weight of the input parameter which was assigned through analytical hierarchy process (See Chapter 4).
3. Once each physical and human inference systems were run, the output variables were given as crisp values which were in turn used as input values for the impact inference systems.
4. Each impact was assessed by its own inference system where two input values; physical and human vulnerability scores were given into the inference system. The rule base was composed of IF-THEN rules which considered combination of both input parameters in the antecedent and the output parameter – vulnerability – in the consequent. These rules were again based on expert intuition. The defining concept for expert intuition was to assign the higher subdivision of output parameter when two different subdivisions are combined in the rule to protect the resources at hand (to be on the safe side at all times). At the same time, sustainability concept was introduced when the rule bases were developed such that in those cases when the input subdivisions combined show vast difference, a middle value was assigned to the output (mostly one step higher than the exact middle value to comply with protection of the resources objective). The output value when defuzzified determines the vulnerability score of the coastal zone with respect to the specific impact of sea level rise.
5. For the comparison of vulnerability of different regions, an overall vulnerability score is used for ranking, which is calculated by using fuzzy arithmetic. Since it is not possible even with expert intuition to develop a rule base for this final module at the moment, simple aggregation of outputs of impact modules in fuzzy format and then defuzzifying this

aggregated fuzzy number into a crisp vulnerability score was determined as the optimum solution.

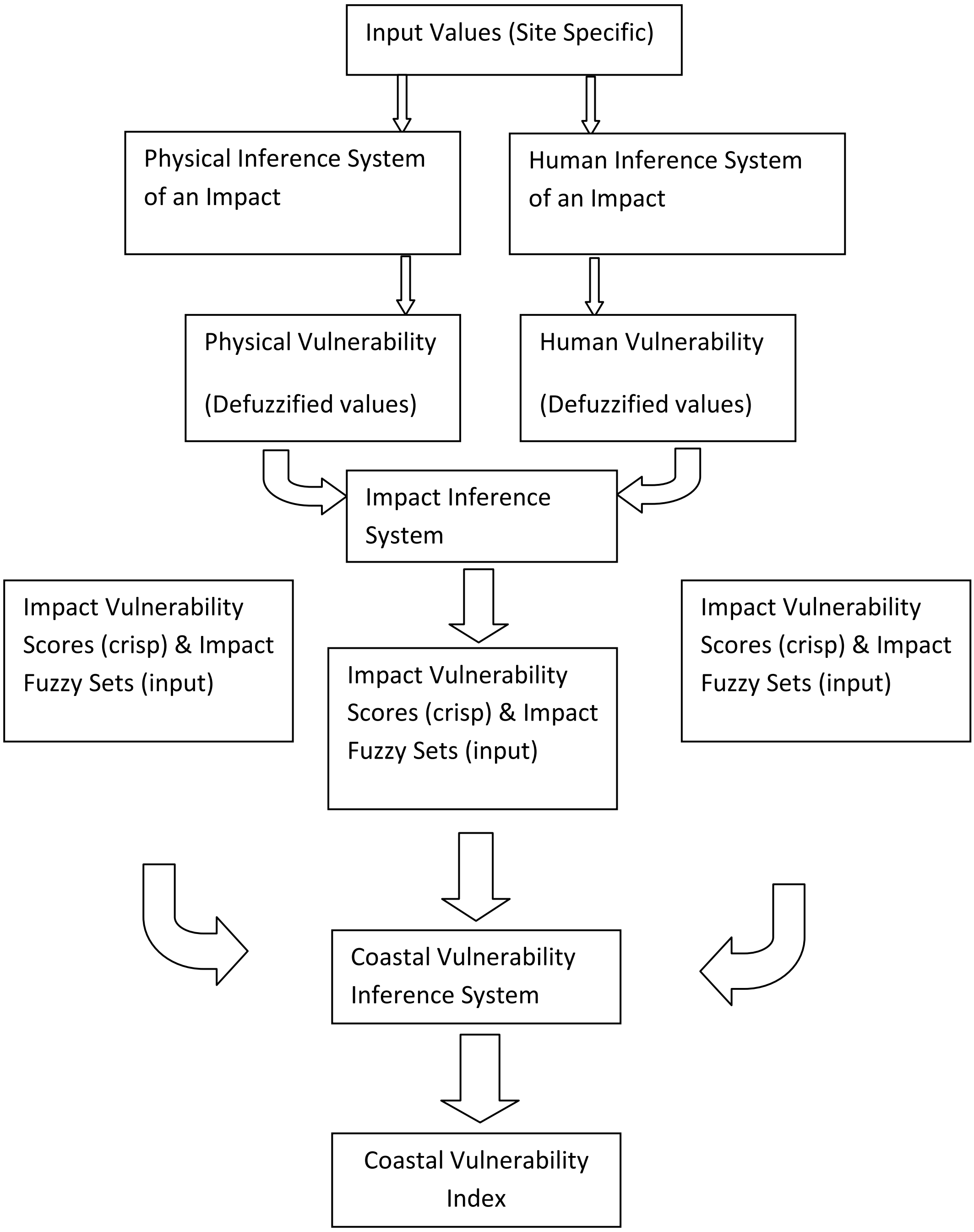


Figure 6.15 Fuzzy vulnerability assessment model structure

Examples for the rule bases of different modules are given below. The complete set of rule bases for impact inference system is given in Appendix D.

Physical Inference System for Salt water intrusion to River/Estuary:

1. If (RSLR is Uplift) then (PPVulRiver is vlow) (0.13)
2. If (RSLR is Low) then (PPVulRiver is low) (0.13)
3. If (RSLR is Equilibrium) then (PPVulRiver is moderate) (0.13)
4. If (RSLR is High) then (PPVulRiver is high) (0.13)
5. If (RSLR is Vhigh) then (PPVulRiver is vhigh) (0.13)
6. If (depth is veryshallow) then (PPVulRiver is vlow) (0.34)
7. If (depth is shallow) then (PPVulRiver is low) (0.34)
8. If (depth is moderate) then (PPVulRiver is moderate) (0.34)
9. If (depth is deep) then (PPVulRiver is high) (0.34)
10. If (depth is verydeep) then (PPVulRiver is vhigh) (0.34)
11. If (Tide is tideless) then (PPVulRiver is vhigh) (0.09)
12. If (Tide is small) then (PPVulRiver is high) (0.09)
13. If (Tide is moderate) then (PPVulRiver is moderate) (0.09)
14. If (Tide is high) then (PPVulRiver is low) (0.09)
15. If (Tide is veryhigh) then (PPVulRiver is vlow) (0.09)
16. If (Q-flow is verylow) then (PPVulRiver is vhigh) (0.45)
17. If (Q-flow is low) then (PPVulRiver is high) (0.45)
18. If (Q-flow is Moderate) then (PPVulRiver is moderate) (0.45)
19. If (Q-flow is high) then (PPVulRiver is low) (0.45)
20. If (Q-flow is veryhigh) then (PPVulRiver is vlow) (0.34)

Human Inference System for Inundation:

1. If (natdeg is excellent) then (HIVulInd is vlow) (0.63)
2. If (natdeg is good) then (HIVulInd is low) (0.63)
3. If (natdeg is underpressure) then (HIVulInd is moderate) (0.63)
4. If (natdeg is degradation) then (HIVulInd is high) (0.63)
5. If (natdeg is majordegradation) then (HIVulInd is vhigh) (0.63)
6. If (CPS is none) then (HIVulInd is vhigh) (0.37)
7. If (CPS is few) then (HIVulInd is high) (0.37)
8. If (CPS is some) then (HIVulInd is moderate) (0.37)
9. If (CPS is protected) then (HIVulInd is high) (0.37)
10. If (CPS is fullyprotected) then (HIVulInd is vhigh) (0.37)

Table 6.7 Impact Inference System for Coastal Erosion:

IF	PPVulEro AND HIVul Ero		Then VulErosion
1	VL	VL	VL
2	L	VL	L
3	M	VL	M
4	H	VL	M
5	VH	VL	H
6	VL	L	L
7	L	L	L
8	M	L	M
9	H	L	H
10	VH	L	H
11	VL	M	L
12	L	M	L
13	M	M	M
14	H	M	H
15	VH	M	VH
16	VL	H	M
17	L	H	M
18	M	H	H
19	H	H	H
20	VH	H	VH
21	VL	VH	M
22	L	VH	M
23	M	VH	H
24	H	VH	VH
25	VH	VH	VH

6.6.3 Decision Making Unit (Inference Engine)

The decision making unit contains all the operators that translates the IF-THEN rules and combines the individual output fuzzy results into an aggregate output value.

The first operator is the fuzzy operator in the antecedent which combines the first part of the rule either by AND or OR. For the physical and human inference systems, there is no fuzzy operator since each input is directly related to output. However the impact inference systems do need fuzzy operator "AND", because the output is mapped to two input values at the same time. The operator used to define “AND” is minimum or min. This is a built-in operator of MATLAB Fuzzy Logic Toolbox.

The second operator is implication operator which modifies the output fuzzy set according to the antecedent of the fired rule. There are two operators that can be used for implication; minimum (MIN) or product (PROD). To comply with Mamdani type system, minimum is used as implication operator which is built-in in MATLAB Fuzzy Logic Toolbox as well.

The final operator is the aggregation operator which combines all the consequents of the rules to generate the overall fuzzy output. There are three operators that can be used for aggregation: maximum (MAX), probabilistic or (PROBOR) and summation (SUM). For the fuzzy vulnerability assessment model, all of the aggregation operators are used for different modules. For human and physical inference systems of each impact PROBOR is used as aggregation to include interaction between input parameters to an extent (which was not considered during rule generation process). Use of PROBOR decreases influence of the most extreme cases on the output parameter enabling consideration of sustainability principle. On the other hand, for the impact inference systems, MAX is used for aggregation since the interaction of human and physical inference systems are already considered in the rule base. The use of MAX but not SUM is to protect the resources of the coastal zone by considering the maximum value that the vulnerability can take. To determine the overall vulnerability of a coastal area, simple aggregation (SUM) is used by summing the impact output fuzzy sets since use of MAX could be considered as overdesign (high factor of safety which is not suitable when sustainability principle is considered) and use of PROBOR is not possible since interaction between these impacts can not be quantified easily (very indirect).

6.6.4 Defuzzification Interface

Among the five defuzzification operators, centroid method (center of gravity or center of area) is used to turn fuzzy output set into crisp value. This is the most widely used defuzzification methodology which is why it was selected for fuzzy vulnerability assessment model.

Vulnerability class for each crisp output value is assigned using the classification given below:

Very low vulnerability: CVI (SLR) <1.25

Low vulnerability: 1.25≤CVI (SLR) <2.25

Moderate vulnerability: 2.25≤CVI (SLR) <3.25

High vulnerability: 3.25≤CVI (SLR) <4.25

Very high vulnerability: 4.25≤CVI (SLR) ≤5

This classification is based on expert opinion to match the linguistic variable with the crisp outputs as defined in the fuzzy membership function of the vulnerability parameter.

6.6.5 Working Example of Fuzzy Vulnerability Assessment Model

After all the blocks of fuzzy expert system were built for each module, they are implemented to MATLAB Fuzzy Logic Toolbox. Working procedure of inundation module of the fuzzy expert system is described in detail on the MATLAB platform.

a) Physical Inference System Module for Inundation:

Site specific values for input parameters of the module are given as:

Rate of sea level rise: 2mm/year

Beach slope: 2%

Tidal range: 1.3m

Figure 6.16 shows the working of decision making unit using the fuzzy, implication and aggregation operators which are MIN, MIN, PROBOR.

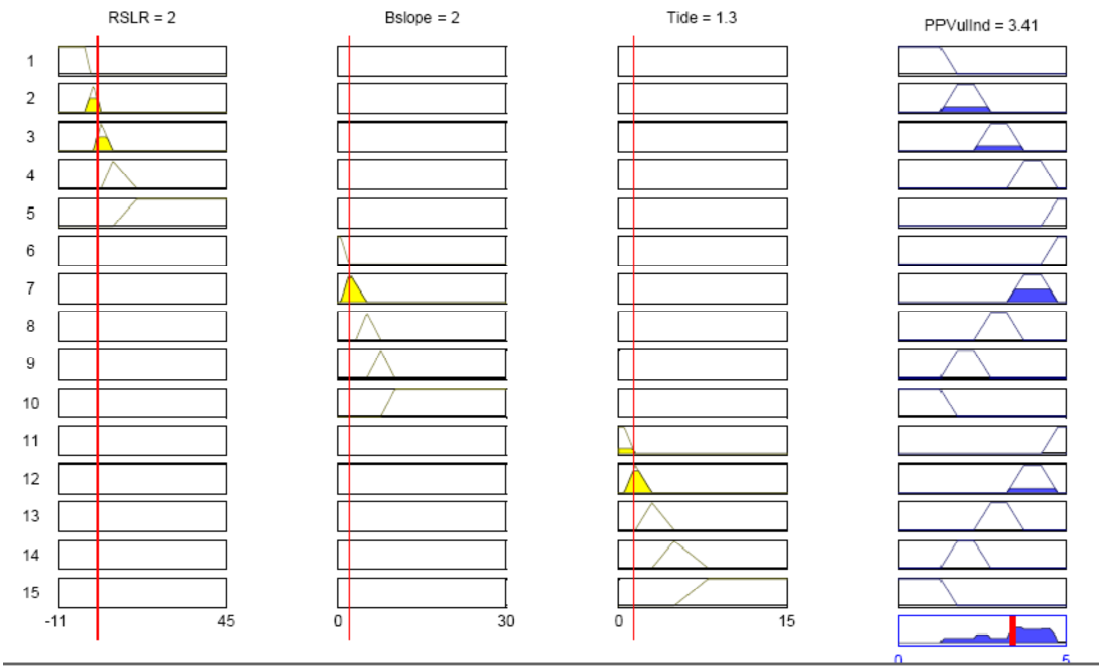


Figure 6.16 Graphical representation of physical inference system for inundation

The output for these input values is 3.41/5 and the fuzzy set result can also be seen in the figure which shows that the possible vulnerability values range between 2 to 5 where the most possible value is 3.41 over 5.

b) Human Inference System Module for Inundation:

Site specific values for input parameters of the module are given as:

Natural protection degradation: 25%

Coastal Protection Structures: 5%

Figure shows the working of decision making unit using the fuzzy, implication and aggregation operators which are MIN, MIN, PROBOR.

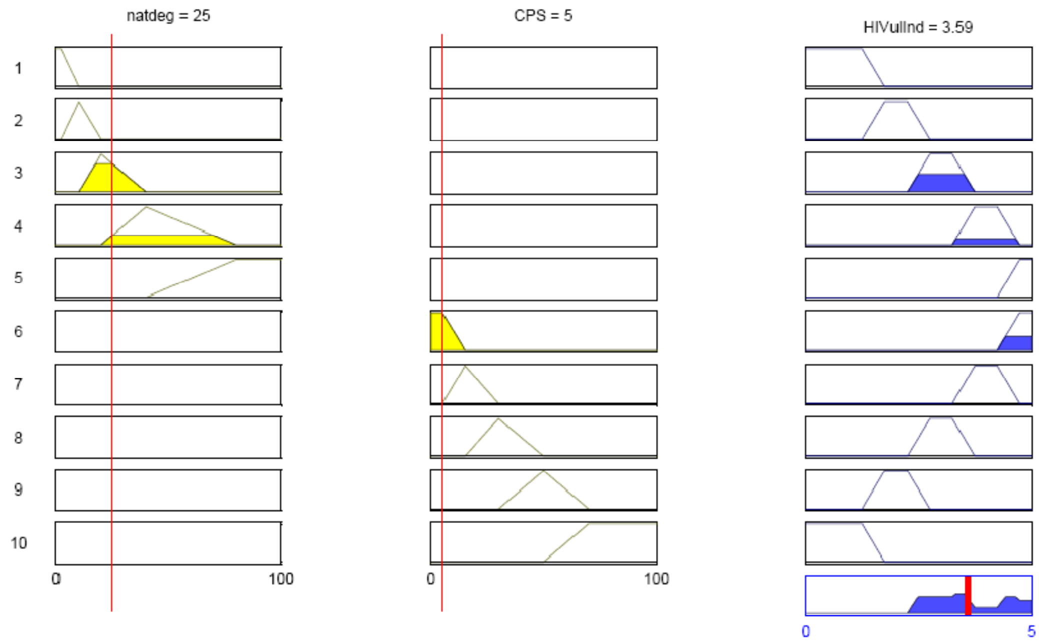


Figure 6.17 Graphical representation of human inference system for inundation

The output for these input values is 3.59/5 and the fuzzy set result can also be seen in the figure which shows that the possible vulnerability values range between 3 to 5 where the most possible value is 3.59 over 5.

When the output fuzzy set of the two systems are compared, it is seen much more clearly that human parameters show higher vulnerability possibility than the physical characteristics of the region. Although the crisp values are close 3.41 to 3.59, the distribution of possible vulnerability scores also indicate that the possibility that the region is more vulnerable to human activities (boundaries of the range of the human inference system result are higher).

c) Impact Module for Inundation

Site specific values for input parameters of the module are given as:

Physical Inference System: 3.41

Human Inference System: 3.59

Figure shows the working of decision making unit using the fuzzy, implication and aggregation operators which are MIN, MIN, MAX.

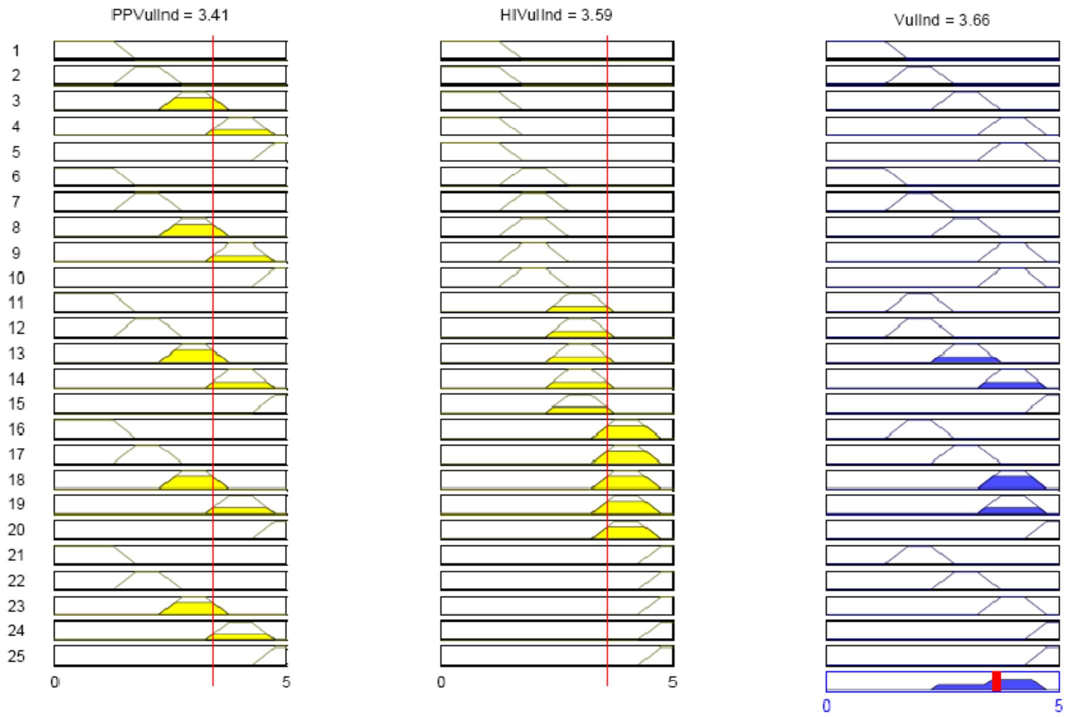


Figure 6.18 Graphical representation of impact inference system for inundation

The output for these input values is 3.66/5 and the fuzzy set result can also be seen in the figure which shows that the possible vulnerability values range between 3 to 5 where the most possible value is 3.66 over 5.

In this result we can see the effect of the rule base much significantly. Physical system score belongs to moderate range than high however; human system score belongs to high range than moderate. As a result of the rule base, the higher range dominates the overall vulnerability and using the maximum operator as aggregation operator ensures that the protection of the resources is established when vulnerability score is assigned. Although the crisp output score could be considered in moderate vulnerability range, the fuzzy set of the result shows otherwise as the high vulnerability range dominates the fuzzy set. Thus the discussion of the output result with the corresponding fuzzy set increases the information given to the decision maker in terms of defining the uncertainty regarding the crisp vulnerability score. This in turn enables decision makers to discuss relevant policies efficiently.

6.7 Graphical User Interface of Fuzzy vulnerability Assessment Model

Each module of the fuzzy vulnerability assessment model was checked for any errors due to rule base and membership function implementations within MATLAB Fuzzy Logic Toolbox environment by putting in several input values and comparing the outputs to the results of preliminary vulnerability assessment model. However it was seen that an independent MATLAB function was needed to combine all the different modules that could be run with one input data file. As a result, the function CVI.m was developed which read the input data from an EXCEL file and showed the output values on the MATLAB command window as shown in Figure 6.19.

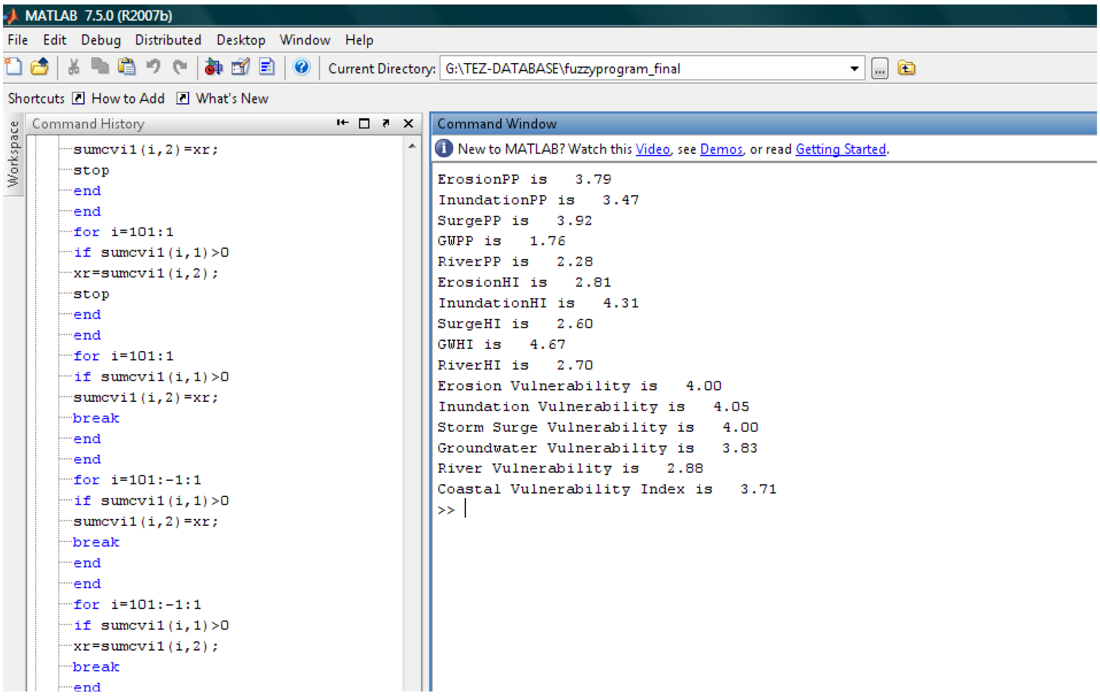


Figure 6.19 Initial output of CVI.m function shown on MATLAB window

This type of output although would be informative for the end user, it was not efficient. Thus a graphical user interface for both input and results were developed using GUIDE toolbox of MATLAB platform. If there was not an interface for the whole vulnerability assessment model, then the user would have to put in the same inputs for different modules and use the outputs of the modules as inputs to other modules manually. This would be both time-consuming and inefficient and liable to many user errors. The developed graphical user interface enables the user to manually put in the input values once, and then the fuzzy vulnerability model is run via clicking “Calculate” button and the results are shown in another window.

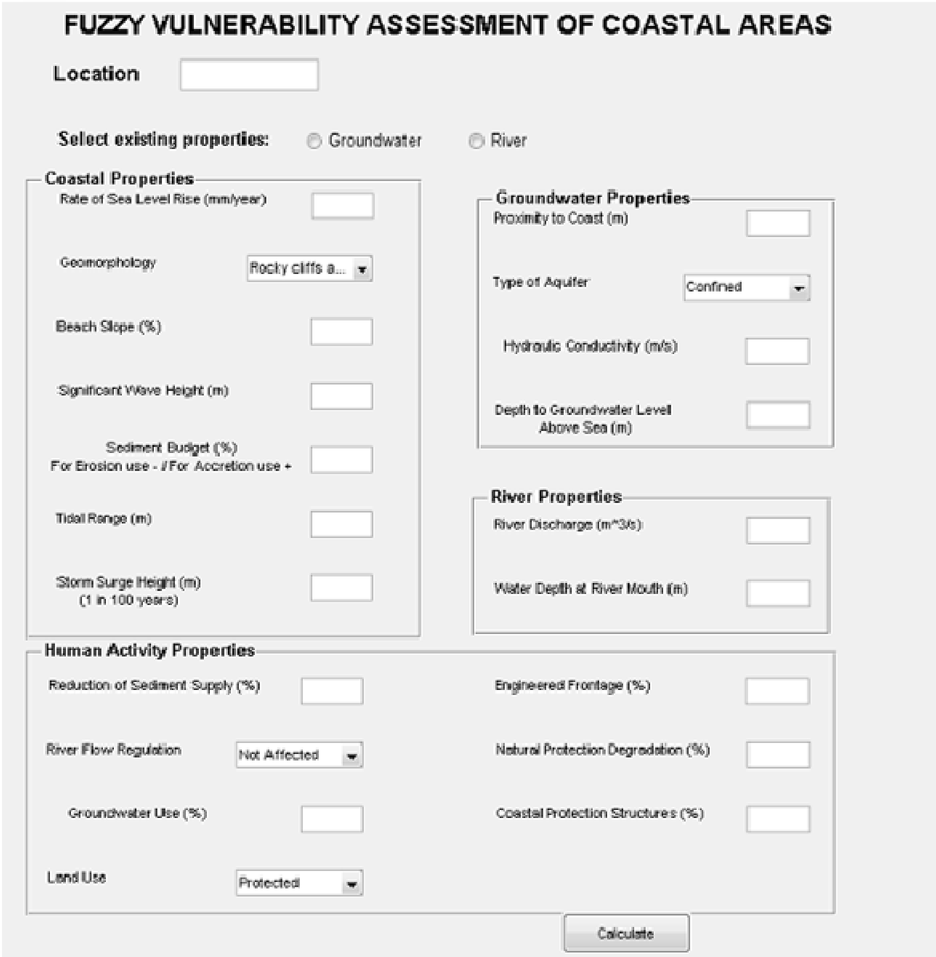


Figure 6.20 Input window of Fuzzy Vulnerability Assessment Model interface

Figure is the input window of the fuzzy vulnerability model, where the user can type in the name of the location, choose which resources are present at the region (groundwater or river or both) by selecting the corresponding alternatives, and then put in the site specific local data accordingly.

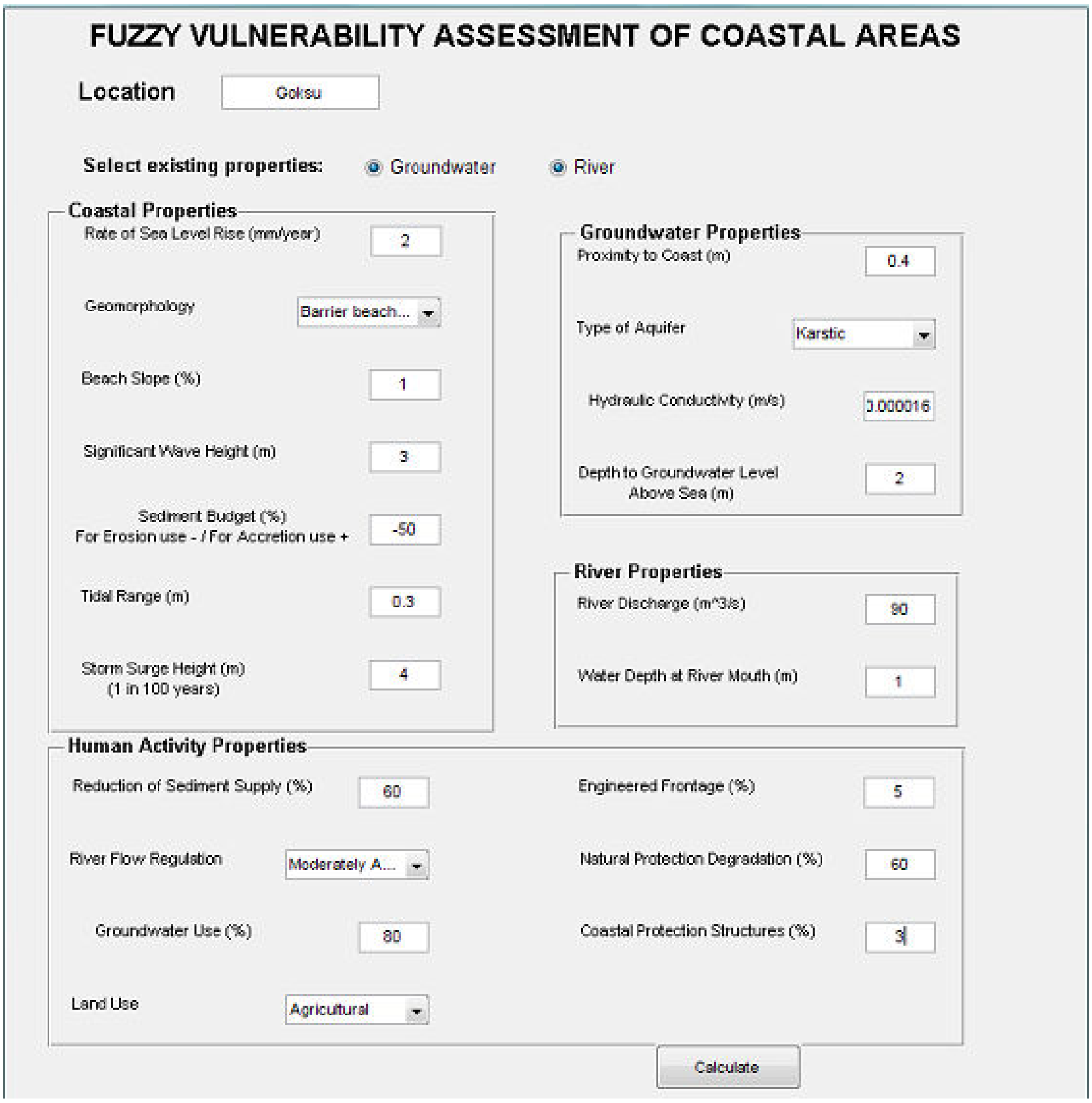


Figure 6.21 Graphical User Interface of Input Window of Fuzzy Vulnerability Assessment Model (inputs given to the model)

The result window again lists the input values for ease of check for the user and shows the vulnerability scores for each module of the fuzzy vulnerability system. The impact scores are also given in linguistic information as well as the overall vulnerability score of the region are given both numerically and linguistically.

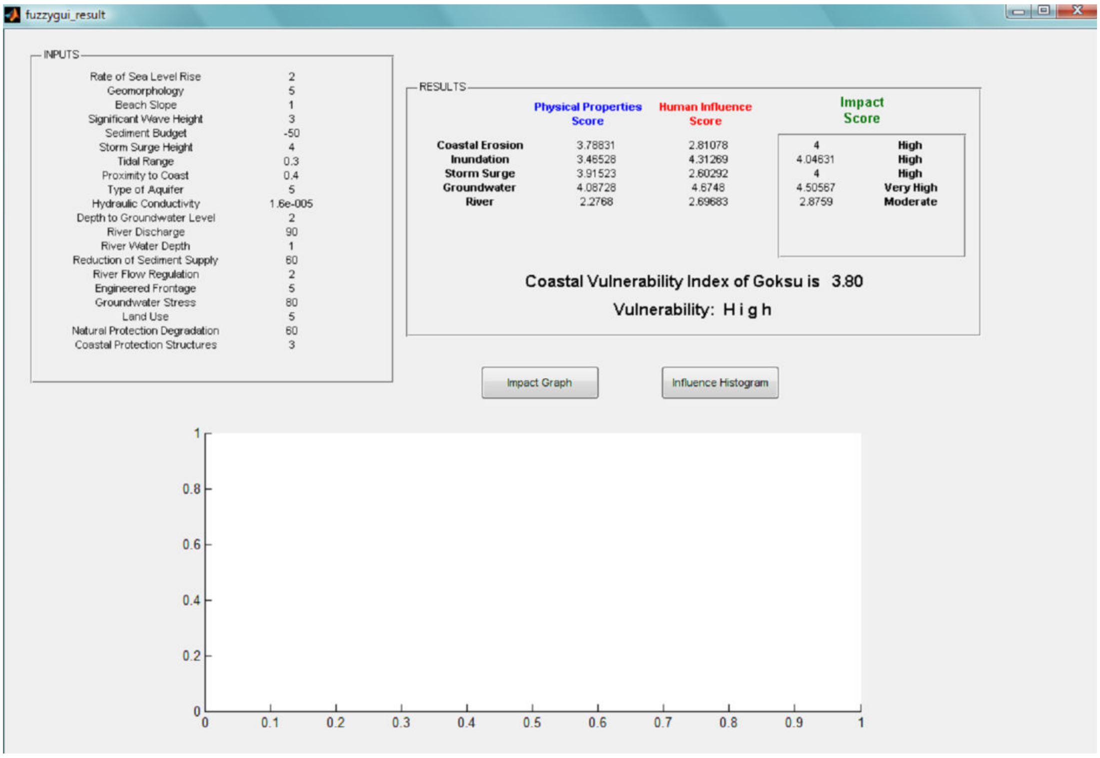


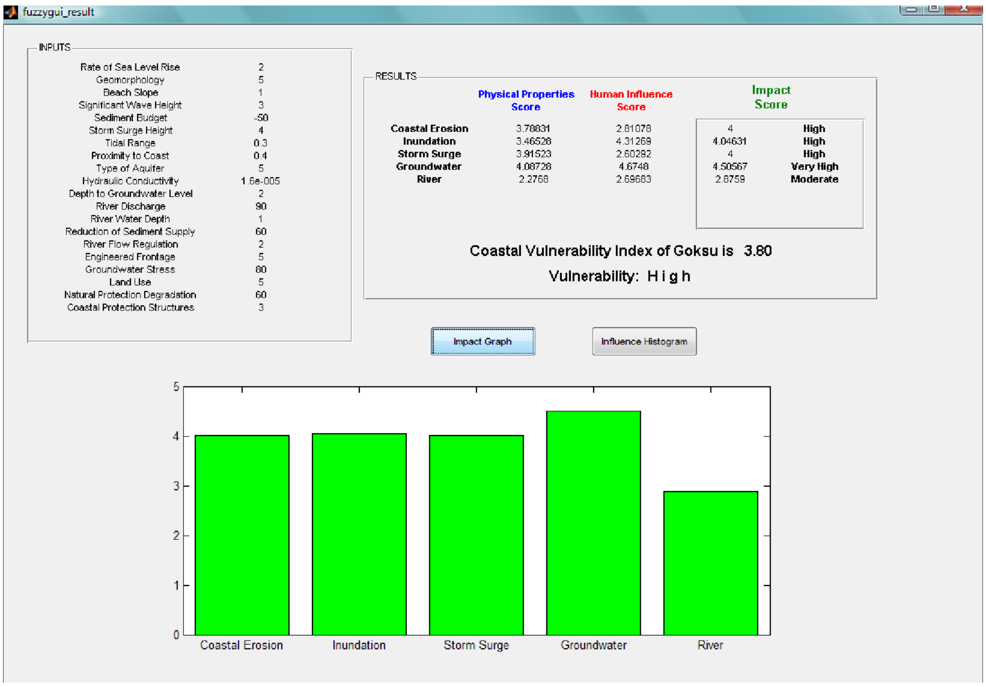
Figure 6.22 Graphical User Interface of output window of Fuzzy Vulnerability Assessment Model (initial)

There are two graphical options where the end user can compare vulnerability of the region with respect to the individual impact scores which is the Impact Graph and Influence Histogram option which shows the comparison of human and physical inference modules for each impact. (Figures 6.23 (a) and (b))

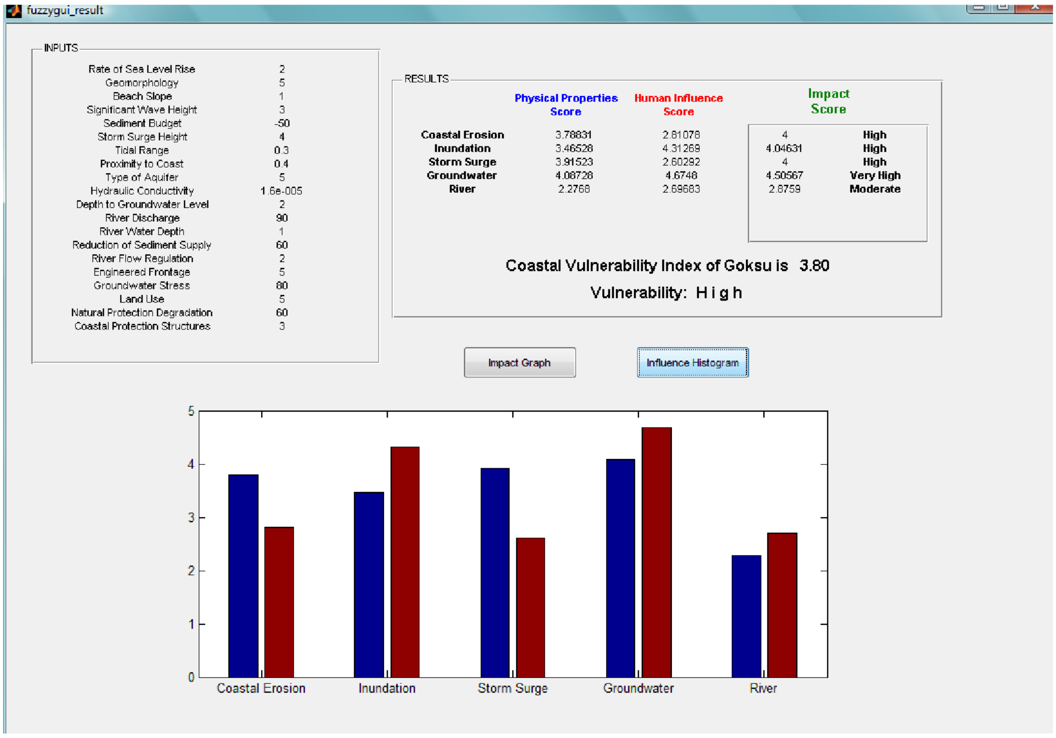
The results given by the model can be used for vulnerability assessment at three different spatial scales. The overall coastal vulnerability index which defines the aggregated vulnerability enables decision makers to compare different regions at a national to regional scale. This comparison would act as a general framework for coastal zone management practices focusing on adaptation measures. Additionally individual impact scores are another tool that could be utilized to compare regions according to each impact at a regional to national level.

At a local level, individual impact scores generate a framework for identifying the dominant impact that can be expected at a coastal region. The prioritization of individual impacts ensures decision makers to develop efficient plans in light of many limitations such as budget, manpower and resources. Although each impact could trigger potential hazards affecting the coastal community and ecosystem, the graph of individual impact scores gives an opportunity to the decision makers to consider other persisting problems as well. Thus an optimization regarding further management of coastal areas is presented.

The histogram comparing physical and human influence modules for each impact at an area is another tool that would have a significant effect on local decision making process. This comparison sets a baseline for adaptation planning with respect to each impact. In case physical system dominates the vulnerability of the region; the decision makers are advised to select structural response measures (if the region is important enough to be protected) or a combination of spatial planning and protection measure to ensure managed retreat proactively. When the vulnerability of the human inference is dominant, then policy-driven measure need to be considered at first. It is much easier to control and regulate vulnerability associated with human inference systems as well as the results are felt more rapidly. Spatial planning, resource management, reorganizing management framework are all also part of coastal zone management practices. Thus these types of adaptation measures are easier to integrate into the available plans. The important aspect to be considered is to identify the most vulnerable parameter of the human inference system. Considering this parameter will ensure much efficient outcome of the adaptation measures taken.



a)



b)

Figure 6.23 Graphical representations presented in output window (a) impact scores (b) influence histogram for each impact

6.8 Model Validation and Application

Coastal vulnerability assessment model is a fuzzy expert model which benefits from experts' knowledge although membership database derived from extensive site specific data reduce the input of expert of knowledge, generation of rule base and the membership function of the output parameter heavily depends on expert knowledge. Thus the model's verification is very important. Although there is no universal definition of coastal vulnerability to sea level rise as well as no direct measurement that can enable comparison between model values and the site specific values, the study validates the model's performance by comparing the results with those of preliminary vulnerability assessment model which has been applied to several coastal regions and found to be consistent with the literature of vulnerability of coastal areas to sea level rise.

To illustrate the capability of fuzzy vulnerability assessment model, the model was applied to Goksu, Gocek and Amasra regions of Turkey where the preliminary model was applied and presented in several papers (Ozyurt 2007;

Ozyurt and Ergin 2009). The characteristics of these three regions used as inputs in both models are given in Table 6.8 and Table 6.9 respectively.

Table 6.8 Vulnerability classes assigned to each location using site specific data for preliminary vulnerability model (Ozyurt and Ergin 2009)

Parameters	**Regions**		
	Amasra	**Gocek**	**Goksu**
Physical Parameters			
Rate of Sea Level Rise	3	2	2
Geomorpholgy	1	3	5
Coastal Slope	2	3	5
H1/3	5	2	4
Sediment Budget	3	3	4
Tidal Range	5	5	5
Proximity to Coast	3	4	4
Type of Aquifer	3	3	3
Hydraulic Conductivity	3	3	1
Depth to Groundwater Level Above Sea	1	4	2
Water Depth at Downstream	-	1	2
Discharge	-	5	4
Human Influence Parameters			
Reduction of Sediment Supply	1	1	3
River Flow Regulation	1	1	3
Engineered Frontage	2	4	2
Natural Protection Degradation	2	3	5
Coastal Protection Structures	3	5	5
Groundwater consumption	1	4	4
Land Use Pattern	3	3	5

Table 6.9 Input values (metric or in case of linguistic variables group number) for each location used in the fuzzy vulnerability model

	Regions		
Physical Inference Parameters	Amasra	Gocek	Goksu
Rate of Sea Level Rise (mm/year)	3	1	2
Geomorphology	1	2	5
Beach Slope (%)	7	5	1
Significant Wave Height (m)	5	2	3
Sediment Budget (%)	-5	-10	-50
Storm Surge Height (m)	7	5	4
Tidal Range (m)	0.3	0.3	0.3
Proximity to Coast (km)	0.7	0.4	0.4
Type of Aquifer	1	1	1
Hydraulic Conductivity (m/s)	0.00044	0.000324	0.000016
Depth to Groundwater Level (m)	5	0.5	2
River Discharge (m3/s)	-	50	90
River Water Depth (m)	-	0.5	1
Human Inference Parameters			
Reduction of Sediment Supply (%)	10	20	60
River Flow Regulation	1	1	2
Engineered Frontage(%)	25	50	5
Groundwater Stress(%)	30	70	80
Land Use	3	3	5
Natural Protection Degradation (%)	25	40	60
Coastal Protection Structures (%)	30	5	3

The outputs of both of the models are given in Table 6.10 below.

Table 6.10 Comparison of results of fuzzy vulnerability assessment model and preliminary vulnerability model (Ozyurt and Ergin 2009)

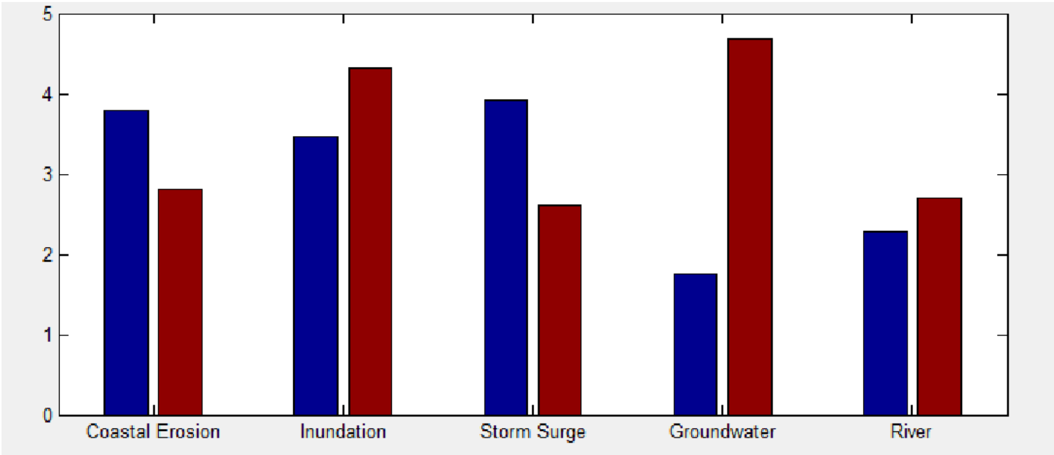
	Fuzzy Vulnerability Model			**CVI-2007**		
	Regions			**Regions**		
Impacts	Amasra	Gocek	Goksu	Amasra	Gocek	Goksu
Coastal Erosion	3.00	3.00	4.00	2.50	2.90	3.90
Inundation	3.00	4.00	4.05	3.00	3.60	4.40
Storm Surge	3.78	4.00	4.00	3.10	3.40	4.00
Groundwater	2.44	2.73	3.83	2.90	3.30	3.00
River	0.00	2.00	2.88	0.00	3.00	3.30
VULNERABILITY INDEX	3.05	3.20	3.71	2.80	3.20	3.70

The comparison table shows that fuzzy vulnerability model clearly provides a good measure for the vulnerability index especially in the case of overall vulnerability. When impact scores are compared, fuzzy vulnerability assessment results are different than the preliminary model which is expected since especially for impacts on groundwater and river were revisited and the membership functions for the system parameters were developed from available data rather than expert intuition which was the case for the preliminary model. The difference between vulnerability values for these impacts shows that the extra information and the data improved the assessment strength of the preliminary model significantly.

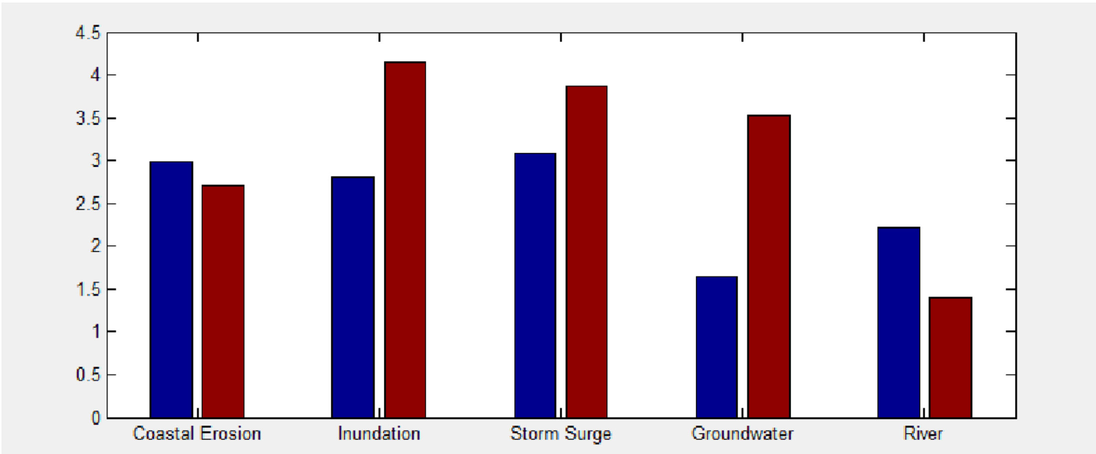
Also in the preliminary case when the site specific data was very close to both of the ranges, the vulnerability scores were affected significantly. However with the use of fuzzy expert system, the classifications of the parameter ranges resemble real life understanding of human mind at the same time capturing the uncertainty due to the perception differences of different experts that might perform the same assessment model. This, in turn, makes the fuzzy vulnerability assessment model more robust and stable.

In addition to the impact and vulnerability scores for the three sites, the influence graphs of each site are given in Figure 6.24 (a), (b) and (c).

(a) Göksu



(b)Göcek



(c)Amasra

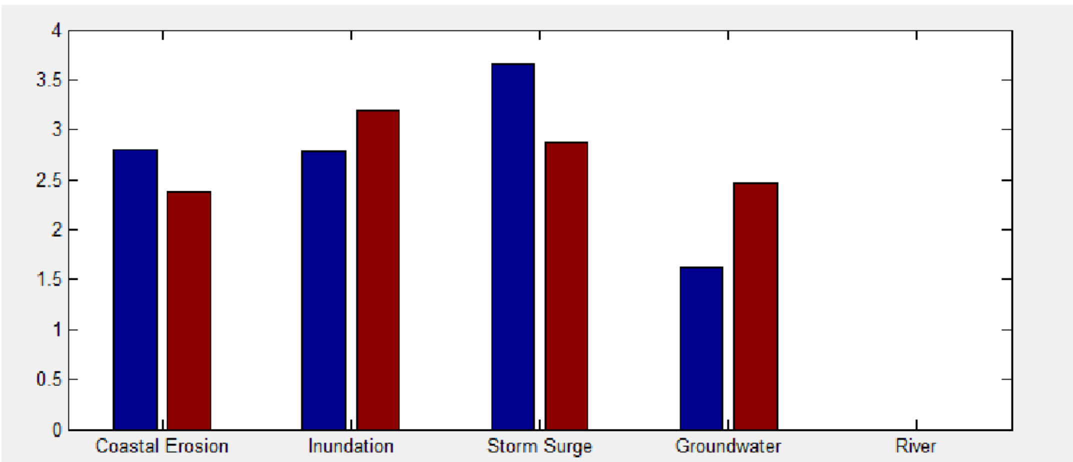


Figure 6.24 Influence Histograms for Goksu (a), Gocek (b) and Amasra (c) (red columns indicate human inference system, blue columns indicate physical inference system)

As also discussed in Ozyurt 2007, these influence graphs are important for local decision making process while the comparison of different sites according to the overall vulnerability scores enables for regional to national management plan of coastal areas.

Comparison of three different sites guides the decision makers to giving initial attention to taking measures against coastal impacts around Goksu region and then considering taking measures for Gocek and Amasra region. This type of classification of coastal area could be of similar use to earthquake zone maps where different criteria are used for different applications when the risk of earthquake is considered.

On the other hand, when the influence graphs are considered, local decision makers could prioritize their use of resources according to the classification of the impacts of a region when a local management plan is prepared. Additionally, the vulnerability of human and natural subsystems to each impact acts as a general guideline for further planning/ problem solving by effectively showing which type of measures should be considered initially. The following outcomes can be stated from analyzing the histograms of each region.

Histogram of Goksu shows that physical characteristics of the region are the main factors that influence vulnerability associated with coastal erosion and flooding due to storm surges. Thus any adaptation measure should consider increasing the resistance of the physical characteristics of the regions such as developing hard or soft coastal protection measures. Since the region is a specially protected area where the ecosystem is unique and under protection, hard structural measures are not allowed as a general rule. Thus soft protection measures such as nourishment of the dunes (which is also part of the human inference system analyzed as natural protection degradation parameter) or for the human population planning for managed retreat are some of the viable options that the decision makers could consider. Contrary to these impacts, vulnerability of inundation is affected by human system more which requires to analyze these parameters. Here, again it is seen that soft measures such as protecting the dunes even reconstructing them while establishing new regulations and monitoring systems to ensure the sustainable use of the coastal area would decrease the vulnerability. If groundwater vulnerability of Goksu region is considered, it can be seen that human subsystem influence is much more than the natural subsystem on the overall impact. This shows that any measures taken should directly affect the human subsystem and their use of the natural subsystem which calls for policy measures rather than structural ones such as monitoring of the water abstraction from the wells, new regulations on the use of water, assessing a different agricultural landscape for the region. All these measures are policy-driven measures that will both ensure protection of the groundwater system and the sustainability of the region. Although vulnerability of the river is low, it is known that several regulatory projects are continued to be constructed and planned. These projects will increase the vulnerability of the river to saltwater intrusion which will in turn affect the agriculture and ecosystem of the region due to salinization of the adjacent soil. On the other hand, effective management of these regulatory structures could be used to keep the salt wedge at a desired distance from the shore by controlling the discharge of the river. Thus, what is necessary is to reassess the national, regional and local river basin and coastal management plans (if available) or develop these plans considering these impacts along the coastal region. On the other hand, these regulatory structures will also increase the vulnerability of the region to coastal erosion. This fact shows that coastal and river basins should be considered when long term management plans including adaptation measures to climate change are considered.

Histogram of Gocek represents the physical characteristics of the region accurately by showing that vulnerability due to physical inference systems are low to moderate. Human activities significantly influences the vulnerability due to inundation, storm surge and groundwater resources. The high use of coastal area which is a very narrow string due to geomorphology of the region combined with high rate of tourism (especially yacht tourism) affect the vulnerability of the region through high rate of engineered structures. One way to change the negative influence of this parameter is to combine these structures with protection measures for flooding due to storm surge and in longer term, inundation. Thus the vulnerability would decrease. On the other hand, the region having a protection status also enables to consider "do nothing" approach since the vulnerability is low to moderate thus the natural ecosystem could adapt in their own way. For the vulnerability of the groundwater resources, again regulating the demand on groundwater is the key to decrease the vulnerability. The area being a tourism hot spot makes high demands on the available groundwater resources especially during summer when the vulnerability is highest due to lower groundwater tables. Again policy-driven measures need to be assessed and implemented. The river considered in the study is a minor creek having a unsteady flow rate. This makes the river vulnerable to impacts of sea level rise especially during summer when the rate of flow is very low. Although it is not used for agricultural purposes and the demand on the system is not high, still it is considered as a source of fresh water thus proper measures would need to be integrated to adaptation plans although secondarily.

For the case of Amasra, where the physical characteristics of the region is resilient to sea level rise due to high elevations, steep slopes and a rocky geomorphology the overall vulnerability is calculated as low. The effect of human inference systems are also generally low to moderate. The significant impact seen from the histogram is flooding due to storm surge where the physical system dominates the vulnerability score. This indicates that any measures taken should directly affect the natural subsystem and its interaction with human subsystem which calls for structural measures to be taken, policy measures such as evacuation plans should still be implemented but as a secondary (backup/additional) measure. Again demand on groundwater resources act is a problem which calls for policy-driven measures however the impact score shows that this impact could be considered secondarily.

These direct applicability of the results of the fuzzy vulnerability assessment model makes it a very powerful tool for the stakeholders of the coastal areas. However, as also heavily underlined in the previous sections, integration of uncertainty to the model as well as quantifying or clearly defining uncertainty is very important in expert systems as well as decision making models, integrated assessments for the end user. The information on uncertainty enables the end user to make more accurate and robust decisions at the same time demonstrates the robustness of the model especially in the case of data scarcity. Thus the next section discusses the sensitivity and uncertainty of the fuzzy vulnerability assessment model in detail.

CHAPTER VII

SENSITIVITY AND UNCERTAINTY ANALYSIS

Models are used to approximate highly complex environments. The approximation mostly is performed through making assumptions and simplifying the factors deriving the processes. Thus after construction of a model, determination of parameters which are most influential on model results is critical both for model validation and to guide future developments of the model.

"Sensitivity analyses are conducted for a number of reasons to determine: (1) which parameters require additional research for strengthening the knowledge base, thereby reducing output uncertainty; (2) which parameters are insignificant and can be eliminated from the final model; (3) which inputs contribute most to output variability; (4) which parameters are most highly correlated with the output; and (5) once the model is in production use, what consequence results from changing a given input parameter"(Hamby 1994).

The use of the term 'important' and 'sensitive' are used for input parameters interchangeably by many researchers however, (Crick et al. 1987) have made a distinction by referring to 'important' parameters as those whose uncertainty contributes substantially to the uncertainty in assessment results, and 'sensitive' parameters as those which have a significant influence on assessment results.

"The models are sensitive to input parameters in two distinct ways: (1) the variability, or uncertainty, associated with a sensitive input parameter is propagated through the model resulting in a large contribution to the overall output variability, and (2) model results can be highly correlated with an input parameter so that small changes in the input value result in significant changes in the output.

The necessary distinction between important and sensitive parameters is in the type of analysis being conducted: uncertainty analysis (parameter importance) or sensitivity analysis (parameter sensitivity). An important parameter is always sensitive because parameter variability will not appear in the output unless the model is sensitive to the input. A sensitive parameter, however, is not necessarily important because it may be known precisely, thereby having little variability to add to the output."(Hamby 1994)

7.1 Sensitivity Analysis

There are various sensitivity analysis methods available in literature from simple to complex procedures. However the end result of all these analysis is a 'sensitivity ranking' or a list which sorts the input parameters by the amount of influence each has on the model output. Each analysis method would result in a slightly different sensitivity ranking, the actual ranking is not too important. The parameters which consistently appear near the top of the list are generally the same. Disagreement among lesser rankings by the various methods is not of practical concern since these variables have little or no influence on model output (Hamby 1994).

Among different methods, the sensitivity index and scatter plots were used to assess the fuzzy vulnerability assessment model (FCVI). 'The sensitivity index' (SI) is calculated using,

$$SI = \frac{D_{max} - D_{min}}{D_{max}} \qquad \text{Eq.7.1}$$

Where D_{min} and D_{max} represent the minimum and maximum output values, respectively, resulting from varying the input over its entire range. "This figure provides a good indication of parameter and model variability. Scatter plots of inputs vs. output are useful for quick determinations of the degree of correlation and the linearity of the input/output relationship" (Crick et al. 1987; Hamby 1994)

The developed fuzzy vulnerability assessment model (FCVI) uses Fuzzy Logic Toolbox of MATLAB software that draws the scatter plots for each input vs. output automatically. For all the fuzzy inference systems components of the vulnerability model, the scatter plot diagrams were analyzed. An example of these diagrams is given for beach slope parameter (Figure 7.1). The scatter plots of all parameters are given in Appendix E.

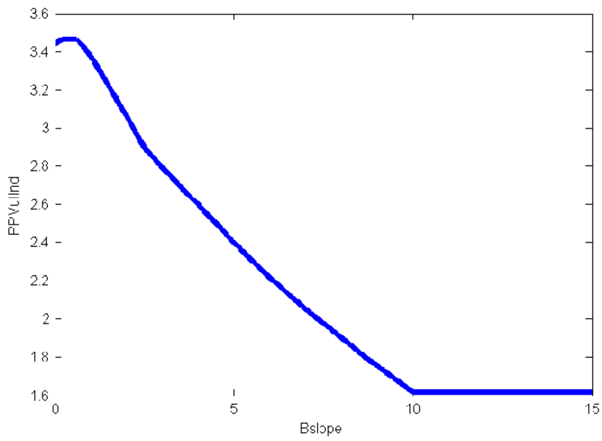


Figure 7.1 Scatter plot of sensitivity analysis for beach slope

For the sensitivity study of fuzzy vulnerability assessment model (FCVI), the following results were calculated using the data for Goksu region (Table 7.1) as base study. Example of rate of sea level rise is given in detail in this section.

The following data was used as an input for sensitivity analysis. The output parameter – overall coastal vulnerability index- was calculated for each increment starting from minimum input value to maximum input value of the parameter while other parameters are kept constant. The graph for each parameter shows the change in output with respect to change in input parameter. Not only the overall coastal vulnerability index is presented, but also impact indices which include the parameter as input are also included in the graphs. The numerical comparisons are then performed and the input parameters are ranked according to their sensitivity indexes.

Table 7.1 Input Data (Goksu Region, Turkey)

Rate of Sea Level Rise	2
Geomorphology	5
Beach Slope	1
Significant Wave Height	3
Sediment Budget	-50
Storm Surge Height	6.7
Tidal Range	0.3
Proximity to Coast	0.4
Type of Aquifer	5
Hydraulic Conductivity	0.000016
Depth to Groundwater Level	2

River Discharge	90
River Water Depth	1
Reduction of Sediment Supply	60
River Flow Regulation	2
Engineered Frontage	5
Groundwater Stress	80
Land Use	5
Natural Protection Degradation	60
Coastal Protection Structures	3

To understand the sensitivity of the model to rate of sea level rise (rslr) parameter, the model is run for each case starting with rslr = -11 mm/year ending with rslr = 45 mm/year, each increment being 0.5mm/year. The graph of rate of sea level rise vs. output values are given in Figure 7.2.

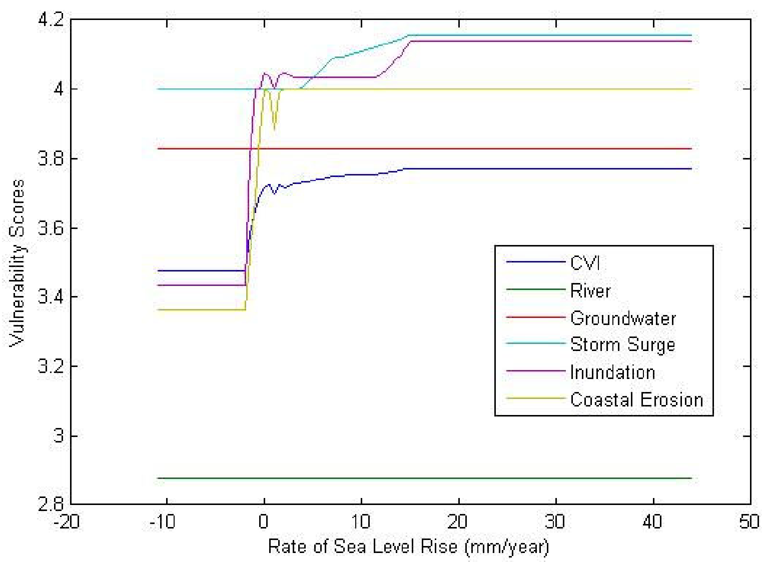


Figure 7.2 Plot showing the sensitivity of vulnerability scores to rate of sea level rise

As can be seen from the graph, change in rate of sea level rise is significantly reflected in overall coastal vulnerability index. It is also reflected in other impacts as well; however in groundwater and river impacts; the influence is not significant/non existent when individual impact scores are compared. The sensitivity index of rate of sea level rise is calculated as (from Eq.7.1) :

$$SI = \frac{3.772 - 3.475}{3.772} = 0.079 \qquad \text{Eq.7.2}$$

The sensitivity of the model to input parameters are given in Table 7.2.

Table 7.2 Sensitivity of the model – coastal vulnerability index

	Dmax	Dmin	Dmax-Dmin	SI
Land Use	3.715	3.126	0.589	0.158
Beach Slope	3.725	3.155	0.570	0.153
Sediment Budget	3.715	3.285	0.430	0.116
Groundwater Stress	3.725	3.315	0.411	0.110
Tidal Range	3.718	3.365	0.353	0.095
Storm Surge Height	3.715	3.367	0.348	0.094
Rate of Sea Level Rise	3.772	3.475	0.297	0.079
River Flow Regulation	3.781	3.507	0.275	0.073
Geomorphology	3.715	3.500	0.215	0.058
Significant Wave Height	3.715	3.500	0.215	0.058
River Water Depth	3.940	3.715	0.225	0.057
River Discharge	3.715	3.546	0.169	0.046
Natural Protection Degradation	3.740	3.572	0.168	0.045
Coastal Protection Structures	3.715	3.584	0.131	0.035
Type of Aquifer	3.804	3.715	0.089	0.023
Engineered Frontage	3.783	3.715	0.068	0.018
Depth to Groundwater Level	3.715	3.670	0.045	0.012
Proximity to Coast	3.715	3.681	0.034	0.009
Hydraulic Conductivity	3.731	3.711	0.020	0.005
Reduction of Sediment Supply	3.715	3.696	0.019	0.005

Table 7.2 shows that the overall vulnerability index of the model is most sensitive to land use and beach slope parameters. This is expected since both parameters have very high weight values assigned as a result of the analytical hierarchy process analysis. Also land use is a crisp input that is not fuzzified due

to nature of the information which is nominal numerical type. The land use of coastal zone can not be fuzzified when it is already approximated to a point by the fuzzy vulnerability model. If different land uses within a region was wanted to be reflected other than implication of the model in a GIS environment, then the use of higher types of fuzzy numbers had to be used in the assessment which is out of scope of this research. Thus any change of the value of this parameter which is crisp significantly affects the output.

Although the model is sensitive to these parameters, overall vulnerability range almost never changes due to this sensitivity which indicates that the fuzzy vulnerability assessment model would give robust results in the case of data scarcity.

7.1.1 Sensitivity of Impacts

When the sensitivity of individual impacts are considered which is another important analysis due to the fact that comparison of impacts are one of the outputs of the FCVI model guiding the decision makers to prioritize local management plans; Table 7.3 shows the most sensitive parameters of each impacts.

The sensitivity of the model is higher when individual impacts are assessed. Especially the input parameters which have the highest weights contribute to the sensitivity of the individual impacts the most, which is to be expected. However the sensitivity ranges are high (double for some parameters at least for this case), which shows that the end user has to be careful when assigning values to these parameters. As the quality of the data increases, the sensitivity, thus input uncertainty would decrease respectively. When the most sensitive parameters are analyzed it is seen that sensitivity is directly related to parameter weight values. The higher the weight, the sensitive the parameter is. Additionally, as expected, the parameters which are defined using crisp values such as river flow regulation show higher sensitivity. For these parameters, the input assignment is actually fairly basic since the characteristic of the region is assigned from a selection of possible characteristics (limited choice of the user). This actually decreases the sensitivity of the model to these parameters on the contrary to the results of sensitivity analysis because the possibility of the user to make a wrong assignment is very low. On the other hand, values of beach slope, storm surge height, river discharge (which are most sensitive parameters) can be assigned fairly accurately since these parameters are directly measurable or can be statistically approximated from direct measurements. For the rest of the sensitive parameters to which numerical values are assigned (such as sediment budget); the end users should be aware of these sensitivities and try to assign input values accordingly.

Table 7.3 Sensitivity analysis of impact vulnerability scores for input parameters

	Maximum					Minimum					Sensitivity Index				
	CE	I	SS	GW	R	CE	I	SS	GW	R	Coastal Erosion	Inundation	Storm Surge	Groundwater	River
Rate of Sea Level Rise	4.00	4.14	4.16	3.83	2.88	3.36	3.43	4.00	3.83	2.88	0.16	0.17	0.04	0.00	0.00
Geomorphology	4.00	4.05	4.00	3.83	2.88	3.00	4.05	4.00	3.83	2.88	0.25	0.00	0.00	0.00	0.00
Beach Slope	4.00	4.05	4.00	3.83	2.88	3.00	3.00	3.00	3.83	2.88	0.25	**0.26**	0.25	0.00	0.00
Significant Wave Height	4.00	4.05	4.00	3.83	2.88	3.00	4.05	4.00	3.83	2.88	0.25	0.00	0.00	0.00	0.00
Sediment Budget	4.00	4.05	4.00	3.83	2.88	2.00	4.05	4.00	3.83	2.88	**0.50**	0.00	0.00	0.00	0.00
Storm Surge Height	4.00	4.05	4.00	3.83	2.88	4.00	4.05	2.00	3.83	2.88	0.00	0.00	**0.50**	0.00	0.00
Tidal Range	4.00	4.05	4.00	3.83	2.88	3.15	3.91	3.00	3.83	2.88	0.21	0.03	0.25	0.00	0.00
Proximity to Coast	4.00	4.05	4.00	3.83	2.88	4.00	4.05	4.00	3.68	2.88	0.00	0.00	0.00	0.04	0.00
Type of Aquifer	4.00	4.05	4.00	4.51	2.88	4.00	4.05	4.00	3.83	2.88	0.00	0.00	0.00	0.15	0.00
Hydraulic Conductivity	4.00	4.05	4.03	3.83	2.88	4.00	4.05	4.03	3.74	2.88	0.00	0.00	0.00	0.02	0.00
Depth to Groundwater Level	4.00	4.05	4.00	3.83	2.88	4.00	4.05	4.00	3.63	2.88	0.00	0.00	0.00	0.05	0.00
River Discharge	4.00	4.05	4.00	3.83	2.88	4.00	4.05	4.00	3.83	2.00	0.00	0.00	0.00	0.00	**0.30**
River Water Depth	4.00	4.05	4.00	3.83	3.88	4.00	4.05	4.00	3.83	2.85	0.00	0.00	0.00	0.00	0.27
Reduction of Sediment Supply	4.00	4.05	4.00	3.83	2.88	4.00	4.05	4.00	3.83	2.88	0.00	0.00	0.00	0.00	0.00
River Flow Regulation	4.00	4.05	4.00	3.83	3.00	4.00	4.05	4.00	3.83	2.00	0.00	0.00	0.00	0.00	**0.33**
Engineered Frontage	4.00	4.05	4.07	3.83	3.00	4.00	4.05	4.00	3.83	2.88	0.00	0.00	0.02	0.00	0.04
Groundwater Stress	4.00	4.05	4.00	3.88	2.88	4.00	4.05	4.00	2.00	2.88	0.00	0.00	0.00	**0.48**	0.00
Land Use	4.00	4.05	4.00	3.83	2.94	4.00	4.05	4.00	2.00	2.00	0.00	0.00	0.00	**0.48**	**0.32**
Natural Protection Degradation	4.00	4.16	4.00	3.83	2.88	4.00	3.44	4.00	3.83	2.88	0.00	0.17	0.00	0.00	0.00
Coastal Protection Structures	4.00	4.05	4.00	3.83	2.88	4.00	3.44	4.00	3.83	2.88	0.00	0.15	0.00	0.00	0.00

7.2 Uncertainty in Fuzzy Vulnerability Assessment Model

"Uncertainty is perceived to be of either due to a lack of knowledge or due to natural variability in the system" (Walker et al. 2003). The process of modelling of nature leads to approximations or omissions of several components of the natural system which in turn leads to uncertainties in models, additional to those introduced through inputs and parameters. "Uncertainty is defined as the result of some information deficiency from fuzzy set theory perspective"(Janssen et al. 2010). Fuzzy sets may express two types of uncertainty; non-specificity (relating to the size of different alternative sets) or fuzziness (or vagueness, relating to the imprecise boundaries of the fuzzy sets).

Three different dimensions of uncertainty (Figure 7.3) are distinguished by (Walker et al. 2003):

- "Level: where the uncertainty manifests itself along the (continuous) spectrum between deterministic knowledge and total ignorance." This is described in detain in Chapter 6 with reference to Table 6.1 both in theory and discussing the fuzzy vulnerability assessment model.
- "Nature: whether the uncertainty is due to imperfection of knowledge (epistemic), or due to the inherent variability of the phenomena being described." This is described in detail in Chapter 6 with reference to Figure 6.1 both in theory and discussing the fuzzy vulnerability assessment model.
- "Location: where the uncertainty manifests itself in the components of a model complex: in the context, in the model itself ('model technical' or 'model structure' uncertainties), in the input, in parameters or in the output." This is developed and analyzed in this section with the use of scenario modelling.

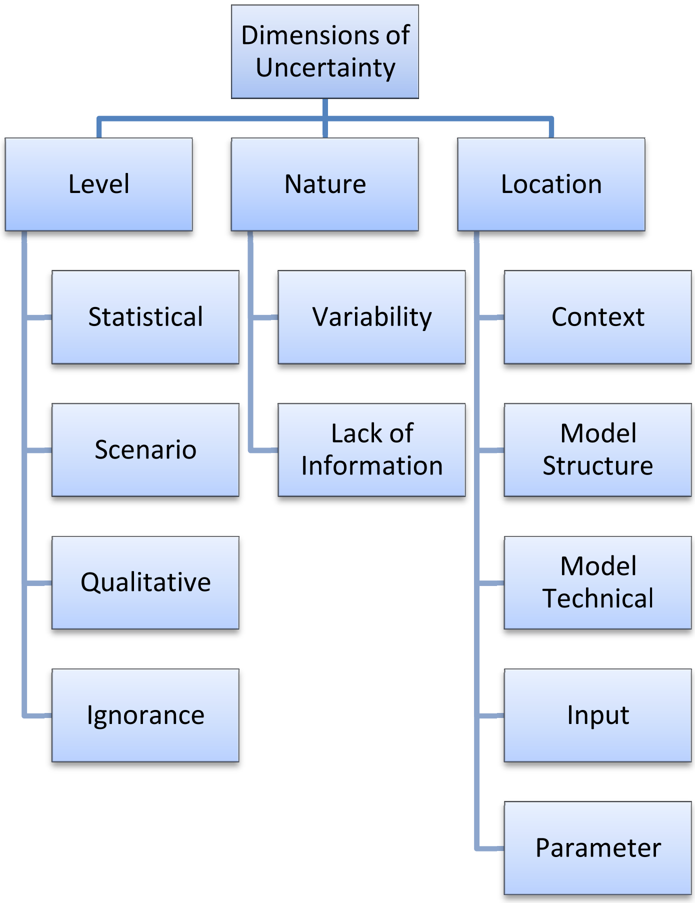


Figure 7.3 Dimensions of uncertainty

The uncertainties of the fuzzy vulnerability assessment model (FCVI) was evaluated according to the dimensions proposed by Walker et al. 2003 and the methodology for fuzzy models proposed by Janssen et al. 2010. First the impacts of separate uncertainties on the model output are described and then, the aggregated impacts of the combined uncertainties were evaluated.

Context uncertainty: "The uncertainty in the model context concerns choices made in the step from natural system to conceptual model. Answers to questions such as 'where and what are the model boundary conditions' and 'which input and output variables represent the system' can be uncertain if there are equally valid alternatives."(Janssen et al. 2010) Fuzzy vulnerability assessment model (FCVI) is developed to represent the 'vulnerability' of a coastal area to impacts of sea level rise. 'Vulnerability', itself is a concept that is quantified through many assumptions although it is defined as a function of exposure, sensitivity and adaptive capacity. The three components of vulnerability are quantified using other models and assumptions and expert opinions which in turn incorporate their own uncertainties. For this model (FCVI), representation of impacts of sea level rise along coastal areas were parameterized excluding some parameters such as angle of incidence for coastal erosion or generalization of others such as geomorphology is used to define the material of beach. Although these assumptions cause uncertainties in the context, integration of human activities on the other hand, decreases the uncertainties since most of the time, the influence of these activities were not included in vulnerability assessments of coastal areas. Also all the impacts of sea level rise were included in the fuzzy vulnerability assessment. Thus, the overall vulnerability ranking of different coastal areas would include less uncertainty with regards to different aspects of vulnerability imposed by sea level rise.

Model structure uncertainty: can be described as ". . . arising from a lack of sufficient understanding of the system that is the subject of the policy analysis, including the behavior of the system and the interrelationships among its elements" (Walker et al. 2003). "It is one of the most difficult uncertainties to address in environmental modelling"(Asselt and Rotmans 2002). Two aspects of this uncertainty are distinguished: the impreciseness of knowledge related to the structure of the data on systems' elements, and the uncertainty in the knowledge on interrelations between elements of the system.

According to the non-specificity as defined by Klir and Yuan (1995), the width of the membership function indicates a lack of knowledge. "This is here interpreted as the experts' inability to connect the different qualitative output states that are distinguished, to precise output values. The size and shape of the output graph, corresponding to a certain combination of input values, reflect an uncertainty in the model structure. The level of this uncertainty is 'qualitative' (can not be quantified by may be described)". Janssen et al. (2010) represent it by the difference between the centers of area (COA) of the subsets left and right of the original center of area as shown in Figure 7.4. "This provides a measure of the uncertainty reflected by the width and overlap of membership functions (MFs), following an interpretation that is consistent with using the COA for defuzzification" (Janssen et al. 2010). When combined with other uncertainties, the result is comparable to the random fuzzy set, with this difference that the uncertainty is here directly measured in the fuzzy output graph.

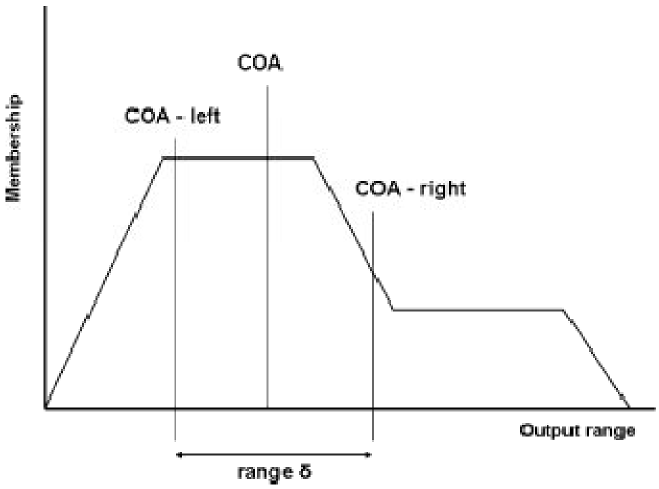


Figure 7.4 Model structure uncertainty: defuzzified value and bandwidth based on COA right minus COA left.

Model structure uncertainty of fuzzy vulnerability assessment model (FCVI) was analyzed for three cases; Goksu, Gocek and Amasra. The results show that model structure uncertainty from impreciseness of knowledge could be large. Table 7.4 shows the result of left and right center of areas when the output fuzzy set is defuzzified as well as the range between these upper and lower values.

Table 7.4 Model structure uncertainty using range of output value

	Goksu	Gocek	Amasra
Centroid (COA)	3.715	3.180	3.053
COA-Left	3.153	2.424	2.510
COA-Right	4.130	3.857	3.597
S (COAR-COAL)	0.977	1.433	1.087

These results (Figure 7.5) also show that the model structure uncertainty can be case dependent such that the large non-specificity of some of the parameters combined with uncertainty of input data might increase or decrease the model structure uncertainty (the spread of the three cases are very different from each other). This range shows us that it is probable that the vulnerability of the coastal area could range from one class lower to one class higher than the assigned value (as in the case of Gocek, Figure 7.5 (b)) however most of the time the vulnerability scores are within one class (from the lower end of the membership function to upper end) as in the cases of Goksu and Amasra (Figure 7.5 (c) and (a)). The important outcome of this analysis is that, this spread of uncertainty should be controlled when the results are interpreted.

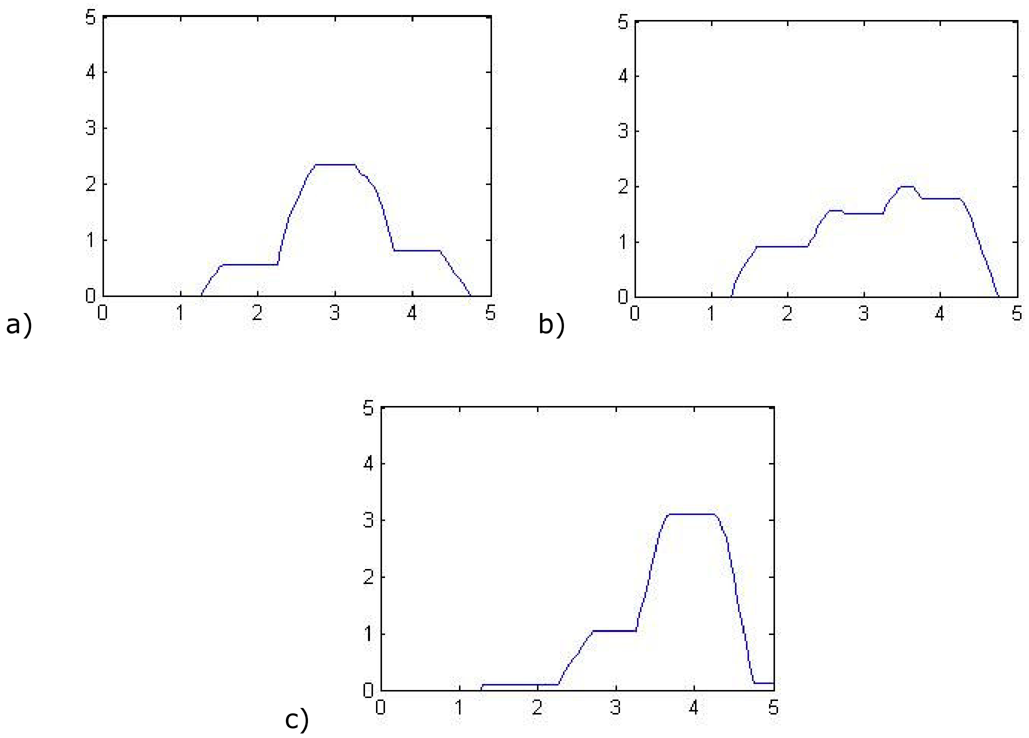


Figure 7.5 Fuzzy sets of coastal vulnerability scores of Amasra (a), Gocek (b) and Goksu (c).

Next, the choice of implication and aggregation operator is considered to contribute to model structure uncertainty. The deviation between outputs obtained with different operators is calculated as a measure for this uncertainty. It is important to underline the fact that, this is valid as long as the operators are considered equally valid. The level of this model technical uncertainty is 'scenario'.

For the inference procedure there is no equally valid alternative, since Mamdani is most suitable for rule-based models based on expert knowledge elicitation.

When implication operators MINIMUM and PRODUCT are compared used in fuzzy vulnerability assessment (FCVI) for Goksu; the overall coastal vulnerability score changes from 3.73 to 3.68 variability of ±2%. Figure shows the impact and overall vulnerability score when different implication operators are used in the model. As can be seen from Figure 7.6, the implication operators do not affect the system output significantly.

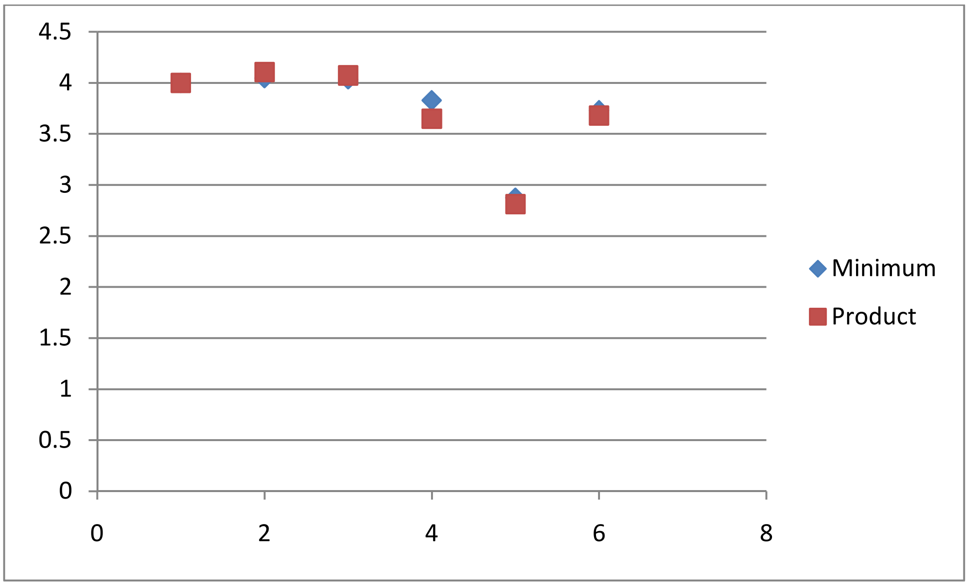


Figure 7.6 Uncertainty of the model due to implication operators

Comparison of aggregation operators is harder since the FCVI model is composed of many modules of fuzzy systems which use different aggregation operators. The human and physical inference systems use PROBOR, impact systems use MAX and the overall vulnerability is calculated by SUM. However all the combinations are analyzed to understand the uncertainty that the aggregation operators exert on the model output. The results are given in the Figure 7.7.

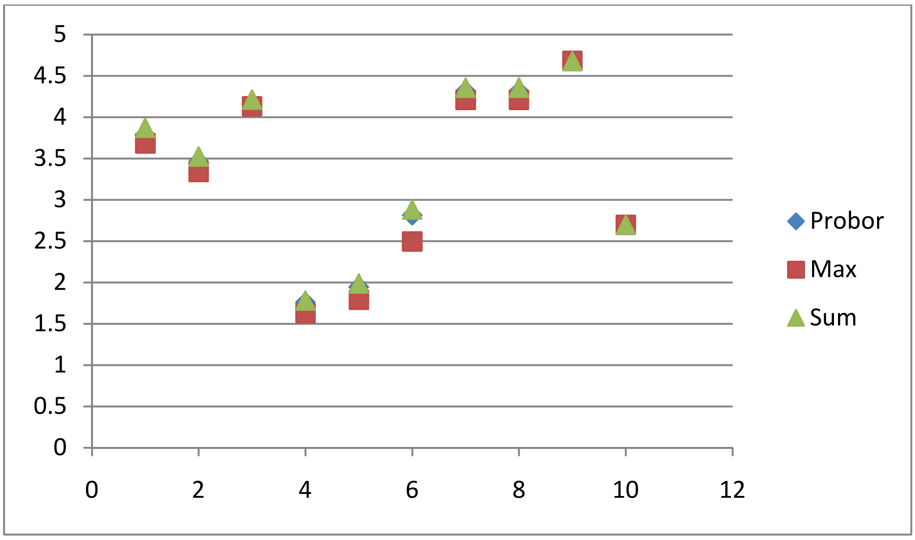


Figure 7.7 Uncertainty due to aggregation operator for human and physical inference systems

When human and physical inference systems are considered, output of PROBOR and SUM operators are very close to each other and output of MAX operator is the same or less (difference is small). This outcome ensures that always the critical condition is analyzed through the fuzzy vulnerability assessment model.

For different combinations of the aggregation operators through all levels of the fuzzy structure are considered, it is seen that the impact of the aggregator operators are significant (when relatively compared) for overall vulnerability index and coastal erosion impact index (Figure 7.8). This is expected since both outputs are consisted of many parameters such that the accumulation of the uncertainties in turn the handling of this aggregation significantly contributes to the outcome. On the other hand the range of the overall vulnerability index is 0.25 (%7 from reference value) which is very acceptable.

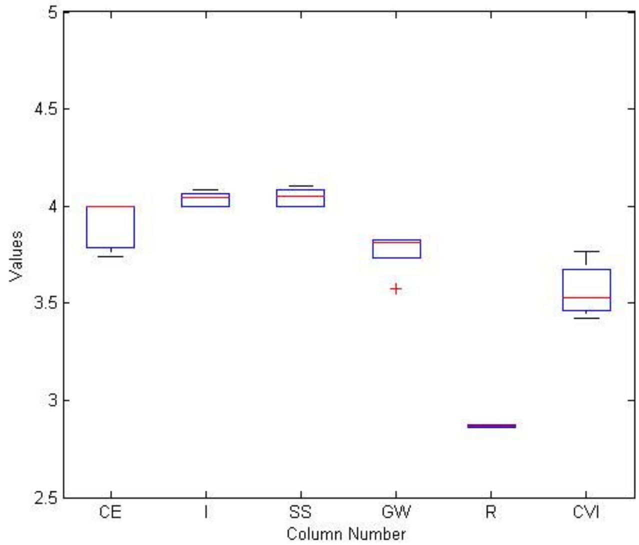


Figure 7.8 Uncertainty due to aggregation operator for impact inference systems (all the combinations are included)

When only the impact of the aggregation operator at the final module is analyzed (Figure 7.9), it is seen that both between the combinations and between the different types of operators, the difference is very small, not more than +/-0.05 (from reference value). This result shows that the operators of the fuzzy system do not generate uncertainty that might influence the outcome significantly.

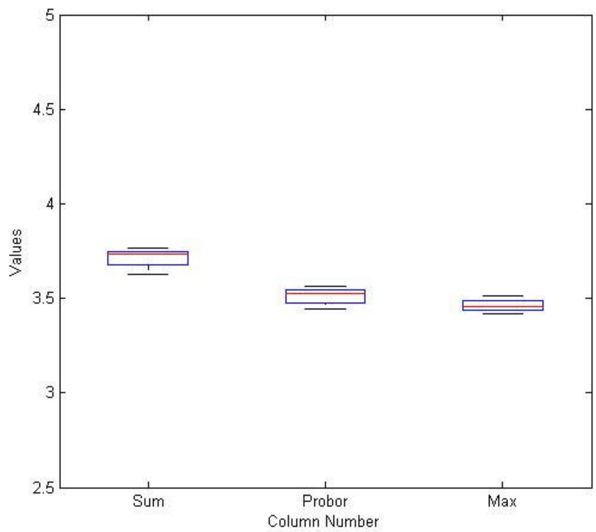


Figure 7.9 Uncertainty due to aggregation operator for overall vulnerability score (all combinations included)

Model technical uncertainty: ". . . aspects related to the computer implementation of the model" (Walker et al. 2003). "The model technical uncertainty comprises both software and hardware problems and errors. Analysis of model technical uncertainty would require multiple simultaneous model implementations."(Janssen et al. 2010) For the fuzzy vulnerability assessment model (FCVI), there were some minor errors throughout the MATLAB function and some rulebases of the inference systems, however through many applications during uncertainty and sensitivity analysis, these were found out and corrected.

Input uncertainty: "both uncertainty about '. . . driving external forces that produce changes within the system' and uncertainty about '. . . the system data that 'drive' the model and typically quantify relevant features of the reference system and its behavior'. This uncertainty is considered to be of a stochastic nature, i.e. due to variability in the system (with level marked as 'statistical' in the framework)"(Janssen et al. 2010). The sensitivity analysis performed in the previous section covers this uncertainty as well in global sense. If local input uncertainties are sought out, or uncertainties due to different set of inputs are needed, then either Monte Carlo analysis or sensitivity analysis with standard deviations of each input could be performed. However for this study, the global sensitivity analysis of different input values (one-at-a time method, using data of Goksu) showed that, the overall vulnerability index changes 7.5% (from the reference value) at most which is generally an acceptable level of uncertainty.

Parameter uncertainty: "is uncertainty related to the a priori chosen parameters, described by Walker et al. (2003) as '. . . parameters that may be difficult to identify by calibration and are chosen to be fixed at a certain value that is considered correct. The value of such parameters is associated with uncertainty that must be estimated on the basis of a priori experience'. Parameters determining the shape and size of the membership functions correspond to this location of uncertainty. If the experts are not so certain about the parameterization of the sets, or if ambiguity exists, a probability distribution of this uncertainty is unlikely to be available. Therefore this uncertainty is assumed to be of 'ambiguous' nature and 'scenario' level."(Janssen et al. 2010)

To determine the uncertainty related to shape of the membership functions a sensitivity analysis on the parameters are run using trapezoidal membership functions for some of the input parameters which were defined by triangular functions initially. The assignment of the trapezoid parts followed the assumption that when the membership values are higher than 0.8 from FCM analysis, those sections were assumed to belong to the class (new membership function value equals to 1.0). The procedure is explained for engineered frontage as an example. The other trapezoid membership functions are given in Appendix F.

The FCM analysis result of the engineered frontage parameter is given in Figure 7.10

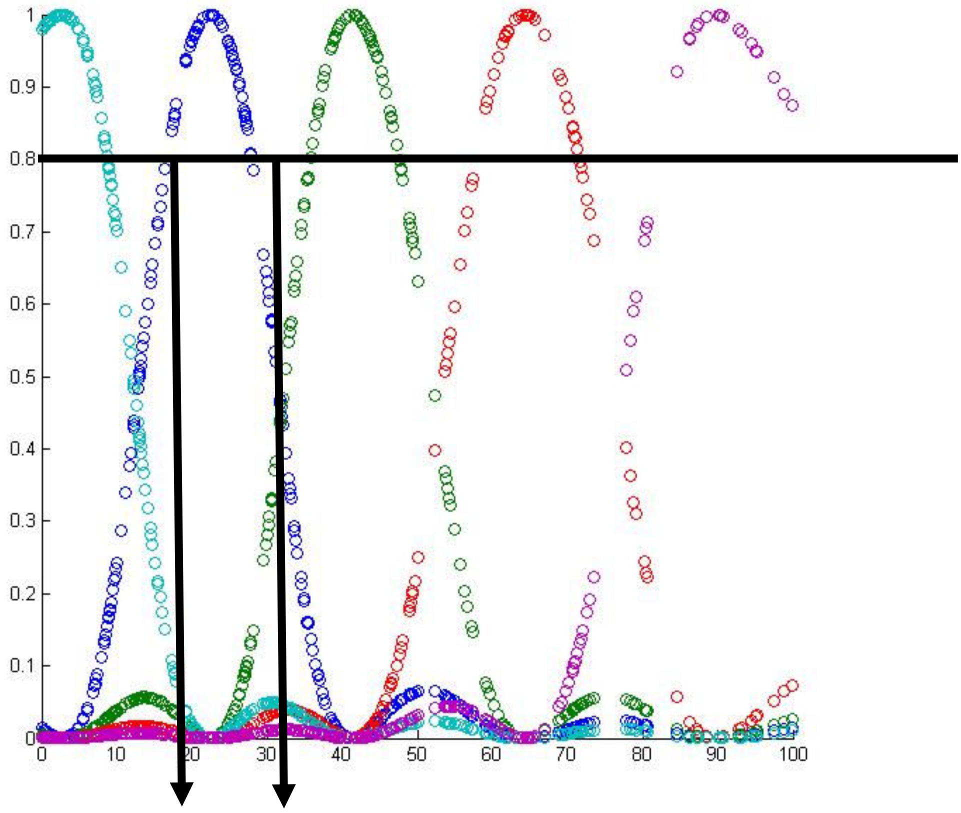


Figure 7.10 Graphical representation of trapezoid membership function generation

The values defining trapezoid functions were read from the graph by intersecting a horizontal line at membership value 0.8. Then the engineered function was generated in MATLAB Fuzzy Logic Toolbox as Figure 7.11.

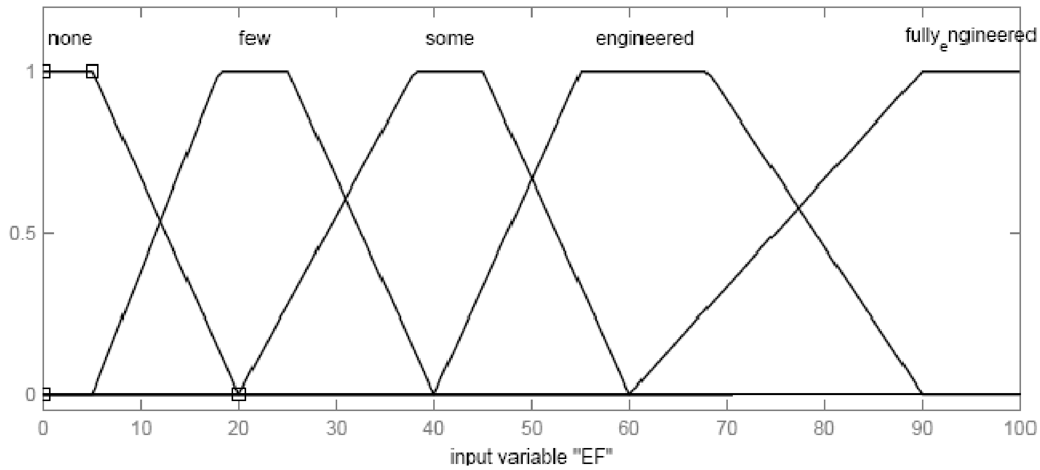


Figure 7.11 Trapezoidal Membership function plot of Engineered Frontage parameter

The parameters which were assigned trapezoid membership functions were significant wave height, storm surge height, tidal range, proximity to coast, discharge, and reduction of sediment supply, engineered frontage, groundwater stress, natural protection degradation and coastal protection structures. The other parameters were kept as their initial membership functions. When the three application site data was run with the new model, the results and comparison to the base model (model with triangular membership function) are given in Table 7.4.

Table 7.4 Uncertainty of vulnerability scores due to shape of membership functions

	Triangular Membership Functions			**Trapezoid Membership Functions**			**Change (from base model)**		
Impacts	Amasra	Gocek	Goksu	Amasra	Gocek	Goksu	Amasra	Gocek	Goksu
Coastal Erosion	3.00	3.00	4.00	3.00	3.00	4.00	0.00	0.00	0.00
Inundation	3.00	4.00	4.05	3.00	4.00	4.02	0.00	0.00	0.01
Storm Surge	3.78	4.00	4.00	3.78	4.00	4.00	0.00	0.00	0.00
Groundwater	2.44	2.73	3.83	2.30	2.76	3.83	0.06	0.01	0.00
River	0.00	2.00	2.88	0.00	2.00	2.88		0.00	0.00
VULNERABILITY	3.05	3.20	3.71	3.02	3.21	3.72	0.01	0.00	0.00

The sensitivity analysis was also performed for physical and human inference systems of each impact and the results are compared in Table 7.5.

Table 7.5 Uncertainty of physical and human inference systems due to membership function shape

	Triangular Membership Functions		Trapezoid Membership Functions		Change (from base model)	
Goksu	PP	HI	PP	HI	PP	HI
Coastal Erosion	3.79	2.81	3.79	2.91	0.00	0.03
Inundation	3.47	4.31	3.47	4.27	0.00	-0.01
Storm Surge	3.92	2.60	3.92	2.69	0.00	0.03
Groundwater	1.76	4.67	1.76	4.67	0.00	0.00
River	2.28	2.70	2.29	2.70	0.00	0.00
Gocek						
Coastal Erosion	2.98	2.72	2.97	2.72	0.00	0.00
Inundation	2.81	4.15	2.81	4.15	0.00	0.00
Storm Surge	3.08	3.87	3.64	3.82	0.18	-0.01
Groundwater	1.65	3.53	1.65	3.60	0.00	0.02
River	2.22	1.40	2.22	1.48	0.00	0.06
Amasra						
Coastal Erosion	2.79	2.38	2.79	2.38	0.00	0.00
Inundation	2.78	3.19	2.78	3.19	0.00	0.00
Storm Surge	3.65	2.87	3.65	2.84	0.00	-0.01
Groundwater	1.63	2.47	1.63	2.39	0.00	-0.03
River	0.00	0.00	0.00	0.00		

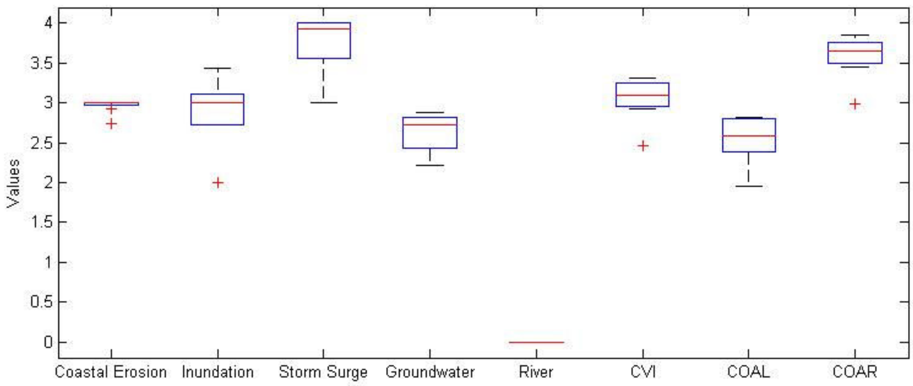
For different cases, the differences in the output values were not significant except storm surge value of Gocek. When the overall vulnerability scores were considered, the difference is again insignificant. Thus the original fuzzy vulnerability assessment model was set to be used for further studies since generation of triangular fuzzy membership functions are much more easier and shorter. The computing time needed is also much shorter.

Sensitivity study for the most sensitive parameters (Table 7.6) was also performed using trapezoid fuzzy membership functions to check if the sensitivity would decrease or not. There was not a persisting pattern of the resulting changes in the sensitivity index. And the change was mostly insignificant. So again, triangular membership functions were the chosen model for fuzzy vulnerability assessment model (FCVI).

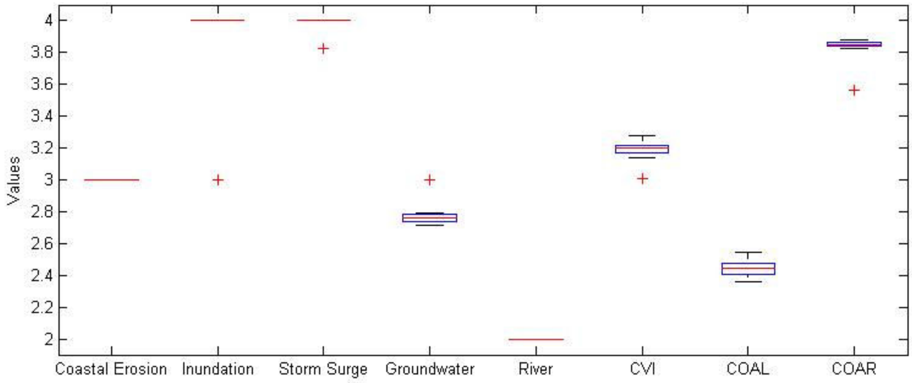
Table 7.6 Sensitivity study for different membership function shapes

	Triangular Membership Functions				Trapezoid Membership Functions				Change (from base model)
	Dmax	Dmin	Dmax -Dmin	SI	Dmax	Dmin	Dmax-Dmin	SI	SI
Land Use	3.715	3.126	0.589	**0.158**	3.716	3.151	0.565	**0.152**	**0.040**
Beach Slope	3.725	3.155	0.570	**0.153**	3.73	3.15	0.577	**0.155**	**-0.011**
Tidal Range	3.718	3.365	0.353	**0.095**	3.73	3.36	0.367	**0.099**	**-0.039**
Storm Surge Height	3.715	3.367	0.348	**0.094**	3.72	3.32	0.393	**0.106**	**-0.129**
Rate of Sea Level Rise	3.772	3.475	0.297	**0.079**	3.78	3.43	0.347	**0.092**	**-0.167**
Proximity to Coast	3.715	3.681	0.034	**0.009**	3.72	3.68	0.033	**0.009**	**0.020**

Aggregated uncertainty: it is assessed by using two case studies and based on a simultaneous variation of all randomly varied values (Monte Carlo simulation where normal distribution was used with standard deviation set to 0.2*input value). 10 random cases were selected for each region and the resulting uncertainty ranges were plotted using boxplot function of MATLAB for each individual impact, overall vulnerability score and the upper and lower center of area values of the overall vulnerability score. Results are given for Amasra and Gocek cases in Figure 7.12 (a) and (b) respectively.



a)



b)

Figure 7.12 Aggregated uncertainties for (a) Amasra and (b) Gocek

The resulting graphs show that, the uncertainty of the FCVI model is depends on input values and parameters. This means that uncertainty of the model is for impact scores case dependent. However when the overall vulnerability score is considered, the uncertainty decreases significantly (CVI values of Amasra and Gocek). Although uncertainty for the vulnerability scores (CVI, COAL and CoAR) are low, when the upper (COAR) and lower limits (COAL) are considered, the range (which was also analyzed in model structure uncertainty) could be large. This is not actually due to any invariability of the impacts or parameters but rather very case specific. When Gocek and Amasra figures are anlayzed it is clearly seen that the uncertainties are low. However scores of individual impacts are very different in the case of Gocek thus the range between upper and lower vulnerability scores is large. On the other hand, the impact scores are very close to each other for Amasra case, thus the range is much lower. The spread of output fuzzy function of the model should also be analyzed as the influence of different impact vulnerabilities of a region rather than uncertainty.

7.3 Concluding Remarks

Description of the uncertainties in model outcomes is considered of paramount importance for the accurate interpretation of these outcomes. This strongly applies to modelled expert knowledge since it is generally difficult to estimate the uncertainty herein. The uncertainty itself is composed of many dimensions that needs to be defined when an application of a model is analyzed. If the probabilities are known as well as all the possible outcomes, then straight forward uncertainty methods such as error propagation equations, sensitivity analysis, monte carlo analysis, etc. can be applied. However a combination of set of methodologies including sensitivity analysis, monte carlo analysis, etc. should be applied with scenario analysis (where output data is generated for a set of input values, thus the uncertainty is mostly case based) for models like vulnerability assessments where the outcome is linguistic variable. This was also the methodology for the fuzzy vulnerability assessment model (FCVI). What is more important than quantification of uncertainty is that, the stakeholders or implementers of the model should be aware of different types of uncertainties included in the model that is applied so that the outputs could be understood better and the decision making would be more reliable. In this study, by showing all types of uncertainties related to fuzzy vulnerability assessment model (FCVI), this objective was established and possible uncertainty issues were clearly stated.

CHAPTER VIII

CONCLUSION

The scope of the study was defined in the introduction considering the research initiatives proposed by IPCC 2007 as:

> **"Improving impact and vulnerability assessments within an integrated assessment framework that includes natural - human sub-system interactions which requires a strong inter-disciplinary approach.** Limited understanding of how development planners incorporate information about climate variability and change into their decisions is one the major obstacles of integrated assessment of vulnerability. Therefore, Improving systems of coastal planning and zoning and institutions that can enforce regulations for clearer coastal governance is required in many countries."

In light of the scope of the study, a coastal vulnerability assessment model based on fuzzy logic has been proposed.

- The Fuzzy Vulnerability Assesment Model (FCVI) model is based on preliminary vulnerability assessment model proposed by Ozyurt (2007) which ranks and prioritize different regions and impacts of sea level rise based on integration of human and physical site specific data
- The FCVI model has a weighting system of parameters through analytical hierarchy process using expert perception through online survey on the influence of sea level rise over the physical impact processes enabling inclusion of stakeholder views throughout the assessment
- The FCVI model is based on a spatial database of European coastlines and 81 river basins including groundwater resources of 9 EU countries to overcome the limitation of available data and to cover different types of

coastal areas (both at physical and human activity levels) to ensure the applicability of the model in large spatial scales such as regional to national levels

- The FCVI model uses fuzzy logic theory as the uncertainty model underlying the vulnerability assessment model to overcome the limitations of crisp boundaries of classification of data, non-linear relationships or unknown relationships between the parameters of human and physical systems and description of linguistic variable (vulnerability).

The fuzzy vulnerability model is successfully applied to three selected regions along coastlines of Turkey having different physical and human subsystem characteristics: Goksu (low-lying delta with high levels of human activity), Gocek (indented coast with high levels of human activity) and Amasra (high cliffed coast with low levels of human activity). The results of the model shows that Goksu shows high overall vulnerability with high impact scores related to coastal erosion, inundation and flooding due to storm surge; Gocek shows moderate overall vulnerability, the significant impacts possibly being inundation and flooding due to storm surge and Amasra shows low overall vulnerability with the most dominant expected impact as flooding due to storm surge. Three different cases act as validation of the fuzzy vulnerability model through comparison of the results with preliminary model results (which were validated through available literature) and ensured that the model is also applicable at local levels by highlighting the small differences within a small spatial scale.

A graphical user interface was developed on MATLAB platform to ensure ease of applicability of the end users. Two graphs can be generated; impact graph showing the impact vulnerability indices and influence histogram showing the influence of natural and human subsystems over individual impacts. The automation of the model structure increases the efficiency of the vulnerability assessment model as well as applicability for real case studies.

The use of fuzzy set theory enabled to include uncertainty modeling of the vulnerability assessment problem through which real system can be represented more accurately. The uncertainty profile of the fuzzy vulnerability assessment model (FCVI) and the uncertainty vector fuzzy set theory was compared to validate the use of fuzzy set theory.

The sensitivity and uncertainty analysis were performed through scenario analysis using the three case studies of selected sites. Although the sensitivity of the model parameters is low and the model is robust, uncertainty is mostly defined by model structure in terms of spread of the outcome fuzzy set.

Comparison of different shapes of membership functions validated the use of triangular membership functions since they are easier to generate and the uncertainties are low.

Influence of implication and aggregation operators of the fuzzy inference system were analyzed. The uncertainty analysis showed that the chosen operators ensured that the most critical case for vulnerability was assessed.

The overall aim of vulnerability assessment studies is to bridge the gap between current knowledge, adaptation and mitigation to a specific problem. This study through the development of fuzzy vulnerability assessment model achieves this objective successfully. The output values of the model enables decision makers to interpret the characteristics of the coastal area, present status of the region, possible vulnerability in the future (if the same trend continues), possible ranges of vulnerability in the future (if different trends prevails) and possible adaptation options in general through the influence histogram. The uncertainty being a part of the whole modeling procedure is a recent concept proposed by several researchers, however with regards to coastal vulnerability assessments; this type of assessment was first applied within this study. Both the model outcomes and the integration of uncertainty strengthen the decision making process and can very well change the perception of stakeholders on implementation of measures for future sea level rise by giving them possible frameworks to base their decisions on.

Overall, the fuzzy vulnerability assessment model can be an important and effective tool for decision makers, local experts and coastal managers. The implementation of the model using geographical information systems is the major further research agenda which will significantly increase the applicability and efficiency of the available model. Another future research could be to focus on the location of uncertainties in detail and to develop methods to decrease the uncertainties by applying rule generation algorithms and developing a larger rule base.

Finally, the model does not include socio-economic system which also significantly influences the adaptive capacity. However, the model having a modular structure makes it easy to integrate other modules without compromising the integrity of the initial model. Thus a more interdisciplinary approach would increase the reliability of the model representing real system in terms of overall vulnerability.

REFERENCES

A Digital Dataset of European Groundwater Resources at 1:500,000. (v. 1.0), Data From a Study Performed by the European Commission (1982 , EUR 7940 EN).

A. T. Vafeidis, Boot G., Cox J., Maatens, R., McFadden L., Nicholls R. J. , Spencer, and Tol, T. a. R. S. J. (2005). "The Diva Database Documentation." Dinas-Coast Project.

Abraham, A. (2005). "Rule-based Expert Systems." In: *Handbook of Measuring System Design*, P. H. S. a. R. Thorn, ed., John Wiley & Sons, Ltd., 911-919.

Afshar, A., Mariño, M. A., Ebtehaj, M., and Moosavi, J. (2007). "Rule-Based Fuzzy System for Assessing Groundwater Vulnerability." *Journal of Environmental Engineering*, 133(5), 532-540.

Arora, V. K., and Boer, G. J. (2001). "Effects of Simulated Climate Change on the Hydrology of Major River Basins." *Journal of Geophysical Research*, 106(D4), 3335–3348.

Asselt, M. B. A. V., and Rotmans, J. (2002). "Uncertainty in Integrated Assessment Modelling." *Climatic Change*, 54, 75-105.

Bashar, K. E., and Hossain, M. A. (2006). "Impact of Sea Level Rise on Salinity of Coastal Area of Bangladesh " *Int. River Symposium and Environmental Flows*, Printpoint, Australia.

Blumberg, A. F. (1978). "The Influence of Density Variations on Estuarine Tides and Circulations." *Estuarine and Coastal Marine Science*, 6, 209-215.

Bode, L., and Hardy, A. (1997). "Progress and Recent Developments in Storm Surge Modeling." *Journal of Hydraulic Engineering*, 123, 315-331.

Cat, V. M., and Duong, B. D. (2006). "Assessment of Saline Water Intrusion Into Estuaries of Red-Thai Binh River During Dry Season Having Considered Water Released From Upper Reservoirs and Tidal Fluctuation." In: *Vietnam-Japan Estuary Workshop 2006*, Hanoi, Vietnam.

CEM. (2003). "Coastal Engineering Manual." US Army Corps of Engineers, Washington, DC.

Chachadi, A. G. (2005). "Seawater Intrusion Mapping Using Modified GALDIT Indicator Model - Case Study in Goa." *Jalvigyan Sameeksha*, 20, 29-45.

Chachadi, A. G., and Lobo-Ferreira, J. P. (2001). "Sea Water Intrusion Vulnerability Mapping of Aquifers Using GALDIT Method." *Prof. Workshop on Modeling in Hydrogeology*, Anna University, Chennai, 143-156.

Chao, B. F., Wu, Y. H., and Li, Y. S. (2008). "Impact of Artificial Reservoir Water Impoundment on Global Sea Level (Supporting online material)." *Science*, doi:10.1126/science.1154580.

Cheng, E. W. L., and Li, H. (2001). "Analytic Hierarchy Process: An Approach to Determine Measures for Business Performance." *Measuring Business Excellence*, 5(3), 30-36.

Crick, M. J., Hill, M. D., and Charles, D. (1987). "The Role of Sensitivity Analysis in Assessing Uncertainty." *Proceedings of an NEA Workshop on Uncertainty Analysis for Performance Assessments of Radioactive Waste Disposal Systems*, Paris, OECD, 1-258.

CSIRO. (2010). "Sea Level Rise: Understanding the Past - Improving Projections of the Future." <http://www.cmar.csiro.au/sealevel>.

Dorsey, D. W., and Coovert, M. D. (2003). "Mathematical Modeling of Decision Making: A Soft and Fuzzy Approach to Capturing Hard Decisions." *Human Factors*, 45(1), 117-135.

Feenstra JF, Burton I, Smith JB, and Tol RSJ, eds. (1998). *Handbook on Methods Climate Change Impact Assessment and Adaptation Strategies*, United Nations Environment Programme.

FitzGerald, D. M., Fenster, M. S., Argow, B. A., and Buynevich, I. V. (2008). "Coastal Impacts Due to Sea Level Rise." *Annual Review of Earth and Planetary Sciences*, 36(601-647).

Giordano, M. (2009). "Global Groundwater? Issues and Solutions." *Annual Review of Environment and Resources*, 34, 153-178.

Gogu, R. C., Hallet, V., and Dassargues, A. (2003). "Comparison of Aquifer Vulnerability Assessment Techniques. Application to the Ne´blon River Basin (Belgium)." *Environmental Geology*(44), 881-892.

Hamby, D. M. (1994). "A Review of Techniques for Parameter Sensitivity Analysis of Environmental Models." *Environmental Monitoring and Assessment*, 32, 135-154.

Hanasaki, N., Kanae, S., and Oki, T. (2006). "A Reservoir Operation Scheme For Global River Routing Models." *Journal of Hydrology*(327), 22-41.

Hansen, B. (1997). "SIGMAR: A Fuzzy Expert System for Critiquing Marine Forecasts." *AI Applications*, 11(1), 59-68.

Harvey, N., Clouston, B., and Carvalho, P. (1999). "Improving Coastal Vulnerability Assessment Methodologies for Integrated Coastal Zone Management: an Approach from South Australia." *Australian Geographical Studies*, 37(1), 50-69.

Hinkel, J., and Klein, R. J. T. (2006). "Integrating Knowledge for Assessing Coastal Vulnerability to Climate Change." In: *Managing Coastal Vulnerability: An Integrated Approach*, R. J. N. a. E. C. P.-R. L. McFadden, ed., Elsevier Science, Amsterdam, The Netherlands.

Hiscock, K. M. (2005). *Hydrogeology Principles and Practice*, Blackwell Publishing.

IPCC. (1994). "Preparing to Meet the Coastal Challenges of the 21st Century." Report of the World Coast Conference. Ministry of Transport, Public Works and Water Management, National Institute for Coastal and Marine Management, the Hague.

IPCC. (2001). "Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.", Cambridge University Press, Cambridge.

IPCC. (2007a). "Intergovernmental Panel on Climate Change(IPCC) Fourth Assessment Report: Climate Change 2007 Impacts, Adaptation and Vulnerability." M.L. Parry, O.F. Canziani, J.P. Palutikof, P. J. v. d. Linden, and C. E. Hanson, eds., IPCC, Cambridge, United Kingdom and New York, NY, USA.

IPCC. (2007b). "IPCC Fourth Assessment Report: Climate Change 2007 The Physical Science Basis." S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller ed., IPCC, Cambridge, United Kingdom and New York, NY, USA.

Ippen, A. (1966). "Tidal Dynamics in Estuaries." In: *Estuary and Coastline Hydrodynamics*, A. Ippen, ed., McGraw-Hill, New York.

Janssen, J. A. E. B., Krol, M. S., Schielen, R. M. J., Hoekstra, A. Y., and Kok, J. L. d. (2010). "Assessment of Uncertainties in Expert Knowledge, Illustrated in Fuzzy Rule-based Models." *Ecological Modelling*, 221, 1245-1251.

Jiongxin, X. (2004). "A Study of Anthropogenic Seasonal Rivers in China." *Catena*, 55, 17–32.

Kana, T. W., Michel, J., Hayes, M. O., and Jensen, J. R. (1984). "The Physical Impact of Sea Level Rise in the Area of Charleston, South Carolina." In: *Greenhouse effect and sea level rise: a challenge for this generation.*, M. Barth and J. Titus, eds., New York.

Klein, R., and Nicholls, R. J. (1998). "Coastal Zones." In: *Handbook on Methods of Climate Change Impact Assessment and Adaptation Strategies*, J. F. Feenstra, I. Burton, J. B. Smith, and R. S. J. Tol, eds., United Nations Environment Programme.

Klein, R. J. T., Nicholls, R. J., and Thomalla, F. (2003). "Resilience to natural hazards:How useful is this concept?" *Environmental Hazards*, 5, 35-45.

Klement Tockner, Urs Uehlinger, and Robinson, C. T., eds. (2009). *Rivers of Europe*, First Ed., Elsevier, Italy.

Kundzewicz, Z. W., Nohara, D., Tong, J., Oki, T., Buda, S., and Takeuchi, K. (2009). "Discharge of large Asian rivers – Observations and projections." *Quaternary International*, in print.

Kuruüzüm, A., and Atsan, N. (2001). "Analitik Hiyerarsi Yontemi ve İsletmecilik Alanindaki Uygulamalari (The Analytic Hierarchy Process Approach and Its Applications in Business)." *Akdeniz İ.İ.B.F. Dergisi*(1), 83-105.

Lenôtre, N., and Thierry, P. (2002). "Methodology to Design the Coastal Erosion Layer for EUROSION Database." BRGM/RC-51916-FR 35 p., 7 fig., 1 app.

Liu, C., Sui, J., and Wang, Z.-Y. (2008). "Sediment Load Reduction in Chinese Rivers." *International Journal of Sediment Research*(23), 44-55.

Liu, W. C., Hsu, M. H., Wu, C. R., Wang, C. F., and Kuo, A. Y. (2004). "Modeling Salt Water Intrusion in Tanshui River Estuarine System—Case-Study Contrasting Now and Then." *Journal of Hydraulic Engineering*, 130(9), 849-859.

MacCready, P., and Geyer, W. R. (2010). "Advances in Estuarine Physics." *Annual Review of Marine Science*, 2, 35-58.

McFadden, L., Nicholls, R. J., Vafeidis, A., and Tol, R. S. J. (2007). "A Methodology for Modeling Coastal Space for Global Assessment." *Journal of Coastal Research*, 23(4), 911-920.

Medasani, S., Kim, J., and Krishnapuram, R. (1998). "An overview of membership function generation techniques for pattern recognition." *International Journal of Approximate Reasoning*, 19, 391-417.

Moore, W. S. (2010). "The Effect of Submarine Groundwater Discharge on the Ocean." *Annual Review of Marine Science*, 2, 59-88.

Morton, R. (2003). "An Overview of Coastal Land Loss: With Emphasis on the Southeastern United States." U.S. Geological Survey, Open Report 03-337.

Morton, R. A. (2005). "Coastal Classification Atlas." *http://coastal.er.usgs.gov/coastal-classification/index.html*.

Nicholls, R. J., and Klein, R. J. T. (2005). "Climate change and coastalmanagement on Europe's coast." In: *Managing European Coasts: Past, Present and Future*, J. E. Vermaat, L. Bouwer, K. Turner, and W. Salomons, eds., Springer, Environmental Science Monograph Series, 199-226.

Nilsson, C., Reidy, C. A., Dynesius, M., and Revenga, C. (2005). "Fragmentation and Flow Regulation of the World's Large River Systems." *Science*(308), 405.

Nohara, D., Kitoh, A., Hosaka, M., and Oki, T. (2006). "Impact of Climate Change on River Discharge Projected by Multimodel Ensemble." *Journal Of Hydrometeorology*, Volume 7(October 2006), 1076-1089.

Ozyurt, G. (2007). "Vulnerability of Coastal Areas to Sea Level Rise: Case Study on Goksu Delta," Master's Thesis. Middle East Technical University, Ankara.

Ozyurt,G. and Ergin, A.(2009). "Application of Sea Level Rise Vulnerability Assessment Model to Selected Coastal Areas of Turkey". *Journal of Coastal Research,*Special Edition 56, 248-251

Ozyurt, G., and Ergin, A. (2010). "Improving Coastal Vulnerability Assessments to Sea Level Rise : A New Indicator Based Methodology for Decision Makers." *Journal of Coastal Research*, 26(2), 265–273.

Pinho, J. L. S., and Viera, J. M. P. (2003). "Mathematical modelling of salt water intrusion in a Northern Portuguese estuary." *Inter-Celtic Colloquium on Hydrology and Management of Water Resources*, Guimarães.

Rigter, B. (1973). "Minimum Length of Salt Intrusion in Estuaries." *J. Hydraul. Div. Proc.*, 99, 1475-1496.

Roussel, O., Cavelier, A., and Werf, a. M. G. v. d. (2000). "Adaptation and use of a fuzzy expert system to assess the environmental effect of pesticides applied to field crops." *Agriculture, Ecosystems and Environment*(80), 143-158.

Saaty, L. T. (1980). *The Analytic Hierarchy Process*, McGraw-Hill Comp., U.S.A.

Saaty, L. T. (1994a). "Highlights and critical points in the theory and application of the Analytical Hierarchy Process." *European Journal of Operational Research*, 74, 426-447.

Saaty, T. L. (1994b). "How To Make A Decision: The Analytic Hierarchy Process." *Interfaces*, 24(6), 19-43.

Saaty, T. L. (2006). "The Analytic Network Process." In: *Decision Making with the Analytical Network Process*, T. L. Saaty, ed., 1-26.

Sherif, M. M., and Singh, V. P. (1999). "Effect of climate change on sea water intrusion in coastal aquifers." *Hydrological Processes*(13), 1277-1287.

Small, C., and Nicholls, R. J. (2003). "A Global Analysis of Human Settlement in Coastal Zones." *Journal of Coastal Research* 19, 584-599.

Sorensen, R. M., Weisman, R. N., and Lennon, G. P. (1984). "Control of erosion, inundation, and salinity intrusion caused by sea level rise. ." In: *Greenhouse Effect and Sea Level Rise: A Challenge for This Generation*, M. C. Barth and J. G. Titus, eds., New York: Van Nostrand Reinhold.

Teknomo, K., < <http://people.revoledu.com/kardi/copyright.html>>(2009).

Vorosmarty CJ, M. M., Fekete B, Sharma K, Green P and Syvitski PM (2003). "Anthropogenic sediment retention: major global impact from registered river impoundments." *Global and Planetary Change*, 39, 169-190.

Walker, W. E., Harremoes, P., Rotmans, J., and Sluis, J. P. V. d. (2003). "Defining uncertainty - a conceptual basis for uncertainty management in model-based decision support." *Integrated Assessment*, 4, 5-17.

Woodroffe, C. D. (2003). *Coasts: Form, Process and Evolution*, Cambridge University Press

Yaning, C., et al. (2009). "Fifty-year climate change and its effect on annual runoff in the Tarim River Basin, China." *Quaternary International*, in print.

Yohe, G., and Tol, R. S. J. (2002). "Indicators for social and economic coping capacity - moving toward a working definition of adaptive capacity. ." *Global Environment Change*, 12, 25-40.

Zadeh, L. A. (1965). "Fuzzy Sets." *Information and Control*, 8, 338-353.

Zadeh, L. A. (2005). "Toward a generalized theory of uncertainty (GTU) - an outline." *Information Sciences*, 172, 1-40.

Zimmermann, H.-J. (2000). "An application-oriented view of modeling uncertainty." *European Journal of Operational Research*, 122, 190-198.

APPENDIX A

AHP SURVEY QUESTIONS

Perception Study on impacts of sea level rise on coastal processes

1. Default Section

Vulnerability of coastal areas to impacts of sea level rise is an important element of adaptation plans integrated with coastal zone management practices. Vulnerability is defined as the degree which a system is unable to cope with adverse effects of climate change including climate variability and extremes. Although it is important to quantify the predicted changes along a coastal area, the term vulnerability is yet to have a universal quantification method.

This survey is a part of a study called "Indicator based fuzzy coastal vulnerability model to sea level rise" funded by Turkish National Science and Technology Foundation carried out in Ocean Engineering Research Center, Department of Civil Engineering, Middle East Technical University, Ankara, Turkey. The study aims to quantify vulnerability of a region using both physical and human induced parameters governing the processes of physical impacts of sea level rise. The scores of vulnerability will enable decision makers to compare and rank coastal areas with respect to their vulnerabilities to sea level rise, to prioritize the impacts of sea level rise of a region and to determine the most vulnerable parameters. Using the knowledge from the coastal vulnerability assessment to sea level rise, optimum resource allocation and appropriate adaptation measures within integrated coastal zone management framework would be ensured.

This survey aims to assess the importance of each parameter with respect to the impact processes through pair wise comparisons and using analytical hierarchy process. The results of this survey will be used to determine global weights for each parameter of the fuzzy vulnerability analysis. Results of this survey will be available through project report.

We kindly remind you that completing the survey takes between 10 - 40 minutes depending on the selected expert areas.

Thank you for your time and consideration!

Please use the buttons at the end of each page to go back and forth when answering the survey.

* 1. Please provide the following personal information.

Name:

Institution:

Country:

Email Address:

Perception Study on impacts of sea level rise on coastal processes

*** 2. Choose at least one or more of the following impacts of sea level rise based on your expertise area. You are asked to provide answers for the impacts that you have chosen.**

- [ ] Inundation
- [ ] Coastal Erosion
- [ ] Flooding due to Storm Surges
- [ ] Salt Water Intrusion to Groundwater Resources
- [ ] Salt Water Intrusion to Estuary/River

2. Inundation

*** 1. Do you want to answer questions on INUNDATION?**

- ○ Yes
- ○ No

3. Inundation-1

Perception Study on impacts of sea level rise on coastal processes

Inundation is the permanent submergence of low lying land.

Parameters that define inundation process are given below:

Physical Parameters	Human Activity Parameters
Rate of sea level rise: indicates relative sea level change including tectonic movement (subsidence/uplift)	Natural Protection Status: indicates the present condition of natural protection such as dunes, marshes or wetlands along the coast
Beach slope	Coastal Protection Structures: percent of shoreline that coastal protection structures occupy
Tidal range of the region	

Perception Study on impacts of sea level rise on coastal processes

Please compare the parameters (described above) in a pair wise manner giving scores according to the criteria given below.

Pair wise Comparison Scale

Verbal Judgment of Preference	Numerical Rating
Extremely Preferred	9
Very strong to extremely	8
Very strongly preferred	7
Strongly to very strongly	6
Strongly preferred	5
Moderately to strongly	4
Moderately preferred	3
Equally to moderately	2
Equally preferred	1

Example: For a given impact of sea level rise when comparing parameter A with other parameters with respect to their influence on the process of the impact of sea level rise, if you think that:

- Parameter A is 3 times more important than (moderately important than) Parameter B.
- Parameter C is 5 times more important than (strongly important than) Parameter A.

Fill in the survey form as:

	Parameter A	Which one is more important?
Parameter B	3	Parameter A
Parameter C	5	Parameter C

202

Perception Study on impacts of sea level rise on coastal processes

1. Compare the following physical parameters with respect to their influence (impact) on inundation process.

	Rate of Sea Level Rise	Which one is more important
Beach slope		
Tidal Range		

2. Compare the following parameters with respect to their influence (impact) on inundation process.

	Beach Slope	Which one is more important
Tidal Range		

3. Compare the following human impact parameters according to their influence on inundation process by giving weight values between 0 and 1 (adding up to 1).

Natural Protection Status	
Coastal Protection Structures	

4. Compare the physical and human impact parameters according to their influence on inundation process by giving weight values between 0 and 1 (adding up to 1).

Physical Parameters	
Human Impact Parameters	

4. Coastal Erosion

*** 1. Do you want to answer questions on COASTAL EROSION?**

- ○ Yes
- ○ No

5. Coastal Erosion - 1

Perception Study on impacts of sea level rise on coastal processes

Coastal erosion represents the physical removal of sediment by wave and current action. One of the reasons of land loss due to sea level rise is the increased coastal erosion.

Parameters that define coastal erosion process are given below:

Physical Parameters	Human Activity Parameters
Rate of sea level rise: indicates relative sea level change including tectonic movement (subsidence/uplift)	Reduction of sediment supply: decrease in amount of sediment due to damming and/or coastal excavations
Geomorphology: type of landforms	River Flow Regulations: amount of impact of regulative structures on rivers at the down drift in terms of flow rate
Beach slope	Engineered Frontage: percent of shoreline that the coastal structures occupy (harbors, marinas, jetties, etc)
Wave Climate	Natural Protection Status: indicates the present condition of natural protection such as dunes, marshes or wetlands along the coast
Sediment budget: indicates overall trend of shoreline whether it is stable, eroding or accreting	Coastal Protection Structures: percent of shoreline that coastal protection structures occupy
Tidal range of the region (low or high)	

Perception Study on impacts of sea level rise on coastal processes

Please compare the parameters (described above) in a pair wise manner giving scores according to the criteria given below.

Pair wise Comparison Scale

Verbal Judgment of Preference	Numerical Rating
Extremely Preferred	9
Very strong to extremely	8
Very strongly preferred	7
Strongly to very strongly	6
Strongly preferred	5
Moderately to strongly	4
Moderately preferred	3
Equally to moderately	2
Equally preferred	1

Example: For a given impact of sea level rise when comparing parameter A with other parameters with respect to their influence on the process of the impact of sea level rise, if you think that:

- Parameter A is 3 times more important than (moderately important than) Parameter B.
- Parameter C is 5 times more important than (strongly important than) Parameter A.

Fill in the survey form as:

	Parameter A	Which one is more important?
Parameter B	3	Parameter A
Parameter C	5	Parameter C

Perception Study on impacts of sea level rise on coastal processes

1. Compare the following physical parameters with respect to their influence on coastal erosion process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Rate of Sea Level Rise	Which one is more important
Geomorphology		
Beach Slope		
Wave Climate		
Sediment Budget		
Tidal Range		

Comments:

2. Compare the following physical parameters according to their influence on coastal erosion process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Geomorphology	Which one is more important
Beach Slope		
Wave Climate		
Sediment Budget		
Tidal Range		

Comments:

Perception Study on impacts of sea level rise on coastal processes

3. Compare the following physical parameters according to their influence on coastal erosion process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Beach Slope	Which one is more important
Wave Climate		
Sediment Budget		
Tidal Range		

Comments:

4. Compare the following physical parameters according to their influence on coastal erosion process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Wave Climate	Which one is more important
Sediment Budget		
Tidal Range		

Comments:

Perception Study on impacts of sea level rise on coastal processes

5. Compare the following physical parameters according to their influence on coastal erosion process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Sediment Budget	Which one is more important
Tidal Range		

Comments:

6. Compare the following human impact parameters according to their influence on coastal erosion process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Recuction of Sediment Supply	Which one is more important?
River Flow Regulation		
Engineered Frontage		
Natural Protection Status		
Coastal Protection Structures		

Comments:

Perception Study on impacts of sea level rise on coastal processes

7. Compare the following human impact parameters according to their influence on coastal erosion process. Use the comparison scale (1-9) provided at the beginning of the survey.

	River Flow Regulation	Which one is more important?
Engineered Frontage		
Natural Protection Status		
Coastal Protection Structures		

Comments:

8. Compare the following human impact parameters according to their influence on coastal erosion process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Engineered Frontage	Which one is more important?
Natural Protection Status		
Coastal Protection Structures		

Comments:

Perception Study on impacts of sea level rise on coastal processes

9. Compare the following human impact parameters according to their influence on coastal erosion process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Natural Protection Status	Which one is more important?
Coastal Protection Structures		

Comments:

10. Compare the physical and human impact parameters according to their overall influence on coastal erosion process by giving weight values between 0 and 1 (adding up to 1).

Physical Parameters

Human Impact Parameters

6. Coastal Flooding due to Storm Surge

*** 1. Do you want to answer questions on COASTAL FLOODING DUE TO STORM SURGES?**

- ◯ Yes
- ◯ No

7. Coastal Flooding due to Storm Surge - 1

Perception Study on impacts of sea level rise on coastal processes

Storm surge is a meteorologically forced long wave motion which can produce sustained elevations of water surface above levels caused by tides. Sea level rise will move the risk zones upward and seaward.

Parameters that define flooding due to increased storm surges are given below:

Physical Parameters	Human Activity Parameters
Rate of sea level rise: indicates relative sea level change including tectonic movement (subsidence/uplift)	Engineered Frontage: percent of shoreline that the coastal structures occupy (harbors, marinas, jetties, etc)
Beach slope	Natural Protection Status: indicates the present condition of natural protection such as dunes, marshes or wetlands along the coast
Storm surge height	Coastal Protection Structures: percent of shoreline that coastal protection structures occupy
Tidal range of the region	

Perception Study on impacts of sea level rise on coastal processes

Please compare the parameters (described above) in a pair wise manner giving scores according to the criteria given below.

Pair wise Comparison Scale

Verbal Judgment of Preference	Numerical Rating
Extremely Preferred	9
Very strong to extremely	8
Very strongly preferred	7
Strongly to very strongly	6
Strongly preferred	5
Moderately to strongly	4
Moderately preferred	3
Equally to moderately	2
Equally preferred	1

Example: For a given impact of sea level rise when comparing parameter A with other parameters with respect to their influence on the process of the impact of sea level rise, if you think that:

- Parameter A is 3 times more important than (moderately important than) Parameter B.
- Parameter C is 5 times more important than (strongly important than) Parameter A.

Fill in the survey form as:

	Parameter A	Which one is more important?
Parameter B	3	Parameter A
Parameter C	5	Parameter C

Perception Study on impacts of sea level rise on coastal processes

1. Compare the following physical parameters according to their influence on coastal flooding due to storm surges process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Rate of Sea Level Rise	Which one is more important?
Beach Slope		
Storm Surge Height		
Tidal Range		

Comments:

2. Compare the following physical parameters according to their influence on coastal flooding due to storm surges process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Beach Slope	Which one is more important?
Storm Surge Height		
Tidal Range		

Comments:

3. Compare the following physical parameters according to their influence on coastal flooding due to storm surges process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Storm Surge Height	Which one is more important?
Tidal Range		

Comments:

Perception Study on impacts of sea level rise on coastal processes

4. Compare the following human impact parameters according to their influence on flooding due to storm surges process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Engineered Frontage	Which one is more important?
Natural Protection Status		
Coastal Protection Structures		

Comments:

5. Compare the following human impact parameters according to their influence on flooding due to storm surges process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Natural Protection Status	Which one is more important?
Coastal Protection Structures		

Comments:

6. Compare the physical and human impact parameters according to their influence on coastal flooding due to storm surges process by giving weight values between 0 and 1 (adding up to 1).

Physical Parameters

Human Impact Farameters

8. Salt Water Intrusion to Groundwater Resources

*** 1. Do you want to answer questions on SALT WATER INTRUSION TO GROUNDWATER RESOURCES?**

- ◯ Yes
- ◯ No

Perception Study on impacts of sea level rise on coastal processes

9. Salt Water Intrusion to Groundwater Resources - 1

Parameters that define salt water intrusion to groundwater resources are given below:

Physical Parameters	Human Activity Parameters
Rate of sea level rise: indicates relative sea level change including tectonic movement (subsidence/uplift)	Groundwater consumption
Proximity to coast	Land Use Pattern
Type of Aquifer	
Hydraulic Conductivity	
Depth to groundwater level above sea	

Perception Study on impacts of sea level rise on coastal processes

Please compare the parameters (described above) in a pair wise manner giving scores according to the criteria given below.

Pair wise Comparison Scale

Verbal Judgment of Preference	Numerical Rating
Extremely Preferred	9
Very strong to extremely	8
Very strongly preferred	7
Strongly to very strongly	6
Strongly preferred	5
Moderately to strongly	4
Moderately preferred	3
Equally to moderately	2
Equally preferred	1

Example: For a given impact of sea level rise when comparing parameter A with other parameters with respect to their influence on the process of the impact of sea level rise, if you think that:

- Parameter A is 3 times more important than (moderately important than) Parameter B.
- Parameter C is 5 times more important than (strongly important than) Parameter A.

Fill in the survey form as:

	Parameter A	Which one is more important?
Parameter B	3	Parameter A
Parameter C	5	Parameter C

Perception Study on impacts of sea level rise on coastal processes

1. Compare the following physical parameters according to their influence on salt water intrusion to groundwater resources process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Rate of Sea Level Rise	Which one is more important?
Proximity to coast		
Type of aquifer		
Hydraulic Conductivity		
Depth to Groundwater level above sea		

Comments:

2. Compare the following physical parameters according to their influence on salt water intrusion to groundwater resources process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Proximity to coast	Which one is more important?
Type of aquifer		
Hydraulic Conductivity		
Depth to Groundwater level above sea		

Comments:

Perception Study on impacts of sea level rise on coastal processes

3. Compare the following physical parameters according to their influence on salt water intrusion to groundwater resources process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Type of aquifer	Which one is more important?
Hydraulic Conductivity		
Depth to Groundwater level above sea		

Comments:

4. Compare the following physical parameters according to their influence on salt water intrusion to groundwater resources process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Hydraulic Conductivity	Which one is more important?
Depth to Groundwater level above sea		

Comments:

5. Compare the following human impact parameters according to their influence on salt water intrusion to groundwater resources process by giving weight values between 0 and 1 (adding up to 1).

Groundwater Consumption

Land Use Pattern

6. Compare the physical and human impact parameters according to their overall influence on salt water intrusion to groundwater resources process by giving weight values between 0 and 1 (adding up to 1).

Physical Parameters

Human Impact Parameters

Perception Study on impacts of sea level rise on coastal processes

10. Salt Water Intrusion to Rivers/Estuary

*** 1. Do you want to answer questions on SALT WATER INTRUSION TO RIVER/ESTUARY?**

○ Yes

○ No

11. Salt Water Intrusion to Rivers/Estuary - 1

Parameters that define salt water intrusion to rivers/estuaries are given below:

Physical Parameters	Human Activity Parameters
Rate of sea level rise: indicates relative sea level change including tectonic movement (subsidence/uplift)	Engineered Frontage: percent of shoreline that the coastal structures occupy (harbors, marinas, jetties, etc)
Tidal range of the region	Land Use Pattern
Water Depth at Downstream	River Flow Regulations: amount of impact of regulative structures on rivers at the down drift in terms of flow rate
Discharge	

Perception Study on impacts of sea level rise on coastal processes

Please compare the parameters (described above) in a pair wise manner giving scores according to the criteria given below.

Pair wise Comparison Scale

Verbal Judgment of Preference	Numerical Rating
Extremely Preferred	9
Very strong to extremely	8
Very strongly preferred	7
Strongly to very strongly	6
Strongly preferred	5
Moderately to strongly	4
Moderately preferred	3
Equally to moderately	2
Equally preferred	1

Example: For a given impact of sea level rise when comparing parameter A with other parameters with respect to their influence on the process of the impact of sea level rise, if you think that:

- Parameter A is 3 times more important than (moderately important than) Parameter B.
- Parameter C is 5 times more important than (strongly important than) Parameter A.

Fill in the survey form as:

	Parameter A	Which one is more important?
Parameter B	3	Parameter A
Parameter C	5	Parameter C

Perception Study on impacts of sea level rise on coastal processes

1. Compare the following physical parameters according to their influence on salt water intrusion to rivers/estuaries process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Rate of Sea Level Rise	Which one is more important?
Tidal Range		
Water Depth at Downstream		
Discharge		

Comments:

2. Compare the following physical parameters according to their influence on salt water intrusion to rivers/estuaries process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Tidal Range	Which one is more important?
Water Depth at Downstream		
Discharge		

Comments:

3. Compare the following physical parameters according to their influence on salt water intrusion to rivers/estuaries process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Water Depth at Downstream	Which one is more important?
Discharge		

Comments:

Perception Study on impacts of sea level rise on coastal processes

4. Compare the following human impact parameters according to their influence on salt water intrusion to rivers/estuaries process. Use the comparison scale (1-9) provided at the beginning of the survey.

	River Flow Regulation	Which one is more important?
Engineered Frontage		
Land Use Pattern		

Comments:

5. Compare the following human impact parameters according to their influence on salt water intrusion to rivers/estuaries process. Use the comparison scale (1-9) provided at the beginning of the survey.

	Engineered Frontage	Which one is more important?
Land Use Pattern		

Comments:

6. Compare the physical and human impact parameters according to their overall influence on salt water intrusion to rivers/estuaries process by giving weight values between 0 and 1 (adding up to 1).

Physical Parameters

Human Impact Parameters

12. Comparison of Impacts

Perception Study on impacts of sea level rise on coastal processes

Please compare the parameters (described above) in a pair wise manner giving scores according to the criteria given below.

Pair wise Comparison Scale

Verbal Judgment of Preference	Numerical Rating
Extremely Preferred	9
Very strong to extremely	8
Very strongly preferred	7
Strongly to very strongly	6
Strongly preferred	5
Moderately to strongly	4
Moderately preferred	3
Equally to moderately	2
Equally preferred	1

Example: For a given impact of sea level rise when comparing parameter A with other parameters with respect to their influence on the process of the impact of sea level rise, if you think that:

- Parameter A is 3 times more important than (moderately important than) Parameter B.
- Parameter C is 5 times more important than (strongly important than) Parameter A.

Fill in the survey form as:

	Parameter A	Which one is more important?
Parameter B	3	Parameter A
Parameter C	5	Parameter C

Perception Study on impacts of sea level rise on coastal processes

* 1. Compare the following impacts of sea level rise according to their influence on vulnerability of coastal areas in a pair wise manner. Use the comparison scale (1-9) provided at the beginning of the survey.

	Coastal Erosion	Which one is more important?
Inundation		
Flooding due to Storm Surges		
Salt Water Intrusion to Groundwater Resources		
Salt Water Intrusion to Estuary/River		

Comments:

* 2. Compare the following impacts of sea level rise according to their influence on vulnerability of coastal areas in a pair wise manner. Use the comparison scale (1-9) provided at the beginning of the survey.

	Inundation	Which one is more important?
Flooding due to Storm Surges		
Salt Water Intrusion to Groundwater Resources		
Salt Water Intrusion to Estuary/River		

Comments:

Perception Study on impacts of sea level rise on coastal processes

*3. Compare the following impacts of sea level rise according to their influence on vulnerability of coastal areas in a pair wise manner. Use the comparison scale (1-9) provided at the beginning of the survey.

	Flooding due to Storm Surges	Which one is more important?
Salt Water Intrusion to Groundwater Resources		
Salt Water Intrusion to Estuary/River		

Comments:

*4. Compare the following impacts of sea level rise according to their influence on vulnerability of coastal areas in a pair wise manner. Use the comparison scale (1-9) provided at the beginning of the survey.

	Salt Water Intrusion to Groundwater Resources	Which one is more important?
Salt Water Intrusion to Estuary/River		

Comments:

Thank you for completing the survey.

APPENDIX B

AHP JUDGEMENT MATRICES

Inundation	RSL	Slope	Tide	Weights
RSL	1.00	0.57	2.62	**0.35**
Slope	1.76	1.00	2.01	**0.47**
Tide	0.38	0.50	1.00	**0.18**
			CR	0.05

	Weights
NDP	**0.63**
CPS	**0.36**

Surge	RSL	Slope	Surge	Tide	Weights
RSL	1.000	0.517	0.172	0.359	**0.08**
Slope	1.934	1.000	0.266	1.565	**0.18**
Surge	5.803	3.761	1.000	3.637	**0.57**
Tide	2.783	0.639	0.275	1.000	**0.16**
				CR	0.029

	EF	NPD	CPS	Weights
EF	1.00	0.65	1.73	**0.32**
NPD	1.53	1.00	2.43	**0.48**
CPS	0.58	0.41	1.00	**0.19**
			CR	0.00

Rivers	RSL	Tide	Depth	Q	Weights
RSL	1.00	1.71	0.30	0.30	**0.13**
Tide	0.58	1.00	0.25	0.23	**0.09**
Dept	3.30	4.00	1.00	0.58	**0.34**
Q	3.30	4.31	1.71	1.00	**0.45**
				CR	0.016

	RF	EF	LU	Weights
RF	1.00	4.31	5.65	**0.71**
EF	0.23	1.00	0.87	**0.14**
LU	0.18	1.14	1.00	**0.14**
			CR	0.016

Erosion	RSL	Geo	Slope	Wave	Sediment	Tide	Weights
RSL	1.000	0.455	0.779	0.570	0.309	0.830	**0.09**
Geo	2.196	1.000	1.866	0.789	0.511	1.914	**0.17**
Slope	1.283	0.536	1.000	0.554	0.291	1.701	**0.11**
Wave	1.755	1.268	1.804	1.000	0.427	2.246	**0.18**
Sediment	3.240	1.958	3.442	2.340	1.000	5.284	**0.37**
Tide	1.205	0.523	0.588	0.445	0.189	1.000	**0.08**
						CR	0.01

	Rs	RF	EF	NPD	CPS	**Weights**
Rs	1.000	3.584	1.677	3.140	2.865	**0.40**
RF	0.279	1.000	0.693	1.004	0.919	**0.13**
EF	0.596	1.443	1.000	1.707	1.091	**0.20**
NPD	0.318	0.996	0.586	1.000	0.799	**0.12**
CPS	0.349	1.088	0.917	1.251	1.000	**0.15**
					CR	0.005

GW	RSL	distance	aquifer	K	depth	**Weights**
RSL	1.000	0.378	0.126	0.250	0.158	**0.04**
distance	2.646	1.000	0.134	1.732	0.447	**0.09**
aquifer	7.937	7.483	1.000	7.937	4.899	**0.60**
conduct	4.000	0.577	0.126	1.000	0.316	**0.08**
depth	6.325	2.236	0.204	3.162	1.000	**0.19**
					CR	0.06

	Weights
GW	0.7
Landuse	0.3

Impacts	CE	I	SS	GW	R	**Weights**
Ce	1.000	3.238	2.182	2.449	1.602	**0.36**
I	0.309	1.000	0.702	0.794	1.020	**0.13**
SS	0.458	1.424	1.000	1.145	1.070	**0.18**
GW	0.408	1.260	0.874	1.000	1.070	**0.16**
R	0.624	0.981	0.935	0.935	1.000	**0.17**
					CR	0.01

APPENDIX C

FUZZY SYSTEM COMPONENTS

Membership Functions

Fuzziness in a fuzzy set is characterised by its membership functions. A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. The features of membership functions have three properties:

Core: The elements, which have the membership function as 1 are the elements of the core; $\mu_A(x) = 1$.

Support: The support has the elements whose membership is greater than 0; $\mu_A(x) > 0$.

Boundary: The boundary has the elements whose membership is between 0 and 1; $0 < \mu_A(x) < 1$.

One of the most commonly used examples of a fuzzy set is the set of tall people. In this case, the universe of discourse is all potential heights, say from 3 feet to 9 feet, and the word tall would correspond to a curve that defines the degree to which any person is tall. If the set of tall people is given the well-defined (crisp) boundary of a classical set, you might say all people taller than 6 feet are officially considered tall. However, such a distinction is clearly absurd. It may make sense to consider the set of all real numbers greater than 6 because numbers belong on an abstract plane, but when we want to talk about real people, it is unreasonable to call one person short and another one tall when they differ in height by the width of a hair.

The figure following shows a smoothly varying curve that passes from not-tall to tall. The output-axis is a number known as the membership value between 0 and

1. The curve is known as a membership function and is often given the designation of μ. This curve defines the transition from not tall to tall. Both people are tall to some degree, but one is significantly less tall than the other.

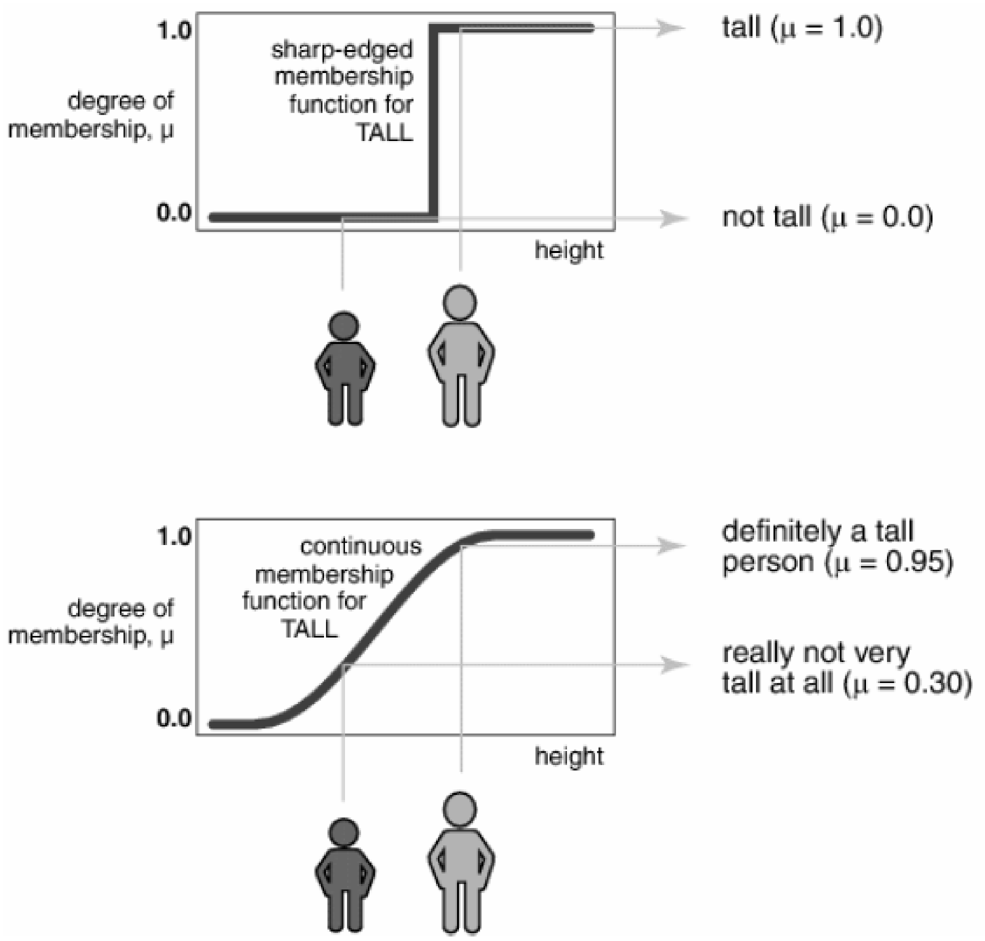


Figure 1 Crisp and fuzzy membership functions (MATLAB Fuzzy Logic Toolbox Tutorial)

There are 11 functions which are generally used in fuzzy logic applications. These are in fact built from several basic functions: piecewise linear functions, the Gaussian distribution function, the sigmoid curve, quadratic and cubic polynomial curves.

The simplest membership functions are formed using straight lines. Of these, the simplest is the triangular membership function. It is a fuzzy number represented with three points as follows:

$$A = (a_1, a_2, a_3)$$

This representation is interpreted as membership functions (Figure 2)

$$\mu_{(A)}(x) = \begin{cases} 0, & x < a_1 \\ \dfrac{x - a_1}{a_2 - a_1}, & a_1 \leq x \leq a_2 \\ \dfrac{a_3 - x}{a_3 - a_2}, & a_2 \leq x \leq a_3 \\ 0, & x > a_3 \end{cases}$$

The trapezoidal membership function has a flat top and really is just a truncated triangle curve. Trapezoidal fuzzy number can be defined as

$$A = (a_1, a_2, a_3, a_4)$$

This representation is interpreted as membership functions (Figure 2)

$$\mu_{(A)}(x) = \begin{cases} 0, & x < a_1 \\ \dfrac{x - a_1}{a_2 - a_1}, & a_1 \leq x \leq a_2 \\ 1, & a_2 \leq x \leq a_3 \\ \dfrac{a_4 - x}{a_4}, & a_3 \leq x \leq a_4 \\ 0, & x > a_4 \end{cases}$$

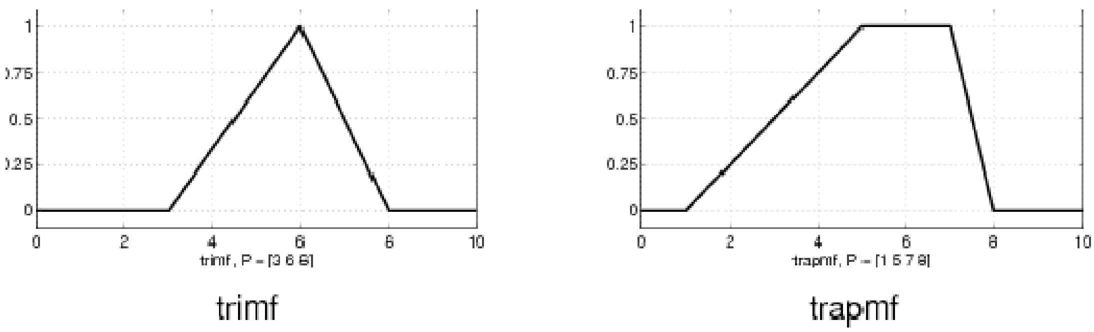


Figure 2 Triangular and trapezoidal membership functions

These straight line membership functions have the advantage of simplicity.

Two membership functions are built on the Gaussian distribution curve: a simple Gaussian curve and a two-sided composite of two different Gaussian curves. The generalized bell membership function is specified by three parameters. The bell membership function has one more parameter than the Gaussian membership function, so it can approach a non-fuzzy set if the free parameter is tuned. Because of their smoothness and concise notation, Gaussian and bell membership functions are popular methods for specifying fuzzy sets. Both of these curves have the advantage of being smooth and nonzero at all points.

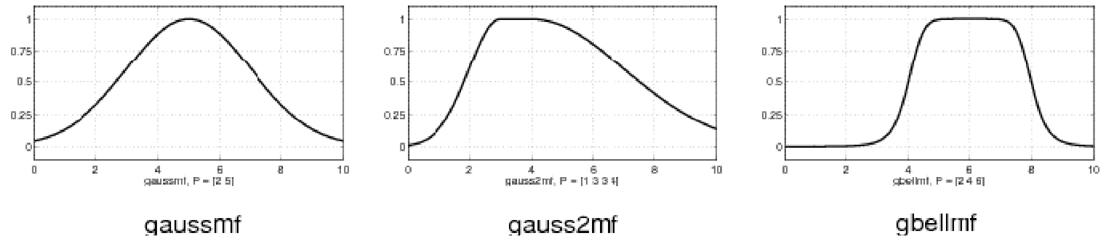


Figure 3 Gaussian membership functions

Although the Gaussian membership functions and bell membership functions achieve smoothness, they are unable to specify asymmetric membership functions, which are important in certain applications. The sigmoidal membership function is either open left or right. Asymmetric and closed (i.e. not open to the left or right) membership functions can be synthesized using two sigmoidal functions.

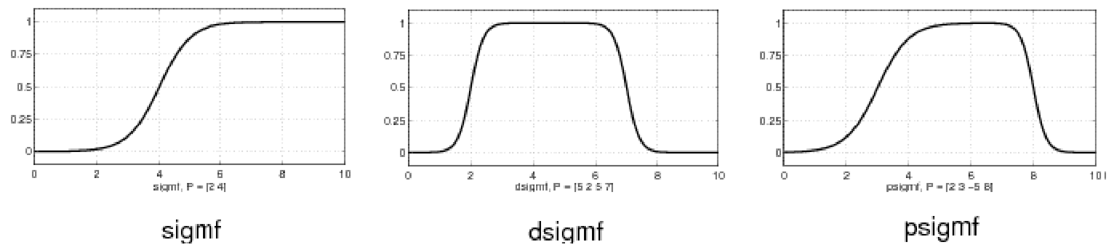


Figure 4 Sigmodial membership functions

Three related polynomial based membership functions are the Z, S, and Pi curves, all named because of their shape. The function Z is the asymmetrical polynomial curve open to the left, S is the mirror-image function that opens to the right, and Pi is zero on both extremes with a rise in the middle.

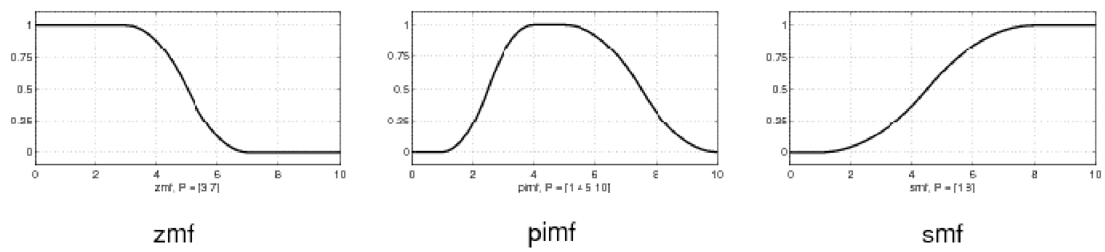


Figure 5 Polynomial based membership functions

The selection of which membership functions to use is one of the fundamental issues associated with the application of fuzzy set theory. There are no guidelines or rules that can be used to choose the appropriate membership generation technique. The problem of membership function generation is of fundamental importance because the success of an algorithm depends on the membership functions used(Medasani et al., 1998).

There are various methods to assign membership functions to fuzzy variables. The approach adopted for acquiring the shape of any particular membership function is often dependent on the application. For most fuzzy logic control problems the assumption is that the membership functions are linear – usually triangular in shape. Once the shape is determined, then it is the problem of determining the parameters that define the selected shape. Whether the shape and parameters selected are suitable for the problem to be modelled have to be elicited directly from the expert, by a 'statistical' approach or by automatic generation of the shapes. The methods for assigning the membership values can be listed as:

Intuition: It is based on the human's own intelligence and understanding to develop the membership functions. The thorough knowledge of the problem has to be known, the knowledge regarding the linguistic variable should also be known. The placement of curves is approximate over the universe of discourse: the number of curves and the overlapping of curves is important criteria to be considered while defining membership functions.

Inference: This method involves the knowledge of deductive reasoning. The membership function is formed from the facts known and knowledge.

Rank ordering or statistical techniques: There are different methods proposed by Bilgic and Turksen such as polling, direct rating, reverse rating, interval estimation, membership exemplification and pair wise comparison. All these methods depend on questioning the user in order to gain information and build a membership function. The main idea is that the differences between the users cause the fuzziness of the system.

Angular fuzzy sets: the angular fuzzy sets are different from the standard fuzzy sets in their coordinate description. These sets are defined on the universe of angles, thus are repeating shapes every 2∏ cycles. Angular fuzzy sets are applied in quantitative description of linguistic variables known truth-values.

Neural networks: *Artificial neural networks* (ANN) are a technique based on the way the brain processes information. They allow for, in particular, the estimation of non-linear mapping functions.

Takagi and Hayashi point out that fuzzy reasoning presents particular problems:

1. the lack of a definite method for determining the membership function;
2. the lack of a learning function.

They describe an approach for using ANNs to overcome these problems. The method is to investigate if-then rules by using neural networks to determine the membership functions of the antecedent and then determine the consequent component as the ouput for each rule. The approach used is to take raw data (say, in a control problem), apply a conventional clustering algorithm to group the data into clusters and to apply an ANN to this clustered data to determine the membership of a pattern within particular fuzzy sets.

As stated earlier, using experts is the most common way to determine membership functions. Wang builds on the expertise provided by an expert and uses ANNs to `fine tune' the membership function. In other words the pairs (X,y) that describe the relationship between **X** and **y** are presented to the neural network which fits a function to the points. They use a version of the standard back propagation algorithm to provide better interpolation between points.

It is mandatory to underline the fact that most of the neural network processes use supervised learning processes where training set of data is needed as an input vs. output dataset. Without this learning process the relationship between inputs and the output can not be represented accurately. When unsupervised learning is used (where the output values are not known), the shape of the membership function is unpredictable. This method allows fairly complex membership functions to be generated from a classification point of view, they are highly suitable for pattern recognition applications, although the membership values may not be necessarily indicative of the degree of typicality of a feature with respect to a class.(Medasani et al., 1998)

Genetic algorithms: Genetic algorithm uses the concept of Darwin’s theory of evolution. Darwin’s theory is based on the rule,”survival of the fittest”. The method adopts some of the ideas from genetics by representing data as chromosomes and genes and performing operations such as crossover and mutation.

Inductive reasoning: The induction is performed by partitioning a set of data into classes based on minimising the entropy. This method needs a well-defined database for the input-output relationships. This method can be suitable for complex systems where the data are abundant and static.

Clustering: Cluster analysis is a technique for grouping data and finding structures in data. The most common application of clustering methods is to partition a data set into clusters or classes where similar data are assigned to the same cluster. Fuzzy clustering can be applied as an unsupervised learning strategy in order to group data. In real applications there is very often no sharp boundary between clusters so that fuzzy clustering is suitable for grouping the data. A fuzzy c-means method is one of the most popular clustering methods based on minimization of a criterion function. It is also useful for specify number and shape of membership functions which consider from the distribution of data points.(Somsung and Pratishthananda)

Logical Operations

The most important thing to realize about fuzzy logical reasoning is the fact that it is a superset of standard Boolean logic. In other words, if you keep the fuzzy values at their extremes of 1 (completely true), and 0 (completely false), standard logical operations will hold.

Using the fact that at the extreme values of fuzzy values, standard logical operations will hold, AND can be defined by MIN (minimum) operation, OR can be defined by MAX (maximum) operation.

Moreover, because there is a function behind the truth table rather than just the truth table itself, you can now consider values other than 1 and 0.The next figure uses a graph to show the same information by a plot of two fuzzy sets applied together to create one fuzzy set. The lower part of the figure displays how the operations work over a continuously varying range of truth values A and B according to the fuzzy operations defined.

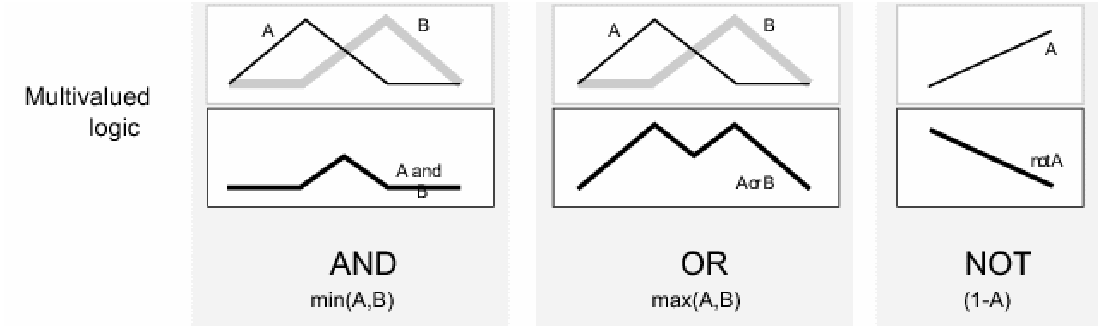


Figure 6 Logical operators in fuzzy systems

Given these three functions, any construction using fuzzy sets and the fuzzy logical operation AND, OR, and NOT can be solved. Typically, most fuzzy logic applications make use of these operations and leave it at that. Fuzzy Logic Toolbox also enables customization of the AND and OR operators.

If-Then Rules

Fuzzy sets and fuzzy operators are the subjects and verbs of fuzzy logic. These if-then rule statements are used to formulate the conditional statements that comprise fuzzy logic. A single fuzzy if-then rule assumes the form if x is A then y is B where A and B are linguistic values defined by fuzzy sets on the ranges (universes of discourse) X and Y, respectively. The if-part of the rule "x is A" is called the antecedent or premise, while the then-part of the rule "y is B" is called the consequent or conclusion.

An example of such a rule might be

If service is good then tip is average

The concept good is represented as a number between 0 and 1, and so the antecedent is an interpretation that returns a single number between 0 and 1. Conversely, average is represented as a fuzzy set, and so the consequent is an assignment that assigns the entire fuzzy set B to the output variable y. In the if-then rule, the word is gets used in two entirely different ways depending on whether it appears in the antecedent or the consequent.

The antecedent of a rule can have multiple parts.

if sky is gray and wind is strong and barometer is falling, then ...

in which case all parts of the antecedent are calculated simultaneously and resolved to a single number using the logical operators. The consequent of a rule can also have multiple parts.

if temperature is cold then hot water valve is open and cold water valve is shut

in which case all consequents are affected equally by the result of the antecedent.

What Are Fuzzy Interference Systems?

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. There are two types of fuzzy inference systems that can be implemented in Fuzzy Logic Toolbox: Mamdani-type and Sugeno-type. These two types of inference systems vary somewhat in the way outputs are determined.

Fuzzy inference systems (FIS) have been successfully applied in fields such as automatic control, data classification, decision analysis, expert systems, and computer vision. Because of its multidisciplinary nature, fuzzy inference systems are associated with a number of names, such as fuzzy-rule-based systems, fuzzy expert systems, fuzzy modeling, fuzzy associative memory, fuzzy logic controllers, and simply (and ambiguously) fuzzy systems.

Decision making is an important part in the entire system. The FIS formulates suitable rules and based upon the rules the decision is made. This is mainly based on the concepts of fuzzy set theory, fuzzy IF-THEN rules and fuzzy reasoning. The basic FIS can take either fuzzy inputs or crisp inputs, but the outputs it produces are almost always fuzzy sets. When the FIS is used as a controller, it is necessary to have a crisp output. Therefore in this case defuzzification method is adopted to best extract a crisp value that best represents a fuzzy set.

Construction and Working of Inference systems

Fuzzy inference system consists of a fuzzification interface, a rule base, a database, a decision-making unit and finally a defuzzification interface (Figure 7). The function of each block is as follows:

- A database which defines the membership functions of the fuzzy sets used in the fuzzy rules
- A rule base containing a number of fuzzy IF-THEN rules
- A decision making unit which performs the inference operations on the rules
- A fuzzification interface which transforms crisp inputs into degrees of match with linguistic values
- A defuzzification interface which transforms the fuzzy results of the inference into a crisp output.

There are five working steps of the fuzzy inference process:

- fuzzification of the input variables,

The first step is to take the inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions. In Fuzzy Logic Toolbox, the input is always a crisp numerical value limited to the universe of discourse of the input variable and the output is a fuzzy degree of membership in the qualifying linguistic set (always the interval between 0 and 1). Fuzzification of the input amounts to either a table lookup or a function evaluation.

- application of the fuzzy operator (AND or OR) in the antecedent,

After the inputs are fuzzified, you know the degree to which each part of the antecedent is satisfied for each rule. If the antecedent of a given rule has more than one part, the fuzzy operator is applied to obtain one number that represents the result of the antecedent for that rule. This number is then applied to the output function. The input to the fuzzy operator is two or more membership values from fuzzified input variables. The output is a single truth value.

As is described in Logical Operations section, any number of well-defined methods can fill in for the AND operation or the OR operation. In Fuzzy Logic Toolbox, two built-in AND methods are supported: min (minimum) and prod (product). Two built-in OR methods are also supported: max (maximum), and the probabilistic OR method probor. The probabilistic OR method (also known as the algebraic sum) is calculated according to the equation

probor(a,b) = a + b - ab

In addition to these built-in methods, you can create your own methods for AND and OR by writing any function and setting that to be your method of choice.

- implication from the antecedent to the consequent,

Before applying the implication method, you must determine the rule's weight. Every rule has a weight (a number between 0 and 1), which is applied to the number given by the antecedent. Generally, this weight is 1 (as it is for this example) and thus has no effect at all on the implication process. From time to time you may want to weight one rule relative to the others by changing its weight value to something other than 1.

After proper weighting has been assigned to each rule, the implication method is implemented. A consequent is a fuzzy set represented by a membership function, which weights appropriately the linguistic characteristics that are attributed to it. The consequent is reshaped using a function associated with the antecedent (a single number). The input for the implication process is a single number given by the antecedent, and the output is a fuzzy set. Implication is implemented for each rule.

Two built-in methods are supported, and they are the same functions that are used by the AND method: min (minimum), which truncates the output fuzzy set, and prod (product), which scales the output fuzzy set.

- aggregation of the consequents across the rules,

Because decisions are based on the testing of all of the rules in a FIS, the rules must be combined in some manner in order to make a decision. Aggregation is the process by which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set. Aggregation only occurs once for each output variable, just prior to the fifth and final step, defuzzification. The input of the aggregation process is the list of truncated output functions returned by the implication process for each rule. The output of the aggregation process is one fuzzy set for each output variable.

As long as the aggregation method is commutative (which it always should be), then the order in which the rules are executed is unimportant. Three built-in methods are supported:

max (maximum)

probor (probabilistic OR)

sum (simply the sum of each rule's output set)

In the following diagram (Figure 7), all three rules have been placed together to show how the output of each rule is combined, or aggregated, into a single fuzzy set whose membership function assigns a weighting for every output (tip) value.

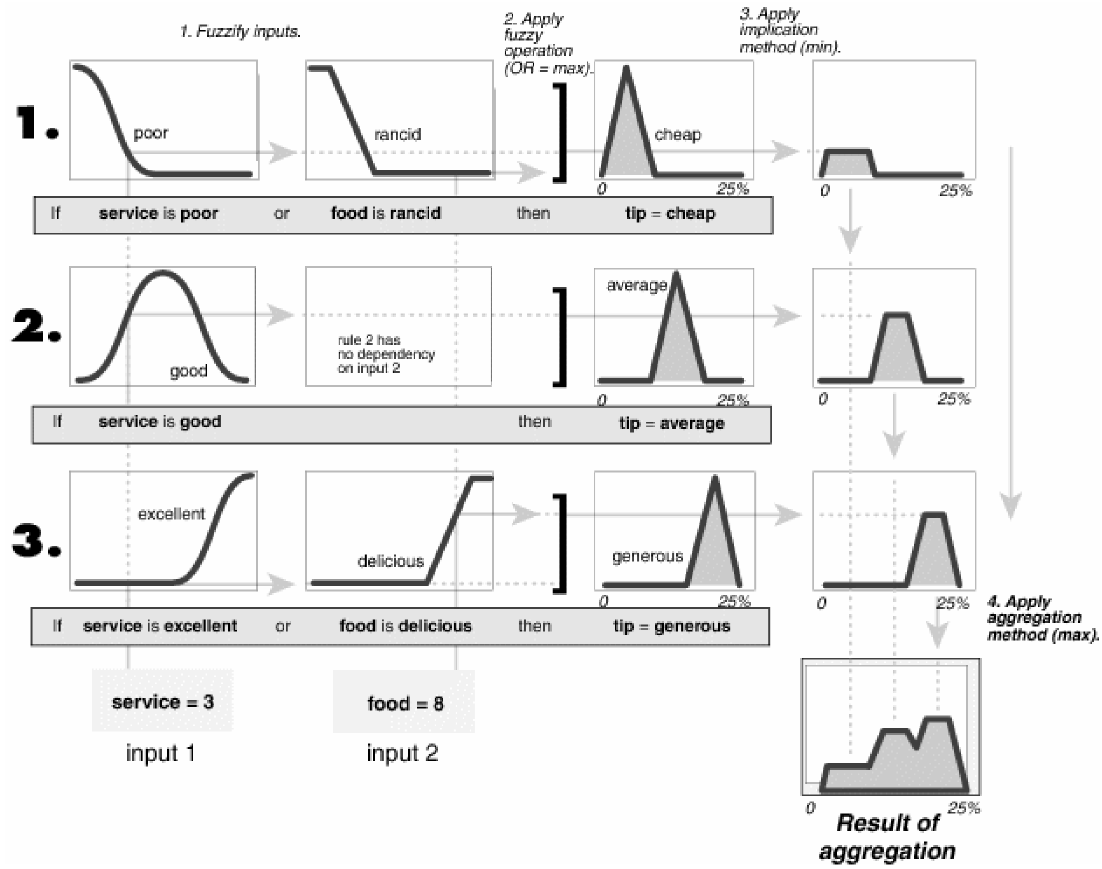


Figure 7 An example of fuzzy inference system

- defuzzification.

The input for the defuzzification process is a fuzzy set (the aggregate output fuzzy set) and the output is a single number. As much as fuzziness helps the rule evaluation during the intermediate steps, the final desired output for each variable is generally a single number. However, the aggregate of a fuzzy set encompasses a range of output values, and so must be defuzzified in order to resolve a single output value from the set.

Perhaps the most popular defuzzification method is the centroid calculation, which returns the center of area under the curve. There are five built-in methods supported: centroid, bisector, middle of maximum (the average of the maximum value of the output set), largest of maximum, and smallest of maximum.

The working of FIS is as follows. The crisp input is converted in to fuzzy by using fuzzification method. After fuzzification the rule base is formed. The fuzzy rule base and the database are jointly referred as the knowledge base. Defuzzification is used to convert fuzzy value to the reeal world value which is the output.

The steps of fuzzy reasoning (inference operations upon fuzzy IF-THEN rules) performed by FISs are:

1. Compare the input variables with membership functions on the antecedent part to obtain the membership values of each linguistic label (fuzzification)
2. Combine (through a specific t-norm operator, usually multiplication or min) the membership values on the premise part to get weight of each rule
3. Generate the qualifed consequents (either fuzzy or crisp) or each rule depending on weights
4. Aggergate the qualified consequents to produce a crisp output (defuzzification).

APPENDIX D

MEMBERSHIP FUNCTIONS

Significant Wave Height

The collected data was analyzed by using FCM algorithm of MATLAB Fuzzy Logic Toolbox to be classified around 5 center points which were statistically derived by the FCM algorithm as well. The center points, fcm plot are given in Figure .

Centers: 0,793 1,181 2,065 2,850 3,500

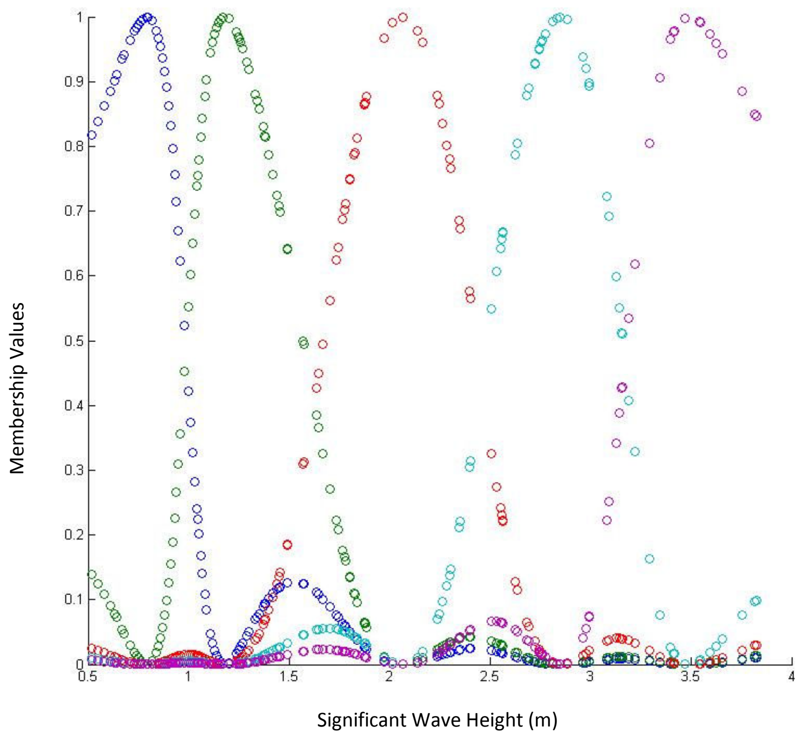


Figure 1 FCM result of significant wave height

As can be seen from the plot (Figure 1) the membership values are scattered following normal distribution. Following the discussion on rate of sea level rise parameter, the end functions were trapezoid fuzzy functions while the middle functions have triangular shape for simplicity. Table 1 shows the parameter membership values, initial classification from the preliminary vulnerability model and the final membership function values. The final fuzzy functions determined as input for inference systems are shown in MATLAB environment as well.

Table 1 Classification of values of significant wave height

Membership function shape	FCM results	Initial Classification	Final Fuzzy Membership Functions
Trapezoid	[0 0 0.8 1.2]	<0.5	[0 0 0.8 1.2]
Triangle	[0.8 1.2 2.0]	0.5-3	[0.8 1.2 3]
Triangle	[1.2 2.0 2.85]	3-6	[1.2 3 4]
Triangle	[2.0 2.85 3.5]	6-8	[3 5 7]
Trapezoid	[2.85 3.5 5 10]	>8	[5 7 8 10]

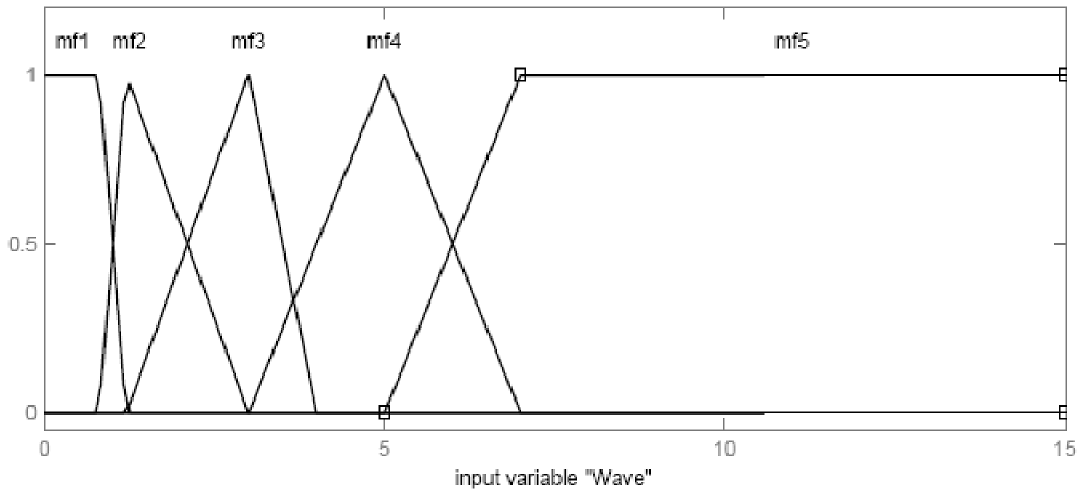


Figure 3 Membership function plots for Significant Wave Height (m).

Storm Surge Height

This parameter is a new addition to the preliminary vulnerability model (See parameters). The collected data for storm surges having return period of 100 years was analyzed by using FCM algorithm of MATLAB Fuzzy Logic Toolbox to be classified around 5 center points which were statistically derived by the FCM algorithm as well. The center points, fcm plot are given in Figure 4.

Centers: 0,79 1,81 3,21 4,45 7,32

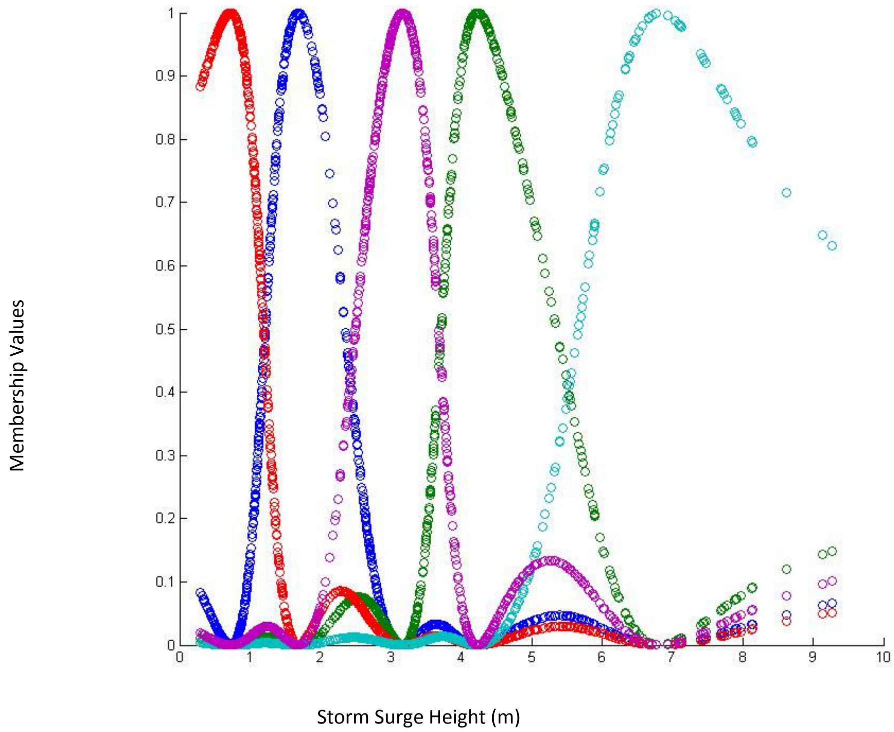


Figure 4 FCM result of storm surge height

As can be seen from the plot (Figure 4) the membership values are scattered following normal distribution. Following the discussion on rate of sea level rise parameter, the end functions were trapezoid fuzzy functions while the middle functions have triangular shape for simplicity. Table 2 shows the parameter membership values, initial classification from the preliminary vulnerability model and the final membership function values. The final fuzzy functions determined as input for inference systems are shown in MATLAB environment as well.

Table 2 Classification of values of storm surge height

Membership function shape	FCM results	Initial Classification	Final Fuzzy Membership Functions
Trapezoid	[0 0 0.8 1.8]		[0 0 0.8 1.2]
Triangle	[0.8 1.8 3.2]		[0.8 1.2 3]
Triangle	[1.8 3.2 4.4]		[1.2 3 4]
Triangle	[3.2 4.4 7.3]		[3 5 7]
Trapezoid	[4.4 7.3 10 15]		[5 7 8 10]

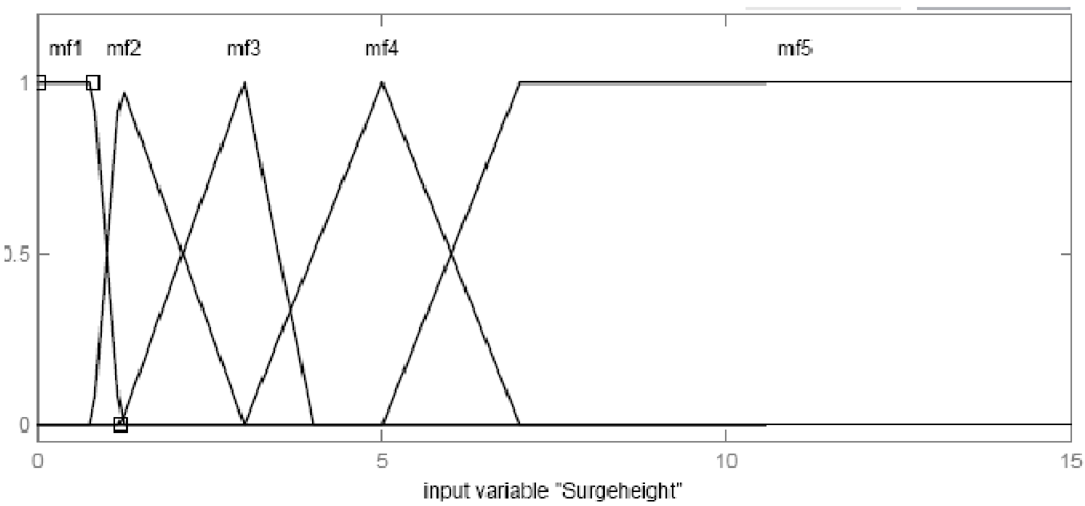


Figure 5 Membership function plots for Storm Surge Height (m).

Tidal Range

The initial data used were gathered from 237 measurements along European coasts. This data then, analyzed by using FCM algorithm of MATLAB Fuzzy Logic Toolbox to be classified around 5 center points which were statistically derived by the FCM algorithm as well. The center points, fcm plot are given in Figure 6.

Centers: 0,083   0,94   1,35   2,14   2,96

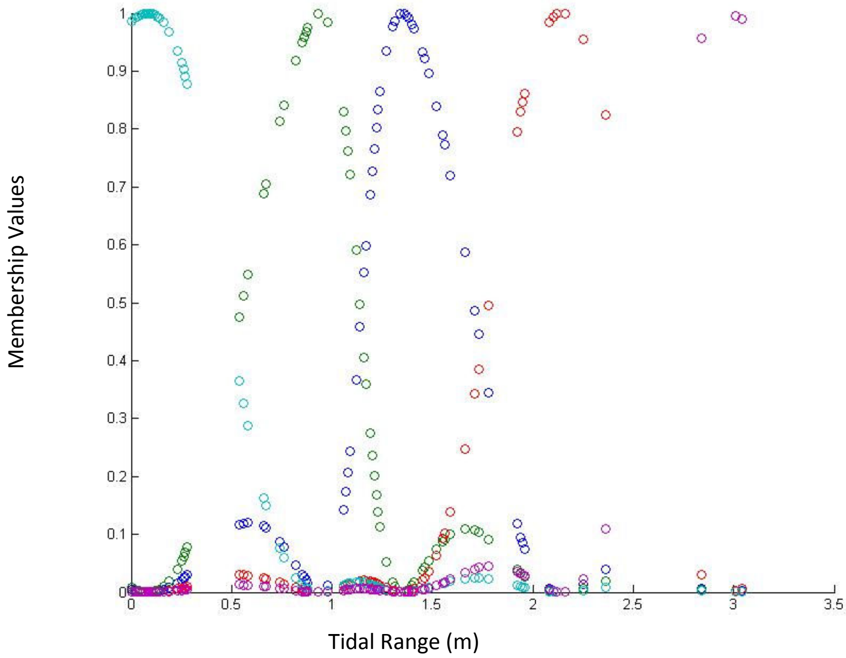


Figure 6 FCM values of tidal range

As can be seen from the plot (Figure 6) the membership values are scattered following normal distribution. Following the discussion on rate of sea level rise parameter, the end functions were trapezoid fuzzy functions while the middle functions have triangular shape for simplicity. Table 3 shows the parameter membership values, initial classification from the preliminary vulnerability model and the final membership function values. The final fuzzy functions determined as input for inference systems are shown in MATLAB environment as well.

Table 3 Classificatin values of tidal range

Membership function shape	FCM results	Initial Classification (%)	Final Fuzzy Membership Functions
Trapezoid	[0 0 0.1 1]	<0.5	[0 0 0.5 1]
Triangle	[0.1 1 1.5]	0.5-2	[0.5 1 1.5]
Triangle	[1 1.5 2.4]	2-4	[1 2 3]
Triangle	[1.5 2.4 3]	4-6	[2 4 6]
Trapezoid	[2 3 15 15]	>6	[4 6 15 15]

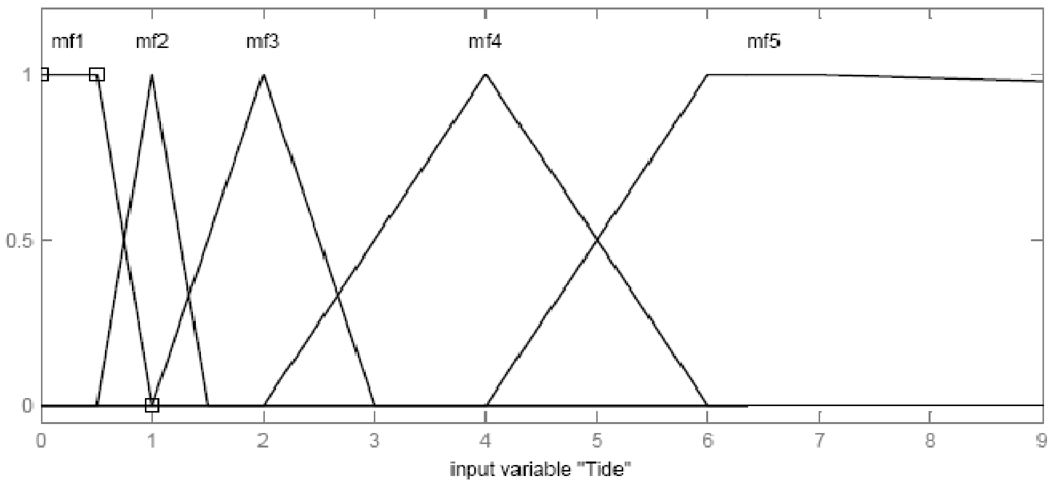


Figure 7 Membership function plots for Tidal Range

Although Figure 7 was used as the input membership function plot for this parameter, sensitivity analysis showed that the membership function needed to be re-evaluated. (See Section for the discussions). In order to re-analyze the parameter, additional data was gathered and integrated to the existing database. Then, this new dataset was analyzed using fcm algorithm. The resulting fcm plot is shown in Figure 8 with centers at 0.5, 1.5, 2.86, 4.8 and 7.6m. And the new membership function plot is given in Table 4 and Figure 9.

Table 4 New classification values of tidal range

Membership function shape	FCM results	Initial Classification (%)	Final Fuzzy Membership Functions
Trapezoid	[0 0 0.5 1.5]	<0.5	[0 0 0.5 1.5]
Triangle	[0.5 1.5 3]	0.5-2	[0.5 1.5 3]
Triangle	[1.5 3 5]	2-4	[1.5 3 5]
Triangle	[3 5 7.5]	4-6	[3 5 7.5]
Trapezoid	[5 7.5 15 15]	>6	[5 7.5 15 15]

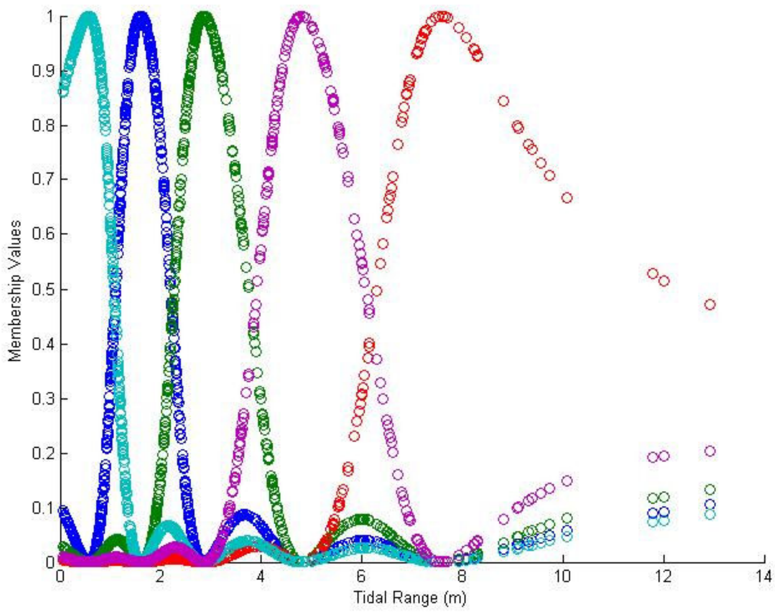


Figure 8 New FCM result for tidal range

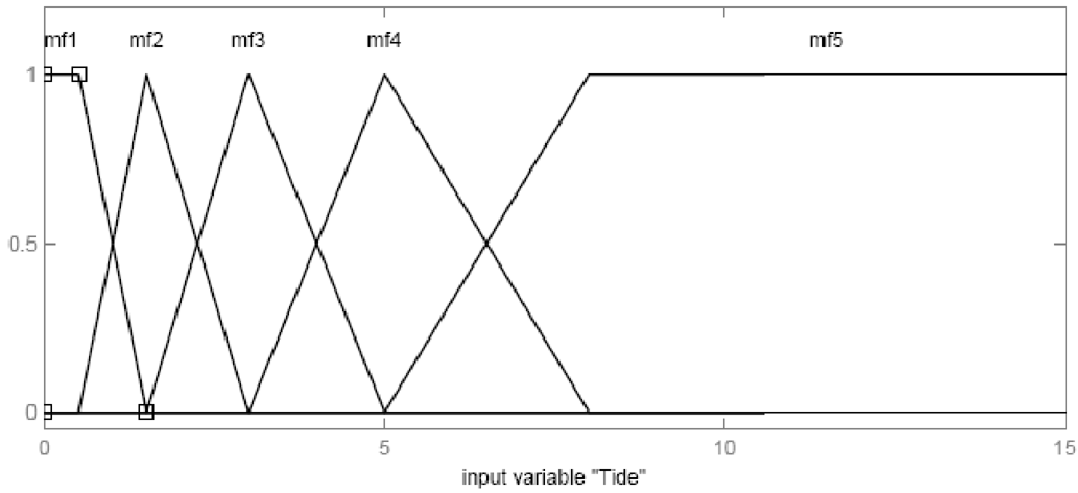


Figure 9 New membership function plot for tidal range

Proximity to coast (Groundwater)

The collected data was analyzed by using FCM algorithm of MATLAB Fuzzy Logic Toolbox to be classified around 5 center points which were statistically derived by the FCM algorithm as well. The center points, fcm plot are given in Figure 10.

Centers (in km): 2.185 12.966 36.886 91.090 230.350

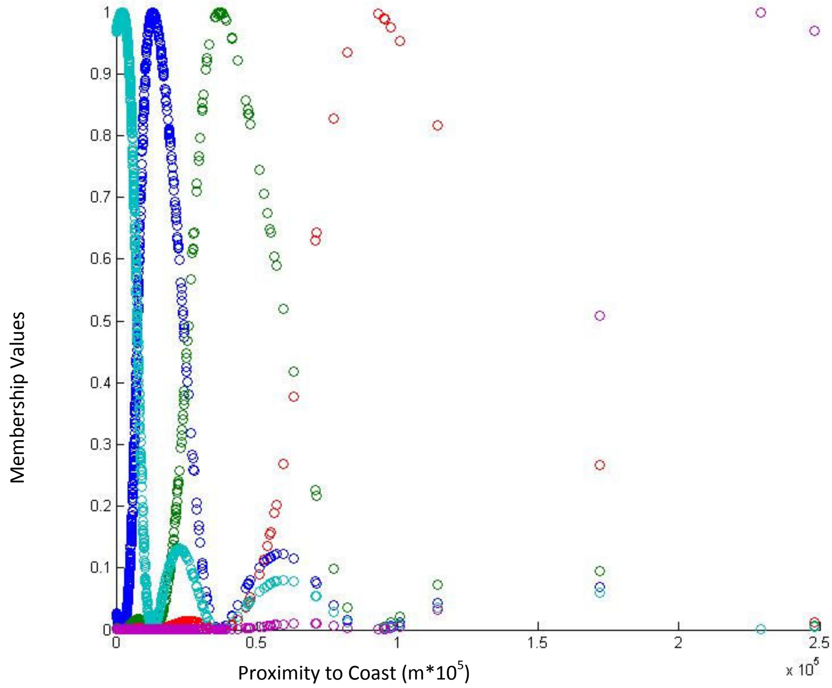


Figure 10 FCM result of proximity to coast of aquifers

As can be seen from the plot (Figure 10) the membership values are scattered following normal distribution. Following the discussion on rate of sea level rise parameter, the end functions were trapezoid fuzzy functions while the middle functions have triangular shape for simplicity. Table 5 shows the parameter membership values, initial classification from the preliminary vulnerability model and the final membership function values. The initial classification values are very different from the data. This is because the parameter is used to describe the amount of the groundwater available by giving an idea on the width of the groundwater body rather than proximity of the first line of water withdrawal. The final fuzzy functions determined as input for inference systems are shown in MATLAB environment as well.

Table 5 Classification values of proximity to coast

Membership function shape	FCM results (km)	Initial Classification (m)	Final Fuzzy Membership Functions
Trapezoid	[0 0 2 13]	<100	[0 0 2 13]
Triangle	[2 13 36]	100-400	[2 13 36]
Triangle	[13 36 90]	400-700	[13 36 90]
Triangle	[36 90 230]	700-1000	[36 90 230]
Trapezoid	[90 230 260 400]	>1000	[90 230 260 400]

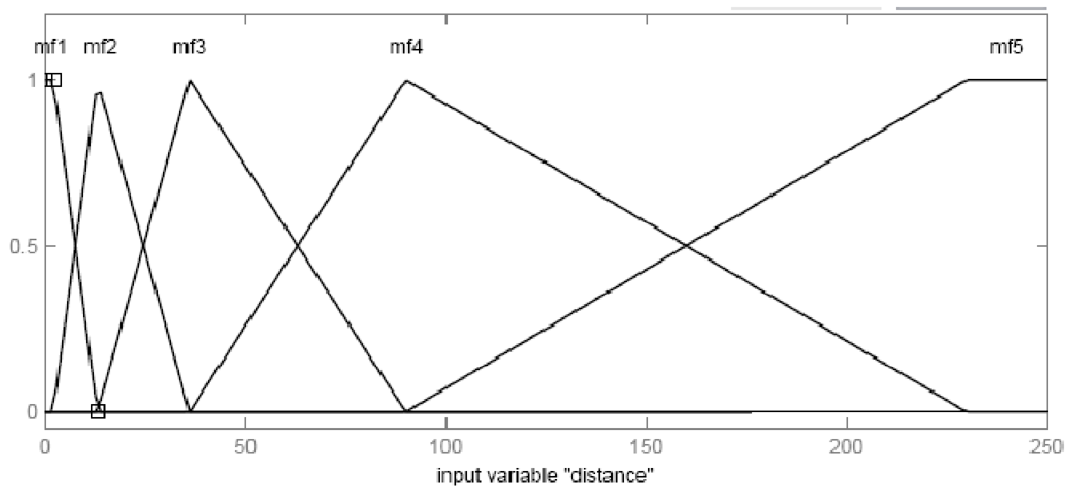


Figure 11 Membership function plots for Proximity to coast (km).

Type of Aquifer

Type of aquifer is also a variable that needs to be defined verbally as seen in geomorphology. Thus the same procedure is used, each classification group was assigned an integer as follows:

Group 1: Confined aquifer = 1

Group 2: Leaky confined aquifer = 2

Group 3: Unconfined aquifer = 3

Group 4: Leaky unconfined aquifer = 4

Group 5: Karstic aquifer = 5

These integers are crisp values that can be used as input of the fuzzy inference system. This is performed by defining these values as straight lines having membership function values as 1 (Figure 11).

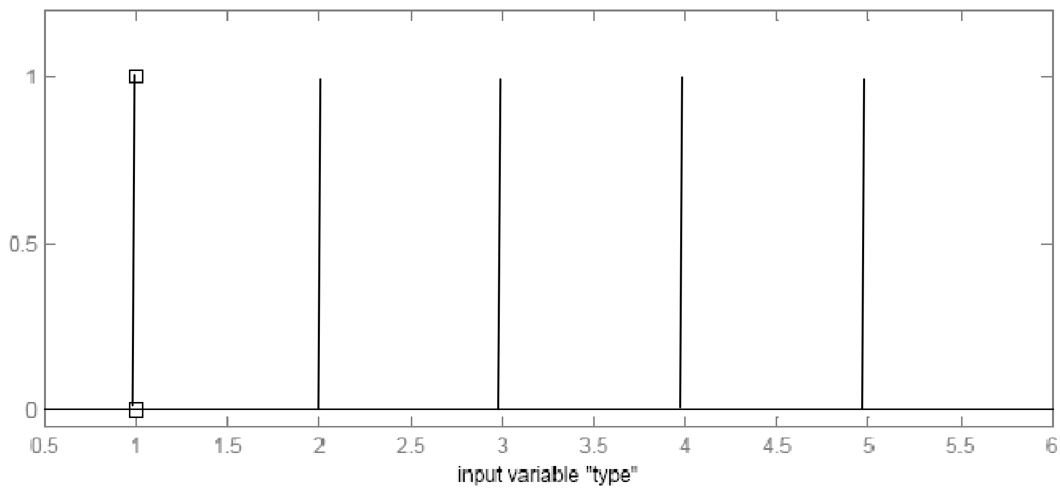


Figure 11 Fuzzy membership function of type of aquifer

Hydraulic Conductivity

Hydraulic Conductivity can be measured or assigned by using geologic material that defines the aquifer. Thus to determine the fuzzy membership functions, in principal, Table 3.2 is used combined with initial classification which was taken from (Chachadi and Lobo-Ferreira, 2001).

Following the discussion on rate of sea level rise parameter, the end functions were trapezoid fuzzy functions while the middle functions have triangular shape for simplicity. Table 6 shows the parameter membership values, initial classification from the preliminary vulnerability model and the final membership function values. The final fuzzy functions determined as input for inference systems are shown in MATLAB environment as well.

Table 6 Classification of hydraulic conductivity

Membership function shape	FCM results	Initial Classification (m/day)	Final Fuzzy Membership Functions (m/s)
Trapezoid		0-12	[1e-15 1e-15 1e-8 1e-7]
Triangle		12-28	[1e-8 1e-6 1e-5]
Triangle		28-41	[1e-6 1e-5 1e-3]
Triangle		41-81	[1e-5 1e-3 1e-2]
Trapezoid		>81	[1e-3 1e-2 1 1]

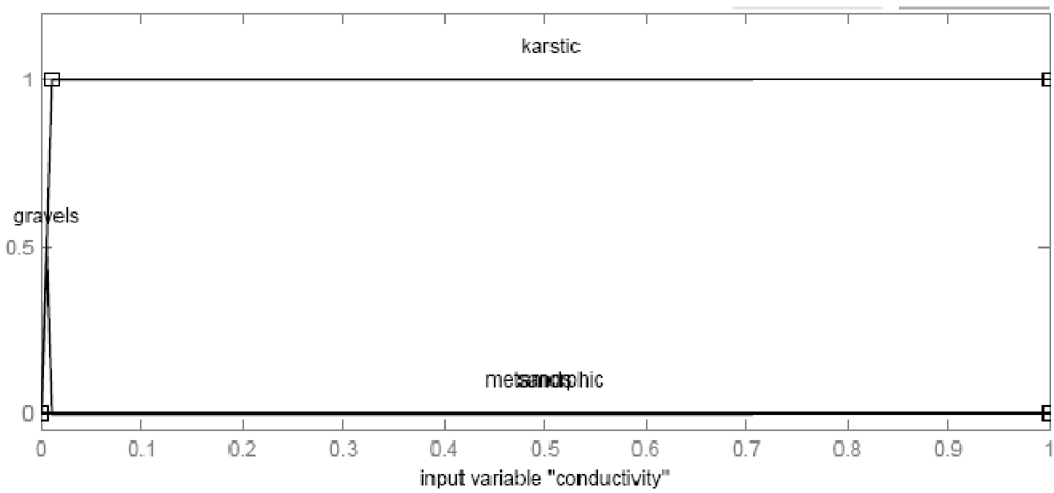


Figure 12 Membership function plot of hydraulic conductivity

Depth to Groundwater Level above Sea Level

The collected data was analyzed by using FCM algorithm of MATLAB Fuzzy Logic Toolbox to be classified around 5 center points which were statistically derived by the FCM algorithm as well. The center points, fcm plot are given in Figure 13.

Centers: -9,71 0,80 2,29 4,89 7,81

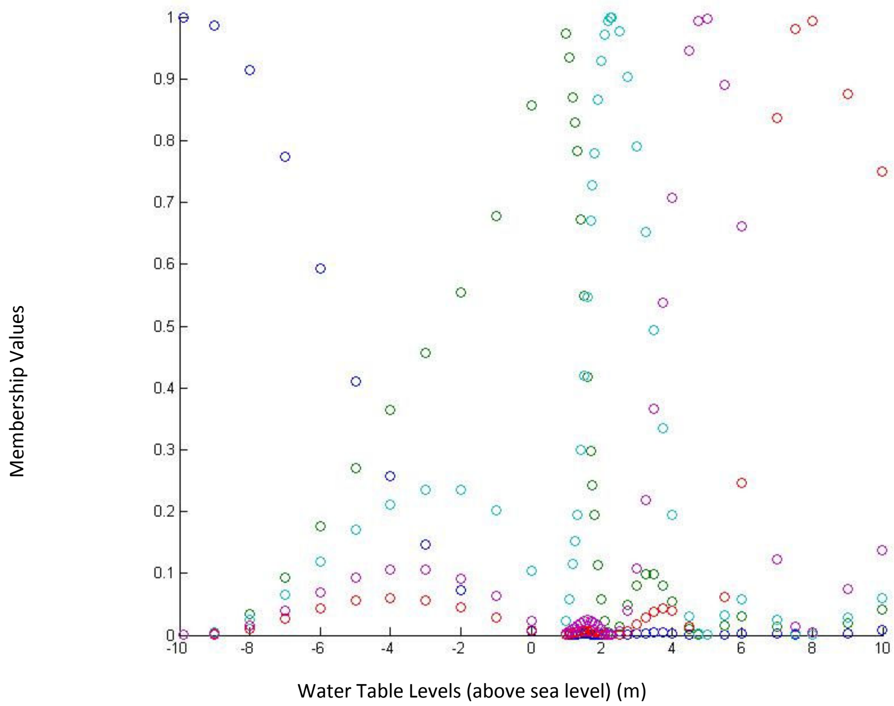


Figure13 FCM result of water table levels

Following the discussion on rate of sea level rise parameter, the end functions were trapezoid fuzzy functions while the middle functions have triangular shape for simplicity. However for the final fuzzy membership functions, one trapezoid function is used to describe those groundwater bodies that are vulnerable since water tables are below the sea level already, one triangle function to describe those bodies that are very close to sea level (above) and another trapezoid function to describe the ones which are least vulnerable (way above sea level). Table 7 shows the parameter membership values, initial classification from the preliminary vulnerability model and the final membership function values. The final fuzzy functions determined as input for inference systems are shown in MATLAB environment as well.

Table 7 Classification of water table level parameter

Membership function shape	FCM results	Initial Classification	Final Fuzzy Membership Functions
Trapezoid	[-20 -10 0.8 2.3]	<0.0	[0 0 0.8 1.2]
Triangle	[-10 0.8 2.3]	0.0-0.75	
Triangle	[0.8 2.3 5]	0.75-1.25	[0 2 5]
Triangle	[2.3 5 8]	1.25-2.0	
Trapezoid	[5 8 10 100]	>2.0	[2 5 9 100]

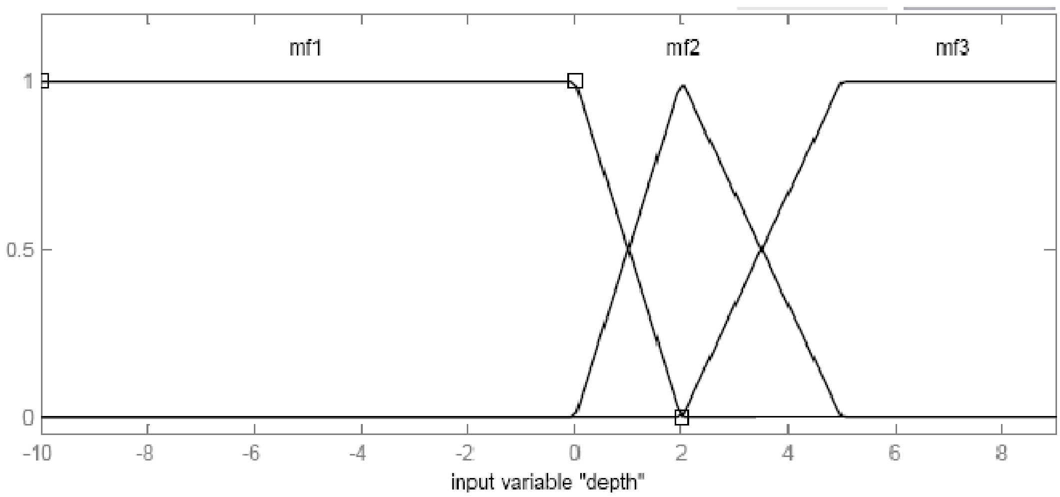


Figure 14 Membership function plots for Groundwater Depth (m).

River Discharge

The collected data was analyzed by using FCM algorithm of MATLAB Fuzzy Logic Toolbox to be classified around 5 center points which were statistically derived by the FCM algorithm as well. The center points, fcm plot are given in Figure 15.

Centers: 82 444 944 2204 6500 (m^3/s)

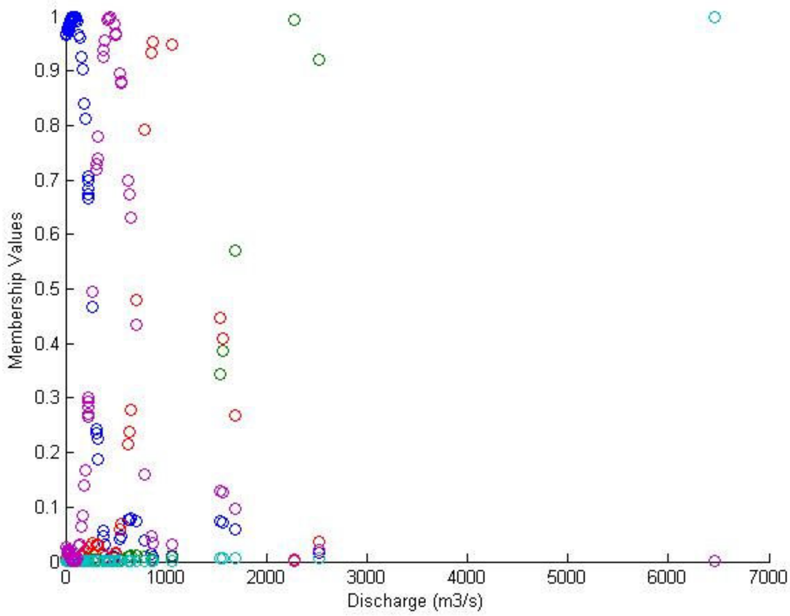


Figure 15 FCM result of discharge

Following the discussion on rate of sea level rise parameter, the end functions were trapezoid fuzzy functions while the middle functions have triangular shape for simplicity. Table shows the parameter membership values, initial classification from the preliminary vulnerability model and the final membership function values. The final fuzzy functions determined as input for inference systems are shown in MATLAB environment as well.

Table 8 Classification of discharge parameter

Membership function shape	FCM results	Initial Classification (m^3/s)	Final Fuzzy Membership Functions
Trapezoid	[0 0 80 440]	0-50	[0 0 80 150]
Triangle	[80 440 940]	50-150	[80 250 500]
Triangle	[440 940 2200]	150-250	[250 500 1000]
Triangle	[940 2200 6500]	250-500	[500 1000 1500]
Trapezoid	[2200 6500 8000 8000]	>500	[1000 1500 8000 8000]

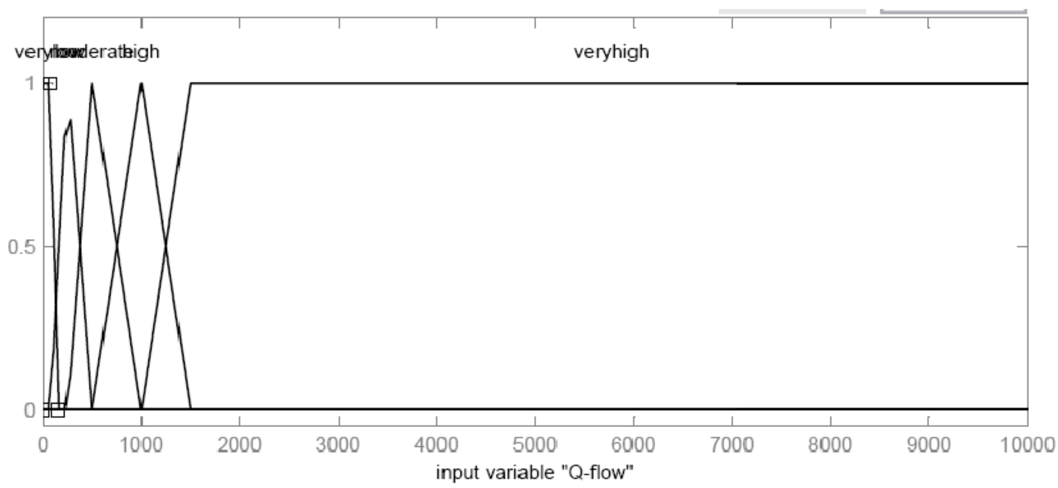


Figure 16 Membership function plots for Discharge (m^3/s).

River Depth

The collected data was analyzed by using FCM algorithm of MATLAB Fuzzy Logic Toolbox to be classified around 5 center points which were statistically derived by the FCM algorithm as well. The center points, fcm plot are given in Figure 17.

Centers: 2.3 3.02 3.6 4.9 7.13

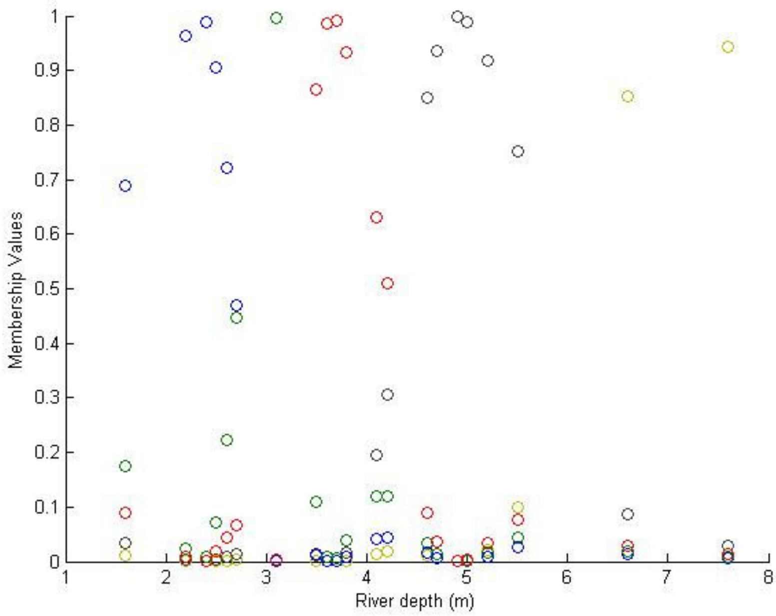


Figure 17 FCM results for river depth

Following the discussion on rate of sea level rise parameter, the end functions were trapezoid fuzzy functions while the middle functions have triangular shape for simplicity. Table 9 shows the parameter membership values, initial classification from the preliminary vulnerability model and the final membership function values. The final fuzzy functions determined as input for inference systems are shown in MATLAB environment as well.

Table 9 Classification of river depth parameter

Membership function shape	FCM results	Initial Classification (m)	Final Fuzzy Membership Functions
Trapezoid	[0 0 2.3 3]	<1	[0 0 1 2]
Triangle	[2.3 3 3.6]	2	[1.5 2.5 3.5]
Triangle	[3 3.6 5]	3	[2.5 3.5 5]
Triangle	[3.6 5 7]	4-5	[3.5 5 7]
Trapezoid	[5 7 15 20]	>5	[5 7 15 20]

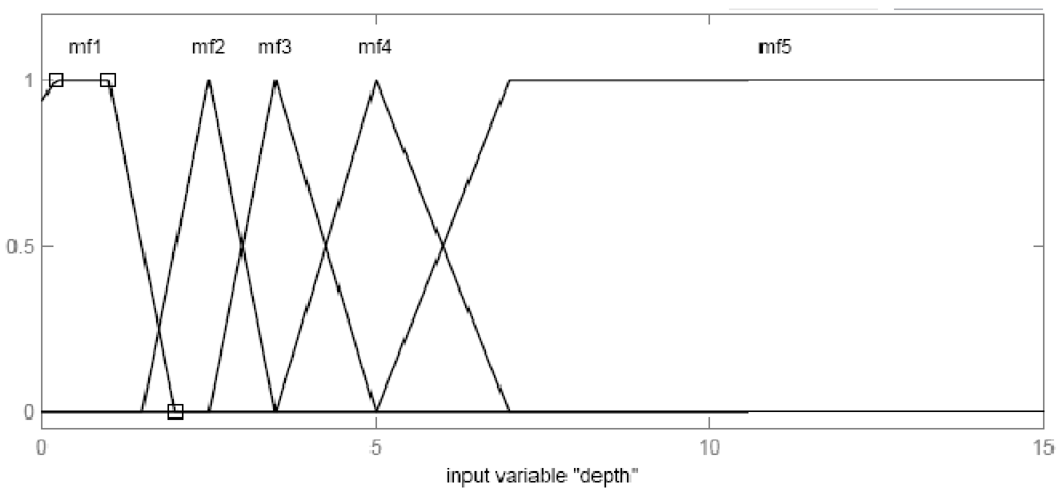


Figure 18 Membership function plots for River Depth (m).

Reduction of Sediment Supply

Reduction of sediment supply as a parameter includes many other parameters such as reduction of sediment transport from rivers, dredging, change in bathymetry, sand excavation from shores, etc. Thus there is not many data available except case studies in various locations around the world. However as a database what could be gathered was some information on reduction of sediment supply from rivers of Europe in percentages. The collected data was analyzed by using FCM algorithm of MATLAB Fuzzy Logic Toolbox to be classified around 5 center points which were statistically derived by the FCM algorithm as well. The center points, fcm plot are given in Figure 19.

Centers: 0.093 0.31 0.52 0.77 0.96

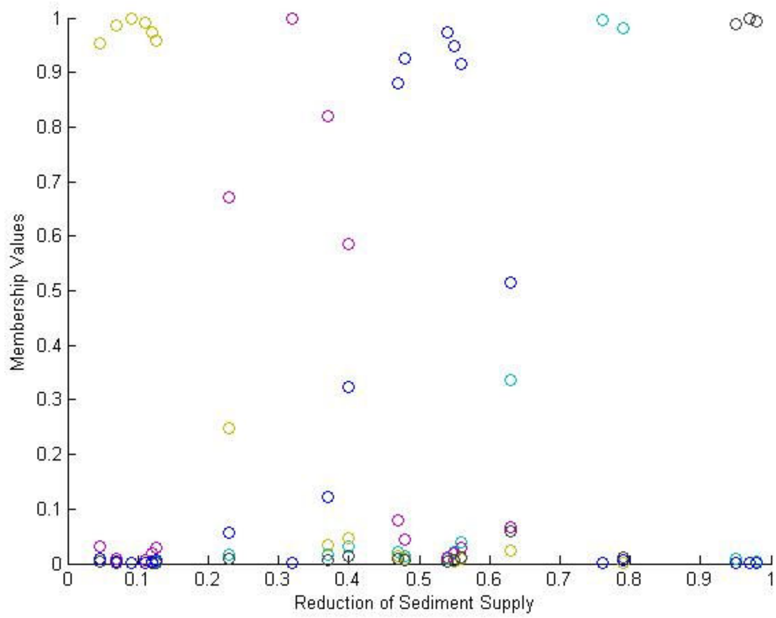


Figure 19 FCM results for reduction of sediment supply

Following the discussion on rate of sea level rise parameter, the end functions were trapezoid fuzzy functions while the middle functions have triangular shape for simplicity. Table 10 shows the parameter membership values, initial classification from the preliminary vulnerability model and the final membership function values. The final fuzzy functions determined as input for inference systems are shown in MATLAB environment as well.

Table 10 Classification of reduction of sediment supply

Membership function shape	FCM results	Initial Classification	Final Fuzzy Membership Functions (%)
Trapezoid	[0 0 0.1 0.3]	<0.2	[0 0 5 10]
Triangle	[0.1 0.3 0.5]	0.2-0.4	[5 10 30]
Triangle	[0.3 0.5 0.75]	0.4-0.6	[20 40 60]
Triangle	[0.5 0.75 0.95]	0.6-0.8	[50 70 90]
Trapezoid	[0.75 0.95 1.1 2]	>0.8	[70 90 200 200]

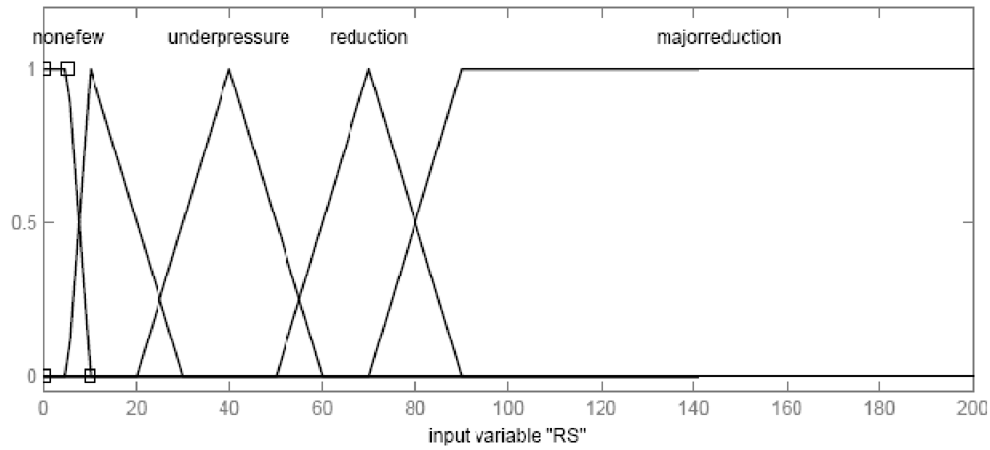


Figure 20 Membership function plots for Reduction of Sediment Supply (%).

River Flow Regulation

River flow regulation is another parameter that is composed of other parameters such as discharge, capacity of reservoirs and dams, undisturbed length of the river as described in Section. The end result of the parameter procedure is a variable that is also defined verbally as seen in geomorphology. Thus the same procedure is used; each classification group was assigned an integer as follows:

Group 1: Not Affected = 1

Group 2: Moderately Affected = 2

Group 3: Strongly Affected = 3

These integers are crisp values that can be used as input of the fuzzy inference system. This is performed by defining these values as straight lines having membership function values as 1 (Figure 21).

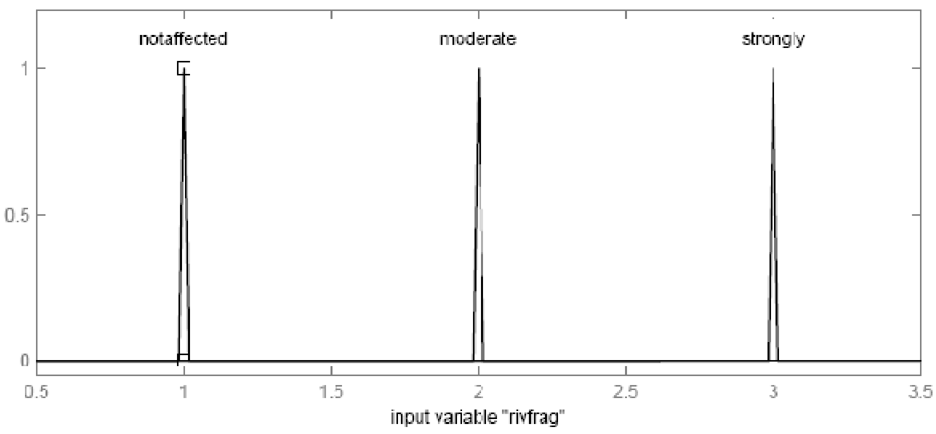


Figure 21 Membership function plots for River Flow Regulation.

Engineered Frontage

The collected data was analyzed by using FCM algorithm of MATLAB Fuzzy Logic Toolbox to be classified around 5 center points which were statistically derived by the FCM algorithm as well. The center points, fcm plot are given in Figure 22.

Centers: 2.71 22,45 41,29 64,34 89,59

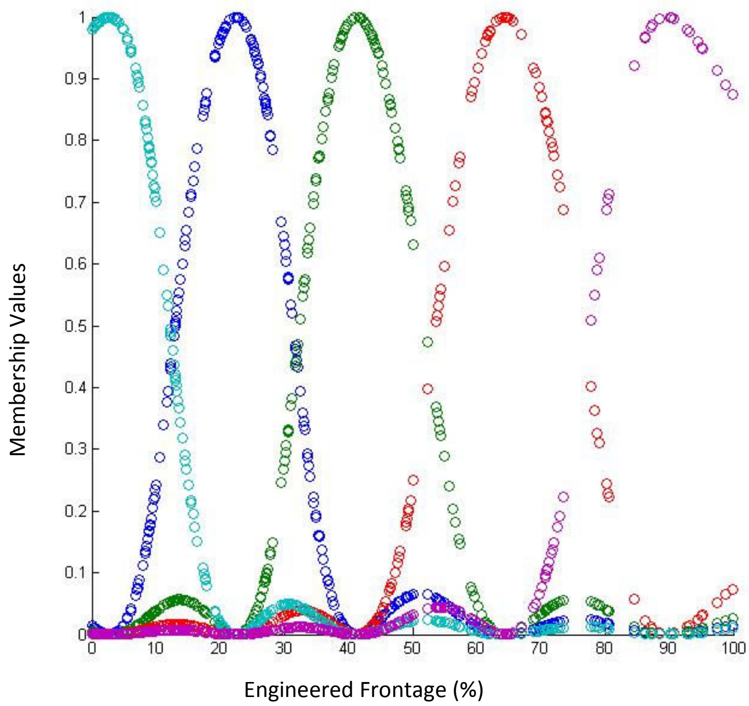


Figure 22 FCM results for engineered frontage

Following the discussion on rate of sea level rise parameter, the end functions were trapezoid fuzzy functions while the middle functions have triangular shape for simplicity. Table 11 shows the parameter membership values, initial classification from the preliminary vulnerability model and the final membership function values. The final fuzzy functions determined as input for inference systems are shown in MATLAB environment as well.

Table 11 Classification of engineered frontage

Membership function shape	FCM results	Initial Classification (%)	Final Fuzzy Membership Functions
Trapezoid	[0 0 3 20]	<5	[0 0 5 20]
Triangle	[3 20 40]	5-20	[5 20 40]
Triangle	[20 40 65]	20-30	[20 40 60]
Triangle	[40 65 90]	30-50	[40 60 90]
Trapezoid	[65 90 100 100]	>50	[60 90 100 100]

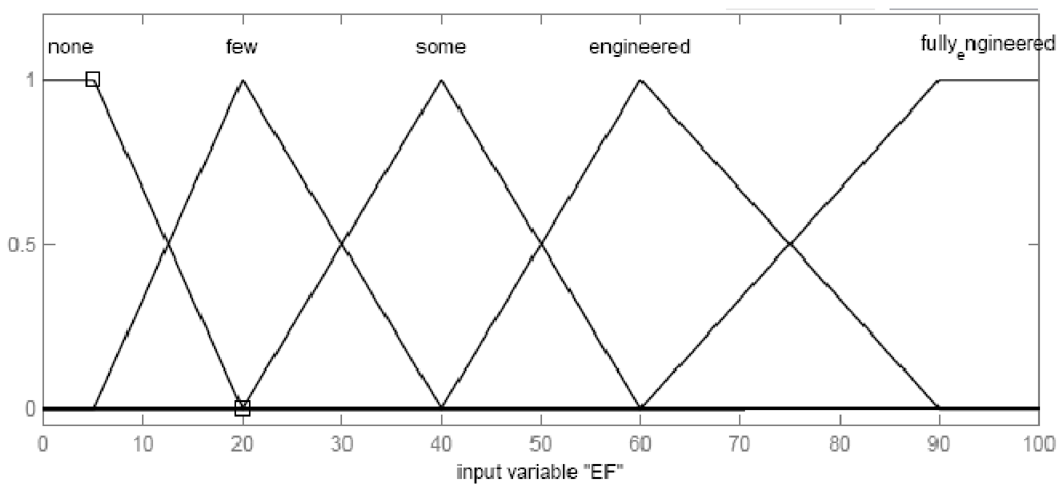


Figure 23 Membership function plots for Engineered Frontage (%).

Groundwater Use

Although there is data on groundwater abstraction quantity of wells around Europe, what this parameter defines is the ratio of the abstraction to total available resource. This is also defined as water stress index. There is data available on country scale. Using both the country water stress index and the expert opinions that were used for initial classifications, the final fuzzy membership functions were defined following the discussions on rate of sea level rise:

Table 12 Classification of groundwater use

Membership function shape	FCM results	Initial Classification (%)	Final Fuzzy Membership Functions
Trapezoid		<20	[0 0 10 20]
Triangle		20-30	[15 25 35]
Triangle		30-40	[30 40 50]
Triangle		40-50	[45 60 80]
Trapezoid		>50	[70 90 200 200]

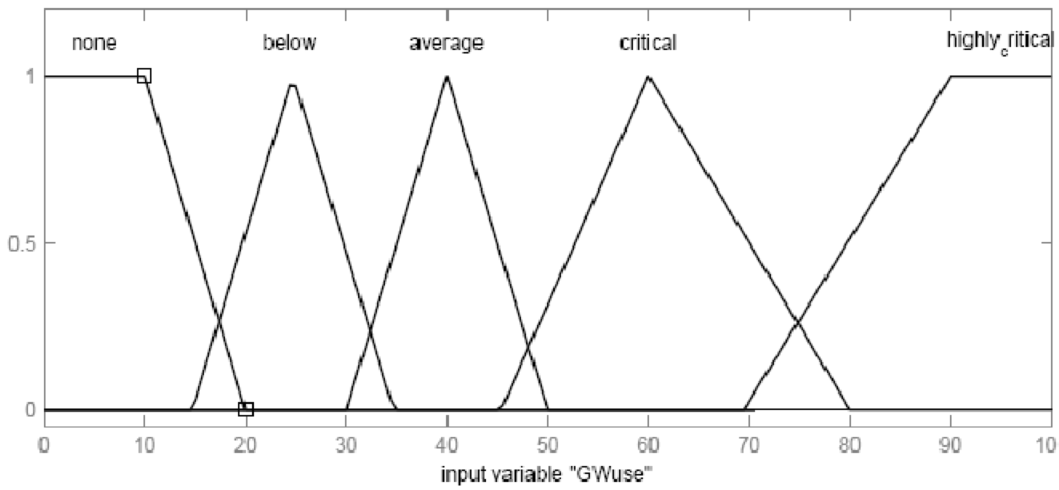


Figure 24 Membership function plots for Groundwater Use (%).

Land use

Land use is also a variable that needs to be defined verbally as seen in geomorphology. The most dominant land use type should be selected as input of the model. The procedure for geomorphology is used; each classification group was assigned an integer as follows:

Group 1: Protected Area = 1

Group 2: Unclaimed = 2

Group 3: Settlement = 3

Group 4: Industrial = 4

Group 5: Agricultural = 5

These integers are crisp values that can be used as input of the fuzzy inference system. This is performed by defining these values as straight lines having membership function values as 1 (Figure 25).

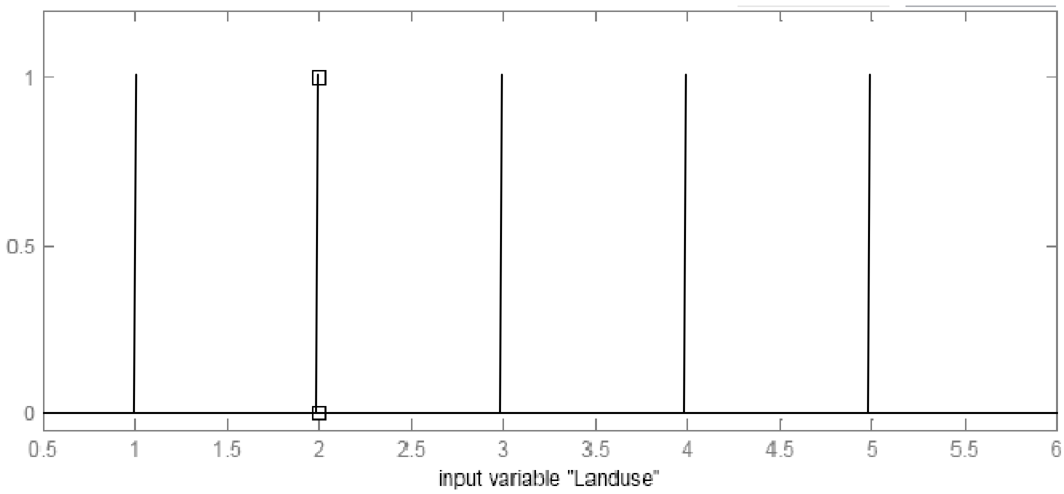


Figure 25 Membership function of landuse

Natural Protection Degradation

The collected data was analyzed by using FCM algorithm of MATLAB Fuzzy Logic Toolbox to be classified around 5 center points which were statistically derived by the FCM algorithm as well. The center points, fcm plot are given in Figure 26.

Centers: 2.3 10.5 21.4 38.7 91.3 (%)

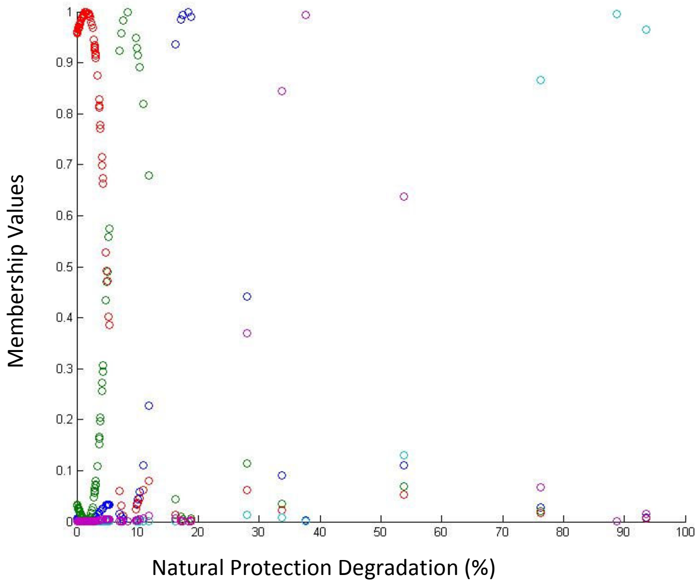


Figure 26 FCM results for natural protection degradation

Following the discussion on rate of sea level rise parameter, the end functions were trapezoid fuzzy functions while the middle functions have triangular shape for simplicity. Table 13 shows the parameter membership values, initial classification from the preliminary vulnerability model and the final membership function values. The final fuzzy functions determined as input for inference systems are shown in MATLAB environment as well.

Table 13 Classificaiton of natural protection degradation

Membership function shape	FCM results	Initial Classification (%)	Final Fuzzy Membership Functions
Trapezoid	[0 0 2 10]	<20	[0 0 2 10]
Triangle	[2 10 20]	20-40	[2 10 20]
Triangle	[10 20 40]	40-60	[10 20 40]
Triangle	[20 40 90]	60-80	[20 40 80]
Trapezoid	[40 90 100 100]	>80	[40 80 100 100]

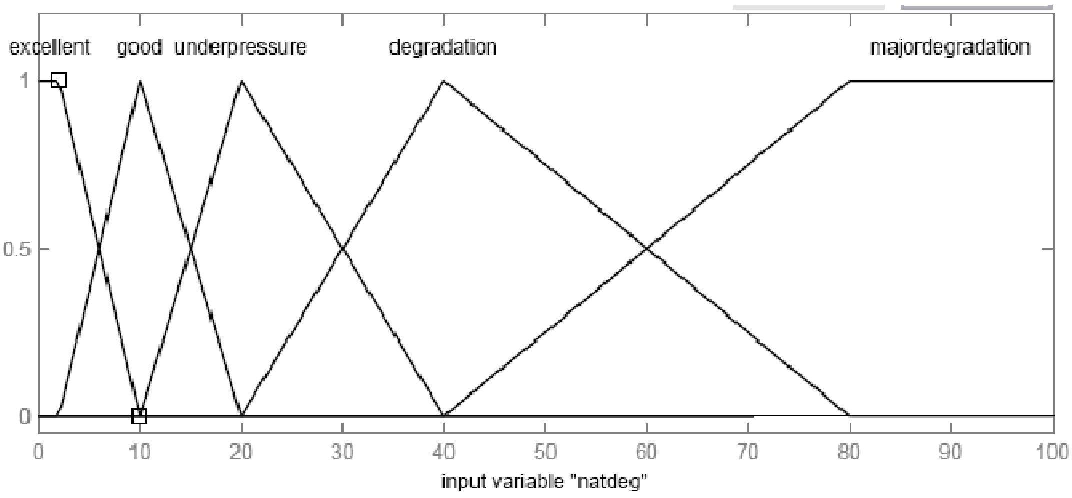


Figure 27 Membership function plots for Natural Protection Degradation (%).

Coastal Protection Structures

The collected data was analyzed by using FCM algorithm of MATLAB Fuzzy Logic Toolbox to be classified around 5 center points which were statistically derived by the FCM algorithm as well. The center points, fcm plot are given in Figure 28.

Centers: 0,97 15,51 31,65 53,21 79,31 (%)

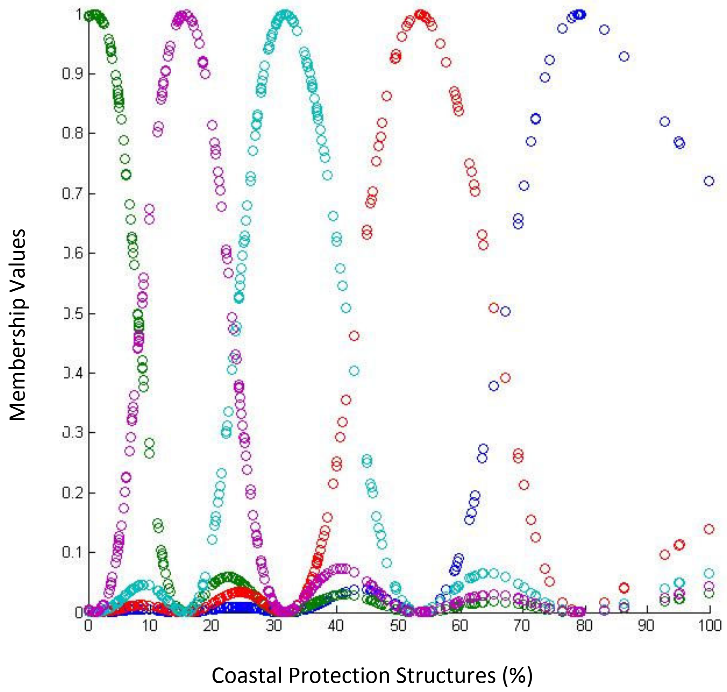


Figure 28 FCM result for coastal protection structures

Following the discussion on rate of sea level rise parameter, the end functions were trapezoid fuzzy functions while the middle functions have triangular shape for simplicity. Table 14 shows the parameter membership values, initial classification from the preliminary vulnerability model and the final membership function values. The final fuzzy functions determined as input for inference systems are shown in MATLAB environment as well.

Table 14 Classification of coastal protection structures

Membership function shape	FCM results	Initial Classification (%)	Final Fuzzy Membership Functions
Trapezoid	[0 0 1 15]	<5	[0 0 5 15]
Triangle	[1 15 30]	5-20	[5 15 30]
Triangle	[15 30 50]	20-30	[15 30 50]
Triangle	[30 50 80]	30-50	[30 50 70]
Trapezoid	[50 80 100 100]	>50	[50 70 100 100]

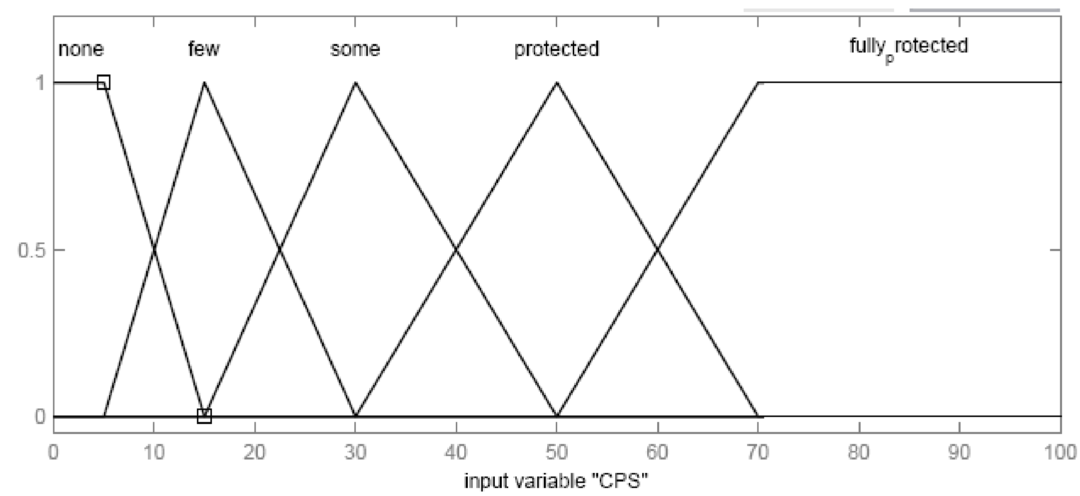


Figure 29 Membership function plots for Coastal Protection Structures (%).

APPENDIX E

INFERENCE RULES FOR IMPACTS

Inundation

IF	PPVulEro AND	HIVul Ero	Then VulErosion
1	VL	VL	VL
2	L	VL	L
3	M	VL	M
4	H	VL	M
5	VH	VL	H
6	VL	L	VL
7	L	L	L
8	M	L	M
9	H	L	H
10	VH	L	H
11	VL	M	L
12	L	M	L
13	M	M	M
14	H	M	H
15	VH	M	VH
16	VL	H	M
17	L	H	M
18	M	H	H
19	H	H	H
20	VH	H	VH
21	VL	VH	M
22	L	VH	M
23	M	VH	H
24	H	VH	VH
25	VH	VH	VH

Flooding

IF	PPVulEro AND	HIVul Ero	Then VulErosion
1	VL	VL	VL
2	L	VL	L
3	M	VL	M
4	H	VL	H
5	VH	VL	H
6	VL	L	L
7	L	L	L
8	M	L	M
9	H	L	H
10	VH	L	H
11	VL	M	L
12	L	M	L
13	M	M	M
14	H	M	H
15	VH	M	VH
16	VL	H	M
17	L	H	M
18	M	H	H
19	H	H	H
20	VH	H	VH
21	VL	VH	M
22	L	VH	M
23	M	VH	M
24	H	VH	VH
25	VH	VH	VH

Groundwater

IF	PPVulEro AND	HIVul Ero	Then VulErosion
1	VL	VL	VL
2	L	VL	L
3	M	VL	L
4	H	VL	M
5	VH	VL	H
6	VL	L	L
7	L	L	L
8	M	L	M
9	H	L	M
10	VH	L	H
11	VL	M	L
12	L	M	M
13	M	M	M
14	H	M	H
15	VH	M	VH
16	VL	H	M
17	L	H	M
18	M	H	H
19	H	H	H
20	VH	H	VH
21	VL	VH	M
22	L	VH	H
23	M	VH	H
24	H	VH	VH
25	VH	VH	VH

River

IF	PPVulEro AND	HIVul Ero	Then VulErosion
1	VL	VL	VL
2	L	VL	L
3	M	VL	L
4	H	VL	M
5	VH	VL	H
6	VL	L	L
7	L	L	L
8	M	L	M
9	H	L	M
10	VH	L	H
11	VL	M	L
12	L	M	M
13	M	M	M
14	H	M	H
15	VH	M	VH
16	VL	H	M
17	L	H	M
18	M	H	H
19	H	H	H
20	VH	H	VH
21	VL	VH	M
22	L	VH	H
23	M	VH	H
24	H	VH	VH
25	VH	VH	VH

APPENDIX F

SENSITIVITY ANALYSIS & SCATTER PLOTS

When sensitivity analysis was performed, the initial evaluation of the diagrams showed that some of the parameter membership functions cause discrepancies in the scatter plots such as rate of sea level rise. Below are the initial evaluations of scatter diagrams. The anomalies of the results are highlighted.

1. Fuzzy inference system for Physical Parameters of Inundation

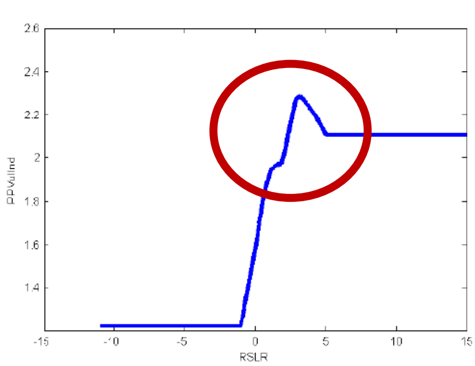
Reference Values are assigned as;

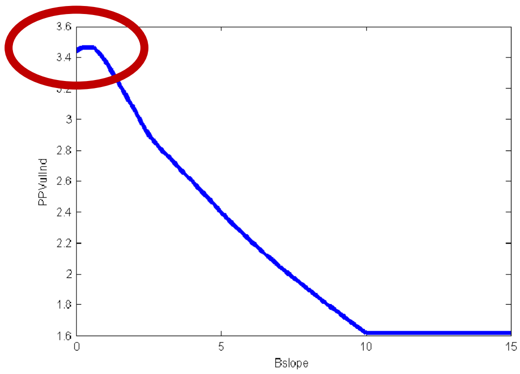
Rate of Sea Level Rise: 2mm/year

Beach Slope: 7.5%

Tidal Range: 4.5m

The scatter diagrams are given below for varying the input over its entire range.





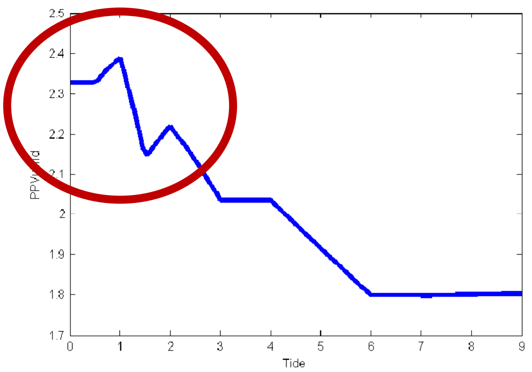


Figure 1 Scatter plots of rate of sea level rise, beach slope and tide

These plots showed anomalies in the output surface. To further analyze which parameter is the cause of the anomalies, other cases were evaluated;

a. When rate of sea level rise is very low (no sea level rise is observed = -2mm/year)
b. When rate of sea level rise changes gradually from 0.5 to 5 mm/year.

The first case showed that the anomalies of the output surface also depends on beach slope and tidal range parameter functions since the resultant output surface also shows anomalies as given in Figure 2.

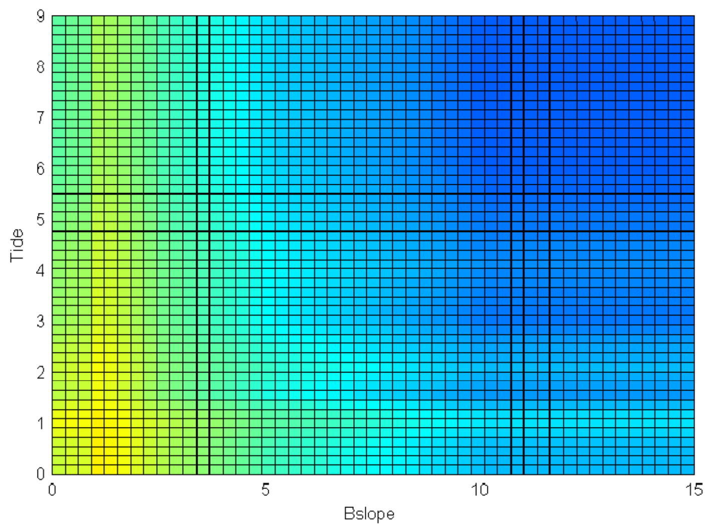


Figure 2 Output surface graph when rslr = 2mm/year

The second set of analyses showed that, the anomalies due to beach slope and tidal range vanish when the sea level rise rate is more than 1 mm/year, but the anomalies are persisting below this value as shown in Figure 3.

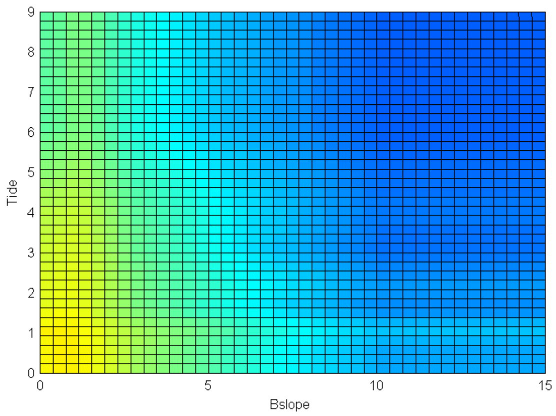


Figure 3 Output surface diagram when rslr = 0.3mm

These results determined that the membership functions of rate of sea level rise, beach slope and tidal range needed to be re-evaluated. The anomalies occur around the following input ranges for each parameter:

Rate of sea level rise: 0 – 2 mm/year

Beach Slope: 0 – 5 %

Tidal Range: 0 – 2 m

Since rate of sea level rise is included in all the other physical parameter systems, only human influence parameter systems were further analyzed.

2. Fuzzy inference system for Human Influence Parameters of Inundation

Reference Values are assigned as;

Coastal Protection Structures: 50%

Natural Protection Degradation: 50%

The scatter diagrams are given below for varying the input over its entire range.

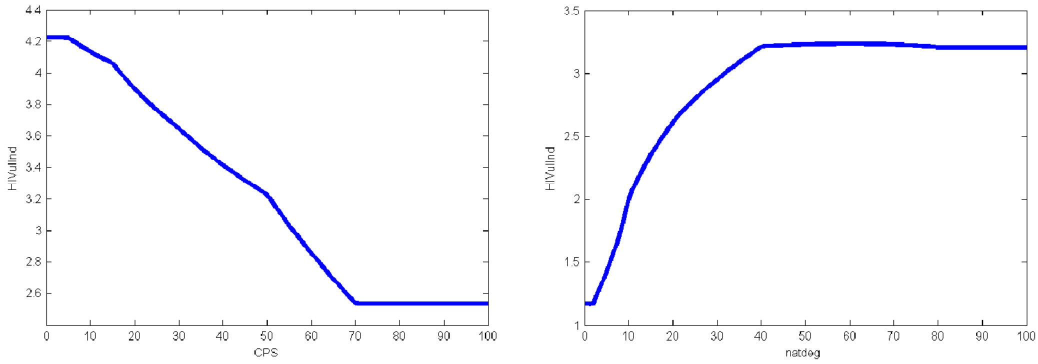


Figure 4 Scatter diagrams for coastal protection structure and natural protection degradation

Both scatter diagrams show that output surfaces were drawn as expected and no anomalies were seen. Additional output surface plots were drawn to show the combination of two input parameters and given in Figure 5 below.

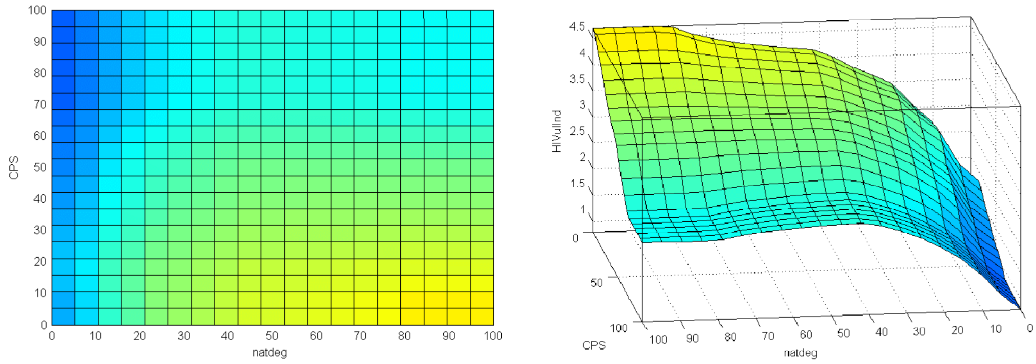


Figure 5 Output surface diagrams of two input variables.

This showed that at this point, the coastal protection structure parameter and natural protection degradation parameter membership functions are valid and can be used for the evaluation of vulnerability of coastal areas.

3. Fuzzy inference system for Human Influence Parameters of Coastal Erosion

Reference Values are assigned as;

Coastal Protection Structures: 50%

Engineered Frontage: 50%

Natural Protection Degradation: 50%

Reduction of Sediment Supply: 50%

River Flow Regulation: 3 (Moderately Affected)

The scatter diagrams are given below for varying the input over its entire range.

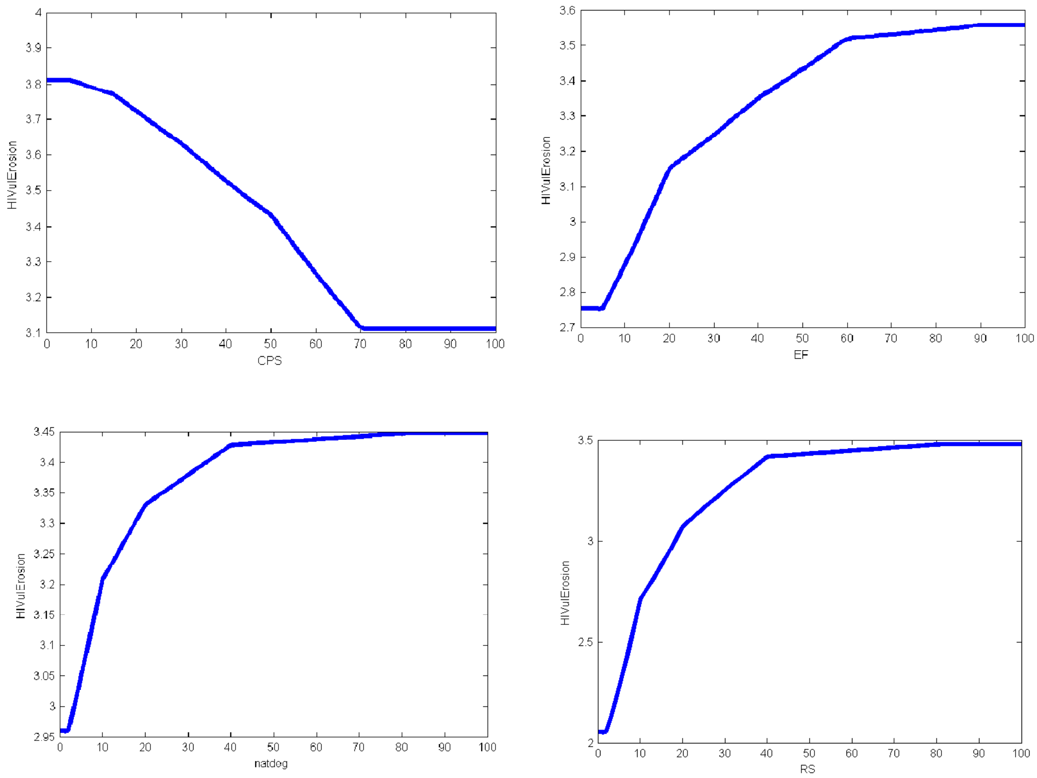


Figure 6 Scatter plots of input parameters

Figure 6 shows that parameter membership functions of coastal protection structures, engineered frontage, natural protection degradation and reduction of sediment can be effectively used in the fuzzy vulnerability assessment model since no anomalies are seen in the scatter plots. However Figure 6 also shows that there are two anomalies in the river flow regulation parameter which is actually a crisp input. As can be seen from the scatter plot, when the input is given as 2 or 4 which are not defined as rules, the fuzzy inference system do not evaluate river flow regulation parameter, thus the output values are higher than they should be (the anomalies presented by red circles). In order to eliminate this situation, the membership function of the crisp river flow regulation parameter was re-evaluated.

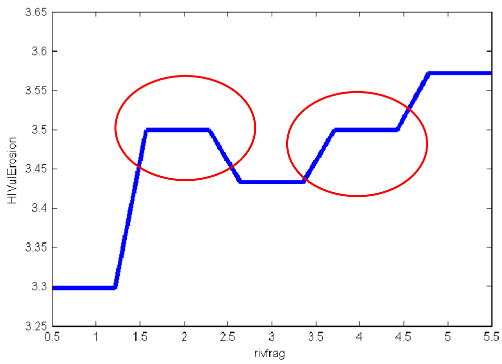


Figure 7 Scatter plot for river flow fragmentation parameter

4. Fuzzy inference system for Human Influence Parameters of Salt Water Intrusion to Groundwater Resources

Reference Values are assigned as;

Groundwater Use: 50%

Land use: 2 (Unclaimed) and 5 (Agriculture)

The scatter diagrams are given below for varying the input over its entire range.

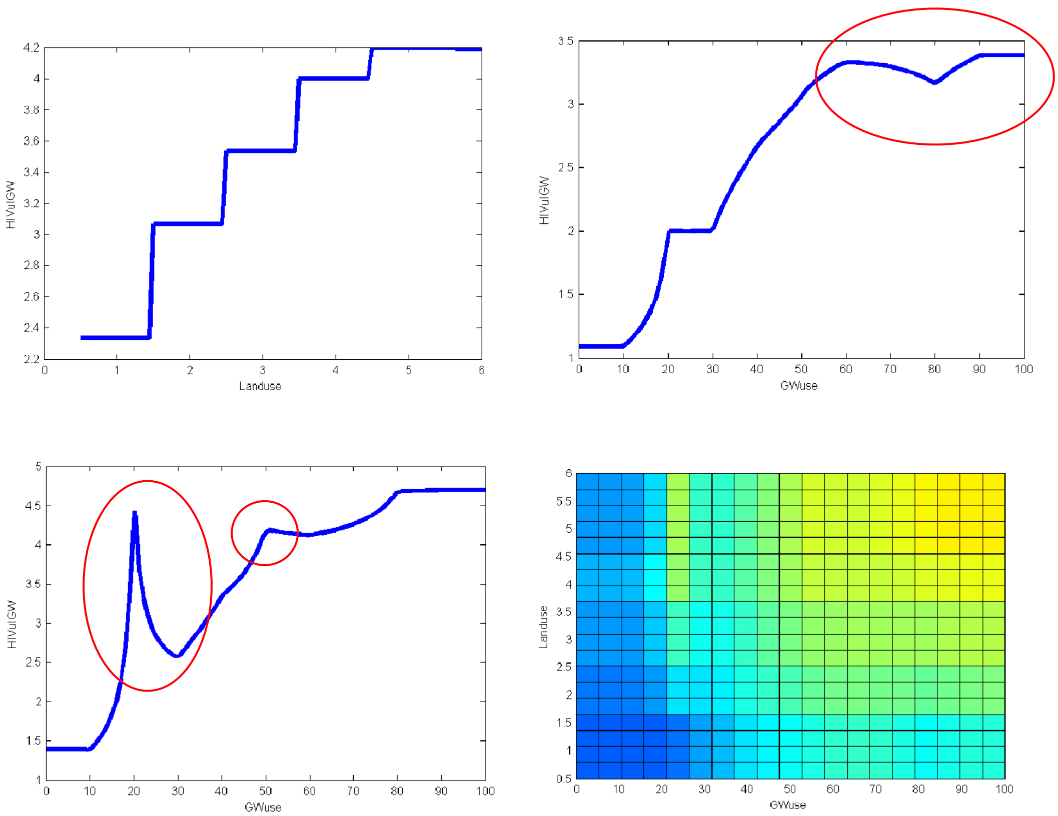


Figure 8 Scatter and surface plots of input parameters

Scatter diagram for land use do not show any anomaly, thus this parameter was continued to be used as it is. However groundwater use parameter showed different anomalies for different input values for land use parameter. Thus the output surface was drawn showing the combination of the two input parameters. As can be clearly seen, there are many anomalies dictated by groundwater use parameter. The membership function of this parameter was re-evaluated accordingly.

In light of the above discussions, the necessary re-evaluations were performed. Although after the re-evaluation still some local maxima and minima existed, the ranges were lower. This is thought to be due to some parameters defining the same impact having reverse influences on the vulnerability causing a maxima or minima at the crossover points. For example, as rate of sea level rise increases, vulnerability increases however as beach slope steepens (the number increases), vulnerability decreases. Thus the combination of these two parameters would cause a maximum vulnerability not at the end of the highest values for each parameter but at a point of cross-over (Figure 9). Regardless of the discussion, re-evaluation of the membership functions through additional data decreased the uncertainty related to parameter inputs and increases the robustness of the overall model.

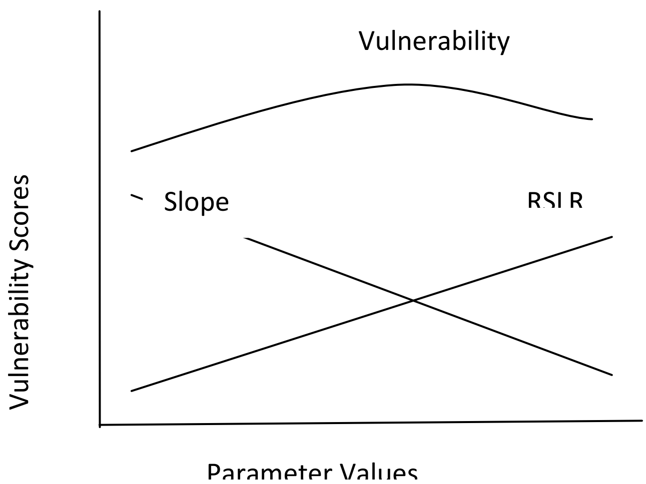
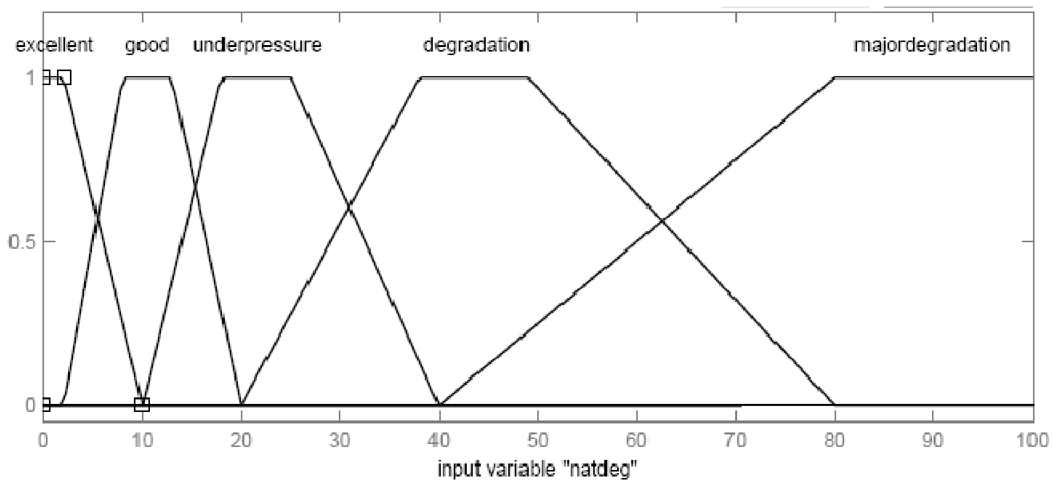


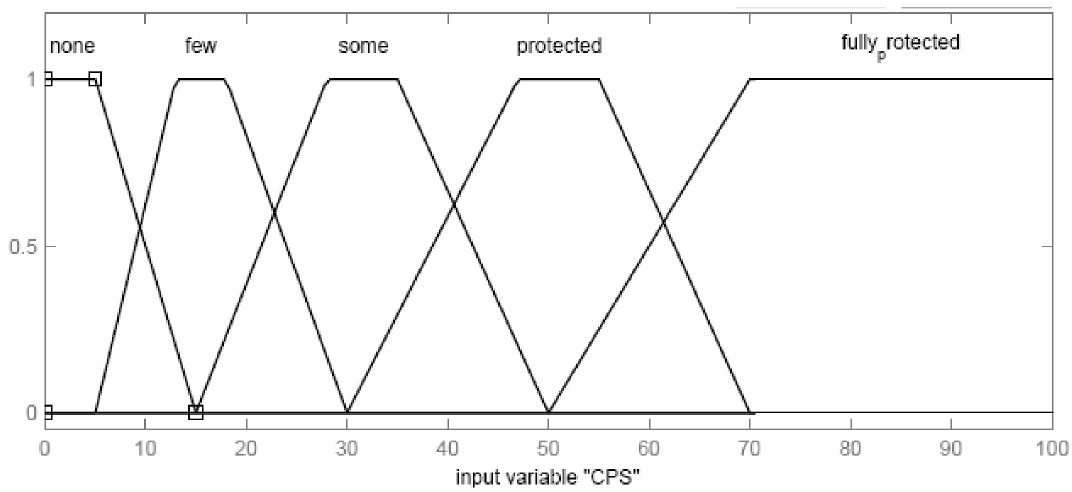
Figure 9 Relationship between input parameters and output parameter

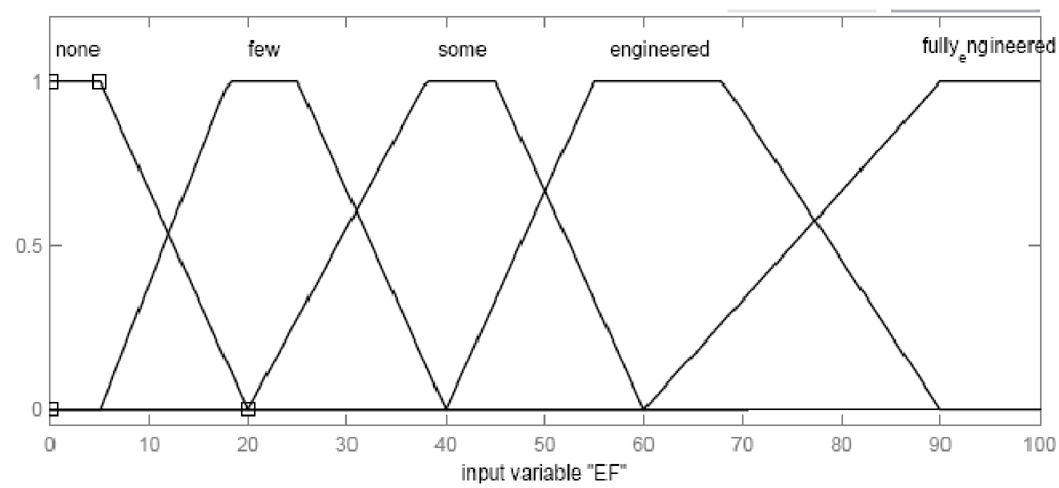
APPENDIX G

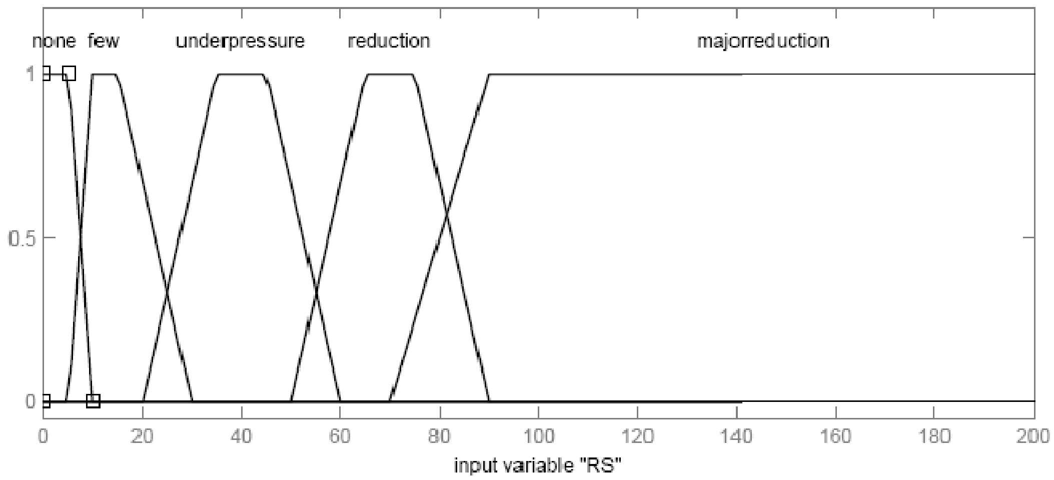
TRAPEZOIDAL MEMBERSHIP FUNCTIONS

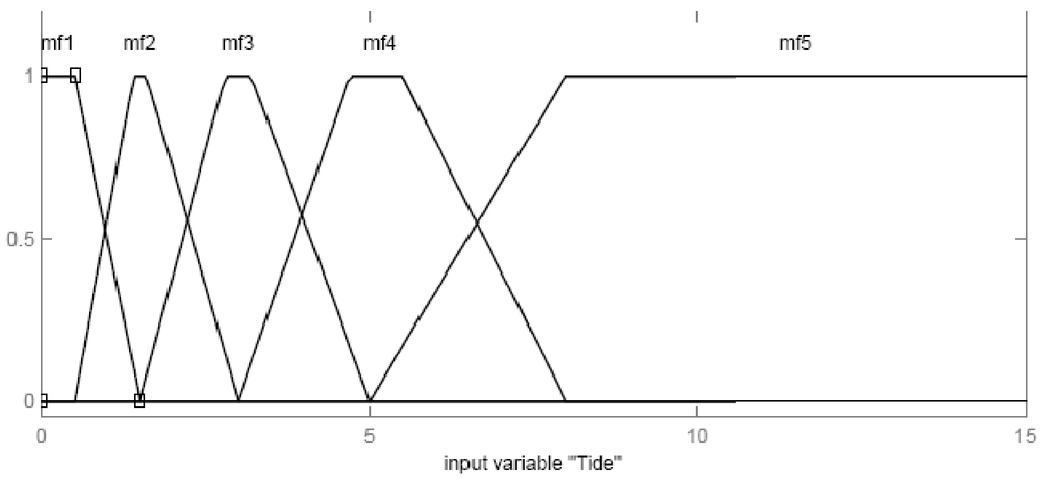
The membership functions diagrams for input parameters defined as trapezoidal membership functions are given below:

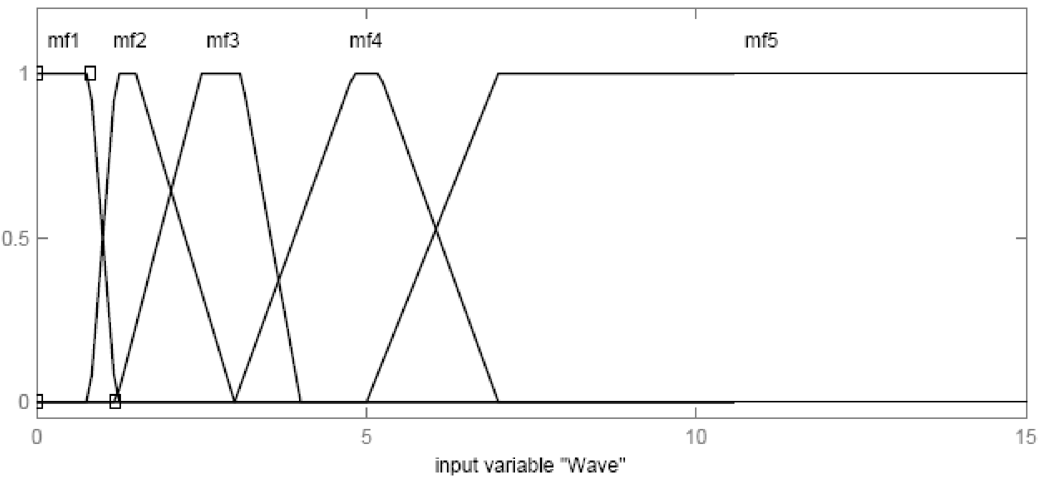


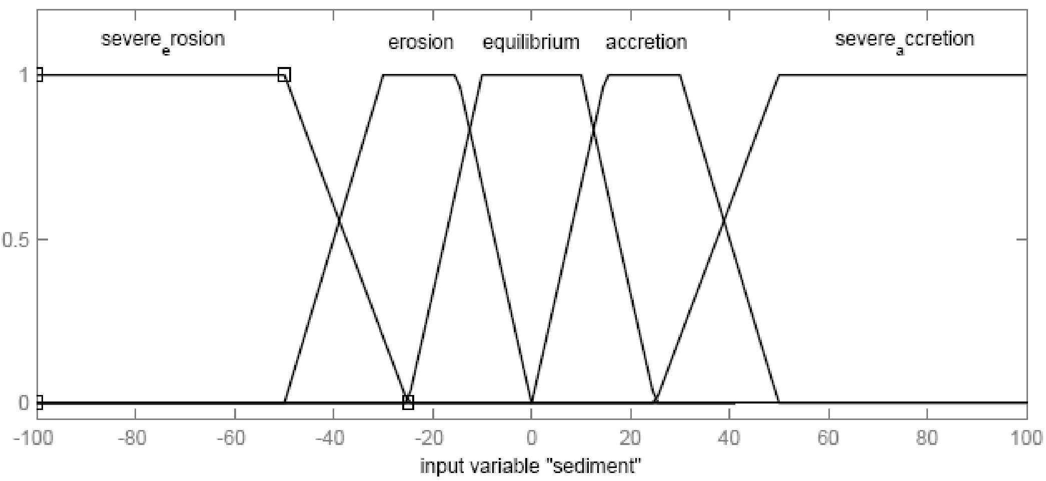


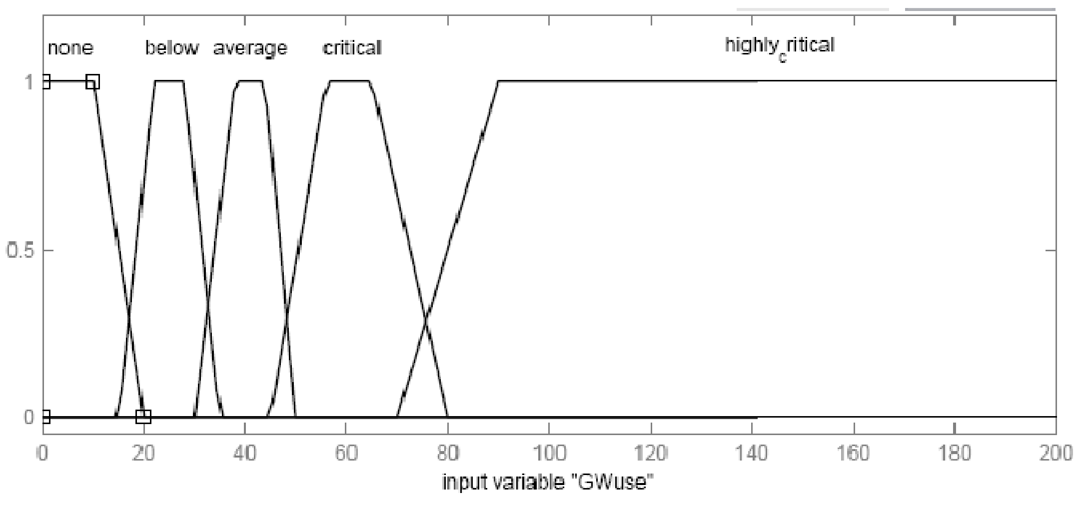

none
few
some
engineered
fully_engineered
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
input variable "EF"

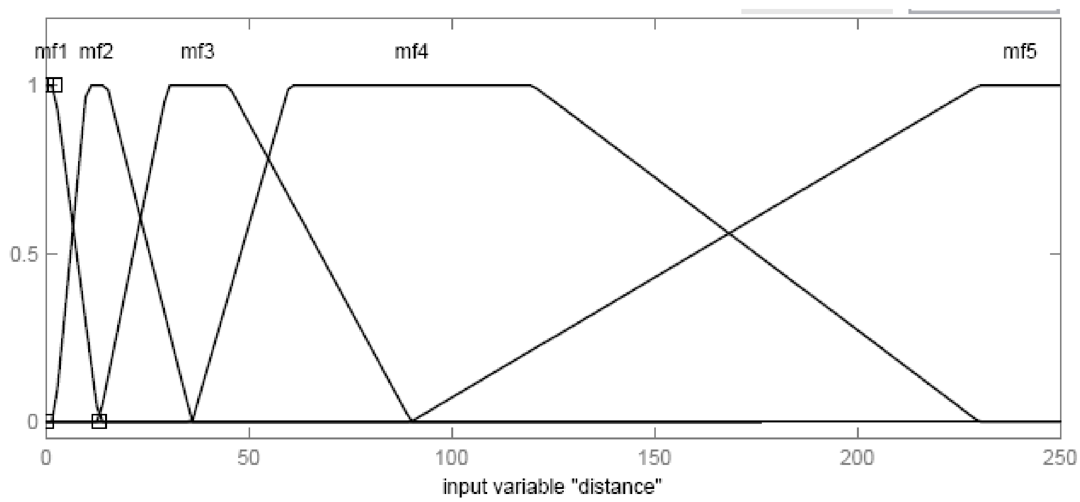

none
few
underpressure
reduction
majorreduction
1
0.5
0
0
20
40
60
80
100
120
140
160
180
200
input variable "RS"

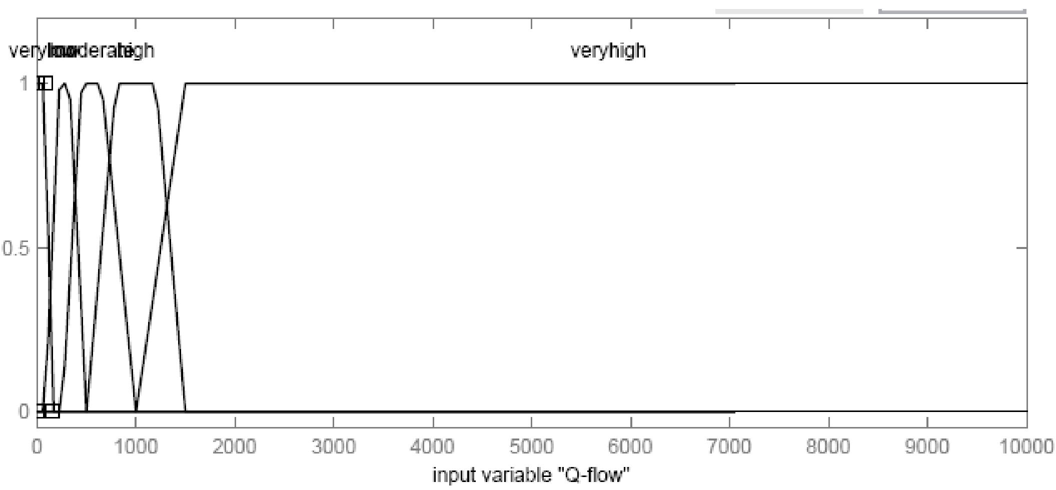

mf1
mf2
mf3
mf4
mf5
1
0.5
0
0
5
10
15
input variable "Tide"

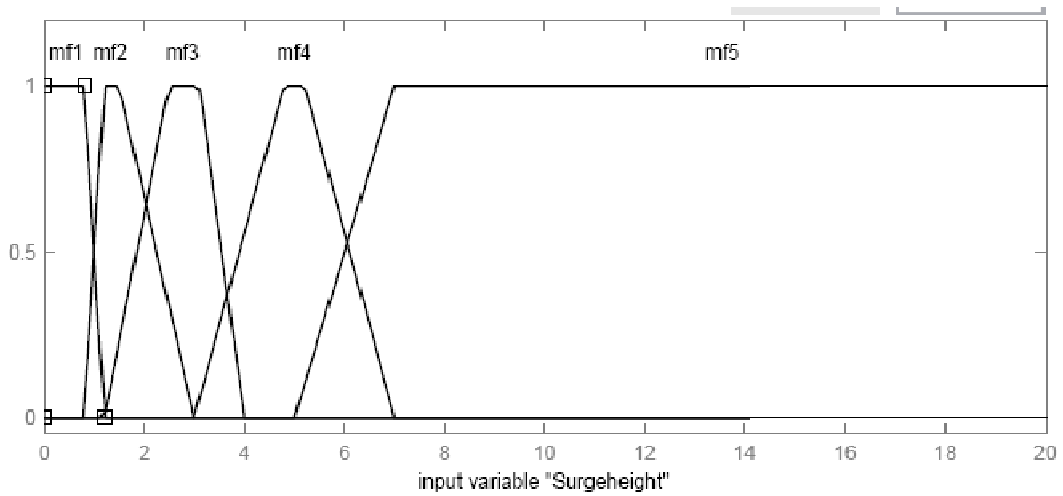

mf1
mf2
mf3
mf4
mf5
1
0.5
0
0
5
10
15
input variable "Wave"


severe_erosion
erosion
equilibrium
accretion
severe_accretion
1
0.5
0
-100
-80
-60
-40
-20
0
20
40
60
80
100
input variable "sediment"


none
below
average
critical
highly_critical
1
0.5
0
0
20
40
60
80
100
120
140
160
180
200
input variable "GWuse"


mf1
mf2
mf3
mf4
mf5
1
0.5
0
0
50
100
150
200
250
input variable "distance"


veryhigh
1
0.5
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
input variable "Q-flow"


mf1
mf2
mf3
mf4
mf5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
input variable "Surgeheight"

CURRICULUM VITAE

PERSONAL INFORMATION

First name(s) / Surname(s) Gülizar Özyurt

Telephone(s) +903124837083

E-mail: gulizar@gmail.com

Nationality Turkish

Date of birth March 5, 1982

EDUCATION

Degree	Institution	Year of Graduation
MS	METU Civil Engineering	2007
BS	METU Civil Engineering	2004
High School	American Collegiate Institute, İzmir	2000

WORK EXPERIENCE

Year	Place	Enrollment
2005- Present	METU Department of Civil Eng.	Research Assistant
2003 July	Port Authority of Gijon, Spain	Intern Eng. Student

FOREIGN LANGUAGES

Advanced English, Intermediate Spanish, Beginner German

PUBLICATIONS

Özyurt, G., Ergin. A. and Baykal C. Fuzzy Vulnerability Assessment of Coastal Areas to Sea Level Rise. 32nd International Conference on Coastal Engineering (ICCE 2010) Shanghai, China. (30 June-5 July 2010) Paper no:504

Özyurt, G. and Ergin, A., Improving Coastal Vulnerability Assessments to Sea-Level Rise: A New Indicator-Based Methodology for Decision Makers (2010) Journal of Coastal Research Vol. 26-2. p265-273

Özyurt, G. and Ergin, A., (2009) Application of Sea Level Rise Vulnerability Assessment Model to Selected Coastal Areas of Turkey. Journal of Coastal Research, SI 56 (Proceedings of the 10th International Coastal Symposium), Lisbon, Portugal

Özyurt, G. and Ergin, A., (2008). Coastal Vulnerability to Sea Level Rise. Proceedings of the Conference on Marine Problems and Specific Solutions (Maldives).

Özyurt, G. and Ergin, A., (2008). Kıyı Alanları Kırılganlık Modeli için CBS uygulaması. Proceedings of Türkiye'nin Kıyı ve Deniz Alanları 7. Ulusal Kongresi (7th National Congress on Turkish Coastal and Marine Areas – KAY '08) (Ankara, Turkey), Paper 200.

Özyurt, G., Ergin, A. and Esen, M. (2008). Indicator based coastal vulnerability assessment model to sea level rise. Proceedings of the 7th International Conference on Coastal and Port Engineering in Developing Countries (COPEDEC) (Dubai, UAE), Paper E-06.

Ozyurt, G. (2007) "Vulnerability of Coastal Areas to Sea Level Rise: A Case Study on Goksu Delta" MSc. Thesis, Coastal Engineering Division, Civil Engineering Department, Middle East Technical University, Ankara

Ozyurt, G. (2007) "Adaptation Strategies for Climate Change on Göksu Delta (presentation)" Transitional Waters Workshop, Joint Research Center, Ispra, Italy October

A.C. Yalciner, E. Pelinovsky, A. Zaitsev, and A. Kurkin, C. Ozer, H.Karakus, G. Ozyurt (2007) “Modeling and visualization of tsunamis: Mediterranean examples” Tsunami & Nonlinear Waves, Springer

DEFRA Project Team (2006) DEFRA Technical Report “The Impact of Climate Change on the Livelihood of people of Goksu Delta”, Ocean Engineering Research Center, METU, Ankara

Ahmet C. Yalciner, Efim Pelinovsky, Andrey Kurkin, Andrey Zaytsev, Ceren Ozer, Gulizar Ozyurt, Hulya Karakus, Jagdish Singh, Ahmet Sabirin (2006) “Tsunami risk in SE Asia and South China Sea, Malaysian achievements for Tsunami Warning System” HAZARDS 2006 Proceedings, Greece

Ahmet C. Yalciner, Efim Pelinovsky, Andrey Zaytsev, Ceren Ozer, Hulya Karakus, Andrey Kurkin, Gulizar Ozyurt (2006) “Tsunami Simulation, Visualization, Animation Software for Supplement to Tsunami Warning Systems and Application to Mediterranean Examples” HAZARDS 2006 Proceedings, Greece

April 2006, UNESCO Intergovernmental Oceanographic Commission Tsunami Modeling Training for the employees of the Malaysian Tsunami Early Warning System Center, Training Assistant, Kuala Lumpur, Malaysia

Yalciner, A.C. and Ozyurt, G. (2006) “Counter Measures for Coastal Disasters in Europe” Int. Workshop on Coastal Disasters Prevention, Tokyo, Japan

HOBBIES

Movies, Motorsports, History, Computer Technologies