VULNERABILITY OF COASTAL AREAS TO SEA LEVEL RISE: A CASE STUDY ON GÖKSU DELTA

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ABSTRACT

VULNERABILITY OF COASTAL AREAS TO SEA LEVEL RISE: A CASE STUDY ON GOKSU DELTA

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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 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 coastal vulnerability matrix and a corresponding coastal vulnerability index – CVI (SLR) of a region to sea level rise using indicators of impacts of sea level rise which use commonly available data are developed. The results of the matrix and the index 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 developed coastal vulnerability assessment model is used to determine the vulnerability of Göksu Delta (Specially Protected Area), Mersin that has unique geological, ecological and socio-economical properties which are protected and recognized by both national and international communities.

Keywords: Vulnerability Assessment, Climate Change, Sea Level Rise, Coastal Areas, Coastal Zone Management

ÖZ

KIYI ALANLARININ DENİZ SUYU SEVİYESİ YÜKSELMESİNE OLAN KIRILGANLIĞI : UYGULAMALI ÇALIŞMA ALANI GÖKSU DELTASI

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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 kmlik 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 uyumluluk çalışmalarına kaynak aktarımının en uygun şekilde düzenlenebilmesi için Türkiye kıyılarının deniz seviyesi yükselmesine karşı kırılganlık analizinin yapılması geremektedir.

Bu çalışmada, deniz seviyesi yükselmesinin yaratacağı olumsuz etkilerin faktörleri kullanılarak, deniz seviyesi yükselmesine karşı kıyı alanlarının kırılganlığını ölçen bir kıyı alanları kırılganlık modeli geliştirilmiştir. Bu model; farklı kıyı alanlarına deniz seviyesi yükselmesine olan kırılganlıkları göz önüne alınarak öncelik verilmesini; herhangi bir kıyı alanında yaşanacak etkilerin o bölge için önem sırasına dizilmesini ve de her hangi bir etki için kritik olan parametrelerin anlaşılmasını sağlamaktadır. Böylece uygulanabilecek uyumluluk stratejilerinin planlaması ve de uygun kaynak aktarımı doğrulukla yapılacaktır.

Ayrıca bu çalışmada, geliştirilen kıyı alanlarının deniz seviyesi yükselmesine karşı kırılganlık analiz modeli, Mersin iline bağlı Özel Çevre Koruma Bölgesi alanı olan Göksu Deltasına uygulanmıştır.

Anahtar kelimeler: Kırılganlık Analizi, İklim Değişikliği, Deniz Seviyesi Yükselmesi, Kıyı Alanları Yönetimi

Dedicated to my family.

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"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. The time she had devoted and the guidance she had provided has helped me overcome the obstacles of both academic and daily life.

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I would like to attend my thanks to every member of my family for all the support they have given.

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CHAPTER 1

INTRODUCTION

Climate change and the expected impacts of climate change has become the most important threat to human kind. The impacts of climate change are increasingly affecting the lives of people all around the world for the past decade although the scientific community discovered the signs of the climate change around 1960's. The research on climate change shows that although the mitigation measures implemented by the governments might be able to slow down the process of climate change, the resulting impacts of climate change will continue to affect the world's population for the next century. Thus, the governments and the decision makers should prepare adaptation measures for these impacts through an integrated coastal zone planning while at the same time continue to implement the mitigation measures.

One of the impacts of climate change is the accelerated sea level rise due to thermal expansion of surface waters around the world, which is initiated by the increased surface temperatures. Sea level rise will trigger other impacts along the coastal areas around the world such as; coastal erosion, inundation of lands, increased flooding of coastal areas due to increased storm surges and extended salt-water intrusion to fresh water resources. The impacts of sea level rise will be most profound on the small islands of the oceans and the low-lying coastal areas around the world.

Turkey having 8333 km of coastline including low-lying deltas which are important both physically, ecologically and socio-economically; should also prepare adaptation measures for the impacts of sea level rise as well as other impacts of climate change while participating in the mitigation efforts. In order to be prepared against the impacts of sea level rise, adaptation measures have to be planned and implemented through impact and vulnerability assessments of coastal areas. Since low-lying lands along the coastline of Turkey are also the important areas of agriculture, industry and tourism, a vulnerability assessment of coastal areas 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 the upcoming problems due to sea level rise.

However, there are not many researches on the impacts of sea level rise on coastal areas of Turkey at the present. In addition, one of the main limitations of any assessment is the availability of data, which in Turkey is a persisting problem that the researchers are aware of. Thus, both to overcome the problem of availability of data as well as to assess the vulnerability of the coastal areas of Turkey, this study is aimed to develop a coastal vulnerability assessment model to sea level rise, which could be used for any region using the commonly available site-specific data. The aim of the assessment model is to

a. Compare different regions and rank them according to their vulnerabilities to sea level rise
b. Prioritize the impacts of sea level rise on the region according to the vulnerability of the region to each impact
c. Determine which parameters are the most vulnerable parameters that need to be considered when planning for adaptation to sea level rise

by using governing parameters of the physical impacts triggered by sea level rise as indicators.

With the scope of this task a “Coastal Vulnerability Index to Sea Level Rise – CVI (SLR)” and the sub-indices of the impacts are defined in order to compare and prioritize the regions and the impacts on a common base.

The developed coastal vulnerability assessment model is used to determine the vulnerability of Göksu Delta (Specially Protected Area), Mersin. The region is a very important low-lying delta having unique geological, ecological and socio-economical properties which are protected and recognized by both national and international communities.

In chapter 2, observed climate changes throughout the Earth, mechanism of climate change, projections of global climate in the future, the mechanism of sea level rise and the impacts of sea level rise on coastal areas are briefly explained.

In chapter 3, the stages of development of the Coastal Vulnerability Index to sea level rise is given in detail. The physical processes of the impacts of sea level rise, the physical parameters governing the impacts of sea level rise and the human influence on coastal areas, which affect the vulnerability of a region to sea level rise, are discussed exclusively. The ranges of the parameters used in the coastal vulnerability assessment to sea level rise are presented and the construction of "Coastal Vulnerability Index – CVI (SLR)" is discussed.

In Chapter 4, coastal vulnerability assessment model to sea level rise is applied to a pilot region, Göksu Delta. First background information is given on the Delta. The corresponding properties of the Delta for the parameters of the coastal vulnerability assessment to sea level rise are discussed and the calculation of the coastal vulnerability index is performed systematically. The discussion of the results of the coastal vulnerability assessment is given in detail.

In Chapter 5, conclusion and discussion of the newly developed model of coastal vulnerability assessment to sea level rise is presented together with recommendation for future studies and for further development of the model.

CHAPTER 2

LITERATURE REVIEW

Climate change is defined as any change in climate over time, whether due to natural variability or as a result of human activity in the Third Assessment Report(TAR) of Intergovernmental Panel on Climate Change (IPCC, 2001). Although the debate on whether there is a climate change due to anthropogenic influences goes on, the evidences show that most of the global warming for the past 50 years is attributable to human activities.

2.1 Observed Changes in Climate System throughout the Earth

According to the scientific evidence presented in the Third Assessment Report of Intergovernmental Panel on Climate Change (2001):

- The global average surface temperature has increased over the 20th century by about 0.6°C. The most recent period of warming has been almost global, however the largest increases have been recorded over the mid- and high latitudes of the continents of Northern Hemisphere. The increase in temperature in the 20th century is likely to have been the largest of any century during the past 1,000 years (Figure 2.1).

- The diurnal temperature range (difference between temperatures of day and night) is decreasing widely, although not everywhere. On average, minimum temperatures are increasing at about twice the rate of maximum temperatures (0.2 versus 0.1°C/decade).

- The data from satellite shows that snow cover and ice extent has decreased significantly. There has been a widespread retreat of mountain glaciers in non-polar regions during the 20th century. Northern

Hemisphere spring and summer sea-ice extent has decreased by about 10 to 15% since the 1950s.

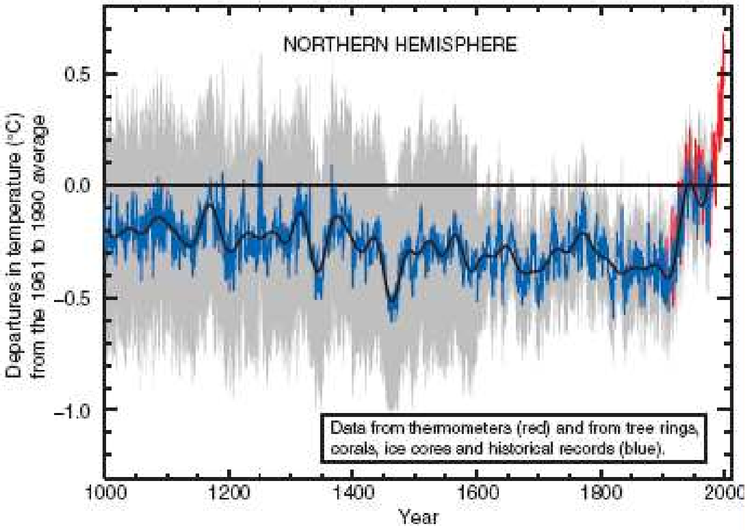


Figure 2.1 Variations of Earth's surface temperature for the past 1000 years (IPCC, 2001)

- It is very likely that precipitation has increased by 0.5 to 1% per decade in the 20th century over most mid- and high latitudes of the Northern Hemisphere continents. Also over the latter half of the 20th century, it is likely that there has been a 2 to 4% increase in the frequency of heavy precipitation events. Since 1950 it is very likely (66-90% certainty) that frequency of extreme low temperatures has been reduced, however frequency of extreme high temperatures has increased a little.

- In some regions of Asia and Africa, the frequency and intensity of droughts have been observed to increase in recent decades.

- Global sea level has risen about 10 cm to 20 cm during past 100 years according to tidal gauges. The central value of the rate of global mean sea level rise is calculated to be 1.5mm/year. The average rate of sea level rise has been larger during the 20th century than during 19th century according to few longest instrumental records.

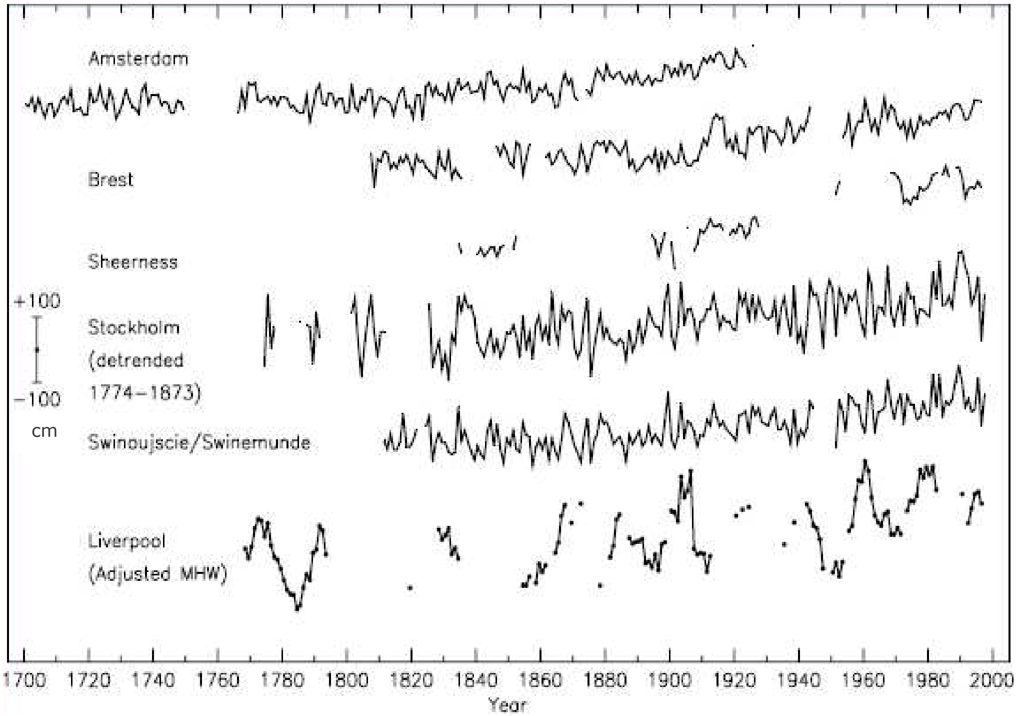


Figure 2.2 Time series of relative sea level for the past 300 years from Northern Europe (IPCC, 2001)

2.2 Mechanism of Climate Change

Changes in climate happen due to two factors; internal variations and external driving forces, which can be both natural and anthropogenic. The driving mechanism of climate change can be explained through the concept of radiative forcing. This concept is defined as “a change in the net radiative energy available to the global Earth-atmosphere system” (IPCC, 2001). The radiation from Sun is absorbed by mainly Earth’s surface. This energy is redistributed and radiated back to space by atmospheric and oceanic circulations. Thus, any change that affects this cycle tends to either increase or decrease the temperature of the surface of Earth.

The warming trend is determined by increases of the concentrations of greenhouse gases, which are mostly water vapour, carbon dioxide, ozone, methane and nitrous oxide. The amount of radiative forcing depends on the size of the increase in concentration of each greenhouse gas, the radiative properties of the gases involved, and the concentrations of other greenhouse gases already present in the atmosphere. Further, many greenhouse gases reside in the atmosphere for centuries after being emitted, thereby introducing a long-term commitment to positive radiative forcing (IPCC, 2001).

The cooling trend due to negative radiative forcing can arise from an increase in anthropogenic aerosols (microscopic airborne particles or droplets (IPCC, 2001)) which are derived from fossil fuel and biomass burning. These particles can reflect solar radiation, which leads to a cooling tendency in the climate system. However, some of aerosols can absorb the solar radiation increasing the effect of greenhouse gases. Since they have a much shorter lifetime (days to weeks) than most greenhouse gases (decades to centuries), and, their concentrations respond much more quickly to changes in emissions (IPCC, 2001). Other than aerosols, volcanic eruptions exert large amounts of sulphur-containing gases (primarily sulphur dioxide), which further influences the cooling trend.

Internal variations are due to the change of the Sun's output of energy, which varies by small amounts (0.1%) over an 11-year cycle (IPCC, 2001). Other than the mentioned short-time variation, throughout the time, there had been variations in the Earth's orbit, which had led to glacial and inter-glacial cycles.

When radiative forcing changes, the climate system responds on various time-scales. The longest of these are due to the large heat capacity of the deep ocean and dynamic adjustment of the ice sheets. This means that the transient response to a change (either positive or negative) may last for thousands of years. Any changes in the radiative balance of the Earth, including those due to an increase in greenhouse gases or in aerosols, will alter the global hydrological cycle and atmospheric and oceanic circulation, thereby affecting weather patterns and regional temperatures and precipitation (IPCC, 2001).

Any anthropogenic changes in climate will be embedded in a background of natural climatic variations that occur on a whole range of time- and space-scales. It is very important that the impact of human activities should be distinguished from the natural variations of the climate system.

Simulations of variations of Earth's temperature showed that both the natural causes and the anthropogenic causes by themselves do not explain the recent warming trend of the Earth's surface.

The best agreement between model simulations and observations over the last 140 years has been found when all the above anthropogenic and natural forcing factors are combined, as shown in Figure 2.3. In the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations.

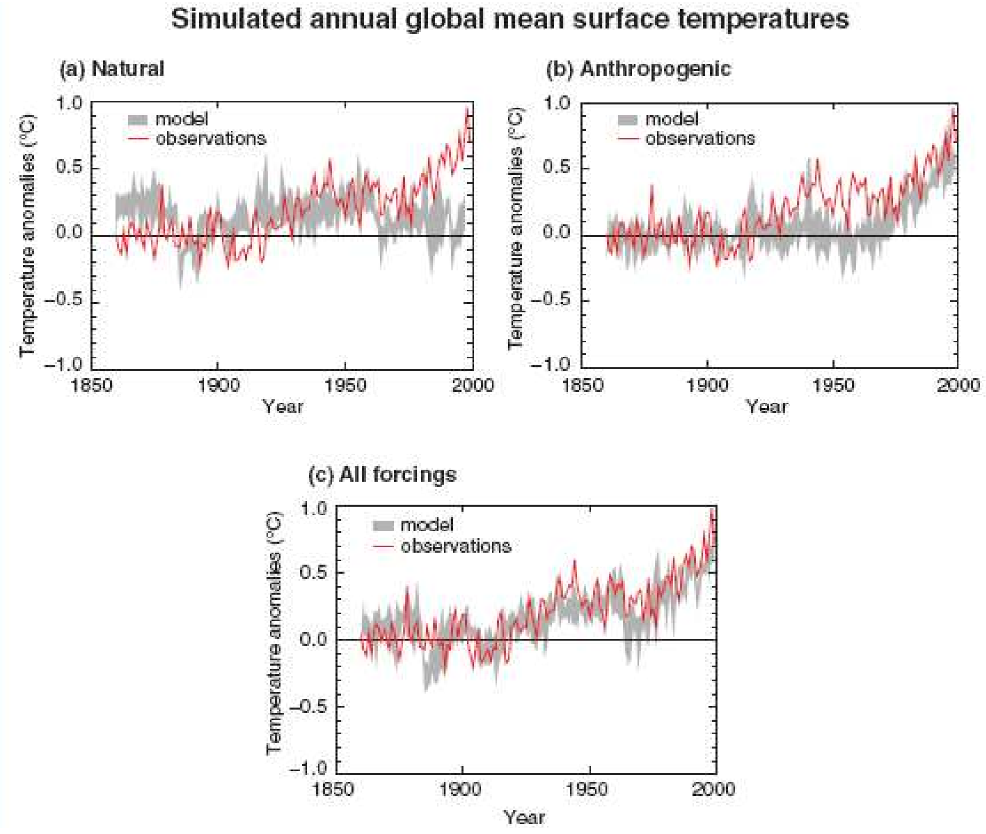


Figure 2.3 Simulations of variations of Earth's surface temperature and comparing the results to measured changes (IPCC, 2001)

Furthermore, it is very likely that the 20th century warming has contributed significantly to the observed sea level rise, through thermal expansion of seawater and widespread loss of land ice (IPCC, 2001).

Concentrations of atmospheric greenhouse gases have continued to increase because of human activities as determined by the measurements done throughout the world. The results of these measurements are given in Third Assessment Report (IPCC, 2001) as:

- The atmospheric concentration of carbon dioxide (CO_2) has increased by 31% since 1750. The present CO_2 concentration has not been exceeded during the past 420,000 years and likely not during the past 20 million years. The current rate of increase is unprecedented during at least the past 20,000 years.

- About three-quarters of the anthropogenic emissions of CO_2 to the atmosphere during the past 20 years are due to fossil fuel burning. The rest is predominantly due to land-use change, especially deforestation.

- The atmospheric concentration of methane (CH_4) has increased by 151% since 1750 and continues to increase. The present CH_4 concentration has not been exceeded during the past 420,000 years. Slightly more than half of current CH_4 emissions are anthropogenic (e.g., use of fossil fuels, cattle, rice agriculture and landfills).

- The atmospheric concentration of nitrous oxide (N_2O) has increased by 17% since 1750 and continues to increase. The present N_2O concentration has not been exceeded during at least the past thousand years. About a third of current N_2O emissions are anthropogenic (e.g., agricultural soils, cattle feed lots and chemical industry).

2.3 Projections of Global Climate in Future

In order to describe the Earth's future climate, mathematical models of the present climate system with future scenarios of forcing agents are used. The degree to which the model can simulate the responses of the climate system hinges to a very large degree on the level of understanding of the physical, chemical and biological processes that govern the climate system. These models with emission scenarios can illustrate and give quantitative estimate on the changes of the climate in the future. Summary of the mostly used scenarios is presented below.

2.3.1 Storylines and Scenarios

Four different narrative storylines were developed to describe the relationships between the forces driving emissions and their evolution by the IPCC. Resulting 40 scenarios cover a range of main demographic, economic and technological driving forces of future greenhouse gases and aerosols. Main four scenario families are identified as A1, A2, B1 and B2. Other than the mentioned scenarios, there are previously used ones named as IS92 scenarios. The detailed information can be found in the Special Report on Emissions Scenarios (SRES, 2000).

The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income.

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

2.3.2 Projected Changes in Parameters of Climate System

The global climate of the 21st century will depend on natural changes and the response of the climate system to human activities. Output of the different global climate models predicts the following changes as stated in TAR (IPCC, 2001);

- The globally averaged surface temperature is projected to increase by 1.4 to 5.8°C (Figure 2.4) over the period 1990 to 2100. These results are for the full range of SRES (2000) scenarios, based on a number of climate models.

- The projected rate of warming is much larger than the observed changes during the 20th century and is very likely to be without precedent during at least the last 10,000 years, based on palaeoclimate data.

- It is very likely that nearly all land areas will warm more rapidly than the global average, particularly those at northern high latitudes in the cold season. Most notable of these is the warming in the northern regions of North America, and northern and central Asia, which exceeds global mean warming in each model by more than 40%. In contrast, the warming is less than the global mean change in south and southeast Asia in summer and in southern South America in winter.

- Global mean sea level is projected to rise by 0.09 to 0.88 meters between 1990 and 2100, for the full range of SRES scenarios. This is due primarily to thermal expansion and loss of mass from glaciers and ice caps.

- Northern Hemisphere snow cover and sea-ice extent are projected to decrease further. Glaciers and ice caps are projected to continue their widespread retreat during the 21st century.

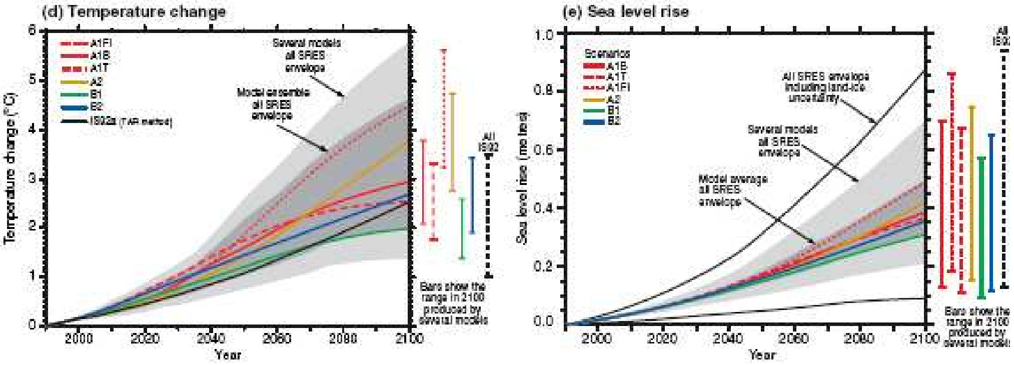


Figure 2.4 Projected global climate of the 21st century (IPCC, 2001)

- The Antarctic ice sheet is likely to gain mass because of greater precipitation, while the Greenland ice sheet is likely to lose mass because the increase in runoff will exceed the precipitation increase.

- By the second half of the 21st century, it is likely that precipitation will have increased over northern mid- to high latitudes and Antarctica in winter. At low latitudes, there are both regional increases and decreases over land areas. Larger year-to-year variations in precipitation are very likely over most areas where an increase in mean precipitation is projected.

- In case of extreme events, higher maximum temperatures and more hot days, higher minimum temperatures, fewer cold days and frost days, reduced diurnal temperature range and more intense precipitation events are projected over nearly all land areas.

The above climate change projections predict a very pessimistic future in terms of changes in climate variables. Although there have been many studies on how to stabilize the emissions of greenhouse gases, the models predict changes on climate even if no further increase in concentration of greenhouse gases and aerosols occur, due to the lasting effect of greenhouse gases on atmospheric composition, radiative forcing and climate. It is predicted that a rise of surface temperature at a rate of only a few tenths of a degree per century. However, the temperature increases and sea level rise are projected to continue for hundreds of years after the stabilization of greenhouse gas concentrations.

2.4 Accelerated Sea Level Rise and the Anticipated Impacts on Coastal Areas

As mentioned in the previous paragraphs, one of the projected changes on climate system is the accelerated rise of sea levels around the world. Although the rate of change of sea level will depend on regional parameters, the expected global sea level rise is 45 cm (average) by the year 2100. Since 75% of Earth consists of oceans and seas, the question of how this rise will affect the coastal areas is needed to be considered and answered seriously.

2.4.1 What causes sea level to change?

Sea level at the shoreline depends on many factors; global and regional. In addition, the factors of changes on sea level are time-dependent; from hourly changes (tides) to millions of years (ocean basin changes due to tectonics and sedimentation). However, when decades are considered as time periods of influence, the sea level change can be related to the changes on global climate system.

One of the major reasons of the change of sea level on global scale is the expansion of oceans due to the increase in the temperature of water. Since deep ocean temperatures changes slowly, the change due to thermal expansion is expected to continue for many centuries.

Other factor contributing to the sea level change is the increase/decrease of water mass of the oceans. This is observed when there is an exchange of mass of water between land and ocean. After thermal expansion, the melting of mountain glaciers and ice caps is expected to make the largest contribution to the rise of sea level over the next hundred years. These glaciers and ice caps make up only a few percent of the world's land-ice area, but they are more sensitive to climate change than the larger ice sheets in Greenland and Antarctica, because the ice sheets are in colder climates with low precipitation and low melting rates (IPCC, 2001).

There are other factors, which are not related to global climate change but mostly regional natural or anthropogenic effects such as extraction of ground water, building of reservoirs, changes in surface runoff, and seepage into deep aquifers from reservoirs and irrigation. In addition, coastal subsidence in river delta regions can also influence local sea level. Vertical land movements caused by natural geological processes, such as slow movements in the Earth's mantle and tectonic displacements of the crust, can have effects on local sea level that are comparable to climate-related impacts (IPCC, 2001).

2.4.2 Impacts of Accelerated Sea Level Rise on Coastal Areas

Coastal areas are one of the most dynamic and complex interfaces on Earth; located at the intersection of air, water and land interfaces. Thus, any change on properties of one of these interfaces will have significant impacts on the coastal area both biophysically and socioeconomically.

Coastal areas support some of the most diverse and productive habitats which include natural and managed ecosystems, economic sectors and major urban centers. These habitats are under constant stress due to land-sourced and marine hazards such as waves and storm surges, tsunamis, river flooding, shoreline erosion, etc. Accelerated sea level rise will intensify these stresses particularly those where human activities have diminished natural and socio-economical adaptive capacities (Klein and Nichols et al., 1998).

Potential impacts of climate change and sea level rise on coastal systems are presented in Coastal Zones and Marine Ecosystems Chapter of TAR, 2001 as follows:

Physical Impacts:

a. Increased coastal erosion
b. More extensive coastal inundation
c. Higher storm-surge heights
d. Landward intrusion of seawater in estuaries and aquifers
e. Changes in surface water quality and groundwater characteristics
f. Reduced sea-ice cover

Related socio-economic impacts:

a. Increased loss of property and coastal habitats
b. Increased flood risk and potential loss of life
c. Damage to coastal protection works and other infrastructure
d. Increased disease risk
e. Loss of renewable and subsistence resources
f. Loss of tourism, recreation and transportation functions
g. Loss of nonmonetary cultural resources and values
h. Impacts on agriculture and aquaculture through decline in soil and water quality

The above-mentioned impacts will be highly variable due to the effect of local differences in the resilience and adaptive capacity of ecosystems, sectors and countries. Even in some countries, it is expected that some of the mentioned potential impacts will have positive results in the end. For example, The climate of Canada will become milder increasing the agricultural production. The effect of sea level rise on the impacts mentioned above will be presented in detail in Parameters section of Chapter 3.

Also, some natural features of the coastal areas will provide efficient protection such as coral reefs, coastal dunes, barrier beaches, coastal vegetation and mangroves, etc. The functions of these natural features add to the resilience of the coastal areas.

In Third Assessment Report of IPCC (2001), the following coastal areas are identified as the most vulnerable areas to accelerated sea level rise; low-elevation coral atolls and reef islands, low-lying deltaic, coastal plains and barrier coasts, coastal wetlands, estuaries and lagoons. On the other hand, rocky coasts and cliffs are mentioned as less vulnerable.

The term 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 in the Third Assessment Report of IPCC. Accordingly, it is a function of exposure, sensitivity and adaptive capacity. However still, there is not a common definition used within the climate change research society. Thus, there exist three different schools of vulnerability assessment.

First approach is called risk – hazard framework (Füssel and Klein, 2006) which treats vulnerability as pre-existing condition and focuses on potential exposure to hazards (Rygel et al., 2006). This approach studies the distribution of the hazard throughout the region, the distribution of people and the loss of life and property.

Second approach is called social constructivist framework by Füssel and Klein, 2006, which approaches to the vulnerability as the social vulnerability of individuals and groups in which the affected people display patterns of differential loss (Rygel et al., 2006).

A third approach represents the definition of vulnerability by IPCC, which aims to integrate the biophysical and social parameters of vulnerability as the risk being biophysical and response social within a specific region (Wu et al., 2002).

Two generations of vulnerability assessments are defined by Füssel and Klein, 2006; first generation and second generation. The step from climate impact assessment to *first-generation* vulnerability assessment is characterized primarily by the evaluation of climate impacts in terms of their relevance for society and by the consideration of potential adaptation. The main novelty of *second-generation* vulnerability assessments is the more thorough assessment of the adaptive capacity of people, thus shifting the focus from potential to feasible adaptation (Füssel and Klein, 2006).

Usually, vulnerability assessments include additional parameters of main stressors affecting the system, including the non-climatic stressors. Non-climatic stresses cover environmental, economic, social, demographic, technological, and political factors. However, these factors may have beneficial effects as well. *Non-climatic factors* can affect the *sensitivity* of a system to climatic stimuli as well as its *exposure* (Füssel and Klein, 2006). Vulnerability assessments also include subjective evaluation of the magnitude and distribution of projected effects as to their desirability and importance. There is a debate on quantification of vulnerability within the research community which Downing et al., 2001 argued that vulnerability is a relative measure rather than something that can be expressed in absolute terms.

It is very important to determine the vulnerable parts of the coastal zones since the before mentioned impacts can influence the livelihood of the people as well as the ecosystem in a very significant way. Many different methods and tools provide different levels of information on the impacts and vulnerability of the coastal areas studied throughout the world. The next section will give information on different types of assessments of impacts of sea level rise on coastal areas.

2.5 Climate Change Vulnerability Assessments

Different types of climate change assessments are conducted for the last two decades (McCarthy et al., 2001) in order to progress scientific knowledge and support the formulation and implementation of mitigation and adaptation policies. Mitigation policies aim at limiting or reducing the emissions of greenhouse gases and enhancing their sinks. Adaptation policies aim at minimizing the impacts of climate change through actions and reduce the risks associated with current climate variability as well (Füssel and Klein, 2006). Although mitigation research has gained more attention, adaptation research should be considered seriously since the impacts of climate change will continue even if the emissions of greenhouse gases is limited as mentioned in the previous sections.

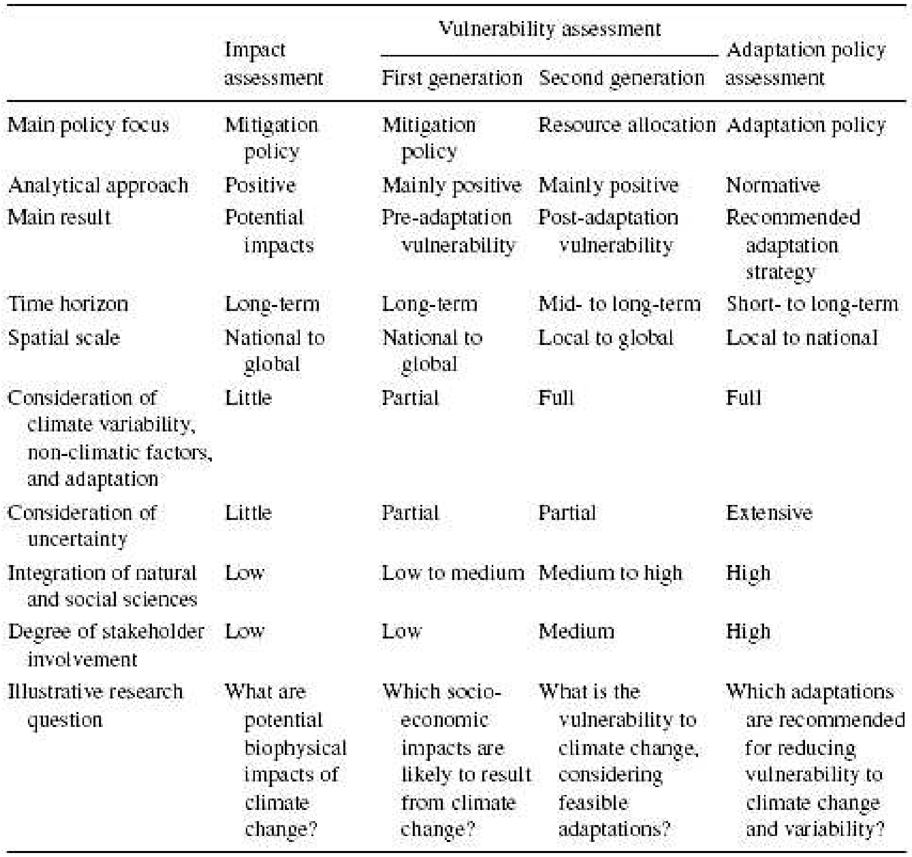
Assessments of the vulnerability to climate change are aimed at informing the development policies that reduce risks associated with climate change.

Assessments of vulnerability to climate change are conducted in a variety of contexts, and for a diverse group of stakeholders motivated by rather different concerns (Füssel and Klein, 2006). There major concern contexts are defined by Füssel and Klein, 2006:

a. Specification of long-term targets for mitigation – impact assessments
b. Identification of vulnerable regions or groups in society to plan resource allocation – vulnerability assessments
c. Recommendation of specific adaptation measures for regions and sectors – adaptation policy assessments

Table 2.1 summarizes characteristic properties of different types of these assessments. However, the authors also state that actual climate change assessments may combine several different features from more than one type of assessment. It is important to take into consideration the availability of data, urgency of threat, local geographical and socio-economical parameters and the research or policy questions asked when constructing or performing a vulnerability assessment. The related parameters should be stated clearly before performing a vulnerability assessment however, one of the main stages is to determine which conceptual framework of vulnerability to use, hence, which uses appropriate analytical definitions of vulnerability (Rygel et al., 2006).

Table 2.1 Characteristic properties of four different stages of climate change vulnerability assessment (Füssel and Klein, 2006)



	Impact assessment	Vulnerability assessment		Adaptation policy assessment
		First generation	Second generation	
Main policy focus	Mitigation policy	Mitigation policy	Resource allocation	Adaptation policy
Analytical approach	Positive	Mainly positive	Mainly positive	Normative
Main result	Potential impacts	Pre-adaptation vulnerability	Post-adaptation vulnerability	Recommended adaptation strategy
Time horizon	Long-term	Long-term	Mid- to long-term	Short- to long-term
Spatial scale	National to global	National to global	Local to global	Local to national
Consideration of climate variability, non-climatic factors, and adaptation	Little	Partial	Full	Full
Consideration of uncertainty	Little	Partial	Partial	Extensive
Integration of natural and social sciences	Low	Low to medium	Medium to high	High
Degree of stakeholder involvement	Low	Low	Medium	High
Illustrative research question	What are potential biophysical impacts of climate change?	Which socio-economic impacts are likely to result from climate change?	What is the vulnerability to climate change, considering feasible adaptations?	Which adaptations are recommended for reducing vulnerability to climate change and variability?

Figure 2.5 shows a schematic representation of the vulnerability assessments. In the first generation vulnerability assessments, non-climatic drivers and adaptive capacity of the region/society is not included. The first generation assessments mostly raise awareness of the vulnerability of valued systems to climate change. They may also assess the relative importance of various climatic and non-climatic factors. Thus, they prioritize the resource allocation for further research and determine the need for mitigation and adaptation measures.

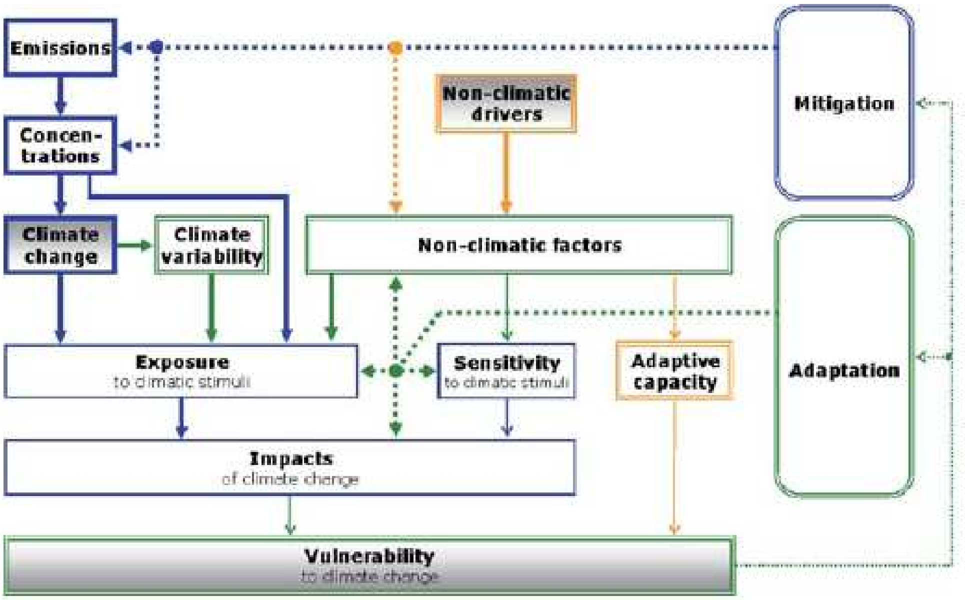


Figure 2.5 Conceptual framework of vulnerability assessments (Füssel and Klein, 2006)

Second-generation vulnerability assessments are conducted to estimate realistically the vulnerability of certain sectors or regions to climate change, in concert with other stress factors and considering the potential of feasible adaptations to reduce adverse impacts. The capacity of people to actually implement these options determines their vulnerability to climate change. More thorough assessment of society’s ability to effectively respond to anticipated risks through various kinds of adaptations is needed to be searched. Thus, second generation vulnerability assessments require the involvement of social scientists in a multidisciplinary research group as well as a stronger involvement of stakeholders more than first-generation assessments (Füssel and Klein, 2006).

CHAPTER 3

COASTAL VULNERABILITY ASSESSMENT TO ACCELERATED SEA LEVEL RISE

Climate change and the anticipated impacts of sea level rise will affect all the countries, mostly in an adverse way. The most affected countries will be the small island countries of the oceans and the countries having coastlines along the oceans and the seas due to accelerated sea level rise as well as other climatic impacts as presented in the previous section.

Turkey, having 8333 km of coastline is also under threat. There have not been many researches undertaken on the impacts of climate change in Turkey. However recently the threat of climate change had come to attention and several research from different universities are now working on the scenarios and impacts on climate and several sectors (e.g. Cukurova University and Hacettepe University in a joint programme with Japanese Universities are investigating impacts of climate change on agriculture, http://www.chikyu.ac.jp/rihn/pro/e2004_1-1.html). However, up to present, there is not a study on impacts or vulnerability of the coastal areas of Turkey. Although sea level rise on coastal areas of Turkey is not expected to be as high as the oceans, there will be consequences especially on low-lying areas and estuaries, which are also Turkey’s most productive agricultural areas, urban centers and tourism zones. Thus, a vulnerability assessment of coastal areas 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 the upcoming problems due to sea level rise.

There are many different levels of vulnerability assessments as mentioned in the previous chapters. They can be classified as strictly quantitative to semi-quantitative, non-adaptive to perfectly adaptive, science-driven to policy driven, simplistic to sophisticated, etc. (Füssel and Klein, 2006). Each assessment needs data with different levels of detail and accuracy. In Turkey, one of the main limitations of a vulnerability assessment, most probably, will be due to the lack of data for a particular region. Most of the available data belongs to major urban centers or there exists no data at all on some of the parameters. Thus, the aim of this thesis is to construct a vulnerability assessment model using the common available data, which gives a detailed result in terms of determining the most vulnerable regions in a country for optimum resource allocation. One example of a similar kind of vulnerability assessment is the United States Geological Survey's National Assessment of Coastal Vulnerability to Sea-Level Rise (Thieler and Hammar-Klose, 2000). They had used basic information on coastal geomorphology, rate of sea-level rise, past shoreline evolution, coastal slope, mean tidal range and mean wave height to assess the vulnerability of the coastline ranking different properties of the region and calculating a vulnerability index. This study yields numerical data that cannot be directly equated with particular physical effects. It does, however, highlight those regions where the various effects of sea level rise may be the greatest (Thieler and Hammar-Klose, 2000).

In this thesis, it was aimed to elaborate the USGS method to develop an advanced assessment method which;

- Assess the vulnerability of a region to sea level rise according to particular impacts such as erosion, inundation, flooding due to storm surges
- Assess the vulnerability of a region to saltwater intrusion to groundwater resources and river/estuary due to sea level rise
- Assess the effect of human activities on the coast affecting the vulnerability of the shoreline to physical impacts of sea level rise

by developing;

- Universal physical and socio-economic indicators which can be used throughout the world
- A weighting system for the parameters used
- An overall vulnerability index to compare the regions in a nation or world.

The important stages of the development of the final coastal vulnerability assessment model of sea level rise will be presented in next sections in detail.

3.1 Stage 1 – Development of physical and socioeconomic parameters

In order to develop a coastal vulnerability assessment to sea level rise method, using indicators for both physical and socioeconomic vulnerabilities; first, the physical impacts were studied.

The physical impacts of sea level rise on coastal areas were mentioned in previous chapters as;

a) Increased coastal erosion
b) Inundation
c) Increased flooding due to increased storm surge
d) Salinity intrusion to groundwater and estuaries
e) Rising water tables

In most vulnerability assessments, either some of the physical impacts were assumed (e.g., USGS National Assessment of Coastal Vulnerability to Sea Level Rise, 2000) or they were quantitatively assessed which needs high-resolution data (Kana et al., 1984). Within the scope of this study at first stage, it was aimed to evaluate the vulnerability of a region to all of the impacts mentioned above using minimum data (which are mostly available or collected easily). Thus, it was decided to use important parameters affecting the processes of physical impacts as indicators for the physical vulnerability of coastal areas.

3.1.1 Physical Impact Processes

Before defining the physical parameters, the processes of physical impacts with the corresponding parameters are explained in detail in order to understand the final set of physical parameters of physical impact processes, which are used in the coastal vulnerability assessment to sea level rise.

a. Coastal Erosion

One of the reasons of land loss due to sea level rise is the increased 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. Depending on different geomorphology types of coastal areas, the process of coastal erosion can be defined as follows:

Beaches. Coastal erosion on beaches mostly depends on wave and current action generated by winds. The movement of sediment can be offshore onshore and/or alongshore.

Offshore movement is dominated by the action of storm-generated waves that break higher up the beach profile and cut the beach face back depositing the sand offshore. After the storm, some of the transported sand moves back by smaller waves. The net amount of sand moved dictates the erosion or accretion rate.

Long shore sand transport occurs when waves approach the shore at an angle causing sand transport in the direction of alongshore component of wave energy. If sand budget is not balanced by other parameters, the movement of sand causes erosion and accretion on different parts of the shoreline.

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). The reasons for this are;

a. Higher water level will permit wave and current erosion processes to act further up on the beach by moving the breaking process further inland.
b. Deeper water level will decrease wave refraction, which increases the long shore transport capacity.
c. Higher water level could change the source of sediments. However, this could also act in a positive way if higher water levels begin to act on erodible land, which are presently untouched.

The best known and most widely applied model to estimate coastal erosion due to sea level rise has been developed by Bruun (Klein and Nicholls, 1998). 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. Other assumptions in his two dimensional analysis are stated in Coastal Engineering Manual (CEM, 2002) as follows;

- The upper beach erodes because of a landward translation of the profile.
- Sediment eroded from the upper beach is deposited immediately offshore; eroded and deposited volumes are equal meaning long shore transport is not a factor.
- The rise in the seafloor off shore is equal to the rise in sea level. Thus, on the offshore side, the water depth is constant.

Bruun Rule;

$$R = \frac{L_*}{B + d_*} S \qquad (3.1)$$

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

The Bruun rule can be expressed schematically as in Figure 3.1.

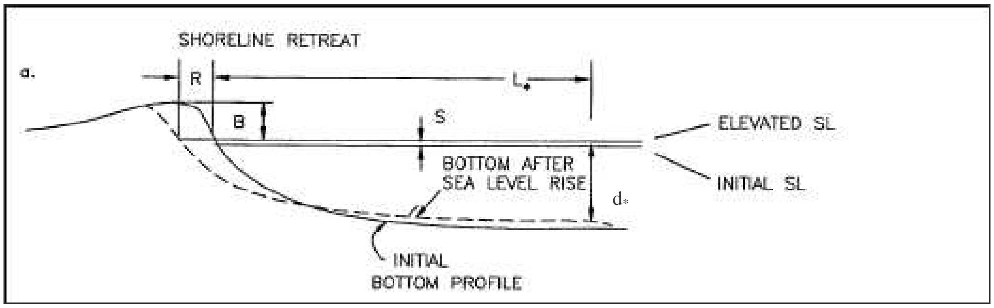


Figure 3.1 Shoreline response to sea level rise depicted by Bruun Rule. (CEM, 2002)

One of the strengths of the Bruun concept is that the equations are valid regardless of the shape of the profile (CEM, 2002).

Cliffs. Erosion on sea cliffs depends on the wave climate and rock type. As waves attack erodible headlands, steep sea cliffs are produced. The waves attack the portion of cliff near sea level, undermining the cliff face in turn causing a recession of the cliff. There may be beaches that protect the base of the cliff however; they can be removed by storms or erosion. Thus, the main parameter of erosion of cliffs is the composition of the cliff (other than wave climate) which may be extremely resistant rock which withstands the wave attacks for years or very loose material which can be cut back tens of feet when attacked during a single storm (Sorensen et al., 1984).

Estuary. The seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes is defined as estuary by Dalrymple, Zaitlin and Boyd (1992) in CEM, 2002. Three coastal forms may result depending on the balance between river input and marine sediment supply:

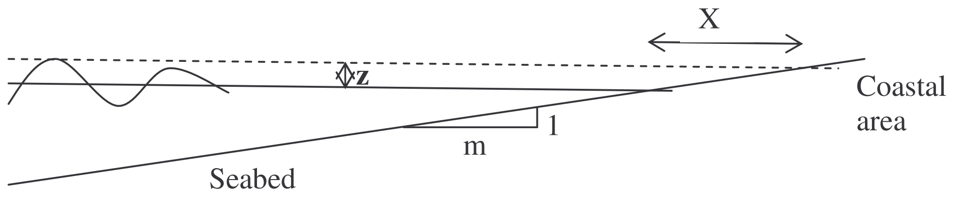
- Delta ; if river supplies more sediment and there is very little wave action
- Beaches, plains or tidal flats ; if most sediment is delivered by marine processes
- New Estuary; if sea level rises at a higher than sediment supply rate, the river valley may be flooded.

The sea level rise will accelerate the erosion through the processes explained in beach part mostly. However, as mentioned above, since most of the time estuary shorelines are exposed to milder wave action and consist of fine materials and very flat shore profiles, the greater land loss will be due to inundation (Sorensen et al., 1984).

Marshes, wetlands and reefs. Wetlands are areas where water covers the soil, or is present either at or near the surface of the soil all year or for varying periods of time during the year, including during the growing season. Marshes are defined as wetlands frequently or continually inundated with water, characterized by emergent soft-stemmed vegetation adapted to saturated soil conditions. (United States Environmental Protection Agency’s website, http://www.epa.gov/owow/wetlands/vital/what.html) Reefs are rock outcrops, detached from the shore, with maximum elevations below the high-water line (Howes et al, 1999). These shores 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 (described in beach part) for erosion or accretion of these shores.

b. 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 3.2). At the water line, typical beach profiles have slopes that can vary from 1:5 to 1:100, so 30 cm of sea level rise will move the shoreline from 1.5 m to 30 m inland (Sorensen et al., 1984).



Where z – rise in sea level
X – inundated distance
m – slope of the coastal area.

Figure 3.2 Inundation Definitions

c. 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 3.3 shows the storm surge-flooding concept schematically.

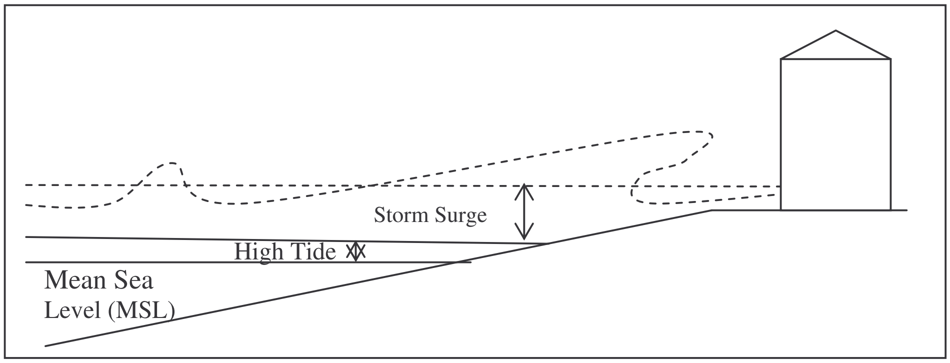


Figure 3.3 Storm surge process

The area of coastal flooding may extend along coast for over 100 kilometers, with water pushing several kilometers inland if the land is low lying. Figure 3.4 shows the different risk zones on any low-lying land where the risk zones are defined according to storm surge expected to occur in once a year (H_1), once in 10 years (H_{10}), once in 100 years (H_{100}) and once in 1000 years (H_{1000}).

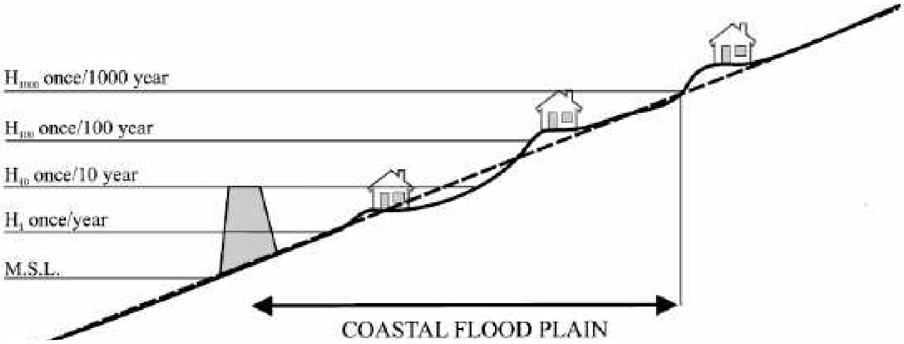


Figure 3.4 Different risk zones on low-lying coastal areas (Nicholls et al., 1999)

The impact of storm surge on any location depends on a mixture of the following parameters:

1. Intensity and path of storm
2. Width and slope of continental shelf
3. Wind and wave characteristics
4. Geometry of local and shelf features
5. Susceptibility of coastal features to dynamic change during storm

stated by Bode and Hardy, 1997.

A rise in sea level will increase the flood risk due to storm surges. It is expected that the coastal areas in danger of inundation will first experience increased flooding due to storm surges. Thus, sea level rise will move the risk zones upward and seaward. The magnitude of the raise in storm surges is usually taken as the amount of rise in sea level (Holman and Loveland, 2001).

Not just the flooding due to storm surge, but also high waters in bays caused by storm surges produce a backwater effect which in turn causes flooding in tidal rivers that drain into the bay or estuary. Because of heavy rains associated with storms, the backwater problem can cause extensive flood damage.

d. Rising groundwater tables

Sea level rise could affect the groundwater tables through raising the elevation of the table. The distance that water table can be affected depends mostly on elevation and subsurface permeability. Low-lying areas, especially deltas, can be affected significantly with effects occurring as far as several tens of kilometers inland. The rising of groundwater table has hazardous impacts on foundations, drainage systems and underground services as well as quality of the water in terms of salinity intrusion (Klein and Nicholls, 1998).

e. Salinity Intrusion

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.

i. Groundwater

In places where surface water is scarce, groundwater comprises the source of freshwater supply. Global warming and climate change in various ways affect groundwater resources. Excess rainfall or runoff, which cannot be stored or used, will accumulate in groundwater basins or oceans. Climate change may both increase and decrease the amount of rainfall in a region thus geographical distribution of rainfall may change and the recharge of aquifers will be affected.

To analyze the effect of climate change on groundwater, four resource categories is mentioned in Sherif and Singh, 1999 which were defined by Jacoby, 1990. One of these categories includes the coastal aquifers, which are subjected mostly saltwater intrusion.

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 3.5 (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).

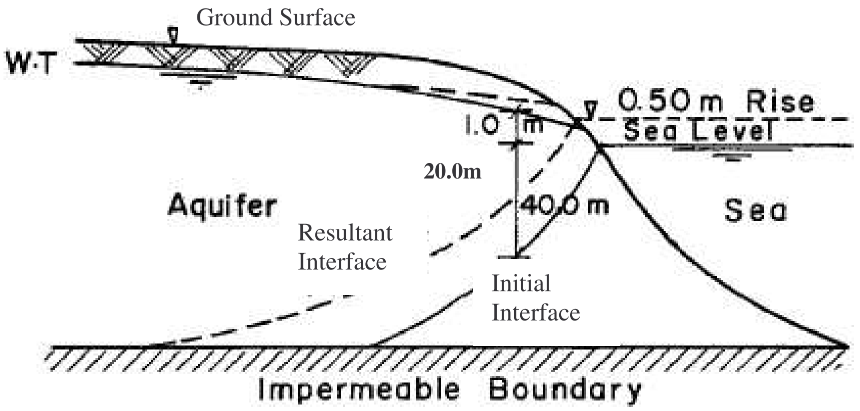


Figure 3.5 Sharp interface and sea level rise (Sherif and Singh, 1999)

The effect of saltwater intrusion is also more profound in locations away from the sea boundary where the water tables and/or piezometric heads are more affected by pumping and recharge activities than the increase or decrease in sea water level. The rate of sea level rise is sufficiently slow so that groundwater heads near or at the coast will increase in parallel. However, increase in the groundwater table near the sea boundary will not be associated with similar increase in groundwater levels at the landside. The gradient of water table and/or piezometric head will decrease and more intrusion will happen. Significant reduction of thickness of freshwater body will be encountered in land (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).

Quantitative prediction of the expected sea water intrusion to groundwater can only be evaluated by mathematical models, but these models need detailed accurate data thus for an initial study, the analytic model presented by Sherif and Singh, 1999 can be considered.

ii. Estuary/River

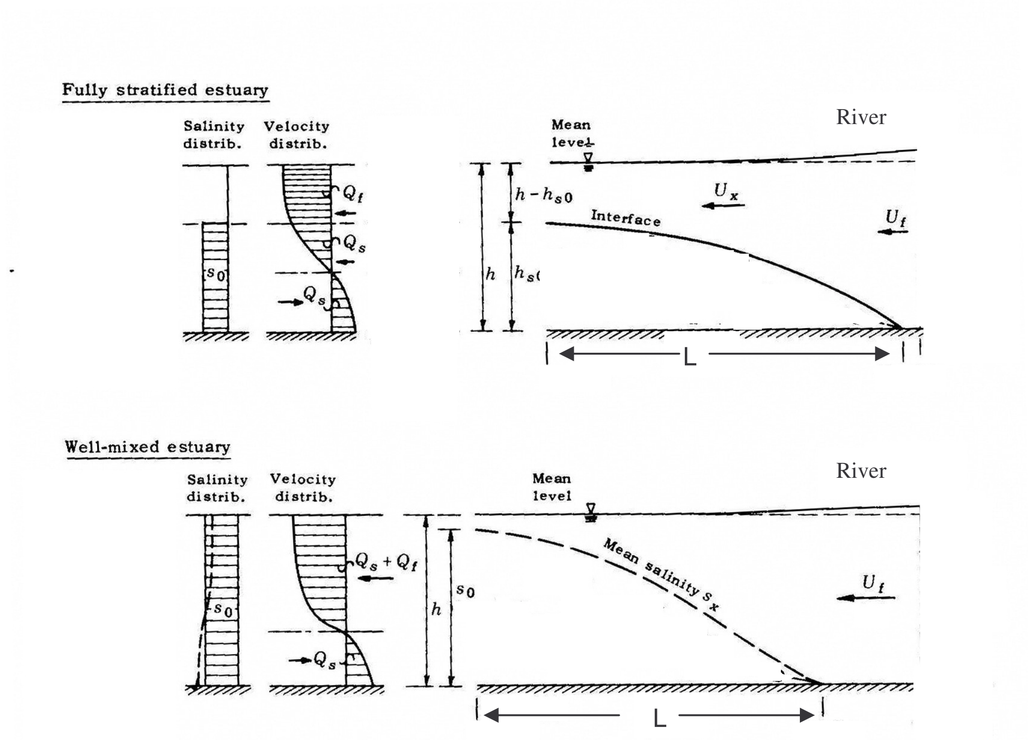
Estuary is the connection zone between river and sea. Circulation and exchange of fresh-saline water, substance even as sediment induced the complication of environment, ecological system and morphology of the estuary (Viet et al., 2006). Estuaries can be classified as

1. Wave-dominated, where wave energy acts more on the estuary than tidal influence
2. Tide-dominated estuary where tide current energy is greater than wave energy at the mouth of the river (CEM, 2002).

This affects the geomorphology of the estuary as well as the salinity intrusion process.

Two extreme cases presented in Figure 3.6 as an example, arise for salinity intrusions as a result of tidal action

1. <u>Fully stratified estuary:</u> minimal tidal action
2. <u>Well-mixed estuary:</u> intensive mixing produced by tidal currents



Q_s – salt water discharge
Q_f – fresh water discharge
s_0 – ocean salinity
s_x – mean salinity
h – depth of water
U_f – mean fresh water velocity
L – salt water intrusion length

Figure 3.6 Schematic representation of salinity intrusions in estuaries (Ippen, 1966)

In fully stratified estuaries, the intrusion of salt in a river communicating with a tide less sea is transpired by the motion upstream of a definable and limited saline layer underlying the fresh water that is called a saline wedge (Keulegan, 1966).

In well-mixed estuaries, the intrusion cannot be defined by a certain boundary (interface) but expressed by local mean salinity value over the salt intrusion length (L), averaged over a tidal period and over depth (Ippen, 1966).

The length of the saline interface whether saline wedge or mean salinity will be affected by sea level rise. As mentioned above, 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.

Quantitative prediction of the expected shift of saline interface can be evaluated accurately by using numerical models. However, the models require detailed data of the river/estuary thus analytical methods can be used for preliminary studies.

The following empirical relations are given in the literature for salt intrusion length (L);

$$L = 4.7\frac{h_0}{f}F_d^{-1}\left(\frac{-\pi Q_f}{1.08A_0 v_0}\right) \quad \text{tidal effect considered Rigter, 1973} \quad (3.2)$$

$$L = 6.0h_0\left(\frac{V_\Delta h_0}{\upsilon}\right)^{\frac{1}{4}}\left(\frac{2V_r}{V_\Delta}\right)^{\frac{-5}{2}} \quad \text{tide-less sea} \quad \text{Ippen, 1966} \quad (3.3)$$

Where h_0 = river depth at downstream

F_d = densimetric Froude number = $\frac{\rho v_0^2}{\Delta\rho g h_0}$

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

For a preliminary study, the parameters defining the length of saline interface can be used as parameters of vulnerability for salt-water intrusion in river/estuary due to sea level rise.

3.1.2 Parameters of the Physical Vulnerability Assessment

The processes of physical impacts of sea level rise are explained in detail in the previous chapter. Using the processes of the impacts, governing parameters of each impact were defined for the vulnerability assessment. Each parameter and the related impact are explained in detail in this section.

- Geomorphology: are the landform features of the region. This parameter is used to determine the relative erodibility of different landform types. Related Impacts: Coastal erosion, inundation, flooding due to storm surge and salt-water intrusion.
- Coastal slope: is slope of the regional coastal region 50km landward and seaward. It is used to determine the relative risk of inundation and potential rapidity of shoreline retreat.

  Related Impacts: Coastal erosion, inundation, flooding due to storm surge and salt-water intrusion.
- Significant wave height (m): is defined as average of the highest one-third of all storm waves in a wave record in meters. It is a statistical definition used to represent the wind waves.

  Related Impacts: Coastal erosion, flooding due to storm surge and salt-water intrusion.
- Historical shoreline change or shoreline erosion/accretion rate (m/year): is the rate of change of shoreline in meters in a year through the history

or as a mean value. It is used to determine the trend of shoreline generation in the region.

Related Impacts: Coastal erosion and inundation.

- Mean tidal range (m): is the average difference of water level in meters between high tide and low tide. It is used to determine the vulnerability of the ecosystem and shoreline to inundation.

  Related Impacts: Coastal erosion, inundation, flooding due to storm surge and salt-water intrusion.
- Rate of sea level rise (mm/year): is the increase or decrease in annual mean water elevation over time as measured at tide gauge stations along the coast in mm/year. This parameter also reflects primarily regional to local isostatic or tectonic effects.

  Related Impacts: Coastal erosion, inundation, flooding due to storm surge, saltwater intrusion.
- Sediment supply: is used in order to determine the stability of coastline. The probable sources of sediments are as follows: major streams, small streams and gullies (a trench that was originally worn in the earth by running water and through which water often runs after rains), cliff erosion and slides and dunes alongshore and onshore movement of sand by wave actions, wind action, coral reefs. The probable reasons for decrease of sediment supply: coastal defense structures, sand extraction, damming rivers.

  Related Impacts: Coastal erosion, inundation and saltwater intrusion.
- Salinity Intrusion in Groundwater: The parameters are;
  - Proximity to coast (km): is the distance of groundwater to the coastline.
  - Type of aquifer: which are classified in three categories as unconfined, confined and semi confined.
  - Depth of water table (m): is the distance between the ground surface and the water table. The higher the water table, vulnerability increases.
  - Hydraulic conductivity: is defined as a soil property that describes the ease with which the soil pores permit water movement. It depends on the type of soil, porosity, and the configuration of the soil pores. In saturated soils, the hydraulic conductivity is represented as Ksat and in unsaturated soils; the hydraulic

  conductivity is represented as K. Soil type can be used for this value as well.
  - Porosity: is the ratio of void space to the bulk volume of soil containing that void space. Porosity can be expressed as a fraction or percentage of pore volume in a volume of soil.
- Salinity Intrusion in River/estuary:
  - Density difference: is given as the density differences between freshwater and saltwater or density ratio of difference between freshwater and saltwater to saltwater ratio. If this ratio is high, vulnerability increases.
  - River discharge (m^3/year): Discharge of river influences the freshwater input, if the river discharge decreases, the salinity intrusion increases as well.
  - Cross sectional area (m^2): is the area at the river mouth. When the area is small, the discharge of saltwater is small thus vulnerability decreases. When the area is large, the vulnerability increases since the discharge of saltwater is larger.
  - Vertical mixing of water or type of estuary: Estuaries are classified as mixed, partially mixed or stratified. Stratified estuary is more vulnerable due to saltwater wedge formed that can reach upstream.

Influence of each parameter on the corresponding impact might be suggested based on expert opinion is given in Table 3.1. The level of influence is scaled as high influence (3), moderate influence (2) and low influence (1). Zero is assigned when the parameter is not applicable to impact.

Table 3.1 Parameters of impacts and the level of influence

Impacts Parameters		Coastal Erosion	Inundation	Flooding due to storm surge	Saltwater intrusion
Geomorphology		3	3	1	3
Coastal Slope		3	3	3	3
Significant Wave Height		3	0	3	2
Historical shoreline change		3	2	2	0
Tide range		1	3	2	3
Rate of sea level rise		3	3	3	3
Sediment supply		3	2	0	3
Groundwater					
	Proximity to coast				3
	Porosity				3
	Type of aquifer				3
	Depth of water table				2
	Hydraulic resistance of aquifer				3
	Hydraulic conductivity				3
River/estuary					
	Density difference				2
	River discharge				3
	Cross sectional area				2
	Vertical mixing of water				3

0 – not applicable 1 - low influence 2 – moderate influence 3 – high influence

3.1.3 Social Vulnerability

Social vulnerability is the exposure of groups or individuals to stress because of social and environmental change, where stress refers to unexpected changes and disruption to livelihoods (Adger, 1998). Most of the time social vulnerability is described using individual characteristics of people (age, race, health, income, etc), it is partially the product of social inequalities, factors that influence or shape the susceptibility of various groups to harm and govern the ability to respond (Cutter et al., 2003).

The nature of vulnerability is fundamental in determining whether hazard exposure will translate into impacts or be mediated by the biophysical and/or human systems. At the same time, vulnerability as a potential state is difficult to assess due to the variety of determinants acting and interacting on different scales. Thus, it is necessary to use indicators that best represent the complex underlying process. Indicators are quantifiable constructs that are useful to summarize a complex reality in simple terms. Also with indicators, the complex reality can be compared across space and time (Vincent, 2004).

In order to assess the social vulnerability, following indicators can be used or defined. Most of the indicators are taken from works of Adger, 2004, Vincent, 204 and Cutter et al., 2003.

a. Economic wellbeing and stability

The relation between economic wellbeing and vulnerability is complex; however, poor societies mostly face greater risk since they tend to live in hazard-prone locations. Also most of the poor immigrants live in hastily constructed settlements, which do not have access to clean water or sanitation, which will increase the risk of diseases after flooding. At the national level, a lack of financial resources will adversely affect the country’s ability to recover. In addition, adaptation to climate change will need funding as well as research, which will also require budget. On the other hand, indicators of economic wellbeing should also capture the inequality of income within the society since any society with high average income, may contain very poor populations, which are vulnerable to impacts of climate change. So indicators of economic well being should represent the total wealth, its distribution and the opportunity of the national government of implement economic policies that enhances the wellbeing of the population.

b. Health and nutrition

People in poor health, and those who are undernourished, will be more vulnerable to impacts of extreme events, such as direct physical injury or food shortage or famine. Ill health can remove individuals from the economically active population, and the sick must be cared for either by the state or society. Illness is intimately linked with poverty in terms of both cause and effect. Indicators of health therefore must capture the processes via which illness undermines the ability of individuals and the state to cope with hazards, and the burden placed by illness on the population at large, including those who are not sick.

c. Education and Technology

The least educated will be most vulnerable members of society since they will be poorer and live in hazard prone areas as well as depend on climate sensitive economic activities in general. Most of the time, they do not participate in political actions thus their welfare may be a low priority for the government.

The capacity to adapt to climate change in an anticipatory manner will depend strongly on the availability of information relating to climate change, and on the ability of those undertaking adaptation to interpret this information. Adaptation will inevitably be associated with conflicts of interest in some instances, and literate, educated populations will be in a better position to negotiate equitable solutions to potential conflicts.

d. Physical infrastructure

The quality and situation of settlements, commercial infrastructure and elements of transport systems will determine their physical vulnerability to the immediate impacts of events such as rainfall extremes, coastal inundation and windstorms. Quality and density of roads and other transport routes (e.g. rivers) will influence the feasibility and efficacy of aid distribution programmes in response to disasters such as droughts, floods and famines. The quality of sanitation infrastructure and the availability of clean water are also indicative of overall physical infrastructure.

e. Demographic factors

Age is an important consideration as the elderly and very young ones are more vulnerable to hazards since they are depended on working age adults. Parents should take care of the children in terms of money and time and the elderly may have mobility concerns increasing the burden of care and lack of resilience.

Gender is another consideration since women can have a more difficult time during recovery than men due to sector specific employment, lower wages and family care responsibilities.

Population density influences vulnerability. Where it is high, vulnerability may increase through settlements in hazard prone areas or by stress on physical infrastructure such as sanitation systems. High population densities are also associated with increased risk of disease.

f. Dependence on agriculture

Agriculture is a very climate sensitive economic activity thus any climate change will have serious impact on societies depending on agriculture. This may take the form of small-scale farming in which people depend directly on agriculture for their own nutrition or agricultural exports that contribute significantly to GDP.

g. Natural resources and ecosystems

The capacity to adapt to climate change will depend to a large extent on the availability of natural resources, particularly water resources. Water availability will be determined by a combination of water from present-day precipitation or runoff and water from aquifers that have been recharged in past episodes of high rainfall.

Land that is not currently used for agriculture also has significant utility value, through processes such as runoff reduction, water purification and other “ecosystem products and services”. It is therefore in the long-term interests of societies to preserve existing ecosystems and help them adapt to climate change. Ecosystem stress and destruction can increase the physical vulnerability of settlements, as well as reducing the potential for people to exploit alternative food resources and livelihoods as part of the adaptation process.

3.1.4 Parameters for social vulnerability

Preliminary parameters of indicators of social vulnerability are defined below. However, these parameters are taken directly from the works of Adger, 2004, Vincent, 2004 and Cutter et al., 2003. After discussions with researchers from the Sociology Department, it is understood that most of these parameters are not practical thus; a study on developing indicators of social vulnerability was decided to be performed as further research. However, in order to complement the discussion of social vulnerability the suggested parameters are summarized below.

Economic well being:

- GDP per capita of the region with respect to the country : to indicate the overall wealth of the region
- GINI coefficient of the region: to indicate the inequality of incomes within the region.
- Seasonal unemployment rate: to indicate the weather sensitivity of the economy of the region.
- Urban and industrial living within the region: to indicate the stage of development of the region.

Health and Nutrition:

- Health expenditure per capita of the region: to indicate the adaptive capacity of the region in case of climate related hazard related diseases.
- Life expectancy at birth: to indicate the general health

Education and Technology:

- Education expenditure per capita of the region: to indicate the educational commitment
- Literacy rate (over 15 years old): to indicate the entitlement to information within the society

- R&D expenditure for the region: in terms of social and economic development as well as physical hazard reduction, to indicate the availability of technology for adaptation

Physical Infrastructure:

- Rural-urban migration rates: to indicate the poor quality housing
- Roads : to indicate the isolation of rural communities
- Population with access to sanitation: to indicate the quality of basic infrastructure
- Rural population without access to safe water: to indicate the quality of basic infrastructure

Demographic factors:

- Population within 100 Km of coastline: population at risk of any climate change impact
- Population density: to indicate the population at risk
- Female to male ratio: to indicate the population at risk
- Population over 50 and less than 10: to indicate the population at risk

Agriculture:

- Agricultural employees: to indicate dependence on agriculture
- Rural population: to indicate dependence on agriculture
- Agricultural area: to indicate dependence on agriculture

Natural resources and ecosystems:

- Protected land area: to indicate environmental stress
- Unpopulated land area: to indicate environmental stress
- Water resources per capita: to indicate the sustainability of water resources
- Groundwater use per capita: to indicate the sustainability of groundwater resources having effect on saltwater intrusion

How most of the indicators mentioned above influences the social vulnerability is presented in Table 3.2. (+/-) means that social vulnerability increases/decreases as the value of the parameter increases.

Table 3.2 Influences of parameters on social vulnerability

Indicator	Parameter	Social Vulnerability (+) increases or (-) decreases
Economic Wellbeing	1. GDP 2. GINI 3. Seasonal unemployment 4. Urbanization	High status (+/-) Low income or status (+)
Health and Nutrition	1. Health expenditure 2. Life expectancy	High (-)
Education and Technology	1. Education expenditure 2. Literacy rate 3. R&D expenditure	Highly educated (-)
Physical Infrastructure	1. Migration 2. Roads 3. Population with access to sanitation 4. Rural population without access to safe water	Extensive infrastructure (+/-)
Demographic factors	1. Coastal population 2. Population density 3. Female/male 4. Old/young	Gender: high ratio(+) Age: high ratio (+) Rapid growth (+)
Dependence on agriculture	1. Agricultural employee 2. Rural population 3. Agricultural area	Highly dependent (+)
Natural resources and ecosystems	1. Protected land areas 2. Unpopulated land areas 3. Water resources per capita 4. Groundwater use per capita	Resources highly used (+)

3.1.5 Combination of physical and social vulnerability

Combination of physical and social vulnerabilities can only determine the accurate level of vulnerability of a region. There are different methods that define the vulnerability of a region, which enables comparison between regions. Some assessments calculate a composite vulnerability index and some calculate output parameters related to human exposure to impacts mentioned above. In the later type of assessments, physical vulnerabilities are also thought as hazard exposure and social vulnerabilities as a way to define adaptive capacity since adaptive capacity and social vulnerability is inversely related (social vulnerability being high means that adaptive capacity is low and vice versa). In the first stage of the development of the vulnerability assessment, several output parameters are defined which show the combined impact of physical and social vulnerability of a region on the human livelihood. The output parameters and the relationships between the vulnerability parameters and indicators are shown in Figure 3.7.

This network of relationships show that any type of assessment concerning climate change and sea level rise is very complicated due to interwoven relationships of both physical and socioeconomic parameters. Most of these relations should be considered together in order to assess the most accurate vulnerability. However, this kind of in depth analysis needs both a larger amount of time as well as people from many other disciplines. Thus, as will be explained in the next chapter, a simplified model will be developed for vulnerability assessment of a region to sea level rise concerning only physical parameters and parameters of human influence on the physical impacts.

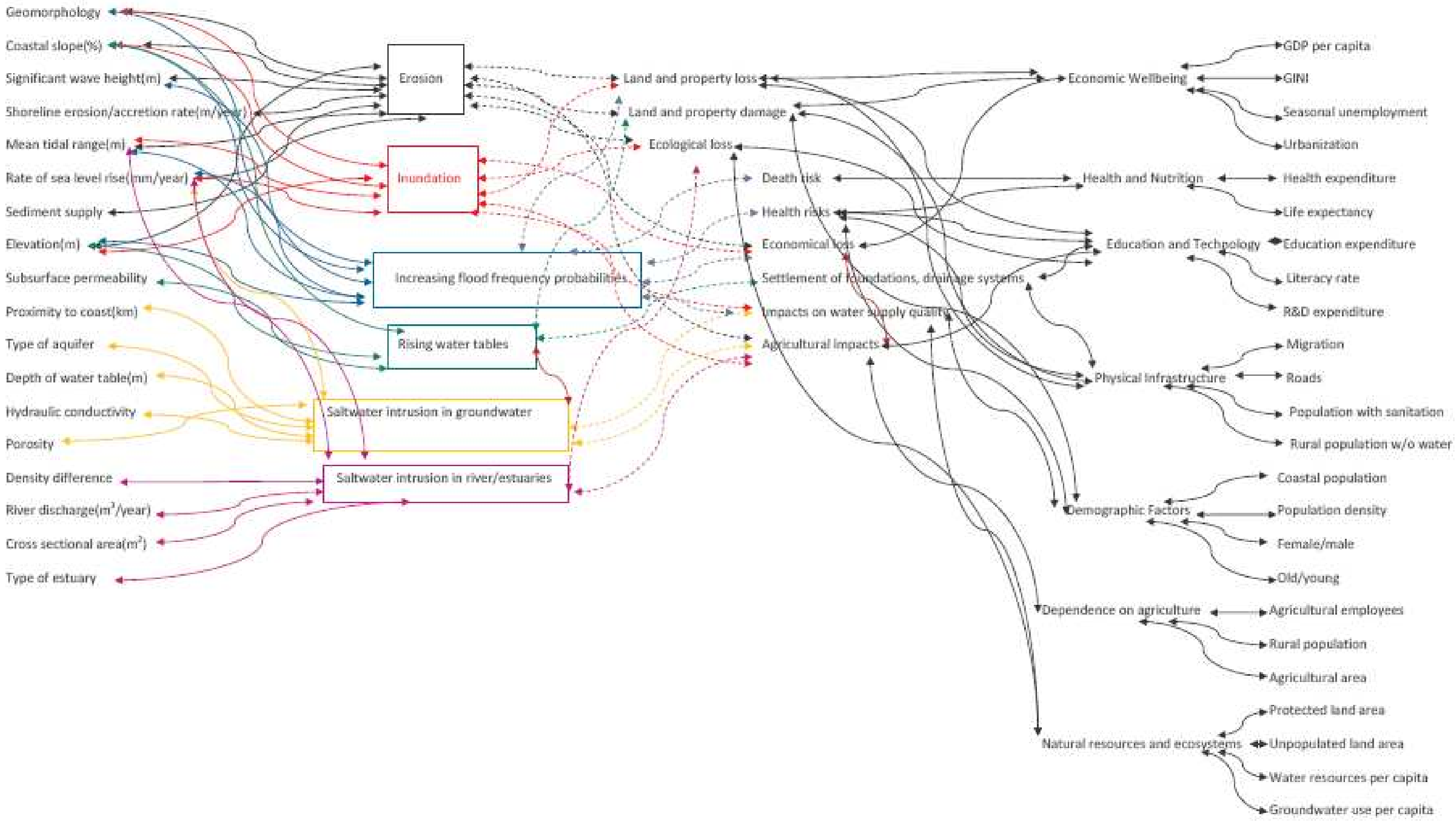


Figure 3.7 The developed network of vulnerability assessment parameters

3.2 Stage 2 – Redefining the parameters and developing a ranking system

At this stage, the physical parameters of vulnerability to sea level rise are redefined. Preliminary study of constructing vulnerability index is also presented.

3.2.1 Physical Parameters of Vulnerability to Sea Level Rise

The initial parameters for the vulnerability assessment of a region to sea level rise was discussed and defined in Stage 1. The initial network of parameters and indicators of the vulnerability assessment was given in Figure 3.7 as well. However, within the scope of this work as only coastal vulnerability assessment due to sea level rise is studied in detail. The impacts of sea level rise on coastal erosion, flooding due to storm surge, inundation and salt water intrusion is can be shown as given in Figure 3.8.

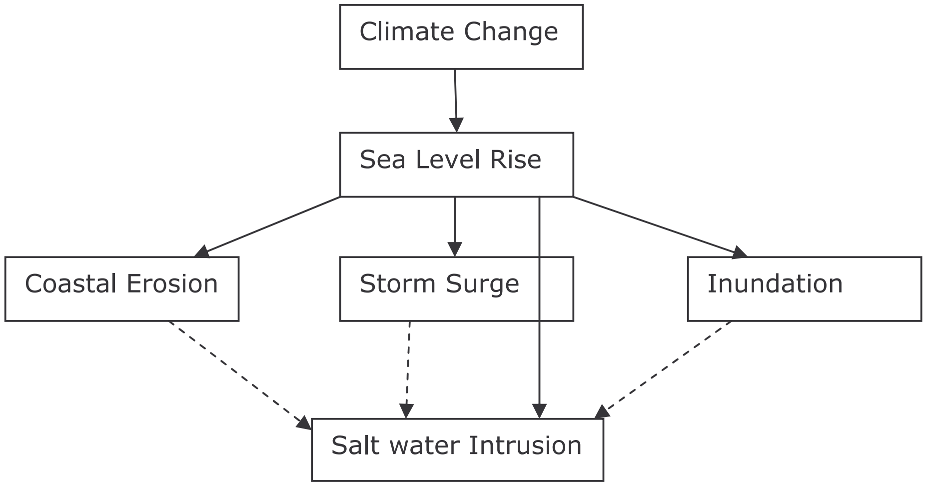


Figure 3.8 Relationships between the impacts of sea level rise

The physical parameters impacting coastal erosion, flooding due to storm surge, inundation and salt water intrusion are taken into consideration are given below:

1. Rate of sea level rise
2. Geomorphology

3. Coastal slope
4. Significant wave height
5. Sediment budget (+historical shoreline)
6. Tidal range
7. Proximity of aquifer to coast
8. Type of aquifer
9. Soil conditions of aquifer (hydraulic conductivity)
10. Depth to water table of aquifer
11. River discharge
12. Cross sectional area of estuary
13. Density ratio
14. Type of estuary

One of the decisions was taken about the parameters of saltwater intrusion to groundwater sources. Most of the parameters of this impact was related to soil conditions, thus for the sake of simplicity just one of these parameters is decided to be used in the assessment. The final soil condition parameter was decided to be hydraulic conductivity however in order to show that this parameter represents the soil condition, the parameter was named as soil condition.

Two other parameters, sediment budget and historical shoreline, was decided to be combined into one parameter named as sediment budget since sediment budget affects the equilibrium condition of the shoreline.

3.2.2 Social Vulnerability Parameters

Although initial indicators and corresponding proxies were defined in previous stage, the assessment of social vulnerability was decided to be within the content of future studies. Main reason for this decision is that in order to develop a global social vulnerability assessment method on sea level rise, it was understood that there is a need of extensive research as well as a collaborative interdisciplinary study with social departments such as sociology. This is mandatory in order to understand the social concepts and the interrelationships of the indicators mentioned in previous chapters. Also in order to determine the final proxies of the indicators, intensive data gathering as well as performing several surveys will be needed which all together will form a base for future studies.

3.2.3 Constructing Vulnerability Index: Preliminary Study

Within the scope of this thesis, it is aimed to develop a coastal vulnerability assessment model, which enables the decision makers to prioritize the regions according to their vulnerability to sea level rise. Also with this assessment, the type of impact, impact parameters that are affecting the region can be identified. Such knowledge will enable the decision makers to select the most appropriate adaptation measures for the region.

In order to establish a comparative methodology between different regions, it is decided to define vulnerability indices, which enable to rank or prioritize the impacts or vulnerabilities of regions. There are different methods of constructing indices as defined in Adger, 2004:

1. Constructing a single index by aggregating all relevant proxies
2. Constructing a single index by defining geographical groupings
3. Constructing separate indicators representing different elements of vulnerability
4. Vulnerability profiles.

The first method is a very “attractive” way of constructing vulnerability index since it enables to rank the regions and identify the “most vulnerable”. However, it tells nothing about the structure of causes of vulnerability (Adger, 2004).

Second method mentioned above uses a number of categories representing different levels of vulnerability such as low, intermediate and high. Data for each parameter is assigned to these categories and each category can be assigned a value such as 1 for low. Overall vulnerability can be calculated by aggregating these scores of each parameter.

Third method is a combination of first and second method for various categories of vulnerability parameters defined. Then different elements of vulnerability can be examined separately, which enables decision makers to concentrate on the areas of need to reduce vulnerability.

For the fourth method, depending on the number of proxies used, either the individual proxies or the indicators constructed from them could be presented for individual regions graphically in terms of vulnerability profiles. These profiles enable a quick assessment of a region's strengths and weaknesses in terms of the structural causes of vulnerability and tell us where to concentrate in terms of reduction and capacity building (Adger, 2004).

Whichever method is used to construct indices, there is a need of aggregation most of the time. When there is aggregation of parameters, the question of how this aggregation will be carried out should be answered which raises the question of weighting the parameters. There is not a rule that parameters should be assigned weights however not all parameters are equally important in every region or of each impact. Thus the method to assign weights for parameters (equal or not) is an important decision in the context of constructing indices.

In terms of weight assignment, different methods of assessment can be used from perception surveys to expert opinions to statistical methods. For the second stage of vulnerability assessment model study, as a preliminary study, the following tables (Table 3.3 and Table 3.4) are worked out to determine the importance of each impact.

In the first attempt, it was decided to assign weights to different impacts such as coastal erosion, inundation, salt-water intrusion and flooding due to storm surge as well to the governing parameters of these impacts in the order of influence based on expert opinion. Table 3.3 shows the weights of each parameter according to level of influence (which are defined as high influence (3), moderate influence (2), low influence (1) and not applicable (0)) on the process of impacts. Impacts if related to parameters are given 1 by assuming an equal importance based on expert opinion.

Table 3.3 Weights of parameters and the ranking of impacts of sea level rise (weights are considered for parameters only)

Impacts Parameters	Weight	Coastal Erosion	Sum	Flooding	Sum	Saltwater Intrusion	Sum	Inundation	Sum
Rate of SLR	3	1	3	1	3	1	3	1	3
Geomorphology	3	1	3	1	3		0	1	3
Coastal Slope	3	1	3	1	3		0	1	3
Storm characteristics	3	1	3	1	3		0		0
Proximity to coast	3		0		0	1	3		0
Type of aquifer	3		0		0	1	3		0
Soil conditions	3		0		0	1	3		0
River discharge	3		0		0	1	3		0
Cross sectional area of estuary	3		0		0	1	3		0
Sediment Budget	2	1	2		0		0		0
Tidal range	2	1	2	1	2		0	1	2
Depth to water table	2		0		0	1	2		0
density ratio	1		0		0	1	1		0
Type of estuary	1		0		0	1	1		0
TOTAL			**16**		**14**		**22**		**11**

Table 3.3 indicates that with the accepted weights of each parameter, impacts are ranked as saltwater intrusion (most important), coastal erosion, flooding due to storm surge and inundation (least important) in terms of importance.

Table 3.4 shows the weights of each parameter according to level of influence (which are defined as high influence (3), moderate influence (2), low influence (1) and not applicable (0)) on the process of impacts when the impacts are also assigned weights based on expert opinion such as 4 being the impact having the highest importance which will determine the level of vulnerability of the region and the next important impact given 3 and so on.

Table 3.4 indicates that with respect to the importance of each impact given as below, impacts are ranked as saltwater intrusion, coastal erosion, flooding due to storm surge and inundation in terms of importance.

Table 3.4 Weights of parameters and the ranking of impacts of sea level rise when weights are considered for both parameters and impacts

Impacts Parameters	Weight	Coastal Erosion	Sum	Flooding	Sum	Saltwater Intrusion	Sum	Inundation	Sum
Rate of SLR	3	4	12	2	6	3	9	1	3
Geomorphology	3	4	12	2	6		0	1	3
Coastal Slope	3	4	12	2	6		0	1	3
Storm characteristics	3	4	12	2	6		0		0
Proximity to coast	3		0		0	3	9		0
Type of aquifer	3		0		0	3	9		0
Soil conditions	3		0		0	3	9		0
River discharge	3		0		0	3	9		0
Cross sectional area of estuary	3		0		0	3	9		0
Sediment Budget	2	4	8		0		0		0
Tidal range	2	4	8	2	4		0	1	2
Depth to water table	2		0		0	3	6		0
density ratio	1		0		0	3	3		0
Type of estuary	1		0		0	3	3		0
TOTAL			**64**		**28**		**66**		**11**

As can be seen from the previous tables, the ranking of the importance of each impact was assumed as coastal erosion, saltwater intrusion, flooding and inundation initially using engineering judgment based on expert opinion. It must be emphasized that both tables take aggregate of all parameters of saltwater intrusion whether there is groundwater and/or estuary is present or not. However since both tables are designed for the most critical case meaning all the parameters are present in the region of impact, above tables could be used as preliminary guidelines.

Although the outcome of the tables indicates that the ranking of impacts might change according to the weights given to both parameters and the impacts, it should be noted that coastal erosion and saltwater intrusion are always more important than the other two impacts as a result. In addition, overall importance determined by the total values is close to each other when coastal erosion and saltwater intrusion is considered.

Another issue emerged from the above preliminary work of ranking of impacts of sea level rise. It was seen that actually the saltwater intrusion is affected by coastal erosion, flooding and inundation indirectly as well as direct effect of sea level rise. For example as the shoreline erodes, proximity of groundwater to coast decreases influencing the saltwater intrusion, or flooding itself causes excess saltwater intrusion from time to time. Coastal erosion, flooding due to storm surge and inundation also affects the physical process of each other as well, mostly it is indirect and the time span of each impact is very different. In the end, because the interrelations of the impacts with each other will complicate the already complex situation, the impacts will be considered independent of each other having an equal weight that is 1.

3.3 Stage 3 – Finalization of Physical Parameters and Ranges

At this stage, the selected physical parameters and the corresponding ranges for the vulnerability are determined based on several other vulnerability studies.

When developing a vulnerability assessment model, it is important to use adequate parameters in order to grasp the most realistic outcome for a region. However this is usually hard to achieve since there are many parameters needed to be considered in terms of physical processes but most of the time either there is lack of available data of the parameters and gathering the data needs a significant amount of budget or too many parameters complicate the assessment needlessly especially when the aim is only to point out the major vulnerability issues. Always there is the possibility of doing an in depth research on any of the impacts mentioned in this thesis if there is time, money and people however most of the decision makers like to allocate money on the most important, persisting subjects thus they would like to have a preliminary study which ranks or prioritize many of the problems in a simple way. In the light of this consideration, it was decided that 12 parameters would be appropriate without reducing the quality of the assessment. These parameters are presented below in detail with the corresponding range values, which will affect the region assigned as very low vulnerability (1) to very high vulnerability (5).

1. Rate of sea level rise: This parameter shows the present sea level change of the region using the historical data of relative sea level change. Using relative sea level change data enables us to use the aggregated value of eustatic sea level rise as well as local isostatic and tectonic land motion. This is important since any submergence of land will accelerate the impact of global sea level rise even if the rate of global sea level rise

is low when seas are considered. On the other hand, any uplift of land will increase the resistance of the region to sea level rise. Rate of sea level rise is ranked to reflect the present rate of sea level rise according to the projected rising levels within 100 years. The best projections expect a rise of 9 cm in 100years while the worst-case scenario indicates a rise of 88 cm by 2100 (IPCC, 2001). Thus if the rate of sea level rise is less than 1 mm/year a very low vulnerability is assigned as (1).

Ranges: <1 mm/year (1); 1-2 mm/year (2); 2-5 mm/year (3); 5-7 mm/year (4); and 7-9 mm/year and over (5)

2. Geomorphology: This parameter expresses the landform of the region, which indicates the erodibility of region in terms of different landform types. The importance of this parameter is self-explanatory as the correspondence of different type of landforms to both erosion and flooding are explained in detail in the previous chapters. Geomorphology is ranked according to the relative resistance of a given landform to erosion. The ranges are taken from the vulnerability assessment of US coasts by Thieler and Hammar-Klose, 2000. The definition of each landform is given in Appendix A.

   Ranges: Rocky cliffs and fiords (1); medium cliffs and indented coasts (2); low cliffs, glacial drift and alluvial plains (3); cobble beaches, estuary and lagoon(4); barrier beach, sand beach, salt marsh, mudflats, deltas, mangroves and coral reefs (5)

3. Coastal slope: This parameter permits an evaluation of not only the relative risk of inundation as explained in previous chapters as well as the potential rapidity of shoreline retreat since low-sloping coastal regions should retreat faster than steeper regions. Coastal slope ranges are ranked from lowest to highest indicating most vulnerable to least vulnerable. The ranges are assigned using the general scale of the coasts around the world (Woodroffe, 2002).

   Ranges: >1/10 (1); 1/10 – 1/20 (2); 1/20 – 1/30 (3); 1/30 – 1/50 (4); 1-50 – 1/100 (5)

4. Significant wave height: This parameter is used as an indicator of wave energy, which drives the coastal sediment budget (USGS, 2000), as well as the main parameter of storm surges causing flooding. In terms of erosion, wave energy increases as the square of wave height in where the mobilization and transportation of beach/coastal materials is a function of it. When storm surges are concerned, one of the main parameters

effecting wave set-up is the breaker height, which also depends on the storm wave height, which is decided to be represented by significant wave height. Significant wave height ranges are ranked from lowest to highest indicating most vulnerable to least vulnerable since the parameter is used to represent the wave energy. The ranges are assigned to define the wave climate of Turkey, which can be applicable throughout the world (Ergin and Özhan, 1986).

Ranges: <0.5 m (1); 0.5-3.0 m (2); 3.0-6.0 m (3); 6.0-8.0 m (4); >8.0 m (5)

5. Sediment budget: As mentioned in the previous stage, this parameter is used to indicate the overall trend of the shoreline whether it is stable or eroding or accreting. Since it is explained in the coastal erosion process, the sea level rise will accelerate the erosion in already eroding shorelines and will initiate erosion in accreting shorelines thus it is important to determine the present state of shoreline in order to define the vulnerability level. Sediment budget ranges defines stable shorelines being moderately vulnerable while highly eroding as most and highly accreting as least vulnerable. The ranges are influenced by shoreline evolution trend status parameter of indicator-based methodology of Europe in terms of coastal erosion by Eurosion project, 2004.

   Ranges: More than %50 of the shoreline is in accretion (1); between %10-30 of the shoreline is in accretion (2); less than %10 of the shoreline is in accretion or erosion (3); between %10-30 of the shoreline is in erosion (4); more than %50 of the shoreline is in erosion (5)

6. Tidal range: This parameter is linked to both permanent and episodic inundation hazards (USGS, 2000) such as flooding due to storm surge as well as salinity intrusion in estuaries and rivers. Tidal range parameter ranges are influenced by USGS National Vulnerability Assessment of US Coasts, 2000 methodology. They had assigned high vulnerability to low tidal range stating that their reasoning is based primarily on the potential influence of storms on coastal evolution and their impact relative to the tidal range such as on a micro tidal coastline, coastline is essentially always near high tide and therefore always at the greatest risk of significant storm impact.

   Ranges: >6.0 m (1); 4.0-6.0 m (2); 2.0-4.0 m (3); 0.5-2.0 m (4); <0.5 m (5)

7. Proximity to coast: This parameter is linked to salt-water intrusion to groundwater resources. The impact of salt-water intrusion generally decreases as one move inland at right angles to the shore (Chachadi et al., 2003).
   Ranges: >1000 m (1); 700-1000 m (2); 400-700 m (3); 100-400 m (4); <100 m (5)
8. Type of aquifer: In nature, groundwater generally is accumulated between geological layers, which can be confined, unconfined or leaky confined which influences salt-water intrusion process. The basic nature of groundwater occurrence has an influence on the extent of seawater intrusion. Unconfined aquifer under natural conditions will be more affected by seawater intrusion as compared with a confined aquifer as the confined aquifer is at a pressure higher than atmospheric pressure (Chachadi et al., 2003).
   Ranges: leaky confined (1); confined (3); unconfined (5)
9. Aquifer hydraulic conductivity: In previous stages, the parameters determining the effect of soil conditions were defined as one parameter named soil condition. The parameter to define the most important soil condition is determined to be hydraulic conductivity of aquifer depending on the studies on saltwater intrusion to groundwater since this parameter is used to measure the rate of flow of water in the aquifer. Hydraulic conductivity is the result of interconnected pores in the sediments or fractures in consolidated rocks. The magnitude of seawater front movement is influenced by hydraulic conductivity thus the higher the conductivity, higher the inland movements of seawater front (Chachadi et al., 2003).
   Ranges: 0-12 m/day (1); 12-28 m/day (2); 28-41 m/day (3); 41-81 m/day (4); >81 m/day (5)
10. Depth to groundwater level above sea: This parameter determines the hydraulic pressure availability to push the seawater front back. Thus the higher the groundwater level, lowest the vulnerability to salt-water intrusion (Chachadi et al., 2003).
    Ranges: >2.00 m (1); 1.25-2.0 m (2); 0.75-1.25 m (3); 0.0-0.75 m (4); <0.00 m (5)

The ranges for parameters of saltwater intrusion to groundwater (proximity to coast, type of aquifer, hydraulic conductivity and depth to groundwater level above sea) are modified from Chachadi et al., 2003 where some of the ranges are taken from Aller et al., 1987. Their work assesses the impact of sea level rise on salt-water intrusion in coastal aquifers using more parameters and a scale of 10. Most vulnerability assessments of groundwater are on pollution of groundwater (e.g., Gemitzi et al., 2006, Gogu and Dassargues, 2000) which use some of the parameters given in Chachadi et al., 2003 with similar values of ranges.

11. River discharge: This parameter determines the turbulent energy for vertical mixing. Increasing river discharge increases the amount of turbulent energy since fresh water velocity increases. Thus saltwater intrusion decreases with increasing river discharge (Bashar and Hossain, 2006).
    Ranges: >500 m^3/s (1); 250-500 m^3/s (2); 150-250 m^3/s (3); 50-150 m^3/s (4); 0-50 m^3/s (5)
12. Water depth at the downstream: This parameter determines the fresh water velocity at the downstream as well as river discharge. Increasing water depth decreases fresh water velocity at downstream. Thus saltwater intrusion increases with increasing water depth. Since sea level rise will increase the water depth at the downstream, the intrusion length will also increase and the effect of salinity intrusion will be present further inland.
    Ranges: <1 m (1); 1-2 m (2); 2-3 m (3); 3-5 m (4); >5 m (5)

For the saltwater intrusion in rivers/estuary parameters, there is not much work on vulnerability assessments of rivers/estuary related to saltwater intrusion due to sea level rise although main parameters can be defined from the salt-water intrusion process itself.

The formulas 3.2 and 3.3 (given in explanation of salt-water intrusion to river/estuary process) indicate that river discharge and water depth at the downstream of river are important parameters as also stated by Savenije, 1993. Although there are other parameters such as density and bed roughness that influence the salinity intrusion length, it is decided that they will be included in further studies since there are not enough data or research to develop ranges for the vulnerability assessment model.

River discharge of dry season is taken as one of the parameters since most critical case occurs when the river flow is minimum during which river velocity decreases enabling salt-water intrusion to further inland. The ranges for flow rate are worked out from mean monthly discharge data of 1000 stations on various rivers around the world. The distribution of this data is shown in Figure 3.9. Using distribution given in Figure 3.9 discharge values are selected as $Q \geq 500$ m^3/s, 250 m^3/s $\leq Q < 500$ m^3/s, 150 m^3/s $\leq Q < 250$ m^3/s, 50 m^3/s $\leq Q < 150$ m^3/s and < 50 m^3/s for vulnerability ranges from 1 to 5 respectively in order to represent rivers all around the world.

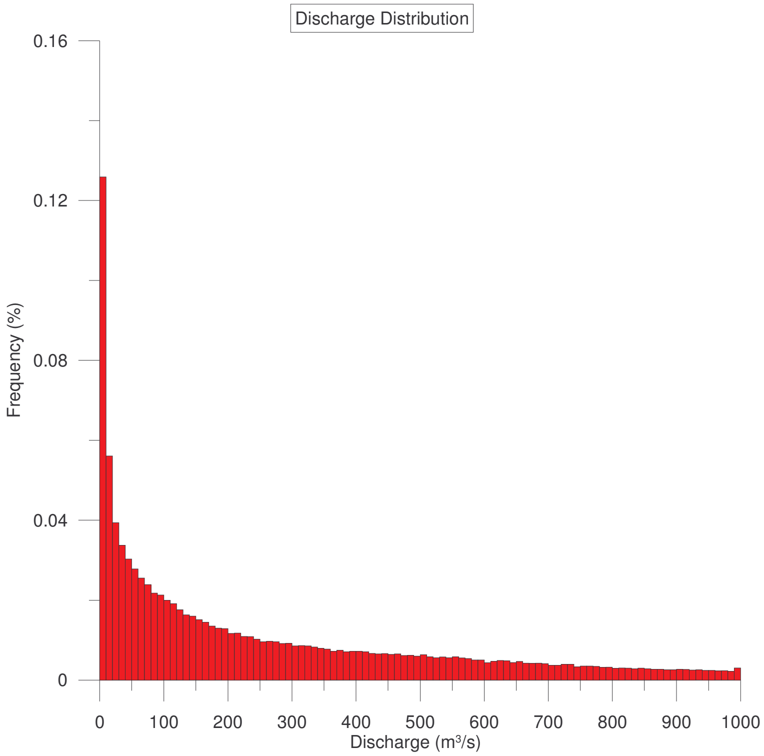


Figure 3.9 Distribution of mean monthly discharges of various rivers around the world

Water depth is the other parameter to be used for vulnerability assessment model since fresh water velocity decreases also with increasing water depth at the downstream (Bashar and Hossain, 2006). In addition, as can be seen from the equations 3.2 and 3.3, the salinity intrusion length is related to water depth on a level of h^3. This also shows that salinity intrusion length is very sensitive to differences in water depth at the downstream.

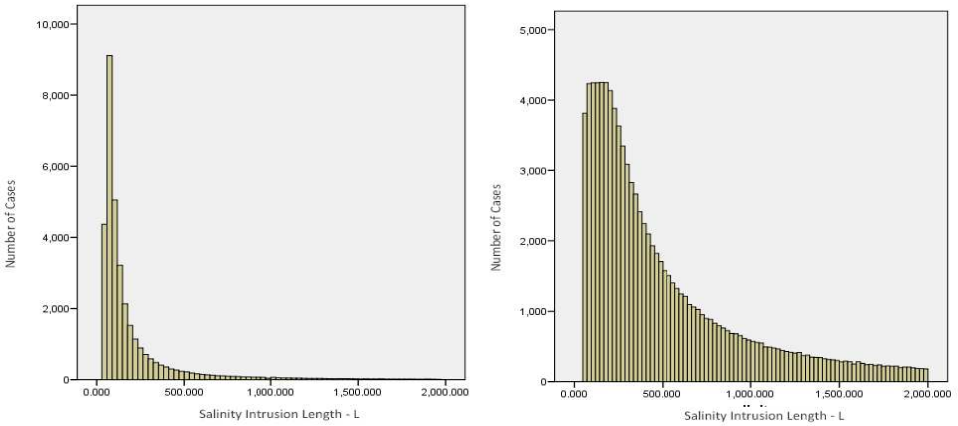
To determine the ranges for water depth of a river at the downstream, Equation 3.2 is solved for random values of parameters by defining constant values for some of the variables and ranges for other variables of the salinity intrusion length equation. As a result, a database of salt-water intrusion lengths with respect to various cases was developed.

As mentioned previously, the lack of data restricted this part of the study thus in order to simplify the procedure, the density parameters were decided to be taken as constant such that the fresh water and salt-water densities are taken as 1000 kg/m^3 and 1025 kg/m^3 respectively. The tidal range is also taken as constant with a value of 0.2 m representing the coasts of Turkey. The other parameters were given different values within the ranges defined which are also believed to represent the rivers of Turkey as;

- Water depth (h): 1 -10 m;
- Discharge (Q): 0-500 m^3/s using Figure 3.9;
- Darchy-Weisbach number (f): 0.01-0.1;
- Width (B): 5-500 m.

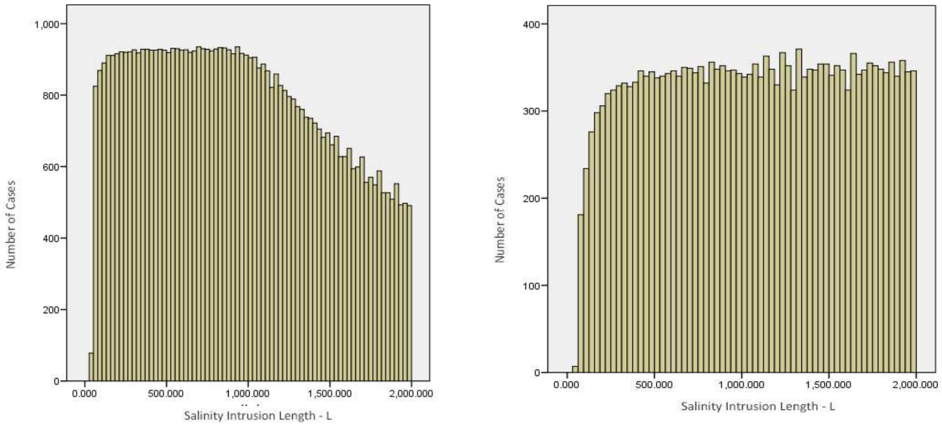
The initial database included 1200000 different joint probability cases of salt-water intrusion length using the values and ranges of parameters defined above. After eliminating the extreme and unrealistic cases, the final database included 285000 cases, which is used to group the distribution of salinity intrusion lengths according to water depth. Histograms of salinity intrusion length (L) for water depth at the downstream h_0 = 1 m, 2 m, 3 m, 4 m, 5 m and more than 5 meters are given in Figure 3.10.

Based on the shapes of the histograms given in Figure 3.10, the water depth values (h_0) are selected as $h_0 \leq 1$ m, h_0 = 2 m, h_0 = 3 m, h_0 = 4-5 m, $h_0 > 5$ m for vulnerability ranging from 1 to 5 respectively.



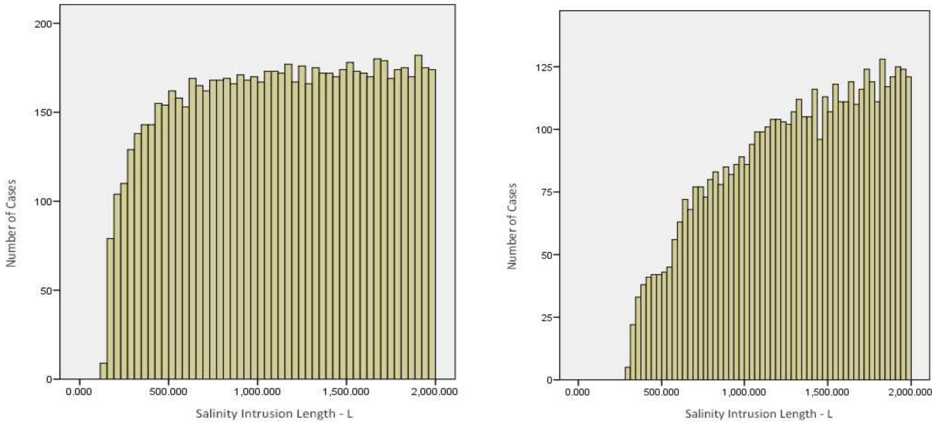
Depth (h) = 1 m

Depth (h) = 2 m



Depth (h) = 3 m

Depth (h) = 4 m



Depth (h) = 5 m

Depth (h) > 5 m

Figure 3.10 Distributions of salinity intrusion lengths with respect to water depth at the downstream.

Table 3.5 shows the parameters defined above ranked on a linear scale from 1 to 5 in order of increasing vulnerability due to sea level rise. This database includes both quantitative and qualitative information thus, numerical variables are assigned a risk ranking based on data value ranges where as non-numerical variables are ranked according to relative resistance to sea level rise.

Table 3.5 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

3.4 Stage 4 – Human Influence on Coastal Areas

The impacts triggered by sea level rise can also be significantly present in most coastal areas although the rate of sea level rise is very low. What will happen is that both the frequency and magnitude of impacts will increase as a result of sea level rise. Therefore, 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 to sea level rise. For example, in the natural state, a region may be moderately vulnerable however due to impacts of human activities such as a harbor construction, the vulnerability of the region may increase to high vulnerability because the existence of the harbor which triggers erosion at the down drift of the harbor.

In order to assess the vulnerability due to human activities, the impacts of sea level rise and how human activities initiate these impacts is considered for vulnerability assessment model.

Coastal erosion as explained in detail in previous chapters is determined by sediment budget deficit. Natural cause of sediment loss is mostly due to wave action. However, 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 et al., 2003). Dams also eliminate peak flood discharges, which is responsible for flushing lower reaches of rivers and transporting most sediment to coast (Morton, 2003).

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 neighboring regions. For example, at the down drift of shore-normal structures, there always starts erosion if any other protection measure is not implemented. Structures parallel to coast such as seawalls initiate the erosion of land in front of the structure and in times, whole land is lost in front of the structure if no other measure is put in practice.

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. If no adaptation measures are taken, these structures will lose their efficiency and accordingly the vulnerability of the region will be increased.

Recent trend is to use soft measures for controlling coastal erosion. These can be reinforcing natural buffers against the rising tides such as dunes and salt marshes and the protection of key sources of sediment which help maintaining coastal sediment balance and the stability of coastal systems (EEA, 2005). Since soft measures do not interfere with the natural process, they do not increase the vulnerability of adjacent coastal areas rather they show a way to improve their resilience. Nevertheless, this type of improvement will depend on the economy since some of these measures need a significant amount of budget.

Coastal excavation causes the most rapid and direct conversion of land to open water. This is used to dredge marinas, open pipeline trenches, create or enlarge navigation channels and construct water front developments and channels. Newly created channels intercept currents and redirect flow altering the hydrodynamics of coastal water bodies and sediment dispersal patterns. In turn these modifications can initiate or accelerate land loss by locally enhancing erosive forces, increasing water levels, and decreasing sediment supply. Long jetties protecting the channels can compartmentalize the coast disrupting the flow of littoral drift and preventing the exchange of sand between adjacent coastal compartments.

Mining sand on the inner continental shelf for beach restoration can cause additional land losses by altering wave refraction patterns and concentrating wave energy on the beach as a result of the depression created. Beach erosion has accelerated at several sites as a result of beach replenishment projects that dredged sand from the nearby continental shelf (Morton, 2003).

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. Another impact of over pumping on deltaic aquifers is the rapid submergence of plain related to decomposition of organic matter and compaction of fine-grained material accompanied by sedimentary deformation (Kapsinalis, 2005). Thus, human induced subsidence will increase the impact of climate change induced sea level rise significantly. 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.

As mentioned above, land use and urbanization directly influences the vulnerability of coastal area increasing the human pressure on natural system. Humans consuming the natural resources unconsciously increase the negative impacts of sea level rise significantly. Thus, the coastal area being protected or used as agricultural land or settlement should be included in the assessment. Although natural areas are thought to be more vulnerable to the sea level rise due to having less adaptive capacity, they are also less vulnerable because they do not experience the additional pressures of human activities.

3.4.1 – Parameters of Human influence on coastal areas

In order to assess the vulnerability of coastal areas to sea level rise due to human pressures, the following parameters with corresponding ranges from least vulnerable (1) to most vulnerable (5) are decided to be used in the vulnerability assessment model.

1. Reduction of sediment supply: this parameter shows the ratio of present sediment supply to the region to the natural state sediment supply. This includes the sediment trapped in dams or reservoirs at the upstream of the river and excavation of coastal zone for various reasons mentioned in previous section. The ranges are given as >%80 (1), %60-80 (2) , %40-60 (3), %20-40 (4) and <%20 (5) from least vulnerable to most based EUROSION study aimed to assess regional indicators for coastal erosion and flooding (EUROSION, 2004).
2. River flow regulation: this parameter shows the amount of impact of any regulative structure on rivers at the down drift in terms of flow rate. As stated before, the peak flows help to flush the sediment to the mouth of the river as well as decrease the salinity intrusion balancing the tidal motion. The three ranges are stated as strongly affected, moderately affected and not affected based on the study done by Nilsson et al., 2005 using their methodology for flow regulation index. Nilsson et al., 2005 determine the flow regulation as the sum of reservoir capacity within a river system and expressed this measure as the percentage of the river systems volumetric annual discharge that can be contained and released by the reservoirs (live capacity). If no data is present for live storage of the reservoir, one-half of the gross capacity was used. They have also considered fragmentation as an important parameter having an impact on

the river system. The fragmentation is ranked into five classes describing the longest portion of main channel left without dams in relation to the entire main channel (0=%100, 1=75-99%, 2=50-74%, 3=25-49% and 4=0-24%). For tributaries, fragmentation is described by three classes (0=no dams, 1=dams only in the minor tributaries and 2=dams in the largest tributary). The overall regulation impact on river can be read from Table 3.6 given below.

Table 3.6 Overall flow regulation impact combining fragmentation and flow regulation (Nilsson et al., 2005)

Fragmentation Main channel and Tributaries	Flow Regulation (%)		
	Not Affected (1)	Moderately Affected (3)	Strongly Affected (5)
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

3. Engineered frontage: this parameter shows the percentage of shoreline the coastal structures occupies. Engineered frontage includes harbors, marinas, jetties and navigation channels that do not have any purpose of protection of shoreline at all as well as coastal protection structures, which have adverse effects at the adjacent shorelines. If this parameter is high, this indicates that there is a past or present erosion problem or flood risk which will be increased by sea level rise putting more pressure on the neighboring coastlines especially soft rock or sediment coast. The ranges are given as <%5 (1), %5-20 (2), %20-30 (3), %30-50 (4) and >%50 (5) based on the EUROSION study mentioned above. However, these ranges will need further refinement as the assessment is used for many regions, as also stated in the methodology report of EUROSION study (2004).

4. Groundwater consumption: this parameter indicates the ratio of annual groundwater use to annual available groundwater. In many areas, groundwater abstraction exceeds the recharging rates thus the aquifer becomes over exploited leading to saltwater intrusion on coastal aquifers. The ranges for groundwater consumption are based on UNDP's sustainability indicators (2003). They are revised as <%20 (1), %20-30 (2), %30-40 (3), %40-50 (4) and >%50 (5) from least vulnerable to most vulnerable.

5. Land use pattern: this parameter is another parameter to indicate the pressure on groundwater use. Throughout the world, agricultural activities are the main pressure on use of water resources. Thus if the coastal area is mainly used for agriculture then the area is more vulnerable to impacts due to sea level rise due to overexploitation of water resources which are driving forces for sediment budget and saltwater intrusion. Industry and domestic use are the next important land use types since they also require massive water resources. If the area is protected or wetland, than the area is less vulnerable to sea level rise impacts since human pressures are minimized through laws. Thus the ranges for this parameter is defined as protected area (1), unclaimed(2), settlements(3), industrial area (4) and agricultural area (5) based on global water use statistics and expert opinion from very low vulnerability to very high.

6. Natural protection degradation: this parameter shows the status of natural protection (such as dunes and marshes and wetlands) along the coast. If the natural protection system is healthy, then the resilience of the area to sea level rise is high. For example, dunes act as both sediment supply against erosion as well as a barrier to inundation. If there is sand extraction from these dunes, although naturally the area may be resilient, this resilience decreases significantly due to human activity. The ranges for this parameter is given as ratio of the naturally protected area of present status to past as >%80 (1), %60-80 (2), %40-60 (3), %40-20 (4) and <%20 (5).

7. Coastal protection structures: this indicator shows the percentage of shoreline the coastal protection structures such as groins, seawalls etc.,

occupy. As previously mentioned, the coastal protection structures increase the resilience of the region if properly designed and adapted to sea level rise scenarios. Since they are used to protect coastal areas against erosion, inundation and flooding due to storm surge that are also the expected impacts of sea level rise, having these protection measures will enable the region to be protected for much longer duration than other regions. The ranges are defined as >%50 (1), %30-50 (2), %20-30 (3), %5-20 (4) and <%5 (5) from least vulnerable to most vulnerable.

Table 3.7 shows the parameter of human influence on coastal regions, which trigger the impacts of sea level rise and the corresponding ranges.

Table 3.7 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

3.5 Coastal Vulnerability Index for Sea Level Rise – CVI (SLR)

The vulnerability assessment model aims to;

a. Compare different regions and rank them according to their vulnerabilities to sea level rise
b. Prioritize the impacts of sea level rise on the region according to the vulnerability of the region to each impact
c. Determine which parameters are the most vulnerable parameters that need to be considered when planning for adaptation to sea level rise.

In order to fulfill the aims mentioned above a coastal vulnerability index - CVI (SLR) is developed which will enable the decision makers to compare different regions together with five sub-indices showing the vulnerability level of the region for each particular impact of sea level rise. The influence of physical and human influence parameters will be given separately in a graph showing the percentage of influence on the vulnerability of the region for each impact.

When constructing indices, as mentioned in previous sections, weighting of parameters is an important concept to decide on. At this stage, weights of the two groups of parameters (physical parameters and human influence parameters) are taken as 0.5, indicating that both groups of parameters will have an equal weight, which adds up to 1. In order to be able to assign different weights to the groups of parameters, there should be some data to base on from scientific studies, which is not available at the present. Therefore, since the present model is planned to be a preliminary model for decision makers, to be on the safe side, equal weights are assigned for each group of parameters meaning that both physical parameters and human influence parameters will have equal effect on the level of impacts. Assignment of different weights to groups of parameters will be the scope of the future studies.

3.5.1 Sub-indices of vulnerability of the impacts of sea level rise

In the first stage of the development of CVI (SLR), sub-indices giving the vulnerability of the region to each impact will be calculated. The impacts and the corresponding parameters used for calculating the sub-indices of vulnerability of impacts of sea level rise are given below in Table 3.8. These parameters (given in Tables 3.5 and 3.6) and how they affect the impacts were explained in detail in previous chapters.

The table indicates that there are some common parameters and there are individual parameters for impacts. It is important to assign weights for the parameters in vulnerability assessments however since there is not available data to base on which enables comparison and ranking of the parameters according to the level of influence on each impact. Therefore, it is decided that equal weights will be assigned to all the parameters. Thus, every parameter will be assumed to affect the impact at the same level.

Table 3.8 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

When constructing sub-indices for the impacts, simple aggregation of the relevant parameters will be done using the weight assigned for the corresponding group of parameters, which is 0.5.

The calculation formula of the sub-indices is presented below.

$$CVI_{impact} = \frac{\left(0.5 * \sum_{1}^{n} PP_n * R_n\right) + \left(0.5 * \sum_{1}^{m} HP_m * R_m\right)}{CVI_{\mathrm{leastvulnerable}}} \tag{3.4}$$

where PP = Physical parameters

HP = Human influence parameters

R = Corresponding vulnerability range of the parameter

$CVI_{leastvulnerable}$ = the value of the summation of the parameters for the least vulnerable case of the given impact (Values can be read from Table 3.9)

The vulnerability sub-index of impacts of sea level rise for any region will lie between the values given above indicating the level of influence on a range of 1 to 5 from least vulnerable to most vulnerable when the sum of the parameter values are divided by the least vulnerable case.

The above formula is used to calculate the sub-index for the most vulnerable case, where all the parameters are rated as 5, and the least vulnerable case, where all the parameters are rated as 1, for each impact. The least and most vulnerable case results are presented in Table 3.9.

Table 3.9 Most Vulnerable and Least Vulnerable Case Results of the impacts of sea level rise

Impact	No of Physical Parameters	No of Human Influence Parameters	Least Vulnerable Case of Impact	Most Vulnerable Case of Impact	CVI impact ranges
Coastal Erosion	6	5	5.5	27.5	1 - 5
Flooding due to SLR	4	3	3.5	17.5	1 - 5
Inundation	3	2	2.5	12.5	1 - 5
Salt water intrusion to groundwater	5	2	3.5	17.5	1 - 5
Salt water intrusion to river/estuary	4	3	3.5	17.5	1 - 5

The sub-indices of vulnerability for the impacts (CVI impact) are ranged between 1 and 5 from least vulnerable to most vulnerable.

3.5.2 Coastal Vulnerability Index - CVI (SLR) of the region

In order to compute the overall coastal vulnerability index of sea level rise, all the impacts that might be expected at the region have to be considered. However not all the impacts should be present at the region. So, the final CVI (SLR) should also reflect the absence of any impact.

On any coastal area, coastal erosion, flooding due to storm surge and inundation can be expected. However, salt-water intrusion to groundwater resources and river/estuary is taken into consideration when the corresponding resource is present at the region. Thus, three different groups are developed for CVI (SLR) construction taking into consideration the absence of any impact.

First group, CVI (SLR) 1, considers only coastal erosion, flooding due to storm surge and inundation. Second group, CVI (SLR) 2, considers the above three impacts as well as either saltwater intrusion to groundwater or river/estuary. And the third group, CVI (SLR) 3, assumes that all of the impacts of sea level rise can be expected at the region of concern. Thus, the coastal vulnerability index of the region will be calculated using the groups mentioned above as given below.

$$CVI(SLR)n = \frac{\sum \text{Parameters of Impacts of the group}}{\sum \text{Least Vulnerable Case of the group}} \tag{3.5}$$

where n indicates the group number.

The least vulnerable and the most vulnerable case results of the groups that are obtained using Table 3.9 are presented in Table 3.10.

Table 3.10 Least and Most Vulnerable Case results for the three groups of coastal vulnerability index - CVI

Groups	Least Vulnerable Case	Most Vulnerable Case
First Group	11.5	57.5
Second Group	15	75
Third Group	18.5	92.5

The calculated coastal vulnerability index will have a value of between 1 and 5 indicating the vulnerability from least to most for each group. Thus a region rated as 5 will be considered as highest vulnerable to sea level rise whether it is in group 1 or 3. The vulnerability groups and the corresponding CVI (SLR) values are determined as follows:

Very low vulnerability: $1 \leq \text{CVI (SLR)} < 1.5$
Low vulnerability: $1.5 \leq \text{CVI (SLR)} < 2.5$
Moderate vulnerability: $2.5 \leq \text{CVI (SLR)} < 3.5$
High vulnerability: $3.5 \leq \text{CVI (SLR)} < 4.5$
Very high vulnerability: $4.5 \leq \text{CVI (SLR)} \leq 5$

3.5.3 Coastal Vulnerability Index – CVI (SLR) Matrix

For the vulnerability assessment model of a region to sea level rise, a matrix given in Table 3.11 is developed. When the corresponding ranges of the parameters are checked for every impact, the matrix will show both the impact vulnerability indices as well as overall coastal vulnerability index to sea level rise. Then using these indices, the decision makers are able to both prioritize the impacts as well as determine the overall level of vulnerability of region to sea level rise. The discussion of the interpretation of results will be given using the results of case study presented in the next chapter.

3.5.4 Histogram of physical and human influence parameters

The distribution of the parameters of each group will give the decision makers an insight to the source of the vulnerability, whether it is due to natural properties of the region or anthropogenic. A simple way to show this distribution is to calculate the level of influence of the groups of parameters with respect to the least vulnerable case of the group of parameters of the impact (Table 3.9).

Table 3.11 Assigned values of vulnerability for groups of each impact as an example

Impact	Level of Influence of Physical Parameters	Level of Influence of Human Parameters
Coastal Erosion	3	4
Flooding due to storm surge	4	4
Inundation	3	5
Saltwater intrusion to groundwater	4	2
Saltwater intrusion to river/estuary	4	3

Figure 3.11 is given as an example where the values in Table 3.11 are assigned for vulnerability of groups of each impact, which may represent any region around the world.

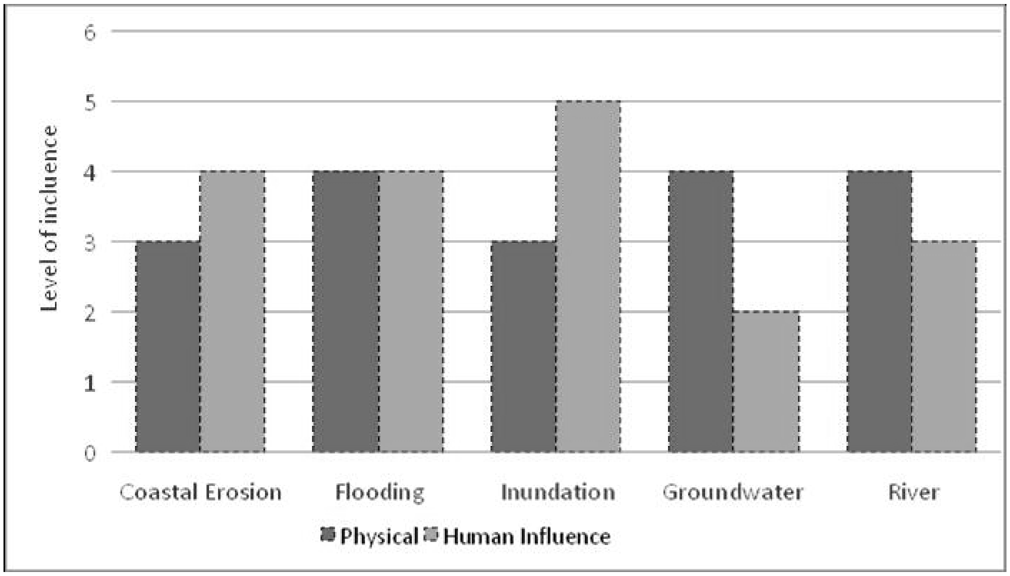


Figure 3.11 Example histogram of physical and human influence parameters for any region, assigned values are given in Table 3.11

This model will give histogram of the physical and human influence groups of every impact ranging from 1 (lowest vulnerability) to 5 (highest vulnerability).

Table 3.12 Coastal Vulnerability Index CVI (SLR) Matrix

Location

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	0	0	0	0	0	0	H1.1 Reduction of Sediment Supply	0	0	0	0	0	0		
	P1.2 Geomorpholgy	0	0	0	0	0	0	H1.2 River Flow Regulation	0	0	0	0	0	0		
	P1.3 Coastal Slope	0	0	0	0	0	0	H1.3 Engineered Frontage	0	0	0	0	0	0		
	P1.4 $H_{1/3}$	0	0	0	0	0	0	H1.4 Natural Protection Degradation	0	0	0	0	0	0		
	P1.5 Sediment Budget	0	0	0	0	0	0	H1.5 Coastal Protection Structures	0	0	0	0	0	0		
	P1.6 Tidal Range	0	0	0	0	0	0									
	TOTAL	0	0	0	0	0	0	TOTAL	0	0	0	0	0	0	0	0
2. Flooding due to Storm Surge	P2.1 Rate of Sea Level Rise	0	0	0	0	0	0	H2.1 Engineered Frontage	0	0	0	0	0	0		
	P2.2 Coastal Slope	0	0	0	0	0	0	H2.2 Natural Protection Degradation	0	0	0	0	0	0		
	P2.3 $H_{1/3}$	0	0	0	0	0	0	H2.3 Coastal Protection Structures	0	0	0	0	0	0		
	P2.4 Tidal Range	0	0	0	0	0	0									
	TOTAL	0	0	0	0	0	0	TOTAL	0	0	0	0	0	0	0	0
3. Inundation	P3.1 Rate of Sea Level Rise	0	0	0	0	0	0	H3.1 Natural Protection Degradation	0	0	0	0	0	0		
	P3.2 Coastal Slope	0	0	0	0	0	0	H3.2 Coastal Protection Structures	0	0	0	0	0	0		
	P3.3 Tidal Range	0	0	0	0	0	0									
	TOTAL	0	0	0	0	0	0	TOTAL	0	0	0	0	0	0	0	0
4. Salt Water Intrusion to Groundwater Resources	P4.1 Rate of Sea Level Rise	0	0	0	0	0	0	H4.1 Groundwater consumption	0	0	0	0	0	0		
	P4.2 Proximity to Coast	0	0	0	0	0	0	H4.2 Land Use Pattern	0	0	0	0	0	0		
	P4.3 Type of Aquifer	0	0	0	0	0	0									
	P4.4 Hydraulic Conductivity	0	0	0	0	0	0									
	P4.5 Depth to Groundwater Level Above Sea	0	0	0	0	0	0									
	TOTAL	0	0	0	0	0	0	TOTAL	0	0	0	0	0	0	0	0
5. Salt Water Intrusion to River/Estuary	P5.1 Rate of Sea Level Rise	0	0	0	0	0	0	H5.1 River Flow Regulation	0	0	0	0	0	0		
	P5.2 Tidal Range	0	0	0	0	0	0	H5.2 Engineered Frontage	0	0	0	0	0	0		
	P5.3 Water Depth at Downstream	0	0	0	0	0	0	H5.3 Land Use Pattern	0	0	0	0	0	0		
	P5.4 Discharge	0	0	0	0	0	0									
	TOTAL	0	0	0	0	0	0	TOTAL	0	0	0	0	0	0	0	0

CVI(SLR)-1	0	0
CVI(SLR)-2	0	0
CVI(SLR)-3	0	0

CHAPTER 4

CASE STUDY: GÖKSU DELTA

The impacts of sea level rise will be more hazardous on low-lying areas as explained in previous chapters. All of the impacts of sea level rise such as coastal erosion, inundation, flooding due to storm surges and salinity intrusion will cause adverse results not only physically but also economically both in micro and macro scale since low-lying areas are regions where some of the most important economic activities take place.

The above statement also holds true when Turkey is considered. Most of the important economic activities take place on or near the coastal areas especially on deltas. One of these regions is Göksu Delta which is located on the south of Silifke, Mersin where Göksu River with a 10000-km2 catchment area reaches the Mediterranean Sea. The delta, surrounded by the Taurus Mountains on the north and northeast is split into two by Göksu River. There are two shallow lakes; Paradeniz and Akgöl on the east and west respectively as shown in Figure 4.1.

Göksu Delta is known for the important biodiversity of flora and fauna which lead to the Specially Protected Area status that it claimed on 1991. On 1994, the wetlands of the delta are included in the RAMSAR list (List of Wetlands of International Importance). The richness of the fauna of the Göksu Delta is largely affected by geographical location as well as ecology. The presence of the major sea turtles (Caretta caretta) nesting beaches on the Mediterranean and its’ importance in terms of ornithology make the Delta one of the most diverse and valuable ecosystems in the region. Some of the birds using the Göksu Delta for nesting and breeding are partridge, turtledove, quail, blackbird, crane, snipe, jungle fowl, marbled dock, etc. Especially purple gallinule (Porphyrio prophyrio) seen in some parts of Mediterranean region and under the threat of extinction, is one of the most important bird species in the Delta (ÖÇK, 2005).

Figure 4.1 Satellite image of Göksu Delta

The importance of the delta is not only due to the important ecological properties it possesses. Since the implementation of irrigation network on 1968, the delta has become an important agricultural area leading to a rapid socioeconomic development. There are 5 municipalities and 7 villages and the corresponding population is given in Table 4.1.

As can be seen from the Table 4.1, the population of the region is increasing with a rate above the average rate of the country. All economical, physical and ecological properties of Göksu Delta are demonstrating the importance of this low-lying land, which has an average elevation of 2m above sea level. Thus, any of the impacts of sea level rise will have adverse effects on the Delta on various levels. Because of this, Göksu Delta is chosen as the case study location for the vulnerability assessment model of sea level rise.

Table 4.1 Population of Göksu Delta (1975-2010) ("Göksu Deltası" report, 2005)

Settlement Locations	**1975**	**1980**	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**
Silifke	19.257	22.041	28.111	46.858	74.130	104.081	146.133	205.176
Taşucu	2.983	4.535	4.385	6.743	7.830	9.294	11.704	14.739
Atayurt	2.294	2.464	2.942	5.107	10.654	15.755	23.298	34.453
Atakent	1.804	2.055	2.545	4.751	10.113	15.671	24.282	37.627
Altınkum	627	656	728	966	1.289	1.545	1.852	2.221
Arkarası	419	530	885	745	807	957	1.134	1.344
Bahçe	241	194	197	192	227	224	221	218
Burunucu	437	589	590	725	740	845	966	1.104
Çeltikçi	397	335	376	355	247	220	196	175
Gülümpaşalı	379	476	497	583	555	611	673	741
Kurtuluş	997	1.093	1.139	1.223	1.182	1.234	1.288	1.344
Sökün	821	674	587	769	704	680	656	634
Ulugöz	555	445	546	559	734	790	850	915
TOTAL	**31.211**	**36.087**	**43.528**	**69.576**	**108.762**	**148.921**	**203.907**	**279.196**

4.1 Assessment of Parameters of Delta

There are studies on Göksu Delta done by many national and international researchers in order to determine the physical, socioeconomic and ecological properties of Delta before and after the implementation of the protected area status. Both the studies and the observations from the field trips done to Göksu Delta are the basis of determining the corresponding parameters of the Delta. The physical parameters of the vulnerability assessment to sea level rise including the discussions on Göksu Delta are presented below.

a. Rate of sea level rise: There is no data for the region however there are some research on the sea level rise for Eastern Mediterranean. As a matter of fact, to have an accurate result, there should be long-term measurements of the Delta. These measurements can be determined using the tide gauge readings or sea level measurements of ports and marinas. Since there is no regional data, research on sea level rise of Eastern Mediterranean will be used for this parameter. Although long-term data is needed (50 years), the data at hand mostly covers only the last decade continuously. However, there is almost an agreement of several different researchers that the average linear sea level change is 2 mm/year (Fenoglio-Marc, 2001; Tsimplis and Rixen, 2002; Piervitali et al., 1997). Although Fenoglio-Marc, 2001 has stated that there is an higher rate of increase in the Eastern Mediterranean such as 9.3 mm/year, the change is thought to be due to seasonal variations of surface temperature thus for the vulnerability assessment average rate of 2 mm/year was used which corresponds to low vulnerability.

b. Geomorphology: The region is an alluvial delta including dunes, wetlands and sand beaches. "The Management Plan of Göksu Delta" report prepared by Authority of Specially Protected Areas and Doğal Hayatı Koruma Derneği in 1999 has extensive information on geomorphology of the Delta. According to "the Management Plan of Göksu Delta" report (1999), the source of the sediment is Göksu River and the amount of sediment transported is very high but the loss due to currents and waves is very low. Thus, the formation of Göksu Delta is a typical example of wave-dominated delta where the sea is tide-less. Another driving factor is the change of riverbed both naturally or due to human activities. One of the important landform of Delta is the sand spit name as Incekum. This spit is the result of opposite currents causing settlement of sediment from Göksu River. Dunes also occupy an important part of the coastal area. On 1999, the dune formation was described as 4.5 km continuous belt of sand with an average height of 5 m (5-10 m) on both sides (east and west) of Delta. Akgöl was formed due to the barrier beaches and sand spit blocking the old estuary mouth. Paradeniz lagoon is protected from the sea by a barrier beach. Thus, the vulnerability range of this parameter was taken as very high.

c. Coastal slope: The coastal slope is given in another resource "Göksu Deltası" report prepared by Authority of Specially Protected Areas in 2005 as, %0-6; where the areas near the shoreline having a slope of %0-2. The Delta is almost flat and the elevation changes between 0-5 m throughout the Delta with an average of 2 m. This parameter indicates that even with the best expectations of sea level rise, the inundation will have a significant effect on the Delta. As a result, the vulnerability range of this parameter was taken as very high.

d. Significant wave height: The significant wave heights for different return periods of the regions are given in Table 4.2. The steepness of the region is given in "Wave Prediction and Design Wave Parameters of 15 Regions in Turkey – Final Report" by Ergin and Özhan, 1986 as 0.0446 and 0.0464 using both data from meteorological station and synoptic maps.

Table 4.2 Significant Wave Height of Göksu Delta

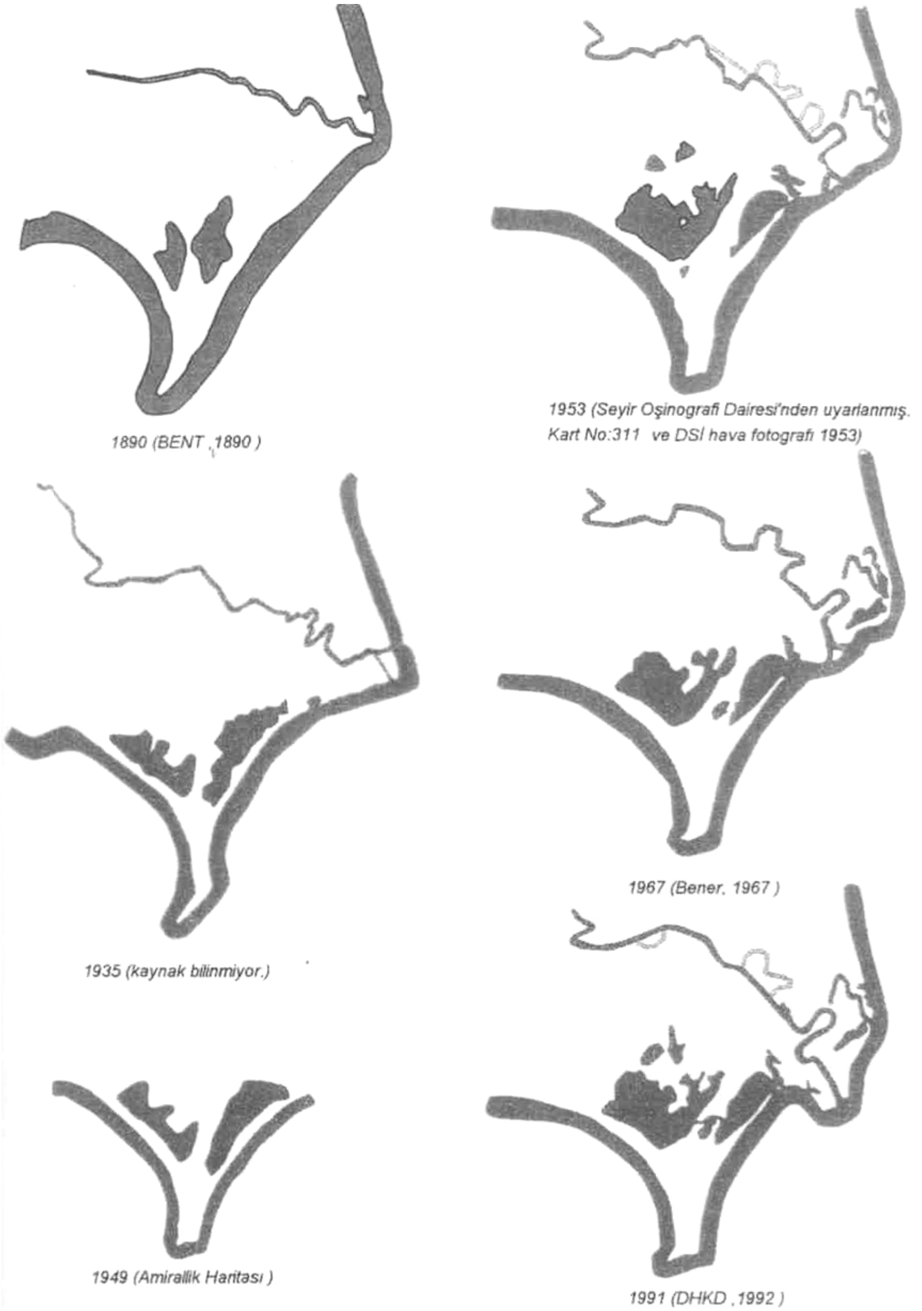
Return Period		10 years	25 years	50 years	100 years
Meteorological Station	H_s(m)	5.17±0.10	5.81±0.14	6.28±0.18	6.76±0.21
	T_s(s)	8.62	9.14	9.50	9.86
Synoptic Maps	H_s(m)	5.62±0.43	6.40±0.61	6.98±0.76	7.55±0.90
	T_s(s)	8.81	9.40	9.82	10.27

According to the data, the vulnerability range of this parameter was assigned as high.

e. Sediment budget: this parameter is used to indicate the stability of the shoreline. In Figure 4.2, the several stages of the shoreline of the Delta for the past 150 years are shown. As can be seen, the shoreline is very dynamic due to changes of riverbed throughout time. There have been both erosion and accretion along the shoreline. However, since 1986, the path or river is stable due to implementation of irrigation network. East part of the Delta where the old mouth of the river was located is under erosion for the past 20 years. According to recent measurements done by the municipality of Arkum, the yearly erosion rate is approximately 10 m (Keçer, 2001). In addition, İncekum region is under erosion as stated in Management Plan, 1999. In 1991, a lighthouse on İncekum formation had collapsed due to erosion. There have been accretion at the mouth of the river however this accretion is right around the mouth not affecting a very large area. On the west side of the Delta, the change is not significant, almost stable. Thus the range for this parameter was assinged as high to very high vulnerable where nearly %50 of the shoreline is under erosion.

f. Tidal range: Since Mediterranean Sea is classified as micro tidal, the tidal range along the Delta is also around 20-30 cm. In "Göksu Deltası"

(2005), it is stated that from time to time, the tidal range is observed as 45 cm. Thus the regions was considered highly vulnerable since the rise of sea level will damage the coastal area increasing the inundated area during high tide almost twice as much since the expected increase will be at least as much as the tidal range.



1890 (BENT ,1890)

1953 (Seyir Oşinografi Dairesi'nden uyarlanmış. Kart No:311 ve DSİ hava fotografı 1953)

1935 (kaynak bilinmiyor.)

1967 (Bener, 1967)

1949 (Amirallik Haritası)

1991 (DHKD ,1992)

Figure 4.2 Shoreline changes for the past 150 years (Management Plan of Göksu Delta, 1999)

g. Proximity to coast: In “Göksu Deltası” report of Authority of Specially Protected Areas, 2005 the region is defined as rich in groundwater resources. There are artesian wells on the shoreline of the Delta. In addition, the amount of groundwater resource decrease as the distance to river increases. On the north part of the Delta, more groundwater resources are present. Although there are not accurate data, considering the artesian wells within 400 m of the shoreline, the vulnerability of groundwater resources was taken as high.

h. Type of Aquifer: According to Crivelli, 1990, most resources are of karstic type. Most of the groundwater resources are confined aquifers as stated in “the Management Plan of Göksu Delta” report, 1999. The confined layer is the compacted sediment deposited by river. In the end, due to lack of detailed data, the vulnerability of this parameter was taken as moderately vulnerable.

i. Hydraulic conductivity: NEDECO, 1990 computed the hydraulic conductivity of the first 4 m layer as 1.36 m/day. Since this is the only available data, the hydraulic conductivity was considered as very low vulnerability.

j. Depth to groundwater level: The artesian wells on the shoreline, which have potentiometric surface level of 2 m above the sea level, indicate that the water table of the groundwater is above sea level. However, there are other groundwater resources, which have the water table under sea level, which through the interviews with local people that are known of. Since no data is available on these resources, the groundwater resources on the shoreline, which are of artesian type having 2m of potentiometric surface level, will be considered only. The corresponding vulnerability of these resources was taken as low accordingly.

k. Water depth: Any data on the water depth at the downstream of Göksu River could not be found thus the vulnerability range for this river was assumed as low since the rivers of Turkey do not have deep-water depths.

l. Discharge: As given in “Göksu Delta” report (2005), the average discharge of Göksu River is measured as 118 m^3/s. The lowest value is measured as 26 m^3/s. The peak value measured is 2800 m^3/s on 2004. The average dry season discharge is around 90 m^3/s during September. The discharge increases up to 700 m^3/s during April. This indicates that vulnerability of river to saltwater intrusion is high during dry seasons according to the ranges of parameters. If the season is too dry, then the vulnerability increases to very high.

Although the human pressure on the Delta is high, because most of the coastal area is within the Sensitive Zone of the Protected Area, the direct human pressure on the coastal zone is believed to be lower than expected. However, indirect pressures due to population, permitted agriculture in the Specially Protected Area and construction of dams affect the coastal area significantly. The corresponding human influence parameters for Göksu Delta are explained below.

a. Reduction of sediment supply: As explained in previous chapters, one of the main factors of sediment supply reduction is the construction of dams on the upstream of the rivers. The operation of Gezende Dam was started on 1992. The reservoir of the dam is approximately 4 km^2, which can store $92*10^6$ m^3 of water. The renewal period of the storage capacity is 20 days thus the effect of this dam is stated as minor in the Management Plan, 1999. Although the dam has a minor effect on reduction of sediment supply, the illegal extraction of sand from the beaches has also increased the reduced amount of sediment. Thus the vulnerability with respect to this parameter was taken as moderate.
b. Flow reduction: The storage capacity of Gezende Dam is given as $92*10^6$ m^3 in previous parameter explanation. The volumetric annual discharge of Göksu River is $3456*10^6$ m^3 (Management Plan of Göksu Delta, 1999). Using the methodology explained in previous sections, the flow regulation is calculated as 3%. When the fragmentation of the river is considered, the main channel do not have a constructed dam at the present thus the index is 0. When the tributaries are considered, Gezende Dam is not on the largest tributary so the corresponding index is 1. Using the table given (Table 3.6), the river was determined to be moderately affected. However, the impacts of construction of Kayraktepe Dam and Ermenek Dam on both the reduction of flow and sediment supply will be much significant and critical in terms of vulnerability of the Delta in every aspect, including sea level rise.
c. Engineered frontage: There is no coastal structure on the shoreline of the Delta because of the protection status. However, there is a port on the west border of the Delta. But the impact of the structure is insignificant on the coastline since the west shoreline has been stable

after the construction of the port. However, the jetties constructed for the drainage of the irrigation channels on the east part of the Delta have a significant impact on the shoreline erosion as stated by Keçer, 2001. Thus, the vulnerability was taken as low although the engineering structures do not occupy a large part of the shoreline.

d. Groundwater consumption: Although the area has an advanced irrigation network, which is distributing water from the river to every part of the Delta, groundwater consumption has increased recently due to increased strawberry production practice. The technique used to water the strawberry plants need pure water without suspended particles. So local people prefer using groundwater resources, which are both suitable for the watering and cheap (when used illegally). As stated in Management Plan, 1999; on the east side of the Delta, many wells were constructed for irrigation, which caused rapid decreasing of the water table of the groundwater resource. Although relevant data could not be found, the vulnerability range was taken as high since the water consumption is steadily increasing.

e. Land use pattern: The Delta is under protection due to the Specially Protected Area status claimed by the government even though only %40 of the property of the Delta is governmental area. More than %50 of the Delta is defined as "Sensitive Zone" where the protection measures are taken at the maximum possible level even though local people reside in this zone. Outside the boundaries of the Sensitive Zone, the main human activity is agriculture especially strawberry and rice production, both consuming the major amount of the available water resources. According to research done by Authority of Specially Protected Area, %80 of the local population depend on only agriculture which increases the vulnerability of the region to climate change. It is hard to determine the corresponding vulnerability to sea level rise of this parameter since while the protection status decreases the vulnerability, the significant effect of agricultural activity outside the sensitive zone increases it at the same time. Thus to be on the safe side, the land use pattern parameter was taken as very high vulnerability.

f. Natural protection degradation: Both wetlands and dunes are present on the coastal zone of the Delta. These landforms act as natural protection against erosion, flooding and inundation as explained in previous chapters. Although the area is under protection by law, before the implementation of protection status, most dunes were destroyed due to illegal sand extraction for secondary house constructions around the Delta. Today the height of most of the dune formation is below 1 m, which indicates a degradation of more than %60. Also, the wetlands are under threat of sedimentation due to suspended particles transported from irrigation channels. In addition, the change of water quality from salty to fresh water of Akgöl increased the vegetation inside the lake, which decreased the area of the lake as well. When all of the above impacts are considered, the vulnerability of the area was taken as high but because of the protection status, this vulnerability will decrease in time because there will be no further degradation.

g. Coastal Protection Structures: As mentioned in engineered frontage parameter, because of the protection measures, construction is not permitted on the shoreline including coastal protection structures even though the local governments want to construct protection structures for coastal erosion. However, the lack of coastal protection structures increases the vulnerability of the region in the long term since there will be no physical barriers nor permission for construction of protection structures against the impacts of the sea level rise. Thus, the vulnerability for this parameter was taken as very high.

The coastal vulnerability matrix for the Delta is given below in Table 4.2, which shows the scores of each parameter as well as the sub-indices of vulnerability of impacts and the overall coastal vulnerability index – CVI (SLR).

4.2 Calculating Coastal Vulnerability Index – CVI (SLR) of Göksu Delta

The Table 4.3 shows the end results of the procedure which was explained theoretically in section 3.5. The calculation steps will be demonstrated in this chapter using the values of the case study.

In order to calculate the coastal vulnerability index – CVI (SLR) of a region, first the sub-indices of each impact have to computed. The impact vulnerability sub-indices for coastal erosion, flooding due to storm surge, inundation, saltwater intrusion to groundwater and saltwater intrusion to river/estuary for Göksu Delta are calculated as 3.9, 4.0, 4.4, 3.0 and 3.3 respectively and given in Table 4.3. Computations of sub-index of vulnerability of coastal erosion will be given as an example.

The 6 physical parameters and 5 human influence parameters, which govern the coastal erosion due to sea level rise with the corresponding level of vulnerability of each parameter, are given in Table 4.3. As presented in Section 3.5.1, in order to calculate the sub-index of the impact, first, the total value of the vulnerability of the parameters have to be summed. Accordingly;

Physical parameters: 1*2+1*5+1*5+1*4+1*4+1*5 = **25**
Human influence parameters: 1*3+1*3+1*2+1*1+1*1 = **18**

Since the weights of each group of parameters are assigned as 0.5, the total value of the vulnerability of parameters for coastal erosion is calculated as;

Total value of impact: 0.5*25+0.5*18 = **21.5**

The construction of the sub-index of an impact requires the total value to be divided by the least vulnerable case value which is given in Table 3.9. The least vulnerable case is defined as when all the parameters determining the vulnerability of the impact is given value of 1.

Least vulnerable case of coastal erosion: 0.5*(6*1) +0.5*(5*1) = **5.5**

So, the sub-index of vulnerability of Göksu Delta to coastal erosion due to sea level rise is;

CVI (erosion) = 21.5/5.5 = **3.909 ≈ 3.91**

Thus, the Delta is **highly vulnerable** when coastal erosion due to sea level rise is considered since **3.91** is between **3.5** and **4.5** (range of high vulnerability).

Table 4.3 Coastal Vulnerability Index – CVI (SLR) matrix for Göksu Delta

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

Accordingly, for Göksu Delta, the vulnerability to flooding due to storm surge and inundation are high with inundation being the most important impact when vulnerabilities are concerned. Saltwater intrusion to groundwater and river/estuary are ranked as moderately vulnerable with saltwater intrusion to groundwater being the lowest vulnerable impact with respect to other four impacts of sea level rise.

The coastal vulnerability index – CVI (SLR) is calculated by following the procedure demonstrated below. First, the total values of the parameters of vulnerability for each impact shown in Table 4.3 are summed.

Total vulnerability of impacts: 21.5+14+11+10.5+11.5 = **68.5**

Then in order to find CVI (SLR), the above value should be divided by the least vulnerable case value of the group. As stated in section 3.5.2, there are three groups of CVI (SLR) according to the presence of impacts of sea level rise on the region. Since all the impacts of sea level rise can be expected on Göksu Delta (both groundwater resources and Göksu river is present), the Delta belongs to group 3. The least vulnerable case value of group 3 can be find by adding the least vulnerable case value of each individual impact (which are presented in Table 3.9), such as;

Least Vulnerable Case of Group 3: 5.5+3.5+2.5+3.5+3.5 = **18.5**

Thus, the coastal vulnerability index – CVI (SLR) can be found by dividing the total value by least vulnerable case of group 3;

CVI (SLR)-3 of Göksu Delta: 68.5/18.5 = **3.702**

According to the calculated CVI (SLR), the Delta is **highly vulnerable** to impacts of sea level rise since the calculated index, **3.702** is between **3.5** and **4.5** (ranges of high vulnerability).

4.2.1 Histogram of Physical and Human Influence Parameters of Impacts for Göksu Delta

As stated previously, the influence of each group of parameters (physical and human influence parameters) is important when adaptation measures are considered. The influence of groups of parameters and the level of influence will be given by histograms for each impact of sea level rise. The procedure for obtaining these histograms is explained below.

In order to determine the level of influence of physical and human influence parameters on each impact, the total value of parameters of each group is divided by the least vulnerable case result of the group. Calculations for the histogram of physical and human influence parameters are given in Table 4.4.

Table 4.4 Calculation of level of influence of groups of parameters according to level of vulnerability for impacts of sea level rise for Göksu Delta

Impact	Physical Parameters total	Human Influence Parameters Total	Least Vulnerable Case of Physical Parameters	Least Vulnerable Case of Human Influence Parameters	Level of influence of PP	Level of influence of HIP
Coastal Erosion	25	18	6	5	4.17	3.6
Flooding due to Storm Surge	16	12	4	3	4	4
Inundation	12	10	3	2	4	5
Salt water intrusion to groundwater	12	9	5	2	2.4	4.5
Salt water intrusion to river	13	10	4	3	3.25	3.33

The corresponding histogram is given as Figure 4.3.

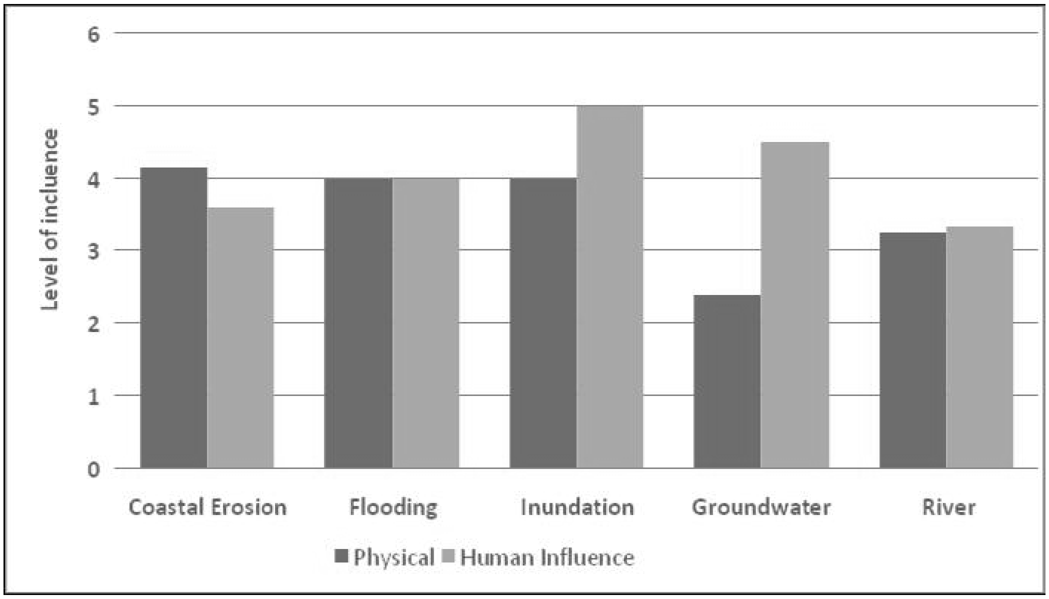


Figure 4.3 Histogram of physcial and human influence parameters with respect to impacts of sea level rise for Göksu Delta.

The histogram presented in Figure 4.3 will give the decision makers an insight to the source of the vulnerability, whether it is due to natural properties of the region or anthropogenic.

4.3 Discussion of Results of Coastal Vulnerability Assessment to Sea Level Rise of Göksu Delta

The coastal vulnerability index – CVI (SLR) for Göksu Delta is calculated as 3.70 using the developed vulnerability assessment model (Table 4.3). This value indicates that the overall vulnerability of the Delta with respect to impacts of sea level rise is determined as high. This result is in agreement with the literature that the low-lying lands, especially deltas are highly vulnerable to sea level rise.

When individual impacts are considered, the ranking of the vulnerability of the Delta to each impact from highest Impact CVI to lowest as presented in Table 4.3 are given below in Table 4.5.

Table 4.5 Ranking of vulnerability of impacts with corresponding impact CVI's

Impact	Impact CVI (SLR)
Inundation	4.4
Flooding due to storm surge	4.0
Coastal erosion	3.9
Saltwater intrusion to river/estuary	3.28
Saltwater intrusion to groundwater	3.0

The Göksu Delta being most vulnerable to inundation (CVI=4.4) is also in agreement with Sorensen et al. (1984) that estuaries whether delta or newly formed, are more vulnerable to land loss due to inundation than coastal erosion as also stated in Section 3.1.1. Also, the human influence parameters increase the vulnerability to inundation due to degradation of dune formation and the absence of coastal protection as is showed in Figure 4.3.

Flooding due to storm surge (CVI=4.0) being the second important vulnerability of the Delta is also compatible with the interviews of local people. The local people confirm that flooding due to storm surges affect the coastal areas frequently, damaging the settlements and agricultural areas especially near Paradeniz lagoon (DEFRA 1st Field Trip Technical Report, 2006). As is the case in inundation, absence of coastal protection and the degradation of natural protection such as loss of dune formation and sedimentation in the lagoon increase the vulnerability of the region although not as much as in inundation as can be seen in Figure 4.3.

Coastal erosion (CVI=3.9) is the most significant problem of the Delta from coastal engineering point of view when shoreline is considered. The CVI value 3.9 is in accordance with the literature that beaches and deltas are highly vulnerable to coastal erosion due to sea level rise. The physical properties of the Delta significantly increase the as well as the human influence on the coastline. The effect of engineering activities such as regulation of the river and the construction of jetties for the drainage of irrigation channels are the governing parameters for the past century as given in Figure 4.2. From Figure 4.3, it is seen that the physical and human influence parameters are equally affecting the vulnerability of the Delta.

Freshwater resources of the Delta are the groundwater resources and Göksu River. Freshwater resources of the Delta are moderately vulnerable to sea level rise (impact CVIs are 3.28 and 3.0 for river and groundwater respectively). Vulnerability of saltwater intrusion to river, which is slightly higher than groundwater, is again in agreement with the interviews of local people who informed that they have already observed that the salty water moved to further inland damaging the lemon trees near the river, which were once very productive (DEFRA 1st Field Trip Technical Report, 2006). The effects of parameters are close to each other as is presented in Figure 4.3.

In case of groundwater resources, local people confirm the low vulnerability that they are pumping out water from 70 meters below ground level and there have been no change in the quality of this resource. However, the wells very close to shoreline, which are shallow (around 7 meters depth) which had moderate quality of water in terms of salinity, now have salty water. The reason can be both sea level rise and the human activities, which increase the vulnerability of the region. Over exploitation of groundwater resources endanger the quality of the water in other wells as well as can be clearly seen in Figure 4.3

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS FOR FURTHER STUDY

An innovative parameter based coastal vulnerability assessment model to physical impacts of sea level rise is developed.

The main features of the coastal vulnerability assessment to sea level rise model are;

- A coastal vulnerability matrix tabulating the site-specific data and calculating the indices of the vulnerability assessment was developed.
- A coastal vulnerability index – CVI (SLR) composed of 12 physical and 7 human influence parameters was developed based on a five-scale rating system from very low vulnerability (1) to very high vulnerability (5) which enables comparison of different regions and ranking them according to their vulnerabilities to sea level rise
- Sub-indices of vulnerability of each impact (coastal erosion, inundation, flooding due to storm surge, salt water intrusion to groundwater resources, salt water intrusion to river/estuary) affecting a region composed of governing physical and human influence parameters are developed based on a five scale rating system from very low vulnerability (1) to very high vulnerability (5) which enable prioritizing the impacts of sea level rise on the region according to the vulnerability of the region to each impact
- A histogram of physical and human influence parameters was developed in order to determine the most vulnerable parameters that need to be considered when planning for adaptation to sea level rise

As a case study,

- Göksu Delta, Mersin was evaluated by using the coastal vulnerability assessment model to sea level rise.

- Using site data, the assessment matrix showing both sub-indices and coastal vulnerability index – CVI (SLR) was prepared.
- The CVI(SLR) of Göksu Delta was calculated as 3.702 with impact indices as 4.4 for inundation, 4.0 for flooding due to storm surge, 3.91 for coastal erosion, 3.28 for saltwater intrusion to river/estuary and 3.0 for saltwater intrusion to groundwater.
- Using site data, histograms of physical and human influence parameters were prepared for each impact of sea level rise expected at the site.

With regard to coastal zone management, the preliminary model introduced can be suitable for evaluating both the potential coastal hazards as well as the vulnerability of coastal areas to the anticipated impacts of sea level rise. As mentioned in previous sections, the impacts of sea level rise are also the potential coastal hazards. Thus, the core of this study can be used as part of coastal zone management studies evaluating the coastal vulnerabilities of a region to hazards using both physical properties and the human influence on the region.

This study is a preliminary study, which lays down the groundwork for a more complex coastal assessment by identifying the major physical problems of coastal areas and the governing physical and human influence parameters. In order to achieve the initial aim of developing universal indicators and corresponding ranges of vulnerability, more sites should be evaluated with extensive data. As the sites are evaluated, the data should also be used to develop a ranking system for governing parameters indicating the level of influence of each parameter on each impact. A ranking system for the impacts might also be developed using the outputs of these assessments.

The uncertainty of the ranges and the influence of parameters should be determined. In addition, research on sensitivity of parameter ranges should also be carried out. Both ranking studies and range sensitivities will determine the final classification of vulnerability index, which is the main output parameter of the assessment model. A mathematical model for the above-mentioned studies will be developed which uses both fuzzy logic and multi criteria decision making techniques in order to overcome both the uncertainty factor and to project the future problems as a result of further studies.

A very important part of the future studies will include the implementation of GIS techniques in order to automate the final coastal vulnerability model including the socio-economic vulnerability parameters and impacts. The socio-economic part of the vulnerability index will be studied with a team of researchers from the Sociology Department. To complement the GIS techniques, coastal zone management software including the impacts of sea level rise can be developed.

Verification of such models developed on vulnerability of coastal areas or coastal zone management needs an accurate data collected over the years. Therefore, monitoring is a process that couples with the implementation of the model on coastal vulnerability to sea level rise. Such a study is the highlight of the future investigations.

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APPENDIX A

COASTAL LANDFORMS

ALLUVIAL PLAIN: A plain bordering a river, formed by the deposition of material eroded from areas of higher elevation.

BARRIER BEACH: A bar essentially parallel to the SHORE, which has been built up so that its crest rises above the normal high water level. Also called barrier island and offshore barrier.

BEACH: (1) A deposit of non-cohesive material (e.g. sand, gravel) situated on the interface between dry land and the sea (or other large expanse of water) and actively "worked" by present-day hydrodynamics processes (i.e. waves, tides and currents) and sometimes by winds. (2) The zone of unconsolidated material that extends landward from the low water line to the place where there is marked change in material or physiographic form, or to the line of permanent vegetation. The seaward limit of a beach - unless otherwise specified - is the mean low water line. A beach includes foreshore and backshore. (3) (SMP) The zone of unconsolidated material that is moved by waves, wind and tidal currents, extending landward to the coastline.

CLIFF: A sloping face that is steeper than 20° usually formed by erosion processes and composed of either bedrock or unconsolidated materials (or both). Also includes material deposited at the base of cliffs as talus or fans by mass movement processes (e.g., rock fall, mudflows, slumping).

COBBLE: Rounded rocks ranging in diameter from approximately 64 to 256 mm.

CORAL REEF: A coral-algal mound or ridge of in-place coral colonies and skeletal fragments, carbonate sand, and organically-secreted calcium carbonate. A coral reef is built up around a wave-resistant framework, usually of older coral colonies.

DELTA: (1) An alluvial deposit, usually triangular, at the mouth of a river of other stream. It is normally built up only where there is no tidal or current action capable of removing the sediment as fast as it is deposited, and hence the delta builds forward from the coastline. (2) A tidal delta is a similar deposit at the mouth of a tidal inlet, put there by tidal currents. (3) A wave delta is a deposit made by large waves which run over the top of a spit or barrier beach and down the landward side.

ESTUARY: (1) A semi-enclosed coastal body of water which has a free connection with the open sea. The seawater is usually measurably diluted with freshwater. (2) The part of the river that is affected by tides. (3) (SMP) The zone or area of water in which freshwater and saltwater mingle and water is usually brackish due to daily mixing and layering of fresh and salt water.

FJORD: A long, narrow arm of the sea, usually formed by entrance of the sea into a deep glacial trough.

GLACIAL DRIFT: deposit of mixed clay, gravel, sand, and boulders transported and laid down by glaciers. Stratified, or glaciofluvial, drift is carried by waters flowing from the melting ice of a glacier. The flowing water sorts the particles, generally depositing layers of coarser particles nearer the point of origin. Till, or boulder clay, which makes up the greater part of the drift, is unstratified, consisting of disorganized heaps of rocks that range widely in size. Till is deposited directly by the glacier itself without water transport. The drift may take the form of a drumlin, kame, an esker, a moraine, or an outwash plain; its thickness varies noticeably from place to place and is not dependent upon topographical factors.

LAGOON: A shallow body of water, as a pond or lake, which usually has a shallow restricted inlet from the sea.

LOW CLIFF: A cliff with a vertical rise of less than 5 metres.

MANGROVE: A tropical tree with interlacing prop roots, confined to low-lying brackish areas.

MARSH, SALT: A marsh periodically flooded by salt water.

MARSH: (1) A tract of soft, wet land, usually vegetated by reeds, grasses and occasionally small shrubs. (2) (SMP) Soft, wet area periodically or continuously flooded to a shallow depth, usually characterized by a particular subclass of grasses, cattails and other low plants.

MEDIUM CLIFF: A cliff with a vertical rise between 5 and 10 metres.

MUD FLAT: A muddy, low-lying strip of ground by the shore, or an island, usually submerged more or less completely by the rise of the tide.

ROCKY CLIFFED COASTS: Shoreline cut into resistant rock.

SAND: An unconsolidated (geologically) mixture of inorganic soil (that may include disintegrated shells and coral) consisting of small but easily distinguishable grains ranging in size from about .062 mm to 2.0 mm.