Regional Technical Report on the Impacts of Climate Change on Groundwater in the Arab Region

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Preface

The Arab region is one of the most arid areas in the world. With less than 200mm of rainfall per year, scarcity of precipitation combined with high variability and frequent drought events places stress on available water resources. With limited or no surface water, groundwater is certainly one of the most important sources of water supply in the Arab region. The region depends significantly on groundwater resources to meet their growing water demands. High water stresses in the region are met with varying degrees of depletion and mining of aquifer systems. Thus, many groundwater resources are at risk of being exhausted through over-pumping. This has been manifested by continuous water level declines and degradation of water quality due to salinization. Groundwater needs to be carefully managed if its use is to be sustained for future generations.

Global climate change has been identified as one of the greatest pressing environmental challenges facing humanity. The environmental changes that we can expect from accelerating global climate change could alter the dynamics of groundwater sustainability. Furthermore, policy responses to global climate change should be considered in forecasting future groundwater availability. There have been significant efforts by the Arab countries for adopting integrated water resources management to cope with water scarcity and sustainable development. Therefore, both climate change forecasts and policy responses should be incorporated into the ongoing work to sustain groundwater supplies in the Arab region.

This report addressing the “Impacts of Climate Change on Groundwater in the Arab Region” is a technical document prepared with the scope of providing a comprehensive review summarizing the theory of climate change and the relationship of climate change to aquifer processes and the effects within the hydrological cycle, climate change and its effect on groundwater sustainability in terms of quantity and quality, desk review of the aquifer systems in the Arab Region with an overview of possible climate change impacts on groundwater resources in the region, outlines of relevant adaptation measures, future challenges of adapting to climate change and advise on the development of responsive sustainable groundwater utilization in the region. Sharing such information on the impacts of climate change on groundwater essentially contributes to the enhancement of climate proof management practices and experience related to groundwater protection region wide.

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Ahmed R. KHATER
August, 2010
Executive Summary

The Arab region is one of the most arid areas in the world. With limited or no surface water, the region depends significantly on groundwater resources, and High water stresses in the region are met with varying degrees of depletion and mining of aquifer systems. Thus, many groundwater resources are at risk of being exhausted.

Global climate change has been identified as one of the greatest pressing environmental challenges facing humanity. Scientific evidence indicates that climate change is already underway. Climate change will alter the hydrological cycle in many ways. This will alter the patterns of rainfall with consequences for runoff, surface and groundwater storage, river flow regimes and greater likelihood of drought and flood extremes, in different parts of the world, including the Arab region.

At present, in most of the Arab countries, the impacts of water scarcity, population growth and land management may be far more significant and critical than climate change. Therefore, the impacts of climate change, which is projected to increase the frequency and intensity of extreme weather events, will contribute to even worse water scarcity, and add to already difficult water management challenges in the region.

The environmental changes that we can expect from climate change could alter the dynamics of groundwater availability and sustainability in the Arab region. This report addressing the “Impacts of Climate Change on Groundwater in the Arab Region” is a technical document prepared with an overall scope of providing an overview of the possible climate change impacts on groundwater resources in the region, outlining future challenges and advises on the development of adaptation measures. Sharing such information on the impacts of climate change on groundwater essentially contributes to enhance the understanding of climate change effects within the hydrological cycle with emphasis on aquifer systems. It should also contribute to the development of climate proof management practices related to groundwater protection in the region.

The aimed scope of this work is achieved through the reporting structure, comprising six chapters; covering the main climate change relevant aspects from theory to adaptation, as summarized below:
Chapter One: “Climate and Water Resources” introduces the global climate system and its natural operation, being the key to understanding climate change. The global climate system has been introduced as a consequence of and a link between the cryosphere, the biosphere and the geosphere. Water is an integral component of climate change and the primary medium through which it exhibits its impacts. Therefore, the outline of this chapter is extended to include the inter-relationship between the climate system, freshwater and climate change.

Chapter Two: “Detecting and Attributing Climate Change” describes the processes to assess climate change, providing a brief on the evolution and progress the work made by the Intergovernmental Panel on Climate Change (IPCC), in this respect. This chapter provides also an overview of the past and recent climate change, as well as the future climate change in the context of global warming and the associated families of greenhouse gases emission scenarios used to model and assess climate change impacts. Evolution of the various types and scales of climate change modeling is also considered.

Chapter Three: “Climate Change and Aquifer Processes” explores the complex aspects of the potential impacts of climate variability and change on groundwater systems. Expected impacts include variations in groundwater level fluctuation, alteration of groundwater flow regimes and changes in the volume and quality of groundwater resources. Climate change could affect groundwater sustainability in several ways, including sea water intrusion, water quality deterioration, potable water shortage and possible increased dependency on groundwater as a backup source of water supply. This chapter demonstrates that our understanding of the impact of climate variability and change on groundwater resources, from a regional or national perspective, remains limited. In general, there is a need to intensify research in this respect.

Chapter Four: “Groundwater and Climate Change in the Arab Region” provides a desk review of the aquifer systems in the Arab Region with an overview of possible climate change impacts on groundwater resources in the region. The objective is not to provide a detailed description of the hydrogeology of the region but rather to point out the groundwater occurrence, magnitude and management considerations with respect to risks that climate change poses for aquifer systems in the region. This chapter furthermore outlines global climate change projections relevant to the Arab
region. It reveals that the simulated ranges of annual average surface temperature for the Arab region will likely to rise a further 2.5° to 4.0° Celsius by 2100. Increased temperature is expected to increase evapotranspiration rates thereby reducing soil moisture, infiltration and aquifer recharge. Projected annual average ranges of precipitation for the 21st century tend to decrease in the Mediterranean region and northern of the Arabian peninsula by 10% to 20%. Simulated ranges also indicate that precipitation is expected to decrease between 30% to 40% in Morocco and north of Mauritania. Djibouti, Egypt, Iraq, Morocco, Somalia and the Arabian gulf countries are at high risk for coastal flooding and exposure to extreme temperatures. However, an increase in precipitation ranging from 10% to 30% is predicted in the southwestern part of Saudi Arabia, Yemen, United Arab Emirates, and Oman. Simulated impact of climate change on long-term average annual diffuse groundwater recharge showed that the increase in surface temperature and reduction in rainfall will result in 30-70 percent reduction in recharge for aquifers in the eastern and southern Mediterranean coast.

Chapter Five: “Water and Climate Change Adaptation in the Arab Region” outlines approaches and actions that are being proposed to facilitate adaptation to climate change in the Arab region in general and those that are specific to the water sector. The concept of vulnerability to climate change impacts and its key elements of exposure, sensitivity, potential impacts and adaptive capacity are introduced. Mitigation measures, and adaptation characteristics and processes are also discussed. Approaches and tools proposed to facilitate adaptation to climate change specific to the water sector are given. An understanding of enabling mechanisms for adaptation is urgently required. The process that addresses these enabling mechanisms, as a whole, is known as “climate proofing” and can be implemented at the basin, national or local level. On the other hand, enhancement of adaptive capacity is necessary to reduce vulnerability, particularly for the most vulnerable regions, nations, and socioeconomic groups. Activities required for the enhancement of adaptive capacity are essentially equivalent to those that promote sustainable development and equity. However, the sense of urgency for climate change adaptation and enhancement of adaptive capacity, with recognition of water centrality therein, have not yet permeated the Arab region and are not systematically reflected in national plans or regional investment portfolios for adaptation.
Chapter six: “Climate Change-Adaptive Management of Groundwater in the Arab Region: Concluding Remarks” points out that the impacts of climate change on the Arab region will include changes in precipitation rates, surface runoff and river flow rates, which will affect the recharge rates of groundwater and also further exacerbate extraction rates of groundwater, as a result of lower availability of surface water. Sea level rise and saltwater intrusion into coastal groundwater aquifers would affect the flow in coastal aquifers leading to further deterioration of groundwater quality. Climate change may also affect the quality of groundwater where reduced rates of recharge and altered flow regimes may increase the concentrations of contaminants in groundwater. Potential quality deterioration of groundwater associated with climate change has been identified as a major concern. It is therefore advisable to prevent or reduce the risk of groundwater pollution rather than have to deal with the consequences of pollution. Groundwater protection should therefore be a top priority, and be an essential part in mainstreaming of “climate proofing” in the management of groundwater resources in the region. Guidelines for climate proof groundwater protection are suggested. Climate proof groundwater management strategies must be based on an integrated water resources management approaches. Water policy reform should be based on the concern of climate change adaptive integrated approach. Research areas of high priority to the climate change adaptive management of groundwater resources in the Arab region are identified to include: (1) improved identification of regional hydrogeologic frameworks; (2) better understanding of groundwater and surface water interaction; (3) effective characterization of groundwater flow in shallow aquifer systems; (4) improving scarcity of data and uncertainties associated with predictions from groundwater models; (5) modeling of climate change impacts on the movement of seawater into coastal aquifers; (6) predictive tools for the rate of increase of the salinity of aquifers; (7) development approaches for non-renewable groundwater; (8) risks that climate change poses for aquifer systems and groundwater availability; (9) applying the output of climate models on to groundwater models; and (10) enhancement of climate change adaptive capacity approaches, methodologies, valuation techniques, geographic information and decision support systems, and rapid assessment tools. While climate change expected impacts have generally been modeled through the development of global climate models, limited research and information has been generated on the effects of climate change at the Arab region level. Therefore, the way forward calls for a vulnerability assessment at the Arab regional and sub-regional levels.
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CHAPTER 1

Climate and Water Resources
CHAPTER 1

Climate and Water Resources

1.1 Introduction

Water is indispensable for all forms of life. Freshwater is finite and vulnerable resource, essential to sustain life, all kinds of human development and livelihood support systems. Quantitative characteristics of water use in large regions and countries of the world are determined by several factors including the level of socio-economic development, population number, physiographic features, and the area of the territory. Combination of these factors determines the volume and structure of water use, its dynamics and tendencies of development in the future. New and growing demands increasingly strain scarce and erratic supplies. With extremely uneven natural space-and-time water resources distribution, intensive human activities, and a rapid population growth, even at the present time a significant fresh water deficit takes place in many countries and regions, especially during dry years.

The water management challenges are becoming increasingly complex. Sustainable management of freshwater resources has gained importance at regional and global scales. ‘Sustainable’ water resources management is generally sought to be achieved by Integrated Water Resources Management. However, the precise interpretation of this term varies considerably. All definitions broadly include the concept of maintaining and enhancing the environment, taking into account competing users, instream ecosystems, and wetlands. Water and land governance are important components of managing water in order to achieve sustainable water resources for a range of political, socio-economic and administrative systems (GWP, 2002).

The movement of water between the land surface, oceans and atmosphere is called the hydrologic cycle. Water in the atmosphere is transported to the land surface and oceans as precipitation (rain, snow or sleet). Upon reaching the land surface, water may immediately become streamflow, or it may infiltrate into the soil where it may later be taken up by plants or it can percolate to the groundwater. Surface streamflow and groundwater flow
move water from the land surface to lakes and the ocean. Water re-enters the atmosphere as vapor either via evaporation from surface waters (ocean, lakes, etc.) or transpiration from plants. This cyclical movement of water is driven by solar energy. Any changes in net solar radiation or temperature will affect the processes within this cycle (evaporation, condensation, precipitation, etc.).

Accordingly, changes to the earth's climate have a direct effect on the global hydrological cycle and hence on water. However, all the methods for estimating water resources, water use, water availability, and their temporal and spatial distribution are based on the conception of a stationary climate. It implies that the climatic conditions and subsequent water resources variations in the future would be analogous to those that took place during the past observational period. In hydrology this conception of stationary climatic situation is so far to a full extent used all over the world not only to assess water resources and water use but also to calculate characteristics necessary for construction design. Regional and global prediction estimates for water use and water availability were always based on the conception. The situation has basically changed in the recent years when the problem of global climate change was raised.

1.2 The Climate System

Climate is the average pattern of weather over the long term. In other words, Climate is the long-term statistical expression of short-term weather. Climate can be defined qualitatively as "expected weather" (Bradley, 1985), or quantitatively by statistical expressions such as central tendencies and variances. The overall distribution of climatological parameters, bounded by weather extremes, defines the climatic variability. Changes in climate can be defined by the differences between average conditions at two separate times. Climate may vary in different ways and over different time scales. Variations may be periodic (and hence predictable), quasi-periodic or non-periodic (Hare, 1979).

The key to understanding global climate change is to first understand what global climate is, and how it operates. The global climate system is a consequence of and a link between the atmosphere, oceans, the ice sheets (cryosphere), living organisms (biosphere) and the soils, sediments and rocks (geosphere).
1.2.1 The Atmosphere

The atmosphere is a mixture of different gases and aerosols (suspended liquid and solid particles) collectively known as air which envelopes the Earth, forming an integrated environmental (climate) system with all the Earth's components. The atmosphere provides various functions, not least the ability to sustain life. Of prime interest for climate change is its ability to control the Earth's energy budget. The gaseous composition of the atmosphere remains remarkably uniform and is the result of efficient biogeochemical recycling processes and turbulent mixing. The two most abundant gases are nitrogen (78% by volume) and oxygen (21% by volume), and together they make up over 99% of the lower atmosphere. There is no evidence that the relative levels of these two gases are changing significantly over time (Kemp, 1994). Despite their relative scarcity, the remaining 1% minor gases, the so-called greenhouse gases, play an important role in the regulation of the atmosphere's energy budget. Carbon dioxide is the most important of these minor gases.

Most of the gaseous constituents are well mixed throughout the atmosphere. However, the atmosphere itself is not physically uniform but has significant variations in temperature and pressure with altitude. Figure 1.1 shows the structure of the atmosphere, in which a series of layers is defined by reversals of temperature.

The lowest layer, often referred to as the lower atmosphere, is called the troposphere. It ranges in thickness from 8km at the poles to 16km over the equator, mainly as the result of the different energy budgets at these locations (Campbell, 1986; Lamb, 1982). Although variations do occur, the average decline in temperature with altitude (known as the lapse rate) is approximately 6.5°C per kilometer. The troposphere contains up to 75% of the gaseous mass of the atmosphere, as well as nearly all of the water vapor and aerosols (Barry and Chorley, 1992), whilst 99% of the mass of the atmosphere lies within the lowest 30km. Owing to the temperature structure of the troposphere, it is in this region of the atmosphere where most of the world's weather systems develop. These are partly driven by convective processes that are established as warm surface air (heated by the Earth's surface) expands and rises before it is cooled at higher levels in the troposphere.
Figure 1.1 Vertical structure of the Atmosphere

The tropopause (Figure 1.1) marks the upper limit of the troposphere, above which temperatures remain constant before starting to rise again above about 20km. This temperature inversion prevents further convection of air, thus confining most of the world's weather to the troposphere.

The layer above the tropopause in which temperatures start to rise is known as the stratosphere. Throughout this layer, temperatures continue to rise to about an altitude of 50km, where the rarefied air may attain temperatures close to 0°C. This rise in temperature is caused by the absorption of solar ultraviolet radiation by the ozone layer. Such a temperature profile creates very stable conditions, and the stratosphere lacks the turbulence that is so prevalent in the troposphere.

The stratosphere is capped by the stratopause, another temperature inversion occurring at about 50km. Above this, lies the mesosphere up to about 80km through which temperatures fall again to almost -100°C. Above 80km temperatures rise continually (the thermosphere) to well beyond 1000°C, although owing to the highly rarefied nature of the atmosphere at these heights, such values are not comparable to those of the troposphere or stratosphere.
Only by consideration of the climate system in these terms it is possible to understand the flows and cycles of energy and matter in the atmosphere, an understanding which is required to investigate the causes and effects of climatic change. It is the fluxes principally of energy but also of moisture, momentum and mass, which determine the state of our climate. Factors which influence these on a global scale may be regarded as causes of global climate change. So far, however, only the fluxes in and out of and within the atmosphere have been considered. The atmosphere forms just one, albeit, major component of the climate system. Before looking at the causes of global climate change then, it is worth devoting a little time to the other components of the climate system (the oceans, cryosphere, biosphere and geosphere), and how the fluxes of energy, moisture momentum and mass operate between them.

1.2.2 The Oceans

It is clear that the atmosphere does not respond as an isolated system. Like the atmosphere, the thermodynamic state of the oceans is determined by the transfer of heat, momentum and moisture to and from the atmosphere. Ignoring for the moment the other components of the climate system, these fluxes within this coupled ocean-atmosphere system exist in equilibrium. Momentum is transferred to the oceans by surface winds, mobilizing the global surface ocean currents (Cubasch and Cess, 1990).

Surface ocean currents assist in the latitudinal transfer of sensible heat in a similar fashion to the process occurring in the atmosphere. Warm water moves pole-ward whilst cold water returns towards the equator. Energy is also transferred via moisture. Water evaporating from the surface of the oceans stores latent heat which is subsequently released when the vapor condenses to form clouds and precipitation.

The significance of the ocean is that it stores a much greater quantity of energy than the atmosphere. This is on account of both its larger heat capacity (4.2 times that of the atmosphere) and its much greater density (1000 times that of air). The vertical structure of the ocean (Figure 1.2) can be divided into two layers which differ in the scale of their interaction with the overlying atmosphere. The lower layer comprises the cold deep water sphere, making up 80% of the oceans' volume. The upper layer, which has closest contact with the atmosphere, is the seasonal boundary layer, a mixed water sphere extending down only 100m in the tropics but several kilometers
in Polar Regions. The seasonal boundary layer alone stores approximately 30 times as much heat as the atmosphere (Henderson-Sellers and Robinson, 1986). Thus for a given change in heat content of the ocean-atmosphere system, the temperature change in the atmosphere will be around 30 times greater than that in the ocean. Clearly then, small changes to the energy content of the oceans could have considerable effects on global climate.

![Figure 1.2 Vertical structure and circulation of the oceans](image)

Energy exchanges also occur vertically within the oceans, between the mixed boundary layer and the deep water sphere. Sea salt remains in the water during the formation of sea ice in the Polar Regions, with the effect of increased salinity of the ocean. This cold, saline water is particularly dense and sinks, transporting with it a considerable quantity of energy.

A large-scale ocean circulation that is thought to be driven by global density gradients created by surface heat and freshwater fluxes; known as global thermohaline circulation, maintains the equilibrium of water (mass) fluxes. Global thermohaline circulation plays an important role in the regulation of the global climate. Broecker and Denton (1990) have proposed that changes in this thermohaline circulation influence climate changes over millennia time scales.
1.2.3 The Cryosphere

The cryosphere consists of those regions of the globe, both land and sea, covered by snow and ice. These include Antarctica, the Arctic Ocean, Greenland, Northern Canada, Northern Siberia and most of the high mountain ranges throughout the world, where sub-zero temperatures persist throughout the year. The cryosphere plays another important role in the regulation of the global climate system. Snow and ice have a high albedo (reflectivity) that is they reflect much of the solar radiation they receive. Some parts of the Antarctic reflect as much as 90% of the incoming solar radiation, compared to a global average of 31%. Without the cryosphere, the global albedo would be considerably lower. More energy would be absorbed at the Earth's surface rather than reflected, and consequently the temperature of the atmosphere would be higher.

The cryosphere also acts to decouple the atmosphere and oceans, reducing the transfer of moisture and momentum, so stabilizing the energy transfers within the atmosphere (Henderson-Sellers and Robinson, 1986). The formation of sea ice in Polar Regions can initiate global thermohaline circulation patterns in the oceans, which greatly influence the global climate system. Finally, the presence of the cryosphere itself markedly affects the volume of the oceans and global sea levels, changes to which can affect the energy budget of the climate system.

1.2.4 The Biosphere

Life may be found in almost any environment existing on Earth. The biosphere, both on land and in the oceans, affects the albedo of the Earth's surface. Large areas of continental forest have relatively low albedos compared to barren regions such as deserts. The albedo of deciduous forests is about 0.15 to 0.18 whilst that of coniferous forests is 0.09 to 0.15 (Barry and Chorley, 1992). Tropical rainforest reflects even less energy, approximately 7 to 15% of that which it receives. In comparison, the albedo of a sandy desert is about 0.3. Clearly, the presences of the continental forests affect the energy budget of the climate system.

The biosphere also influences the fluxes of certain greenhouse gases such as carbon dioxide and methane. Plankton in the surface oceans utilizes the dissolved carbon dioxide for photosynthesis. This establishes a flux of carbon dioxide, with the oceans effectively "sucking" down the gas from the
atmosphere. On death, the plankton sink, transporting the carbon dioxide to the deep ocean. Such primary productivity reduces by at least four-fold the atmospheric concentration of carbon dioxide (Broecker, 1982), weakening significantly the Earth's natural greenhouse effect.

The biosphere also influences the amount of aerosols in the atmosphere. Millions of spores, viruses, bacteria, pollen and other minute organic species are transported into the atmosphere by winds, where they can scatter incoming solar radiation, and so influence the global energy budget. Primary productivity in the oceans results in the emission of compounds known as dimethyl sulphides (DMSs). In the atmosphere these compounds oxidize to form sulphate aerosols called marine non-sea-salt (nss) sulphate (Charlson et al., 1987). These nss sulphates act as condensation nuclei for water vapor in the atmosphere, thus allowing the formation of clouds. Clouds have a highly complex effect on the energy budget of the climate system. Thus changes in primary productivity in the oceans can affect, indirectly, the global climate system.

There are other mechanisms and processes which couple the biosphere with the rest of the climate system (Broecker, 1982) and (Charlson et al., 1987), however, the major influences of the biosphere upon the global climate system has been considered.

1.2.5 The Geosphere

The final component of the global climate system is the geosphere, consisting of the soils, the sediments and rocks of the Earth's land masses, the continental and oceanic crust and ultimately the interior of the Earth itself. These parts of the geosphere each play a role in the regulation and variation of global climate, to a greater or lesser extent, over varying time scales. Variations in global climate over tens of millions or even hundreds of millions of years are due to modulations within the interior of the Earth (Pickering and Owen, 1994; Raymo and Ruddiman, 1992; Ruddiman and Kutzbach, 1991). Changes in the shape of ocean basins and the size of continental mountain chains (driven by plate tectonic processes) may influence the energy transfers within and between the coupled components of the climate system.

On much shorter time scales physical and chemical processes affect certain characteristics of the soil, such as moisture availability and water run-off,
and the fluxes of greenhouse gases and aerosols into the atmosphere and oceans (Cubasch & Cess, 1990; McBean & McCarthy, 1990). Volcanism, although driven by the slow movement of the tectonic plates, occurs regularly on much shorter timescales. Volcanic eruptions replenish the carbon dioxide in the atmosphere, removed by the biosphere, and emit considerable quantities of dust and aerosols. Volcanic activity can therefore affect the energy budget and regulation of the global climate system (Sear et al., 1987).

1.3 Climate and Freshwater

Freshwater is indispensable for all forms of life and is needed in almost all human activities. The importance of freshwater to our life support system is widely recognized. Water is involved in all components of the climate system. Climate and freshwater systems are interconnected in complex ways. Any change in one of these systems induces a change in the other. For example, the draining of large wetlands may cause changes in moisture recycling and a decrease of precipitation in particular months, when local boundary conditions dominate over the large-scale circulation (Kanae et al., 2001). Conversely, climate change affects freshwater quantity and quality with respect to both mean states and variability (e.g., water availability as well as floods and droughts).

Water is an integral component of climate change and the primary medium through which it exhibits its impacts. With the world facing growing water challenges in many regions, how climate change will affect future societies cannot be understood without looking at its impact on this most vital of our planet’s resources. Changes in our water resources are shaped to a great extent by a number of key externalities, among them climate change, and that decisions taken far from the conventionally defined water sector have a tremendous influence on water resources.

Climate change directly affects the water cycle and, through it, the quantity and quality of water resources available to meet human and environmental demands. It can lead to both floods and drought. Rising sea levels have a serious effect on coastal aquifers, a major source of urban and regional water supply systems, and higher water temperatures and changes in extremes can exacerbate many forms of water pollution. Water supply reliability, health, agriculture, energy and aquatic ecosystems – all will feel the impact of these
changes to the water cycle. The demand for water to meet these needs is also affected by climate change. The importance of water to sustainable social and economic development cannot be underestimated, yet many countries are already facing multiple water challenges, all of them compounded by climate change.

Global climate change is expected to have negative effects on water resources as a result of increased variability in extreme events such as droughts and floods. With respect to water supply, it is very likely that the costs of climate change will outweigh the benefits globally. One reason is that precipitation variability is very likely to increase, and more frequent floods and droughts are anticipated. Any substantial change in the frequency of floods and droughts, or in the quantity and quality or seasonal timing of water availability, will require adjustments that may be costly, not only in monetary terms but also in terms of societal and ecological impacts, including the need to manage potential conflicts.

Hydrological changes may have impacts that are positive in some aspects and negative in others. For example, increased annual runoff may produce benefits for water users by increasing renewable water resources, but may simultaneously generate harm by increasing flood risk. Increased runoff could also damage areas with a shallow water table. In such areas, a water table rise disturbs agricultural use and damages buildings in urban areas. In addition, an increase in annual runoff may not lead to a beneficial increase in readily available water resources, if that additional runoff is concentrated during the high-flow season. Heavy precipitation events are identified as one of the major climate-change-related concerns. Increased precipitation intensity may result in periods of increased turbidity and nutrient and pathogen loadings to surface water sources, requiring substantial additional treatment and monitoring costs.

Higher temperatures and increased variability of precipitation would, in general, lead to increased irrigation water demand, even if the total precipitation during the growing season remains the same. The goal of improved safe access to drinking water will be harder to achieve in regions where runoff and/or groundwater recharge decreases as a result of climate change. The greater availability of water due to increased precipitation is the principal cause of decreasing water stress, while growing water withdrawals are the principal cause of increasing water stress.
Water use is impacted by climate change, and also, more importantly, by changes in population, lifestyle, economy, and technology; in particular by food demand, which drives irrigated agriculture, globally the largest water-use sector. Significant changes in water use or the hydrological cycle (affecting water supply and floods) require adaptation in the management of water resources. Therefore, the relationship between climate change and freshwater resources is of primary concern and interest.

So far, water resource issues have not been adequately addressed in climate change analyses and climate policy formulations. Likewise, in most cases, climate change problems have not been adequately dealt with in water resources analyses, management and policy formulation. According to many experts, water and its availability and quality will be the main pressures on, and issues for, societies and the environment under climate change; hence it is necessary to improve our understanding of the problems involved.

The development of water management strategies must, therefore, take climate change into account, as it adds to uncertainty and unpredictability in the water supply. Managing water resources is made more difficult by a lack of knowledge and information required for decision-making and long-term planning. Few countries know how much water is being used, for what purposes, nor the quantity and quality of water that is available. Few know how much water can be withdrawn without serious environmental consequences, nor the amount of finance being invested in water management and infrastructure. Climate change complicates these uncertainties.
CHAPTER 2

Detecting and Attributing Climate Change
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Detecting and Attributing Climate Change

2.1 Introduction

The climate has changed in the past, is changing presently and will change in the future. The scale of the fluctuations varies from hundreds of millions of years to decades or less (Huggett 1991; Issar 2003). Using knowledge of past climates to qualify the nature of ongoing changes has become a concern of growing importance during the last decades.

Detection of climate change is the process of demonstrating that climate has changed in a defined statistical sense, without providing a reason for that change. Attribution of causes of climate change is the process of establishing the most likely causes for the detected change, with some defined level of confidence. Attribution of anthropogenic climate change must be pursued by: (a) detecting that the climate has changed according to a defined statistical judgment; (b) demonstrating that the detected change is consistent with models calculated simulations that is to occur in response to anthropogenic forcing; and (c) demonstrating that the detected change is not consistent with alternative physical explanations other than anthropogenic forcings.

Both detection and attribution rely on observational data and model output. Estimates of century-scale time series of natural climate fluctuations are difficult to obtain directly from observations due to the relatively short length of most observational records. Model simulations with no changes in external forcing (e.g., no increases in atmospheric CO$_2$ concentration) provide valuable information on the natural internal variability of the climate system on time scales of years to centuries.

Attribution, on the other hand, requires output from model runs that incorporate historical estimates of changes in key anthropogenic and natural forcings, such as well-mixed greenhouse gases, volcanic aerosols and solar irradiance. These simulations can be performed with changes in a single forcing only (which helps to isolate the climate effect of that forcing), or with simultaneous changes in a whole set of forcings.
In the early years of detection and attribution research, the focus was on a single time series—the estimated global-mean changes in the Earth’s surface temperature. While it was not possible to detect anthropogenic warming until Wigley and Raper (1990) used a simple energy-balance climate model to show that the observed change in global-mean surface temperature from 1867 to 1982 could not be explained by natural internal variability.

As the science of climate change progressed, detection and attribution research ventured into more sophisticated statistical analyses that examined complex patterns of climate change. Climate change patterns or ‘fingerprints’ were no longer limited to a single variable (temperature) or to the Earth’s surface. More recent detection and attribution work has made use of precipitation and global pressure patterns, and analysis of vertical profiles of temperature change in the ocean and atmosphere. Studies with multiple variables make it easier to address attribution issues. While two different climate forcings may yield similar changes in global mean temperature, it is highly unlikely that they will produce exactly the same ‘fingerprint’.

Such model-predicted fingerprints of anthropogenic climate change are clearly statistically identifiable in observed data. The common conclusion of a wide range of fingerprint studies conducted over the past 15 years is that observed climate changes cannot be explained by natural factors alone (Santer et al., 1995; Hegerl et al., 1997, 2000; Hasselmann, 1997 et al., Stott et al., 2000). A substantial anthropogenic influence is required in order to best explain the observed changes. This work strengthens the scientific case for an evident human influence on global climate.

Attribution of observed regional changes in natural and managed systems to anthropogenic climate change is complicated by the effects of natural climate variability and non-climate drivers. Nevertheless, there have been several joint attribution studies that have linked responses in some physical and biological systems directly to anthropogenic climate change using climate, process and statistical models.

The present climatic trend (i.e. a warming trend), which is no longer a hypothesis but a planet-wide observation, may correspond to a natural warming phase, probably at the scale of a few hundred years, which began in the nineteenth century; the warming is being accelerated and increased because of the anthropogenic release of greenhouse gases from fossil fuels burnt during the last two centuries.
2.2 The IPCC Assessments

The World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) in 1988 with the assigned role of assessing the scientific, technical and socioeconomic information relevant for understanding the risk of human induced climate change. The IPCC is open to all UNEP and WMO members. The original mandate for the IPCC involved: identification of uncertainties, potential impacts, policy implications and response strategies; and the transfer of this information to governments and intergovernmental organizations.

A main activity of the IPCC is to provide on a regular basis an assessment of the state of knowledge on climate change. The IPCC also prepares Special Reports and Technical Papers on topics for which independent scientific information and advice is deemed necessary. It does not directly support new research or monitor climate-related data. However, the IPCC process of synthesis and assessment has often inspired scientific research leading to new findings.

The IPCC First Assessment Report (FAR) was completed in 1990. It made a persuasive, but not quantitative, case for anthropogenic interference with the climate system. Most conclusions from the FAR were non-quantitative, (e.g., emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases). The Policymakers Summary of the FAR gave a broad overview of climate change science and its Executive Summary separated key findings into areas of varying levels of confidence ranging from ‘certainty’ to providing an expert ‘judgment’. However, the importance of identifying those areas where climate scientists had high confidence was recognized in the Policymakers Summary.

The IPCC Second Assessment Report (SAR) was culminated in the government plenary in Madrid in November 1995. The most cited finding from that plenary, on attribution of climate change, suggests an evident human influence on global climate. The SAR provided key input to the negotiations that led to the adoption in 1997 of the Kyoto Protocol.

The IPCC Third Assessment Report (TAR) was approved at the government plenary in Shanghai in January 2001. The major summary statements from
the TAR strengthened the attribution statement: ‘The Earth’s climate system has demonstrably changed on both global and regional scales since the pre-industrial era, with some of these changes attributable to human activities’. Since the TAR, progress in understanding how climate is changing in space and time has been gained through improvements and extensions of numerous datasets and data analyses, broader geographical coverage, better understanding of uncertainties and a wider variety of measurements.

The IPCC Fourth Assessment Report (AR4) "Climate Change 2007", has been completed as the fourth in a series of reports intended to assess scientific, technical and socio-economic information concerning climate change, its potential effects, and options for adaptation and mitigation. The report is the largest and most detailed summary of the climate change situation ever undertaken comprising The Physical Science Basis, Impacts, Adaptation and Vulnerability and Mitigation of Climate Change. AR4 provided assessment of the current scientific knowledge of the natural and human drivers of climate change, observed changes in climate, the ability of science to attribute changes to different causes, relationship between adaptation and mitigation and projections for future climate change.

2.3 Climate Change

The overall state of the global climate is determined by the balance of solar and terrestrial radiation budgets. Regulation of the energy balance depends upon the fluxes of energy, moisture, mass and momentum within the global climate system, made up of its five components; the atmosphere, the oceans, the cryosphere, the biosphere and the geosphere. Arguably there is a sixth component; an anthropogenic system. In the last 200 years, through increased utilization of the world's resources, humans have begun to influence the global climate system, primarily by increasing the Earth's natural greenhouse effect.

Any change to the global system, results in climate change. Changes in the system are produced by either internal or external forcing mechanisms; involving agents acting from either inside or outside the climate system. Therefore, the exploration of climate change encompasses many fields, including physics, chemistry, biology, geology, meteorology, oceanography, and even sociology.
Climate change in the International Panel on Climate Change (IPCC) refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity.

This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), where climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods (IPCC, 2007).

Accordingly, climate change refers to any significant change in measures of climate (such as temperature, precipitation, or wind) lasting for an extended period (decades or longer). Climate change may result from:

- natural factors, such as changes in the sun's intensity or slow changes in the Earth's orbit around the sun;
- natural processes within the climate system (e.g. changes in ocean circulation);
- human activities that change the atmosphere's composition (e.g. through burning fossil fuels) and the land surface (e.g. deforestation, reforestation, urbanization, desertification, etc.)

The term global warming refers to an average increase in the temperature of the atmosphere near the Earth's surface and in the troposphere where clouds and "weather" phenomena occur (the lowest part of the atmosphere from the surface to an altitude ranging from 9 km in high latitudes to 16 km in the tropics on average), which can contribute to changes in global climate patterns. Global warming can occur from a variety of causes, both natural and human induced. In common usage, "global warming" often refers to the warming that can occur as a result of increased emissions of greenhouse gases from human activities.

The term climate change is often used interchangeably with the term global warming, but according to the U.S. National Academy of Sciences, "the phrase 'climate change' is growing in preferred use to 'global warming' because it helps convey that there are other changes in addition to rising temperatures."
2.3.1 Past and Recent Climate Changes

The period for which we have instrumental records of climate change, such as observational records of temperature and rainfall, spans only a tiny fraction of Earth History. Furthermore, although we are now concerned with global warming due to mankind's greenhouse gas pollution of the atmosphere, this contemporary climate change should be placed in the context of much longer term changes in climate that have taken place quite naturally. Prehistoric climate change is known to climatologists and Earth scientists as palaeoclimatic change. Palaeoclimatology provides a longer perspective on climate variability that can improve our understanding of the climate system, and help us to predict future climatic changes as a result of man-made global warming. Evidence for palaeoclimatic change can be obtained by the study of natural phenomena which are climate-dependent. Such evidence comes from palaeoclimatic records.

The Earth's climate has changed many times throughout the planet's history. With events ranging from glacial periods or "ice ages" where ice covered significant portions of the Earth to interglacial periods where ice retreated to the poles or melted entirely to long periods of warmth, the climate has continuously changed. Historically, natural factors such as volcanic eruptions, changes in the Earth's orbit, and the amount of energy released from the Sun have affected the Earth's climate. Therefore, the global climate has shifted and varied for billions of year, perhaps since the Earth first had an atmosphere. The oldest palaeoclimatic records have allowed us to reconstruct climate fairly reliably during the last 500 million years. Over this time, the global climate has moved from extensive periods of global warmth to periods of global cold several times, each lasting 100 million years or more.

Although today we are concerned about global warming, we do in fact lie in the middle of global ice-house climate, which began 40 million years ago, when the first permanent ice sheets formed on Antarctica. The change from the much warmer global climate which existed during the age of the dinosaurs, when global average temperature was perhaps 10°C higher than at present, is thought to have been caused by changes in the distribution of landmasses and the associated changes to energy redistribution throughout the climate system.
Within the long-term global icehouse climate, much shorter-term fluctuations in global climate have occurred. Relatively cold periods known as Ice Ages or glacialis, each lasting roughly 100,000 years, are interspersed with much shorter warmer episodes or interglacials, lasting only 10,000 years. We now have a relatively clear record of such climatic fluctuations over the last 2 million years. Currently, the global climate lies within an interglacial. Global average temperature 20,000 years ago towards the end of the last Ice Age was some 5°C lower than today, when the north polar ice sheets were expanded to cover a considerably greater area of the continental Northern Hemisphere than is the case today. These glacial-interglacial fluctuations are believed to be driven by changes in the position of the Earth in its orbit around the Sun, and enhanced by climatic feedback processes which involve changes in ocean circulation and the greenhouse gas composition of the atmosphere.

Within the latest present interglacial period, further fluctuations in the global climate can be seen in the palaeoclimatic records and more recently in the instrumental records. During the last 1000 years, the climate has moved from a period of Medieval warmth to a "Little Ice Age" between the 16th and 19th centuries, with changes of between 0.5 and 1°C in the global average surface temperature. Although it is not clear what has caused these climatic changes, variations in the Sun's energy output, ocean circulation and the occurrence of major volcanic eruptions are believed to play a part.

Many natural systems are dependent on climate. From these it may be possible to derive palaeoclimatic information for variables such as temperature or rainfall. Such proxy or indirect records of climate contain a climatic signal. Deciphering that signal is often a complex business. Four types of palaeoclimatic record are commonly analyzed for past climate variations. These include historical records, glaciological records (for example ice cores), biological records (for example tree rings), and geological records (for example ocean sediments). Scientists have been able to reconstruct a picture of the Earth's climate dating back decades to millions of years ago by analyzing such surrogate, or "proxy," records of climate.

The suitability of a particular palaeoclimatic record for reconstructing a past climate will be largely dependent upon the time scale of past climate change under study. Recent climate changes during the last few thousand years can be reliably reconstructed from tree ring analyses, which often yield continuous records and provide high-resolution (annual or even seasonal)
data. Over the longer term, ice cores and sea sediments offer information about palaeoclimates stretching back hundreds of thousands of years, although the data resolution may not be as fine. Generally, the further back in time we go the greater the margins of uncertainty that will be attached to palaeoclimatic reconstructions.

Most recently, we have entered a renewed period of global warming since the beginning of the 20th century that we suspect is the result of mankind's enhancement of the natural greenhouse effect through the pollution of the atmosphere. Global average temperature is now about the same as it was during the Medieval warm period, although still much lower than it was 100 million years ago during the age of the dinosaurs. Beginning late in the 18th century, human activities associated with the Industrial Revolution have also substantially added to the amount of heat-trapping greenhouse gases in the atmosphere. The burning of fossil fuels and biomass (living matter such as vegetation) has also resulted in emissions of aerosols that absorb and emit heat, and reflect light. The addition of greenhouse gases and aerosols has changed the composition of the atmosphere. The changes in the atmosphere have likely influenced temperature, precipitation, storms and sea level (IPCC, 2007).

Recent climate change may be studied by analyzing instrumental records of common climate elements such as temperature, precipitation (rain, snow and hail), humidity, wind, sunshine and atmospheric pressure, which have been obtained with standard equipment. According to internationally recognized procedures, the measuring instruments must be properly installed in suitable places, carefully maintained and conscientiously observed. Although it is not possible to measure the climate per se, the records of individual climate elements taken together can be used to specify the physical state of the climate at a given place, for a particular period of time. Such records of climate elements collected over time are known as "time series".

The most commonly measured element is temperature. Temperature is a valuable climate element in climate observation because it directly provides a measure of the energy contained within the system under inspection. For example, a global average temperature reveals information about the energy content of the Earth's climate system, and most significantly the global energy balance. A higher temperature would indicate that more energy is stored within the Earth's climate. Changes in global temperature indicate changes in the global energy balance.
Many surface air temperature records extend back to the middle part of the 19th century. The oldest record comes from central England and is over 300 years in length. The measurement of surface air temperature is essentially the same now as it was then, using a mercury-in-glass thermometer, which can be used down to -39°C, the freezing point of mercury. For lower temperatures, mercury is usually substituted by alcohol. More recently, observations of surface ocean temperature have been collected to provide a more accurate picture of the global average surface temperature. Maximum and minimum temperatures measured during specified time periods, usually 24 hours, provide useful information for the construction and analysis of temperature time series. Analysis involves the calculation of averages and the identification, using various mathematical techniques, of periodic variations and trends, which may reveal evidence of climate change.

Rainfall is measured most simply by noting periodically how much has been collected in an exposed vessel since the time of the last observation. Care must be taken to avoid underestimating rainfall due to evaporation of the collected water and the effects of wind. Time series can be constructed and analysis performed in a similar manner to those of temperature. Rainfall, however, varies much more widely than temperature over relatively small geographical areas, and over short periods of time. Typically, a sharp thunderstorm may affect one locality, but not another perhaps only 10 miles away. Consequently, analysis of precipitation time series is more complex than for temperature. The measurement of global rainfall offers an indirect assessment of the energy of the Earth's climate system. Increased heat storage within the atmosphere and surface oceans will increase the rate of evaporation, cloud formation and ultimately precipitation.

Understanding and attribution of observed changes also presents a challenge. For hydrological variables such as runoff, non-climate factors may play an important role locally (e.g., changes in extraction). The climate response to forcing agents is also complex.

Despite such uncertainties, a number of statements can be made on the attribution of observed hydrological changes (IPCC, 2007). However, these features of the climate also vary naturally, so determining what fraction of climate changes are due to natural variability versus human activities is challenging. Though climate change is not new, the study of how human activity affects the earth’s climate is.
2.3.2 Future Climate Change

Greenhouse gas concentrations in the atmosphere will increase during the next century unless greenhouse gas emissions decrease substantially from present levels. Increased greenhouse gas concentrations are very likely to raise the Earth's average temperature, influence precipitation and some storm patterns as well as raise sea levels (IPCC, 2007). The magnitude of these changes, however, is uncertain.

The amount and speed of future climate change will ultimately depend on:

- Whether greenhouse gases and aerosol concentrations increase, stay the same or decrease.
- How strongly features of the climate (e.g. temperature, precipitation and sea level) respond to changes in greenhouse gas and aerosol concentrations.
- How much the climate varies as a result of natural influences (e.g. from volcanic activity and changes in the sun’s intensity) and its internal variability (referring to random changes in the circulation of the atmosphere and oceans).

It is important to recognize that projections of climate change in specific areas are not forecasts comparable to tomorrow’s weather forecast. Rather, they are hypothetical examples of how the climate might change and usually contain a range of possibilities as opposed to one specific high likelihood outcome.

As with any field of scientific study, there are uncertainties associated with the science of climate change. This does not imply that scientists do not have confidence in many aspects of climate science. Some aspects of the science are known with virtual certainty, because they are based on well-known physical laws and documented trends. Current understanding of many aspects of climate change ranges from “very likely” to “uncertain.”

Scientists know with virtual certainty that:

- Human activities are changing the composition of Earth's atmosphere. Increasing levels of greenhouse gases like carbon dioxide (CO₂) in the atmosphere since pre-industrial times are well-documented and understood.
The atmospheric buildup of CO$_2$ and other greenhouse gases is largely the result of human activities such as the burning of fossil fuels.

An “unequivocal” warming trend of about 0.56 to 0.92°C occurred from 1906-2005. Warming occurred in both the Northern and Southern Hemispheres, and over the oceans (IPCC, 2007).

The major greenhouse gases emitted by human activities remain in the atmosphere for periods ranging from decades to centuries. It is therefore virtually certain that atmospheric concentrations of greenhouse gases will continue to rise over the next few decades.

Increasing greenhouse gas concentrations tend to warm the planet.

The Intergovernmental Panel on Climate Change (IPCC) has stated "Most of the observed increase in global average temperatures since the mid-20$^{th}$ century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations" (IPCC, 2007).

In short, a growing number of scientific analyses indicate, but cannot prove, that rising levels of greenhouse gases in the atmosphere are contributing to climate change (as theory predicts). In the coming decades, scientists anticipate that as atmospheric concentrations of greenhouse gases continue to rise, average global temperatures and sea levels will continue to rise as a result and precipitation patterns will change.

Important scientific questions remain about how much warming will occur, how fast it will occur, and how the warming will affect the rest of the climate system including precipitation patterns and storms. Answering these questions will require advances in scientific knowledge in a number of areas:

- Improving understanding of natural climatic variations, changes in the sun's energy, land-use changes, the warming or cooling effects of pollutant aerosols, and the impacts of changing humidity and cloud cover.
- Determining the relative contribution to climate change of human activities and natural causes.
- Projecting future greenhouse emissions and how the climate system will respond within a narrow range.
- Improving understanding of the potential for rapid or abrupt climate change.
Human-induced climate change has the potential to alter the prevalence and severity of extremes such as heat waves, cold waves, storms, floods and droughts. Though predicting changes in these types of events under a changing climate is difficult, understanding vulnerabilities to such changes is a critical part of estimating vulnerabilities and future climate change impacts on human health, society and the environment.

For the next two decades a warming of about 0.2°C per decade is projected for a range of emissions scenarios. Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected. Afterwards, temperature projections increasingly depend on specific emissions scenarios.

Since the IPCC’s first report in 1990, assessed projections have suggested global averaged temperature increases between about 0.15 and 0.3°C per decade from 1990 to 2005. This can now be compared with observed values of about 0.2°C per decade, strengthening confidence in near-term projections.

Our current level of understanding, as summarized in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC, 2007), is as follows: Since 1950, the number of heat waves has increased and widespread increases have occurred in the numbers of warm nights. The extent of regions affected by droughts has also increased as precipitation over land has marginally decreased while evaporation has increased due to warmer conditions. Generally, numbers of heavy daily precipitation events that lead to flooding have increased, but not everywhere.

The IPCC projects the following likely, very likely, or certain changes in extreme events and associated effects between now and 2100 (Table 2.1):
Table 2.1 Projections of extreme events and associated impacts by sector

<table>
<thead>
<tr>
<th>Projected Change</th>
<th>Likelihood of projected impacts</th>
<th>Projected Impacts by Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Agriculture, forestry</td>
</tr>
<tr>
<td>Warmer/fewer cold warmer/more hot days/nights over most land areas.</td>
<td>Virtually certain</td>
<td>Increased yields in colder areas; decreased yields in warmer areas.</td>
</tr>
<tr>
<td>Warm spells/heat waves: frequency increases over most land areas</td>
<td>Very likely</td>
<td>Reduced yields due to heat stress at key growth stages.</td>
</tr>
<tr>
<td>Heavy precipitation: frequency increases over most areas</td>
<td>Very likely</td>
<td>Damage to crops; wind-throw of trees.</td>
</tr>
<tr>
<td>Area affected by drought: increases</td>
<td>Likely</td>
<td>Land degradation, lower yields/crop damage failure; livestock deaths.</td>
</tr>
<tr>
<td>Number of intense tropical cyclones: increases</td>
<td>Likely</td>
<td>Damage to crops; wind-throw of trees</td>
</tr>
<tr>
<td>Incidence of extreme high sea level increases</td>
<td>Likely</td>
<td>Salinization of irrigation.</td>
</tr>
</tbody>
</table>
2.3.3 Emissions Scenarios and Climate Change

The realization that Earth’s climate might be sensitive to the atmospheric concentrations of gases that create a greenhouse effect is more than a century old. Fleming (1998) and Weart (2003) provided an overview of the emerging science. The Special Report on Emissions Scenarios (SRES) is a report prepared by the IPCC in 2001, on future emission scenarios to be used for driving global circulation models to develop climate change scenarios. The SRES Scenarios were also used for the IPCC report in 2007.

Because projections of climate change depend heavily upon future human activity, climate models are run against scenarios. There are 40 different scenarios, each making different assumptions for future greenhouse gas pollution, land-use and other driving forces. Assumptions about future technological development as well as the future economic development are thus made for each scenario. These emission scenarios are organized into families with common themes. IPCC assessment report projections for the future are often made in the context of a specific scenario family. The six families of scenarios discussed in the IPCC's Assessment Reports are A1FI, A1B, A1T, A2, B1, and B2.

The A1 scenarios are of a more integrated world. The A1 family of scenarios is characterized by:

- Rapid economic growth.
- A global population that reaches 9 billion in 2050 and then gradually declines.
- The quick spread of new and efficient technologies.
- A convergent world - income and way of life converge between regions. Extensive social and cultural interactions worldwide.

There are subsets to the A1 family based on their technological emphasis:

- A1FI - An emphasis on fossil-fuels.
- A1B - A balanced emphasis on all energy sources.
- A1T - Emphasis on non-fossil energy sources.

The A2 scenarios are of a more divided world. The A2 family of scenarios is characterized by:

- A world of independently operating, self-reliant nations.
• Continuously increasing population.
• Regionally oriented economic development.
• Slower and more fragmented technological changes and improvements to per capita income.

The B1 scenarios are of a world more integrated, and more ecologically friendly. The B1 scenarios are characterized by:
• Rapid economic growth as in A1, but with rapid changes towards a service and information economy.
• Population rising to 9 billion in 2050 and then declining as in A1.
• Reductions in material intensity and the introduction of clean and resource efficient technologies.
• An emphasis on global solutions to economic, social and environmental stability.

The B2 scenarios are of a world more divided, but more ecologically friendly. The B2 scenarios are characterized by:
• Continuously increasing population, but at a slower rate than in A2.
• Emphasis on local rather than global solutions to economic, social and environmental stability.
• Intermediate levels of economic development.
• Less rapid and more fragmented technological change than in B1 and A1.

Carbon dioxide-equivalent (CO2-eq) emissions and concentrations
Greenhouse gases differ in their warming influence (radiative forcing) on the global climate system due to their different radiative properties and lifetimes in the atmosphere. These warming influences may be expressed through a common metric based on the radiative forcing of CO2.

• CO2-equivalent emission is the amount of CO2 emission that would cause the same time-integrated radiative forcing, over a given time horizon. The equivalent CO2 emission is obtained by multiplying the emission of a greenhouse gas by its Global Warming Potential (GWP) for the given time horizon. For a mix of greenhouse gases it is obtained by summing the equivalent CO2 emissions of each gas. Equivalent CO2 emission is a standard and useful metric for comparing emissions of different greenhouse gases but does not imply the same climate change responses.

• CO2-equivalent concentration is the concentration of CO2 that would cause the same amount of radiative forcing as a given mixture of CO2 and other forcing components.
Global greenhouse gases emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2004. Carbon dioxide (CO₂) is the most important anthropogenic greenhouse gases. Its annual emissions have grown between 1970 and 2004 by about 80%, from 21 to 38 giga-tonnes, and represented 77% of total anthropogenic greenhouse gases emissions in 2004. The rate of growth of CO₂-eq emissions was much higher during the recent 10-year period of 1995-2004 (0.92 giga-tonnes CO₂-eq per year) than during the previous period of 1970-1994 (0.43 giga-tonnes CO₂-eq per year).

The SRES scenarios project an increase of baseline global greenhouse gases emissions by a range of 9.7 to 36.7 giga-tonnes CO₂-eq (25 to 90%) between 2000 and 2030. In these scenarios, fossil fuels are projected to maintain their dominant position in the global energy mix to 2030 and beyond. Hence CO₂ emissions from energy use between 2000 and 2030 are projected to grow 40 to 110% over that period.

Studies published since SRES (i.e. post-SRES scenarios) have used lower values for some drivers for emissions, notably population projections. However, for those studies incorporating these new population projections, changes in other drivers, such as economic growth, result in little change in overall emission levels. Economic growth projections for Africa, Latin America and the Middle East to 2030 in post-SRES baseline scenarios are lower than in SRES, but this has only minor effects on global economic growth and overall emissions.

### 2.4 Climate Change Modeling Evolution

Virtually all published estimates of how the climate could change in the future are produced by computer models of the Earth’s climate system. Climate models attempt to simulate the behavior of the climate, in an attempt to understand the key physical, chemical and biological processes which govern climate. Climate models give us a better understanding of the climate system, providing us with a clearer picture of past climates by comparison with records of instrumental and palaeoclimatic observations, and enabling us to predict future climate change. The basic laws and other relationships necessary to model the climate are expressed as a series of mathematical equations. The climate however, is a very complex system, and supercomputers are needed for the task.
Global climate models have been used extensively to project global warming in the 21st century due to mankind's greenhouse gas pollution of the atmosphere. Estimates of future increases in greenhouse gases are inputted into the model, which then calculates how the global climate might evolve or respond in the future to the enhanced greenhouse effect. Although climate models can aid understanding in the processes which govern the climate, the confidence placed in such models should always be questioned. Critically, it should be remembered that all climate models represent a simplification of the climate system, a system that may ultimately prove to be too complex to model accurately.

General Circulation Models (GCMs) are the basic tool used for modeling climate change. There are 30 modeling groups around the world using a variety of GCMs to investigate the potential impact of human activity on the climate. The key equations are those relating to the conservation of mass, momentum and energy in the atmosphere and ocean, and are solved at a large number of points on a three-dimensional grid covering the whole world.

The models used to evaluate future climate changes have therefore evolved over time. Most of the pioneering work on CO2-induced climate change was based on atmospheric general circulation models coupled to simple ‘slab’ ocean models (i.e., models omitting ocean dynamics), from the early work of Manabe and Wetherald (1975) to the review of Schlesinger and Mitchell (1987). At the same time the physical content of the models has become more comprehensive. Similarly, most of the results presented in the IPCC FAR were from atmospheric models, rather than from coupled climate system models. Atmospheric models were used to analyze changes in the equilibrium climate resulting from a doubling of the atmospheric CO2 concentration. Current climate projections can investigate time-dependent scenarios of climate evolution and can make use of much more complex coupled ocean-atmosphere models, sometimes even including interactive chemical or biochemical components.

It has been known since the work of Lorenz (1963) that even simple models may display complex behavior because of their nonlinearities. The inherent nonlinear behavior of the climate system appears in climate simulations at all-time scales. In addition, many of the key processes that control climate sensitivity or abrupt climate changes (e.g., clouds, vegetation, oceanic convection…) depend on very small spatial scales. They cannot be
represented in full detail in the context of global models, and scientific understanding of them is still notably incomplete. With the development of computer capacities, simpler models have not disappeared; on the contrary, a stronger emphasis has been given to the concept of a ‘hierarchy of models’ as the only way to provide a linkage between theoretical understanding and the complexity of realistic models (Held, 2005). Simple models have also played a central role in the interpretation of IPCC scenarios: the investigation of climate scenarios presented in the SAR or the TAR has been extended to larger ensembles of cases using idealized models.

The notion of model hierarchy is also linked to the idea of scale: global circulation models are complemented by regional models that exhibit a higher resolution over a given area, or process oriented models, such as cloud resolving models or large eddy simulations. Earth Models of Intermediate Complexity are used to investigate long time scales, such as those corresponding to glacial to interglacial oscillations. This distinction between models according to scale is evolving quickly, driven by the increase in computer capacities. The techniques that have been developed to derive regional-scale climate projections range from applying the GCMs at a finer horizontal resolution (which is very computationally intensive) through statistical ‘downscaling’. To date, the large differences between the various models in regional-model climate projections suggest a low level of confidence in their reliability for producing realistic climate projections (BoM 2003). The results of these models, however, are useful for undertaking an analysis of the sensitivity of a particular region to climate change.

Uncertainties in climate predictions arise mainly from model uncertainties and errors. One of the areas of greatest uncertainty associated with the current generation of GCMs is their treatment of feedback mechanisms. A series of systematic comparisons of the different existing models has been used to achieve an increase in the number and range of simulations being carried out in order to more fully explore the factors affecting the accuracy of the simulations. Inter-comparison of existing models and ensemble model studies are still undergoing rapid development. Running ensembles was essentially impossible until recent computer power advances. Such progress has marked the evolution of climate change modeling and is likely to continue in the future.
CHAPTER 3

Climate Change and Aquifer Processes
CHAPTER 3

Climate Change and Aquifer Processes

3.1 Introduction

Water is involved in all components of the climate system (atmosphere, oceans, cryosphere, biosphere and geosphere). Therefore, climate change affects water through a number of mechanisms. Climate change is expected to exacerbate current stresses on water resources from population growth and economic and land-use changes. The main concern raised by global warming is that climatic variations alter the water cycle; indeed, in many cases, the data show that the hydrological cycle is already being impacted (Labat et al. 2004; Huntington 2006; IPCC 2007).

Mass losses from glaciers and reductions in mountains snow cover are projected to accelerate reducing water availability in regions supplied by melt-water. Changes in precipitation and temperature lead to changes in runoff and hence water availability. Runoff is projected to increase at higher latitudes and in some wet tropical areas. On the other hand, due to decreases in rainfall and higher rates of evapotranspiration, runoff is projected to decrease over some dry regions at mid-latitudes and dry tropics. There is high confidence that many semi-arid areas will suffer a decrease in water resources due to climate change. Drought-affected areas are projected to increase in extent, with the potential for adverse impacts on multiple sectors. Regionally, large increases in irrigation water demand as a result of climate changes are projected.

It is expected with high confidence that the negative impacts of climate change on freshwater systems outweigh its benefits. Areas in which runoff is projected to decline face a reduction in the value of the services provided by water resources. The beneficial impacts of increased annual runoff in some areas are likely to be tempered by negative effects of increased precipitation variability and seasonal runoff shifts on water supply, water quality and flood risk. Available research suggests a significant future increase in heavy rainfall events in many regions, including some in which the mean rainfall is projected to decrease. The resulting increased flood risk poses challenges to society, physical infrastructure and water quality. Increased temperatures
will further affect the physical, chemical and biological properties of freshwater lakes and rivers, with predominantly adverse impacts on many individual freshwater species and water quality. In coastal areas, sea level rise will exacerbate water resource constraints due to increased Stalinization of groundwater supplies.

Groundwater is an important natural resource. Worldwide, more than two billion people depend on groundwater for their daily water supply (Kemper 2004). The global volume of groundwater is estimated at between 13% and 30% of the total volume of fresh water of the hydrosphere (Jones 1997; Babklin & Klige 2004) and groundwater provides 15% of the water used annually (Shiklomanov 2004). A large proportion of the world’s irrigated agriculture is dependent on groundwater. As a result of the growth in the global population, the demand for clean water is rising and the pressure on surface water and groundwater resources is increasing, particularly in semiarid and arid regions of the world.

In terms of groundwater, the demand has been poorly managed and intensive use for irrigated agricultural crop production has placed groundwater resources under stress. Spatial and temporal changes in groundwater quantity and quality in an aquifer are conditioned by both anthropogenic and natural factors. To better manage groundwater resources, the vulnerability of groundwater resources to drought, over-abstraction and quality deterioration must be assessed both now and in the context of climate change (Struckmeier et al. 2004). Groundwater is the world’s largest accessible store for freshwater yet groundwater remains largely peripheral to current analyses and discussions of climate change and adaptation.

Understanding climate variability and change is vital for society and ecosystems, particularly with regard to complex changes affecting the availability and sustainability of surface-water and groundwater resources (Dragoni and Sukhija, 2008). The potential effects of climate variability and change on water resources are well recognized globally and have been identified as a major issue facing the availability of groundwater resources. Climate variability and change can affect the quantity and quality of various components in the global hydrologic cycle. The components of the surface hydrologic cycle that may be affected include atmospheric water vapor content, precipitation and evapotranspiration patterns, snow cover and melting of ice and glaciers, soil temperature and moisture, and surface runoff and streamflow (Bates et al. 2008). Such changes to the surface components
of the global hydrologic cycle will likely influence the subsurface hydrologic cycle within the soil, unsaturated zone, and saturated zone, and may affect recharge, discharge, and groundwater storage of many aquifers worldwide.

Understanding the potential effects of climate variability and change on groundwater is more complex than with surface water (Holman, 2006). Groundwater-residence times can range from days to tens of thousands of years or more, which delays and disperses the effects of climate and challenges efforts to detect responses in the groundwater to climate variability and change. Furthermore, human activities, such as groundwater pumping and resulting loss of storage and capture of natural discharge, are often on the same time scale as some climate variability and change, which makes it difficult to distinguish between human and climatic stresses on groundwater. Climate change induced effects at the human scale, on the other hand, are not well understood. From a regional or national perspective, our understanding of the impact of climate variability and change on groundwater resources, in terms of availability, vulnerability and sustainability of fresh water, remains limited.

3.2 Climate Change and Groundwater Systems

The hydrological cycle is an integral part of the climate system and climate change is expected to have negative effects on water resources such as a shorter precipitation season and an increase in hydrological extremes of floods and droughts. The hydrological cycle is closely linked with changes in atmospheric temperature. Warming of the climate system in recent decades is recognizable, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global sea level. The best-estimate linear trend in global surface temperature from 1906 to 2005 is a warming of 0.74°C (likely range 0.56 to 0.92°C), with a more rapid warming trend over the past 50 years. Attribution studies show that most of the observed increase in global temperatures is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. For widespread regions, cold days, cold nights and frost have become less frequent, while hot days, hot nights and heatwaves have become more frequent over the past 50 years (IPCC, 2007).
It has long been known that natural climate variability, particularly seasonal variability, affects groundwater systems. The groundwater aquifers are recharged mainly by precipitation or through interaction with surface water bodies; hence climate change influence on precipitation and surface water ultimately affects groundwater systems. One can predict that as an important part of the hydrologic cycle, groundwater resources will be affected by climate change in relation to the nature of recharge, the kinds of interactions between the groundwater and surface water systems, and changes in water use.

### 3.2.1 Climate Change and Aquifer Response

Spatial and temporal changes in temperature and precipitation may modify the surface hydraulic boundary conditions of, and ultimately cause a shift in the water balance of an aquifer. For example, variations in the amount of precipitation, the timing of precipitation events, and the form of precipitation are all key factors in determining the amount and timing of recharge to aquifers. The changing frequency of droughts or heavy precipitation can also be expected to impact on water levels in aquifers. Droughts result in declining water levels not only because of reduction in rainfall, but also due to increased evaporation and a reduction in infiltration that may accompany the development of dry topsoils. Paradoxically, extreme precipitation events may lead to less recharge to groundwater in upland areas because more of the precipitation is lost as runoff. Similarly, flood magnitude and frequency could increase as a consequence of increased frequency of heavy precipitation events, which could increase groundwater recharge in some floodplains.

Expected impacts include variations in groundwater level fluctuation (Chen et al., 2004), alteration of groundwater flow regimes (Scibek and Allen, 2006) and changes in the volume and quality of groundwater resources (Brouyère et al., 2004; Bloomfield et al. 2006; Ranjan et al. 2006). Climate change could affect groundwater sustainability in several ways, including sea water intrusion, water quality deterioration, potable water shortage and possible increased dependency on groundwater as a backup source of water supply.

Relative to surface water resources, the potential consequences of climate change on groundwater have not received as much attention (IPCC, 2001). Several studies have aimed to quantify the likely direct impacts of changing
precipitation and temperature patterns on groundwater recharge (Eckhardt and Ulbrich, 2003), while another has extended this analytical approach to include the indirect effects on recharge of alterations in soil and landscape resulting from different socio-economic scenarios under future climate change (Holman, 2006). Groundwater systems generally respond more slowly to climate change than surface water systems. Groundwater levels correlate more strongly with precipitation than with temperature, but temperature becomes more important for shallow aquifers and in warm periods. However, on the other hand, climate change induced effects at the human scale are not well understood. From a regional or national perspective, our understanding of the impact of climate variability and change on groundwater resources, in terms of availability, vulnerability and sustainability of fresh water, remains limited.

3.2.2 Climate Change and Hydrologic Processes

Observed climate warming over the past several decades is consistently associated with changes in a number of components of the hydrological cycle and hydrological systems such as: changing precipitation patterns, intensity and extremes; widespread melting of snow and ice; increasing atmospheric water vapor; increasing evaporation; and changes in soil moisture and runoff. There is significant natural variability, on inter-annual to decadal time-scales, in all components of the hydrological cycle, often masking long-term trends. There is still substantial uncertainty in trends of hydrological variables because of large regional differences, and because of limitations in the spatial and temporal coverage of monitoring networks (Huntington, 2006). At present, documenting inter-annual variations and trends in precipitation over the oceans remains a challenge, on the other hand, understanding and attribution of observed changes also presents a challenge (IPCC, 2007).

To the hydrologist, the question of climate change and whether or not global mean surface-air temperature has increased or will continue to increase at some rate every one hundred years is of secondary importance. The scope of the hydrologist’s work is delimited by their capacity to measure hydrologic fluxes, to analyze them, and to make meaningful and useful inferences and predictions about them at relevant spatial scales. In the practical realm, where most hydrologic work lies, the intersection of hydrologically relevant spatial scales and administrative boundaries defines a clear context for the study of hydrologic processes, with or without climate change (Loáiciga
These relevant spatial scales are referred to as regional scales. Therefore, to the hydrologist, climate change must be resolved in terms of precipitation, surface-air temperature, evapotranspiration, sediment transport, groundwater levels, water quality, and runoff changes at the relevant spatial scales. Hydrologic time-scales encompass a wide spectrum. In flood studies, the relevant temporal scales of precipitation range from minutes to days. In drought-impact studies, the precipitation and temperature temporal scales of interest vary from days to years, depending on the inter-seasonal and intra-seasonal disposition of water in the environment (Loáiciga et al., 1993).

Apart from climate influence, recharge to aquifers is very much dependent on the characteristics of the aquifer media and the properties of the overlying rocks and soils. Several physical, chemical, and modeling approaches can be used to estimate recharge on the basis of surface water, unsaturated zone, and groundwater data. Among these approaches, modeling is the only tool that can predict recharge, and it is also extremely useful in isolating the relative importance of different controls on recharge, provided that it properly accounts for the all process involved. The accuracy of recharge estimations depend largely on the availability of hydrogeologic and climatic data. However, the heterogeneous nature and, often, less knowledge of the recharge flow paths makes recharge estimation through modeling very challenging and a difficult task (McCarthy et al., 2001).

Early studies of the regional-scale hydrologic consequences of climate change, many produced between 1970 and the mid-1980s were mostly based on simple scenarios for precipitation and temperature under a warmer climate (Gleick, 1989). Precipitation was increased or decreased a certain percentage relative to historical values (the ± 10% range was commonly used). Historical temperature was increased a few degrees (typically between 1 and 5°C). Hydrologic models were then run using the two forcing variables to carry out simulations in the region of interest.

The results in terms of fluxes or other variables of interest (e.g., groundwater recharge, stream flow, groundwater levels, water quality characteristics, etc.) were compared with those corresponding to the historical climate simulations. The differences between the two sets of results were then attributed to climate change; all other forcing variables were kept unchanged (e.g., population, water use, cropping patterns, water technology, etc.).
Studies emerged in the early 1990s, have been based on the linkage between climate predictions from general circulation models (GCMs) and regional climate models (RCMs) (Henderson-Sellers and Pitman 1992; Giorgi, Marinucci, and Bates 1993a, 1993b; Giorgi, Shields-Brodeur, and Bates 1994). GCMs, which appeared in the late 1960s, have been steadily improved in their physically based structure and numerical-solution algorithms. They have also evolved by incorporating refined spatial resolution of their numerical grids. RCMs have the same physical basis as GCMs but a much finer spatial resolution, and are confined to synoptic-scale and mesoscale simulation regions, rather than planet-wide simulations. At present, a GCM may have a spatial grid with cells on the order of 200 km×200 km, while the RCMs have achieved resolutions on the order of 20 km×20 km. The RCMs rely on the coarser output from GCMs, which they use as initial and boundary conditions to drive their spatially refined simulations of climate change.

The great majority of GCM and RCM climate-change simulations are based on the so-called 2xCO$_2$ scenario, whereby the 1990 CO$_2$ atmospheric concentration (about 355 ppmv, a base level adopted by the climate-change community; e.g., Houghton et al. 1996) is doubled and that value is used in the GCMs and RCMs to simulate the 2xCO$_2$ warmer climate. The climate models simulate various climate forcing variables of hydrologic interest at the land-atmosphere interface: precipitation, air temperature, radiant-energy fluxes, wind speed, atmospheric pressure, atmospheric humidity, latent-heat flux, and runoff averaged over the models’ surface-grid cells. The RCMs’ key output variables (such as precipitation, surface-air temperature, ground level radiant-energy fluxes, water vapor pressure, and wind speed) become the forcing input variables to hydrologic models. Hydrologic models then calculate, in a classical fashion, the dependent hydrologic variables of interest, of which streamflow and groundwater levels are examples.

In some instances, GCMs and RCMs have undergone ‘‘subgrid’’ parameterizations that introduce approximate numerical representations of hydrologic processes at the land surface interface, which allows them to make calculations of hydrologic fluxes at fine spatial resolution or at selected locations. However, watershed scale hydrologic models are better suited to carry out fine resolution hydrologic simulations due to their more realistic, physically based structure and internal parameterization (Panagoulia 1992; Vaccaro, 1992). This is particularly true when attempting to simulate groundwater response to climate change.
3.3 Impacts and Vulnerabilities

Human-induced effects on groundwater resources are well known in many parts of the world and may include: seawater intrusion, reduced aquifer storage, land subsidence, the diminishment of base flow in rivers and streams, and increased potential for contamination. Similarly, it has been long known that climate variability, particularly seasonal variability, affects water levels in aquifers. Climate change induced effects at the human scale, on the other hand, are not well understood. From a regional or national perspective, our understanding of the impact of climate variability and change on groundwater resources, in terms of availability, vulnerability and sustainability of fresh water, remains limited. Examples of potential impacts of climate change on groundwater resources include:

Direct impacts
- Variation in duration, amount and intensity of precipitation and evapotranspiration will increase or decrease recharge rates.
- Rising sea levels will allow saltwater to penetrate farther inland and upstream in low lying river deltas.
- Variation in CO$_2$ concentrations may affect carbonate dissolution and the formation of karst.

Indirect impacts
- Land cover changes (viz. natural vegetation and crops) may increase or decrease recharge.
- Increase in groundwater extraction due to decrease in reliability of surface water as a result of increased floods and droughts.
- Increase in flood frequencies may affect groundwater quality of alluvial aquifers.
- Variation in soil organic carbon content may affect the infiltration properties above aquifers.

3.3.1 Droughts and Groundwater Sustainability

The term "drought" has different meanings, depending on the effects and results of water deficiency. Droughts have been classified into different types such as meteorological drought (lack of precipitation), agricultural drought (lack of soil moisture), or hydrologic drought (reduced streamflow or groundwater levels). It is not unusual for a given period of water deficiency to represent a more severe drought of one type than another type. For example, a prolonged dry period during the summer may substantially
lower the yield of crops due to a shortage of soil moisture in the plant root zone but have little effect on groundwater storage replenished the previous spring. On the other hand, a prolonged dry period when maximum recharge normally occurs can lower groundwater levels to the point at which shallow wells go dry.

Groundwater systems are a possible backup source of water during periods of drought. If groundwater storage is large and the effects of existing groundwater development are minimal, droughts may have limited, if any, effect on the long-term sustainability of aquifer systems from a storage perspective. In contrast, where groundwater storage and heads have been substantially reduced by withdrawals of groundwater before a drought occurs, groundwater may be less useful as a source of water to help communities and others cope with droughts. Furthermore, previous groundwater withdrawals can cause water levels and flows in lakes, streams, and other water bodies during droughts to be below limits that would have occurred in the absence of groundwater development. Likewise, reduced freshwater discharges to coastal areas during droughts may cause seawater to move beyond previous landward limits, or reduced heads in aquifers may cause renewed land subsidence.

A common response to droughts is to drill more wells. Increased use of groundwater may continue after a drought because installation of wells and the infrastructure for delivery of groundwater can be a considerable investment. Thus, a drought may lead to a permanent, unanticipated change in the level of groundwater development. Use of groundwater resources for mitigating the effects of droughts is likely to be most effective with advance planning for that purpose.

Groundwater systems tend to respond much more slowly to short-term variability in climate conditions than do surface-water systems. As a result, assessments of groundwater resources and related model simulations commonly are based on average conditions, such as average annual recharge or average annual discharge to streams. This use of average conditions may underestimate the importance of droughts.

The effect of potential long-term changes in climate, including changes in average conditions and in climate variability, also merits consideration. Climate change could affect groundwater sustainability in several ways, including (1) changes in groundwater recharge resulting from changes in
average precipitation and temperature or in the seasonal distribution of precipitation, (2) more severe and longer lasting droughts, (3) changes in evapotranspiration resulting from changes in vegetation, and (4) possible increased demands for groundwater as a backup source of water supply. Shallow aquifers, which supply much of the flow to streams, lakes, wetlands, and springs, are likely to be the part of the groundwater system most sensitive to climate change; yet, limited attention has been directed at determining the possible effects of climate change on shallow aquifers and their interaction with surface water.

In summary, consideration of climate can be a key, but underemphasized, factor in ensuring the sustainability and proper management of groundwater resources. As increasing attention is placed on the interactions of groundwater with land and surface-water resources, concerns about the effects of droughts, other aspects of climate variability, and the potential effects of climate change are likely to increase.

### 3.3.2 Impacts on Groundwater

Groundwater maintains surface water systems through flows into lakes and base flow to rivers, which are crucial for maintaining the sensitive ecosystems. However, all these functions become increasingly vulnerable as changes in climate occur. This has seen the ecologic and socioeconomic consequences in recent years. The interaction of groundwater and surface water has been shown to be of significant concern in issues related to water supply, water quality and degradation of aquatic environment. In this context, groundwater resources are of primary importance because they are one of the best protected reserves of water for distribution and also contribute water to streams and rivers during the recession period, in the winter and summer.

Variations in temperature and precipitation during the year will have a direct impact on changes in groundwater levels, reserves and quality. Indirectly, climate change will influence irrigation with water extracted from aquifers, which would alter hydrological systems, regional land uses and agricultural practices. Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems. During the 20th century, precipitation totals have mainly increased over land in high northern latitudes and
decreased in some sub-tropical and lower mid-latitude regions. Global average air and ocean temperatures have also increased and over the past 50 years hot days, hot nights and heat waves have become more frequent and it is predicted that these trends will continue into the 21st century. It is not only precipitation totals which are likely to change but also precipitation intensities and variability. The frequency of heavy precipitation events has increased whilst the area of land classified as dry has more than doubled since 1970s (Bates et al. 2008). These climatic extremes are likely to cause increased frequencies of severe droughts and floods.

Groundwater reacts to climate change mainly due to changes in groundwater recharge, in response to increases in mean temperature, precipitation variability and sea level, as well as changes in mean precipitation. Aquifers generally are replenished by effective rainfall, rivers, and lakes. This water may reach the aquifer rapidly, through macro-pores or fissures, or more slowly by infiltrating through soils and permeable rocks overlying the aquifer. A change in the amount of effective rainfall will alter recharge, but so will a change in the duration of the recharge season. Increased winter rainfall, as projected under most emissions scenarios for mid-latitudes, generally is likely to result in increased groundwater recharge. However, higher evaporation may mean that soil deficits persist for longer and begin earlier, offsetting anticipated increase in total effective rainfall.

Deeper aquifers react, with delay, to large-scale climate change but not to short-term climate variability. Shallow groundwater systems, especially built in unconsolidated sediment or fractured bedrock, are more responsive to smaller scale climate variability. Increased precipitation variability leads to changes in recharge. In semi-arid and arid areas, alluvial aquifers are recharged mainly by inundations due to heavy rainfalls and floods. However, in compacted soils, infiltration during heavy rainfall is low. In sub-humid and humid areas, groundwater recharge may decrease because more frequent heavy precipitation events result in frequent exceeding of the infiltration capacity of the soil.

Various types of aquifer will be recharged differently. The main types are unconfined and confined aquifers. An unconfined aquifer is recharged directly by local rainfall, rivers, and lakes, and the rate of recharge will be influenced by the hydraulic conductivity of overlying rocks and soils. Macro-pore and fissure recharge is most common in porous soils and less common in poorly structured soils. It also occurs where the underlying
geology is highly fractured or is characterized by numerous sinkholes. Such recharge can be very important in some semi-arid areas. In principle, “rapid” recharge can occur whenever it rains, so where recharge is dominated by this process it will be affected more by changes in rainfall amount than by the seasonal cycle of soil moisture variability. Shallow unconfined aquifers along floodplains, which are most common in semi-arid and arid environments, are recharged by seasonal streamflows and can be depleted directly by evaporation. Changes in recharge therefore will be determined by changes in the duration of flow of these streams, which may locally increase or decrease, and the hydraulic conductivity of the overlying beds, but increased evaporative demands would tend to lead to lower groundwater storage.

Changes in precipitation and temperature caused by the elevated level of CO$_2$ in the atmosphere can increase the infiltration rate of water through the vadose zone. A model that simulates the effect of increased CO$_2$ level on plants, groundwater and the vadose zone was applied in subtropical and Mediterranean regions of Australia. The subtropical regions responded more to the frequency and volume of precipitation whereas the Mediterranean region was influenced more by changes in temperature. In both locations, groundwater recharge rate varied significantly i.e., 75-500% faster in Mediterranean region and from 34% slower to 119% faster in subtropical regions (Green et al. 2007).

As global temperatures rise, sea level rise is also expected due to the melting of ice sheets and glaciers. Rising sea levels would allow saltwater to penetrate farther inland and upstream in low lying river deltas (IPCC 1998). Higher salinity impairs surface and groundwater supplies, damaging urban water supplies, ecosystems, and coastal farmland (IPCC 1998). Furthermore, a reduced groundwater head caused by lower rainfall will aggravate the impacts of sea level rise. Saline intrusion into alluvial aquifers may be moderate, but higher in limestone aquifers. Reduced rates of groundwater recharge, flow and discharge and higher aquifer temperatures may increase the levels of bacterial, pesticide, nutrient and metal contamination. Similarly, increased flooding could increase the flushing of urban and agricultural waste into groundwater systems, especially into unconfined aquifers, and further deteriorate groundwater quality.

Sea-level rise will cause saline intrusion into coastal aquifers, with the amount of intrusion depending on local groundwater gradients. Shallow
coastal aquifers are at greatest risk. Groundwater in low-lying islands therefore is very sensitive to change. A reduction in precipitation coupled with sea-level rise would not only cause a reduction of the harvestable volume of water; it also would reduce the size of the narrow freshwater lenses. If the groundwater table is one unit above sea level, then the freshwater-saltwater interface is approximately 40 units below sea level (Ghyben-Herzberg relation). Thus, a small sea level rise results in a larger (by the factor of 40) decrease of the depth of the freshwater-saltwater interface. For many coastal aquifers, seawater intrusion into fresh groundwater has been observed as a result of overpumping of aquifers. Any sea-level rise would worsen the situation.

Hence, unconfined aquifers are sensitive to local climate change, abstraction, and seawater intrusion. However, quantification of recharge is complicated by the characteristics of the aquifers themselves as well as overlying rocks and soils. A confined aquifer, on the other hand, is characterized by an overlying bed that is impermeable, and local rainfall does not influence the aquifer. It is normally recharged from lakes, rivers, and rainfall that may occur at distances ranging from a few kilometers to thousands of kilometers. Recharge rates also vary from a few days to decades. Such aquifers may not be seriously affected by seasonal or inter-annual rainfall or temperature changes of the local area.

Attempts have been made to calculate the rate of recharge by using modeling and isotopes techniques. This has been possible for aquifers that are recharged from short distances and after short durations. However, recharge that takes place from long distances and after decades or centuries has been problematic to calculate with accuracy, making estimation of the impacts of climate change difficult. The medium through which recharge takes place often is poorly known and very heterogeneous, resulting in challenging recharge modeling.

In areas where water demand and water stress will increase, groundwater withdrawals are very likely to increase in the future. In addition, groundwater withdrawals as a fraction of total human water withdrawals are likely to increase where surface water becomes scarcer, either due to increased surface water withdrawals or due to less reliable surface water supply caused by increased precipitation variability.
Increased groundwater withdrawals are not sustainable if they do not remain well below groundwater recharge. Where not only surface water availability but also groundwater recharge is reduced due to climate change, the opportunities to balance the effects of more variable surface water resources by groundwater use are restricted. Climate change may lead to vegetation changes which also affect groundwater recharge.

Significant decreases in groundwater recharge are projected to take place along the southern rim of the Mediterranean Sea. Percentage decrease of groundwater recharge is higher than that of total runoff. Many semi-arid areas that suffer from water stress already today may face decreased groundwater recharge. Groundwater is not likely to ease freshwater stress in those areas where climate change is projected to decrease groundwater recharge.

In general, there is a need to intensify research on modeling techniques, aquifer characteristics, recharge rates, and seawater intrusion, as well as monitoring of groundwater abstractions. This research will provide a sound basis for assessment of the impacts of climate change and sea-level rise on recharge and groundwater resources.
CHAPTER 4

Groundwater and Climate Change
in the Arab Region
CHAPTER 4

Groundwater and Climate Change in the Arab Region

4.1 Introduction

The area of the Arab region contains almost ten percent of the dry land on earth while water resources do not exceed one percent of the world’s total. Arab countries share many common features in terms of climate, water and land resources and development issues. These include arid and semi-arid climate, limited water resources, agricultural development forced by water availability and high economic and social value of water.

About two thirds of the renewable water resources of the Arab countries originate outside the region. Eighty percent of the area of the Arab countries is barren desert, and therefore the region is mainly arid with small pockets of semiarid climatic conditions. The average annual rainfall varies between 0 and 1800 mm while the average evaporation rate is more than 2000 mm/year. Scarcity of water is a major constraint in the region. In many countries, all available water resources, which can be used for economic purposes, have already been developed or are in the process of development. It is evident that water scarcity will remain the dominant state in the Arab region.

Groundwater exploitation in the region has increased dramatically during the last decades due mainly to an increase in irrigated agriculture. Thus, many groundwater resources are at risk of being exhausted through over-pumping. With withdrawal exceeding the internally renewable water resources, the resulting groundwater scarcity is rapidly becoming a major concern in most countries of the Arab region. It is not only the quantity of fresh water that might be affected by climate change, the quality of groundwater might also be worsened, as fresh water supplies might get contaminated by sea water intruding coastal aquifers, thereby affecting potable water supplies for millions of Arabs. Furthermore, some considerable water volumes stored in large deep aquifers in Libya, Tunisia, Egypt, Algeria and Arabian Peninsula are non-renewable resources and their use is consequently not sustainable.
In most of the Arab countries, population, growth and land management may be far more significant and critical than climate change. Therefore, the impacts of climate change add to already difficult water management challenges in the region. Hence, the Arab region is one of the most water stressed areas in the whole world, and climate change, which is projected to increase the frequency and intensity of extreme weather events, will contribute to even worse water scarcity in the region.

Climate change is also expected to have extended socio-economic and ecological impacts associated with changing ecosystems and human environments. While these expected impacts have generally been modeled through the development of global climate models, limited research and information has been generated on the effects of climate change at the Arab region level, and specifically what implication different climate change scenarios may have for water resources, and socio-economic and environmental vulnerability in the region. Determining the extent to which relevant sectors may be affected by climate change impacts on water resources in the region, however, requires the conduct of a regionally-specific vulnerability assessment, which is beyond the scope of this work.

4.2 Groundwater Occurrence and Management

Our objective in this section is not to provide a detailed description of the hydrogeology of the aquifers systems in the region but rather to point out their occurrence, magnitude and management considerations with respect to risks that climate change poses for aquifer systems and groundwater availability in the region.

4.2.1 Aquifer Systems in the Region

Groundwater in the Arab region is found in numerous aquifer systems with storage and yield characteristics that depend on each aquifer’s areal extent and its hydrologic and hydrogeologic properties. A brief description of the major aquifer systems in the region is given (Al-Eryani 2001), (Khater, 2001). The major aquifer systems are either of sandy and/or calcareous facies. Also, unconsolidated and alluvium deposits as well as volcanic deposits prevail in the region. From the hydrologic point of view, the water bearing formations are either naturally recharged or of fossil or non-
renewable nature. Most of the naturally recharged aquifers are moderately replenished due mainly to the limited precipitation rates prevailing in the region.

The geological history of the region dates back to the Pre-Cambrian (more than 500 million years BP). The basement rock is exposed in large surfaces in the region, principally in Mauritania, South and West of Algeria, the southern part of Libya, Southwest and East of Sudan, and East of Egypt, forming the so-called African Shield. It is also exposed along the coast of the Red Sea forming the Arabian Shield.

Thick layers of sand and sandstone suitable for groundwater storage were deposited on the basement rock during the Paleozoic some 300 million years ago. During the Mesozoic period additional layers of sand and Nubian sandstone covered a large surface extending from North Sudan to the Western Desert in Egypt and Libya. In the latter part of that period, estimated at 120 million years BP, thick layers of low permeable limestone were deposited in the Arabian Peninsula.

In the Tertiary (Eocene up to the beginning of the Pleistocene) and Quaternary (Pleistocene and Recent), alternating series of calcareous rocks and sand were deposited in many areas forming Al-Hamada in Algeria and Morocco, and together with limestone in Egypt, Syria, Iraq, and the southern part of the Arabian Peninsula. The Atlas region belongs in fact to the Mediterranean region and is characterized by formations where clays and other rocks, such as calcareous rocks and dolomites belonging to the lower Jurassic, are dominant.

Because of the similarity in the geologic history of the region, many of the major aquifers are shared between two or more countries. In the following paragraphs, a brief description of the major shared aquifer systems identified in the region is given below (Khater, 2001):

**Eastern Mediterranean Carbonate Aquifer System**

This aquifer system is part of the Eastern Mediterranean basin which covers an area of about 48,000 km² extending through four Arab countries: Jordan, Lebanon, Syria, and Palestine. The Lebanese rivers (Orontes, Litani, and others) and the Jordan River form the major drainage network of this basin. This regional aquifer system is best observed in the Alouite mountains.
(Syria), the Palmyrian mountains (Syria), the Anti-Lebanon range (Syria and Lebanon), Mount Hermon (Syria and Lebanon), the Lebanon mountains, and the eastern and western highlands (Jordan). Hydrogeologically, the aquifer is a regional complex of carbonate rocks consisting of two major units: a lower Jurassic unit and an upper Cenomanian-Turonian unit, both composed mainly of limestones and dolomites.

**Jebel el-Arab Basaltic Aquifer System**

This aquifer system is part of the Horan and Arab Mountain basin which cover an area of 15,000 km² extending through three Arab countries: Jordan, Saudi Arabia, and Syria. The Golan plateau constitutes the main occurrence of water resources for this basin, which is considered a main source of the Yarmouk and Azraq basins through the springs of Mazreeb, El-Hamma and El-Azraq. Hydrogeologically, the main aquifer is made of a complex layering of basalt flows of different ages. The thickness of the basalt layers changes markedly from the vast volcanic plateau of Southwest Syria to Eastern Jordan and Northern Saudi Arabia. The total thickness ranges from 20 m in the Hamad basin up to 300 m near Jebel el-Arab. Also, the saturated thickness and degree of saturation vary from one place to another.

**Jezira Tertiary Limestone Aquifer System**

This limestone and dolomite aquifer is of Middle Eocene to Oligocene age. It forms one hydrogeological unit in the Jezira area of Syria and is up to 300 m thick in Turkey. The thickness of the Paleogenic limestones increases in an eastwardly direction to about 560 m in the Jezira (Syria), and to 1,034 m in Qaratchik. In spite of its great thickness in the eastern area, the aquifer is hydrogeologically more important in the northwestern part of a Jezira.

The waterbearing limestone formation outcrops in Turkey to the north of the border zone, extending from the Belikh area to the Khabour River in Syria. The aquifer extends along the Syrian border with Turkey, from Ain Al-Arab east of the Euphrates to Ras Al-Ain and beyond. The Khabour River channel between Ras Al-Ain and Hassakeh forms the southern border of the aquifer system, which also extends southward as far as Jebel Abdel Aziz area in Syria. The annual recharge to the aquifer system is estimated at 1.600 Bm³ and discharge occurs via two large springs in Syria: Ras Al-Ain (40 m³/s) and Ain Al-Arus (6 m³/s).
**Jezira Lower Fars-Upper Fars Aquifer System**

The Lower and Upper Fars formation consists of gypsum beds interbedded with limestones, clays and marls. It extends over the vast Mesopotamian plain of the Lower Jezira of Syria, and in Iraq from the Belikh River in the west to the Tigris River and Tharthar depression. The southern boundary coincides, more or less, with the middle reach of the Euphrates from Raqqa in Syria to Al-Ramadi in Iraq.

**Western Arabia Sandstone Aquifer System**

Four principal sandstone aquifers are recognized in the Arabian Peninsula; the Saq, Tabuk, Wajid and Minjur. They range in age from Cambrian to Triassic. Hydrodynamically, they can be subdivided into three major subsystems: 1) The Rum-Saq-Tabuk sandstone aquifer subsystem, extending from Northern Saudi Arabia to Jordan; 2) The Minjur sandstone aquifer subsystem, occupying the middle of the Riyadh area in Saudi Arabia; and 3) The Wajid sandstone aquifer subsystem, which mainly occurs in Southern Saudi Arabia and Northern Yemen.

Water of good quality for domestic, industrial, irrigation and livestock uses is available from various members of the Palaeo-Triassic aquifer system. The salinity of groundwater from the Saq aquifer does not generally exceed 1,000 ppm, although water in the deeper horizons usually has higher salinity and is of a sodium-chloride type. Freshwater from the Wajid aquifer is of a bicarbonate type salinity is commonly less than 1,000 ppm water from the Tabuk aquifer is generally fair to good quality with salinity ranging from 400 to 3,500 ppm. Water from the Minjur aquifer is of a calcium-sodium / sulfate-chloride type. Its sodium and chloride ion concentrations increase with depth. The Rum group, which is underlain by the Araba Complex and Basement rocks, mainly comprises the Disi and Umm Sahm formation of the lower Paleozoic. Its outcrops extend from Central Saudi Arabia westwards and northwards through Tabuk, Disi, and Petra, with the most northwesterly occurrence at the eastern shores of the Dead Sea. In sub-cropping areas, this formation is known to extend northwards and eastwards underlying the whole of the Rum group aquifer. Structures such as faults, intrusions, and dykes are present in the area.

This aquifer has a generally uniform consistent lithology over large areas and attains thickness of over 2,000 m. The depositional environment is fluvial. The overlying Hiswah Shale, which is a confining layer, represents a
post transgression, fully marine depositional environment. Groundwater flow in this aquifer commences from beyond Tabuk (Saudi Arabia) moving broadly northwards, crossing into Jordanian territory, and converges towards the Dead Sea. Groundwater extractions since the 1980s have changed the pattern of groundwater flow, with a significant change in the Tabuk area. High rates of extraction for irrigation purposes have produced a very extensive cone of depression, locally diverting the natural northeasterly groundwater flow direction.

**Central Arabia Sandstone Aquifer System**

The Cretaceous aquifer system comprises the Biyadh and Wasia sandstone in Saudi Arabia. Their combined thickness is about 1,000 m. Groundwater occurs under unconfined conditions, especially in the outcrop of the aquifer, which extends over a vast area (from Wadi Al-Dawasir in Saudi Arabia to Rutba in Iraq). The salt content of the lower member, the aquifer outcrop/recharge area, is about 150 ppm. In the Kharj area, the salinity ranges from 550 to 900 ppm. The water quality of the Wasia sandstone aquifer varies widely from one place to another. The salinity ranges in the outcrop area from 1,000 to 3,000 ppm, while the water in the Biyadh aquifer stagnates and its salinity rises substantially from 4,000 to 150,000 ppm. The Wasia aquifer then flow on with a salinity of 4,000 to 5,000 ppm. Groundwater resources in the Biyadh and Wasia aquifers are estimated to have a potential annual recharge of 252 and 420 Mm$^3$, respectively. The water in storage could be as much as 290,000 Mm$^3$.

The hydraulic characteristics of the Cretaceous aquifer system vary widely in the extensive confined and unconfined parts of the hydrogeological systems. For many areas in Iraq, Jordan, Kuwait and Northern and Southern Saudi Arabia, information on this aquifer system is scarce or incomplete. In some areas, the aquifer is either saline or unproductive, and its development is consequently not feasible.

**Eastern Arabia Tertiary Carbonate Aquifer System**

The East Arab Peninsula basin covers an area of about 1,600,000 km$^2$ extending through the Gulf States, Iraq, Jordan, Syria, and Yemen. Rainfall is the main water resource at the north of the basin and feeds the eastern section of the basin. The aquifers consist primarily of limestone and dolomites. The whole sedimentary complex is hydraulically interconnected
and is a recharging-discharging aquifer system. The subdivisions (or main aquifers) are as follows:

- The Umm er Radhuma aquifer, which is composed of limestone and dolomites ranging in thickness between 240 and 700 m (it occurs in 8 Arab countries: Bahrain, Iraq, Kuwait, Oman, Yemen, Qatar, Saudi Arabia, and the UAE).

- The Dammam aquifer, which is composed of limestone and dolomite with shale ranging in thickness between 20 and 500 m (it occurs in Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE).

- The Neogene aquifer, which is composed of sandstone, sandy marl and chalky limestone of variable thicknesses (it occurs in Bahrain, Kuwait, Oman, Qatar, and the UAE).

Groundwater recharge into the Tertiary carbonate aquifers was estimated at 1,150 Mm$^3$, while the estimated discharge from the system is 1,200 Mm$^3$. Other estimates for the annual recharge of the Umm er Radhuma, Dammam, and Neogene aquifers are 406, 200 and 238 Mm$^3$, respectively. Freshwater is relatively rare in the aquifer complex, occurring in the upper and lower zones of the hydrodynamic system.

**Nubian Sandstone Aquifer System**

The Nubian sandstone basin covers an area of 2,350,000 km$^2$ extending through Egypt (850,000 km$^2$), Sudan (750,000 km$^2$), Libya (650,000 km$^2$), and Chad (100,000 km$^2$). It has a huge groundwater reservoir though limited in the segment from Chad to Sudan, and perhaps the Ethiopian plateau. Springs, oases, and depressions represent the major drainage areas of this basin. This system is made up of a sequence of continental sandstones and sands intercalated with argillaceous beds of the Carboniferous to Middle Cretaceous ages. Its thickness reaches up to several thousand meters. In the eastern desert of Egypt, the Nubian sandstone complex is water bearing formation where groundwater occurs under confined artesian condition (flowing wells). Water can be obtained there from shallow, carbonate and deep sandstone formations. The deeper formations are more extensive and contain larger quantities of groundwater.

The thickness of the aquifer complex in the central eastern desert is about 400 m. In the Sinai Peninsula, the Nubian sandstone complex is the principal aquifer. On the average, the depth to the aquifer is 700 to 900 m in Central Sinai, increasing northwestward to about 2,500 m along the Mediterranean.
coast. Artesian pressure in Central Sinai is about 200 m above sea level. Groundwater encountered in this aquifer system is generally of excellent quality (100-800 ppm). The storage volume in the aquifer system in Egypt (western and eastern deserts and Sinai) is estimated at 5,000 km³. Local groundwater is extracted in the eastern desert, but the annual extraction quantities do not exceed 600 Mm³. Groundwater extractions for agricultural use in Sinai occurs predominantly along the northern coastal (Al-Arish) area. Average annual withdrawal is about 30 Mm³.

**Grand Occidental Erj**

The Grand Occidental Erj, often referred to as the Continental Intercalaire, is located south of the Atlas in Algeria with estimated surface area of 330,000 km², of which 180,000 km² forms an artesian basin. The average thickness is between 250 and 600 m. The annual natural recharge is estimated at 0.3 Mm³.

**Grand Oriental Erj**

The Grand Oriental Erj, sometimes referred to as the Complex Terminal, is located to the east of the Occidental Erj and its eastern edge runs along the Algerian-Tunisian frontier. The total surface area is estimated at about 375,000 km², 90% of which forms an artesian basin. The depth of the aquifer varies from 100 to 400 m. The annual recharge is estimated at 600 Mm³.

### 4.2.2 Groundwater Quality in the Region

Due to the scarcity of water in the region, a direct and critical link exists between water quantity and water quality. Comprehensive data on water quality in the region are not available, but recent World Bank studies suggest that deteriorating water quality is becoming a serious issue in many countries. Although reliable comparative information is not available, numerous examples of emerging water quality problems are quoted. Pollution by fertilizers and pesticides, dumping of municipal and industrial wastewater into rivers and lakes, solid waste deposits along riverbanks, and uncontrolled seepage from unsanitary landfills are degrading freshwater resources and impose health risks. The principal sources of pollution include the following:
• Untreated municipal wastewater, leaching from poorly maintained and functioning cesspools, and washing of fecal matter and other waste from the surface of the ground into water bodies.

• Untreated industrial waste, discharging into municipal sewer systems or directly into water bodies.

• Seepage from unsanitary landfills where the majority of the region’s solid waste is dumped.

• Seepage and runoff of agrochemical such as fertilizers and non-biodegradable pesticides.

Declining water quality caused by pollution from these sources is affecting public health, the productivity of resources, and the quality of life. Once contaminated, groundwater seldom regenerates and, although rivers are to some extent self-cleansing, declining quality increases treatment costs to downstream users and may preclude reuse for particular purposes. Seawater intrusion into coastal aquifers is a critical issue in several countries and waterlogging and associated secondary salinity are widespread problems in many major irrigated areas. Accordingly, water shortages in the Arab region are compounded by water quality degradation and pollution.

In Morocco and Algeria, fresh groundwater can be found in the north, but the salinity increases to the south. Fresh groundwater can hardly found in Tunisia. In Libya, fresh groundwater is available in the Nubian sandstone aquifer systems. Egypt also obtains fresh groundwater from the Nubian sandstone, as well as the aquifer underlying the Nile Delta and Valley. The fresh groundwater of the Nubian is also obtainable in Sudan. Precipitation in the mountainous areas in Northwest Jordan, North Iraq and Lebanon maintains a fresh quality for the groundwater there. In Iraq, the groundwater quality deteriorates in a southerly direction due to the presence of evaporites. In Syria, the groundwater is generally brackish. In Palestine, fresh groundwater exists in the coastal plain aquifer extending from Haifa to Gaza, which disappears at the foothills of the West Bank Mountains. The Sinai Peninsula and the Eastern Desert in Egypt hardly contains any fresh groundwater. In Saudi Arabia, fresh groundwater exists in the Riyadh-Wasia-Aruma aquifer. However, it deteriorates eastwards and becomes highly saline near the border of Kuwait. Groundwater salinity in the Umm-er Radhuma aquifer in the eastern part of Saudi Arabia increases from east to west. Groundwater salinity of the Dammam aquifer is generally brackish,
and deteriorates rapidly towards the south and the east where it becomes saline. The Dammam aquifer in Kuwait contains groundwater ranging from brackish in the southwest to highly saline in the northeast. In the northern part of Qatar fresh groundwater occurs as floating lenses within the Dammam-Rus formation. In the South of Qatar and all over Bahrain, brackish water covers the entire area. In UAE, groundwater salinity ranges from brackish to saline. In Yemen, fresh groundwater occurs in the high land of Tihama plain and deteriorates in a westerly direction towards the Red Sea.

Because when groundwater becomes polluted, it is difficult, if not impossible to fully rehabilitate, even when the source of pollution has been removed. Therefore, it is better to prevent or reduce the risk of groundwater pollution than to deal with its consequences. Accordingly, protection of groundwater quality is of great importance.

4.2.3 Groundwater Management in the Region

With little or no surface water resources, the majority of Arab countries depend significantly on groundwater to meet the growing water demands. Groundwater resources of the Arab region are either the main sources of freshwater or are vitally needed to supplement surface-water sources. Table 4.1 shows estimates of average annual groundwater recharge and groundwater withdrawal. The region’s dependency on groundwater is expressed in terms of the ratio of groundwater withdrawal in relation to the annual groundwater recharge as well as the ratio of the contribution of groundwater withdrawals to the total demand in year 2000. The present levels of groundwater abstraction have exceeded the annual groundwater recharge in 53% of the countries in the Arab region; and withdrawal in relation to recharge ranged from twofold to sevenfold.

The contribution of groundwater to the total demand in the region amounts to about 52%, and groundwater abstractions are currently the main source of water in over 60% of the Arab countries. In quantitative terms, Figure 4.1 shows groundwater dependency in the region in terms of groundwater contribution to total water use in the region in year 2000 (Khater, 2001).

Thus, the high water stresses are met with varying degrees of groundwater depletion and considerable groundwater mining is taking place in the region. Such process is likely to exacerbate with time. Therefore, strategies are needed to stabilize heavily stressed aquifers in the region.
Table 4.1 Groundwater availability in the Arab Region

<table>
<thead>
<tr>
<th>Country</th>
<th>Annual groundwater recharge (km³)</th>
<th>Annual groundwater withdrawal Total (km³)</th>
<th>% Recharge</th>
<th>% Demand 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algeria</td>
<td>1.70</td>
<td>2.90</td>
<td>171</td>
<td>64.44</td>
</tr>
<tr>
<td>Bahrain</td>
<td>0.10</td>
<td>0.26</td>
<td>260</td>
<td>91.49</td>
</tr>
<tr>
<td>Egypt</td>
<td>5.10</td>
<td>4.60</td>
<td>90</td>
<td>7.11</td>
</tr>
<tr>
<td>Iraq</td>
<td>13.00</td>
<td>0.20</td>
<td>2</td>
<td>0.78</td>
</tr>
<tr>
<td>Jordan</td>
<td>0.30</td>
<td>0.50</td>
<td>167</td>
<td>51.02</td>
</tr>
<tr>
<td>Kuwait</td>
<td>0.16</td>
<td>0.30</td>
<td>188</td>
<td>68.64</td>
</tr>
<tr>
<td>Lebanon</td>
<td>0.60</td>
<td>0.24</td>
<td>40</td>
<td>17.00</td>
</tr>
<tr>
<td>Libya</td>
<td>0.70</td>
<td>3.70</td>
<td>583</td>
<td>95.12</td>
</tr>
<tr>
<td>Morocco</td>
<td>9.00</td>
<td>2.70</td>
<td>30</td>
<td>24.43</td>
</tr>
<tr>
<td>Oman</td>
<td>1.00</td>
<td>1.64</td>
<td>164</td>
<td>89.01</td>
</tr>
<tr>
<td>Qatar</td>
<td>0.09</td>
<td>0.19</td>
<td>211</td>
<td>67.86</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>3.85</td>
<td>14.40</td>
<td>374</td>
<td>84.71</td>
</tr>
<tr>
<td>Sudan</td>
<td>7.00</td>
<td>0.30</td>
<td>4</td>
<td>1.69</td>
</tr>
<tr>
<td>Syria</td>
<td>6.60</td>
<td>3.50</td>
<td>53</td>
<td>24.30</td>
</tr>
<tr>
<td>Tunisia</td>
<td>4.20</td>
<td>1.60</td>
<td>38</td>
<td>59.71</td>
</tr>
<tr>
<td>UAE</td>
<td>0.13</td>
<td>0.90</td>
<td>692</td>
<td>75.83</td>
</tr>
<tr>
<td>Yemen</td>
<td>1.50</td>
<td>1.40</td>
<td>93</td>
<td>61.60</td>
</tr>
</tbody>
</table>


Relative to many other parts of the world, the Arab region is already critically dependent on groundwater, at least outside the major river valleys of the Nile and the Tigris/Euphrates. In some countries, it is already the predominant source of supply. It comprises essentially the only naturally occurring freshwater resource in the Gulf States, and accounts for about 95% of freshwater abstractions in Libya, 64% in Algeria, 61% in Yemen, 60% in Tunisia and 51% in Jordan.
While recharge rates and flows are not always well known, the quantity and quality of groundwater are increasingly of concern. Over-pumping has led to rapid declines in groundwater levels in many locations. Saline intrusion and pollution from urban and industrial wastewater are commonly encountered and reversible only at great cost. Groundwater abstractions approach or exceed renewable limits in many countries including Algeria, the Gulf States, Jordan, Libya, and Yemen. Potential for further abstractions still exists, for instance, in some parts of Iraq and Egypt. But in these two countries, recharge is almost wholly from major rivers, however, it does not add to supply.

It is always essential to address issues constraining groundwater abstraction, since this will normally contribute more to achieving water balance. Complementary supply-side measures, such as rainwater harvesting, aquifer recharge enhancement from other sources of water, such as treated wastewater, should always be encouraged where conditions are favorable. Moreover, reducing groundwater resources used for irrigated agriculture is of paramount importance in the region, being the main consumer, and obviously where major savings can be achieved. In aggravated aquifer conditions where larger water savings are needed, then consideration should also be given to modifying cropping patterns and land use. An even
more radical option would be to place restrictions or a ban on irrigated agriculture in critical groundwater abstraction areas.

Management of groundwater resources has to deal with balancing supply, in terms of quantity, quality, and surface water interactions, with the increasing demands of water. Calls for groundwater management do not usually arise until a decline in well yields and/or quality deterioration affects resources. It is essential to recognize that managing groundwater is as much about managing people as it is about managing water. In practical terms it will be necessary to set possible management interventions in the context of development. However, it must be noted that preventive management approaches are likely to be more cost-effective than purely reactive ones.

Areas of high priority to the management of groundwater resources in the Arab region include: improved identification of regional hydrogeologic frameworks; better understanding of groundwater and surface water interaction; scarcity of data and uncertainties associated with groundwater models predictions; modeling the movement of seawater into coastal aquifers; risks that climate change poses for aquifer systems and groundwater availability; and downscaling and linking climate models to hydrologic groundwater models.
4.3 Climate Change in the Arab Region

4.3.1 Global Projections

Global Temperature increased by $0.74 \pm 0.18 \, ^\circ C$ during the last century due to the increase in greenhouse gas concentrations from human activities. This conclusion has been endorsed by most of scientific research on global climate change (Figure 4.2).

![Observed continental and global-scale changes in surface temperature with results from climate models. (IPCC, 2007)](image)

**Figure 4.2** Observed continental and global-scale changes in surface temperature with results from climate models. (IPCC, 2007)
On other hand, Climate model projections summarized by the Intergovernmental Panel on Climate Change (IPCC) indicate that average global surface temperature will likely rise a further 0.6° to 4° Celsius with a likely range between 0.3° and 6.4° Celsius during the 21st century (Figure 4.3). The range of values results from the use of differing scenarios of future greenhouse gas emissions as well as models with differing climate sensitivity.

![Figure 4.3 Projected surface temperature changes for the 21st century; projections are for the A2, A1B and B1 SRES scenarios averaged over decades 2020-2029 and 2090-2099. (IPCC, 2007)]
Increases in the amount of precipitation are very likely in high-latitudes, while decreases are likely in most subtropical land regions (Figure 4.4).

![Figure 4.4 Changes in precipitation % (2090-2099); values are multi-model averages relative to 1980-1999 based on SRES A1B scenario for December to February (left) and June to August (right). (IPCC, 2007)](image)

The demand for groundwater is likely to increase in the future, the main reason being increased water use globally. Another reason may be the need to offset declining surface water availability due to increasing precipitation variability in general and reduced summer low flows in snow-dominated basins. Climate change will affect recharge rates of the renewable groundwater resources. There has been very little research on the impact of climate change on groundwater, including the relationship between surface waters and hydraulically connected aquifers (Alley, 2001). However, changes in river level may influence groundwater levels much more than changes in groundwater recharge (Allen et al., 2003).

As a result of climate change, in many aquifers of the world the spring recharge will shift towards winter, and summer recharge will decline. In high latitudes, thawing of permafrost will cause changes in groundwater level and quality. Climate change may lead to vegetation changes which also affect groundwater recharge. Also, with increased frequency and magnitude of floods, groundwater recharge may increase, in particular in semi-arid and arid areas where heavy rainfalls and floods are the major sources of groundwater recharge. Alluvial and bedrock aquifers in semiarid regions are replenished by direct infiltration from irrigation and precipitation.
Accordingly, an assessment of climate change impact on groundwater recharge should include the effects of changed precipitation variability and inundation areas.

According to the results of a global hydrological model (Figure 4.5), groundwater recharge, when averaged globally, increases less than total runoff (by 2% as compared with 9% until the 2050s for the ECHAM4 climate change response to the SRES A2 scenario: Döll and Flörke, 2005). For all four climate change scenarios investigated (the ECHAM4 and HadCM3 GCMs with the SRES A2 and B2 emissions scenarios), groundwater recharge was computed to decrease by the 2050s by more than 70% in north-eastern Brazil, south-western Africa and the southern rim of the Mediterranean Sea (Figure 4.5).

![Figure 4.5 Simulated impact of climate change on long-term average annual diffuse groundwater recharge, as computed by the global hydrological model WGHM based on SRES A2 and B2 scenarios. (Döll and Flörke, 2005)](image-url)
However, as this study did not take account of an expected increase in the variability of daily precipitation, the decrease might be somewhat overestimated. Where the depth of the water table increases and groundwater recharge declines, wetlands dependent on aquifers are jeopardized and the base flow runoff in rivers during dry seasons is reduced. Regions in which groundwater recharge is computed to increase by more than 30% by the 2050s include the Sahel, the Near East, northern China, Siberia and the western USA. In areas where water tables are already high, increased recharge might cause problems in towns and agricultural areas through soil salinization and waterlogged soils. The few studies of climate change impacts on groundwater for individual aquifers show very site-specific and climate model-specific results. For example, in the Ogallala Aquifer region, projected natural groundwater recharge decreases more than 20% in all simulations with warming of 2.5°C or greater (Rosenberg et al., 1999). With increasing temperature, the sensitivity of groundwater levels to temperature increases (Chen et al., 2004), particularly where the confining layer is thin.

Climate change is likely to have a strong impact on saltwater intrusion into aquifers as well as on the salinization of groundwater due to increased evapotranspiration. Sea level rise leads to intrusion of saline water into the fresh groundwater in coastal aquifers and thus adversely affects groundwater resources. Any decrease in groundwater recharge will exacerbate the effect of sea-level rise. In inland aquifers, a decrease in groundwater recharge can lead to saltwater intrusion of neighboring saline aquifers (Chen et al., 2004), and increased evapotranspiration in semi-arid and arid regions may lead to the salinization of shallow aquifers. Model based projections of global mean sea-level rise between the late 20th century (1980–1999) and the end of this century (2090–2099) are of the order of 0.18 to 0.59 m, based on the different SRES scenarios (Figure 4.6). Thermal expansion is the largest component, contributing 70–75% of the central estimate in these projections for all scenarios.

Although most studies focus on the period up to 2100, warming and sea level rise are expected to continue for more than a thousand years even if greenhouse gas levels are stabilized. The delay in reaching equilibrium is a result of the large heat capacity of the oceans. Catastrophic and unpredicted events such as ice shelf collapse in the Arctic, Antarctic and/or Greenland could however push the sea level rise to shoot past likely ranges. Remaining scientific uncertainties include the amount of warming expected in the
future, and how warming and related changes will vary from region to region around the globe.

Figure 4.6 Projected Local sea level change (m) due to ocean density and circulation change relative to the global average for the 21st century (positive values indicate greater local sea level change than global), calculated as the difference between averages for 2080 to 2099 and 1980 to 1999, forced with the SRES A1B scenario. (IPCC,2007)

4.3.2 The Arab Region’s Vulnerability

The Arab region is one of the world’s driest, most water-scarce and most water-stressed regions. Indeed, most Arab countries belong to a critical combination of low rainfall and high spatial and temporal rainfall variability, and evapotranspiration is dramatically increased by the aridity of the region. Among the world’s regions, the Arab region is especially vulnerable to climate change (World Bank, 2006).

The disruptive effects of climate change will be multidimensional and will represent an important additional stress to the already vulnerable Arab region given the limited water resource endowment and the increase in demand for natural resources exacerbated by population growth over the next decades. In addition, climate-induced resource scarcity could further
tensions in the region’s conflict-ridden areas, potentially escalating violence and political turmoil even beyond the region’s boundaries. This is supported by the fact that 80% of surface water resources and 66% of total water resources in the Arab region are transboundary shared water resources.

Climate change is putting additional stress on the region’s marginal environment. It is estimated that the impacts of climate variability on the Arab region will include changes in precipitation rates, surface runoff and river flow rates, including shared river basins from which Arab countries draw most of their water, according to the above presented recent scientific assessments (IPCC 2007). Water quality in rivers and coastal areas is also expected to be affected due to sea level rise and saltwater intrusion into coastal groundwater aquifers. In addition, the changes of precipitation rates and drought frequency would reduce the recharge rates of groundwater and also further exacerbate the extraction rate of groundwater, including non-renewable fossil groundwater resources, as a result of lower availability of surface water. Climate change impacts are felt through the two principal mechanisms of higher temperatures and altered precipitation patterns. These two effects combine to produce the other impacts.

According to the (IPCC 2007) reporting, simulated ranges of warming indicate that annual average surface temperature for the Arab region will likely rise a further 2.5° to 4.0° Celsius by 2100. Model results indicate that future increases in daily maximum and minimum temperature will be similar to the changes in average temperature. Increased temperature is expected to increase evapotranspiration rates thereby reducing soil moisture, infiltration and aquifer recharge.

Based on the (IPCC 2007) reporting, projected annual average ranges of precipitation for the 21st century tend to decrease in the Mediterranean region and northern of the Arabian peninsula by 10% to 20%. Simulated ranges also indicate that precipitation is expected to decrease between 30% to 40% in Morocco and north of Mauritania. However, an increase in precipitation ranging from 10% to 30% is predicted in the southwestern part of Saudi Arabia, Yemen, United Arab Emirates, and Oman. Increased rainfall intensity, is expected to lead to reducing infiltration and potential aquifer charge. Simulated impact of climate change on long-term average annual diffuse groundwater recharge showed that the increase in surface temperature and reduction in rainfall will result in 30-70 percent reduction in recharge for aquifers in the eastern and southern Mediterranean coast.
According to research on global climate change, the Arab region can be identified as the home to 5 of the top 10 countries most exposed to the impacts of climate change: Djibouti, Egypt, Iraq, Morocco, and Somalia. Djibouti is ranked globally as the most exposed to the impacts of climate change in the region. Djibouti’s population is already regularly buffeted by tropical storms from the Indian Ocean and will be increasingly vulnerable to inland flooding as sea levels rise. Egypt ranks as the second most exposed country in the region. With the vast bulk of its population concentrated in the Nile Valley and Delta, it is at high risk of inland flooding. There will also be a high degree of uncertainty about the flow of the Nile because of the uncertainty about rainfall patterns in the basin. Iraq, Morocco and Somalia, next most vulnerable respectively, are at high risk for coastal flooding and exposure to extreme temperatures.

In the Arabian Gulf, all six countries of the Gulf Cooperation Council (GCC): Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE); are projected to suffer significant consequences from global warming. Bahrain has a relatively small land mass that is in danger of being inundated as sea levels rise with climate change. Qatar is especially susceptible to inland flooding. Bahrain and Qatar, together with Kuwait, figure among the countries exhibiting “extreme” vulnerability. Oman, Saudi Arabia, and the UAE are globally rated “highly” vulnerable. Many other countries in the region are also expected to be significantly affected by climate change. Yemen ranks among those “extremely” vulnerable, and Jordan, Lebanon, Libya, and Tunisia are also “highly” vulnerable.
CHAPTER 5

Water and Climate Change Adaptation in the Arab Region
CHAPTER 5

Water and Climate Change Adaptation in the Arab Region

5.1 Introduction

Scientific evidence indicates that climate change is already underway. Climate change will alter the hydrological cycle in many ways. The trigger is the warming of the atmosphere and oceans, which will change major weather systems. This will alter the temporal and spatial patterns of rainfall with consequences for runoff, surface and groundwater storage, river flow regimes and greater likelihood of drought and flood extremes, in different parts of the world. Although climate change induced changes in water resources and water services have yet to be observed, they are universally anticipated. The negative impacts of climate change are expected to outweigh the benefits. With the expected impacts, the hydrological cycle is clearly the aspect of the Earth system that will be most affected by climate change. Therefore, water is at the heart of the problem of climate change and many of its impacts will be manifested on water resources.

The wide-ranging impacts of climate change on local water resources and water services will, in turn, affect major human livelihood systems, particularly those dependent on direct access to natural assets. Climate change impacts will affect the function and operation of existing water infrastructure, including hydropower, structural flood protections, drainage, and irrigation systems, as well as vital services provided by natural ecosystems. On the other hand, as populations grow and move their demand for water resources will change, both spatially and temporally. Taken together, the net effect of these supply and demand-side changes will present major challenges to future management of water resources for human and ecosystem development. Demand management, which aims to regulate withdrawals at sustainable levels, will become increasingly important in areas where relative scarcity and competition between sectors is increasing. Supply side management will become a priority where inter-annual resource availability is likely to change significantly and where populations are more vulnerable.
The immediate impacts of climate change pose a threat to a large share of the world population, not so much for the higher or lower levels of temperature and rainfall that they yield, but rather for the fact that global warming is altering these levels drastically and rapidly. In past eras of dramatic climate change, human populations simply migrated to a more favored climate. Today, human populations are no longer nomadic, and where groups of people still do migrate, adjacent lands are often settled and unavailable for extensive in-migration.

Moreover, economic progress is based, in part, on the accumulation of capital in the form of physical infrastructure, namely our cities, harbors, airports, roads, railroads, factories, and farms. Our economic system is tied to this infrastructure. Adapting to sharply altered climatic conditions thus involves massive investments to adapt or relocate infrastructure, as well as towards providing for basic human needs and livelihoods. Uncertainty about the exact pattern of these climate changes makes the adaptation task doubly difficult.

Climate change, water and food security are closely interlinked in the Arab countries, where fresh water availability is projected to decline due to climate change effects over the next decades. Thus, the countries face a serious and vital challenge as to whether they would be able to keep on providing enough fresh water to sustain their growing population, social cohesion, accelerating urbanization, evolving economies, changing land-use, and vulnerable environment.

In the Arab region, fresh water stress and scarcity are a threat to national security by impacting economic growth, social wellbeing, and political stability, marginally affecting poorer populations. Increased pressure on water resources will result, as the growth rate remains relatively high in the region. Failing to take on this challenge could have dire consequences on the social, capital, natural and cultural assets and future generation well-being and livelihood in the Arab region during the 21st century.

Climate change presents very serious water-related risks and challenges with implications at the global, regional and local levels, and thus demands a portfolio of mitigation and adaptation measures of global and regional actions, as well as tailored responses for specific locations and specific sectors.
This chapter outlines approaches and actions that are being proposed to facilitate adaptation to climate change in the Arab region in general and those that are specific to the water sector.

5.2 Climate Change Vulnerabilities and Risks

Risk is a function of the probability of an event occurring and the severity of its impacts (IPCC, 2001). IPCC defines vulnerability as “the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change impacts, including climate variability and extremes”. As depicted in Figure 5.1, vulnerability to a potential impact is related to the extent of exposure to a hazard and to sensitivity. Vulnerability to flood hazards serves as a good example. When floods occur more frequently, exposure to floods increases. Sensitivity also increases in the form of reduced food security after floods. The resulting impacts of these increases tend to increase vulnerability.

![Figure 5.1 Vulnerability Concept (after Schröter et al., 2004)](image)

Thus, vulnerability to climate change impacts is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity. While efforts to mitigate climate change can reduce exposure, a society’s adaptive capacity is critical in determining how seriously people will be affected by the changes in climate that will inevitably occur. Adaptive capacity is a complex function
of a society’s physical, human, and institutional resources, its infrastructure, its wealth, the structure of its economy, and other factors. Strengthening this capacity is the key to successful adaptation. This concept of vulnerability underlies a framework that links human welfare to climate through the key elements of “exposure,” “sensitivity” and “adaptive capacity.” Important relevant terms are defined briefly below.

**Exposure**: is the nature and extent of the changes in climate that a region experiences or will experience. It is expressed in the form of outputs of global circulation models (GCMs) and, increasingly, as results of analyses of past climatic records showing longer-term changes arising from global warming. GCM outputs must generally be scaled down, using more refined regional models to yield regionally useful results. Nonetheless, there is still substantial uncertainty in predictions obtained, stemming both the uncertainty inherent in such models themselves and from the uncertain trajectory of future GHG emissions resulting from our actions.

**Sensitivity**: is the degree to which a human–environment system is affected, either adversely or beneficially, by climate change. The sensitivity of a system to changes in climate specifies how its key natural resource-related units respond to exposure to climate change. Responses, of course, will differ from region to region and from ecosystem to ecosystem. As precipitation decreases, for example, things like river flows, groundwater recharge, populations of native plants and animals, and agricultural crops will change in linked ways. A huge variety of factors influence system sensitivity. Modeling is usually needed for a comprehensive understanding of interrelated causes and effects.

**Potential Impacts**: are all impacts that may occur given projected climate change, without considering planned adaptation.

**Adaptation**: is the key to a society’s ability to deal with climate change. It comprises the sum of actions taken to change behavior, shift priorities, produce necessary goods and services, and to plan and respond in those ways that reduce harmful climate change impacts or transform them into positive opportunities. Adaptation can be anticipatory or reflexive, come from the public or the private sector, and be short- or long-term in perspective.
Adaptive capacity: is the potential to implement planned adaptation measures; or, simply, the ability to adapt. It is a function of a society’s stock of infrastructure, its human resources, its technology base, its educational system, its research capacity, its wealth, its natural resource base, the structure of its economy, and many other factors. This is a key intervention point in the vulnerability paradigm. Vulnerability is reduced, however, by capacity to adapt to an impact. Adaptive capacity enables planning and implementation of adaptation measures to reduce risk by increasing preparedness or enabling coping mechanisms.

The IPCC Fourth Assessment Report (2007) described criteria for identifying vulnerabilities of ecological and socio-economic systems. The criteria are based on magnitude of impacts, timing, persistence, the extent to which systems are resilient to external pressures, and reversibility and likelihood, among others. Potential for adaptation, distribution of impacts and vulnerabilities, and importance of the systems are also identified in terms of criteria.

The scientific literature, as consolidated by the IPCC, demonstrates that the ongoing changes in climate will have a wide range of impacts on human populations that will vary in nature and intensity across the world. It has been said that while warming is global, climate change is local. The climate signal is likely to be more intense and rapid in certain locations (e.g. the Mediterranean), creating patterns of hazards and threats across the globe. Analysis of the various perspective documents reveals a huge geographical and social inequity in the distribution of vulnerability and capacity to cope with climate change shocks and stresses. Depending on where they occur, the impacts of increasing sea level rise, storm surges, floods and droughts will look very different. The developing world and the poorest fringes of societies will undoubtedly be affected most severely.

The distribution of vulnerabilities relates to geographically-defined “hot spots” where water especially mediates impacts and where sensitivities are high (e.g. for populations whose livelihoods are based on a narrow range of assets). Potential for adaptation is based on mechanisms that enable responses to climate change at various levels. The more coping mechanisms available and accessible, the greater the adaptive capacity of the countries and communities concerned.
Areas critically at risk from short and long-term hydrological impacts of climate change will form the so called ‘hot spots’ of vulnerability. Following the definition of risks and vulnerability, these may be countries, or locations or communities within a country, where the likelihood of dangerous climate change hazards and sensitivity to their effects are relatively high, and local adaptive capacity to cope is relatively low. Determining the locations of hot spots is a crucial step in adaptation planning, as they provide the basis for raising political awareness, setting priorities and mobilizing adaptation funding in relation to needs. Geographical categories perceived as potential hot spots essentially include the Arab region being part of the arid and semi-arid region subject to drought risks, sea level rise, flooding and coastal inundation and salt-water intrusion.

5.3 Climate Change Mitigation and Adaptation

5.3.1 Mitigation Measures

Climate change mitigation is any action taken to eliminate or reduce the long-term risk and hazards of climate change. Most often, mitigations involve reductions in the concentrations of greenhouse gases (GHG), either by reducing their sources or by increasing their sinks. The IPCC defines mitigation as: “An anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases.”

In the context of mitigation, economic growth, energy, transport and industrialization are only considered in terms of contributing to global warming, and therefore having a marginal climate change effect on water resources in the Arab region. The Arab region GHG emissions are relatively small and not exceeding 4.5 percent of the present global emission, according to various sources. However, the region’s economies are becoming more carbon-intensive with GHG emissions growing at a rate faster than the world's average. Three quarters of the GHG emissions in the region are due to energy combustion mainly in terms of electricity and heat, and are concentrated in the oil producing countries. Arab countries, though not primary contributors to atmospheric greenhouse gas emissions, will have to undertake mitigation efforts as part of global action. Mitigation programs shall focus on implementing various climate friendly policies and measures, encompassing both measures to reduce anthropogenic GHG emissions as well as those to enhance carbon sinks.
Ongoing efforts include the production and use of cleaner fuels, improving the efficiency of energy use in all sectors, diversifying energy sources in accordance with the prevailing economic and social conditions, expanding the use of cleaner production techniques and environmental friendly technologies, as well as expanding the use of economic incentives to encourage more efficient products. Specific examples are the utilization of wind energy in Egypt; widespread use of solar heating in Palestine, Tunisia, and Morocco; the introduction of compressed natural gas as a transport fuel in Egypt; introduction of solar power in Egypt, Tunisia, Morocco, and Algeria; the massive forestation program in the UAE; the first zero-carbon city in Abu Dhabi; and the pioneering carbon capture and storage project in Algeria. However, most of these initiatives are fragmented and do not appear to have been implemented as part of a comprehensive policy framework at the national level, nor at the regional one.

5.3.2 Adaptation Characteristics and Processes

Adaptation refers both to the process of adapting and to the condition of being adapted. The term has specific interpretations in particular disciplines. The broad interpretation of adaptation includes adjustment in natural or human systems in response to experienced or future climatic conditions or their effects or impacts, which may be beneficial or adverse.

Adaptation to climate change has the potential to substantially reduce many of the adverse impacts of climate change and enhance beneficial impacts, though neither without cost nor without leaving residual damage. In natural systems, adaptation is reactive, whereas in human systems it also can be anticipatory. Experience with adaptation to climate variability and extremes shows that in the private and public sectors there are constraints to achieving the potential of adaptation. The adoption and effectiveness of private, or market-driven, adaptations in sectors and regions are limited by other forces, institutional conditions, and various sources of market failure. The ecological, social, and economic costs of relying on reactive, autonomous adaptation to the cumulative effects of climate change are substantial. Many of these costs can be avoided through planned, anticipatory adaptation. Designed appropriately, many adaptation strategies could provide multiple benefits in the near and longer terms. However, there are limits on their implementation and effectiveness.
Planned anticipatory adaptation has the potential to reduce vulnerability and realize opportunities associated with climate change, regardless of autonomous adaptation. Adaptation facilitated by public agencies is an important part of societal response to climate change. Implementation of adaptation policies, programs, and measures usually will have immediate and future benefits. Adaptations to current climate and climate-related risks are generally consistent with adaptation to changing climatic conditions. Adaptation measures are likely to be implemented only if they are consistent with or integrated with decisions or programs that address non-climatic stresses.

Vulnerabilities associated with climate change are rarely experienced independently of non-climatic conditions. Impacts of climatic stimuli are felt via economic or social stresses, and adaptations to climate (by individuals, communities, and governments) are evaluated and undertaken in light of these conditions. The costs of adaptation often are marginal to other management or development costs. To be effective, climate change adaptation must consider non-climatic stresses and be consistent with existing policy criteria, development objectives, and management structures.

The key features of climate change for vulnerability and adaptation are related to variability and extremes, not simply changed average conditions. Societies and economies have been making adaptations to climate for centuries. Most sectors, regions, and communities are reasonably adaptable to changes in average conditions, particularly if the changes are gradual. However, losses from climatic variations and extremes are substantial.

These losses indicate that autonomous adaptation has not been sufficient to offset damages associated with temporal variations in climatic conditions. Communities therefore are more vulnerable and less adaptable to changes in the frequency and/or magnitude of conditions other than average, especially extremes, which are inherent in climate change. The degree to which future adaptations are successful in offsetting adverse impacts of climate change will be determined by success in adapting to climate change, variability, and extremes.

5.3.3 Adaptation in the Water Sector

Adaptation strategies in the water sector will need to address a number of emerging trends driven by climate change. These include increased
uncertainty, variability and extreme events. Social and political contexts will further determine the net impacts of climate change on social systems and on the effectiveness of adaptation interventions.

Approaches proposed (Lim and Siegfried, 2004) to facilitate adaptation to climate change specific to the water sector comprise the following options:

1. Hazards-based approach, which aims to reduce climate induced risks. This approach assesses the current risk to which a system is exposed and then uses climate scenarios to estimate future vulnerability.

2. Vulnerability-based approach, which aims to ensure that critical thresholds of vulnerability in socio-ecological systems are not exceeded under climate change. Vulnerability assessment takes into account both development conditions and sensitivity to climate change.

3. Adaptive-capacity approach, which starts with an assessment of current adaptive capacity and aims to increase this capacity to enable systems to better cope with climate change and variability;

4. Policy-based approach, which aims to ensure a robust policy under climate change.

Under the proposed approaches, a number of technical, policy and market based instruments are being formulated, these include: ‘mainstreaming’, which requires development planning to take into account the effects of climate change; insurance frameworks, which build adaptive capacity; disaster risk preparedness and reduction, which aims to reduce climatic hazards; and safety net programs, which aim to reduce the vulnerability of local communities (Table 5.1).

Table 5.1: Proposed adaptation approaches and tools

<table>
<thead>
<tr>
<th>Approaches</th>
<th>Tools</th>
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<tbody>
<tr>
<td>Hazards-based approach</td>
<td>Building protection physical infrastructure; Disaster Risk Reduction and Preparedness planning</td>
</tr>
<tr>
<td></td>
<td>Disaster Risk Reduction and Preparedness planning</td>
</tr>
<tr>
<td>Vulnerability-based</td>
<td>Safety Net Programs; strengthening livelihood asset availability</td>
</tr>
<tr>
<td>approach</td>
<td></td>
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<tr>
<td>Adaptive-capacity</td>
<td>Insurance; improving technological know-how</td>
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<tr>
<td>approach</td>
<td></td>
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<tr>
<td>Policy-based approach</td>
<td>Mainstreaming within sectors; Climate proofing</td>
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Specific to the water sector, the IPCC Technical Paper on Water (2008) outlines three approaches that can be used to address climate change adaptation planning in the light of uncertainty in future hydrological conditions. These include:

1. Scenario-based approaches to planning: to develop plausible future storylines to facilitate decision making in the context of uncertainty. Scenario development is based on a set of assumptions of the key relationships and driving forces of change. These include predictable and unpredictable features of changes in climate, the environment and socio-economic factors.

2. Adaptive management: involving the increased use of water management measures that are robust enough to withstand uncertainty;

3. Integrated Water Resource Management (IWRM): by including on board diverse stakeholders; reshaping planning processes; coordinating land and water resources management; recognizing water quantity and quality linkages; conjunctive use of surface water and groundwater; and protecting and restoring natural systems. IWRM can ensure inclusive decision-making and resolve conflicts between competing water uses and, therefore, facilitate adaptation in the water sector. However, in order to address the impacts of climate change, IWRM will need to consider the different types of uncertainties involved.

In the water sector, planned interventions include both supply and demand side. While supply side adaptation options involve increases in storage capacity or abstraction from water courses; demand side options, like increasing the allocation efficiency of water to ensure that economic and social benefit is maximized through use in higher-value sectors, aim to increase value per volume used and to ensure that quality is maintained. Given the imbalanced state of water resources in the Arab region, calibrating water demand with available supply is the most important step to reduce the climate change effects but warrants sector-wide policy and institutional reforms. The effects of climate change can but re-affirm the urgency of implementing these reforms without delay as to make water resource management more environmentally, socially, economically and financially sustainable.

Improving water demand management and services coupled with associated environmental health gains will require sector-wide water reforms in most Arab countries to overcome the current state of scarcities of governance, i.e.,
accountability and organizational capacity, and physical resources. These reforms will allow for more accountability in terms of: efficient water allocation to the highest value use (trade-offs valuation); transparent decision-making with water allocations being responsive to demand and supply variability; and enforcing rules and regulations to ensure equity, quality service provision and environmental health outcomes. Water resources and environmental health outcomes should not however be considered in isolation as they cut across important drivers notably: population; poverty; urbanization; economic growth, energy, transport and industrialization; tourism; and agriculture. Adjusting the drivers’ distortions could also complement the water resources reform stance that could help prevent certain climate change effects in the future.

Also, institutional reforms should improve the organizational capacity in terms of: integrated planning that will help secure sustainable public and private water and wastewater investments; effective regulation of providers; demand management that secures reliable services; and water supply management through regional and national river basin management that would help arbitrate water allocation among countries and sectors especially through drought events.

As for the physical scarcity reforms, a series of solutions and innovative techniques could be envisaged such as: better storage systems to reduce evapotranspiration; consider water reuse through secondary and even tertiary wastewater treatment; flood risk mitigation combining watershed management and land-use planning; eutrophication management; river basin water transfers; protection and conservation of surface water and groundwater resources; rain harvesting, aquifer recharging; low carbon-intensive desalination plants; water-saving irrigation; and supporting irrigation scheduling management techniques.

Although not exhaustive, adaptive responses, which should take into account risk factors, will also require to: climate-proof existing construction and infrastructure to withstand extreme events and natural disasters, especially in rural areas, and update construction standards and norms; build contingency plans for population resettlement and livelihood in flood-prone areas; enhance preparedness to mitigate natural events, especially droughts and floods; improve environmental health outcomes through better health risk management and health sector preparedness; develop climate change risks special credit guaranties and insurance policies; etc. However, raising
awareness to develop better knowledge and moral commitment are a prelude. Climate change impacts on water cut across sectors, so sectoral responses need to be integrated to enable climate proofing.

A number of constraints could impede the adaptation responses. Sector-wide reforms are difficult, costly and lengthy processes. They could face resistance and turn unpopular. With regards to the water or other sectors, stakeholder inclusiveness, building trust and mutuality, sharing and discussing the pros and cons of good practice reforms, and promoting a fair, transparent and constructive dialogue among stakeholders could help facilitate the reform process, which could encourage donors to provide support. These reforms present opportunities and very cost-effective ways to containing and/or delaying some of the climate change effects.

5.3.4 Enabling Mechanisms for Adaptation

Coping with climate change requires transformation of the sectoral approach in water management to an approach where water is considered the principal and crosscutting medium for climate resilient development. Mainstreaming climate into water policies and IWRM alone will not accomplish this. Water management will have to go beyond the familiar approaches to address evolving complexities and develop innovative governance modalities, financing mechanisms and technologies; in combination with capacity development, structural reform and transfer programs for vulnerable societies. An understanding of enabling mechanisms and additional instruments is urgently required.

Given the many linkages between the impacts of climate change and social and economic systems, adaptation cannot be implemented efficiently by itself or as a strictly environmental issue, and a sensible combination of different kinds of enabling responses is needed. Sustainable development can be promoted by identifying clear responses to the consequences of climate change on water resources and water services.

The process that addresses these enabling mechanisms, as a whole, is known as “climate proofing” and can be implemented at the basin, national or local level.
5.4 Climate Change Adaptive Capacity

5.4.1 Vulnerability and Adaptive Capacity

Responses of natural systems to climate change, modified and buffered by the adaptive actions undertaken by societies and individuals, result in of climate change. If a society was capable of adjusting perfectly to cope with all of the harmful impacts which would otherwise result from exposure to climate change, then vulnerability would be nil and population well-being would be unaffected. Vulnerability, in this framework, comprises the residual effects on human well-being after a society has employed its adaptive capacity to moderate harmful changes. Overall, this model has two important aspects that distinguish it from more traditional “vulnerability” frameworks.

First, it considers more aggregate levels of society, up to and including the national level, in addition to individual households. Traditional vulnerability models are centered on the household and focus largely on response capacity and decision making at this level. The focus here emphasizes larger-scale public actions as a complement to those individual ones taken at the household level.

Second, the model focuses on adaptation rather than on vulnerability. It thus places greater importance on those points that can be altered to help adapt to harmful climatic change than it does on the characteristics of individual households that may constrain their ability to adapt. That is not to say that household level strengths and weaknesses are unimportant, but simply to acknowledge that the magnitude and scope of expected climatic change impacts will often require larger-scale intervention that is well beyond the capability of individual households. This focus on adaptation leads to a more pro-active attitude than the more passive vulnerability approach.

Adaptive capacity refers to the potential, capability, or ability of a system to adapt to climate change stimuli or their effects or impacts. Adaptive capacity greatly influences the vulnerability of communities and regions to climate change effects and hazards. Human activities and groups are considered climate-sensitive and can be affected by its change. It is also widely accepted that systems with high levels of capacity to cope with historical and/or existing stresses can be expected to have high adaptive capacity for stresses associated with climatic change. Such premises have formed the
basis for broad assessments of sensitivity and adaptability. Of course, sensitivity and adaptive capacity vary according to the climate change-related stress being considered. Thus, adaptive capacity to gradual changes in mean temperature may be high (or not much needed), but adaptive capacity to changes in the magnitude or frequency of extreme climatic conditions may not be so high.

5.4.2 Determinants of Adaptive Capacity

Adaptive capacity is the potential or ability of a system, region, or community to adapt to the effects or impacts of climate change. Enhancement of adaptive capacity represents a practical means of coping with changes and uncertainties in climate, including variability and extremes. In this way, enhancement of adaptive capacity reduces vulnerabilities and promotes sustainable development (Smit et al., 2000).

The capacity to adapt varies considerably among regions, countries, and socioeconomic groups and will vary over time. The most vulnerable regions and communities are highly exposed to hazardous climate change effects and have limited adaptive capacity. Considerable attention has been devoted to the characteristics of communities, countries, and regions that influence their tendency or ability to adapt and hence their vulnerability to risks associated with climate change.

Determinants of adaptive capacity relate to the economic, social, institutional, and technological conditions that facilitate or constrain the development and deployment of adaptive measures. The ability to adapt and cope with climate change impacts is a function of wealth, scientific and technical knowledge, information, skills, infrastructure, institutions, and equity. Adaptation takes place in a dynamic complex mix of conditions that determines the capacity of systems to adapt.

Although knowledge on adaptive capacity is extremely limited in the climate change field, there is considerable understanding of the conditions that influence the adaptability of societies to climate stimuli in the fields of hazards, resource management, and sustainable development. From this literature, it is possible to identify the main features of communities or regions that seem to determine their adaptive capacity.
Countries with limited economic resources, low levels of technology, poor information and skills, poor infrastructure, unstable or weak institutions, and inequitable empowerment and access to resources have little capacity to adapt and are highly vulnerable. Groups and regions with adaptive capacity that is limited along any of these dimensions are more vulnerable to climate change damages, just as they are more vulnerable to other stresses.

Whether it is expressed as the economic assets, capital resources, financial means, wealth, or poverty, the economic condition of nations and groups clearly is a major determinant of adaptive capacity. Lack of technology has the potential to seriously impede a nation’s ability to implement adaptation options by limiting the range of possible responses. Adaptive capacity is likely to vary, depending on availability and access to technology at various levels, from local to national and in all sectors. Hence, a community’s current level of technology and its ability to develop technologies are important determinants of adaptive capacity.

These determinants of adaptive capacity are not independent of each other, nor are they mutually exclusive. Adaptive capacity is the outcome of a combination of determinants and varies widely between countries and groups, as well as over time. Not only are conditions for adaptive capacity diverse, they also behave differently in different countries and regions, particularly depending on the level of development. These determinants represent conditions that constrain or enhance the adaptive capacity and hence the vulnerability of regions, nations, and communities.

5.4.3 Enhancing Adaptive Capacity

At the global scale, there is considerable variation among countries with regard to their capacity to adapt to climate change. Given their economic affluence and stability; their institutions and infrastructures; and their access to capital, information, and technology, obviously, developed nations are broadly considered to have greater capacity to adapt than developing regions or countries in economic transition.

In general, countries with well-developed social institutions supported by higher levels of capital and resources of human knowledge are considered to have greater adaptive capacity.
Adaptation options, including traditional coping strategies, often are available in developing countries; in practice, however, the capacity of those countries to provoke timely response actions may be beyond their infrastructure and economic means. For those countries, the main barriers are (Mizina et al., 1999):

- Financial/market (uncertain pricing, lack of capitals and credit)
- Institutional/legal (weak institutional structure, institutional instability)
- Social/cultural (rigidity in land-use practices, social conflicts)
- Technological (existence, access)
- Informational/educational (lack of information, trained personnel).

Although there is considerable literature on the determinants of adaptive capacity and examples of how they influence the adaptability of particular communities, there is little knowledge (and even less agreement) on criteria or variables by which adaptive capacity can be measured and by which the adaptive capacity of global regions can be quantitatively compared. Various studies have attempted to identify overall trends that cause increased or decreased vulnerability to environmental hazards (Blaikie et al., 1994).

Because vulnerability is a composite concept, social change has the potential to make individuals or activities more vulnerable in some ways and less vulnerable in others. The influence of changes in the determinants of adaptive capacity are not necessarily direct or clear, rendering the attempt to develop systematic indices for measurement and comparison a difficult task.

The adaptive capacity of a system or nation is likely to be greater when the following requirements are met:

1) The nation has a stable and prosperous economy. Regardless of biophysical vulnerability to the impacts of climate change, developed and wealthy nations are better prepared to bear the costs of adaptation than developing countries (Goklany, 1995; Burton, 1996).

2) There is a high degree of access to technology at various levels (i.e., from local to national) and in all sectors (Burton, 1996). Moreover, openness to development and utilization of new technologies for sustainable extraction, use, and development of natural resources is key element to strengthening adaptive capacity (Goklany, 1995).
3) The roles and responsibilities for implementation of adaptation strategies are well delineated by central governments and are clearly understood at national, regional, and local levels (Burton, 1996).

4) Systems are in place for the dissemination of climate change and adaptation information, nationally and regionally, and there are forums for the discussion and innovation of adaptation strategies at various levels (Gupta and Hisschemöller, 1997).

5) Social institutions and arrangements governing the allocation of power and access to resources within a nation, region, or community assure that access to resources is equitably distributed because the presence of power differentials can contribute to reduced adaptive capacity (Mustafa, 1998; Handmer et al., 19999).

6) Existing systems with high adaptive capacity are not compromised. For example, in the case of traditional or indigenous societies, pursuit of western/European-style development trajectories may reduce adaptive capacity by introducing greater technology dependence and higher density settlement and by devaluing traditional ecological knowledge and cultural values.

Because actions taken without reference to climate have the potential to affect vulnerability to it, enhancement of adaptive capacity to climate change can be regarded as one component of broader sustainable development initiatives. Hazards associated with climate change have the potential to undermine progress with sustainable development. Therefore, it is important for sustainable development initiatives to explicitly consider hazards and risks associated with climate change. Clearly, adaptive capacity to deal with climate risks is closely related to sustainable development and equity. Enhancement of adaptive capacity is fundamental to sustainable development. By assessing differences in vulnerability among regions and groups and by working to improve the adaptive capacity of those regions and groups, planned adaptation can contribute to equity considerations of sustainable development.

The vulnerabilities and anticipated impacts of climate change will be observed at different scales and levels of society, and enhancement of adaptive capacity can be initiated at different social scales, and successful adaptation will depend on actions taken at a number of levels.
In the absence of planned adaptation, communities will adapt autonomously to changing climatic conditions, but not without costs and residual damages. Societies and economies have been making adaptations to climate for centuries. However, losses from climate-related extreme events are substantial and, in some sectors, increasing, indicating patterns of development that remain vulnerable to temporal variations in climatic conditions and to climate change. The ecological, social, and economic costs of relying on reactive, autonomous adaptation to the cumulative effects of climate change are substantial and largely avoidable through planned, anticipatory adaptation.

Enhancement of adaptive capacity is necessary to reduce vulnerability, particularly for the most vulnerable regions, nations, and socioeconomic groups. Activities required for the enhancement of adaptive capacity are essentially equivalent to those that promote sustainable development and equity.

However, the sense of urgency for climate change adaptation and enhancement of adaptive capacity, with recognition of water centrality therein, have not yet permeated the Arab region and are not systematically reflected in national plans or regional investment portfolios for adaptation.
CHAPTER 6

Climate Change-Adaptive Management of Groundwater in the Arab Region: Concluding Remarks
6.1 Climate Change, Groundwater and the Arab Region

One of the main concerns in predicting the effects of climate change on water resources is to assess the vulnerability of streams and aquifers to the expected alterations of the hydrologic cycle. Vulnerability of a given hydrologic system is its capability to resist changes from external conditions; to be adapted to the adverse effects of increasing temperatures and decreasing rainfall. Such effects will actually modify the whole hydrologic cycle and its potential to supply water needs.

Vulnerability of water resources to climate change can be addressed through: 1- analysis of water demand to define the level of stress on water resources in the future; 2- better understanding of surface and groundwater hydrological systems, including storage capacity and resilience to varying recharge rates; 3- development of hydrological models that simulate the response of hydrological systems to changing conditions; and, 4- the use of indicators, as the Climate Vulnerability Index (CVI) which is an extension of the Water Poverty Index (WPI), that includes additional geo-referenced factors to express the vulnerability of people to global environmental change, and climate change (Sullivan and Meigh, 2005).

Changes in temperature and precipitation will likely alter recharge to groundwater aquifers, causing shifts in water table levels in unconfined aquifers as a first response. Decreases in groundwater recharge will not only affect water supply, but may also lead to reduced water quality. On the other hand, aquifers mitigate droughts as they have a high storage capacity and are less sensitive to direct climate change than surface water. Other potential impacts include altering the equilibrium in coastal aquifers, and reducing the volume of water stored in aquifers with associated potential for increased land subsidence.
Different types of aquifers respond differently to surface stresses. Shallow aquifers consisting of weathered or fractured bedrock or unconsolidated sediments are more responsive to stresses imposed at the ground surface compared to deeper aquifers. Similarly, shallow aquifers are affected by local climate changes, whereas water levels in deeper aquifers are affected by regional changes. Therefore, climate variability, being of relatively short term compared to climate change, will have greater impact on these shallow aquifer systems. In contrast, deep aquifers have an increased capacity to buffer the effects of climate variability, and are therefore able to preserve the longer-term trends associated with climate change. It is important to note, however, that deep aquifers can be vulnerable to climate variability, as shallow groundwater resources become limited or contaminated, deeper groundwater resources are often exploited.

Climate change is expected to affect the hydrological cycle and may alter surface water levels and groundwater recharge to aquifers. The accuracy of recharge estimations depend largely on the availability of hydrogeologic and climatic data. However, the heterogeneous nature and, often, less knowledge of the recharge flow paths makes recharge estimation an uncertain undertaking. Sea level rise leads to intrusion of saline water into the fresh groundwater in coastal aquifers and thus adversely affects groundwater resources. Although the most noticeable impacts of climate change could be changes in surface water levels and quality, the greatest concern of water managers and governments is the potential quality deterioration of groundwater supplies.

Climate variability is defined as the natural, often cyclic, and high frequency variation in climate. In contrast, climate change may be either natural or human-induced, and displays longer-term trends. While surface waters typically see rapid response to climate variability, the response of groundwater systems is often difficult to detect because the magnitude of the response is lower and delayed. Longer-term variations in climate are often well preserved in aquifers. Thus, the magnitude and timing of the impact of climate variability and change on aquifers, as reflected in water levels, are difficult to recognize and quantify. This is because of the difference in time frame that exists between climate variations and the aquifer's response to them.
From a regional or national perspective, our understanding of climate variability and change impacts on groundwater resources, related to availability, vulnerability and sustainability of freshwater, remains limited. The Arab region is one of the most water stressed areas in the whole world. Majority of the region is arid to semi-arid, receiving less than 200mm of annual rainfall. With limited or no surface water resources, many of the Arab countries depend significantly on groundwater to meet the growing water demands. Groundwater contribution in the total water use varies, not only from one country to another, but also from sector to sector within the same country. Generally, groundwater is the main source for irrigated agriculture and for domestic water supply in many parts of the region; whether solely or mixed with desalinated water.

Groundwater exploitation in the region has increased dramatically during the last decades due mainly to the increased demands. With withdrawal exceeding the internally renewable water resources, the resulting groundwater depletion is rapidly becoming a major concern in most countries of the Arab region. Thus, many groundwater resources are at risk of being exhausted through over-pumping. Such process is likely to exacerbate with time. Furthermore, considerable water volumes stored in large deep aquifers in the region are non-renewable resources and their use is therefore none sustainable. Accordingly, aquifers in the region are experiencing an increasing threat of pollution from urbanization, industrial development and agricultural activities. Measures and actions are essentially required to protect the natural quality of groundwater in the region’s aquifer systems.

In most of the Arab countries, consequences of population growth, land-use practices and improper management of water resources may be far more significant and critical than climate change. However, the impacts of climate change, which is projected to increase the frequency and intensity of extreme weather events, will contribute to even a worse water scarcity situation, and add to already difficult water management challenges in the region.

It is estimated that the impacts of climate change on the Arab region will include changes in precipitation rates, surface runoff and river flow rates, which will affect the recharge rates of groundwater and also further exacerbate extraction rates of groundwater, as a result of lower availability of surface water. Water quality in rivers and coastal areas is also expected to
be affected due to sea level rise and saltwater intrusion into coastal groundwater aquifers. These changes would affect the flow in coastal aquifers leading to further deterioration of groundwater quality. Climate change may also affect the quality of groundwater where reduced rates of recharge and altered flow regimes may increase the concentrations of contaminants in groundwater.

If groundwater becomes polluted, it is difficult and usually very costly to rehabilitate. It is therefore advisable to prevent or reduce the risk of groundwater pollution rather than have to deal with the consequences of pollution. Groundwater protection should therefore be a top priority, and be an essential part in mainstreaming of “climate proofing” in the management of groundwater resources in the region.

6.2 Guidelines for Climate Proof Groundwater Protection

Approaches to groundwater protection essentially involve intervention by government. This can take place in three main ways: (i) by direct command over activities; (ii) by the introduction of market approaches; and (iii) by raising social awareness through community participation and education.

The most common example of the first way of intervention would be the many government regulations, which directly control actions and activities. Government regulations are a direct way and the quickest way of stopping pollution when it can be easily identified. However, the link between a pollution source and the long-term vulnerability of an aquifer to pollution can be hard to define. These problems may not justify such form of intervention over long periods since the monitoring; enforcement and political costs to government can be very high.

The second type of intervention can be by market approaches, which provide financial incentives for proper behavior and provide more efficient and equitable distribution of the costs of pollution or the cost of protection measures. The efficient and equitable implementation of one or a mix of market approaches to groundwater requires a thorough economic analysis. For groundwater protection strategies, application of the "polluter pays principle" would lead to potential polluters paying for the monitoring and reporting of contaminant levels in aquifers.
The third form of intervention covers a range of social actions, which involve community participation and education. In the development of strategies, public participation processes can greatly improve the general understanding of the need for groundwater protection in general, and climate proofing in specific. Community participation process informs the community of the problems and their options, improves decision making, and creates a sense of ownership. Long-term protection of groundwater against climate change impacts is an example that requires the development of protection strategies through a community participation process. This form of intervention is strongly recommended.

The discussed, three types of government intervention, all have a part to play in groundwater protection. Most strategies will involve action derived from utilizing more than one of these intervention methods.

A groundwater protection strategy is in part a plan for intervention. It is made up from a detailed set of policies, plans and actions which together aim to achieve certain objectives. Consequently, the purpose of strategy development is to plan ways in which the government and the community at large can adopt a coordinated and comprehensive approach to “climate proofing” the protection and management of groundwater resources. In this respect, there are various types of groundwater protection measures which are used in different parts of the world. Each measure has its strengths and weaknesses. Consequently, there is not a unique set of measure that can be universally adopted to protect a country's groundwater. Each country will need to examine the range of, measures available and adapt one or more of these measures to their particular circumstances and local needs. The choice of suitable measures will not only depend on the physical properties of the groundwater body, sensitivity to a changing climate, exposure to threats and the nature and type of pollution, but also on legislative, financial, social, environmental and political considerations.

If groundwater is to be climate-proof protected in the long term, a plan should then be drawn up. Such planning activity will also determine the protection measures which are pertinent to the situation being examined. There are a variety of government legislative powers that can be utilized to develop and implement groundwater protection plans. This legislation can be grouped under three broad headings: (1) Groundwater Management; (2) Land-use Planning; and (3) Environment Protection.
Groundwater management legislation typically includes controls on groundwater extraction rates. In some cases, legislation will also specifically include powers to protect groundwater quality particularly in stressed areas or public water supply areas. These powers can take the form of by-laws to control and regulate the disposal and storage of materials underground, and intervene in relevant risky activities.

Land-use planning legislation places controls over the broad uses to which land is put. Inevitably, long-term effects result from land uses which are detrimental to groundwater. Land-use planning is a critical factor in implementing effective groundwater management strategies at a regional scale. For socio-economic reasons, significant progress has not been made of land-use planning legislation to control degradation of groundwater. However, land-use controls are likely to be more widely adopted as pollution problems are linked to the expected climate change impacts and become more critical over broad areas in future.

Environment protection legislation varies in its coverage, though it tends to be generally built on pollution control concepts. As such, it can protect aquifers by directly applying controls to point-source pollution and indirectly applying controls to diffuse-source pollution through regulations on contaminants. Such legislation would also be expected to cover the remediation of contaminated sites and polluted groundwater bodies.

A groundwater protection plan will need to take into account the available legislative tools, which will involve the above three elements. If current legislation is deficient it will be necessary to recommend new legislation or amendments to existing legislation to ensure that an adequate legislative base exists for climate proofing of groundwater protection. Groundwater managers in the water sector favor intervention measures, which derive their power from existing groundwater management legislation, because they can intervene under this type of legislation. However, protection of groundwater in the long-term, including climate proofing, will not only rely on traditional groundwater management measures but will also rely more and more on land-use planning and environmental protection measures.

Strategies can be applied to a specific groundwater resource under an overall protection plan. Groundwater protection plans and their component measures may take many forms. They may vary from policy statements outlining broad management objectives to prescriptive regulatory programs,
including statutory controls and specific regulations on contaminating activities. Their intent may be limited to influencing decision-making regarding approval of potentially contaminating activities, or it may be to control closely these activities. Protection plans may apply to specific geographic localities of various sizes from Statewide to a small aquifer. They may cover part or whole of an aquifer, or groups of aquifers.

Groundwater protection plans may be directed to minimizing climate change future pollution of groundwater, or to detecting and managing pollution associated with past or existing activities. The scope of protection plans and the range of measures, which may be incorporated in these plans, are endless. Development of a protection plan for a specific region will need to address several issues. The involvement of the public in the planning process will be an important initial decision.

Implementation of the plan will also require definition of the roles of the various agencies involved, and co-ordination of their efforts. It is important that the decision-making and management of the plan should have a clear responsibilities, proposed outcomes and schedules for action, and the procedures for regular reporting to government and the community on the achieved progress.

A groundwater protection plan is not a static event. It must evolve with improvements in the information base and changes in society and land use. This requires an adaptive management approach entailing regular review of strategies, their priorities, effectiveness, direction and focus and the evolution of adapted or different strategies in order to continually meet protection objectives (Page, 1987).

6.3 Groundwater Climate Change-Adaptive IWRM

Water resources development in the Arab region has long been directed to satisfy water demand without considering the impact of such process on the available water resources and without taking also into account the scarcity of these resources in the region. Economic policies in some countries encourage over-pumping of groundwater for irrigated agriculture. It is obvious that such policies need serious assessment in terms of their impact on the sustainability of water resources in general, and groundwater resources in particular.
Although agriculture is the largest user of water in the region, rapid urbanization and improved quality of life have also contributed to the sharp increase in water demands. Conflict between the water use sectors is rising in most of the region, and as a result, groundwater over-exploitation and mining is expected to continue in order to meet growing demand in all sectors. In addition to over-exploitation, the quality of groundwater deteriorates and, thereby reducing available groundwater supplies, increasing overall water shortages, and intensifying the problem of water scarcity in the region.

Management of groundwater resources has to deal with balancing supply, in terms of quantity, quality, and surface water interactions, with the increasing demands of water. Calls for groundwater management do not usually arise until a decline in well yields and/or quality deterioration affects resources. It must be noted that preventive management approaches are likely to be more cost-effective than purely reactive ones. It is also essential to recognize that managing groundwater is as much about managing people as it is about managing water.

Integrated Water Resource Management (IWRM) has been identified as one of the main approach that can be used to address climate change adaptation (IPCC, 2008) by including on board diverse stakeholders; reshaping planning processes; coordinating land and water resources management; recognizing water quantity and quality linkages; conjunctive use of surface water and groundwater; and protecting and restoring natural systems. IWRM can ensure inclusive decision-making and resolve conflicts between competing water uses and, therefore, facilitate adaptation in the water sector. However, in order to address the impacts of climate change, IWRM will need to consider the different types of uncertainties involved.

The growing demand for water and socio-economic development in the region, coupled with limited available water supplies, and expected future climate change impacts, represent a serious problem for most of the Arab countries. Governments in the region are increasingly recognizing the urgency of addressing water issues, and policy and institutional reforms are being considered in most countries. Water resource management can be conveniently considered as a twofold undertaking; supply management (which covers those activities required to locate, develop and exploit new sources), and demand management (which addresses measures and mechanisms to promote more desirable levels and patterns of water use).
The adoption of a comprehensive policy framework and treatment of water as an economic good, combined with decentralized management and delivery structures, is the basis for integrated water resources management. So long as water is abundant and of good quality, interaction between different water users and stakeholders may not be so essential, and water project could be implemented with little regard to their impacts elsewhere. But as pressures mount, so does the need for such interaction.

Fragmented management approaches essentially fail to account for competition for the same resource among users. The result could incur rapidly increasing cost of water quality deterioration, water allocation to low-value uses, and overall aggravation of the water situation. Therefore, governments need to establish a policy framework that takes a long-term perspective for the management of water demand and supply. An integrated climate proof approach to water resources management calls for giving due consideration to technical, economic, social and environmental requirements during the planning of water resources development programs, as well as implementing inter-related activities in an efficient integrated and comprehensive manner. It also calls for setting priorities that meet social expectations and the availability of financial resources. It emphasizes the need for water to be regarded as a finite and scarce resource that constitutes a portion of infrastructural input in development activities. Meanwhile, the integrated water resources management approach must be achieved according to established water policies and strategies.

Climate proof groundwater management strategies must be based on an integrated water resources management approaches taking into consideration the following principles;

- Groundwater is owned and controlled by the state and ownership of land does not include ownership of groundwater.
- Extraction and use of groundwater is authorized by a license to the landowner.
- Groundwater is part of the hydrological cycle and must be included in a global framework for water resources management with a long term perspective.
- It is also important that groundwater management should be regularly reviewed and updated to meet the policy needs that can change over time.
Strategies are needed to stabilize heavily stressed aquifers. Such strategies are generally sub-divided into demand-side management interventions and the supply-side engineering measures. Furthermore, it should be noted that although groundwater management is conducted at local aquifer level, national food and energy policies, including subsidies, can exert an overriding influence on the behavior of groundwater users, and thus on resource development pressures and management strains. In general, subsidy policy should always be reviewed, and consideration be given to climate proof water-saving technology.

It is always essential to address the issue of constraining demand for groundwater abstraction, since this will normally contribute more to achieving the groundwater balance. Complementary supply-side measures should always be encouraged where conditions are favorable. Moreover, reducing groundwater resource used for irrigated agriculture is of paramount importance in the region, being the main consumer of groundwater resources, and obviously where major savings can be achieved. In aggravated aquifer conditions where larger water savings are needed, then consideration should also be given to modification of cropping patterns and land use. An even more radical option would be to place restrictions or a ban on irrigated agriculture in critical groundwater abstraction areas.

Comprehensive water resource planning requires government intervention in the management of the resources. Government is inevitably required to establish the policy, legislative, and regulatory framework for managing water supply and demand. This does not mean that governments must control each and every aspect of resources management. Many important activities are preferably decentralized to autonomous local, private, and user group entities. Indeed as a general principle, functions that can be done better at a lower level should not be done at a higher level. Nor does it mean that governments alone should set objectives and priorities (Khater, 2001).

Though most of the Arab countries conduct water resources planning, the adopted processes are still fragmented and have not evolved to a level sufficient for effective management of water resources. Therefore, the current planning practices should be modified to account for the requirements of integrated water resources management. Water policy reform in the region must involve review of activities within the water sector, as well as other water-related sectors of the economy. Policy reform should involve formulation and enforcement of comprehensive regulations.
and improvement of institutional structure in order to achieve efficient management and development of scarce water resources. Policy reform based on the concern of climate change adaptive approach should also define water-planning procedures, level of planning and the extent of involvement of specialists and decision-makers.

6.4 Climate Change Adaptation Research Priorities

Climate change adaptation in an integrated water resources management framework calls for efforts to be devoted to research and development in all facets of the water field. There is a need to identify research priorities and apply the results of these studies through coordination between research bodies and government agencies. Encouraging research and development in each country, and technical cooperation between countries in the region is an effective way of focusing on the problems being faced, and the need to find cost effective solutions for the development and adoption of new technologies. In our arid environment, efforts need to be focused on the improvement of assessment and monitoring methodologies, management techniques that are socially and economically acceptable, and implementation of various supply augmentation schemes including non-conventional water resources.

Research areas of high priority to the climate change adaptive management of groundwater resources in the Arab region include: (1) improved identification of regional hydrogeologic frameworks; (2) better understanding of groundwater and surface water interaction; (3) effective characterization of groundwater flow in shallow aquifer systems; (4) improving scarcity of data and uncertainties associated with predictions from groundwater models; (5) modeling of climate change impacts on the movement of seawater into coastal aquifers; (6) predictive tools for the rate of increase of the salinity of aquifers; (7) development approaches for non-renewable groundwater; (8) risks that climate change poses for aquifer systems and groundwater availability; (9) applying the output of climate models on to groundwater models; and (10) enhancement of climate change adaptive capacity approaches, methodologies, valuation techniques, geographic information and decision support systems, and rapid assessment tools.
Human resources development is essential for integrated water resources management, and the need for promotion of capacity building for climate change adaptation in the water sector has been widely recognized at national and regional levels. In the Arab region, human resources capability in the public water sector varies considerably from country to country. As a result, consultants do much of the planning and many countries do not have sufficient qualified interdisciplinary staff even to review and comment on the work of consultants. Indeed, in some countries, governments may have surprisingly limited input into development plans that go forward for authorization, and then implementation.

There is a need to promote and strengthen training capacity at all levels throughout the region. Identification of training needs is an important phase of professional water resources development and management. Emphasis should be placed on formulating efficient training programs for new recruits as well as keeping existing professionals updated and informed on new techniques and management procedures. Department managers and staff responsible for projects should receive management training in addition to their technical background. It is essential to recruit personnel in deficient areas of specialization in order to maintain well balanced interdisciplinary staff.

The existing educational infrastructure in hydrology and water resources in each country should be utilized for training courses, workshops, and degree programs in water resources planning and management with emphasis on climate change adaptation in the water sector. Integrated water resources management frameworks should define the institutional capacity, either the existing or to be built. A comprehensive and long term analysis of the existing situation, taking a long-term view is required for developing a strategy, which would address the mobilization of staff, capital resources and political support for sector enhancement.

In the context of climate proof integrated management of groundwater resources, high priority training needs in the region essentially involve: water resources planning; policy and strategy formulation; public-private partnership; stakeholder participation; monitoring systems; resources assessment; pollution control; protection of resources; mathematical modeling; informatics; and water legislation.
6.5 The Way Forward

The Arab region is facing possibly a vital challenge with regards to the impacts of climate change in the 21st century. The tasks at hand in the near to long terms seem critical. Nevertheless, adopting a climate change adaptive management in the water sector coupled with an enabling socio-economic environment could mitigate, absorb or delay some of the expected effects of climate change in the Arab region. Hopefully, climate change models will certainly be refined with time and produce better knowledge and more accurate projection scenarios. As a result, this will prove invaluable to better plan, prioritize and sequence mitigation and adaptation interventions to climate change especially for water resources.

Better risk management will however require building strategic and dynamic partnerships nationally (public-private-academia-communities), regionally (oil countries) and internationally (donors, foundations, etc.). This will ensure fund leveraging, regional economies of scale, and the adopting of good practices. Better risk management calls also for shaping policies that promote innovation and breakthroughs in certain areas such as water use rationalization and saving techniques.

Rule-bound governance, transparency and coherence with regards to water resources could moderate climate change effects by increasing efficiency, equity and sustainable outcomes through: participatory planning; legal adjustments; cross sectoral institutional harmonization and disaster preparedness along government tiers; enhanced adaptive capacity building; and close monitoring. Financial resource availability could vary among Arab countries; therefore not all planned adaptation interventions could be implemented. Intervention options should be based on quantitative analysis (socio-economic and environment) that will allow decision-makers to evaluate trade-offs between various policy options to make better and selective choices based on urgency, value-added, and multiplier effects.

A vulnerability assessment of climate change impacts can determine how and where a community is subject to climate change risks. A vulnerability assessment can be qualitative in nature (e.g. class risks in terms of high, medium, low threats) and/or quantitative and present empirical findings such as changes in the water balance, the percentage share of the population at risk, or the loss to national revenues due to increased frequency of natural disasters. Once the purpose, scope and scale of a vulnerability assessment
are identified, vulnerability indicators can be used to monitor changes in human conditions and ecosystem over time as well as measure exposure risks and the effectiveness of future adaptation strategies.

Additionally, to prepare a vulnerability assessment, major issues of concern are about the availability of global and regional models that are transferable for application at the Arab regional and sub-regional levels, and the technical capacity to perform the assessment as well. It is very important not only to recognize the purpose, scope and scale of the vulnerability assessment to be conducted, but also to identify the methodological approach to be taken, in view of the fact that there is not one approach currently applied, tested and accepted that examines the Arab regional context.

In determining which methodological approach to take, care should be taken to ensure that the approach is flexible, dynamic yet sufficiently specific to reflect the impact of climate changes on water resources so as to be able to translate the assessment of the natural resource sensitivity to an assessment of the vulnerability of related socio-economic and environmental conditions.

There are many other challenges that must also be overcome in preparing this vulnerability assessment for the Arab region, such as the: 1) inadequacy of information and research material on the vulnerability of communities and ecosystems to climate and water resource variability; 2) limited technological skills and human resources; 3) shortage of data and available regional climate models downscaled from global GCMs; 4) high degree of uncertainty associated with extreme climate events and the effectiveness of associated contingency planning and implementation; and 5) difficulty of multi-disciplinary coordination among stakeholders and regional actors dealing with climate change issues.

While climate change expected impacts have generally been modeled through the development of global climate models, limited research and information has been generated on the effects of climate change at the Arab region level, and specifically what implication different climate change scenarios may have for water resources and socio-economic and environmental vulnerability in the region. The climate change projection models need to be built into a knowledge infrastructure on climate change effects in conjunction with water resources and vulnerability areas in the Arab countries. The knowledge infrastructure should build on harmonized
information systems, which could serve as a national decision support system to improve climate change risk management. The knowledge infrastructure should have compatible platform to allow for data aggregation at the sub-regional and regional levels.

Climate change projection models under various scenarios gave in most cases clear trends on the climatic variables on regional scales. However, some inconsistencies and uncertainties were reported in the results, which call for a new set of harmonized projections for the Arab region, sub-region and countries under IPCC scenarios, which could be updated and calibrated on demand, to help formulate better responses based on more robust results.
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