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Environmental Security

Climate Change and its Effects on Water Resources

Issues of National and Global Security

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Series C: Environmental Security

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Preface

National and global security can be assessed in many ways but one underlying factor for all humanity is to access to reliable sources of water for drinking, sanitation, food production and manufacturing industry. In many parts of the world, population growth and an escalating demand for water already threaten the sustainable management of available water supplies. Global warming, climate change and sea level rise are expected to intensify the resource sustainability issue in many water-stressed regions of the world by reducing the annual supply of renewable fresh water and promoting the intrusion of saline water into aquifers along sea coasts where 50% of the global population reside. Pro-active resource management decisions are required, but such efforts would be futile unless reliable predictions can be made to assess the impact of the changing global conditions that would impart upon the water cycle and the quality and availability of critical water reserves.

Time is of the essence as relatively little is known about the likely effects of global warming, climate change and sea level rise on the world's renewable water resources. If the emission of greenhouse gases continues at currently projected levels, global temperatures would rise faster in this century than in any time during the last 10,000 years. For such a scenario, global climate models predict that many regions would experience drier summers, higher annual rates of evapotranspiration and a significant increase in the frequency of extreme events such as droughts and floods. One of the worst affected areas would be the Mediterranean Basin where 75% of the renewable water supply is currently derived from surface runoff (river flows) and the remaining 25% is obtained from groundwater (as represented by aquifer recharge). In this region, in the south of latitude 45°N, temperatures are expected to increase well above the global average and annual precipitation is projected to decline by 10–40%, causing a significant reduction in river flows. In terms of groundwater, aquifer recharge rates are expected to fall by as much as 50–70% due to the combination of lower rainfall and increased evapotranspiration.

Coastal areas are especially threatened. A rise in global atmospheric temperature would cause thermal expansion of the ocean, melting of mountain glaciers and small ice caps, and accelerate the ablation of the polar ice sheets. Predictions of sea level rise vary, but most models suggest that ocean levels could rise by up to a meter by the end of this century, with some regions experiencing far more severe impacts. Rising sea-levels would reduce aquifer recharge along low-lying coasts due the landward transgression of the sea and cause saline groundwater to advance in land where it would compromise the quality of fresh groundwater reserves.

In September 2010, the effects of climate change on water supply and the potential threats to resource sustainability and long-term water security became the focus of attention for 50 specialists who were invited to Izmir, Turkey to contribute their knowledge and experience to an Advanced Research Workshop (ARW) conducted under the auspices of NATO's Science for Peace and Security Programme. Over a period of three days, 40 research papers were presented on a wide range of important topics dealing with climate change and water-security concerns at the national, regional and global levels. The papers stimulated considerable discussion and intellectual debate, and highlighted the complexity of the problem and the urgent need for the development of modeling tools that could reliably predict the potential impacts of global warming on water supplies. Also, valuable discussions took place on the formulation of strategies for adaptation and mitigation. These discussions further drew attention to the differences between groundwater and surface water resources in the way that they respond to climate change, and generated agreement on the need to manage the water resources of a basin holistically to derive optimal benefits. In terms of water security, this was seen to lie at the interface among scientists, engineers, economists, and politicians and demonstrated the need for all stakeholders to work co-operatively if strategies for sustainable resources management under conditions of climate change are to be both scientifically sound and acceptable to the public from social and economic perspectives.

Overall, the workshop provided a valuable platform for urgently required dialogue on the impacts of climate change on the global water resources, the long-term resource management goals at global and local scales, data requirements and the scientific and technical advances necessary to achieve success. The exchange of experiences and scientific thought produced creative ideas for potential solutions, but more importantly sowed seeds for strong future international scientific collaboration towards a common goal of a vital global significance.

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Chapter 1
Resilience Analysis of Climate Change Effects on Water Quality and Health

Mustafa M. Aral

Abstract The purpose of this paper is to provide an overview of the application of the resilience methodology to analyze quantitative engineering problems and demonstrate how this analysis can be used in making policy decisions in water quality and climate change problems. The resilience thinking is a relatively new paradigm which has found its roots in the analysis of social-ecological systems. Engineering and thus quantitative applications of this conceptual framework is at its infancy and the topics discussed in this paper may shed some light to this path which is full of mathematical and computational difficulties.

Keywords Climate change • Water quality • Resilience analysis

1.1 Introduction

"Resilience Thinking" is a relatively new paradigm that maybe used in the evaluation and management of complex systems. Up to now this conceptual framework was mostly used for the management of social-ecological systems. The goal of managing for a resilient complex system is finding ways to maintain the ability of the system to absorb stochastic and human induced perturbations and eventually return to the stable domain of the current state. Or, as the question goes, understanding what happens to the complex system behavior if it is improperly managed and a tipping point is reached and the system is kicked out of the stability domain of the current state. The likelihood of such a change may yield the

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following possibilities: (i) the system crosses a threshold and enters into an alternate stability domain where the resilience of the overall system may increase or decrease; and, (ii) the system may not find another stability domain and the outcome is unsustainable chaotic behavior of the complex system. This is a concept which is extremely useful especially for those cases where we anticipate that the command and control approach of classical analysis of environmental systems may not work.

More and more we are recognizing that the surroundings in which we live in, function and enjoy life as human beings can only be described in terms of the principles embedded in the complex system theory [1, 2]. Extracting some parts of this complex system and only incorporating those parts into our analysis renders the overall analysis to be fragmented and inadequate. For the overall assessment to be more representative and inclusive, more coherence to the complex nature of the environment studied is needed and in this analysis the integration of various components of the complex system we live in (environmental and non-environmental stressors) must be represented. Computational aspects of this analysis must integrate deterministic and stochastic approaches. The treatment of uncertainties must be based on sound scientific procedures that represent probabilistic and heuristic uncertainty that are inherent in the data used.

Current environmental models and accompanying methods of analysis are mostly compartmentalized, that is they use reduced dimensionality in both conceptual and quantitative level. This analysis is mostly based on information that is obtained from environmental models that are designed to control change in systems that are assumed to be stable. The aim in "control based" approach is to evaluate the capacity of the system to cope with, adapt to, and shape the change that will be imposed. This has been the case for most water resources, environmental management models and applications. However, there are risks with this "command-and-control" analysis principle. Stochastic or human induced changes or stresses may change the state of the system with serious impacts on the outcome. Perception of the stability of human-environmental systems and the concept of "change is possible to control," has proven to be false in many occasions in the past. Today we know that human-environmental systems do not respond to change in a smooth and predictable manner. Rather, a stressed system can suddenly shift from a seemingly steady state to a state that is difficult to reverse [3, 4]. As a result, proper system evaluation methodologies are becoming increasingly complex and it is beneficial to reflect this in climate change analysis as well. Taking this complexity seriously has fundamental consequences for our understanding of what we are defining here to be a resilience based analysis of climate change effects on water quality and other state variables such as health effects.

Basic concepts of this conceptual framework will be covered in what follows and some insight will be provided for the quantification of this analysis which may prove to be useful in the application of this methodology in this field and also in other related fields.

1.2 Conceptual Framework

There are several ways to define the resilience measure of a complex system. In its simplest definition, Resilience is defined as the capacity of the complex system to absorb disturbances while undergoing change as it retains essentially its function, structure, identity, and response state. In essence, in the context of climate change based water quality issues, a resilient system's water quality would be the one that would have the capacity to respond to climate change based environmental or human induced stressors without exhibiting failure modes such as uncontrollable pollution levels that would yield adverse human or ecological health effects outcome. The loss of resilience may lead to more vulnerable states in which even minor disturbances can cause a significant shift to another state that is difficult or even impossible to recover from. Thus, vulnerability is the flip side of resilience concept and occurs when a system loses its resilience and becomes vulnerable to change that previously could have been absorbed. In the context of climate change based water quality problems, the resilience concept has four components which are quantifiable using basic engineering and science based tools. These are Latitude (L), Resistance (R), Precariousness (Pr), and Panarchy (Pa). In our context Latitude is defined as the maximum amount the system can be changed before it loses its ability to recover; Resistance is the ease or difficulty of enacting a change on the system; Precariousness is the current trajectory of the complex system, and how close it currently is to a threshold which, if breached, makes the recovery difficult or impossible or moves the system to another state; Panarchy is an indicator to measure how the above three attributes are influenced by the states and dynamics of the other systems that comprise the overall complex system at scales above and below the scale of interest. In this manner, when all stressors are included, the overall system analyzed will be an integrated complex system.

Most complex systems studied in the literature in this framework include human systems as is the case with climate change based problems. Since human perception or response is an important component in the resilience methodology, the proposed models we may also include the quantifiable concept, maybe in the possibilistic sense, of adaptability and transformability. This concept is associated with a measure of the ability of a community to cope with the stress imposed on them due to a stressor in their community namely health effects of water pollution. In this sense, social resilience differs fundamentally from natural or engineered system resilience since it exhibits the capacity of humans to anticipate, adapt and plan for the future. This plays an important role in the overall evaluation of the behavior of the complex system.

The purpose of implementing this methodology would be finding ways of making desirable system basins of attraction wider and/or deeper, while shrinking undesirable states and the introduction of new stability landscapes by introducing new components. In summary, the purpose is to manage the complex system such that the overall system would work harmoniously. In essence, the analysis of stability dynamics of the linked systems of humans, environment and pollution merge from the three complementary attributes of resilience, adaptability, and transformability.

Quantification of these measures and providing a path to the analysis of system performance is not straight forward. Here we will explore the basic principles that may be used in this analysis using lower dimensional models and provide insights for higher dimensional analysis along these lines.

1.3 Model and Resilience Analysis

To introduce the concept we will start with a simple model. The premise of the model is that climate change effects may results in deterioration of water quality throughout a region of the world and this would eventually affect the public health of populations. The relationship between the three parameters considered in this model, namely the water quality, public health and the climate change effects parameter can be represented in terms of a box model characterized by the following simultaneous ordinary differential equation:

$$\frac{dC}{dt} = f_1(C, P_H, CC, t)$$
$$\frac{dP_H}{dt} = f_2(C, P_H, CC, t) \qquad (1.1)$$

In the model discussed here, Eq. 1.1 is a nonlinear ordinary differential equation which will be calibrated using data on regional water quality and public health. The non dimensional climate change parameter CC is a variable that would represent the climate change forcing function. In this case it is varied in between 0.05 and 0.45 indicating and increase in temperature. The nonlinear ordinary differential equation system has two stable points, one is at high public health level with low contamination and the other one is at low public health level with high contamination. In this case high contamination implies low water quality. There is the possibility of the system to converge to either of these two stability points depending on the initial conditions of the problem. The low water quality (high contamination) and low public health level is not a desired stability point for this system. On the other hand the stability point of high public health and high water quality (low contamination) is a desired stability point. The resilience of the system is defined as the return time required to any of these stable points given an initial starting point [5] and a disturbance. Obviously, after a disturbance, smaller return time to a stability point indicates the system is more resilient for that stability point even though one of the stability points may not be desired. Notice that the stability points are also a function of the parameter CC, the climate change parameter. The model selected indicates that the domain of attraction of the desired stable point shrinks as the climate change parameter is increased, implying the overall system behavior

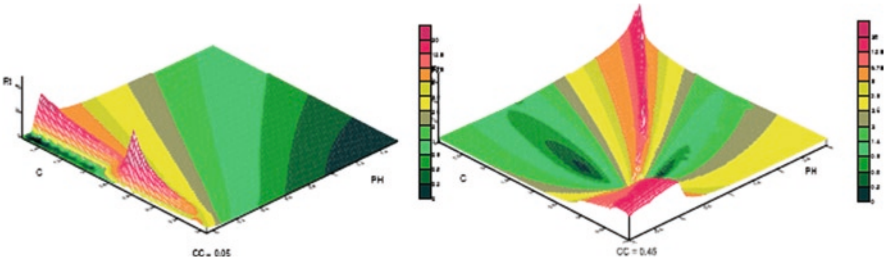

Fig. 1.1 Resilience landscape for CC = 0.05 and 0.45

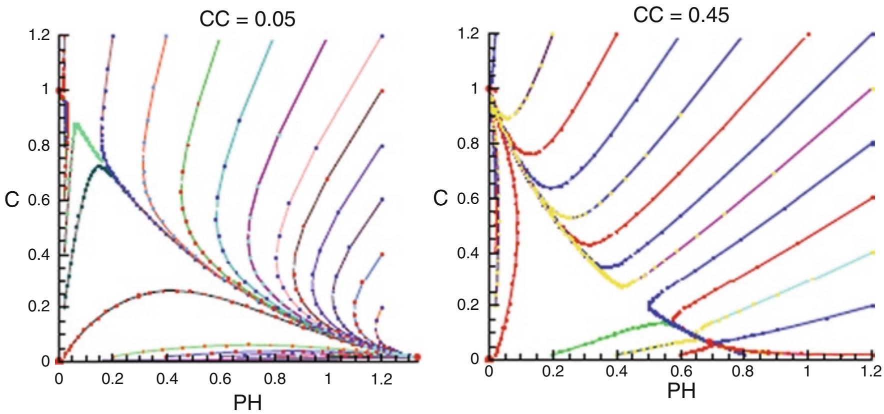

Fig. 1.2 Return time pathways on the phase diagram

is dominated more and more by the undesired state (Fig. 1.1). In the phase space, the domain of attraction of these two stability points can be observed as shown in Fig. 1.1 for the climate change parameter range $CC = 0.05$–0.45. All starting points on either side of the dividing surface will converge to the respective stability regions ending up in one of the desired or undesired conditions for the system. In Fig. 1.2 some of these paths are shown for several different starting points for $CC = 0.05$ and $CC = 0.45$.

The analysis of Fig. 1.2 indicates that some of the initial conditions which represent the current state of the public health and water quality conditions of a population that would be in the basin of attraction of a desired stability state may find itself in the basin of attraction of an undesired stability state as the climate change parameter is increased from 0.05 to 0.45 indicating deteriorating climate conditions. Thus, the policy decision that needs to be made for the populations is not uniform across the regions of the world. There are some populations and regions of the world which are in a more vulnerable state than others. These are those regions of the world which are currently at low public health level. In these regions, although the water quality may be at an acceptable level the vulnerability state to climate change of these regions is high. If the public health level is low and the water quality is also low than those populations will immediately feel the adverse effects of deteriorating climate and they will end in very low water quality levels and unsustainable public health conditions.

As a policy decision less vulnerable populations may manage to stay in the basin of attraction of the desirable stability point if they are able to improve their public health state and the local water quality standards. This can only be achieved if the rate of improvement implemented as a policy is higher than the rate of deterioration due to climate change effects. These rates are a function of the rate of movement of the public health factors along the trajectory and also the rate of deterioration effects. These two rates are also not the same for all populations and all regions of the world. These rates are also not constant for a given region and it varies as a function of time. Every starting point shown in Fig. 1.2 has to implement a different rate of improvement at every time step since the constant rate climate deterioration manifests itself at different rates of deterioration depending on these starting points and where the population is along the trajectory when the climate change effects are observed. That is, not only the initial conditions of the population and the region are important but also it is important to know where the region and population is on the phase space at each time when an adverse climate change effect occurs. Thus, uniform policy decisions across the board may not solve the problem in certain cases. The least vulnerable populations are those which are currently at high public health levels with low water quality problems. Seemingly those will survive the easiest according to the model implemented here which ignores the systemic risk. However, that is not the case as will be discussed below. This outcome only reflects the limitations of the model selected for this analysis. More realistic complex system models are necessary to address those conditions.

The outcome observed above may also be reversed. If the climate quality is improved than the basin of attraction of the desired stability point will enlarge and most populations of the world will have good chance of survival. According to the model used here some populations of the world may be already under stress under current climate conditions. The outcome maybe improved significantly, especially for most vulnerable populations, if all regions of the world and both industrialized and developing nations of the world not only collectively contribute to reduce the adverse effects of climate change but also help improve the current water quality conditions and public health levels of most vulnerable countries. Under these conditions it may be possible to control the adverse effects of deteriorating condition of climate change.

1.4 Perspectives Gained

The simplified example discussed in this study demonstrates that the policy decisions to be made to reduce the adverse effects of climate change on public health of populations from a water quality perspective are not unique. Although eventually all populations will be affected to a certain degree, the degree of urgency and the rate of implementation of public policy decisions to reduce the adverse effects are not the same for all regions and populations of the world. This simple application demonstrates that point. Different regions of the world represented by different initial conditions on the phase diagram will determine the urgency and the relaxed nature of the policy decisions that needs to be implemented. The problem discussed here demonstrates that there are critical points in the system behavior which should be very carefully analyzed. These are identified as "tipping points" in the literature. These tipping points are not fixed and various tipping points may be observed at different times. It is important to recognize that the tipping points of different regions and different populations are also critical to the overall system behavior. In the problem discussed here it is demonstrated that these tipping points can be predicted and certain preventative measures can be implemented to avert the critical points avoiding an undesirable outcome for the population and the state of population in question. What is not modeled and thus could not be demonstrated in this problem, simply because the desire was to keep the analysis simple, is the effect of the failure of some populations on the rest of the system behavior. When this effect is considered we should recognize that although some regions and populations of the world may exhibit more resilient behavior to adverse effects of climate change, at the end the overall effect of the failure of certain populations may also reduce the resiliency condition of more stable parts of the world. This is identified as the "systemic risk." This feedback mechanism may produce a domino effect which may turn the behavior of the overall complex system into a chaotic behavior. In this case it can be said that sum of small failures, which may initially be considered to be unimportant in isolation, may lead to the failure of the overall system. That is, sum of the failure components of the system may become larger yielding a tipping point for the system as a whole. Thus systemic risk is a very important point to recognize and include in the overall analysis. The other important point that is observed from this analysis is that if the climate change is not controlled gradually from the current state the controls that will have to be implemented will be more drastic later on to keep the system within the desired stability domain. In that case the overall control will be achieved over a much longer period and at higher cost rather than implementing controls right away which will reduce the time period to achieve the a stable system at much reduced levels of cost.

1.5 Conclusions

The quantifiable resilience thinking may yield an actionable set of observations and management practices that is based on the broad understanding of complex environmental-human-climate systems. This approach does not assume or require that the system studied, is in equilibrium or near equilibrium at all times, nor it is controllable. For the previous command and control paradigms of environmental management, precise understanding of the system was needed and the policy decisions made relied on the accuracy of this understanding and related predictions. This command and control concept has been shown to fail in several applications in the past. Currently, the mathematics of resilience thinking is at its infancy. The deterministic analysis discussed here is for the purpose of introducing and demonstrating the concept. It is not sufficient to characterize the complex environmental-human-climate systems we are currently working on. However, the idea is promising and many applications in complex systems analysis and management are shifting to models that include resilience concepts, which offer a broader understanding of possible system behavior and the effects of stochastic and human intervention on this behavior.

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Chapter 2
Implications of Climate Change on Water Security in the Mediterranean Region

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Abstract Throughout the Mediterranean Region, a combination of population growth and climate change will compromise our ability to manage available water resources. Pro-active resource management decisions are required; however, these efforts will prove futile unless reliable predictions can be made of the impact that changing conditions will impart upon the hydrologic cycle and water reserves. Groundwater is a particular concern as its unique characteristics are rarely adequately accommodated within IWRM (Integrated Water Resource Management). Moreover, few studies have considered the potential impacts of climate change on groundwater resources in a region where meteorological conditions and sea and lake levels are expected to change at rates that are unprecedented in modern times. Time is of the essence. Groundwater is resilient to drought and promises to play a crucial role in regions where climate change threatens renewable water resources. Questions that need to be addressed are: (1) How will climate change affect the nature and seasonality of aquifer recharge? (2) How will fresh groundwater levels beneath coastal areas respond to changing sea/lake levels, and to what extent will rising sea levels promote the intrusion of seawater? (3) Will a decline in sea/lake levels accelerate the release of contaminants stored in coastal aquifers to receiving water bodies? (4) Over what time frame will changes to the groundwater system occur?

Keywords Climate change • Groundwater • Water security • Mediterranean

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2.1 Introduction

Currently, 400 million people live throughout the Mediterranean Region and pose a heavy burden on fragile water supplies. The problem is compounded by nearly 200 million international visitors each year, the majority of whom stay in water-parched coastal areas. A globally changing climate, rising Mediterranean Sea levels and an increasing demand for safe, potable water due to population growth will exacerbate current water supply problems, and urgent, pro-active decisions will be necessary to secure adequate supplies. Groundwater is a particular concern as its unique characteristics are rarely adequately accommodated within IWRM (Integrated Water Resource Management) and few, if any, studies have examined the potential impacts of climate change on the region's aquifers.

2.2 Current Situation

The present Mediterranean climate is characterised by mild winters and hot, dry summers, similar to conditions found in central Chile, the southwestern United States and the southern tip of Africa. Three central-northern countries, France, Italy and Turkey, enjoy half of the region's precipitation, while dry areas predominate to the south and east (Fig. 2.1) [1–4]. Although mountains and inland seas create an

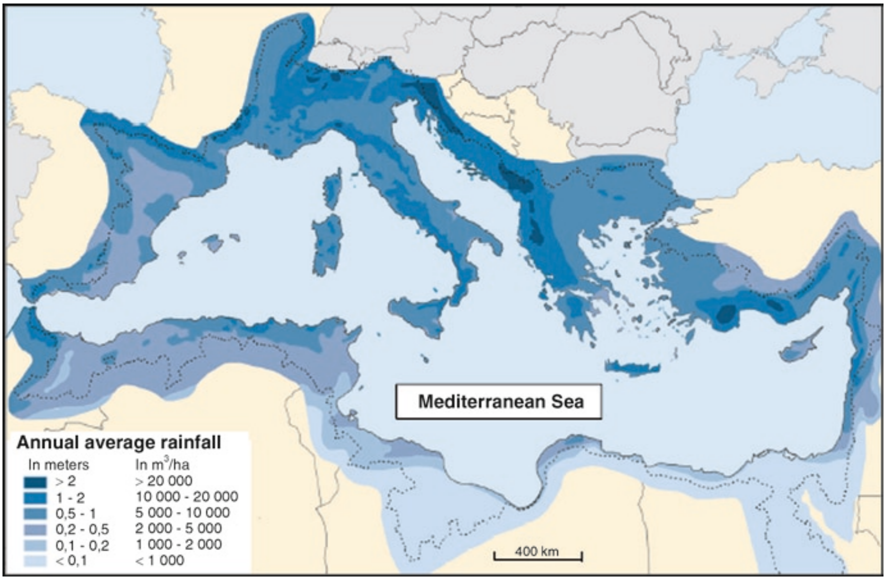

Fig. 2.1 Mean rainfall distribution in the Mediterranean basin (After Margat [2])

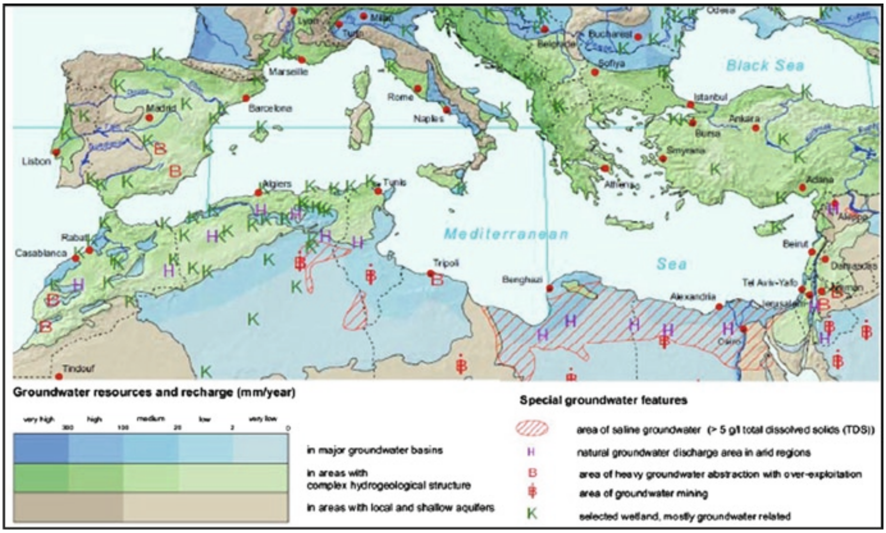

Fig. 2.2 Hydrogeological characteristics of the Mediterranean region as classified by the world hydrogeological mapping program WHYMAP (Extracted from Struckmeier and Richts [5])

abundance of local microclimates, most areas receive about three times more rainfall in the winter than they do in the summer months [6, 7].

About two thirds of water supplied in the region is used for irrigation (48% in the north and 82% in the drier south). The remainder is used for domestic supply, industry and the energy sector. It is estimated that 20 million Mediterranean people are still deprived of access to safe drinking water, particularly in the south and east. Currently, 8 of the 12 southern- and eastern-rim nations (the SEMED countries - Algeria, Cyprus, Egypt, Israel, Jordan, Lebanon, Libya, Morocco, Palestinian Territories, Syria, Tunisia and Turkey) use over 50% of their renewable water resources, with two countries (the Palestinian Territories and Libya) exceeding 100%. Seventy-five percent of the renewable water supply is derived from surface runoff while aquifer recharge represents the remaining 25%. Figure 2.2 shows a hydrogeologic map of the Mediterranean region, and indicates areas where groundwater resources are compromised by low aquifer recharge, over exploitation and high groundwater salinity.

2.3 Potential Future Threats

2.3.1 Water Demand Due to Increased Population

The combined population of countries that rim the Mediterranean Sea is projected to increase by over 100 million between 2000 and 2025 with the vast majority of this growth occurring in the 12 drier SEMED countries [1]. Due to population growth alone it is estimated that by 2025, 10 of the 12 SEMED countries will be consuming over 50% of their renewable water resources, with 8 of them exceeding 100%. Most of the demand increase will come from irrigation and domestic supply needs.

2.3.2 Changing Climate

Existing climatological data sets reveal the Mediterranean Sea climate to be highly sensitive to changes in the atmospheric forcing functions, most notably the North Atlantic Oscillation (NAO) [8–12]. According to Palutikof and Holt [13], the combined influence of the NAO and global climate change represents a serious threat to water resources in the region. Current indications are that global temperatures will rise more rapidly during the twenty-first century than at any time since the end of the last ice age. Regional predictions of the resulting change in climate remain uncertain; however, the Mediterranean region is expected to warm significantly, well above the global average (Intergovernmental Panel for Climate Change (IPCC) [14, 15]). The outlook for precipitation is even less certain, but IPCC projections suggest that annual precipitation throughout most of the Mediterranean will be appreciably lower (Fig. 2.3) with fewer precipitation days, significantly drier summers and a higher risk of drought. Rates of evaporation are expected to increase, thereby further reducing aquifer recharge and surface runoff.

2.3.3 Sea Level Rise and Sea Water Intrusion

Global sea level rise is one of the many anticipated consequences of global warming. A rise in global atmospheric temperature will cause thermal expansion of the oceans, melting of mountain glaciers, and promote the ablation of the polar ice sheets. Predictions of sea level rise vary widely and generally range up to 0.6 m over the period 1980–1999 to 2080–2099. This sea level change will not be distributed uniformly around the world [16] and some regions may experience more severe impacts.

Predictions of sea level rise in the Mediterranean are complicated by numerous factors such as prevailing hydraulic conditions and pressure gradients across the Strait of Gibraltar, steric variations and associated changes in the thermohaline circulation, and adjustments to the water budget driven by atmospheric forcing [10]. Over the next 100 years, sea surface and air temperatures are expected to rise between 1.4°C and 5.8°C, and sea level is predicted to rise annually by between 2 and 9 mm per year. The rise in sea level is expected to increase rates of coastal erosion and promote the incursion of salt water into fresh water resources [17].

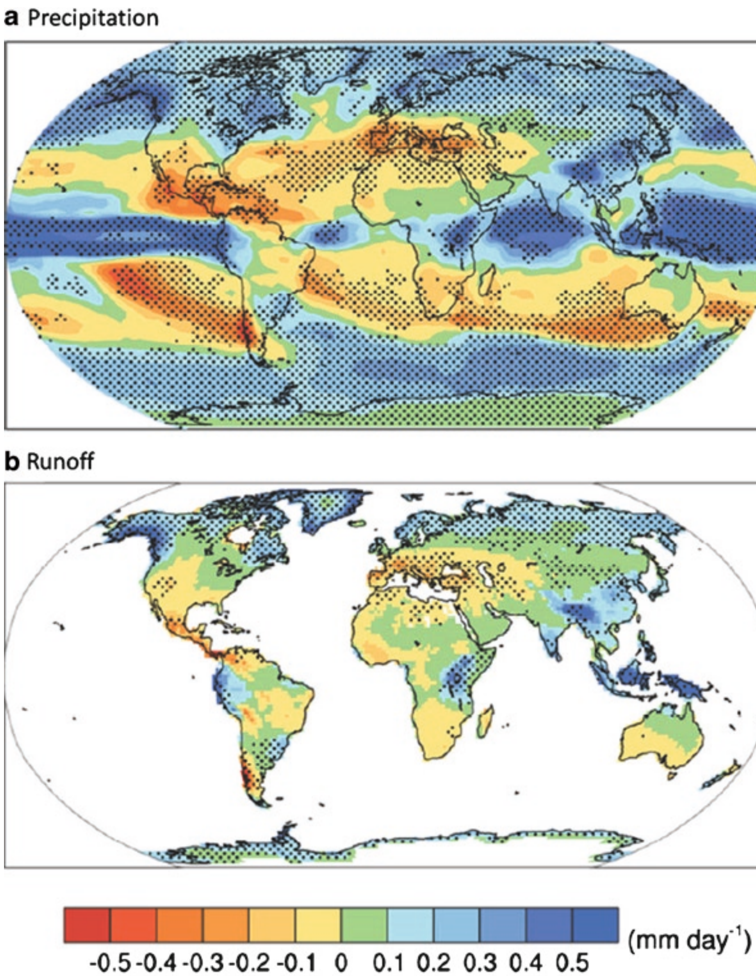

Fig. 2.3 IPCC predicted multi-model mean changes in (**a**) precipitation (mm day^{-1}) and (**b**) runoff (mm day^{-1}) for the period 2080–2099 relative to 1980–1999. Regions are stippled where over 80% of models agree on the sign of the mean change (Modified after Meehl et al. [18])

2.3.4 Water Quality Degradation

An inevitable consequence of population growth and intensification of agricultural activity is the degradation of water quality. Water pollution represents a significant threat to renewable water resources in the region but can also compromise reserves of fossil groundwaters which are an essential supplementary source to the south and east of the region. Contaminated water poses health risks and increases the cost of water supply, notably for water treatment.

2.4 Achieving Water Security

Population growth and a changing climate seriously threaten water security throughout the Mediterranean region. Important resource management decisions will be required but any such efforts will prove inconsequential unless reliable predictions can be made of the influence that changing conditions will have on the hydrologic cycle and available water reserves. By 2025 it is expected that 80 million Mediterranean people will face water shortage conditions (with less than 500 m^3/capita/year) and an inevitable consequence is that the percentage of unsustainable water supplies derived from fossil sources or from over-exploitation will rise. Under these circumstances, there is a risk that some fossil groundwater resources will become depleted and that coastal aquifers will be damaged by seawater intrusion. To achieve water security in the region, the challenge will be to:

- decrease water demand
- increase water supply, and
- use available water more efficiently.

Ultimately, there will be a need to develop management strategies that fully integrate groundwater and surface water, are holistic in approach and are based on sound scientific and socio-economic principles. In turn, this will demand a solid scientific database, reliable predictions of climate change, population growth and resource demand, and the judicious application of powerful computer codes capable of simulating both ground and surface water flow under transient conditions.

As the world's largest reserve of fresh, accessible water, groundwater, with its general resilience to drought [19] promises to play a crucial role in regions, such as the Mediterranean, where climate change threatens existing renewable resources. However, it is equally clear that despite the much touted merits of Integrated Water Resource Management (IWRM) [20], groundwater is often neglected, and the true benefits of managing groundwater and surface water resources conjunctively, will not emerge until the special and unique attributes of groundwater are adequately incorporated within IWRM. Time is of the essence as very little is known about the relationship between global climate change, sea level rise and groundwater resources. The types of question that need to be addressed are: (1) How will climate change affect the nature and seasonality of aquifer recharge? (2) How will fresh groundwater levels beneath coastal areas respond to changing sea/lake levels, and to what extent will rising sea levels promote the intrusion of seawater? (3) Will a decline in sea/lake level accelerate the release of contaminants stored in coastal aquifers to receiving water bodies? (4) Over what time frame will changes to the groundwater system occur?

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Chapter 3
Climate Change Effects on Ecosystem Services in the United States – Issues of National and Global Security

Michael J. Friedel

Abstract Climate change is one possible external driver of ecosystem services. In the tropical Pacific, short-term climate change is influenced by oceanic Kelvin waves that induce remote temperatures to rise (El Niño event) or decrease (La Niña event). This teleconnection is not globally uniform; in the United States (U.S.) drought conditions induced by El Niño commonly appear in the northern latitudes, whereas drought induced by La Niña occurs in the southern latitudes. Should natural or anthropogenic climate forcing influence the frequency or intensity of drought, there is a potential for catastrophic events to occur placing our national and global security at risk. Because climate forcing interacts with ecosystems characterized by nonlinear and multivariate processes over local-to-global and immediate-to-long-term scales, their assessment and prediction are challenging. This study demonstrates the efficacy of an alternative modeling paradigm based on using a self-organizing map to examine and predict the role that climatic change has on water-resource related ecosystem services. Examples include: (1) hindcasting 2,000 years of temperature and precipitation across states in the south-central and southwestern U.S.; (2) forecasting climate-induced groundwater recharge variability across subbasins in mid-western U.S.; and, (3) forecasting climate-change effects on post-fire hydrology and geomorphology in the western U.S.

Keywords Climate change • Ecosystem services • El Niño • La Niña • Groundwater recharge • Self-organizing map • Hindcasting • Forecasting • Uncertainty

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3.1 Introduction

Humans benefit from a multitude of resources and processes supplied by natural ecosystems [1]. These benefits (collectively known as ecosystem services) include water resources suitable for supporting various sectors of society, such as agriculture, construction, daily living, energy, fishing, forestry, manufacturing, public health, recreation, and transportation. Climate change is frequently cited as one possible external driver of ecosystem services [2]. Because climate is temporally and spatially dependent, change at a global scale differs from regional or local scales. Some considerations when discussing temporal climate change include amplitude, duration, and gradient [3].

In many studies, the duration of climate change is considered short-term (years to decades) and long-term (hundreds to thousands of years) variability [3]. Short-term climate variability is attributed to oscillations in the sea surface temperature (SST) that alter ocean currents and overlying air pressure resulting in a redistribution of temperature and precipitation [4]. Long-term climate variability is attributed to alterations in external processes leading to a redistribution of heat at depth in the world's oceans [4]. Some possible long-term processes [3] are (1) the changing solar radiation due to sunspot activity, (2) the addition of carbon dioxide from volcanic activity, and (3) the reversal of the earth's magnetic field.

The El Niño Southern Oscillation (ENSO) is considered the strongest short-term periodic fluctuation (2–7 years) with a rise (El Niño) or decrease (La Niña) of SST in the equatorial Pacific Ocean [5]. This teleconnection is not globally uniform in the U.S., and drought conditions induced by an El Niño event commonly affect the northern latitudes, and a La Niña event affects the southern latitudes [3]. Droughts have tremendous consequences on the physical, economic, social, and political elements of our environment [6]. They affect surface and groundwater resources by diminishing the water supply, water quality, riparian habitat, power generation, and range productivity. Other consequences often include crop failure, debris flows, insect infestations, pestilence, violent conflict, wildfires, and disruptions to economic and social activities [7].

Should natural or anthropogenic forcing influence the frequency or intensity of climate change, there is an increased likelihood for drought hazards placing national and global security at risk [7]. For this reason, accurate and timely climate-change information and related predictions could benefit many sectors of society, but the scale-dependent complexities render it a challenge to model. Specifically, climate forcing is known to interact with ecosystems which is characterized by coupled, nonlinear, and multivariate processes. Data associated with these systems are typically sparsely populated ranging spatially from local (1,000s km^2) to global and temporally from immediate (1–10s years) to long-term (100s to 1,000s years). This makes the construction of process-based models difficult. One critical issue is the lack of essential calibration data which results in large inaccuracies [8]. Also, process-based modeling schemes are commonly too rigid with respect to detecting unexpected features like the onset of trends, non-linear relations, or patterns restricted to sub-samples of a data set. These shortcomings created the need for an alternate modeling approach capable of using available data. This paper demonstrates the efficacy of using data mining to understand the effects of climate change on water-resource dependent ecosystem services. The objectives are: (1) hindcasting 2,000 years of temperature and precipitation across states in the south-central and southwest U.S.; (2) forecasting climate-induced groundwater recharge variability across subbasins in mid-western U.S.; and (3) forecasting climate-change effects on post-fire hydrology and geomorphology in the western U.S.

3.2 Methodology

3.2.1 Conceptual Model

A conceptual model is defined to facilitate understanding of the climate-change effects on water-resource dependent ecosystem services. In this model, the response can be climatic (annual temperature and precipitation), hydrologic (debris flows, flooding, groundwater recharge, water quality), or ecologic (fish and macroinvertebrate index of biotic integrity). It is functionally related to natural and anthropogenic stresses on coupled and nonlinear processes induced by drought, urbanization, and wildfire across land segments and sub-basins. A self-organizing map (SOM) is used to evaluate the various conceptual models.

3.2.2 Self Organizing Map

A self-organizing map (SOM) is a type of unsupervised artificial neural network [9]. The method projects sparse, coupled, nonlinear, and multidimensional data into a lower dimensional space using vector quantization. Following the initial distribution of random seed vectors (weights) and numerous iterations, the competitive learning process results in a network of information in which topological relationships within the training set are maintained by a neighborhood function. Unlike other types of artificial neural networks, the SOM does not need target output to be specified, and its neighborhood function can be used to impute values based on the organized data vector relations. It is this imputation process that facilitates hindcasting and forecasting in this study.

3.2.3 Data

This study uses readily available data published by various authors [10, 11, 12]. These data are sparsely populated with numerical and categorical observations sampled at different scales and across natural and anthropogenic gradients. Gradients relate one (or more) dependent responses, such as biological, physical, and chemical variables, as a function of space or time changes in multiple environmental variables that include climate observations (precipitation, temperature); or derived metrics, such as urban intensity, Palmer drought severity index (PDSI), and others.

3.3 Results

3.3.1 Hindcasting 2,000 Years of Climate Data Across States in the South-Central and Southwestern U.S.

The effective planning of water resources requires accurate information about climate variability. The short time period for which instrument records exist, however, limits our knowledge of long-term temperature and precipitation variability. To overcome this limitation, a simultaneous reconstruction of annual temperature and precipitation values was conducted for eight states across a gradient of modern climate zones: Arizona (Desert), California (Mediterranean), Colorado (Semiarid to Alpine), Kansas (Semiarid to Humid Continental), Nevada (Semiarid to Arid), New Mexico (Semiarid), Texas (Semiarid to Humid Subtropical), and Utah (Semiarid). The reconstruction involved imputation of values based on the self-organized nonlinear data vector relations among 2,000 years (0–2000 AD) of reconstructed warm-season (June–August) Palmer drought severity index data (PDSI; [11]), and 114 years (1895–2009) of annual state precipitation and temperature data [13]. The reconstruction was verified against independent precipitation and temperature data for the years: 1896, 1900, 1911, 1919, 1923, 135, 1940, 1952, 1960, 1966, 1968 (La Niña), 1986, 1993, 1998 (La Niña), and 2005 (El Niño) using split- and cross-validation (leave one out) approaches. The Spearman Rho correlation among observed and imputed values was greater than 95% with a p-value of 0.001.

Quantile modeling [4] of the reconstructed temperature change data (annual temperature minus 2,000 year median) revealed that the long-term global climate was interrupted by short-term changes. For example, the so-called Medieval Warm Period (~900 to ~1250) and Little Ice Age (~1400 to ~1850) were two changes over the last two millennia that appeared independently in the northern hemisphere [15], and our Arizona, Colorado but not Kansas (Fig. 3.1) reconstructions. The muted peaks and increased uncertainty (0.05 and 0.95 quantile models) in these reconstructions corroborates previous findings that PDSI data are best suited to spatial rather than temporal reproduction of peaks [3]. Regionally, our reconstructions revealed 2,000 year trends with increasing temperature for Arizona, constant temperatures for Colorado, and decreasing temperatures for Kansas. These findings are attributed to a strong ENSO teleconnection with Arizona, mixed ENSO signals in Colorado because it is a region between El Niño and La Niña latitudes, and Kansas

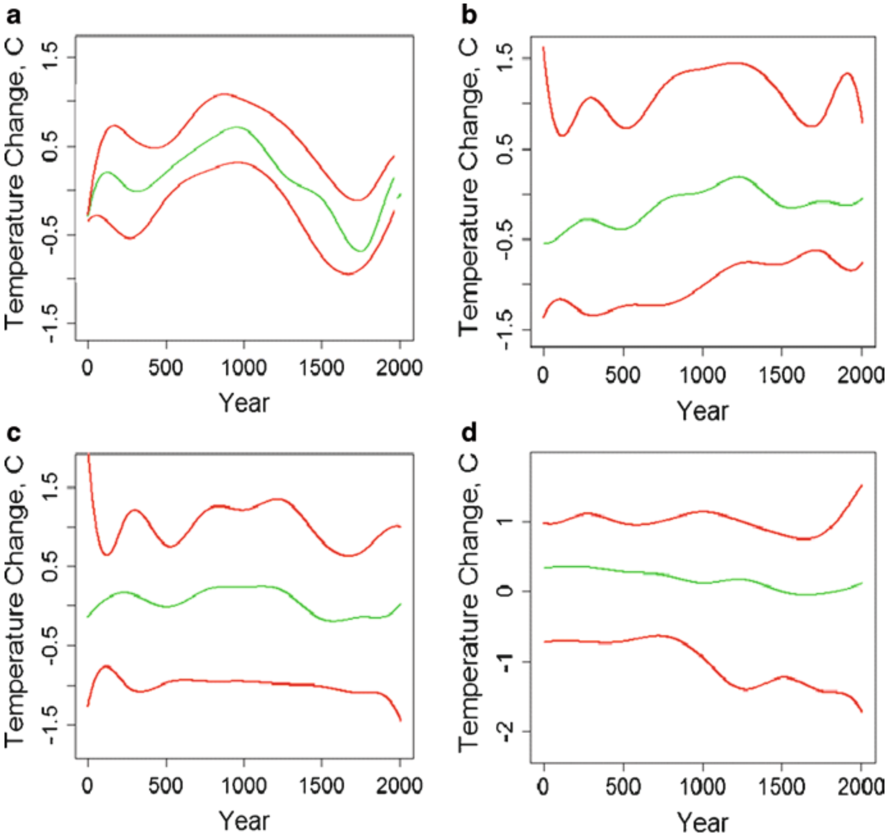

Fig. 3.1 Temperature change reconstruction: (**a**) Northern hemisphere (After Loehle [15]); (**b**) Arizona (desert); (**c**) Colorado (alpine to semiarid) and (**d**) Kansas (semiarid to humid). *Colored lines* are quantile regression models with b-spline smoothing (*upper* 0.05, *middle* 0.5, and *lower* 0.95)

because it is in continental interior and influenced by the Gulf of Mexico. These findings suggest that the natural multicentennial and regional climate variability may be larger than commonly believed.

3.3.2 Forecasting Climate-Induced Ground Water Recharge Variability Across Subbasins in the Mid-Western U.S.

Optimal groundwater resource management under changing climate requires knowledge of the rates and spatial distribution of recharge to aquifers. The SOM technique was used to estimate groundwater recharge from available and uncertain hydrologic, land use, and topographic information without long-term monitoring [10].

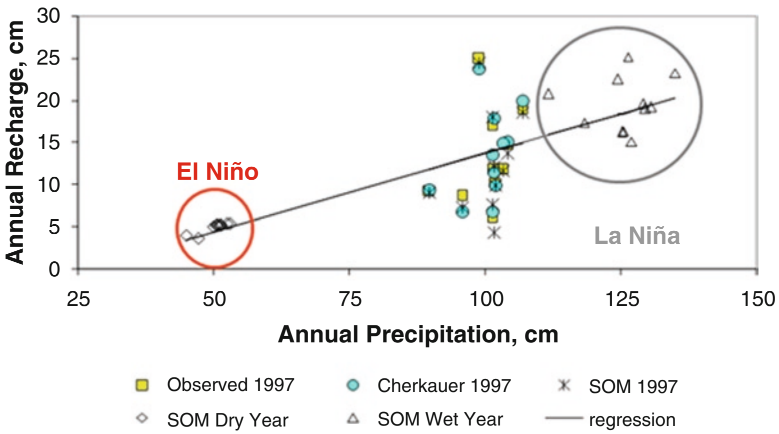

Fig. 3.2 Comparison of observed and forecasted annual recharge as a function of short-term ENSO climatic events

The technique was applied to twelve basins in southeastern Wisconsin where recharge observations were determined using a recession-curve-displacement technique and normalized by annual precipitation. Uncertainty was introduced and nonlinear correlation preserved among these explanatory and response variables using a Monte Carlo (MC) technique. Common patterns among the MC realizations were identified and mapped onto a two-dimensional torroid. Fitted data vectors in the SOM were then used to impute normalized recharge ratios that compared well with the observations and published results (Fig. 3.2). The effects of climate change on spatial groundwater recharge were evaluated using the model and precipitation extremes associated with the ENSO.

3.3.3 Forecasting Climate-Change Effects on Post-Fire Hydrology and Geomorphology in the Western U.S.

Few studies attempt to model the range of possible hydrologic and geomorphic responses following rainfall on burned basins because of the sparseness of data, and the coupled, nonlinear, spatial, and temporal relationships among post-fire landscape variables. This study used an unsupervised artificial neural network (ANN) to project data from 540 burned basins in the western United States [12] onto a SOM. The sparsely populated data set included independent numerical landscape categories (climate, land surface form, geologic texture, and post-fire condition), independent landscape classes (bedrock geology and state), and dependent initiation processes (runoff, landslide, and runoff-and-landslide combination) and responses (debris flows, floods, and no events). Clustering of the SOM neurons identified eight conceptual models of regional post-fire hydrologic and geomorphic

Basin	State	Climate-Change Forecast											
		Response						Initiation Process					
		Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
		Debris flow		Flooding		None		Landslide		Runoff		Runoff + Landslide	
1	MT	Yes	Yes							Yes			
2	CA	Yes	Yes							Yes	Yes		
3	MT	Yes					Yes						
4	CA			Yes			Yes			Yes			
5	CO					Yes	Yes						
6	CA	Yes					Yes			Yes			
7	MT	Yes					Yes			Yes			
8	MT					Yes	Yes						
9	CO					Yes	Yes						
10	CA			Yes			Yes			Yes			
11	CO					Yes	Yes						
12	CO	Yes					Yes						
13	UT	Yes	Yes							Yes	Yes		
14	CA			Yes			Yes			Yes			
15	CO					Yes	Yes						
…													
20	ID	Yes	Yes					Yes	Yes				
21	CO					Yes	Yes						
22	NM		Yes			Yes					Yes		
23	MT		Yes			Yes					Yes		
24	CO					Yes	Yes						
25	CA		Yes	Yes						Yes	Yes		
26	MT	Yes					Yes			Yes			
27	CA	Yes					Yes						
28	CO					Yes	Yes						
29	CO					Yes	Yes						
30	CO		Yes			Yes					Yes		
…													
57	CO					Yes	Yes						
58	MT	Yes					Yes			Yes			
59	ID					Yes	Yes						
60	ID	Yes			Yes			Yes			Yes		
Number of events =		26	15	4	2	30	41	2	2	24	14	0	0

Fig. 3.3 The forecast effects of short-term climate variability on post-fire initiation processes and associated responses were evaluated using the self-organizing map. Wet and dry conditions were characterized by El Niño and La Niña associated precipitation events recorded in last 100 years

landscape interaction. Stochastic cross-validation of the SOM demonstrated that initiation process and response predictions were globally unbiased.

A split-sample validation on 60 basins (not included in the training set) revealed that the simultaneous predictions of initiation process and response events were 78% accurate. Using this model, forecasts across post-fire landscapes revealed a decrease in the total number of debris flow, flood, and runoff events as climate shifted from wet (El Niño) to dry (La Niña) conditions (Fig. 3.3). Insight on individual basin changes and variability with respect to initiation process and response events also was revealed.

3.4 Conclusions

The self-organizing map (SOM) was useful for evaluating climate change effects on water-resource dependent ecosystem services. In case 1, it was possible to simultaneously reconstruct temperature and precipitation change over 2,000 years from which short-term breaks similar to global results for the northern hemisphere were observed in some states. The regional differences in long-term trends were attributed to variations in the ENSO teleconnection. In case 2, the SOM was found to useful for forecasting the effects of ENSO events on ground-water resources in basins with perennial streamflow. In case 3, the SOM made it possible to forecast the simultaneous and probable effects of ENSO events on multiple post-fire response variables including runoff, landslides, flooding, and debris flows.

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Chapter 4
Climate Change Mitigation with Renewable Energy: Geothermal

Alper Baba

Abstract On a global scale, there is increasing evidence that climate is changing and of a discernible human influence. Many of scientists are confident that if current emissions of greenhouse gases continue, the world will be warmer, sea levels will rise and regional climate patterns will change. According to some scientist, global temperatures are expected to rise faster over the next century than over any time during the last 10,000 years. From this token, geothermal energy is now considered to be one of the most important alternative energy sources to minimize climate change. Geothermal technologies for power generation or direct use operate with little or no greenhouse gas emissions. Geothermal energy is generally accepted as being an environmentally-friendly energy source, particularly when compared to fossil fuel energy sources. Geothermal resources have long been used for direct heat extraction for district urban heating, industrial processing, domestic water and space heating, leisure and balneotherapy applications. Geothermal energy is used in more than 80 countries for direct heat application and 24 countries for power generation. Re-injection of fluids maintains a constant pressure in the reservoir, thus increasing the field's life and reducing concerns about environmental impacts. Geothermal energy has several significant characteristics that make it suitable for climate change mitigation.

Keywords Climate change • Environment • Geothermal energy • Renewable energy

4.1 Introduction

Due to global warming, global temperatures are expected to rise faster over the next century than any 100 years period during the past 10000 years [1–2]. Recent reports from the Intergovernmental Panel on Climate Change [3–4] confirm that climate

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change is occurring at a larger and more rapid rate of change than was thought likely only 6 years ago. Eleven of the last 12 years (1995–2006) rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850). The 100-year linear trend (1906–2005) of 0.74°C [0.56–0.92°C] is larger than the corresponding trend of 0.6°C [0.4–0.8°C] (1901–2000) [1, 2, 5]. Climate warming observed 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 vapour; increasing evaporation; and changes in soil moisture and runoff. There is significant natural variability 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 [6]. At present, documenting inter-annual variations and trends in precipitation over the oceans remains a challenge [3].

Greenhouse gases are considered to be the foremost parameter influencing the climate change. Carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas with annual emissions growing by about 80% between 1970 and 2004 [4]. The long-term trend of declining CO_2 emissions per unit of energy supplied reversed after 2000. Global atmospheric concentrations of CO_2, methane (CH_4) and nitrous oxide (N_2O) have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years. During the past 50 years, the sum of solar and volcanic forcing would likely have produced cooling. Observed patterns of warming and their changes are simulated only by models that include anthropogenic forcing [5]. Global carbon dioxide (CO_2) emissions from residential, commercial, and institutional buildings are projected to grow from 1.9 Gt C/year in 1990 to 1.9–2.9 Gt C/year in 2010, 1.9–3.3 Gt C/year in 2020, and 1.9–5.3 Gt C/year in 2050. It must also be noted that 75% of the 1990 emissions are attributed to energy production [3].

Controlling greenhouse gases emission and adapting human settlements to withstand the extreme climatic conditions have become the most formidable challenges of our times. Geothermal energy development has thus great CO_2 emission reduction potential when substituting fossil sources of energy. Geothermal energy is one of the contributors to any future energy mix. The advantages of geothermal energy are numerous. It is an environmentally friendly and economically rewarding resource, which is still only marginally developed. Its two main utilization categories power generation and direct use are already introduced in many countries around the globe [7]. Geothermal development estimates for 2050 indicate that CO_2 emissions could be mitigated by 100s of Mt/year with power generation from geothermal resources and more than 300 Mt/year with direct use, most of which could be achieved by geothermal heat pumps [8]. Based on these fundamentals, the purpose of this study is to explain application of geothermal energy and its effect on climate change and to assess environmental impacts of the utilization of geothermal resources.

4.2 Application of Geothermal Energy

People have been using geothermal energy for bathing and washing of clothes since the dawn of civilization in many parts of the world. However, it was first in the twentieth century that geothermal energy was used on a large scale for direct heat extraction for district urban heating, industrial processing, domestic water and space heating, leisure, balneotherapy applications and electricity generation. Prince Piero Ginori Conti initiated electric power generation with geothermal steam at Larderello in 1913. The first large scale municipal district heating service started in Iceland in 1930 [9]. In 2010, geothermal resources have been identified in more than 80 countries and there are quantified records of geothermal utilization in more than 50 countries in world. The result shows that use of geothermal energy for both electrical generation and direct heat extraction is going to accelerate in the near future.

4.2.1 Direct-Use of Geothermal Energy

Direct-use of geothermal energy is one of the oldest, most versatile and also the most common form of utilization of geothermal energy [10]. The early history of geothermal direct-use has been well documented for over 25 countries in the *Stories from a Heat Earth – Our Geothermal Heritage* [11] that documents geothermal use for over 2,000 years [12].

As of 2009, direct utilization of geothermal energy worldwide is 50,583 MWt. The total annual energy use is 438,071 TJ (121,696 GWh). The five countries with the largest installed capacities are: USA, China, Sweden, Norway and Germany accounting for 60% of the world's capacity, and the five countries with the largest annual energy use are: China, USA, Sweden, Turkey, and Japan, accounting for 55% of the world use. However, an examination of the data in terms of land area or population shows that the smaller countries dominate, especially the Nordic ones. The largest increase in geothermal installed capacity (MWt) over the past 5 years are: United Kingdom, Korea, Ireland, Spain and Netherlands; and the largest increase in annual energy use (TJ/year) over the past 5 years are: United Kingdom, Netherlands, Korea, Norway and Ireland. All of these increases are due to geothermal heat pump installations [12]. During the last decade, a number of countries have encouraged individual house owner to install ground source heat pumps to heat their houses in the winter and cool them in the summer.

Summary of various categories of direct use worldwide is given in Fig. 4.1. The result shows that geothermal heat pumps were increased exponentially during the last 10 years. Other uses also increased with a linear trend.

Geothermal fluids contain certain minerals leached from the reservoir rock and variable quantities of gas, mainly carbon dioxide and a smaller amount of

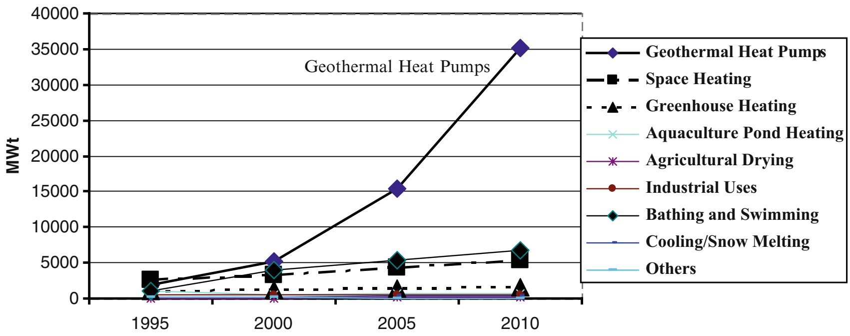

Fig. 4.1 Summary of the various categories of direct use worldwide, referred to period 1995–2010 [12]

hydrogen sulphide. The gas composition and quantity depend on the geological conditions encountered in different fields. Virtually the entire mineral content of the fluid and some of the gases are reinjected back into the reservoir. Most non-condensable gases are released to the environment. Some plants remove H_2S in a gas treatment process before releasing CO_2 to the environment. At one plant in Kizildere, Turkey, the non-condensable gases are scrubbed of H_2S, and CO_2 are recovered to provide about 80% of CO_2 used by the country's soft drinks industry [13].

4.2.2 Power Generation of Geothermal Energy

Electricity is produced with geothermal steam in 24 countries spread over all over the world. The worldwide total installed capacity of geothermal power plants is given in Fig. 4.2. The present value of 10.7 GW is an important result. The expected target from hydrothermal resources of 70 GW for year 2050 is very ambitious, as can be seen from Fig. 4.3 [14].

4.3 Greenhouse Gas Emissions and Climate Impacts

For the last century, human activities have been altering the global climate. Climatic warming is a fact; it endangers the environmental living conditions as well as global economy [8]. The global average surface temperature increased from 1900 to 2006 by at least 1.0°C; during the same time period the CO_2 content of the atmosphere doubled [4]. It is widely recognized that the most probable cause of climatic warming is the increasing content of greenhouse gases in the atmosphere. Observations show that the Earth's surface has warmed by approximately 0.6°C during the twentieth

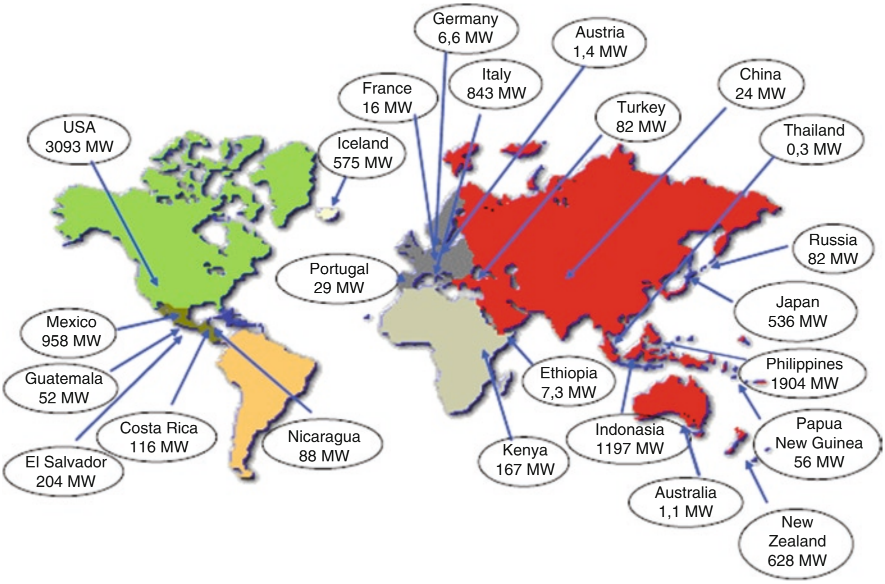

Fig. 4.2 Installed capacity in 2010 worldwide (total 10.7 GW) [14]

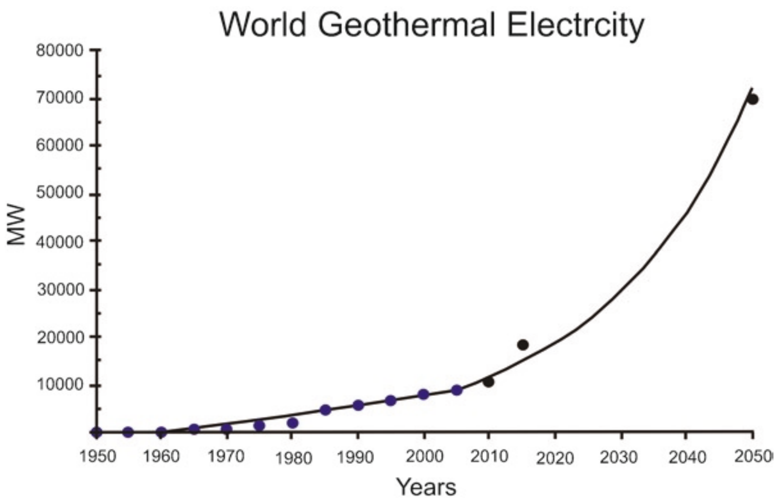

Fig. 4.3 Forecasting up to year 2050 [14]

century [16]. Atmospheric abundances of the major, human-generated greenhouse gases, i.e. CO_2, CH_4, and nitrous oxides (NOx), reached their highest recorded levels in modern history by the year 2000 and are continuing to rise. About 37% of incremental atmospheric CO_2 accumulation is caused by electric power generation, mainly from coal combustion power plant [17].

When compared to other energy source of power generation, geothermal power plants have much lower CO_2 emissions. The results show that geothermal power production has a significant environmental advantage over burning fossil fuels for electrical power production. Electrical production from geothermal fluids results in an order of magnitude less CO_2 per kilowatt-hour of electricity produced compared to burning fossil fuels (Fig. 4.4).

A highly respected source (World Energy Assessment – a collaborative effort between UNDP, UNDESA and the World Energy Council) attests the largest potential value to geothermal energy among all forms of renewable energy sources. The comparison is given in Fig. 4.5. The values are given in capacity units, i.e. energy per unit time. It is obvious that geothermal energy has the largest capacity, although the accuracy of the reported number is limited [7].

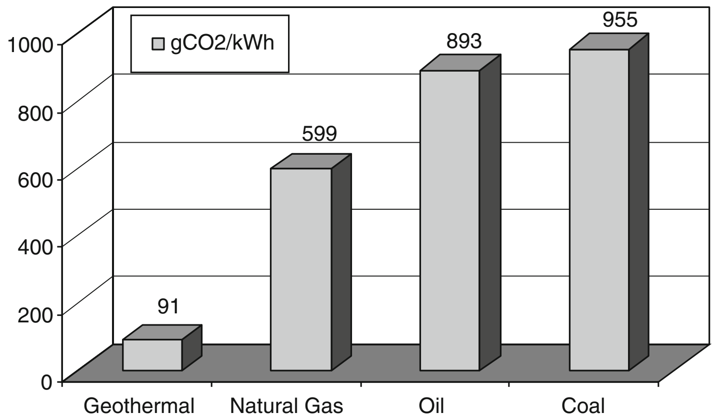

Fig. 4.4 Comparison of CO_2 emission from electricity generation from different energy sources [15]

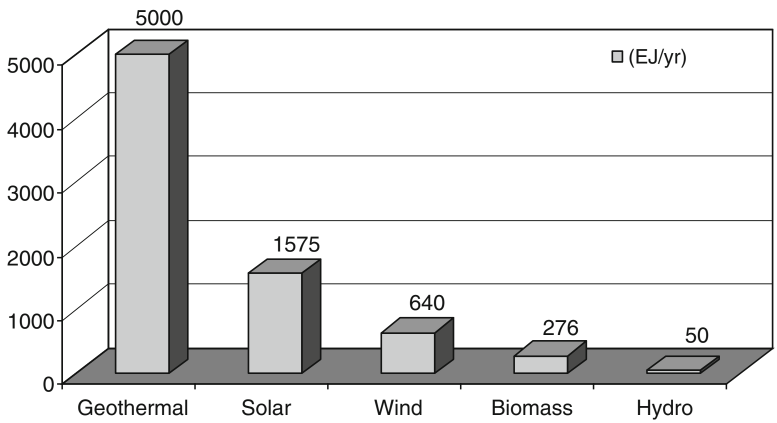

Fig. 4.5 Potential of renewable energy sources [18]

CO_2 emission from geothermal power plants in high temperature fields is about 120 g/kWh (weighted average of 85% of the world power plant capacity). With the present engineering solutions, it could be possible to increase geothermal power from the expected value of 11 GW for year 2010 up to a maximum of 70 GW in 2050; the gradual introduction of the new developments (binary plants, EGS systems) may boost the growth rate with exponential increments, thus reaching the global world capacity of 140 GW in 2050. The corresponding electricity production of about 1,000 TWh/year in 2050 will mitigate (depending on what is substituted) hundreds of million tons CO_2/year. Future technology including reinjection will result in negligible emissions (10 g CO_2/kWh). The extrapolations to year 2050 are given in Figs. 4.6 and 4.7 [7, 8].

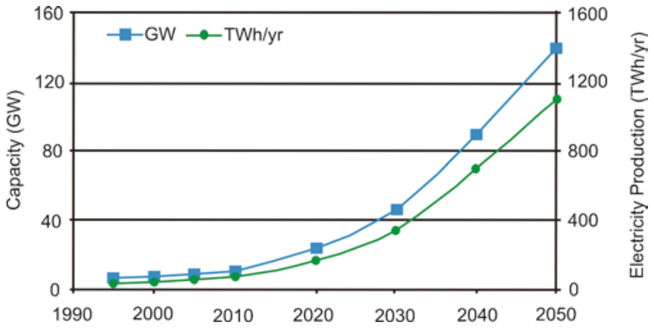

Fig. 4.6 Installed global geothermal capacity and electricity production 1995–2005 and forecasts for 2010–2050 (From Fridleifsson et al. [8, 19])

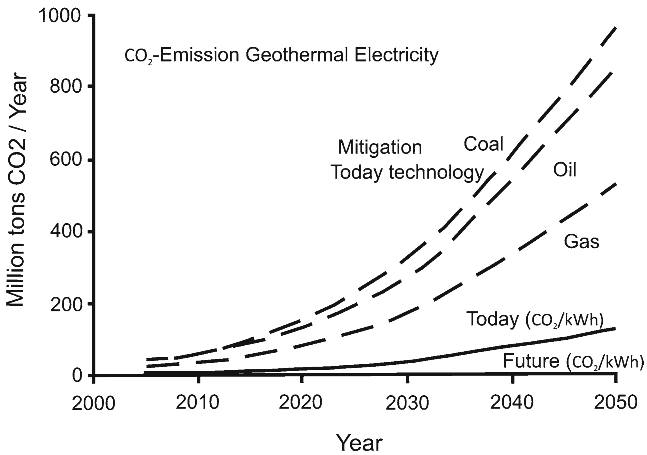

Fig. 4.7 Mitigation potential of geothermal power plants in the world and assumptions for emission of 120 CO_2/kWh for today and 10 g CO_2/kWh for future technology (From Fridleifsson et al. [7, 19])

Geothermal technologies for power generation or direct use operate with little or no greenhouse gas emissions. Since no burning processes are involved they are low in CO_2 emissions. Geothermal energy development has thus great CO_2 emission reduction potential when substituting fossil sources of energy. Further development – depending on future growth rates – could reduce CO_2 emissions even more significantly. The current and future potential contributions to reduce CO_2 emission by geothermal power generation and direct use have been assessed in a study carried out for the Intergovernmental Panel on Climate Change [8, 19].

4.4 Conclusion

Geothermal resource utilization although widely accepted as a clean energy source, has also contributed to the decreasing of air quality due to carbon dioxide emissions. Several studies have shown that CO_2 emissions from geothermal systems occur naturally and in some cases these natural emissions exceed the amount of CO_2 emitted from the geothermal power plant utilizing the geothermal resource.

Geothermal technologies produce little or no greenhouse gas emissions since no burning processes are involved. Geothermal development estimates for 2050 indicate that CO_2 emissions could be mitigated by 100s of Mt/year with power generation from geothermal resources and more than 300 Mt/year with direct use, most of which could be achieved by geothermal heat pumps.

The environmental benefits of geothermal development are obvious: increasing development can help to mitigate the effects of global warming. The societal benefits are developing in parallel: the positive effects are also increasing, regionally and globally. More importantly, improved and increased injection to sustain reservoir resources has diminished the CO_2 released from geothermal power plants.

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Chapter 5
Climate Change and Water Resources – Challenge of Our Civilisation

Zbyněk Hrkal

Abstract The geological view to the issue of impact climate change on water resources on the Earth is the main objective of the paper. The geological excursion into the past of the Earth clearly shows that the climate cannot be stabilized. The volume of water existing on the Earth is stable and has never changed. About 96% of countries have sufficient resources of water. The major reason for water scarcity on the Earth is not unfavorable distribution of natural resources but poverty and lack of education.

Keywords Climate change • Geological time scale • Water scarcity

5.1 Introduction

One of the most discussed issues in the first half of the twenty-first century is the struggle against climate change and the subsequent crucial question is whether the shortages in water worldwide may be related to climate change [1–5]. As a consequence, water management becomes a factor playing a decisive role in the social, economic and even political sphere, which occasionally causes political tensions in a number of regions because of virtual or real lack of water. The geological approach to this issue brings new aspects and scales calculating with tens of millions of years, which are free of subjective and short-term perception of the present short or transient problems or trends.

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5.2 Is There Any Chance to Stabilize the Climate? Looking Back on the Recent Geological History of the Earth

In science, there are only a few questions that can be answered without any doubt or explicitness. A professional or scientist should always be skeptical to a certain extent and should also tolerate some degree of uncertainty or disbelief. However, one of the few statements that a geologist can stand for quite flatly is the fact that climate on the Earth has never been stable and will never be. Let us have a look at what dramatic changes in climate the Earth had been through in a relatively recent history (Fig. 5.1).

In the Eocene, i.e. roughly 50 million years ago, the mean temperature on the Earth was about 12°C higher than nowadays [6, 7] and the content of CO_2 reached values fluctuating around 1,000 ppm.

It is obvious that this content of carbon dioxide was three times higher than the value, which we presently consider alarming. In the period between the Eocene and Oligocene the climate began to gradually cool down so that the Antarctic was covered with ice for ten million years. This period was then followed by a warming up interval when the Antarctic glacier melted completely away. Another wave or spell of cooling down arrived as late as in middle of the Miocene, which is characterized by fierce, short-term climate oscillations, by alternating the so- called glacial and interglacial ages. For today's human beings, the following can be deduced from these facts:

i. We are now living in the coolest period of the Earth during the last 65 million years. Possible warming up even by 2–3°C stays within the common natural variations. Similar dramatic changes in temperature occurred without any contribution of human beings so that they can be unambiguously attributed to natural processes,

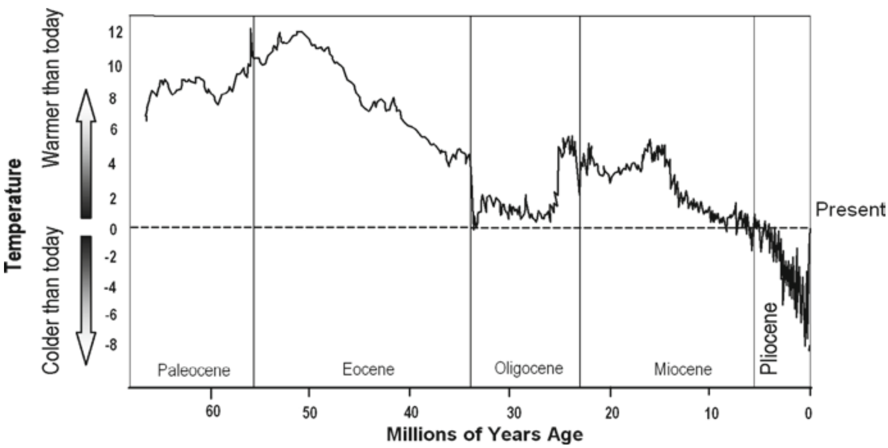

Fig 5.1 Changes in temperature on the Earth during the last 65 million years [7]

ii. The recent warming up of the climate is a fact, but the trend in the global temperature rise has already began before ca 300 years, after the termination of the so-called Little Ice Age. The rate of temperature rise corresponds to ca 0.6°C per century even in a period without any carbon dioxide emissions. The glaciers were also thawing, and as supported by data published by glaciologists, this process of thawing goes back to 1790 [8, 9].

iii. It is notable that the present content of CO_2 is the lowest during the whole history of the Earth because the concentrations of this gas have tended to become lower for millions of years [7]. During the Earth's evolution the concentrations of CO_2 decreased because carbon was deposited during the formation of coal, crude oil and, in particular, of limestone, while oxygen escaped to the atmosphere.

iv. The climate is such a complex phenomenon and process that its evolution cannot be restricted to a simple and direct relationship between CO_2 content in the atmosphere and the temperature. Isotope investigations of drill cores from the Antarctic glacier at the Vostok research station showed a close relationship between the two factors but in inverse relation than expected [10]. Temperature rise preceded the increase of CO_2 contents by ca 600 years. So, a classical question arises- what was the first: the egg or the chicken? If the theory of blaming CO_2 for being responsible for global warming would be unambiguously valid, then the above-mentioned time shift would have been reverse. As a consequence, this gas evidently is not the only and decisive factor governing or influencing the climate on the Earth.

To point a finger at a sole perpetrator that is responsible for large climate variability is an intuitive but wrong suggestion because the climate is such a complex phenomenon that it is difficult, or even impossible, to determine a single decisive factor governing climate change. Nevertheless, only one reason stands out.

Greenhouse gases, sea currents, air circulation, volcanic eruptions, etc., are secondary phenomena only to the primary source of energy which enables life on our planet – the Sun. The power of the solar radiation impacts on the surface of our atmosphere corresponds to 1,373 W per m^2. However, solar activity is not steady but fluctuates in more or less regular 11-year cycles. It rises for 4 years to reach its peak and then gradually decreases during the next 7 years. Only a few exceptions have been recorded in these 11-year cycle in the history of observations, but whenever the cycle was shorter, then the peak of the next cycle was more intense. On the other hand, when the cycle was longer the solar activity decreased. Since 1600, the above 11-year cycle was longer only twice always followed by an anomalous interval with lower solar activity. In 1790, the cycle took 12 years and 7 months followed by a quiet Sun lasting until 1830. This anomaly is called "Dalton Minimum". An even more significant event was represented by the so-called "Maunder Minimum" in the years 1638–1715 when sunspots disappeared for 77 years. Is it just a coincidence that this interval exactly corresponds to the decrease of temperatures during the Little Ice Age? Is it another coincidence when the subsequent 300 years of warming up of the planet falls in the period when the regular and moreover intense cycle of solar activity returns and culminates in the twentieth century? Astronomers predicted that the subsequent 24th cycle will be extremely intensive and will even surpass the record of the period of observations. According to all computations and simulations the new 24th cycle was supposed to begin in 2006 but actually started at the beginning of 2010. It is notable that 13 years elapsed since the beginning of the 23rd cycle.

It is almost certain that the 24th solar cycle will enter the modern history of astronomy [11]. We can only speculate on what effect on climate evolution this phenomenon will have; however a variant of the cooling down period cannot be excluded. Because of highly variable set of factors that influence the climate, including mankind, we are not able to answer a question: what is going to happen with temperatures and atmospheric precipitation within a few 100 or 1,000 years?

The global warming has stopped for a few years. Discussion about the effect of solar cycles or concentrations of greenhouse gases or other phenomena on the climate could be an interesting and useful scientific dispute that is a driving force of progress. We have to confess that the question of how important a role mankind plays in global change is still difficult to answer seriously. Apart from this uncertainty, we spend enormous financial means on activities related to stabilization of the climate. But, as mentioned above, the geological excursion into the past of the Earth clearly shows that the climate cannot be stabilized. We tend to reduce energy consumption, insulating and warming up buildings, but we are wasting huge expenditures on elimination of CO_2 emissions that could be better spend on reasonable adjustments to global change. As will be demonstrated by the next example, the major reason of water scarcity on the Earth is not unfavorable distribution natural resources but poverty and lack of education.

5.3 Will Human Civilization Face the Exhaustion of Water Resources Due to Global Change?

The climate had always been changing and will continue to evolve in the future. So far the only acceptable conception has been based on the outputs of IPCC [12], which declare that warming up of the Earth is caused by anthropogenic activities – specifically by emissions of carbon dioxide. But a series of scandals disclosed a specialized handling of the primary data so that the seriousness of the so far achieved results was challenged or even damaged. Nevertheless, the ever present question, which the public should ask with regard to climate change is, whether the planet will ever run out of water and similarly if fossil fuels would ever be exhausted. Therefore, to simply compare the exploitation of water resources with deposits of crude oil, coal and earth gas is evidently not correct. The volume of water existing on the Earth is stable and is estimated to attain 1,386,100,000 km^3 [13], and has never changed. Nevertheless, due to great dynamics of water the spatial distribution of water and/or its state on the Earth are changing. In contrast to estimates based on the concept of global warming, then it is to be emphasized, that cooling of the Earth would paradoxically have much more devastating impact on water resources. The ocean water level during the last Ice Age was by 120 m lower than it is nowadays. This huge volume of water was contained in glaciers so that this water did not participate in the water cycle.

As a consequence, cooling would result in a decrease of atmospheric precipitation and the subsequent expansion of arid areas. It is not a chance that the largest area without precipitation is Antarctica and not the Sahara Desert. The problem is that the civilization will not be threatened by a shortage of water in the near future but by its irregular distribution over the planet far from ideal to suit mankind.

As emerges from WHO [14] data, around 1.1 billion people globally do not have access to improved water supply sources, whereas 2.4 billion people do not have access to any type of improved sanitation facilities. About two million people die every year due to diarrheic diseases and most of them are children less than 5 years of age. When using just simple calculations some very alarming figures arise- the world population is growing but the volume of water remains the same so that the number of countries suffering from water scarcity will gradually increase. The WRI in 1998 predicted that the number of people suffering from water scarcity should increase from 3.7% in 2000 to 8.6% in 2025 and even up to 17.8% in 2050.

Let us ask ourselves a question – what is water scarcity? To define this concept the most frequent term is the "Water stress index" [15]. These authors proposed 1,700 m^3 of renewable water resources per capita per year as the threshold, based on an estimate of water requirement in the household, agricultural and energy sectors, and the needs of the environment. Countries whose renewable water supplies cannot sustain this figure are said to experience water stress. When water supply falls below 1,000 m^3, a country experiences water scarcity, and below 500 m^3, absolute scarcity.

Presently there are six countries that can be placed in the category of "absolute water scarcity". They include: Kuwait 30 m^3/person, United Arab Emirates 174 m^3/person, Libya 275 m^3/person, Saudi Arabia 325 m^3/person, Jordan 381 m^3/person and Singapore 471 m^3/person. The category of countries suffering from water scarcity closes with Israel with 969 m^3/person. Apart from almost fatal water scarcity the great majority of these countries are doing well by having a high standard of living. For comparison the United Kingdom has 3,337 m^3 at one's disposal.

On the other hand, there are countries, which from the viewpoint of water supply are on the verge of humanitarian crisis, namely Somalia and Nigeria Somalia has at one's disposal 3,206 m^3 water per person and Nigeria even 5,952 m^3.

It is evident that we have to distinguish two types of water scarcity – Physical and Economic. A total of 96% of countries [16] have sufficient water resources so that problem is not in physical water scarcity but in water mismanagement and poverty.

It is known that the largest volume of water is used in agriculture. While in Europe ca 30% of total consumption is used in farming, in developing countries this figure is often in excess of 90%. Major reserves exist that can be demonstrated on water management in Israel. The water balance between atmospheric precipitation and consumption is fluctuating around the verge so that only the less water demanding crops are grown in Israel and the efficiency of “drip irrigation” became a world model. The large part of agricultural production in high demand for water is resolved by importation of these crops. This method allows covering 87% of corn consumption so that it actually imports 1,000 L of so-called virtual water in one ton of imported corn. This is one of the methods of fighting water scarcity – to take advantage of the global market and to grow water demanding crops in countries with favorable climatic conditions.

Perhaps one of the most dramatic examples of the reverse approach is the ecological disaster of the Aral Lake caused by the meaningless attempt to grow cotton in the semi-desert regions of Tajikistan and Uzbekistan in the 1960s and 1970s.

Nevertheless, similar problematic projects exist even nowadays. Irrigation in the Indian state of Andhra Pradesh is dependent on limited groundwater resources with the exception of the monsoon season. Regardless of these unfavorable climatic conditions this state has focused on the cultivation of rice at the cost of huge loss due to evapotranspiration caused by temperatures exceeding 40°C. Government subsidies for drilling wells and particularly the free water abstraction and free electricity consumption for pumping groundwater result in overexploitation of water resources and dramatic lowering of the groundwater level.

One of the possible ways to resolve the issue of water scarcity is desalinization of sea water. On a global scale only 0.2% of potable water and 2.4% of industrial water are presently covered by desalinization of sea water. The main reason for this negligible proportion is the cost associated with desalinization which uses the three most common technologies- thermal distillation, freezing, and reverse osmosis, all of which are highly energy demanding. The cost of production of 1,000 L of potable water varies around 0.5 USD, while expenditures related to the production of industrial water are roughly half the cost [17]. It is obvious that desalinization of sea water can hardly be employed in poor African countries. On the other hand Lomborg [18], reports that only 0.5% of global GNP would be enough to cover worldwide consumption of water obtained by desalinization of sea water. This clearly shows great perspective of water scarcity solution.

5.4 Conclusions

Water can be considered an inexhaustible resource on our planet but its distribution is spatially random and extremely varying with time both on short- or long term horizons. In order for human society to be capable of ensuring enough water for new generations it not only has to search for new water resources but has to learn how to exploit water more efficiently and economically. About 96% of countries have sufficient resources of water. The problem is not in the physical lack of water but in water mismanagement and poverty. So the challenge for human society is to fight poverty and to exploit existing water resources more reasonably and efficiently.

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Chapter 6
Impacts of Decreasing Recharge Rates on Sustainable Groundwater Management

Hasan Yazicigil, Koray K. Yilmaz, Burcu Unsal Erdemli, and Ozlem Yagbasan

Abstract Groundwater is a vital resource for living and food security for at least two billion people worldwide. Ever increasing demand on groundwater has led to overexploitation of the aquifers and degradation of groundwater quality. Climate change will exacerbate these problems by producing reduced recharge rates in some areas, more reliance on groundwater resources due to decrease in reliability of surface waters, farther inland penetration of saltwater intrusion in response to both sea-level rise and excessive groundwater extraction and deterioration of groundwater quality by increased flushing of urban and agricultural waste due to more frequent flooding. These problems emerged the concern about the sustainable management of groundwater so that it is not depleted while the increasing demand is satisfied under the pressures exerted by the climate change. This paper examines one of the most significant consequences of climate change, decreasing recharge rates, on the sustainable management of groundwater resources using a hypothetical case study.

Keywords Groundwater • Climate change • Decreasing recharge • Groundwater management

6.1 Introduction

Water is a vital resource for the survival of not only human population but also almost all ecosystems. Therefore, access to safe freshwater is regarded as a universal human right [1]. Although water is globally abundant, 97% of the whole is

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saline water in oceans. Fresh water constitutes only the remaining 3%, 69% of which is attained in ice-caps and glaciers [2]. These numbers reveal the importance of groundwater, constituting 30% of all fresh water, as a main source of fresh water on which at least two billion people worldwide depends for domestic, industrial and agricultural activities.

As a part of the hydrologic cycle, groundwater is a renewable resource, yet it is not infinite. Rate of the renewal is limited to the rate of the replenishment, and closely related to the rate of depletion. Ever increasing demand on groundwater has led to overexploitation of the aquifers and degradation of groundwater quality. Consequently, the time when abundant supplies of water were readily available for development at low economic, social and environmental cost has passed. Now, the great challenge facing the world is to cope with the impact of economic growth on the environmental processes [3]. Moreover, climate change will exacerbate groundwater related problems by producing reduced recharge rates in some areas, more reliance on groundwater resources due to decrease in reliability of surface waters, farther inland penetration of saltwater intrusion in response to both sea-level rise and excessive groundwater extraction and deterioration of groundwater quality by increased flushing of urban and agricultural waste due to more frequent flooding. These problems emerged the concern about the sustainable management of groundwater so that it is not depleted while the increasing demand is satisfied.

The most important pressure that climate change will exert on groundwater resources will be the changing rate of recharge which is closely related to the changes in precipitation. Therefore, following similar trends with precipitation, groundwater recharge rates will either decrease or increase for different geographical regions. For instance, IPCC reported that a more than 70% decrease in groundwater recharge is computed in north-eastern Brazil, southwest Africa and along the southern rim of the Mediterranean Sea, whereas more than 30% increase in groundwater recharge is computed in Sahel, the Near East, northern China, Siberia and the western USA [4]. However, the most dramatic impacts of changing recharge rates on groundwater resources is foreseen at the locations where precipitation and accordingly recharge is expected to decrease. Decreasing recharge rates will definitely affect the quantity of the available groundwater resources, while the quality of the groundwater resources, especially in coastal regions, will be threatened by the saltwater intrusion and salinisation of groundwater due to the increased evapotranspiration [5]. Consequently, decreasing recharge rates will also enhance the impacts of processes which have already been observed, such as saltwater intrusion. Hence, this study aims to assess the impacts of decreasing recharge rates on management of groundwater resources using a hypothetical coastal aquifer system under various pumping scenarios.

6.2 A Hypothetical Case Study

Small islands are among the most vulnerable places to the effects of climate change and hence are given special attention in IPCC Assessment Reports. In this hypothetical study, a simplified circular island is simulated to assess the impacts of decreasing recharge rates on groundwater resources. The groundwater stored within the freshwater lens enclosed by the saline water serves as the only source of freshwater; like most small islands having no surface water or streams and therefore being fully reliant on rainfall and groundwater harvesting [5]. This dependency on rainfall significantly increases the vulnerability of small islands to future changes in precipitation. Moreover, increasing demand related to population and economic growth will exert additional stress on existing water resources. That is why such a system is chosen to examine the effects of decreasing recharge rates and increasing demand on the freshwater resources.

6.2.1 Method of Analysis

A three-dimensional numerical model, namely SEAWAT Version 4 [6] which is capable of simulating variable-density, saturated groundwater flow and multi-species transport in three-dimensions is used to simulate groundwater flow and solute transport in the hypothetical aquifer system.

The model developed is further utilized to assess the long term affects of decreasing recharge rates on the groundwater reserves, groundwater budgets and the saltwater intrusion rate in lateral and vertical directions. The outcomes of the model are used to assess the future sustainability of groundwater, considering both the quantity and the quality of the resource.

6.2.2 Model Description

The model domain is discretized into uniform finite-difference grid composed of 60 rows and 60 columns, so that each model cell has the size of 100 m by 100 m in horizontal plane. Due to the fact that higher vertical resolution is required for the accurate simulation of variable density flow systems, the model domain is discretized into 16 layers. Each of these layers has a thickness of 5 m except the uppermost layer having top elevation equal to the topography, ranges between 5 m asl (above sea level) in the middle of the circular island and 0 m along the coast and the sea, and bottom elevation is fixed at 5 m bsl (below sea level). Finally, a grid of cells having uniform volume, except the top layer, is achieved (Fig. 6.1).

The aquifer parameters and boundary conditions were modified after Masterson and Garabedian [7] who simulated a similar island aquifer (Fig. 6.1). The upper boundary of the model is represented by the water table and the lower boundary of the freshwater aquifer is the calculated boundary between the freshwater and the saltwater. Bottom of the model is simulated as a no flow boundary at a depth sufficient not to affect the flow and transport system. Sea surface at the uppermost model layer and the outermost extent of the model corresponding to all vertical cells are simulated by constant head (0 m) and constant concentration (35,000 mg/L) boundaries. A recharge rate of 700 mm/year is applied to the uppermost active cells of the model.

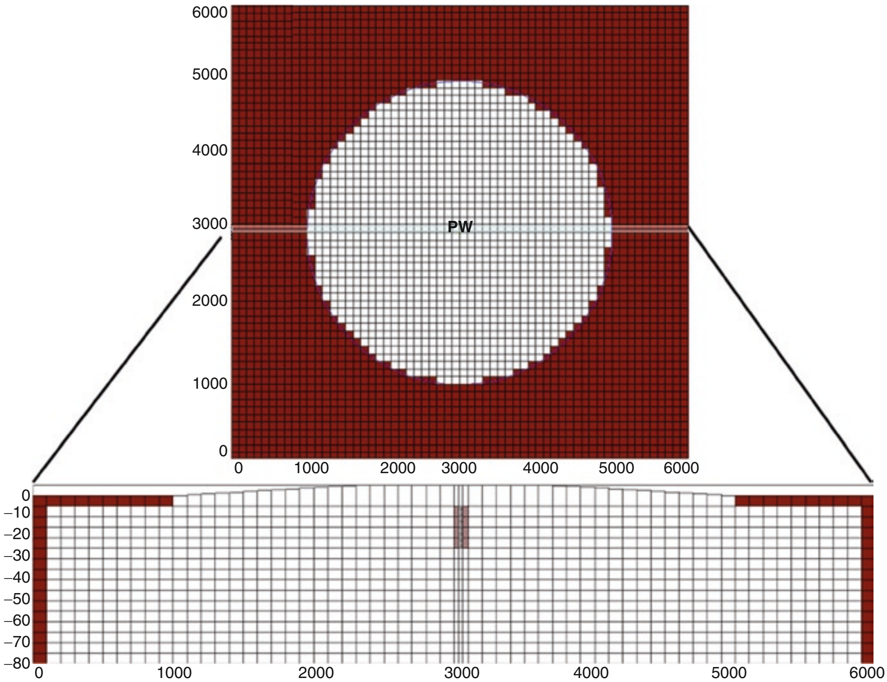

Fig. 6.1 Model extent and boundary conditions in plan view and cross-section

The system is assumed to be isotropic in lateral direction with a hydraulic conductivity of 90 m/day, while an anisotropy ratio of 1:10 is used to determine the vertical conductivity (9 m/day). Flow parameters such as specific storage, specific yield, total porosity and effective porosity are assumed to be uniform throughout the model domain, having the numerical values of 10^{-5} m^{-1}, 0.25, 0.3 and 0.25, respectively. Longitudinal, transverse and vertical dispersivity values are also assumed to be uniform and equal to 10, 1 and 0.1 m, respectively.

To assess responses of the system to the imposed change of recharge, initial conditions of hydraulic head and concentration distribution at the virgin state should be known. Consequently, modeling is performed at two stages: setting up the virgin conditions and imposing different pressures to the system. First stage of the modeling is the development of the freshwater lens and freshwater-saltwater interface at virgin conditions. In this stage, initial concentration is assumed to be equal to that of saltwater and initial head is assigned to be zero throughout the model domain. Then a transient simulation of 100 years is performed and due to the recharge having the concentration of freshwater, a freshwater lens floating above the saltwater has emerged. During this simulation, it is observed that system reached steady state conditions in terms of both hydraulic heads and concentrations after 75 years; hence the hydraulic head and concentration distribution at the end of 100 years can be regarded as virgin conditions (Fig. 6.2).

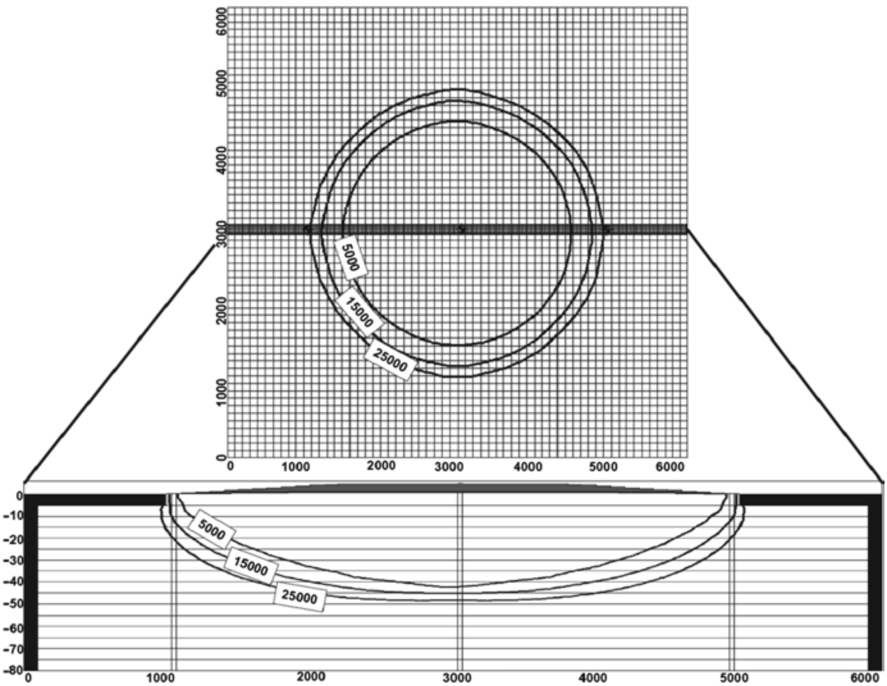

Fig. 6.2 Freshwater lens and concentration (mg/L) distribution in plan view and cross-section

The freshwater lens is bounded above by the water table and below by the freshwater-saltwater interface. However, rather than a sharp interface, there is a transition zone between the freshwater and saltwater. For this reason, the concentration limit of 5,000 mg/L is determined as the lower bound of the freshwater lens. This boundary is calculated to be at an elevation of −41.5 m at virgin conditions, and the volume of water contained within the lens between the interface and the water table is 68 hm^3.

6.2.3 Predictive Simulations

Results from the first stage of modeling, which ended up with the equilibrium (or virgin state) hydraulic head and concentration distribution, are used as initial conditions for the second stage in which the long term effects of decreasing recharge rates and increasing demand are assessed. In the second stage, effects of a 15% decrease in recharge are examined together with five different pumping stresses (0, 5, 10, 15 and 20 L/s). For simulation of the effects of groundwater pumping, a well is placed in the middle of the island aquifer where depth to the freshwater-saltwater interface is at maximum and the well is screened between the elevations −5 and −25 m (Fig. 6.1).

For each sub-scenario, the well is pumped at different rates. Consequently, two sets of simulations representing the change in recharge rates are performed for 100 years period, while each set is composed of five sub-scenarios corresponding to different pumping stresses.

6.3 Results and Discussions

The results of the simulations provide insights into the degree of sustainability of the groundwater under the imposed pressures in terms of both quantity and quality. To investigate the sustainability of the quantity, groundwater budget calculated by the model is examined. Recharge and discharge components of the groundwater budget, as well as the changes in these components induced by the simulated pressures are determined for each sub-scenario. Based on these outcomes, capture attributable to pumping is evaluated and compared to the pumping rate of the corresponding scenario. However, it is observed that for each of the sub-scenarios, system attains an equilibrium state by reducing the groundwater discharge into the sea at an amount equal to the rate of groundwater pumped. Even though this situation could be referred as "sustainable" in terms of water quantity, increased pumping rates – despite the compensation by the reduced discharges – causes a gradual upconing which eventually causes pumping of the saltwater. Hence, it is concluded that; such a groundwater budget analysis, discarding the groundwater quality is not sufficient to assess the sustainability of this coastal system. Therefore, rather than the budget analysis, decreases in the volume of the freshwater lens due to the saltwater intrusion caused by decreasing recharge rates are calculated for each of the sub-scenarios. Melloul and Collin [8] refer this volumetric loss from the freshwater reserves caused by the intruding saltwater to as permanent reserve loss, which is very difficult to be replaced. Results indicated that:

- In the base scenario, volume of the freshwater lens decreases in the range 0-6% only in response to the changing pumping rates
- In the second scenario, volume of the freshwater lens decreases in the range 10–16% due to the combined effects of changing pumping rates and decreasing recharge rates

The reserve loss as a consequence of decreasing recharge rate is more significant than that of increasing demand at the end of the 100 years simulation period. Moreover due to the fact that it imposes additional stress to the groundwater resource, it should be considered in determination of the sustainable yield of the system. It is obvious that there has to be a compromise between the groundwater reserve loss and the pumping rate that will supply the increasing demand, which is even more severe under accelerating stresses exerted by the climate change.

Lateral intrusion and upconing of the freshwater-saltwater interface are the two main criteria concerned in determination of the sustainability of groundwater quality. Lateral intrusion of the freshwater-saltwater interface is examined at the end of

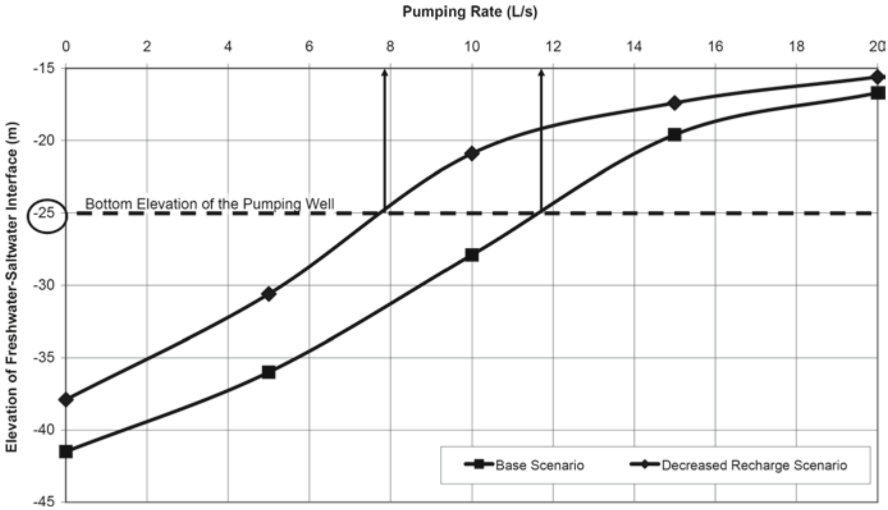

Fig. 6.3 Elevation of the freshwater-saltwater interface versus pumping rate

100 years at the model layer corresponding to the bottom elevation of the pumping well. The numerical results, listed below, reveal that the effect of decreasing recharge rate on lateral saltwater intrusion is higher than that of increasing demand:

- In the base scenario, freshwater-saltwater interface laterally intrudes a distance in the range 0–26 m only in response to the changing pumping rates
- In the second scenario, freshwater-saltwater interface laterally intrudes a distance in the range 94–130 m due to the combined effects of changing pumping rates and decreasing recharge rates

The changes in the elevation of freshwater-saltwater interface due to upconing for the two scenarios and their sub-scenarios that correspond to different pumping rates are demonstrated in Fig. 6.3. This figure reflects a very crucial response of the system to the imposed stresses of increasing demand and decreasing recharge rates. Accordingly, for the base scenario, almost 12 L/s of water can be pumped sustainably considering water quality, as the freshwater-saltwater interface is below the bottom of the well (at −25 m elevation). This amount, however, reduces by about 30% (to almost 8 L/s) in case of a decrease in recharge by 15%.

6.4 Conclusions

Decreasing recharge rates, which is one of the most significant impacts of climate change on groundwater resources, affects sustainable management of the coastal aquifer systems. The results of this study demonstrates that decreasing recharge rates has a more significant effect on the quantity and the quality of groundwater reserves compared to the effect of increasing pumping rates on a simulation period of 100 years. Moreover, there should be a compromise between the quantity and quality of groundwater and the pumping rate that will supply the increasing demand, which is even more severe under accelerating stresses exerted by the climate change. The results also indicate that decreasing groundwater recharge that may be imposed by the climate change reduces the sustainable pumping rates by almost one-third. Finally, it should be emphasized that groundwater quality has to be a binding constraint in the determination of the sustainable groundwater pumping policies for coastal aquifer systems.

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Chapter 7
A Model for Integrated Water Resources Management in Water-Scarce Regions: Minimization of the Impacts of Groundwater Exploitation on Society and the Environment

Nava Haruvy and Sarit Shalhevet

Abstract Israel is a developed, water-scarce country, with problems of increasing aquifer water salinity resulting from its exploitation of groundwater resources. To address this problem, we developed a model for planning water supply from diverse sources, including groundwater, the National Water Carrier, wastewater and seawater, and implemented it on two case studies in Israel. The model integrates hydrological, technological and economic considerations, and estimates the economic and environmental impacts of alternative water management policies. The hydrological model forecasts the concentration of chlorides in the aquifer under alternative scenarios in the short term and long term. The economic model estimates the costs of various desalination processes under the regional conditions, and the total costs of the water supply to the region under these scenarios. The conclusions are that desalination of brackish water involves lowest costs; desalination of National Carrier water is effective when there is large-scale use; desalination of wastewater is significant for maintaining the chloride concentration threshold in water for agriculture; and desalination of seawater is recommended when it makes an important contribution to maintaining the national water balance. Most importantly, we conclude that the economic cost of improving the quality of the supplied water and of the aquifer water should be considered in decision making.

Keywords Groundwater scarcity • Water salinity • Israel • Economics • Water management

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7.1 Introduction

Israel is a developed, water-scarce country, with mostly arid or semi-arid climate. Unlike many developed countries, Israel's population is rapidly growing, causing an increase in the domestic demand for water. Additionally, Israel's economy has continued to expand in the past few years, even in the face of a global recession, thereby creating an additional source of demand for the local water resources. Domestic demand places the greatest pressure on water resources, constituting about half of the total national demand for water (Table 7.1). This is followed by agriculture water use, and finally by industrial water use, which is about 6% of the total.

To meet to the needs of the rapidly growing population and local expansion, Israel has increased its exploitation of groundwater resources; this causes an increase in the salinity level of local aquifers, leading to some severe issues of local aquifer contaminations. Additionally, local trends of urban development, as well as increased adoption of water desalination and irrigation with wastewater, have combined to further accelerate the buildup of groundwater salinity. Recurring droughts, attributable to the global climate changes, will exacerbate these problems of over-exploitation and contamination of groundwater resources.

To address these problems, Israel has adopted to use of several alternative water sources, including treated wastewater for agricultural use and desalinated seawater for domestic water use. Treated wastewater constitutes about 16% of the total water supply (Table 7.2), and its share is growing as the freshwater supply decreases. Wastewater and brackish water together account for more than half of the total agricultural water use (Table 7.3), with wastewater alone supplying 36% of the total water use in agriculture.

Desalinated water supply is 300 mcm (22% of the total water supply), and expected to increase to 750 mcm/year by 2020. However, desalination is relatively expensive and energy-intensive, using up scarce fossil fuels and increasing greenhouse gas emissions that contribute to global climate change. If all the domestic water supply was based on desalinated seawater, the process would require an energy supply equivalent of 5% of the total electricity consumption in Israel [1].

Table 7.1 Water consumption by sector (mcm) [2]

Sector	2008	2009	Change 2008/2009 (%)
Agriculture	673	599	−11
Industry	82	75	−8
Households	731	663	−9
Total	1,485	1,337	−10

Table 7.2 Water supply by source (mcm) [2]

Source	2008	2009	Change 2008/2009 (%)
Freshwater	1,125	995	−12
Wastewater	231	219	−5
Brackish water	130	124	−5
Total	1,485	1,337	−10

Table 7.3 Water supply for agriculture by source (mcm) [2]

Source	2009	Percent of total (%)
Freshwater	259	44
Wastewater	218	36
Brackish water	122	20
Total	599	100

A commonly advocated alternative of renewable energy supply from bio-fuels is problematic in Israel's case, because as an agricultural crop these fuels require land and large quantities of water for production [3]. Other methods of decreasing energy use in desalination processes may become available by increasing capital investment in production technologies.

Irrigation with treated wastewater makes it possible to delay desalination. Wastewater is treated to secondary or tertiary treatment level to decrease organic and inorganic hazards. However, as its salinity is higher than source water, it is major cause of groundwater salinity.

Advantages of wastewater treatment

- A reliable supply of water at a low cost.
- A partial solution for effluent disposal.
- Reduces the need for fertilizer use.

Disadvantages

- Damage to crops and soils.
- Increases the risk of groundwater contamination.

Treatment

- Higher level treatment reduces the potential damage, but is more expensive.

7.2 Method

We developed a model for planning water supply from diverse sources, including groundwater, the National Water Carrier, wastewater and seawater. The model integrates hydrological, technological and economic considerations, and estimates the economic and environmental impacts of alternative water management policies; it was implemented in a case study of the Emek Heffer and northern Sharon regions in Israel. We constructed a unique hydrological database, which included detailed groundwater data for each hydrological cell in the case study area, and developed and ran a hydrological model for planning the allocation of the water resources and forecasting the concentration of chlorides in the aquifer under alternative scenarios. These scenarios included a variety of threshold policies for water supply to the city, irrigation or to the aquifer, irrigation with and without wastewater, and various well water pumping policies. We developed an economic model that estimated the costs of various desalination processes under the regional conditions, and calculated the costs of the water supply to the region under these scenarios.

7.2.1 *Planning Model*

The model is a combined hydrological- environmental-economic water management model (Fig. 7.1), which compares varying alternatives of -water supply for drinking and for irrigation and different water treatment alternatives. The goal was to identify the optimal treatment and reuse methods that- will ensure a sustainable and economic management of groundwater. The hydrological model, shown in Fig. 7.2, simulates two processes:

- Contaminants flow through the unsaturated zone of the soil.
- The effect of irrigation with wastewater on chlorides in groundwater.

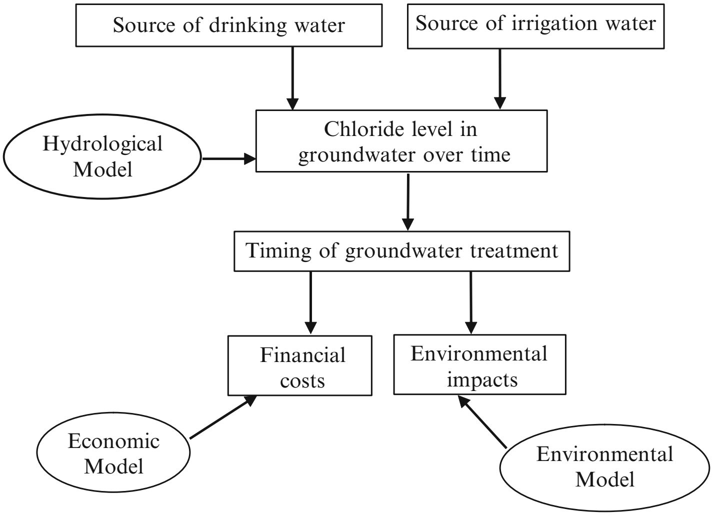

Fig. 7.1 The planning model

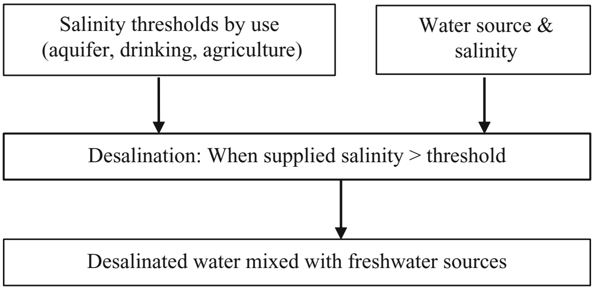

Fig. 7.2 The hydrological model

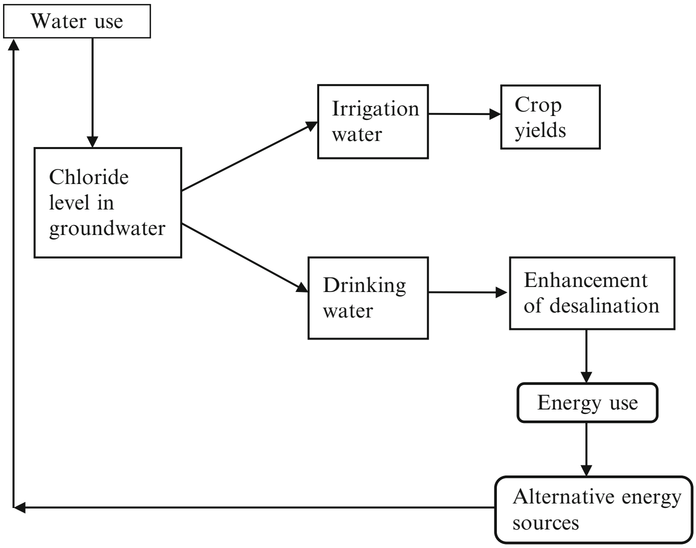

Fig. 7.3 The environmental model

When chloride concentration increases and reaches a predefined threshold, water sources are desalinated and combined with freshwater sources, to reach the permitted salinity level. The assumptions and mathematic description of the model are outlined in a separate paper [4].

The results of the hydrological model then serve as inputs to estimate the environmental impacts through the environmental model (Fig. 7.3). Finally, the hydrological and environmental model outputs then serve as inputs for the economic model that calculates the total cost of three factors:

- Desalination
- Wastewater treatment, storage and conveyance
- Water supply.

7.2.2 *Model Applications*

Alternatives of Water Sources used in the model included the following:

- Local groundwater
- National carrier water
- Treated wastewater
- Desalinated seawater

Model Inputs and Outputs include the following.

Inputs (data):

- Mapping of the area's settlements
- Location and types of crops
- Hydrological data

Outputs (predictions):

- Water demand and supply
- Aquifer water levels and salinity
- Quantity of desalinated water
- Water treatment methods
- Financial costs

7.2.3 Case Study

The case study included eight hydrological cells in the coastal aquifer of Israel, as described in Tables 7.4 and 7.5. The case study included two areas, each with four hydrological cells. The first area, Coastal 1, is almost exclusively devoted to agricultural land use. The main water source is wastewater (more than 50% of total), followed by local aquifer (a little over 40%). The second area, Coastal 2, is divided between agriculture (two thirds) and urban land use (one third). The main water source is National carrier water (more than 50% of total), followed by local aquifer (less than 40%).

Table 7.4 Case study hydrological cells

	Coastal 1	Coastal 2
No. of hydraulic cells	4	4
Groundwater salinity	>230 mg/L Cl	<164 mg/L Cl
Other		Effluents from wastewater plant

Table 7.5 Land and water use in the coastal region

	Coastal 1[a]		Coastal 2[a]		Total region[a]	
	Land use	Water use	Land use	Water use	Land use	Water use
Agriculture: Total	99%	24.46	51%	34.88	67%	59.34
National carrier		0.9%		34.3%		20.5%
Local aquifer		38.5%		55.6%		48.6%
Wastewater		60.6%		10.1%		30.9%
Urban: Total	1%	2.57	49%	24.71	33%	27.29
National carrier		0.8%		88.1%		79.8%
Local aquifer		99.2%		11.9%		20.2%
Total	8,354	27.03	16,164	59.59	24,518	86.63

[a]Land use – total ha or % of total; water use – total mcm or % of total

Table 7.6 Case study scenarios

Scenario	Threshold for water salinity		Priority of pumped water
	Freshwater: town (mg/L Cl)	Wastewater: irrigation (mg/L Cl)	
1	250	250	Town
2	250	250	Town
3	150	250	Town
4	50	250	Town
5	250	Not included	Town
6	250	Not included	Agriculture
7	250	350	Agriculture
8	250	350	Town

7.2.4 Scenarios

The policy variable is the setting of chloride thresholds for drinking water and for irrigation. We constructed eight different scenarios, with chloride thresholds for drinking water and for irrigation ranging from 50 up to 250 mg/L Cl for drinking water and from 250 to 350 mg/L Cl for wastewater. The water for irrigation may be either freshwater or wastewater, and allocation of the pumped water (aquifer water) may give a priority to urban use or to agricultural use. The specific variables for each scenario are shown in Table 7.6.

The model analyzes these scenarios for a variety of desalination alternatives: brackish groundwater, national carrier water, wastewater, and seawater. The hydrological model produces a forecast of the groundwater chloride concentration over time for each scenario. These results are then used as inputs in the economic model in order to calculate the costs of the alternative policy scenarios. The results can be applied to a variety of other types of policies, for example, we have applied the model to examine the issue of transboundary river management [5].

7.3 Results

The hydrological model produces annual forecasts of chloride concentration in groundwater in the short term and long term. The results for each case study area are presented in Fig. 7.4 for Coastal 1 area and Fig. 7.5 for Coastal 2 area, for each of the scenarios described in Table 7.6. The figures show that the salinity level is lower in scenarios with greater restrictions.

The results are shown for scenarios 1–8, with the following characteristics described next to each scenario: Town freshwater/ Wastewater salinity/ Pumped water priority: T = Town, A = Agriculture.

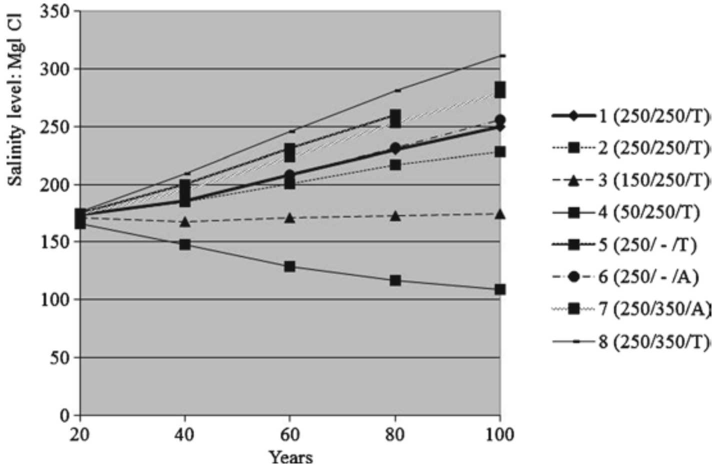

Fig. 7.4 The predicted increase in aquifer salinity by scenario for Coastal 1 area

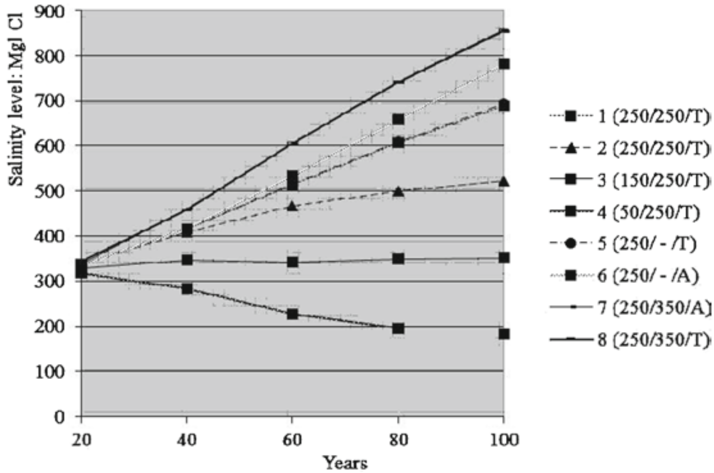

Fig. 7.5 The predicted increase in aquifer salinity by scenario for Coastal 2 area

7.3.1 Economic Implications

The economic model produces forecasts of the implementation costs. These forecasts are shown in Fig. 7.6 for Coastal 1 area and Fig. 7.7 for Coastal 2 area, for scenarios 2–8 as described in Table 7.6. The columns show the total cost of implementation in millions of New Israeli Shekels (NIS), and the lines show the cost of water desalination as a percentage of total costs. The model output, as illustrated in these figures, shows that irrigation with wastewater increases salinity

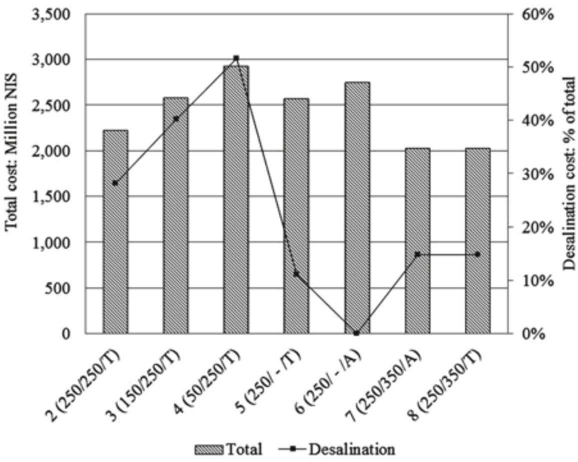

Fig. 7.6 The predicted increase in aquifer salinity by scenario for Coastal 1 area

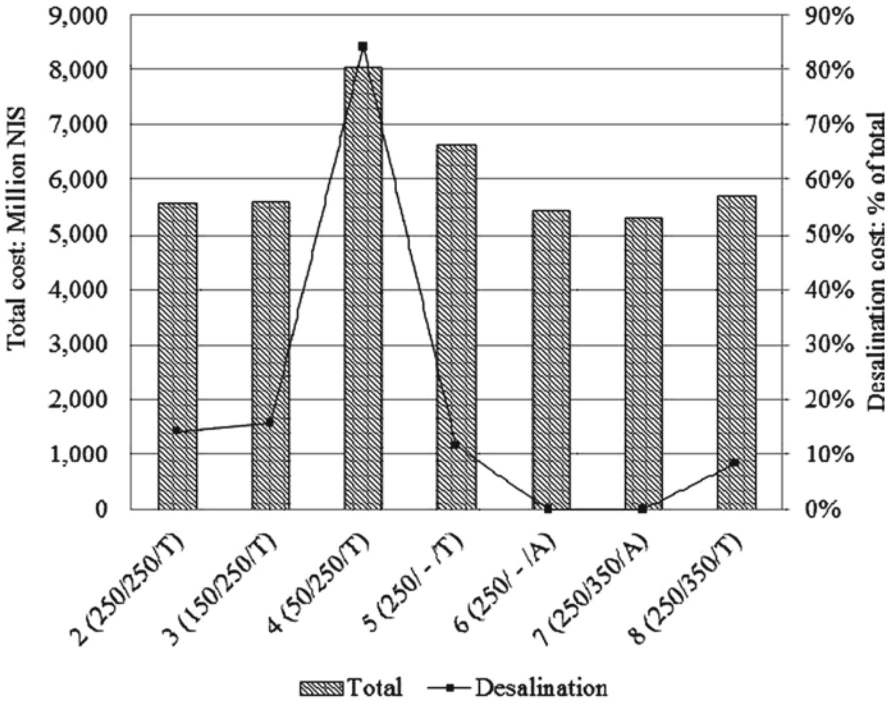

Fig. 7.7 The predicted increase in aquifer salinity by scenario for Coastal 2 area

levels, and consequently increases the cost of desalination, but decreases the total cost of water supply. Greater restrictions increase the total costs significantly.

The results are shown for scenarios 2–8, with the following characteristics described next to each scenario: Town freshwater/ Wastewater salinity/Pumped water priority: T = Town, A = Agriculture.

The results are shown for scenarios 2–8, with the following characteristics described next to each scenario: Town freshwater / Wastewater salinity / Pumped water priority: T = town, A = Agriculture.

7.4 Conclusions

The conclusions from the planning model are that we can protect the groundwater resources by adopting higher restrictions on salinity levels, so more treatment and desalination is needed. This is followed by higher treatment and supply cost. The main points are that:

- Supplying desalinated sea or brackish water is a solution for quantity and quality of water;
- Irrigation with wastewater decreases supply costs but increases salinity;
- All supply alternatives should be considered regarding their impact on groundwater salinity as well as on economic cost.

The conclusions from calculating the costs of improving the threshold chloride levels in the water supplies to city and/or agriculture or the steady-state levels in the aquifer are the following:

- Desalination of brackish water involves the lowest costs;
- Desalination of National Carrier water is effective when there is large-scale use;
- Desalination of wastewater is significant for maintaining the chloride concentration threshold in water for agriculture;
- Desalination of seawater is recommended when it makes an important contribution to maintaining the national water balance;
- Most importantly, we conclude that the economic cost of improving the quality of the supplied water and of the aquifer water should be considered in decision making.

To summarize, climate change increases the stress on water sources, and overexploitation of groundwater sources results in aquifer contamination and increased salinity. Therefore, alternative water sources should be developed, including treated wastewater use in agriculture and desalination of sea water for domestic water use. Restrictions on water quality are needed to ensure sustainable groundwater management, but these restrictions involve increased costs. National decision makers should take into account both the environmental impacts and the economic costs of different water supply sources, including their impacts on groundwater resources as well as the impacts of different policies on climate change.

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Chapter 8
Assessing the Impact of Climate Change on Groundwater Resources Using Groundwater Flow Models

Alper Elçi

Abstract Climate change is a potential stressor of groundwater resources and its effects on the availability of groundwater need to be understood and determined. The impacts of climate change on groundwater systems are conceptually known, however in the context of climate change impact assessment there has been little research conducted on groundwater compared to surface water resources. One of the tools used to quantify the effects of climate change is to use groundwater flow models in conjunction with downscaled GCM (global circulation model) results and groundwater recharge estimation. The purpose of this study is to present an overview of groundwater modeling approaches to assess the impacts of climate change on groundwater resources. Basic requirements, challenges and different approaches to overcome them are presented. The principal challenge of any climate change impact study is the downscaling of GCM results to the basin scale. Furthermore, the estimation of the impacted groundwater recharge is particularly important in groundwater modeling studies. A summary of case studies demonstrating the various methodologies are provided, following with an overview of a recent climate change impact study conducted for Tahtalı stream basin in Turkey.

Keywords Groundwater • Numerical modeling • Recharge • Water budget • Downscaling • Tahtalı stream basin

8.1 Introduction

Groundwater is a significant component of the freshwater cycle and its significance is becoming more prominent as the more accessible surface water resources are increasingly more exploited. In many cases, groundwater is a sufficient, secure

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and cost-effective water supply. However, it is increasingly becoming stressed due to overexploitation, contamination and in some areas of the world due to climate change. It was emphasized in a technical paper by the second working group of the Intergovernmental Panel of Climate Change [1] that the information about the water-related impacts of climate change is insufficient, especially with respect to water quality, aquatic ecosystems and groundwater. Therefore, impacts of climate change on groundwater quantity and quality need to be comprehended and determined.

The main objective of this study is to present an overview of the modeling approach to assess the impact of climate change on groundwater systems. Basic requirements and different approaches of impact assessment studies are also presented. Some case studies demonstrating the various methodologies are summarized to provide the reader with contemporary applications of groundwater flow modeling with respect to climate change impacts. The article concludes with recommendations for more reliable impact studies.

8.2 Impacts of Climate Change on Groundwater

The impacts of climate change on groundwater systems are conceptually known; however, in the context of climate change impact assessment there has been little research conducted on groundwater compared to surface water resources. Nevertheless, from a qualitative point of view, it is known that aquifers respond to precipitation variability and climate fluctuations much more slowly than surface water. Aquifers act as a more resilient buffer during droughts, especially when they have a large capacity [2]. Furthermore, it is expected that predicted global changes in temperature and precipitation will alter groundwater recharge to aquifers, causing shifts in water table levels in unconfined aquifers as a first response to climate trends. Therefore, determining the change in groundwater recharge is the key to estimate climate change impacts on groundwater. The effect of changing precipitation patterns on groundwater recharge rates depends on whether the region of interest has humid or arid climate characteristics besides other factors such as the magnitude, intensity and the period of precipitation [3].

Increased variability in rainfall may decrease groundwater recharge in humid areas because more frequent heavy rain will result in the infiltration capacity of the soil being exceeded, thereby increasing surface runoff. In semi-arid and arid areas, however, increased rainfall variability may increase recharge, because only high-intensity rainfalls are able to infiltrate fast enough before evaporating, and alluvial aquifers are recharged mainly by inundations during floods [1]. In the case where an aquifer is hydraulically connected to surface water, the groundwater levels are expected to be affected by any hydrological alteration. This type of interaction is relatively complicated to quantify compared to groundwater recharge change driven impacts on groundwater levels.

There are other indirect impacts of climate change on groundwater that can be considered in impact assessment studies. One of them is the deterioration of groundwater quality in coastal aquifers due to increased saltwater intrusion driven by sea level rise. Also, elevated evapotranspiration rates cause changes in soil moisture and in particular increases in groundwater salinity. Another indirect implication of higher temperatures and less precipitation is the exacerbation of water demand, which in turn triggers more groundwater withdrawal from the aquifers.

8.3 Approach for Groundwater Impact Modeling Studies

The general approach for any kind of climate change impact modeling assessment is principally straightforward. The process starts by selecting one or more climate change scenarios that explore possible future changes in climate variables. If the scenarios are taken from the results of a GCM (global circulation model) then the next crucial step is to downscale the GCM results to the basin scale. The downscaled GCM results are then used as input for the hydrological model that is constructed for the study area of interest. Finally, the hydrological model is run for the current and future climate, and both simulation results are compared to further assess the impacts of climate change. The attractive side of this approach is that it will always yield a result, for whatever part of the hydrological cycle. The simulations will give changes in floods, low flows, groundwater recharge, and whatever else is requested. The question here, however, is the confidence one can have in these simulations [4].

8.3.1 Data Requirements

A climate change impact study on groundwater resources requires in addition to the basic groundwater flow modeling input data, observed climate data recorded at relevant meteorological stations and future climate data in the form of GCM projections. Climate data of particular interest are precipitation, temperature and evaporation measurements, which are used in the estimation of groundwater recharge. On the other hand, basic groundwater flow modeling data requirements include but are not limited to the hydrostratigraphy, hydraulic conductivity distribution, storage coefficients, water table or piezometric surface measurements, surface water gauging data, spring flow rates, production well pumping rates, recharge and evapotranspiration rates of the studied area. The latter two are key parameters for groundwater impact studies as they are often the most significant components of the basin's water budget. In semi-arid and arid regions, evapotranspiration becomes a more pronounced component of the water budget. Ultimately, the future change in groundwater recharge and evapotranspiration causes the alteration of groundwater levels and fluxes within a basin.

8.3.2 Groundwater Recharge Estimation

Areal groundwater recharge to the aquifer occurs due to infiltration of precipitation and/or irrigation return flow. The estimation of current and future recharge rates is an essential element of climate change impact assessments. Relative changes in recharge rates are of interest, and how these changes affect the groundwater levels.

There are several methods to quantify groundwater recharge; Scanlon et al. [5] provide a useful review on choosing the appropriate technique to determine recharge. The methods can be divided into physical, chemical (tracer) and numerical modeling approaches. One of the well-known physical methods is the water table fluctuation method [6], which is based on the premise that groundwater level rises in unconfined aquifers are due to recharge water percolating through the vadose zone. Groundwater dating and the chloride mass balance methods are examples for tracer methods to determine recharge. Moreover, numerical modeling can be a useful and robust approach to quantify recharge. Spatially-distributed recharge estimates can be obtained by inverse modeling of groundwater flow models. Another method is to use soil-vegetation-atmosphere-transfer (SVAT) models, which are 1-D process-based models that calculate unsaturated groundwater flow through the vadose zone. One example for a SVAT model is the 1-D Hydrologic Evaluation of Landfill Performance model [7], HELP, which simulates vertical leakage of water through the soil profile. It accounts for precipitation in any form, surface storage, runoff, evapotranspiration, snowmelt, vegetative interception and growth, unsaturated flow and temperature effects. Since the model is 1-D, like most SVAT models are, recharge rates are estimated for specific combinations of soil type and depth, vadose zone conductivity and water table depth. Hence, the model outcome needs to be upscaled and extended to all points of the study area. The recharge boundary condition for a finite-difference groundwater flow model can be obtained by linking the HELP model with a GIS (Geographical Information System). Thereby, the spatial distribution of recharge rates can be obtained, where recharge rates are determined for each grid cell of the groundwater flow model (e.g. [8, 9]).

Precipitation-runoff models are used to estimate lumped recharge rates at the basin or sub-basin scale. They provide a single recharge estimate for the entire watershed and generally yield groundwater recharge estimates as a residual term in the water budget equation. There are also groundwater-centered recharge estimate approaches; groundwater flow model calibration is another technique to predict recharge rates from information of observed hydraulic heads, hydraulic conductivity and other parameters (e.g. [10]).

8.3.3 Downscaling of GCM Projections

GCMs are coupled land-atmosphere-ocean numerical models that are used to estimate climate variables such as temperature and precipitation, and are set up for various greenhouse gas and aerosol emission scenarios. GCMs use horizontal grid cells that can have dimensions in the range of 150–500 km. Therefore, GCMs are not capable of accurately estimating climate variables at the groundwater basin scale.

Consequently, spatial downscaling methods have been developed to derive finer resolution data from coarse resolution GCM results. These methods can be grouped into two major categories; the first of these is dynamical downscaling, where higher resolution regional climate models (RCMs) or limited area models (LAMs) are set up using boundary conditions derived from the coarser resolution GCM. The second group of downscaling approaches consists of statistical methods, which rely on the fundamental concept that regional climates are largely a function of the large-scale atmospheric state. This relationship may be expressed in the form of transfer functions, which cover a range of methods: multiple regression, non-linear regression, artificial neural networks, principal component analysis, and canonical correlation analysis. Stochastic weather generators and weather classification schemes are more sophisticated statistical methods.

Both approaches of downscaling have their advantages and limitations. However, comprehensive comparison studies suggest that dynamical downscaling methods provide little advantage over statistical methods. Given the data intensive structure of dynamical methods, it may be preferable to select a statistical downscaling method in groundwater impact studies. The main objective of this type of downscaling is to establish a quantitative relationship between large scale atmospheric variables (predictors) and local surface variables (predictands), which is not always straightforward due to the often weak correlation between the predictors and predictands.

8.4 Overview of Case Studies

Most studies to date dealt with estimating the potential impacts of climate change on surface water resources. Relatively fewer studies deal with the modeling of impacts on groundwater. In this section, an overview of some selected case studies about groundwater impact modeling are presented in chronological order, followed by a summary of a recent impact modeling study for the Tahtalı basin in Izmir-Turkey that was conducted by Elçi and Fıstıkoğlu [11]. The overview is intended to focus on the methodology rather than on the specific results.

8.4.1 Some Selected Case Studies

Kirshen [12] used MODFLOW [13] to study the impact of climate change on a highly permeable aquifer in the northeastern United States. Groundwater recharge was estimated using a separate model based on precipitation and potential evapotranspiration. Both hypothetical and GCM-predicted changes to the input parameters were used, resulting in higher, no different, and significantly lower recharge rates and groundwater elevations, depending on the climate scenario used.

In another study, Croley and Luukkonen [14] investigated the impact of climate change on groundwater levels in Lansing, MI, USA. The groundwater recharge rates were based on an empirical streamflow model which was calibrated using the results from two GCMs.

Scibek and Allen [9] developed a different approach by downscaling GCM model results using the Statistical Downscaling Model (SDSM) and then applying the resulting change factors in the LARS-WG weather generator to obtain future climate conditions. The HELP model was applied as the recharge model and a transient groundwater flow model was used to simulate four climate scenarios. Groundwater levels were compared to the present and it was found that the effect of spatial distribution of recharge on groundwater levels, compared to that of a single uniform recharge zone, is much larger than that of temporal variation in recharge, compared to a mean annual recharge representation. A very similar modeling approach was taken by Jyrkama and Sykes [8] who studied the Grand River watershed in Ontario, Canada. The difference in their approach was that recharge zoning was not used and recharge values were calculated for each grid cell.

Woldeamlak et al. [15] studied the potential impacts of climate change on the Grote-Nete basin in Belgium. Wet, cold and dry future climate scenarios were formulated by assigning percentage and absolute changes on current precipitation and temperature, respectively. Based on these scenarios and present climate, recharge was simulated with a distributed water-balance model. Annual, summer and winter recharge rate maps were obtained and used as recharge boundaries for the steady-state MODFLOW model. Simulated changes in groundwater head, discharge rates and discharge areas were presented.

Hsu et al. [16] applied a different method in the recharge estimation for the Pingtung Plain in Taiwan. Records of historical precipitation data were analyzed to determine the long-term pattern of climate change. Regression equations were obtained to predict future precipitation. Methods of water-table fluctuation and model inversion were combined to estimate recharge in this study. An annual precipitation rate reduction of 7.8 mm/year and its corresponding reflection in the decrease of recharge were applied in the groundwater flow modeling.

In another study, a groundwater flow model was developed for the Okanagan basin in British Columbia, Canada, by Toews and Allen [17], where irrigation return flow was considered in the determination of current and future recharge. Downscaling of GCM results was performed with multi-linear regression and recharge was estimated using the HELP model. It was also used to explicitly calculate irrigation return flow for present and future conditions. Transient groundwater flow simulations were performed with MODFLOW.

Rozell and Wong [18] investigated the relationship between climate change and seawater intrusion for an island with a variable-density transient groundwater flow model. Global predictions from the IPCC for changes in precipitation and sea-level rise over the next century were used to create two future climate scenarios, therefore no downscaling was performed.

8.4.2 *Modeling the Climate Change Impact on the Izmir-Tahtalı Groundwater System*

This section presents an overview of the climate change impact study on the Izmir-Tahtalı basin groundwater system. This study by Elçi and Fıstıkoğlu [11] is the first published study of its kind performed for a basin in Turkey. The main goal of this study is to estimate climate change induced groundwater level and flow changes in the Izmir-Tahtalı stream basin with a numerical groundwater flow model by considering the IPCC's SRES scenarios. The Tahtalı dam reservoir was built on the Tahtalı stream, which has a drainage area of 550 km^2. It is a major water resource meeting 35–40% of Izmir's total drinking water demand. The Tahtalı stream basin is a subbasin of the larger Küçük Menderes basin and receives an annual areal mean precipitation of 820 mm. The annual mean temperature in the area is 17.4°C.

The general methodology of the impact modeling study is similar to previous studies in other parts of the world and consists of three stages. First, two scenario results of the HadCM3 model, the 20C3M scenario representing the current climate and the A1B scenario representing the future climate, were downscaled to the basin scale using the artificial neural network method. Historical time series of precipitation and temperature station records and the relevant NCEP/NCAR Re-analysis data were used in this process. By comparing downscaled 20C3M and A1B projections, expected changes in precipitation and temperature monthly mean values were calculated for the period of 2040–2059, which is referred to as "2050 scenario" from here on. These changes are presented in Table 8.1. Projected changes in precipitation fluctuate on a monthly basis, however on an annual basis it is expected to decrease by 3.74%. Temperature is expected to rise for all months and the annual increase in calculated as 2.96°C.

Table 8.1 Differences between downscaled HadCM3 projections for the Tahtalı basin

	A1B (2040–2059) – 20C3M (1950–1999)	
	Relative change in mean precipitation (%)	Absolute change in mean temperature (°C)
January	27.24	2.10
February	9.27	2.46
March	−17.24	2.86
April	2.05	3.01
May	−10.34	2.17
June	−81.55	3.08
July	142.22	2.95
August	530.25	3.01
September	−70.31	3.27
October	−26.72	3.58
November	−1.05	3.57
December	5.83	3.49
Annual	3.74	2.96

The next stage in the assessment process is to simulate groundwater recharge for the current climate and 2050 scenario. For this purpose, an independent, water budget based precipitation-runoff model was applied [10]. The model uses monthly total precipitation and potential evapotranspiration (estimated from temperature data) to determine basin averaged surface and subsurface flow components, including groundwater recharge. As input data for the model, future time series of precipitation and temperature valid for the period 2040–2059 were obtained by applying the changes in Table 8.1 on the observed time series for the period of 1970–1989. Time series for the current and future climates are shown in Figs. 8.1 and 8.2. Recharge estimates from the precipitation runoff model are presented in Fig. 8.3. Recharge values range from 5.1 to 71.1 mm for the current climate and the 20-year average recharge is 31.63 mm. For the 2040–2059 period, recharge is estimated to fluctuate in the range of 2.2–71.2 mm, with a 20-year average of 33.21 mm. It becomes clear that a future increase in precipitation and temperature translates into a 4.8% decrease in groundwater recharge.

The final stage of the study is to run the groundwater flow model to obtain current and future water table depths and groundwater fluxes in the Tahtalı basin. The groundwater system is simulated on a 150-m resolution finite-difference grid using the groundwater flow model MODFLOW-2000 [13]. The model has one layer and is set up to simulate steady-state flow conditions of the wet season of the year. It receives recharge estimates from the precipitation-runoff model. Model properties, calibration and validation of the model are described in Elçi et al. [10].

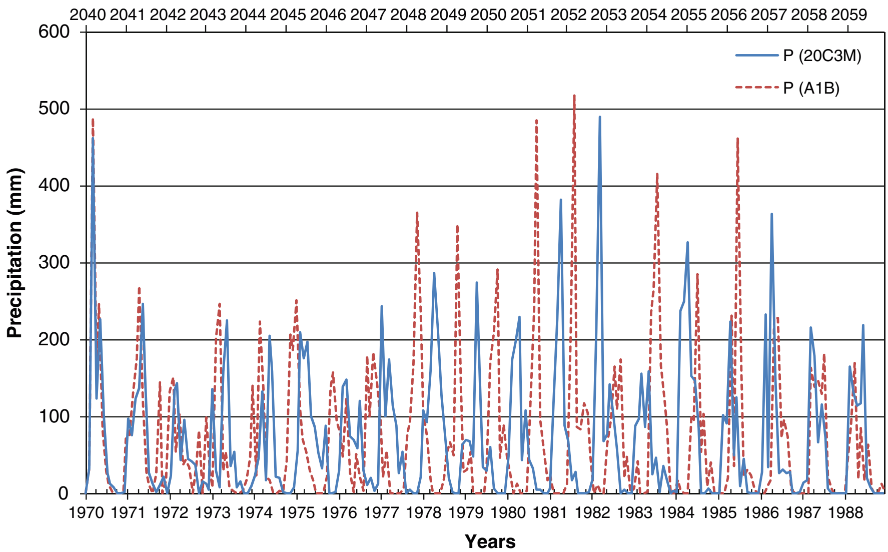

Fig. 8.1 Downscaled precipitation time series for current and future climate

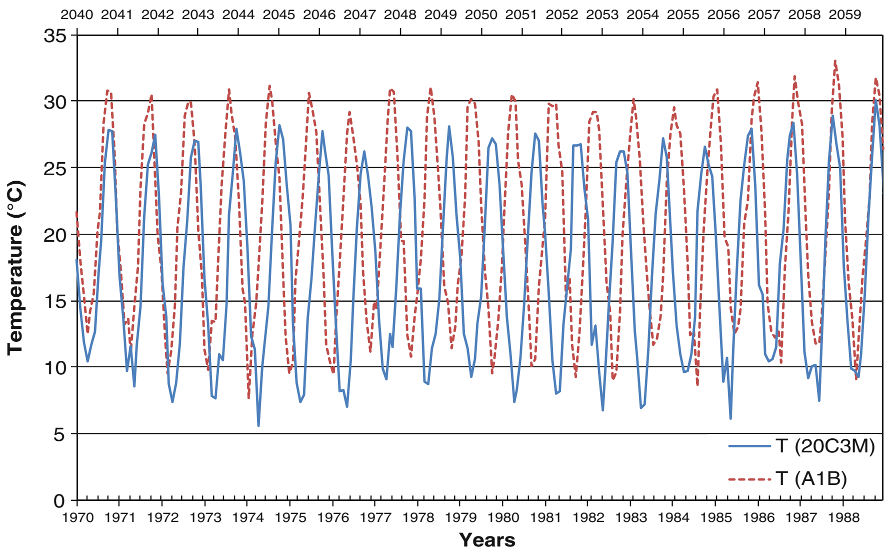

Fig. 8.2 Downscaled temperature time series for current and future climate

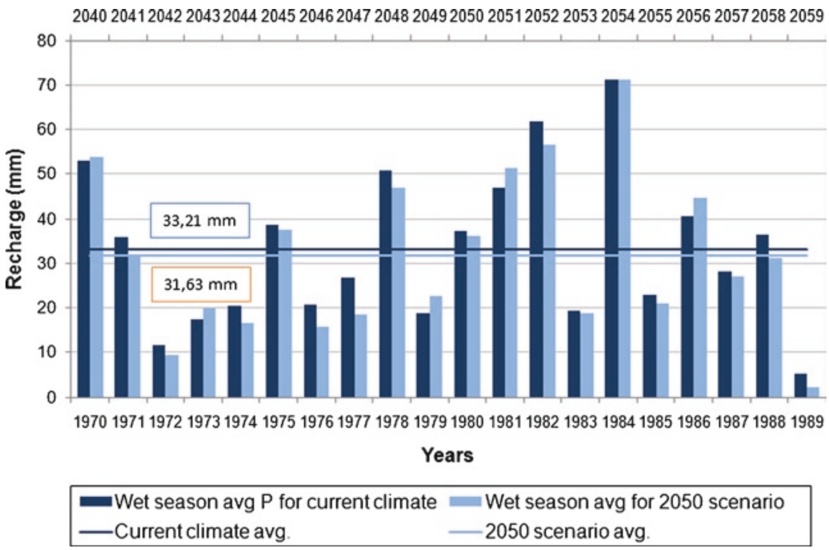

Fig. 8.3 Wet season groundwater recharge totals calculated by the precipitation-runoff model for the current climate and the 2050 scenario. Averages represent a 20-year average of 6 month wet periods

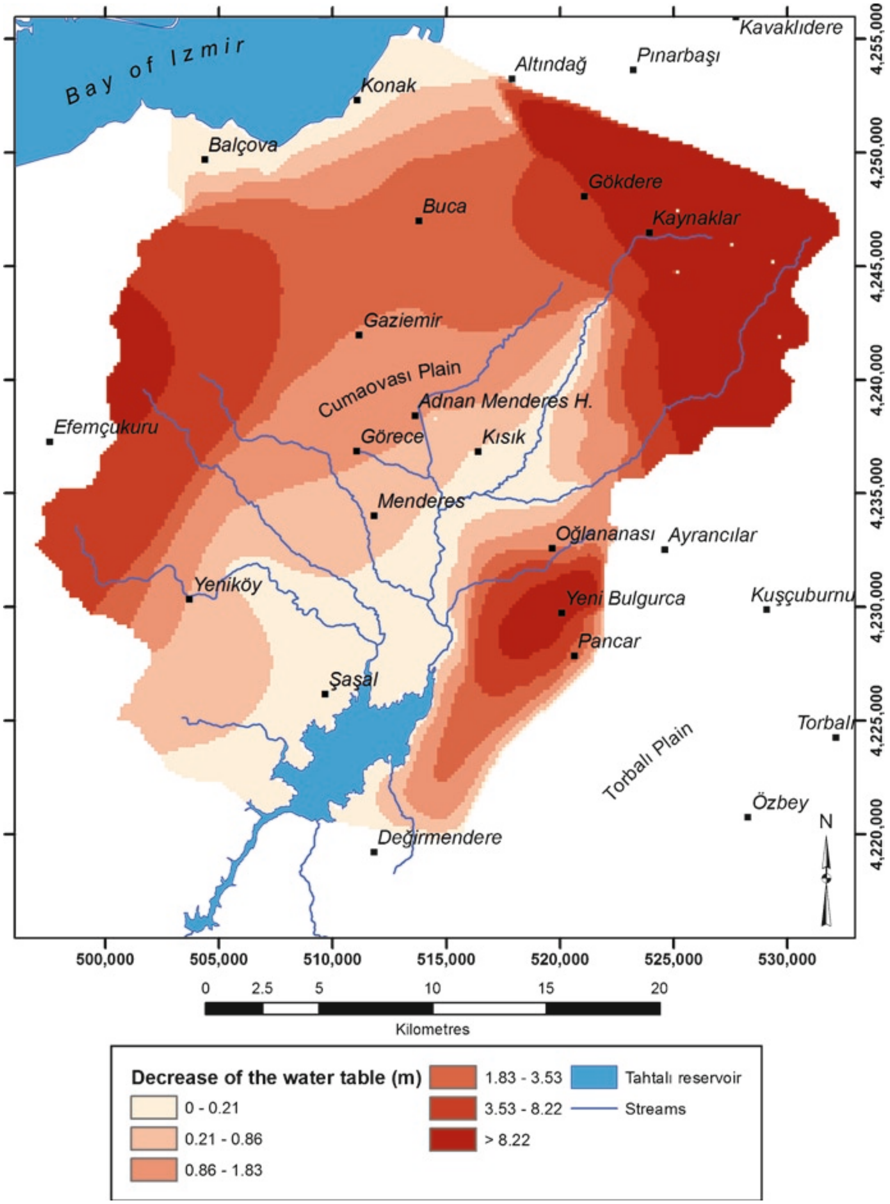

Fig. 8.4 Predicted water table differences for Tahtalı stream basin (current climate – 2050 scenario)

Modeling results were evaluated in many ways. To obtain the spatial distribution of climate change induced changes on the water table depth, the difference between the water table surfaces for the present situation and the 2050 scenario was determined (Fig. 8.4). It can be observed that the water table is expected to

Table 8.2 Comparison of the groundwater flow model's current and future water budgets for the Tahtalı stream basin (negative values in the inflow columns imply net outflow from the groundwater system)

	Net inflow to the aquifer (m^3/day)			
Water budget component	Current climate	2050 scenario	Change (m^3/day)	Change (%)
Net groundwater recharge	610,408.75	581,346.56	−29,062.19	−4.8
Reservoir and bay	−218,399.83	−213,206.47	5,193.36	2.4
Other model boundaries	−348,294.71	−331,717.45	16,577.26	4.8
Wells	−25,859.40	−25,859.40	0.00	0.0
Streams	−6,207.20	477.81	6,685.02	107.7
Springs	−11,648.69	−11,042.18	−606.51	5.2

decline everywhere in the model domain, where the magnitude of the decline depends on the hydraulic conductivity variation in the aquifer and the extent of surface-groundwater exchange at the Tahtalı stream network. The water budget calculation results are summarized in Table 8.2.

Based on these results it can be concluded that the largest component in the budget is and will be net groundwater recharge, which is predicted to decrease for the 2050 scenario causing a reduction of 29,062 m^3/day in the water inflow to the system. Furthermore, spring discharge rates are predicted to decrease by 5.2%. Groundwater seepage to the Tahtalı reservoir and Izmir bay is predicted to decrease by 2.4%. Another significant outcome of the water budget analysis is the change in the water interaction between the streams and the aquifer. For the current climate, streams gain 6,207.20 m^3/day of water. The overall net direction of water flow is expected to reverse for the 2050 scenario, as the net loss of water from the streams is predicted to be 477.81 m^3/day.

8.5 Recommendations for More Reliable Groundwater Impact Modeling Studies

In this study, an overview of the methodology and case studies of climate change impact modeling studies on groundwater are presented. Impact modeling studies on groundwater are relatively new, and innovative approaches with respect to climate data analysis, downscaling of GCM projections, groundwater recharge estimations are still being developed. Some challenges lie ahead for more reliable climate change impact assessments. For example, there is considerable uncertainty about the predictions made by GCMs, specifically precipitation predictions vary between different GCMs. Moreover, uncertainties exist for groundwater flow modeling because of aquifer heterogeneity and the difficulty to quantify certain hydrogeological parameters. These uncertainties in data and models can be mitigated by opting for stochastic modeling approaches that provide means to quantify uncertainties. Evaluating multiple GCM model results and aggregating them can be helpful in reducing the uncertainty in climate data.

Furthermore, the modeling methods on key processes like recharge and evapotranspiration need to be improved. With respect to recharge, other mechanisms such as irrigation return flow, leaking pipes in urban areas and losing surface water should also be considered for a more rigorous modeling study. Projections of future irrigation water demand, groundwater withdrawal for domestic and industrial use, future land use and future levels of surface water features are other improvements that can be considered. Lastly, if data and conditions permit, studies based on a transient groundwater flow modeling approach should be conducted because climate change impact studies based on steady-state simulations have limitations in representing boundary conditions. It is preferable to use them for assessing sensitivities before implementing more rigorous and data-intensive transient modeling.

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Chapter 9
Management of Karst Aquifers Under Climate Change: Implications for Sustainable Use

Mehmet Ekmekci and Levent Tezcan

Abstract Among several other factors, spatial and temporal variability of some basic characteristics is of primary importance in defining the vulnerability of a hydrogeological system against external/internal stresses. Response of a hydrogeological system to climatic changes is reflected in dynamics of recharge, storage and flow, which consequently alters water quality. Managing karst aquifers is more difficult compared to non-karstic aquifers, due to the fact that recharge-storage-flow mechanism is not as straightforward as in non-karstic aquifers. In this paper, management of karst aquifers, with special emphasis on climatic changes, is discussed, based on some examples from Turkish karst. It was demonstrated that well karstified rock masses, which normally do not contain significant phreatic zones, can be developed, in order to capture and store the flush waters of floods for later use.

Keywords Aquifer • Climate change • Groundwater • Hydrogeology • Karst • Management • Sustainable use • Turkey

9.1 Introduction

In general, sustainable use of groundwater resources requires a thorough understanding of the hydrodynamics of groundwater system and its interactions with other environmental and anthropogenic systems. The highly heterogeneous character of karst systems needed massive research on groundwater exploration techniques for more than three decades, beginning from the 1960s. Research on groundwater exploitation techniques in karst have been followed by management strategies.

Groundwater management is a term which concerns to the sustainability of the resource in terms of quantity and quality, thus requiring the knowledge of the

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distribution of the groundwater flow velocity vector in the flow domain [1]. The only way of defining such a vector field seems to be a distributed parameter modeling [2]. However, modeling efforts in karst have been concentrated in the identification of the processes inside the karst system by analyzing hydrologic, chemical and isotopic observations at the outflow point, mostly springs. The success of the distributed numerical models is very poor, and utilization of such models in water resources management is still not possible. In general, the available numeric groundwater flows are designed for laminar flow conditions. There are attempts to combine the groundwater flow models with conduit-based turbulent flow modules [3, 4, 5] to simulate the karst system. Formulations for the conduit turbulent flows within a network of cylindrical pipes and for high conductivity turbulent flow layers are incorporated into well-known groundwater USGS groundwater model, MODFLOW 2005 [6], to simulate the conduit and preferential flow paths. However, this type of models are yet not able to predict the well yields, flow directions and velocities, due to all uncertainties in hydraulic, geometry and boundary definitions of the karst system.

Studies have revealed that even short term climatic changes affect the hydrological and chemical response of aquifers, including karst springs. This fact suggests that future climatic changes will increase the uncertainty of the models when and if they are to be used for karst groundwater management. Discussion of the pros and cons of different approaches in modeling is beyond the aim of this paper. Instead, a simplified approach is suggested herein this paper to classify karst aquifers toward adaptation of management strategies under climate change.

Therefore, any attempt to establish an effective management needs to be based on a sound conceptualization of the hydrogeological system. Hobbs and Smart [7] proposed a very important model to conceptualize a karst aquifer. They use three fundamental parameters, namely recharge, storage and flow, to describe the response of a carbonate rock aquifer. Classification of karst aquifers according to their morpho-hydrological characteristics can be regarded as the first step of conceptualization. Extension and thickness of karst formation, karstification base, mode of natural discharge, recession characteristics, regulation power coefficient, residence time, basin constant, and Fourier number or time constant of karst aquifer are among the major parameters to be used in classifying karst aquifers.

9.2 Distinctive Characteristics of Karst Aquifers

With their specific morpho-hydrology, karst terrains are distinct from non-karstic areas. Effective porosity is mostly tertiary in karstic terrains, which gives rise to high anisotropy and heterogeneity, distinctive characteristics of karst aquifers. Flow in a dissolutional (karstic) porosity media is likely rapid and turbulent, which, in most cases, prevents the application of Darcy's law to predict flow. Recharge may occur either as concentrated (not seen in granular aquifers) or dispersed, depending on the existence and type of surficial karst morphological features. Type of recharge is controlled by karst morphological features and development: concentrated where sinkholes and dolines dominate the area, diffuse where non karst features are predominant. On the other hand, storage may be only present in the saturated zone or also in the subcutaneous zone. To a great extent, the types of recharge and storage control the response of the karst aquifer to an input. This response is recorded in terms of variability degree in head (or flow rate) and in water quality. Temporal variations of head (or flow rate) and water chemistry are generally recorded as moderate or extreme in karst aquifers. The variability of water chemistry and the magnitude, timing and duration of response of springs and wells to storms is indicative of the hydrologic behavior of karst aquifers. In many real cases, springs are fed by a mixture of both types of flow [1, 9].

On the other hand, the size of the aquifer has a significant influence on this response. Large aquifers dampen the response [9]. Time of transmission depends on the size and hydraulic conductivity of the aquifer. Geologically, carbonate rock mass can be very thick. But it is the karstification (or erosion) base that controls the depth and thickness of the phreatic (saturated) zone. Three main types of erosion bases can be defined in karst terrains. The contemporary sea level is the main and the ultimate base of karstification. The lithological contact between karstifable carbonate rock mass and non-karstic unities above the contemporary sea level marks the ultimate base of karstification. A former base of karstification can be inundated by the eustatic rise of sea level or land subsidence due to epeirogenic movements, or, on the contrary, karstification base may rise as a consequence of decline of sea level or uplift of land due to epeirogenic movements. In mountainous areas, local base of karst may develop at some lower lands and topographical depressions such as river valleys or inland lakes. In areas where mechanic erosion is faster than karst development, deep valleys are incised and karstification base stands at a level higher than the bottom of the incised valley.

The knowledge of the type and position of the karstification base is important in developing projects to mitigate the adverse affects of climate change on karst groundwater resources. Most karst aquifers are naturally discharged by springs. Character of spring recession curve provides an indication of the type of spring flow. Worthington [10] has classified karst springs in relation to the recession curve. Flow characteristics of a spring can be used to have a preliminary assessment of vulnerability of karst aquifers against the impacts of climate changes. Residence time is another important parameter that might indicate the hydrologic behavior of karst aquifers. Karst aquifers with typical short residence times are generally classified as systems closer to surface waters. This conception stems from the fact that karst aquifers have a rapid flow component and in most cases the rapid flow component dominates the total flow.

9.3 Management of Karst Aquifers Under Climate Change: Sustainable Use of Un-sustained Resource

The consequences of climate change on water resources is due to the alteration of the seasonal distribution of precipitation, temperature increase and the change in evapotranspiration, as a result of the change on vegetation cover. All these changes affect the recharge regime of groundwater systems. Long-term droughts may result in storage reduction and in groundwater discharge to streams and other surface water bodies. Therefore, if the effects of the droughts are to be mitigated by the use of groundwater resources, it is essential to establish in advance an effective management plan. Karst aquifers are developed primarily by the use of springs and galleries, because in most cases the system is generally too complex to locate a proper borehole on the right place. There are several methods of spring development in karst aquifers. Springs are either captured or regulated for development. Practices of karst spring capture include installing pumps in dissolution channels below spring elevation. Horizontal galleries or large deep wells that reach a phreatic conduit are among the best methods. Numerous examples are documented in the literature [11, 12].

In contrast to capture water at the possible lowest elevation, management of karst aquifers under climate change should consider raising the discharge elevation by capturing the flush waters of floods and thus store more water for later use during the long-term droughts. However, the shorter the residence times the lower the possibility of availability of the flood water. This hydraulic behavior is reflected in a high recession coefficient and low regulation power. According to the conceptual scheme suggested by Hobbs and Smart [7], karst aquifers with point recharge, low storage and conduit type flow are considered to be hypersensitive to external factors. They behave like surface waters rather than groundwater systems. This is also true for upper sections of large karst rock masses where karst is better developed than the deeper parts. Shallow karst may either be the subcutaneous (epikarst) zone or the vadose and immediately underlying epiphreatic zone.

Under normal climatic conditions, the relatively small size, well karstified carbonate rock masses with shallow karst base are not considered as reliable aquifers in the sense of sustainable use. This is mainly because of the rapid transit time (short residence time) and the lack of a permanent and large volume of phreatic (saturated) zone. The carbonate rocks where karst morphology is well developed, usually having high recession coefficient, low regulation power, and where the flow is dominantly of conduit type, and the recharge is overwhelmingly point input type, are found in specific karst types. In northeastern Central Anatolian region, where evolutionary karst has been developed, dissected/relict karst is common. Rock masses of various sizes, from less than a kilometer to several tens of kilometers, with shallow karst base, occur in this region where people generally suffer of lack of adequate water. Similarly, karst in rock blocks of allocthonous carbonate units of various sizes is very well developed and the karstification base is generally marked by the underlying non-karstic units at shallow depths.

Because of the characteristics outlined above, these blocks are considered to be less reliable as a water supply source. Allocthonous carbonate rock masses are scattered at various regions of Turkey, but mostly at the southern and western parts. On the contrary, authocthonous carbonate units form high yield karst aquifers owing to their large size, large thickness, and deep karstification base, generally lower than the sea level. Thick phreatic zone provides a significantly large storage capacity and long residence times, making the aquifer reliable for water supply. Thick to very thick vadose zones are common in the recharge areas of these aquifers in the upland regions. Significant portion of the water stored in this type of aquifers are discharged through karst springs close or beneath the sea level. Therefore, it is hard to get groundwater at the highlands of the authocthonous carbonate rocks, except at mostly seasonal small springs of shallow circulation which are normally related to a local karstification base. These intermittent springs with high recession coefficient and low regulation power are regarded as unreliable for water supply.

Based on their hydraulic characteristics, these carbonate rock masses are extremely sensitive according to the conceptual scheme of Hobbs and Smart [7] when they are regarded as aquifers. With the expected adverse affects of the climate changes, their sustainability even worsen. However, it is possible to utilize these well developed karst systems to mitigate the adverse effect of seasonal precipitation distribution due to climate change. This can be achieved by elevating the discharge level of the aquifer, which will help to capture and store the flood waters for later use.

Construction of cutoff wall in front of the lowest discharge point (or zone) to raise the water level in the aquifer is one of the techniques that proved to be effective (Fig. 9.1). This technique can be applied for capturing flood waters coming rapidly from infiltration in dolines and sinking streams trough a well developed karst system inside the allocthonous carbonate rock mass. It is also efficient to tap the water of highland springs discharging at a local karstification base of a thick authocthonous carbonate rock aquifer.

Another technique is to construct a cutoff wall all around a relict karst block by for instance, shotcrete application (Fig. 9.2). Due to well developed karst, the specific yield of these aquifers is very high. So, a cutoff wall to raise the groundwater level only about 2–3 m is sufficient to capture a significant amount of flood water that otherwise would be discharged rapidly from the groundwater system.

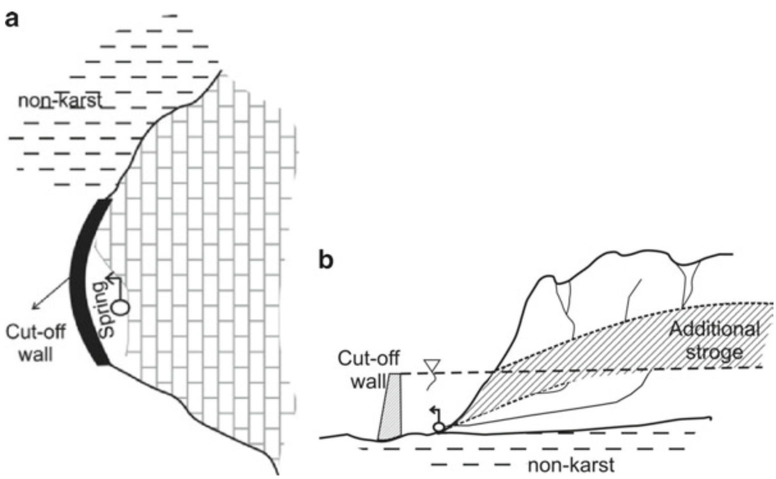

Fig. 9.1 Capture and storage of flood waters in well developed karst aquifers by cut-off walls. (**a**) Plan view, (**b**) cross-section. This method is suitable for allocthonous carbonate rock masses

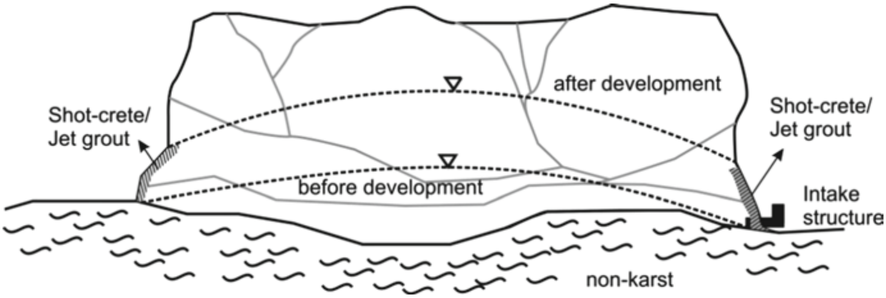

Fig. 9.2 Capture and storage of flood waters in dissected/relict karst aquifers by shotcrete application

This method of storing flood water in a karst aquifer is more advantageous than surface reservoirs, at least in decreasing the evaporation loss during long-term droughts.

The method has proved to be effective in karst aquifers of allocthonous carbonate rocks, as shown by a case study in Elmalı, Antalya, Turkey. The Kazanpınarı karst springs discharge along about 500 m with a total flow rate of about 2.3 m^3/s. The recession coefficient is calculated as 0.004 day^{-1}. These springs function as spills of the aquifer and full flow type of springs. Pumping tests in wells drilled in this aquifer revealed a transmissivity coefficient ranging between 500 and 20,300 m^2/day, a large interval indicating a very high heterogeneity.

The flow rate of the springs was measured and ranges between 0.2 and 5.7 m^3/s. The variation of flow is about 238% and highly variable according to Meinzer's variability index. The discharge level of the springs was first lowered and the increase in flow rate with time was recorded together with the decline in groundwater level in the aquifer. The storage coefficient (which is the specific yield in this case) was calculated for the aquifer using the relationship between the water level and the amount released from the aquifer. This was later used to compute the amount of water that can be stored by raising the water level in the aquifer by elevating the discharge level of the springs [8]. Construction of a cutoff wall in front of the spring zone caused a rise of about 2.5 m in the aquifer. This average rise in groundwater corresponds to an increase of about 5×10^6 m^3. This means that an amount of flood water can be stored in the aquifer by raising the discharge level of the springs. Moreover, a gate at lower elevation than the actual level of the springs can be constructed to regulate the flow rate.

Different from the Kazanpınarı karst springs which are a full flow type, the Kırkgöz karst springs are sort of overflow of the aquifer. They discharge at an elevation of 300 m above sea level at the edge of a large travertine plateau. The mean discharge is about 13 m^3/s, and the minimum and maximum rates are recorded as about 5 m^3/s and above 25 m^3/s respectively. The springs have a discharge variability of more than 200% according to Meinzer's index. The recession coefficient is around 0.0035 day^{-1}. The transmissivity of the aquifer is calculated to vary between 500 and 5,000 m^2/day. The specific yield of the karst aquifer is calculated from the observations of groundwater levels and the amount of water abstracted from the

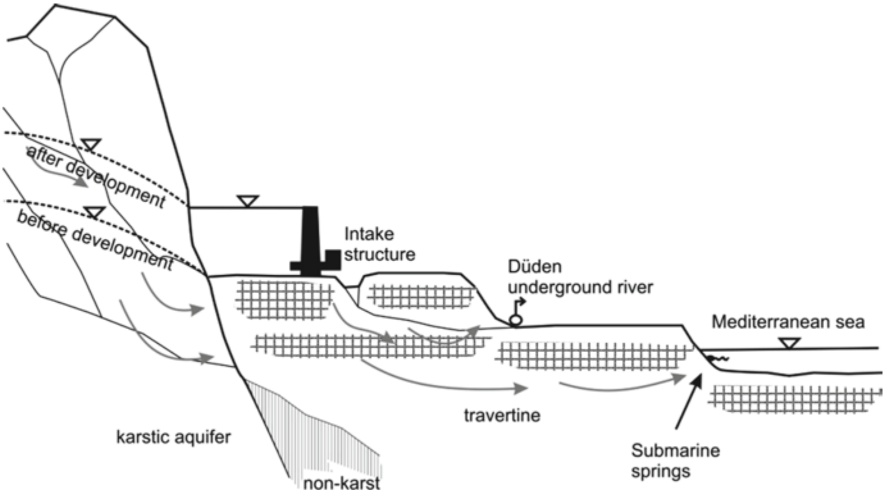

Fig. 9.3 Capture and storage of flood waters in the Kırkgoz karst aquifer

reservoir [13]. The spring water forms a large wetland in front of the orifices along a 1 km long zone. Naturally, the wetland water is discharged into a sinkhole through a small stream. A project to raise the water level in the wetland has been planned but not implemented yet. Hydraulic calculations have shown that about 2.5 m raise in groundwater level in the aquifer would allow extra storage of about 65×10^6 m^3 of water in the aquifer. However, because the karst base of the aquifer is far below the elevation of the springs, an increase of about 2.5 m head will also increase the discharge of springs at lower elevations in the travertine plateau, including the submarine springs (Fig. 9.3). It is most likely that further storage will be possible at the travertine aquifer which supplies drinking water to about one million of people in the Antalya city. Flush water during flood periods will be captured and stored in the aquifer for later use during long-term droughts.

In spite of its efficiency in terms of sustainable use of an un-sustained groundwater resource, the impact of this capturing flood water technique on the existing ecosystem should be studied prior to this practice becomes common.

9.4 Conclusions

The major aquifers in Turkey are installed in the carbonate rocks which cover more than 30% of the territory. The well karstified subcutaneous zone of these carbonate rocks have high permeability and large karstic openings such as caves and solution channels. The surface morphological features function as point recharge features which allow rapid inflow into the aquifers. Flow in these rock masses is dominantly of conduit type. Particularly in allocthonous carbonate rock masses, whose karstification bases are usually marked by non-karstic units or those of relict/dissected karst, the residence time is much shorter, which makes these rock masses "unreliable" for water sustainable use. In these systems the inflow is quickly discharged. Normally, these rock masses are not considered and developed as aquifers, which is due to the lack of a permanent phreatic (saturated) zone. However, these rock masses can provide an important storage media during flood periods which are followed by long-term droughts, an expected consequence of the climate change projections. Storage of flood water in surface storage structures such as dams has several disadvantages, including high loss by evaporation during dry periods. Well karstified rock masses which normally do not contain significant phreatic zone can be developed to capture and store the floods flush waters for later use. Construction of cutoff walls to elevate the discharge level (mostly springs) is proved to be an effective method in this regard. The type and design of the cutoff wall depends of the karst type developed in the rock mass. Based on the practices in Turkey, it is suggested that as a potential source of water, karst hydrogeological studies should be focused on well karstified carbonate rock masses with shallow karstification base which are not considered reliable aquifers so far, all this without ignoring the impact of this works in the dependent ecological systems. Climate change will alter the sustainability conditions of most water resources. Due to the consequences of climate change, most water resources will be "un-sustained". The methodology suggested herein is a contribution to the sustainable use of an un-sustained resource.

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Chapter 10
Impact of Climate Change on Hydropower Generation and Irrigation: A Case Study from Greece

Jacques Ganoulis and Charalampos Skoulikaris

Abstract Due to climate change, water availability for different uses such as domestic water supply, hydropower production and agricultural irrigation could be significantly reduced in the near future mainly in regions with arid and semi-arid climate. Precipitation data in the form of time series from different stations in South East Europe (SEE) as well as results from global atmospheric circulation models indicate that climate change will reduce water availability in this part of the Mediterranean. In this presentation the coupling of hydrological, hydraulic and climate change models is suggested in order to explore the impact of climate change on water resources at the river basin level. The methodology is illustrated for the Mesta/Nestos river basin, which is shared between Bulgaria and Greece. The case study is part of the worldwide UNESCO-HELP initiative.

Keywords Climate change • Hydropower • Irrigation • Mesta/Nestos River

10.1 Introduction

Recent studies on climate change and climate modelling indicate that there is at least a 90% probability that global warming is due to human activities and more specifically to gaseous emissions since the beginning of the industrial revolution in 1750 [1]. Data from various measurement stations around the globe show that gaseous emissions, such as carbon dioxide (CO_2) and methane (CH4), have constantly increased since 1850. CO_2 concentration in the atmosphere has increased more than 40% since pre-industrial times with an annual increase of about 80% between 1970 and 2003, and there is a trend for systematic increase [2]. Global warming is related

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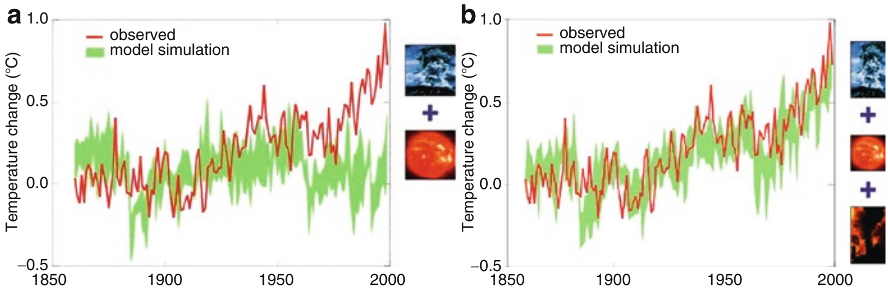

Fig. 10.1 Comparison between observed and simulated temperature change (**a**) without and (**b**) taking into account human gaseous emissions [2]

to the so-called greenhouse effect, in which high concentrations of gases in the atmosphere are responsible for the increase in air temperature in the troposphere.

Atmospheric temperature fluctuations are induced by variabilities and instabilities of different origin, such as air turbulence and density distribution. The following three causes are also responsible for these fluctuations:

- Temporal changes in solar energy
- Volcanic emissions of aerosols, and
- Gas emissions from anthropogenic activities, mainly from fossil-fuel burning.

As shown in Fig. 10.1, climate models are able to predict temperature increase after 1950 only if the man-induced gas emissions are taken into account. Climate change primarily and additionally man-made modifications in land use result in modifications of different components of the hydrological cycle, such as evapotranspiration and precipitation. This is already the case in arid or semi-arid climates like the Mediterranean, where data time series recordings have shown a decreasing trend in precipitation over the last few decades.

10.2 Climate Model Downscaling

Climate models simulate global atmospheric circulation by use of mathematical equations expressing the mass, momentum and energy balance governing the atmosphere and the circulation behaviour of the oceans. These models are derived from the latest advances in fluid dynamics and thermodynamics taking into account chemical interactions. However, these non-linear partial differential equations can only be solved using approximate numerical solutions. These solutions are very sensitive to the correct setting of initial and boundary conditions.

The assessment of possible effects of climate change on river hydrology has been conducted using results from two GCMs both developed by the Max Planck Institute for Meteorology in Hamburg: the ECHAM4/OPYC3 and the ECHAM5/MPIOM coupled models.

10.2.1 The Climate Local Model (CLM)

CLM, which stands for Climate version of the “Local Model”, is a non hydrostatic European regional climate model, which can be used for simulations on time scales up to centuries and spatial resolutions between 1 and 50 km [3]. The boundary conditions of the CLM are provided by the simulation results of the coupled atmosphere-ocean global climate model ECHAM5/MPIOM [4] at six hourly intervals. This coupling results in a physical dynamical downscaling, where the Global Circulation Model (GCM) output data are used as boundary conditions (idem, “forcing”) to dedicated Regional Climate Models (RCM) [5]. The CLM regional climate model covers the west European region including the Baltic Sea and the greater part of the Mediterranean Sea.

For the European region two simulation datasets were produced to investigate IPCC scenarios: one covers the past climate, i.e. from 1960 to 2000, and the other covers predictions until 2100. The climate of the twentieth century was simulated by three twentieth century realisation runs, which are all based on the same control run, but set off at different initialisation times. The climate of the twenty-first century was modelled based on the A1B and B1 IPCC climate scenarios, and five more transient experiments are planned, since the generation of results is still in progress.

For predictive studies, the main difficulties in using climate models at local level lie in the transfer of spatial scale, also known as “downscaling”. Ad hoc downscaling statistical regression methods were developed for the transfer of CLM data to the hydrology model grid (Fig. 10.2).

10.2.2 The MODCOU Hydrological Model

The hydrological model MODCOU (MODélisation COUplée in French) is able to simulate the spatial and temporal relationship between precipitation and the evolution of the water table and river flows. It is a physically based distributed hydrological model developed by the Centre d’Informatique Géologique of the Ecole Nationale Supérieure des Mines de Paris to simulate surface-groundwater interactions [6]. It was applied at different spatial scales (river watersheds from a few to hundreds of thousands of square kilometres) located mainly in France but also elsewhere. It has been used with satisfactory results for the study of the Seine river basin, Paris region [7], the Aquitaine basin [8] and the Rhone river catchment [9].

In the MODCOU model, the water budget is computed for each grid box over a two-dimensional grid. The main components of the hydrological cycle are taken into account by using the so-called ‘production functions’, which refer to a system made of four reservoirs, including seven parameters which have to be calibrated [10].

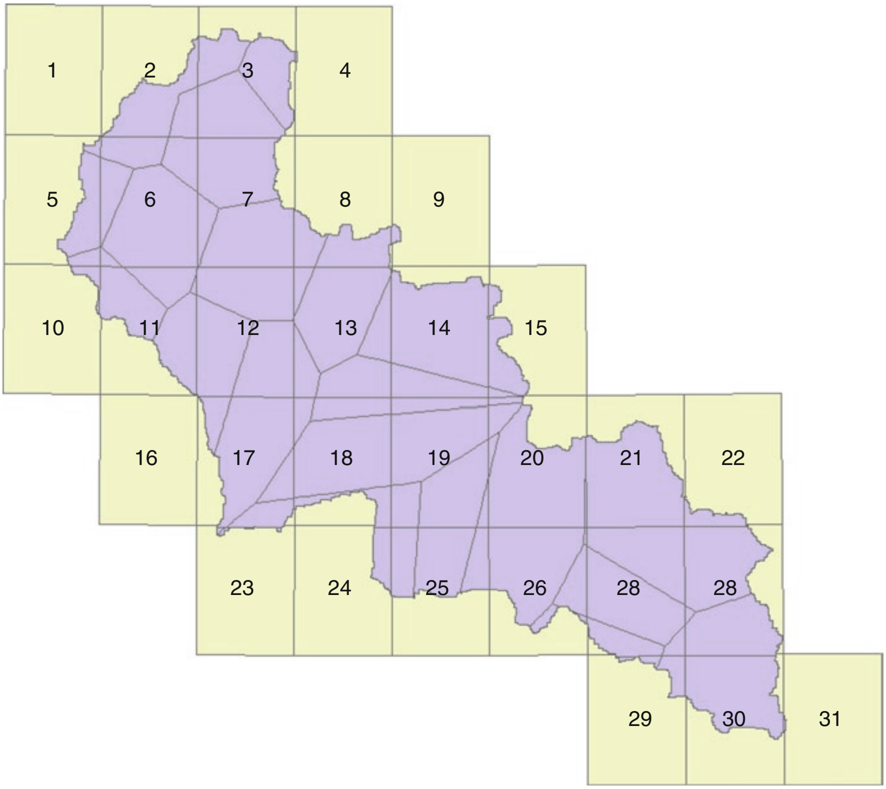

Fig. 10.2 Downscaling from the CLM (20×20 km) to the hydrological grid

10.3 Emission Scenarios

Since its creation, IPCC has regularly prepared assessment reports on available scientific information on climate change and has proposed possible response strategies. The First IPCC Assessment Report (FAR) was presented in 1990 and was devoted to creating an inventory of climate change. The Second Assessment Report (SAR) was presented in 1995 and coupled with the initial Special Report on future Emissions Scenarios (SRES). The future emission scenarios, also known as IS92, were subsequently used in climate simulation models in order to quantitatively assess their impacts. A follow-up Third Assessment Report (TAR) was presented in 2001 and the updated version of the SRES scenarios of the TAR was definitively adopted in the Fourth Assessment Report (AR4), which was presented in 2007.

The global CO2 emissions for the six SRES scenarios, A1B, A2, B1 and B2, A1FI and A1T are presented in Fig. 10.3. The IS92a scenario derived from the Second Assessment Report (SAR) is also presented. Obviously, the most optimistic scenarios are A1T and B1, where clean energy technologies are developed. At the

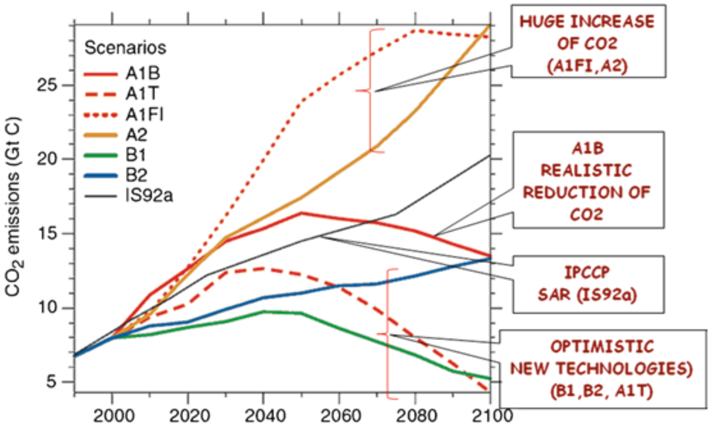

Fig. 10.3 Different scenarios of CO_2 emissions

other extreme, the scenarios A1FI and A2 demonstrate a huge increase in CO2 emissions, since economic development is not coupled with environmentally friendly policies and technologies.

10.4 The Case Study

The Mesta/Nestos transboundary river catchment, shared between Bulgaria and Greece is part of the UNESCO/HELP network of basins, for the following reasons: (1) it combines internationally shared surface and ground waters, (2) there are serious issues of environmental concern in the upper basin and the delta region, and (3) competing water uses have been increasing from the time when Greece built a series of hydro-electrical plants and Bulgaria entered a market economy and embarked on a struggle for a rapid economic growth.

The main geographical and hydrological characteristics of the basin may be summarised as follows (Fig. 10.4):

Area of river basin: 6.280 km^2 (46% located in Greece)
Length of river: 230 km
Altitude range: 0–2.925 m (Rila and Pirin mountains in Bulgaria)
Average annual rainfall: 700 mm
Average flow rate: 20–30 m^3/s

10.4.1 Hydropower Generation

Two major hydropower plants (Thissavros and Platanovrissi) were constructed in the Greek part of the Nestos river basin and their characteristics are shown in Fig. 10.5. A third dam (Temenos) is under consideration (Fig. 10.5).

Fig. 10.4 Geographical location and local characteristics of the Mesta/Nestos river basin

One of the main uses of these dams is the exploitation of hydropower. Since the fuel of a hydro-power plant is water, the management of its water resources is essential for the optimisation of the plant's operation in order to meet power and water demands while increasing overall operating efficiency [11]. Hydropower exploitation has many beneficial characteristics mainly because it is renewable and can quickly satisfy peak demands for energy [12]. The dams also store water for the irrigation of agricultural land located at the river's delta.

10.4.2 Irrigation Needs

In order to have a complete view of the current agricultural production in the Nestos delta region, agricultural survey data aggregated by municipality were obtained from the National Statistic Service of Greece for the years 1999–2003. The collected data were stored in the ArcGIS project database and contain the aggregated field areas by town district for the ten main products of the region: soft wheat, durum (hard) wheat, sugar beet, cotton, rice, barley, maize, asparagus, alfalfa and tobacco. These production statistics show a distinct difference in crops and farmer revenues between the irrigated areas on the right (west) bank of the Nestos and the non-irrigated areas on the left (east) bank around the town of Xanthi (Fig. 10.6).

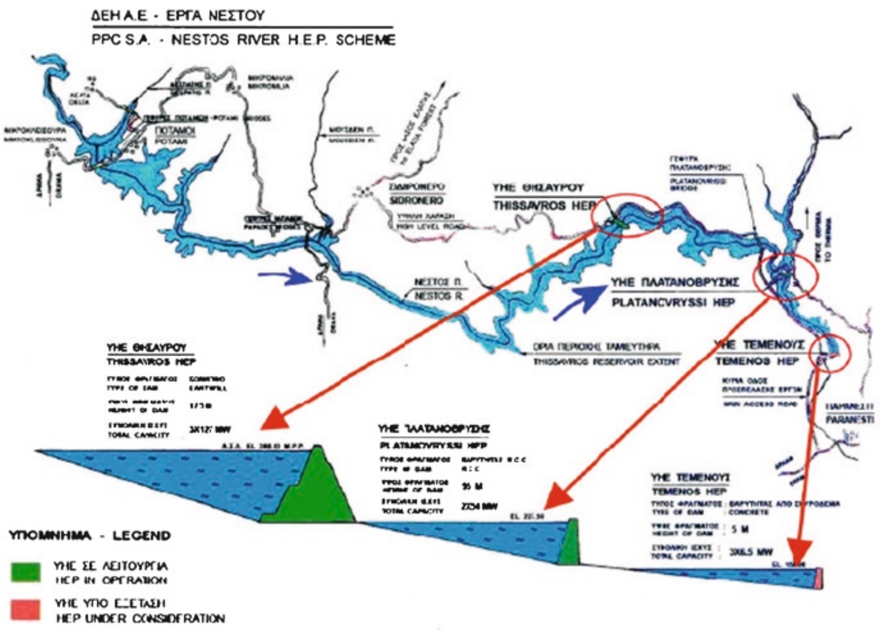

Fig. 10.5 Dams and hydroelectric power plants in the Greek part of the Mesta/Nestos river basin

Fig. 10.6 Irrigation networks at the Nestos river delta

Evaluation of the income increase between irrigated and dry agriculture has been conducted using the agro-economic model produced by the Common Agricultural Policy for Regional Impact, also known as CAPRI model [13]. The model was used in order to determine the average income from the two types of farms for three EU Common Agriculture Policy (CAP) scenarios: the reference conditions of 2001, the Agenda 2000 and the Mid-Term Review (MTR) 2003 measures.

The benefits of the Temenos project were evaluated using an expected average income increase (idem, marginal benefit) of 950 Euros/ha (in Euro value of year 2001) if farms are irrigated. This figure is used in order to evaluate the "Lost Crop" term for periods when the Temenos irrigation system is unable to satisfy the irrigation needs of the farmers in the Xanthi area.

10.4.3 Impacts of Climate Change

Figure 10.7 presents a comparison between the flow computed upstream of the Thissavros dam on the Nestos River for the IPCC A1B climate scenario and a reference flow series under prolonging climate conditions of the past 25 years. It is worth noting that this reference series contains similar dry spells to the ones experienced in the area in the early 1990s. This climate stability hypothesis is also sometimes referred to as "business as usual" or "baseline scenario" in the EU WFD nomenclature. Compared to climate conditions in the recent past, the A1B scenario clearly predicts a flow decrease.

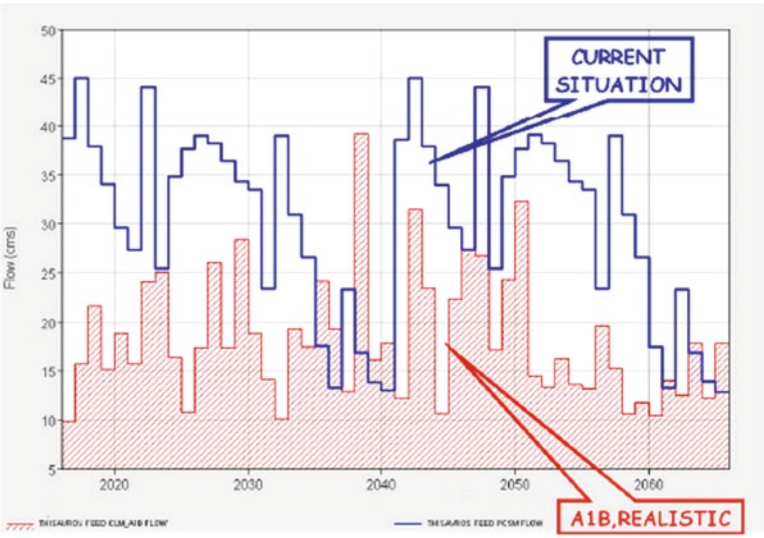

Fig. 10.7 Average year river flow simulated for the IPCC A1B case and a prolongation of past climate conditions (baseline scenario, current situation)

10.5 Conclusions

Future temperature, precipitation and evapotranspiration characteristics were estimated for the next 50 years using the CLM regional climate model developed by the Max Planck Institute for Meteorology, Germany. The results obtained from the climate simulation model were introduced into the hydrological model in order to simulate the future time series of yearly average flows upstream from the two large dams of Thissavros and Platanivrissi, located on the Greek territory. The results show a net decrease of river annual flows, which means difficulties in ensuring hydro-electrical production and irrigation needs in the Nestos river delta region.

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Chapter 11
Analysis of Climate Change Effects on Floods Frequency Through a Continuous Hydrological Modelling

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Abstract The relationship between climate change and floods frequency is of great interest for addressing the complex analysis on the hydrologic cycle evolution. In this context, this study aims to assess, by a preliminary investigation, the climate change effects on the floods frequency in several basins of the upper Tiber River, whose area is ranging from 100 to 300 km^2. For that, a continuous hydrological model coupled with a stochastic generation of rainfall and temperature has been used. Therefore, a long synthetic series of discharge were generated from which the annual maximum discharges were extracted and, hence, the flood frequency curves were defined. For the stochastic generation of precipitation, the Neyman-Scott Rectangular Pulse model was used, while for the synthetic generation of temperature, an ARIMA model with fractional differentiation was applied. The time series of discharge was assessed by applying a continuous hydrological model developed ad hoc for the investigated basins. The model structure was inferred by investigating the effects of antecedent wetness conditions on the outlet response of several experimental basins located in Central Italy. The analysis proposed here compares the actual time series of precipitation and temperature and the perturbed ones by assuming two different future scenarios obtained by the Global Circulation Model HadCM3. Results showed that geo-morphological and land-use characteristics of basins might have a paramount role in the changing of floods frequency.

Keywords Climate change • Floods frequency • Continuous hydrological modelling

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11.1 Introduction

The climate change is a process strongly affecting the water resources management as well as the flood frequency of the extreme events. Indeed, the improving of the flooding forecast is strongly felt in Europe. The European Directive 2000/60/CE is the reference framework for the water resources management which is also considering the hydraulic risk. However, although there is struggle in finalizing rules for the defence of the territory, the floods frequency across the Europe is drastically increased. The phenomenon is quite complex because many interacting variables are involved such as climate change, hydro-geological structure of the territory, land use, education of the population to understand the risk. It is well known that the climate change may affect the hydrological cycle and, hence, the flood frequency. For studying the phenomenon, probable scenarios can be inferred by an integrated use of Global Circulation Models (GCMs) which provide, at worldwide scale, indications on future climate change and hydrological models that, once these indications are downscaled, incorporate them into the hydrological cycle of basins [1, 2]. In this context, this work attempts to assess the effect of the climate change on the flood frequency by using a continuous hydrological model coupled with a stochastic generation of rainfall and temperature. Scenarios based on forecasts of the GCM-HadCM3 models for temperature and rainfall is used for perturbing time series. Information provided by HadCM3 is only considered here to address the proposed procedure. Four sub-catchments located in the Upper Tiber basin, Central Italy, are considered as case study.

11.2 Methodology

The analysis is based on the application of a continuous hydrological model coupled with stochastic generation models of rainfall and temperature at hourly scale. Such a coupling permits to achieve long synthetic series of discharge through which, by extracting the maximum annual flow, the flood frequency of extreme events can be obtained. Then, by considering hypothetical future scenarios of temperature and rainfall predicted by the GCM-HadCM3 of Hadley Centre (http://www.ipcc-data.org/sres/hadcm3_download.html), the previous stochastic series can be perturbed and a comparison on the flood frequency curves can be addressed.

In particular, for the stochastic rainfall and temperature generation, the Neyman-Scott Rectangular Pulses (NSRP, [3]) and the Fractionally Differenced ARIMA models were used (FARIMA, [4]), respectively. These synthetic time series were used as input data of a continuous rainfall-runoff model (named MISDc, [5]) that finally allowed determining of the synthetic discharge time series.

The NSRP model is characterized by a flexible structure in which the model parameters broadly relate to underlying physical features observed in rainfall fields. The model has a total of five parameters, estimated through six sampling statistics computed from the observed data (for each month taking the rainfall seasonality into account): hourly mean, hourly and 24 h variances, lag-one autocorrelation of the daily data, and hourly and 24 h skewness. The estimation procedure of such model parameters can be carried out by minimizing an objective function evaluated as a weighted sum of normalised residuals between the statistical properties of the observed time series and their theoretical expression derived from the model. As shown by previous studies [6], the main feature of the model is its ability to preserve statistical properties of a rainfall time series over a range of time scales. Full details of the NSRP may be found in Cowpertwait et al. [3].

The FARIMA model, unlike classical ARIMA models that are powerful tool for modelling stationary time series, is able to fit the autocorrelation function which is characterized by a slow decay suggesting the presence of long-term persistence. This dependence was detected in many time series of hydrological data and, very often, in the air temperature series [7]. The procedure for the implementation of the FARIMA model is not straightforward, particularly in the identification phase for the preliminary evaluation of model parameters. The method employed in this study is the one suggested by Montanari et al. [4].

Finally, MISDc is a continuous rainfall-runoff model developed for the simulation of flood events in the Upper Tiber River basin at sub-hourly time scale. The model consists of two components: the first is a soil water balance model that simulates the soil moisture temporal pattern and sets the initial conditions for the second component which is an event-based rainfall-runoff model for flood hydrograph simulation. The two models are coupled through a simple linear relationship that was derived from an intense monitoring activity of soil moisture and runoff over experimental catchments located in the region [2]. The model incorporates a limited number of parameters and it is characterized by low computational efforts which make it very attractive for the hydrological practice. For that the MISDc model is an appropriate tool to be used for the generation of long discharge time series at hourly (or less) time scale (e.g. 1,000 or more years). For a detailed description of the model the reader is referred to Brocca et al. [5].

11.3 Case Study

The analysis is addressed to four sub-catchments of the Upper Tiber River basin. The basin is located in Central Italy and its topography varies from 200 m above sea level in the south and 1,080 m in the east. The region is characterized by a Mediterranean semi-humid climate with precipitations occurring mostly in the autumn-spring period. Based on the period 1951–1999, the average annual precipitation is about 890 mm. The maximum mean monthly precipitation occurs in November (130 mm) and the minimum in July (40 mm). The minimum and maximum temperature are, on average, 16.9°C and 26.7°C in summer, respectively and 3.2°C and 9.7°C in the winter, respectively. The four sub-catchments, Niccone (137 km^2), Caina(206 km^2), Genna (91 km^2) and Cerfone (284 km^2), are shown in Fig. 11.1a.

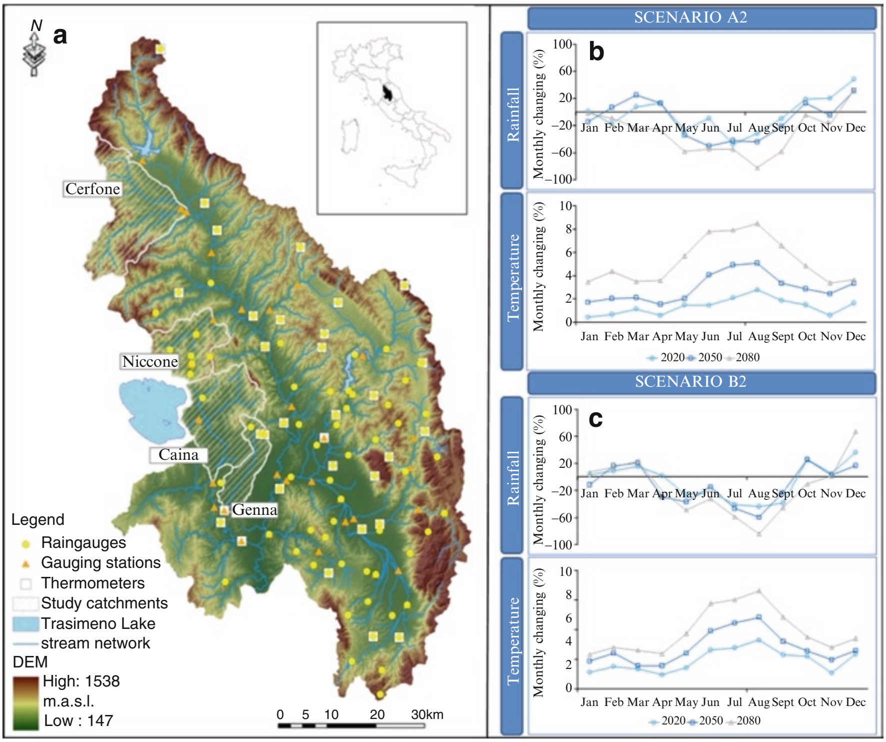

Fig. 11.1 (**a**) Morphology of the Upper Tiber River Basin and location of the hydro-meteorological monitoring network. The *shaded regions* refer to the four catchments selected for this study. (**b**, **c**) Monthly changing of rainfall and temperature derived by the emission scenarios A2 and B2, provided by GCM-HadCM3 models for Central Italy

The methodology has been applied considering both the actual climate conditions such us defined by time series of rainfall and temperature observed in the period 1989–2007 and the ones derived by the emission scenarios A2 and B2 provided by GCM-HadCM3 models of Hadley Centre (UK) and underlined in the "Special Report on Emission Scenarios" (SRES). These two scenarios are of reference for two opposite hypothesis of social development [9, 10]. In particular, the analysis has been addressed considering the scenarios for rainfall and temperature at 2020, 2050, 2080 that are representative of the average monthly changing at short term (2010–2039), medium term (2040–2069) and long term (2070–2099), respectively. Based on A2 and B2 scenarios, for the central Italy, it is expected that in 2080 the total annual rainfall decrease of –0.5 mm/day and 0.14 mm/day, respectively, while the mean annual temperature increase 5.3°C and 3.9°C for A2 and B2 scenario, respectively (see Fig. 11.1b, c). The rainfall, overall, tends to decrease in the summer for all scenarios; whereas in October and April the rainfall fluctuations go from –30% to 50%, for both the scenarios. These monthly changes were applied to time series observed in the four sub-catchments of Upper Tiber basin to obtain perturbed series of temperature and rainfall. In this way, three perturbed series of temperature and rainfall were generated, each one representative for the period 2020, 2050 and 2080.

11.4 Results and Discussion

The estimation of the optimal parameter set for the stochastic rainfall model, NSRP, was first conducted. Then, the NSRP model was used to simulate ten rainfall realizations, each one 100 years long. More simulation runs were considered to take account the uncertainty in the rainfall series linked to the stochastic nature of the model. The capability in preserving the statistical properties of rainfall time series and the good agreement between the Depth-Duration-Frequency (DDF) curves extracted from observed and synthetic rainfall record demonstrated the goodness of the model in reproducing the observed data (not shown here for sake of brevity).

Following the calibration procedure proposed by Montanari et al. [4], the FARIMA model was implemented for generating ten temperature series, each one 100 years long. The obtained series of rainfall and temperature were employed as input for discharge computation through the MISDc, previously calibrated on a number of significant observed flood events. For instance, Fig. 11.2 shows the comparison between observed and simulated discharge through MISDc for the three most significant flood events occurred for the Niccone and Genna catchments. As it can be seen, a fairly good agreement was detected.

Finally, once the ten discharge time series were obtained by MISDc, the maximum annual discharge was extracted, thus having ten flood frequency curves. The mean flood frequency curve was then used as reference for the two scenarios A2 and B2. Then, for each scenario, such flood frequency curve was compared with the one inferred by the actual observations. The comparison was first based on the changing of temperature and then adding also the rainfall. The results showed that the effects of the only temperature change on flood frequency were less evident than the ones obtained by perturbing both rainfall and temperature time series (see also Table 11.1). Through the comparison of two scenarios (see Table 11.1), it is evident that A2 was more critical for the short term (2020) with an increase of the maximum discharge up to 78%; whereas for the long term (2080) the differences in magnitude were not exceeding 15% for all sub-catchments, except for the Caina, for which (see Table 11.1) the discharge reduction drops below 30%. On the contrary, for the scenario B2, the forecast at 2080 was such that the change in maximum discharge was much higher than the other ones. It is worth noting that, for the two neighbouring catchments, Genna and Caina, which are characterized by similar rainfall regimes, the climate change effects on flood frequency were different, as shown in Fig. 11.3.

In particular, for the Genna catchment, the forecast based on the scenario A2 was characterized by a high increase of discharge at short term which tends to dampen

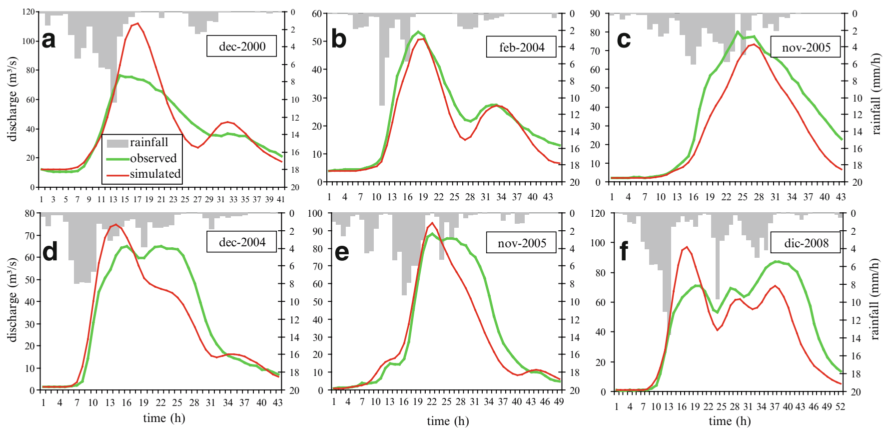

Fig. 11.2 Comparison between observed and simulated discharge through the MISDc model for several flood event occurred in the study period for: (**a**–**c**) Niccone, and (**d**–**f**) Genna catchment

Table 11.1 Percentage differences, for different return periods, between the peak discharges estimated considering the emission scenarios A2 and B2 and the ones inferred by the actual observations

Forecasting period	Scenario A2			Scenario B2			Scenario A2			Scenario B2		
	Return period (years)						Return period (years)					
	20	50	100	20	50	100	20	50	100	20	50	100
	Caina catchment						Genna catchment					
2020	26	24	31	3	2	6	78	63	40	40	39	39
2050	−12	−12	−12	−15	−13	−11	33	15	−4	28	24	12
2080	−31	−31	−26	28	23	23	12	−3	−15	54	43	21
	Cerfone catchment						Niccone catchment					
2020	34	37	35	22	31	29	56	57	53	34	38	38
2050	9	14	24	4	11	9	37	39	28	7	14	22
2080	8	14	12	30	29	25	1	8	8	66	69	57

at long periods. For the Caina catchment, the increase of maximum discharges at short term was much more limited than that of Genna catchment; whereas for the other two periods a decrease is estimated. These differences might be due to different permeability of two sub-catchments which is greater for the Caina catchment. Therefore the geomorphological and land use characteristics might have a fundamental role in the impact of climate change. This aspect is important also for the consequence of climate change in terms of territorial forward planning.

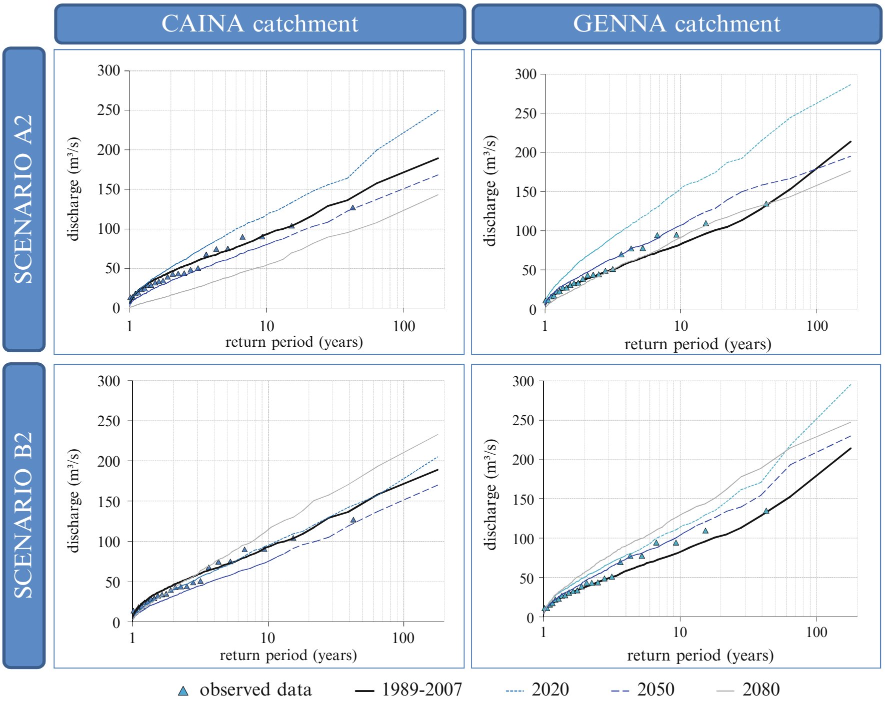

Fig. 11.3 Flood frequency curves: comparison between the observed and the simulated peak discharge inferred by the actual observations (1989–2007) and for the emission scenarios A2 and B2 with different forecasting periods (2020, 2050, 2080)

11.5 Conclusions

The proposed procedure for analysing climate change effects on the hydrological cycle turned out quite useful for assessing how much the floods frequency can be affected. Based on the HadCM3 model, the analysis in four sub-catchments located in Central Italy showed that the geo-morphological and land-use characteristics of basins might have a non trivial role in changing floods frequency. Further investigations based on disaggregated data of the GCMs are necessary to support these finding.

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Chapter 12
Potential Impacts of Climate Change on Turkish Water Resources: A Review

Koray K. Yilmaz and Hasan Yazicigil

Abstract Water resources are mainly controlled by the climate conditions. Global warming will therefore have evolving impacts on water resources and poses important challenges for sustainable development. Studies are rapidly emerging with focus on potential implications of climate change on Turkish water resources. These studies can be grouped into two major fields: (1) Studies investigating the degree of climate change reflected in the past observed hydro-meteorological records, and (2) studies investigating potential future impacts of climate change on water resources. In this paper, we present a summary of the current knowledge in the area of climate change impacts on Turkish water resources with emphasis on the two major fields listed above. Overall conclusion of the review is that climate change will put additional pressure on already stressed water resources in Turkey. The credibility of water management scenarios – whether focused on maintaining ecosystems or on food and energy security – largely depends on improved consideration of plausible climate change scenarios, and their potential uncertainties, in decision making.

Keywords Climate change • Water resources • Turkey • Observed trends • Prediction • Global circulation models

12.1 Introduction

Natural and anthropogenic change in climate conditions will have evolving impacts on water resources. The Reports of the Intergovernmental Panel on Climate Change (IPCC) are increasingly making more definitive statements about the role of

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anthropogenic forcing in climate change: "Most of the observed increase in global average temperatures since the mid-twentieth century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations" [1]. Human activities – primarily the combustion of fossil fuels and clearing of forests – have greatly boosted the concentrations of greenhouse gases (GHG). Because many GHGs stay in the atmosphere for more than a century, warming is expected to continue during the twenty-second century, even if emissions are stabilized soon.

Most of the damaging consequences of global warming are associated with water cycle, including changes in amount/pattern of precipitation, evapotranspiration, runoff and groundwater recharge, melting of snow/ice, intensification of extreme events (floods, droughts) and rise in sea levels. These changes will have a diverse impact on ecosystem functioning and will unfold much vulnerability to the society in health, food, energy and settlement sectors.

In a warming environment the already hot and semi-arid climate of southern Europe is expected to become warmer with less rainfall, prolonged dry spells and increased evaporation, thus increasing the frequency of droughts [2]. Therefore, Turkey, already approaching physical water scarcity, is highly vulnerable to climatic change. This situation is further exacerbated by rapidly increasing population. In this paper we present a summary of the current knowledge in the area of climate change impacts on Turkish water resources with emphasis on past and predicted future trends in hydro-meteorological variables.

12.2 Observed Patterns/Trends

In this section we present a review of the studies, to date, on historical trends of atmospheric (temperature, precipitation) and hydrologic (streamflow and groundwater level) data in Turkey.

12.2.1 Atmospheric Variables

12.2.1.1 Temperature

Temperature controls evapotranspiration and snow/ice melt processes and has a strong affect on the amount and seasonal distribution of soil moisture and runoff. According to the recent IPCC report global average temperature records show significant warming trends between 1910–1940 and 1960s-recent, which is more significant over the last 50 years [1].

Many researchers analyzed a large number of station records scattered over Turkey to detect overall trends and regional/seasonal characteristics in observed temperature. The review of the studies broadly reveal two distinct periods with opposite behavior: an earlier cooling trend which extends from 1960s to early

1990s and a more recent warming trend which extends from early 1990s to the present day [3–10].

Apart from this overall warming trend, there exist, however, regional and seasonal differences in temperature variations over Turkey. Geographically, this warming trend was found to be more significant in western [11, 12], southern [6, 8, 11] and southeastern [7, 8] regions. Conversely, general cooling trends have been found to prevail in Black Sea Region [6, 11, 12] and Central Anatolia [12]. An exception to this trend was the study of Tecer and Cerit [13] which reported warming trend for Rize station located in eastern Black Sea Region after 1994. A prominent feature in seasonal temperature changes is the widespread and consistent increase in summer temperatures [6, 8, 11, 12] followed by an increase in the number of summer days [5]. For winter season consistent change in temperature records have not been detected. Another pronounced characteristic in temperature time series is the increasing trend in minimum temperatures [4–8, 11] and night-time temperatures [12] which are generally attributed to the urbanization [6–8, 11, 12, 14].

Of course, in addition to the anthropogenic effects, natural weather patterns control temperature changes. Recently, Turkes and Erlat [15] found close associations between the North Atlantic Oscillation (NAO) indices and temperature signals over Turkey. Thus it can be concluded that the temperature patterns/trends prevailing over Turkey is the result of both natural and human-induced forcing on climate. Their relative importance and the extent of anthropogenic influences on natural weather patterns are yet to be understood.

12.2.1.2 Precipitation

Precipitation is the main driver of the hydrologic system over land. Therefore any change in the intensity, frequency and duration of precipitation will have a direct impact on water resources.

Recent climatic studies showed a decreasing precipitation trend in most of the Eastern Mediterranean [16]. The studies that focus on long-term changes in Turkish precipitation generally agree with this decreasing trend [17–19], but regional and seasonal differences exist. Many studies reported general decreasing precipitation trend over western [6, 11, 17, 19, 20] and southern [17–19] parts of Turkey that are dominated by the Mediterranean climate. Some researchers also indicated a decreasing precipitation trend in the southeastern [6, 19] and northwestern [21] parts which are partly influenced by the Mediterranean climate. In contrast, in northern regions and northern parts of Central Anatolia increasing precipitation trend has been reported [6, 11, 17]. In terms of seasonal changes, a decrease in winter precipitation over Turkey [6, 18, 19, 22] has been reported which is more dominant in the western and southwestern parts [11, 19]. The winter precipitation is especially important for Tigris–Euphrates (TE) River flows which are mainly fed by snow melt. A decrease in the amount of snow and an increase in temperature will likely have negative consequences for energy and irrigation projects along the TE river system, in addition to the potential conflicts with the downstream countries.

In spring and fall, an increase in precipitation has been generally reported throughout the country [6, 19]. In the northwest (European) part of Turkey, no coherent behavior in long term precipitation trends have been reported. Focusing on the European part, Aksoy et al. [22] reported insignificant trends at seasonal scale: a decreasing trend in winter and an increasing trend in fall.

Many researchers investigated the link between precipitation trends and weather patterns, e.g NAO. Karabörk et al. [23] showed that precipitation and streamflow in winter have significant negative correlations with the NAO Index. Recent consistently more positive phase of the NAO could, to some extent, explain the decreasing trends in precipitation in western parts of Turkey. It is not yet clear whether the global warming is altering NAO and other natural weather patterns.

12.2.2 Hydrologic Variables

12.2.2.1 Streamflow

Streamflow represents the integrated response of a watershed to precipitation and evapotranspiration (partly driven by temperature) processes after being filtered by watershed physical characteristics and, in some cases, human-induced factors. Due to this close link between global warming and streamflow response of a watershed, several studies focused on possible trends in Turkish streamflow records.

The regional patterns emerging from these studies are in general parallel to the trends in atmospheric variables. Most consistent pattern is the decreasing behavior in streamflow in western parts (Marmara and Aegean) [5, 11, 20, 22, 24–28]. Similar behavior has also been reported for Central Anatolia and southern parts [24, 27, 28]. In other regions of Turkey no consistent trend has been reported, except a few stations with increasing streamflow trend in the north [11, 28].

The trans-boundary Tigris-Euphrates (TE) River system located in eastern Turkey is fed by seasonal snowmelt and is critical for a series of socio-economic development projects in irrigation and energy production sectors. Few studies [5, 33] have reported significant decrease in low flow conditions for many stations in eastern Turkey. In the Upper Euphrates basin, insignificant decreasing trend in annual average runoff and slight earlier melting of snow for the period 1994–2004 was detected [10]. Snow data could provide further insight into the streamflow potential of the TE system. For example, Sürer et al. [30] investigated the snow cover variation in Karasu basin during 2000–2009 using remote sensing (MODIS). Although no apparent change in snow cover was detected, the runoff significantly decreased during 2008–2009. One possible explanation is the reduction in snow water equivalent due to the decrease in the amount of precipitation over the years.

12.2.2.2 Groundwater

Relative to surface water resources, the potential consequences of climate change on groundwater have not received as much attention. Groundwater reacts to climate change due mainly to changes in recharge characteristics. Considering that the precipitation and runoff exhibit decreasing trends over many regions in Turkey, it is likely that groundwater levels in these regions will reveal decreasing behavior, perhaps generally with a time-lag. This situation will be further intensified due to increasing water demand. Negative consequences include: decrease in recharge and hence in groundwater levels, deterioration in water quality due to increased demand, sea water intrusion along coastal aquifers and salinization due to increased evapotranspiration.

The trend studies on precipitation, temperature and streamflow time-series mostly agree that basins located in western Turkey are highly vulnerable to impacts of climate change. The groundwater vulnerabilities in this region could be revealed by an investigation of the atmospheric, hydrologic and water use data for the Kucuk Menderes River basin [31]. Groundwater is the dominant source of agriculture in the basin. Temporal variations in precipitation (Odemis station), streamflow (Selcuk station) and baseflow in the basin are shown in Fig. 12.1. The figure shows that streamflow (and baseflow) fluctuates in response to general trends in precipitation. Now focusing on the groundwater system, Fig. 12.2 shows the temporal variations in water-table depth in an observation well near Torbali and average yields and depths of the registered private wells in the basin. Comparison of Figs. 12.1 and 12.2 reveals a close link between time variation in streamflow and water table depths due to changes in recharge conditions. Another factor responsible for declining water table is the significant increase in groundwater pumping. It is estimated that over-utilization of groundwater resources initiated in the early 1980s [31].

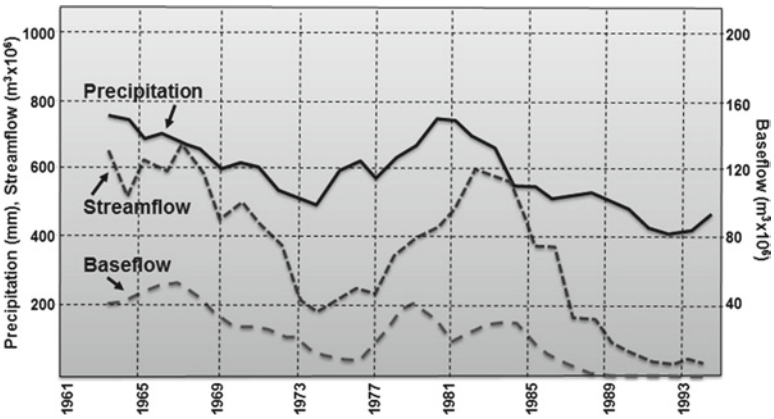

Fig. 12.1 Temporal variations in precipitation, streamflow and baseflow in the Kucuk Menderes River basin, Western Turkey. Precipitation data is from Odemis meteorological station and streamflow data is from K. Menderes River Selcuk station (Modified from Yilmaz [31])

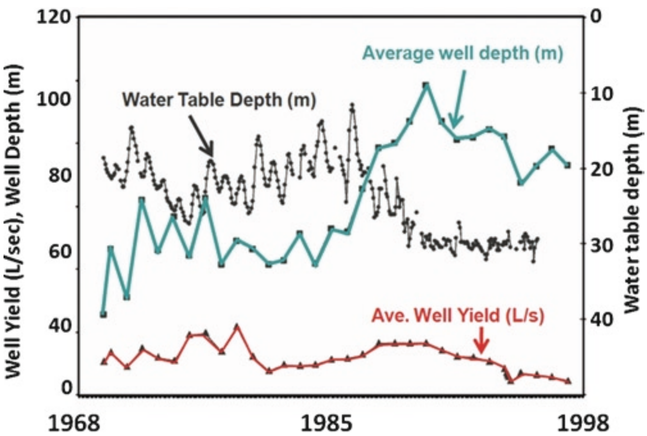

Fig. 12.2 Temporal variations in water table depth, average well yields and depths of private wells. Water table data is from an observation well near Torbali (Modified from Yilmaz [31])

It can be seen from Fig. 12.2 that, drastic increase in water table-depth initiated in the early 1980s making deeper wells necessary. More importantly, the average well-yields declined in response to increase in well-depths. It is expected that, with global warming, climate will become drier; the water tables will continue to drop in response to both decrease in recharge (reduced surface water) and increase in dependence on groundwater. Together with the predicted rise in sea levels, already existing sea water intrusion problem [32] will be exacerbated, further deteriorating water quality along the coastal aquifers.

12.3 Predicted Patterns/Trends

Climate predictions made by Global Circulation Models (GCMs) are excellent tools for assessing the possible impacts of climate change on water resources. However, their coarse spatial resolution is insufficient to support basin scale hydrologic applications. Downscaling methods for GCM outputs have been proposed which can be classified as: statistical and dynamical downscaling methods. The studies focused on climate predictions over Turkey utilized the latter ones, in which regional climate models (RCMs) are nested within a GCM.

GCMs provide information on the response of the atmosphere to different scenarios of global GHG emissions. Among the standard GHG emission scenarios defined by IPCC, A2 and B2 scenarios are the most commonly used by the climate change studies focusing on Turkey. The A2 scenario reflects a somewhat pessimistic view of future with a very heterogeneous world, continuously increasing population and slow technological change. The B2 scenario, foresees moderate global population growth and intermediate levels of economic development and technological change. These scenarios possibly reflect the upper limits of human-induced global warming.

Until now, only a few studies utilized RCMs to investigate the potential role of global warming on the future climate of Turkey. Among others, Onol and Semazzi [33] and Dalfes et al. [11] used the regional climate model RegCM3 (30 km horizontal resolution) forced by the general circulation model NASA-fvGCM to simulate the future climate change projections (2071–2100) over the Eastern Mediterranean (EM) based on A2 emission scenario. Their projections have shown general warming over EM (2–8°C). Over Turkey, the increase in summer temperatures is predicted to be more pronounced (5–7°C) in western Turkey with a prolonged summer season, whereas the increase in winter temperatures is predicted to be more pronounced in the eastern parts. Their simulations predicted a significant increase (10–50%) in winter precipitation along the east coast of the Black Sea whereas significant decrease (30%) in winter precipitation was predicted across western and southern Turkey. Note that these predictions are in line with the past observed trends (Sect. 12.2).

Fujihara et al. [34] investigated the potential impacts of climate change on the Seyhan River Basin (southern Turkey). They dynamically downscaled the hydrometeorologic variables to 8.3 km using the TERC-RAMS regional model forced by two GCMs utilizing A2 emission scenario. The RCM output was also used to drive a hydrology model after bias correction. They concluded that the Seyhan Basin will be significantly impacted by 2070s, with the drastic decrease in annual runoff (52–61%) due to an increase in temperature (2.0–2.7°C) and a decrease in precipitation (25–29%). They however concluded that water scarcity will not be an issue in the future, given that the water demand stays constant. In a parallel study, Tezcan et al. [35] used the same downscaled RCM output used by Fujihara et al. [34] as input to the models simulating surface flow, groundwater flow and salt water intrusion processes. Their predictions indicated significant decrease in precipitation (~30%), streamflow (~40%), groundwater recharge (~25%) and snow storage and deterioration in water quality due to sea water intrusion along the coastal zone by 2070s.

Focusing on western Turkey, Ozkul [20] assessed possible impacts of global warming on Gediz and Buyuk Menderes River basins. The assessment was based on the model for the Assessment of GHG Induced Climate Change (MAGICC; v.4.1) coupled with a regional climate change scenario generator (SCENGEN). Using this model setup, Ozkul [20] simulated temperature and precipitation changes in 2030, 2050, and 2100 based on A2-ASF and B2-MESSAGE emission scenarios. The predictions indicated a mean annual temperature increase of 1.2°C, 2°C, 4.4°C for years 2030, 2050 and 2100. For the same years, mean annual precipitation was predicted to decrease by 5%, 10% and 24% respectively. Ozkul [20] also investigated the impact of these changes on runoff using a simple downscaling method (alpha method) and a simple monthly water balance model. The runoff predictions indicated that, by the years 2030, 2050 and 2100, the surface waters in the basin will be reduced by 20%, 35% and 50% respectively. Aksoy et al. [22] studied climate variability and change in the European part of Turkey for the twenty-first century. In the procedure they used MAGICC/SCENGEN software to generate outputs from global climate models HadCM2 and ECHAM4 based on A2 and B2 emission scenarios and a simple downscaling method to estimate localized estimates of future climate. Their analyses indicated that the study area will be under the effect of increasing temperature and decreasing precipitation during the twenty-first century with higher variability and wider range reflecting vulnerability of the region to extreme events, floods, and droughts in the twenty-first century.

To summarize, climate modeling studies performed at the regional scale over Eastern Mediterranean and at selected basins projected an increase in temperatures and a decrease in precipitation and runoff over much of the country, especially in the western and southern parts. It should be noted that all projections made by climate models depend on various assumptions, including the model structure and trajectory of future global greenhouse gases. Hence the uncertainty in model projections of future climate should be explicitly incorporated in climate change studies. The most common uncertainty assessment method has been the ensemble approach which requires a collection of simulations from different climate models, with varying assumptions of the future atmospheric composition and with different initial conditions [36].

12.4 Conclusions

In this paper we presented a summary of the current knowledge in the area of climate change impacts on Turkish water resources with emphasis on past and predicted future trends in atmospheric variables (precipitation, temperature) and hydrologic variables (streamflow and groundwater levels). In general terms, many studies reported that warming trend has been prevailing in Turkey since early 1990s. The most significant changes have been reported for the Mediterranean climate region (western and southern Turkey) with increase in temperatures and decrease in precipitation. Prominent long-term observed changes that are consistent over Turkey include increase in annual minimum temperatures and summer temperatures and decrease in winter precipitation. Streamflow and groundwater levels are found to respond to the changes in atmospheric variables, indicating potential water scarcity problems in many regions. This situation is exacerbated due to population growth and over-exploitation of water resources. Climate modeling studies generally predict likely intensification of the observed trends in hydro-meteorologic variables by the end of the twenty-first century based on IPCC emission scenarios.

Hence global warming will likely worsen already existing water scarcity and water allocation problems in Turkey, especially in the western and southern regions. To better assess the evolving impacts of global warming on – both quality and quantity of – water resources, basin-scale impact assessment studies that utilize coupled land surface and regional climate model outputs are needed together with a method for quantification of the prediction uncertainty. Studies that help to understand isolated influences of human impacts and natural weather patterns (and their interaction) on the observed climatic change are also needed.

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Chapter 13
Impacts of Climate Change on Groundwater Resources: Review of a Case Study in Azerbaijan

Rauf G. Israfilov and Yusif H. Israfilov

Abstract Groundwater and surface water are the sources of water supply in Azerbaijan. The hydroeconomic balance of Azerbaijan is characterized by annual and seasonal deficits arising from the implementation of hydroeconomic measures for increasing the water supply to different branches of the national economy. When almost all available surface water resources are involved in the national economical production, the optimal use of aquifers' fresh groundwater resources are currently playing pivotal role. That is the reason that the interest in the impacts of climate change on groundwater resources in Azerbaijan has developed greatly. This paper examines the scientific and technical aspects of evaluating the fresh groundwater resources formation in the hydrogeological structures, such as deposits in the mountainous regions, foothill and intermountain plains. It also investigates the role of the climatic factors and impacts of climate change on groundwater resources.

Keywords Groundwater resources • Aquifers • Azerbaijan • Mountainous regions • Foothill and intermountain plains • Impact of climate change • Water balance

13.1 Introduction

The main territory of Azerbaijan is situated within arid climates and approximately 95% of the river runoff is used in the national economic production. This situation is further complicated by the fact that, after the disintegration of USSR, about 20% of the territory of Azerbaijan is occupied by Armenia. In states with a deficit of general water resources, the optimal use of fresh groundwater resources (FGWR) acquires great significance and strategic importance for economy of the new

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independent country in the current situation. These resources are generally characterized by their high quality and better protection against contamination than surface waters and they are only single source of fresh water in more parts of Azerbaijan. Also, being less dependent upon annual precipitation, they serve as important source of potable water supply. Simultaneously, natural conditions such as low annual rainfall, high potential evaporation, and complex geological structure militate against the formation of a sustainable fresh groundwater resource. Moreover, fresh groundwater resources are limited within territory of Azerbaijan. Due to the stress of water use for various activities, climate change, and other interventions in the water cycle by mankind, it is vital that the groundwater resources in Azerbaijan should be developed and managed in a sustainable and integrated manner.

13.2 Hydrogeological and Geological Conditions

Due to the diversity of natural environments and geological structure of Azerbaijan, the hydrogeological conditions are extraordinarily complex. Azerbaijan is situated within the Alpine fold belt and includes mountain regions of the Greater and the Lesser Caucasus (the mountainous Talish region is considered part of the Less Caucasus region), the Kura intermountain depression and part of the Caspian Sea (Fig. 13.1). The FGWR are limited within the territory of Azerbaijan and distributed irregularly [1].

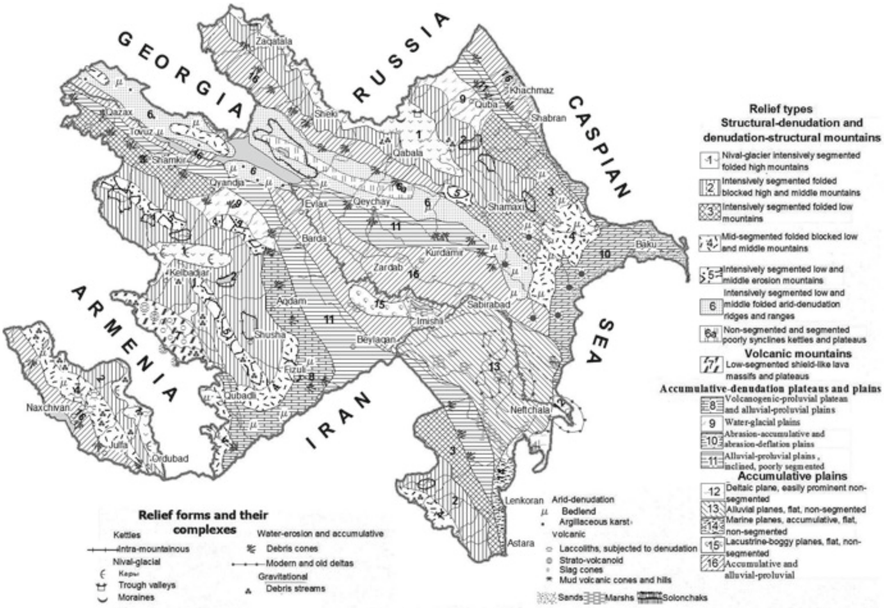

Fig. 13.1 Geomorphological map of Azerbaijan

The mountainous regions of Azerbaijan are formed of Mesozoic-Cenozoic rocks and characterized by significant relief, thick weathering zones, fracturing, abundance of mantles of deluvial/eluvial loam, and river valleys and small troughs of alluvial and fluvioglacial sediments. Groundwater is mainly associated with the weathering zone and tectonic dislocations. Shallow circulating groundwater, discharging as springs is observed in valleys and ravines of the foothills. Thickness of this zone is associated with drainage erosion depth, which is about 1,500–1,800 m. The main FGWR in these regions originates from atmospheric precipitation and melt water of the zones of glacier and ice.

The foothill and intermountain plains of the country are the regions of the richest fresh water. The foothill plains here are composed of fluvial drift cone deposits characterized by development of stratum – pore groundwater within Upper Pliocene-Quaternary and Quaternary alluvial and deluvial/eluvial sediments.

Analysis of numerous hydrogeological profiles, both longitudinal and perpendicular to ground runoff, showed the presence, in nearly all drift cones, of lithological cavities composed of boulder-gravel-pebble deposits favourable for ground runoff accumulation. The coarsest material occurs toward the top-centre of the drift cones (boulder, gravel, pebbles) while in the periphery, predominantly fine-grained loam-clay deposits occur (Fig. 13.2). In the cross section, loam-clay deposits are observed in the central part of the drift cones representing about 10% of the vertical section, but this increases to 70–90% along the periphery. This longitudinal structure is called "ridged" and plays a significant role in the formation of unconfined and confined conditions in the aquifers Cross sections and vertical sections are characterized by chaotic distributions of continental material originating from the mountain areas. These distributions are part responsible for the meandering pattern

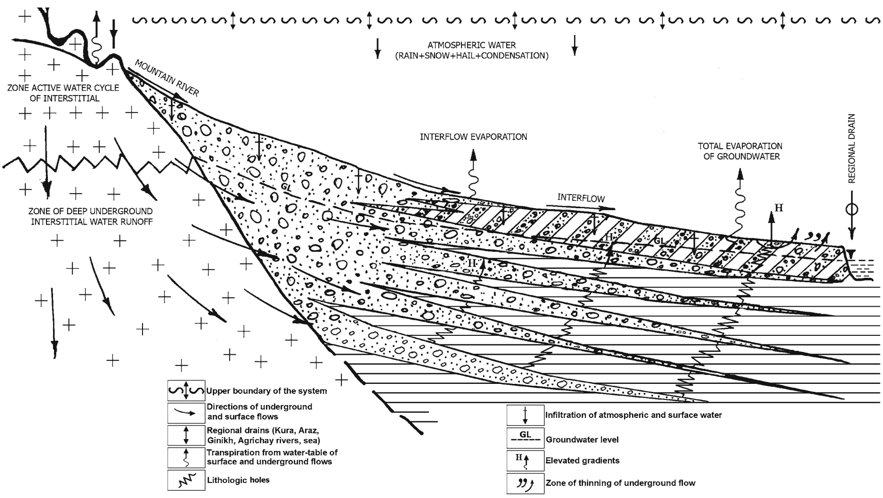

Fig. 13.2 The conceptual model of formation and expenditure of stratum – pore groundwater formation of foothill plains

of rivers. The chaotic nature of the sedimentation can lead to isolated aquifer units separated by poorly permeable beds, and can also provide “lithological windows” that allow good hydraulic interaction between otherwise discrete aquifers. So, recharge of intensive precipitation and surface drainage takes place in the upper part of the alluvial cones.

Groundwater flow beginning at the top of drift cones occurs within a single aquifer. Down flow, this aquifer becomes divided in plan and section into a series of aquifers separated by loamy-clayey deposits. These aquifers are closely associated with each other hydraulically and share a common piezometric level. They are regarded as an integrated aquifer system. The thickness of the aquifers varies from several meters to 100 m or more.

The results of research [1, 2] demonstrate that about 85–95% of the nature groundwater resources recharge, as in the aquifers of the mountain regions (fractured bedrock aquifers) as such as in the foothill and intermountain plains aquifers (strata and fluvial aquifers), are infiltration from atmospheric precipitation, condensation waters and surface water. Obtained data confirm that the FGWR formation in Azerbaijan very depends on the climatic factors. The changes of the hydrological cycle will deteriorate the availability of potable water resources for inhabitants, in terms of quantity, quality and accessibility of water supplies.

13.2.1 Natural Climatic Conditions

The peculiarities of physico-geographical conditions, complexity of a terrain and general atmospheric circulation causes the unique natural climatic conditions of Azerbaijan. In Azerbaijan, there exist 9 of the world’s 11 climate zones, including semi-desert, arid steppe, and mountain tundra [1, 3]. At the same time, the formation of climate in the country is influenced by cold air masses of arctic (Kara and Scandinavian anticyclones) and temperate (Siberian anticyclones) and maritime (Azores maximum) hot air masses of tropical zones (subtropical anticyclone and southern cyclones), Central Asian anticyclones and local weather conditions.

13.3 Impacts of Climate Elements on Groundwater

13.3.1 Total Water Balance

The total water balance (excluding water resources of transboundary rivers) in Azerbaijan are: precipitation – 427 mm (3,696 km^3); and river discharge – 119 mm (10.31 km^3) which consists of 69 mm (5.96 km^3) of a direct run-off and 50 mm (4.35 km^3) of a groundwater run-off. The average long-term drainage modulus is 3.78 l/s per km^2 (drainage coefficient – 0.28). The total evaporation is 308 mm

(26.66 km^3) [4, 3]. Over the whole territory, the evaporation is twice more than discharge and it is significant factor in a predictive modeling of climate change impacts' on groundwater resources [1].

13.3.2 Groundwater Resources Balance Calculation

For quantification of the climate elements impacts on groundwater resources their balance parameters have been analyzed. Because of various formation conditions of the fractured and fluvial aquifers, their balance structures are also different. The most complete balance approach for the estimation is the equation of water balance, where the groundwater run-off is taken into account. This is giving possibility to assess the basic part of annual renewable groundwater resources and symbolically it is stated as:

$$P = R + E \tag{13.1a}$$

$$P = S + U + E \tag{13.1b}$$

$$W = P - S = U + E \tag{13.1c}$$

where, P: atmospheric precipitation, R: river run-off, S: surface flow, U: groundwater run-off, E: evaporation, and W: gross soil-moisture.

The preponderance of groundwater recharge compared with evaporation or vice versa is characterized by the recharge coefficients of Cr and Ce which are symbolically stated as $Cr = U/W$ and $Ce = E/W$, subjected to $Cr + Ce = 1$. These coefficients offer a clearer view about the general water balance structure within the mountainous zones.

For quantification of the fractured bedrock aquifers, water resources of the mountainous regions, the upper groundwater stream (free water exchange zone and at the same time the underground component of river runoff) and the lower groundwater stream (difficult water exchange zone) are treated separately.

Estimation of the underground component of river runoff is performed based on the method of separation of the river flow hydrograph. The quantitative assessment of the water exchange zone was computed using the following formula:

$$Wo = Xo - Yo - (Zo - Ko) \tag{13.2}$$

where; Wo is deep groundwater run-off, Xo is atmospheric precipitation, Yo is surface flow, Zo is evaporation, and Ko is condensation.

The formation of the FGWR in the foothill and intermountain plains aquifers is a result of an infiltration from the atmospheric precipitation (Qp^+), condensation (Qc^+), river run-off (Qr^+), and the rate of inflow along the valleys of mountain rivers (Qrv^+) and from the foothill bedrock aquifers (Qd^+). The natural groundwater outflow elements are as follows: spring stream (Qs^-), evapotranspiration (Qet^-), groundwater drainage into rivers (Qdr^-) and regional drainage basins – river or sea

Table 13.1 The natural fresh groundwater balance of mountainous regions and foothill plains in Azerbaijan

Inflow		Outflow	
Elements	Percentage from total quantity	Elements	Percentage from total quantity
Elements of the groundwater balance for the mountainous regions			
Infiltration from precipitation	83	Groundwater discharge into rivers (local groundwater run-off)	53
Infiltration from condensation waters	17	Deep groundwater run-off	29
		Evapotranspiration	18
Total	100%	Total	100%
Elements of the groundwater balance for the foothill plains			
Infiltration from precipitation	24	Groundwater outflow	43
Infiltration from condensation waters	9	Evapotraspiration	32
Infiltration from rivers' water	32	Groundwater drainage into the rivers' valleys	25
Groundwater inflow from the mountainous regions	35		
Total	100%	Total	100%

(Qrs^-), outflow from foothill and intermountain plains (Qoo^-). Thus, the general natural groundwater balance can be expressed as:

$$Qp^+ + Qc^+ + Qr^+ + Qrv^+ + Qd^+ = Qs^- + Qet^- + Qdr^- + Qrs^- + Qoo^- + Qv \quad (13.3)$$

Qv here is a variation of the groundwater natural resources within the limits of the plans. In the long-term Qv tends to zero. The results of the general water –balance calculations of the FGWR are shown in Table 13.1. The presented results are showing that the all groundwater balance elements are derivative of a precipitation and directly related to precipitation. Climate conditions play special role in formation of the potable water resources.

13.3.3 Climate Change Assessment

Anomalies in the long-term monitoring data (1935–2006) of the climate parameters in Azerbaijan are not identified yet. As such this fact should be taken into account when making future groundwater resources protection.

By the National Climate Change Centre of Azerbaijan, to calculate climate change impacts on water resources, the following scenarios had been used: increase of annual air temperature by 4.8–5.3°C and annual precipitation by 6–12% and an increase of annual air temperature by 4.2–4.4°C and annual precipitation by 1–4% [2].

Taking into account changes of air temperature and precipitation, the regional groundwater flow models with different climate change scenarios improves the understanding of the relationship between hydrogeology and climate change, predicts changes in groundwater resources and assists pro-active decision making. For the detail analysis and developing prediction models for optimization of the use of groundwater aquifer resources and deterioration of their quality, it is extremely necessary to get additional relevant field data. This will give possibility for practical use of the obtained results and it is a significant help for a national economic development strategy.

13.4 Conclusion

The research data demonstrate that the FGWR formations in Azerbaijan are very dependent on the climate components and highly sensitive to variations in climate. Research suggests that groundwater resources and water quality could all be significantly affected by climate change over the course of the coming decades. The integrated regional groundwater flow models with climate model simulations (based on the relevant field data) will allow to predict the possible changing of the FGWR and to develop the recommendations for their rational use.

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Chapter 14
The Global Climate Change Impact on Water Resources of Armenia

Anahit Adanalyan and Suren Gevorgyan

Abstract The global climate change impact on water resources of Armenia is shortly reviewed. The mountainous character of Armenia causes the great differentiation in landscape types, as well as geological characteristics, climate, soils and water resources. The present day Armenia is disposed to significant ecological risks and becomes a country which economy is based on the intensive use of natural resources which eco security vulnerability is continually increasing. It is noted that the strategy of ecological security is based on the defensive, adaptation, cooperative and other approaches but the country needs to have ecological security concept based on the ecological ideology in beforehand. We highlighted in this presentation that the reduction of water reserves will coincide with the growth of the demand on water resources, since due to the climatic peculiarities namely due to the high air temperature the households will require more potable water and the needs of agriculture in irrigation water supplies will increase. Corresponding risk assessments are preliminary evaluated and some possible recommendations to be done are presented.

Keywords Climate change • Water resources • Water-deficit-risk assessment

14.1 Introduction

Armenia is the mountainous dry land country which lowest point is 375 m above the sea level (on the north of the country at the Debed River) and the highest point is 4,095 m (the top of the mountain Aragats). Generally, the average altitude of the

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country's territory is 1,850 m but the variations of altitudes (up to the 3,700 m and more frequently up to the 1,500–2,000 m) have great importance on climate and landscapes of zones of territory.

The mountainous character of Armenia causes the great differentiation in landscape types, as well as geological characteristics, climate, soils and water resources. The landscapes ensure great diversity of the environmental conditions which in turn contribute to the flora and fauna peculiarities. The climate changes from the subtropical to dry type, air temperature vary from −41°C to +42°C. In the southern districts the climate is dry and arid. The climate of the northern mountainous districts is milder and moister. The average precipitations amount is about 570 mm with variation from 114 mm in semi-deserts to 900 mm in high mountains.

The present day Armenia is disposed to significant ecological risks and becomes a country which economy is based on the intensive use of natural resources which eco security vulnerability is continually increasing. In the country there are three ecological regions: Lori- Tavush (with 28% forest cover), Zangezur (13% forest cover) and Sevan Lake zone. The main components of ecological sustainability are water resources, forests, meadows and landscapes which are presently endangered. The huge mining industry around the Agarak- Kadjaran- Kapan 30 km circle, as well as Alaverdi- Akhtala-Teghut, where the ore extraction volumes are continually increasing. The situation is worsens with the perspective of the construction of the Sotq gold processing plant on the Sevan Lake shore. In short times the uranium mining will be developed. The mentioned enterprises are creating big tailings which contain large amounts of toxic heavy metals and cyanides containing wastewater.

The ecological situation in Armenia is appreciated as utmost critical [1]. In the most agricultural region- Ararat Valley- the nuclear power station is functioning. The irrigation water is highly polluted, sometimes contaminated with sewage water. The desertification and erosion processes are strongly activated. In the deteriorated agricultural lands it has become impossible to implement ecological and environmental programs and to secure the environmental monitoring. On the other hand, no soil re-cultivation works are implemented and subsequently the deteriorated areas are constantly increasing. The whole country is covered with various production and domestic unsafe wastes. The worn tires, obsolete pesticides, consumer commodities and food of bad quality are imported. And this is the most negative waste created factor, because of the absence of waste treatment safe techniques. In industrial developed countries the environmental requirements are demanded from all enterprises independent on the form of property [2].

The strategy of ecological security is based on the defensive, adaptation, cooperative and other approaches but the country needs to have ecological security concept based on the ecological ideology in beforehand. The absence of such ideology can have negative consequences for any country [3].

That's why the risk assessment is necessary to prevent any negative impacts on the environment. The risk assessment is analysis category designed to appreciate the probability of the environmental damage caused by the project.

14.2 On Risk Assessment of Climate Change on Water Resources of Armenia

The risk assessment process includes:

- Identification of the possible risks
- The evaluation of their probability
- Environmental impacts of risks
- Risk control measures

It is very important to evaluate the risks of not implementation of different measures designed in the project, as well as to develop the mitigation measures.

The risk assessment level (extent of details) depends on the nature of the implemented project, impacted subject and intensity and so on.

It is predicted that due to the increased air temperature and evaporation the flow of Armenian rivers will be reduced on 21% in 2010, which will create great irrigation and energetic problems for agriculture and energetic needs of the country [4]. No investigations are carried out and consequently no data are available on the impact of the river flows reduction on the underground water reserves so it is not possible to appreciate the short term and long term magnitudes of potable water in country.

The reduction of water reserves will coincide with the growth of the demand on water resources, since due to the climatic peculiarities namely due to the high air temperature the households will require more potable water and the needs of agriculture in irrigation water supplies will increase.

The real impact on agriculture will depend on the distribution of irrigation water between the agricultural farms, on the resolutions about water users permits' limits, as well as on the application of water saving technologies.

The share of water-resistant and vulnerable to drought conditions agricultural plants is 14% from GDP [9]. So the climate change in Armenia will result in the reduction of agricultural production. These will in turn lead to the reduction of the productivity since irrigation water demand will increasingly exceed the supply quantity. The irrigation problems will arise on one hand due to the lack of necessary infrastructure, on other hand due to the decline of the river flows.

Strong winds and heavy rains will damage the crop and can cause the natural catastrophes such as erosive mud flows and floods, which in turn can damage the soil and the irrigation structures.

It is necessary to implement a series of climate change adaptation measures in Armenia, particularly [6]

- to improve the irrigation and other water supply structures in the context of the present and up-coming changes in air temperature conditions, in the amount of precipitations and of the river flows The mentioned measure is undoubtedly effective since is oriented on future changes and is targeted to ensure the adaptation. This measure will require construct additional water use structures, rehabilitation of the majority of the existing ones, as well as the expansion of the irrigation structures.

- to stimulate the rise of the effectiveness of water and energy use in the households, agricultural farms and other businesses The reduction of the water demand is one of most important ways to avoid the water deficit caused by the climate changes.
- to provide trainings and consultations on the effective methods of water use For example, the training of the population and/or the necessary technical assistance.

The climate change can impact also the social components such as raise of poverty and social inequity. The following impacts are possible:

- the decline in water provision, the growth of health threatening risks, the probability of floods and other nature catastrophes
- the reduction of the water provision level: the deficit of water resources will lead to the decrease of water resources caused by the climate changes
- health threatening risks: The population health situation depends also on the quality of water and on the ultimate climatic phenomenon
- decline of the productivity of agricultural production
- the raise of frequency of ultimate weather phenomenon, as well as of flood probability

The general kinds of damages in Armenia are expected to be of social and qualitative nature [7]. The key climate change adaptation measures are the improvement of water resources use management and water supply structures, which are at the same time the measures targeted to the economic development.

The lower level of precipitations and the higher air temperature are speeding up the evaporation processes, reducing the snow cover and the spring water flows. As a result the less amount of water comes to rivers. The river water flows, the water levels in lakes and underground water reserves are changing as a result of climate changes.

According to the investigations in Armenia the total river water flows will decline for 7% [8]. In the number of rivers the major reason for changes in water flows are the result of smaller quantities of the snow and ice covers accumulated during the winter season, which in turn is the sequence of the reduced precipitations and high air temperature.

The spring time snow melting is the major source of cold alpine waters in the Sevan Lake. The 28 rivers and inflows flowing into the Sevan Lake will lose up to 41% of their flows. And even the large scale programs directed to raise the water level in the Lake will not be able to compensate the decline and lose of the water level.

The 4/10 of the used water is ground water resources and the 6/10 is taken from rivers and lakes.

- the preparatory adaptation with the purpose to be ready to the forthcoming water reduction The measures of the private sector are the installation of the water collecting containers, as well as to reuse the water if possible. For example, use of the wastewater /not sewage wastewater/ for irrigation purposes. The new saving practices are very important for households and individuals. The investments from the state budget are to be done for large scale infrastructural programs aimed to prevent the water losses through the enlargement of the water saving facilities and raising the effectiveness of the water supply facilities. The investments must involve the followings:

to build the dams and water reservoirs with water collecting conveniences
to develop irrigation supply system to prevent the water losses
to enlarge the current irrigation system network
to increase the water inflow into the Sevan Lake
to adapt new environmental legislation focused on the stimulation of the water use savings which will limit the water use volumes of households, industrial and agricultural enterprises
the Government can initiate trainings and educational programs to raise the awareness of water users in the regions with high water consumption figures

Because of the Climate Changes it is necessary [9]:

- to revise the current standards of the sanitary zones of protection of the potable water sources
- to establish a new management system of the Water National Program
- to implement the soil melioration works and thus to reduce the negative environmental impact
- to account the water use levels
- to make water use balances for water basins
- to develop the programs of rehabilitation of the hydro ecosystems of the Sevan Lake
- to develop the National Action Plan to prevent the negative impact on water resources
- to develop the principles of the social and private cooperation for the effective use of water resources
- to develop new experimental irrigation system practices and so on

The great number of different types of risks will be generated by the natural catastrophes prevention of which requires significant expenses. Integrated international cooperation to control the Climate changes requires the coordination of the governmental ecological policies of different countries in long term perspective. The major components of the policies are the reduction of pollution, the reduction of the forests' cuttings, the enlargement of the cleaner productions and technologies.

The constantly going on climate changes modifying the physical geographical parameters of the whole planet on one hand, and the local geography of the human's activity on the other hand. The scientists predict the raise of the average air temperature for 5°C in compare to the preindustrial human society.

The consequences of the climate changes will be also:

- the large scale migrations of the population of the planet and as a result the economic and political crisis

- poverty and hunger as a result of the reduction of the agricultural land resources
- drastic reduction in biodiversity since lots of species will not be able to adapt to the new climate conditions
- the raise of diseases and mortality level

14.3 Conclusion

The impact of the each type of risk is evaluated. The generated risks are evaluated by the scientists investigating the climate change impacts. The evaluations are aimed to prevent the significant changes using some Kioto regulating mechanisms. The political- economic process of the regulation can be considered as one of the most important factors to solve the problems generated as a result of the climate changes. For instance, green- house gases can create significant forms of global catastrophe which requires for effective decision making the political willingness of the Governments to withstand the gigantic business, to join the efforts of a variety of social stakeholders, to integrate the informational resources, etc.

In the post- soviet countries the society responds to the problem of global climate changes by joining to the UN Climate Change Convention and to the Kioto Protocol [10]. According to the social inquiry the 62% of interviewed Russians considers the global warming as a really threatening danger [12]. The mostly expressed fears are the emergence of new previously unknown diseases and techno generated catastrophes. The global warming threatens are deepening by the gigantic businesses and Governments which didn't join neither to the Climate Change Convention nor to the Kyoto Protocol like such giants as USA, China, India, etc. [11].

In order to make the Climate Changes control it is very important to raise the awareness of the society and each individual living on the planet to be conscious of the consequences of the global warming and impacts on their interests, including the interests of the Republic of Armenia.

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Chapter 15
Regional Climate Changes in Kyrgyzstan: Impact of Natural and Anthropogenic Factors

Kazimir A. Karimov and Razia D. Gainutdinova

Abstract The results of long-term researches of the atmosphere temperature changes above middle latitudes of Central Asia region and the causes of climatic changes in atmospheric parameters considering man caused and natural factors are presented. In recent years global temperature has sharply dropped by 0.6°C, compensating the temperature increase by 0.6–0.7°C in the 100 previous years. The restoration of the equilibrium is an indirect confirmation of solar factor influence on the Earth's climate. Recently detected tendencies of temperature increase and small decrease of its average values in Kyrgyzstan, do not promote water inflow increase in mountain rivers, enhancing a water resources deficit in future in Central Asia.

Keywords Climate changes • Warming • Temperature • Atmosphere • Ocean • Solar activity • Model • Prognosis

15.1 Introduction

The causes of global warming are still being discussed among scientists all over the world. Two main causes seems to prevail, the first one connected with natural sources such as solar, space, and other factors, the second one connected with man-induced factors resulting in greenhouse effect in atmosphere. An assessment of the role and contribution of these two factors in the warming process is presented in this article.

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15.2 Causes of Warming in Surface Atmosphere

Solar radiation in visible and infra-red areas of the spectrum widely controls the temperature of Earth's surface and adjacent atmosphere. Small admixtures as CO_2, methane CH_4, water H_2O, ozone O_3, gas hydrates and others impact on the atmosphere balance. Recent models [1] point to the essential contribution of water vapors in the radiation condition of lower atmosphere. In papers [2, 3] is made a conclusion that in nearest future a CO_2 concentration growth and, respectively, greenhouse effect reduction (earth's surface temperature decrease) is expected.

The solar radiation factors influencing the atmosphere temperature behavior must be considered. It is known that the maximums and minimums of 11-year cycles of solar activity coincided with maximums and minimums in surface atmosphere temperature changes.

It is also known that in solar cycles the cycles with periods of 11–13, 21–23, 35–42, 55–60, and 90–100 years prevail [4–6]. These periodicities point to a real connection of surface temperature variations with solar activity. The recent 60 years were characterized by a high level of solar activity for the period of the last 500 years. From 1998 on the solar activity decrease began, and in this period maximum warming was marked. This period can be also characterized as a beginning of global temperature fall [7]. The analysis of surface temperature climatic variations in troposphere above Kyrgyzstan, according to meteorological stations located at altitudes 2,040 and 3,700 m above sea level, shows their clear dependence on the solar activity level in 21th and 22nd 11-year cycles. In periods of maximum solar activity the atmosphere temperature at these levels was 0.7°C higher in winter relative to average background temperature, and in periods of its minimum it was 0.8°C lower [5, 6, 8].

From maximum to minimum of the 11-year solar activity cycle the atmosphere temperature changed by 1.5–1.6°C. Following the researchers [4], a global air temperature sharply decreased lately by 0.6°C. So, if for the previous 100 years global temperature increased an average of 0.6°C, in a few recent years the nature rehabilitated itself the temperature equilibrium.

In the winter periods of 2006–2010 the increase of temperature was not observed in Kyrgyzstan. By contrary, the temperature average values decreased by 0.5–0.7°C during winter.

High-altitude structure of a warming process development in atmosphere is of special interest. We conducted special researches and analyzed high-altitude variations of warming rate. For the analysis, temperature measurements of meteorological and aerological stations of Kyrgyzstan were used, for a period between 1984 and 2006. The analysis of these data showed that a process of warming occurs basically (to 90%) in troposphere, from surface layer up to altitudes 3.5–4.0 km [5, 7]. Higher than 6 km, the warming changes into a fall in the temperature and practically all layer of lower stratosphere becomes cold.

Actually, the investigation of the causes of warming tries to define if carbon dioxide concentration increase in atmosphere is really a cause or a consequence of warming. According to experimental data, CO_2 concentration increase in atmosphere does not precede a process of warming, but occurs after it.

Following the theoretical researches at the Institute of Atmospheric Physics RAS [1] the temperature variations in recent decades pass ahead the variations of CO_2 concentration.

The researches of scientists dedicated to oceans showed that around 90% of natural CO_2 is dissolved in ocean water [9], and many-year variations of ocean water surface temperature for 5 years periods correlate well with variations of solar activity. Moreover, according to the researches of the ice cores in the Antarctic and Greenland, CO_2 concentration increase in Earth's atmosphere occurs after the warming in atmosphere, but not before it. This again points to the fact that CO_2 concentration increase in Earth's atmosphere is not a cause, but an aftermath of warming.

Our researches, based on the classical theory of M. M. Budyko [10], identified a share of anthropogenic contribution, as CO_2, not higher than 25–30%, in warming process above Kyrgyzstan region [6, 11]. At present, these data are quite real as a man-caused factor. Special attention was paid to the influence of H_2O water vapor in lower atmosphere.

15.3 Surface Temperature Variations and Solar Activity

We shall consider a connection of surface air temperature variations with variations of solar activity with periods more than 11 years from 1925 up to 2000. Wolf numbers W, as parameter of solar activity are considered in this study. The deviations of these values from mean-periodical values are analyzed. Figure 15.1a–c shows the variations of deviations of the solar activity secular component ΔW – (*a*) and surface temperature deviations ΔT for a cold half year according to data of Bishkek meteorological station – (*b*), from which the 11-year component and a component averaged on all stations of the Northern hemisphere – (*c*) were excluded [7]. One can see in the figure the good correlation between these values (correlation coefficient $k = 0.75$), and that the maximums in large-scale variations of surface temperature are marked in a period of 2–3 years after solar maximums.

Next, the calculations of time temperature series frequency spectra were made using data of Bishkek, Cholpon-Ata, Naryn, and Tien-Shan meteorological stations. Frequency components were selected with confidence probability level $P > 0.87$, corresponding to periods 5.0–5.5; 11–12; 21–23; 49–52; 85–95 years. The same periodicities are available in solar activity variations frequency spectra. These results testify statistical connection of surface temperature variations at middle and high altitudes of Kyrgyzstan with solar activity variations.

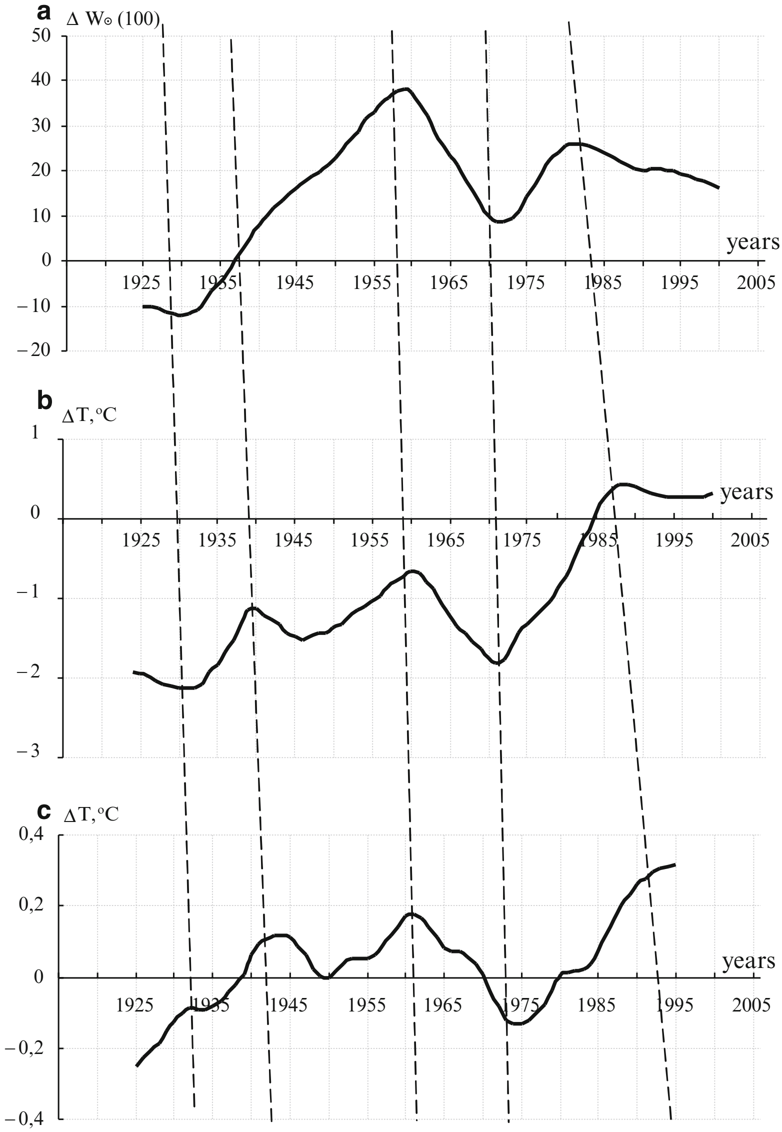

Fig. 15.1 Variations of deviations of the solar activity secular component in Wolf numbers, ΔW_{100} – (**a**), surface atmosphere temperature anomalies, ΔT, in winter, according to meteorological station Bishkek – (**b**) and all stations of the Northern Hemisphere – (**c**)

15.4 The Results of Experimental Calculations

In recent years a wavelet-analysis of the considered time series values was widely spread. The main advantage of this method is that it gives reliable results at non-stationary series of analyses.

The results of wavelet-transformation [7] applied to time series of average annual air temperature according to data of Naryn meteorological station (2,040 m above sea level) have been considered. Measured data for processing cover an 110-year period from 1897 to 2008. It is known that global warming increase is 0.7°C per 100 years. Average annual warming velocity at middle altitudes of Kyrgyzstan for all period of observations is 60 times lower than the global one, but warming velocity in winter period is at the level of the global average. This can be explained by spatial and time heterogeneity of the warming process.

For wavelet-transformation the anomalies of average annual temperatures $\Delta T_i(t)$ were used with extraction of trend temperatures, calculated by a least-square method. A continuous wavelet-transformation method was applied to this temperature series.

The analysis of wavelet-transformation data scalograms shows that in temperature variations with confidence probability level $P > 0.87$ the peaks correspond to periods 2.8–3.0; 5.0–5.5; 8.0; 11–12; 16–18; 21–23; 25–27; 35–37; 40–43; 49–52; 85–95 years. These results testify a real connection of surface temperature variations above mid and high altitudes of Kyrgyzstan, in central part of Central Asia region, with solar activity variations.

The level of available data allowed the implementation of an empiric modeling of long-term temperature variations regime of lower atmosphere above Central Asia. Beginning in 2005, the average annual temperature stabilized at a level of 12.1°C and, consequently, temperature trend was absent in that period. So, the observed increase in CO_2 concentration is accompanied by temperature stabilization at the near-surface atmosphere, which puts in doubt the greenhouse effect theory.

Natural climate fluctuations are connected with temperature fluctuations of the ocean surface temperature. The ocean contribution in atmosphere warming is comparable with energy contribution of the Sun. At that it is necessary to connect phases and variations of ocean streams and ocean surface water temperature with cyclic variations of the Sun radiation regime.

On the other hand, the ocean scientists say that the increase in the ocean temperature just by 0.1°C will cause the increase of CO_2 emissions to the atmosphere in the order of tens or even hundreds times higher than the emissions of all industrial companies in the world.

In this connection it is necessary to note that scientists in area of physics of atmosphere, meteorology, geophysics, and climatology gathered at the conference of UN Commission on climate change (IPCC) in December 2009 in Copenhagen could not adopt a unique declaration on climate change on the Earth and greenhouse emissions quotes, because the opinions of scientists divided into two camps. One part of scientists considered that climate warming will continue, the other part tried to prove that there will be no warming except the resulting from the secular solar activity, and, if the ocean surface temperature decrease, the temperature of surface atmosphere will also decrease.

According to many-year data of surface temperature variations in Kyrgyzstan, a stabilization of its growth and even some decrease in recent 3–4 years is marked, though CO_2 concentration is slowly increasing. According to data of Bishkek meteorological station, average annual temperature stabilization occurred from 2005 to 2009, and temperature growth is not forecasted for the future.

When periods and phases of surface atmosphere temperature regime fluctuations are known, it is possible to do model calculations of their variations against a background of average periodical temperature values linear trend growth. So, the implemented model calculation subjected to solar factor shows that by 2013–2015 the average annual temperature values can decrease up to the level of 1991–1995.

15.5 Conclusion

In recent 2–3 years global temperature has sharply dropped by 0.6°C. So, if for 100 previous years the average global temperature increased by 0.6–0.7°C, in the last years the nature restored itself the equilibrium, and relative balance became even. This fact is an indirect confirmation of solar factor influence on the Earth's climate.

Stabilization of air surface temperature increase and small decrease of its average values observed, for example, in recent years in Kyrgyzstan, do not promote water inflow increase in mountain rivers. This fact enhances water resources deficit, according to experts of European Union, and can serve as a cause of social, economic, and even political conflicts in Central Asia region.

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Chapter 16
Manufactured Nanoparticles: A New Threat to the Security of Some Groundwater Supplies?

John H. Tellam

Abstract Although climate change is potentially a major threat to the security of water resources, other possible new threats should not be ignored. Nanotechnology is a rapidly expanding industry, and already manufactured nanoparticles (mNPs) are being used in many products. Past experience suggests that use of new chemicals leads to subsurface pollution. The seriousness of this threat depends on two factors: the toxicity of mNPs and their mobility. Many mNPs, particles typically <100 nm across, are composed of metals, metal compounds (e.g. Ag, ZnO, CdSe) or carbon (e.g. carbon nanotubes). An active research area, nanotoxicology is showing toxic effects can occur under some conditions for bacteria, invertebrates, and vertebrates from low ppm concentrations upwards. Factors affecting mNP mobility in groundwater include aggregation, interactions with other particles, attachment to rock, and straining, with behaviour being very dependent on solution chemistry. The limited research available on intact rock samples indicates an encouraging degree of attenuation, at least in matrix flow systems, but field evidence suggests that a small proportion of particles can travel considerable distances.

Keywords Groundwater • Nanoparticles • Nanotechnology

16.1 Introduction

In considering the major threat to water resource security posed by climate change, we should not forget other new threats. ‘New’ pollutants, which include a range of new synthetic organics including industrial endocrine-disrupting

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chemicals, pharmaceuticals and other personal care products, manufactured nanoparticles, and antibiotic-resistant microbes, comprise one such threat.

This paper concerns manufactured nanoparticles (mNPs), the basic product of the nanotechnology industry. mNPs are generally defined as particles with dimensions between 1 and 100 nm manufactured either intentionally, or unintentionally as a by-product of some other activity. The commonest types of mNPs are based on carbon [e.g. carbon nanotubes (CNTs)] or metals/metal oxides (e.g. Ag, ZnO), and are used in the production of clothes, medical products, cars, and personal care products (Sect. 16.2). In future, such mNPs, and new types, are expected to be produced for many other purposes, including groundwater remediation [1]. Nanotechnology is thus a very rapidly expanding industry, forecast to reach $\$10^{12}$ turnover by 2015 [2]. With vastly increased production, increasing amounts of mNPs will find their way into the subsurface, and this will be a problem if mNPs are both toxic and mobile. There is therefore a major international research effort underway to determine the toxicity and environmental mobility of mNPs.

The aim of this paper is, therefore, after a brief introduction to mNPs (Sect. 16.2), to review the findings to date, firstly in toxicity (Sect. 16.3), and secondly in mobility in groundwaters (Sect. 16.4), and to make an interim judgement about the potential threat to water security from mNPs.

16.2 An Introduction to Nanoparticles

Nanoparticles exist everywhere, the vast majority of them being naturally formed. In wellwaters sampled from a sandstone aquifer in Birmingham, we [3] have estimated there to be around 10^{11} particles /L, most <100 nm. In unpolluted sandstone groundwaters, this work found most particles to be of silica, though other elements also present included Al, Fe, and Ti. Humic acids, fulvic acids, exudates from bacteria, and viruses are also present.

However, industrial manufacture has widened the range of NP types very considerably. mNPs are presently used in skin care products such as sun blocking creams (TiO_2, ZnO, SiO_2), self-cleaning glass (TiO_2), self-cleaning refrigerators (Ag), anti-odour impregnation in clothes (Ag), car components (CNT), medicines (Au, Fe oxides), plastics (CNTs, Fe oxides), biotechnology ('quantum dots', CdSe), solar panels (TiO_2), fuel additives (Ce oxides), paper (TiO_2), paints (TiO_2, Au), some food additives (TiO_2), electronics (Au), fuel cells (CNTs), and sports equipment (C60) [4, 5]. Morphologies are also diverse, from carbon nanotubes (CNTs), ribbons, and wires, to acicular crystals, to spheres composed of one metal coated by a second. The types of particle available are growing, and the total number possible is vast.

The main reason that NPs are of interest is that they have chemical behaviours very different from the same material in larger particle size. This is partly caused by their large surface areas: a 1 cm cube of SiO_2 would produce 10^{15} cubes of side 100 nm, increasing the surface area from 6×10^{-4} m^2 to 60 m^2! – at 1 nm, the surface area would be 6,000 m^2. The fraction of total atoms present on the particle surface increases approximately exponentially as size decreases, reaching ~50% by about 3 nm [6], thus greatly increasing reactivity. Also, at these sizes, quantum effects become important and various properties are altered relative to dissolved and bulk phases, including those associated with magnetic, optical, electronic state, and catalytic reactions. This results in different types and extents of interaction with dissolved species and biological materials. It is these 'new' properties that industry is exploiting with such élan.

16.3 Toxicity of mNPs

Evaluating the various toxicities of mNPs is a very active research area [7, 8], made difficult by the number of variables [types of mNP and organism; NP properties (shape, size, crystal form, composition, concentration); types of 'cap' or suspension stabilizers/dispersants used], and by the difficultly of separating the toxicological effects of the NPs from those of the associated dissolved phases [4, 7]. Not surprisingly, some apparently contradictory results exist, though these may be resolved in future. Nevertheless, some general conclusions can be made.

Many studies have shown mNPs to have toxic effects, and in some cases this has been demonstrated to be in excess of that produced by exposure to the dissolved phase of the same element [7, 2]. 'Organisms' examined include bacteria, algae, invertebrates, fish cells/organs, and various mammalian cells and organs, including human cells. mNP types examined include CNTs, metals (e.g. Ag and Au), and metal oxides (including those of Ti, Ag, Zn, and Fe). When seen, significant effects typically occur at low aqueous concentrations, of the order of ppm to tens of ppm. Size is not the only important property – shape, for example, has also been found to be of importance in some systems, at least via airborne exposure [7].The toxicity of mNPs can arise through a range of mechanisms including [2]: the production of reactive oxygen species (ROS) leading to membrane, protein, and DNA damage and oxidative stress; oxidative stress affecting enzyme activity and mitochondrial performance; protein denaturation and degradation; uptake by neuronal tissue leading to brain damage; and disturbance of phagocytic ('cell engulfing') function leading to reduction in efficiency in removal of infectious agents. NPs are potentially very mobile within organisms (cf. viruses, which are typically 10s nm in diameter and hence NPs in their own right), being able to pass through membranes including by phagocytosis. Thus, another possibility is that mNPs can act as carriers for other contaminants [9]. In some instances, interaction with other contaminants may change the toxicity of the NPs [7].

16.4 Mobility of mNPs in Groundwaters

16.4.1 Particle/Particle and Particle/Surface Interactions

Provided they are of limited solubility, surface chemistry will dominate mNP behaviour in most groundwaters. The surface charge on one mNP will tend to repel other mNPs of the same type, thus promoting suspension stability. However, if collisions induced by Brownian motion, flow, or sedimentation are sufficiently energetic, the colliding particles will get close enough for van der Waals forces to overcome the electrostatic repulsion, resulting in particle attachment/aggregation. Figure 16.1a shows that two types of attachment are possible: a primary (energy) minimum attachment, which is effectively irreversible and is attained either by fortuitously energetic collisions or by migration from a secondary minimum attachment; and a secondary minimum attachment, which is reversible upon fall in ionic strength or agitation. As ionic strength increases, the energy barrier between the primary and secondary minimum disappears, thus leading to much easier aggregation (Fig. 16.1b). This is essentially the 'DLVO' model.

Thus for higher ionic strength groundwaters, particle suspensions will tend to aggregate and then either fall out of suspension, or be strained (filtered) out by small pore throats. Though NP concentration does not determine stability, greater concentrations promote quicker aggregation. mNPs will also attach to rock or nNPs, the mechanism being effectively the same.

Though ionic strength is perhaps the single most important factor determining aggregation/attachment, pH, ionic composition, and material type are also important. In addition, many suspensions are stabilized using a variety of compounds, often polymers. The latter form a coating around the particle, and can provide charge and/or steric stabilization. Thus the presence of the stabilizer is also an issue of concern. Finally, particle dissolution needs to be considered in any risk analysis.

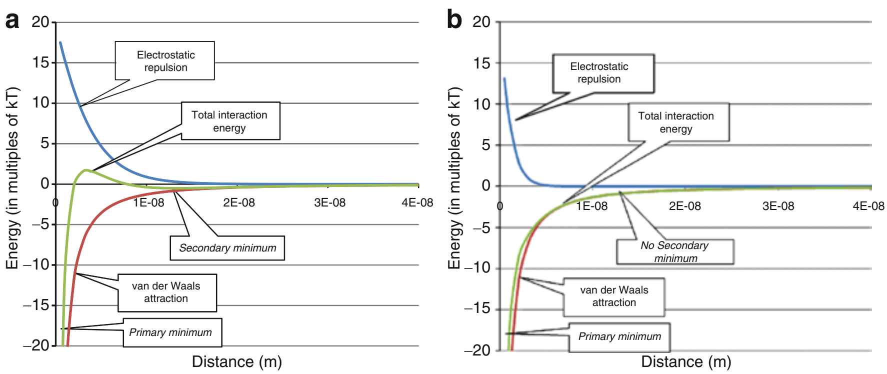

Fig. 16.1 Example DLVO predictions for attraction (+ve) and repulsion with distance from a NP surface. (**a**) Low ionic strength. (**b**) Higher ionic strength. k, Boltzmann const (J/K), T, temp (K)

All these processes have yet to be reliably quantified in the environmental context, even the well-established DLVO theory is only an approximation even in idealized laboratory settings.

16.4.2 Laboratory Evidence on the Mobility of mNPs

Most research has concentrated on artificial porous media, e.g. glass bead columns, in order to try and understand the basic processes [10]. In general, it has been found that a filter coefficient can be used to quantify the removal of particles during passage through a porous medium, based on the product of: a collector efficiency factor (η), representing the efficiency with which an aquifer grain (the 'collector') captures a passing NP; and a collision efficiency factor (α) representing the average number of collisions necessary before attachment occurs. Relationships exist for estimation of η, but α requires laboratory experimentation [11]; α but not η is a function of ionic strength. The most common models for η assume electrostatic repulsion to be negligible, which may or may not be appropriate. The product $\eta\alpha$ can be related to the familiar first order decay constant and used in modelling solute breakthroughs. The equilibrium concentration at any given distance, assuming that α remains constant, will be independent of the dispersivity, directly dependent on porosity, on velocity, and on grain size, and related inversely but weakly to temperature and particle density. Greater α and η values result in lower breakthrough concentrations.

However, during breakthrough conditions may change: the porous medium may 'ripen', i.e. clogging will occur and the breakthrough of particles becomes impeded, or 'blocking' may occur where the rock attachment sites fill up leading to greater breakthrough concentrations. Addition of organic solutes, either representing stabilizers form the NP source or natural organic matter, will often encourage particles to remain unattached [10]. At lower concentrations, polymers may encourage attachment / aggregation, as polymer ends attach to polymer-free parts of two particles. Under some conditions, initial breakthrough of particles may be early relative to solute breakthrough, due to pore size exclusion and/or lower diffusion rates into slower-flowing parts of the system caused by lower diffusion coefficients of NPs.

Overall, mobility will be maximized where the mNP and the rock surface are of the same charge (often the case), the ionic strength is low (fresh/ very fresh groundwater), and where pore sizes are not too small. Some experiments have been undertaken on intact rocks. Figure 16.2 shows some results of experiments on passage of 100 nm diameter silica colloids through 3–10 cm long cores of UK Permo-Triassic continental redbed sandstones (median pore size 10–40 μm). In the case of pure water (PW), the relative concentration at breakthrough is close to 100% (Fig. 16.2a) but, as the ionic strength increases towards that of fresh groundwaters (AGW) the breakthroughs become small, and often below detection limit (<~1%). With greater lengths of time, flushing with ionic strengths equivalent to fresh groundwater results in a long slow breakthrough, suggesting a blocking mechanism (Fig. 16.2b).

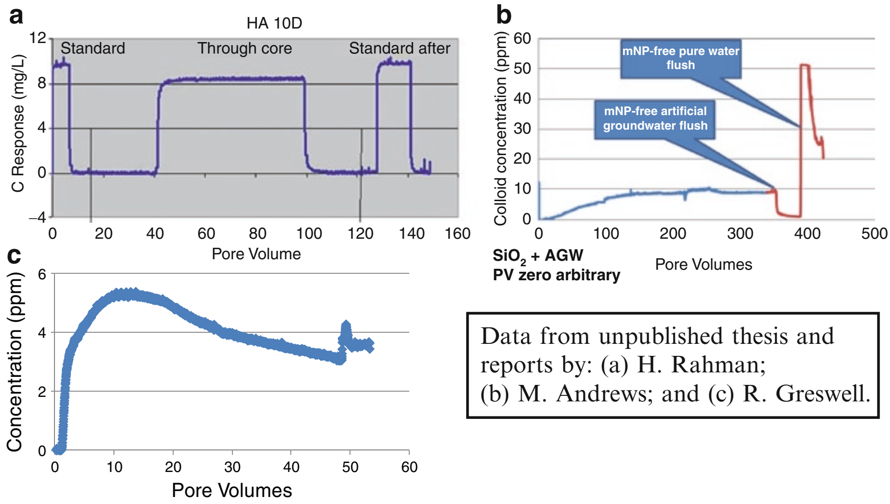

Fig. 16.2 Sandstone column breakthrough curves for: (**a**, **b**) SiO_2 100 nm NPs; (**c**) Sb_2O_5 30 nm NPs

In the case of 30 nm diameter Sb_2O_5 NPs, breakthrough also occurs in PW but soon concentration declines (Fig. 16.2c) as ripening occurs. TiO_2 NPs behave similarly, but breakthrough is even more limited for Ag and Ce oxides. In all cases the attachment to the rock surfaces can be reversed to some extent by lowering the ionic strength, suggesting some secondary minimum attachment. Frequently it is found that small peaks in breakthrough concentrations occur, even in the AGW experiments, and these were dubbed 'navalanches': with no cause obvious, it may be that these are due to the dislodging of a 'key' particle behind which had been held other particles. Investigation will continue to confirm that these events are not artifacts, what their cause might be, and whether the 'hop-stop' mechanism implied does allow significant mass movement.

16.4.3 Field Evidence of the Mobility of Manufactured Nanoparticles

There is little evidence of the mobility of mNPs in the field, largely because mNPs are a relatively new potential pollutant and measurement is problematic. Most work has been undertaken in the context of nNP-facilitated radioactive nuclide transport. However, we [12, 3] have sampled groundwaters from urban and rural areas in a UK sandstone aquifer, and found a distinct difference (Table 16.1), the urban groundwaters containing significantly more metal-containing particles (sub-ppb), interpreted as unintentional mNPs. These results suggest that some mNPs may be mobile, at least over the distances from ground surface to the base of the well casing,

Table 16.1 Summary of colloid (1 nm–1 µm) particle compositions from wellwaters from the Birmingham and Nottingham urban Permo-Triassic Sandstone aquifers, UK, and a rural Permo-Triassic Sandstone aquifer, UK, as determined by electron microscope EDX analysis (Modified after Kleinert et al. [12])

Property	Birmingham	Nottingham	Lower Mersey Basin
Population (p/l)	10^{10}–10^{11}	10^{11}–10^{13}	10^{10}–10^{11}
Main inorganic comp	Al/Si, Si	Al/Si, Si	Al/Si, Si
Organic	Very few	Very few	None seen
Bacteria	Moderate freq	Mod freq	Low
Occurrence of metals	High freq	Moderate freq	Low freq
Metals assoc with	Inorganic coll	Inorganic coll	–
Metals detected	Ni, Cr, Ti, Zn, Co, Sn, Fe, Al, Mn, As, Zr	Fe, Ni, Pt, Ti, Zn, Pb, Mn, Cr	Fe

usually around 30–40 m, and potentially much further. However, even these data are not unequivocal: some particles may have been mobilized by pumping, and some particles may have been the product of precipitation within the aquifer (probably < likely). Even with these uncertainties, results suggest that some mNPs particles can be mobile in at least some intergranular flow dominated aquifers: in fracture flow dominated aquifers, transport is likely to be much easier.

16.5 Concluding Comments

Mounting evidence suggests that mNPs are toxic to a range of organisms, including subsurface bacteria, at concentrations from one to tens of ppm. In general, mNPs are likely to be fairly strongly attenuated in many intergranular flow aquifers, but attenuation may be easily reversed in some cases, and laboratory and field evidence suggests transport distances of concern for a small proportion of the initial pollutant loading. In fracture flow systems, mNP migration distances will be potentially considerable. mNPs may also have a role to play in modifying groundwater chemistry, and as an agent in dissolved contaminant remediation. Remediation of mNP pollution may involve the use of bacteria [7].

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Chapter 17
Regulation of Cyanobacteria in Large Open Water Reservoirs

Rashid A. Khaydarov, Renat R. Khaydarov, and Olga Gapurova

Abstract This paper introduces a novel method for controlling of the cyanobacteria concentration in open water reservoirs during periods of global warming. The technology is based on usage of nanophotocatalysts made from nanocarbon-metal composition with titanium as the metal. Under the natural ultraviolet radiation, the nanophotocatalysts form OH-radicals in water that destroy cyanobacteria. Field tests in natural water revealed it to be efficient with low consumption of nanocompositions (about 10 g/ha or 50 l of aqueous solution of the nanocomposition with the concentration of 200 mg/l), OH-radicals formed only in the upper water layers where cyanobacteria grow, and nanocompositions coagulate and precipitate harmless water-insoluble particles within the first day.

Keywords Climate change • Global warming • Cyanobacteria • Water purification • Carbon nanoparticle

17.1 Introduction

Global warming promotes the occurrence of cyanobacterial blooms in surface waters throughout the world [1]. Some climatic effects of global change include the variation in rainfall patterns [2], floods, droughts, dust storms [3], tropical storms, and intensity of hurricanes [4] which synergistically (along with nutrients) impact cyanobacterial and algal communities and bloom dynamics. Cyanobacteria often favor warm water and high light environments [5, 6]. Active growth occurs largely at temperatures above 20°C. Cyanobacteria also have been shown to be

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dominant in the warmer months in subtropical estuaries [7]. Many cyanobacteria are UV-tolerant since evolving various mechanisms to counteract UV radiation [8– 10].

The cyanobacterial blooms in fresh water are formed by cyanobacteria, such as *Microcystis aeruginosa, Anabaena circinalis, Anabaena flos-aquae, Aphanizomenon flos-aquae, Cylindrospermopsis raciborskii* [11]. They are dangerous for the following listed below:

1. Dense cyanobacterial blooms can block sunlight and use up oxygen in water, killing other plants and animals.
2. Dense cyanobacterial blooms can disable water pumps. For example, in 2009 several Russian cities located near Tsimlyanskaya Reservoir on the Don River and Ijevskaya Reservoirs on Ij River lost drinking water because of clogged water pumps at water treatment stations.
3. Some cyanobacteria produce toxins that are among the most powerful natural poisons known [12–18]. For example, they produce neurotoxins (Anatoxin-a, Anatoxin-a(s), Saxitoxin, Neosaxitoxin) which affect the nervous system, hepatotoxins (Microcystins, Nodularins, Cylindrospermopsin) which affect the liver, tumor promoters (Microcystins) which can promote tumor growth, and Lipopolysaccharides which can affect the gastrointestinal system. Many of these toxins have no known antidotes. Cyanobacterial blooms can make people and animals sick. Children are at higher risk than adults for illness because they weigh less thereby receiving a larger comparative dose of the toxin.

These potential dangers underscore the importance of removing cyanobacteria from water. But this process should be conducted carefully because cyanobacteria account for 20–30% of the Earth's photosynthetic productivity and convert solar energy into biomass-stored chemical energy at the rate of ~450 TW. Cyanobacteria utilize the energy of sunlight to drive photosynthesis, a process where the energy of light is used to split water molecules into oxygen, protons, and electrons. While most of the high-energy electrons derived from water are utilized by the cyanobacterial cells for their own needs, a fraction of these electrons are donated to the external environment through electrogenic activity. Cyanobacterial electrogenic activity is an important microbiological conduit of solar energy into the biosphere. Moreover, in some countries cyanobacteria is sold as food, notably *Aphanizomenon flos-aquae* and *Arthrospira platensis* [19].

Usually chemical and biological methods are used to control cyanobacteria in fresh water. These chemical methods adjust the balance between concentrations of phosphorus and nitrate in water, using peroxides, algicides and antibiotics like erythromycin to kill cyanobacteria. Unfortunately, these methods are expensive and cannot be used to control cyanobacteria in large water reservoirs. The biological methods are based on introducing a strain of chlorella into reservoirs, but they are not very efficient. This paper describes a new technology to control cyanobacteria in open water reservoirs using nanocarbon-metal compositions (NCMC).

17.2 Principle of the Method

This method is based on the destruction of bacteria and decomposition of toxins by nanophotocatalysts (NPC) that are dispersed in water. Under natural ultraviolet radiation, these nanophotocatalysts form OH-radicals in water which destroy bacteria and decompose toxins. In brief, the photocatalytic reactions of aqueous NPC suspension system can be described as follows:

$$NPC + h\nu \rightarrow NPC + e^{-}_{CB} + h^{+}_{VB} \tag{17.1}$$

$$h^{+}_{VB} + OH^{-}\left(\text{surface}\right) \rightarrow OH \tag{17.2}$$

$$h^{+}_{VB} + H_2O \rightarrow OH^{\bullet} + H^{+} \tag{17.3}$$

$$e^{-}_{CB} + O_2 \rightarrow O^{-}_{2} \tag{17.4}$$

$$e^{-}_{CB} + h^{+}_{VB} \rightarrow \text{heat} \tag{17.5}$$

where hν is the UV irradiation, h_{VB}^{+} is valence band holes, and e_{CB}^{-} is the conduction band electrons. The active oxygen and radical species existing in the presence of oxygen and water take part in the oxidation-reduction reaction and destroy bacteria and decompose toxins.

The nanophotocatalysts must be harmless; their concentration in water must be lower than the permissible level; and nanoparticles must form agglomerates during a specified period of time, coagulate, and precipitate. Many semiconductor metal compounds are used as photocatalysts; the most commonly known photocatalyst is TiO_2. The reaction efficiency of TiO_2 photocatalyst decreases in water and its performance deteriorates when the surface of photocatalyst particles becomes fouled up. For this reason, it is necessary to develop a new type of nanophotocatalyst which can meet all of the necessary requirements.

Nanocomposites combine the properties of two or more different materials with the possibility of novel mechanical, physical, or chemical behavior arising [20]. Nanocomposites of conjugated materials and metal nanoparticles are prepared from different metals, different types of conjugated polymers and oligomer linkers [21–28]. Other types of nanoscale materials are formed as composites of carbon nanoparticles and polymers. For example, electrolytically generated nanocarbon colloids (NCC) have functional groups such as carbonyl, hydroxyl and carboxyl groups formed on the surface of carbon nanoparticles [29–32]. These nanocomposites can be modified by attaching different cations. On the other hand, most polymers can react with different ions and molecules, and participate in modification of nanocomposites. For example, nanocarbon–polymer nanocomposites (NCPC) prepared with electrolytically generated NCC and polyethylenimine PEI [33]. A similar method can be used to prepare nanocarbon-metal nanocomposites (NCMC) as the nanophotocatalysts to control cyanobacteria.

17.3 Materials and Equipment

Carbon-metal nanocomposites with titanium as the metal NCMC(Ti) were prepared by the electrochemical method. The process was based on the use of a two-electrode device; one electrode made of a high-density isotropic graphite OEG4 (Russia) (65 mm × 30 mm × 15 mm) and a second electrode was made of titanium plate (65 mm × 30 mm × 1 mm). The electrodes were immersed in a plastic electrolytic cell (120 mm × 140 mm × 105 mm) filled with 0.025 M H_2SO_4 as the electrolyte. The electrodes had a separation distance of about 10 mm and applied voltage in the range of 5–30 V. The device operation involved two consecutive steps: (1) electrolysis for 2–10 min while the Ti-electrode was as an anode and (2) electrolysis for 2–5 min while the carbon electrode was as an anode. The process was conducted automatically using a twin timer ST-T (Korea).

The size and the shape of nanoparticles were determined by transmission electron microscopy (TEM) (LEO-912-OMEGA, Carl Zeiss, Germany). The size values were averaged over more than 200 nanoparticles from different TEM micrographs of the same sample. Conductivity and pH of the solutions were measured with a WTW bench Multiparameter MultiLab 540. The concentration of Ti in solutions was determined by neutron activation analysis by irradiating water samples in the Nuclear Reactor of the Institute of Nuclear Physics (Tashkent, Uzbekistan). A Ge(Li) detector with a resolution of about 1.9 keV at 1.33 MeV and a 4096-channel analyzer were used for detection of gamma-ray quanta. The area under γ-peak of radionuclide ^{51}Ti (half-life $T_{1/2}$ is 5.8 min, energy of γ-peak E_γ is 0.319 MeV) was measured to calculate the amount of Ti.

The photocatalytic oxidation of methyl orange (MeO) in a NCMC(Ti) suspension under UV illumination was investigated to evaluate the photocatalytic activity of the nanoparticles. A 150 ml of a 3.2×10^{-3} mol/l MeO solution was filled into a Petri dish. A 60 W UV lamp (DB-60, Russia) fixed at a distance of 25 cm above the solution surface was used as the UV light source and provided radiation power of 1 W/m^2 in the interval from 220 nm to 320 nm. The absorbance of the MeO solution was measured with Cary 50 UV-Vis spectrophotometer (Varian) with Xenon flash Lamp.

17.4 Results and Discussion

Experiments revealed that yield of NCMC(Ti) in the electrolysis process depends on voltage V between electrodes and pH of the solution. The yield dC_{Ti}/dt of Ti after 6 min of the electrolysis process, where C_{Ti} is the concentration of Ti in the electrolyte, increases with increasing voltage between electrodes up to 12–13 V but then decreases slowly (Fig. 17.1). This behavior is explained as the formation of three valence titanium on the surface of Ti-electrode (electrode becomes of blue color). Figure 17.2 depicts the dependence of dC_{Ti}/dt against the concentration of H_2SO_4 in solution for 6 min after beginning the electrolysis process. When the

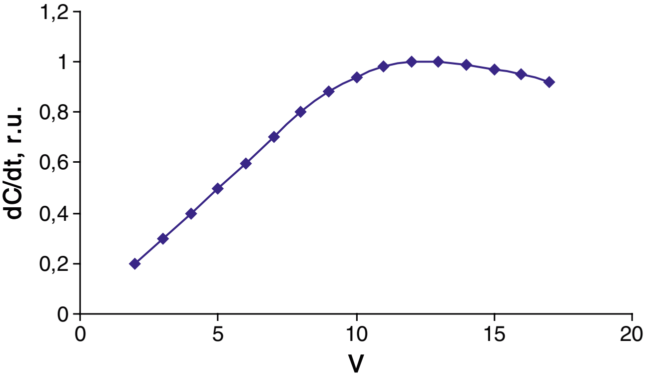

Fig. 17.1 Dependence of the titanium yield as a function of electrolysis voltage

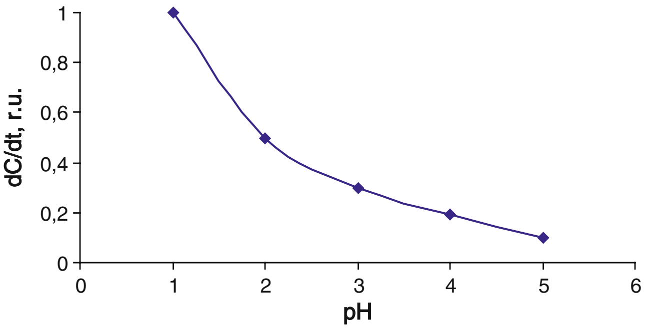

Fig. 17.2 Dependence of titanium yield as a function of solution pH

electrolyte pH is close to neutral, three valence titanium is formed on the surface of the Ti electrode.

In the first stage of electrolysis, when the Ti-electrode is an anode, the current between electrodes is about 3–4 mA/cm^2. Oxygen is released during the stage onto the titanium anode. Titanium oxides and sulfates are then formed on its surface and titanium ions leaving the anode are either oxidized near the surface of anode in the solution or they react with NCC active carboxyl groups. The thin semiconductor layer formed on the surface of the titanium electrode has a high resistance and small (about 3–4 mA/cm^2) electric current between electrodes. At the same time, the negatively charged carbon nanoparticles move away from the graphite cathode and functional groups such as carbonyl (>C═O), hydroxyl (–OH), and carboxyl (–COOH) are formed on the surface of carbon particles.

In the second stage of electrolysis after changing polarity, the electric current increases to 180–200 mA/cm^2 in about 0.1–0.2 s. During this stage, oxidation is occurring at the carbon anode. The magnitude of repulsion forces formed between the stacked layers of graphite becomes larger than van der Waals attraction forces

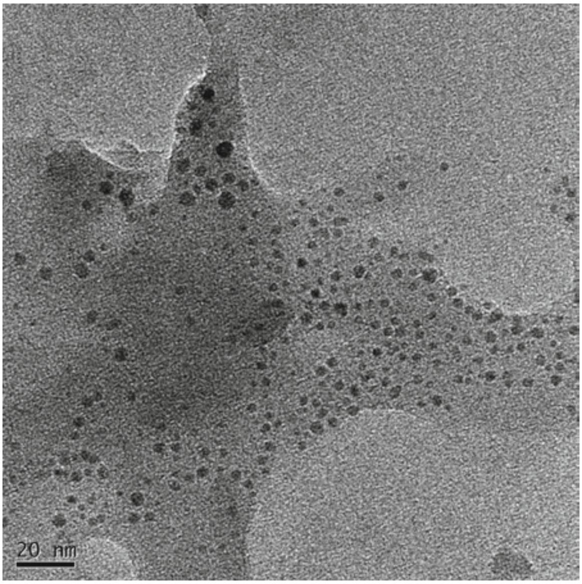

Fig. 17.3 Typical TEM micrograph of NCMC(Ti)

between the layers, initiating formation of carbon nanoparticles when polarity of the electrode is changed. The titanium cathode surface is cleaned from the oxides, and the electric current between electrodes increases up to 180–200 mA/cm^2. Titanium ions and charged particles of titanium oxide interact with carbon nanoparticles forming NCMC(Ti). Oxygen adsorbed on the surface of particles forms –Ti(OH)–O–Ti(OH)–, which can help the photo-generated holes h^+ to change into $OH^•$ free radicals. Otherwise, the oxidization activity of $OH^•$ is the strongest in aqueous solution. Typical TEM micrograph of NCMC(Ti) is given in Fig. 17.3 and shows that nanoparticles have a spherical morphology. Measurements of nanoparticles reveal their size is about 6 ± 2 nm.

Photodegradations of MeO solution, containing NCMC(Ti) as a photocatalyst, were analyzed for pH values of 1.0, 2.0 and 4.4. The relationships between the degradation degree of MeO and pH value of the solution under UV lamp and solar irradiation are shown in Figs. 17.4 and 17.5, respectively. Photodegradations of MeO were not observed in the sample without NCMC(Ti), and in the sample with NCMC(Ti) which was not irradiated by UV and sunlight. These results indicate that a low pH value can facilitate the decolorization reaction. This means that the number of $OH^•$ radical increases on the surface of NCMC(Ti) particles in solution by trapping electrons and H_2O can be absorbed on the NCMC(Ti) surface and reacts with h_{VB}^+ in Eq. 17.3, producing larger amounts of $OH^•$ radicals at a lower pH value. This can promote photogenerated electrons to transfer to the surface of NCMC(Ti) and react with adsorbed oxygen.

The photodegradation of cyanobacteria by NCMC(Ti) was studied under laboratory conditions. A colloidal solution of NCMC(Ti) was added to a Petri dish

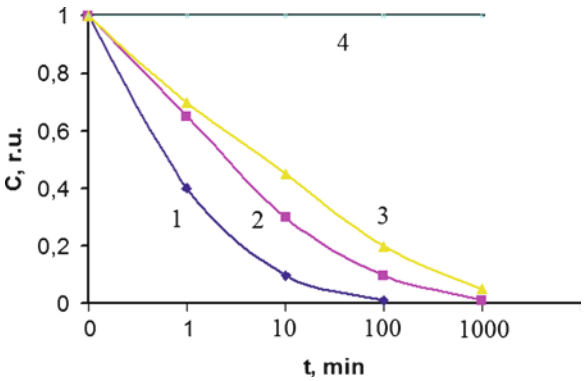

Fig. 17.4 MeO degradation degree under UV lamp: pH = 2.2 (*1*), pH = 4.4 (*2*), pH = 6.0 (*3*). Without NCMC(Ti) is curve (*4*)

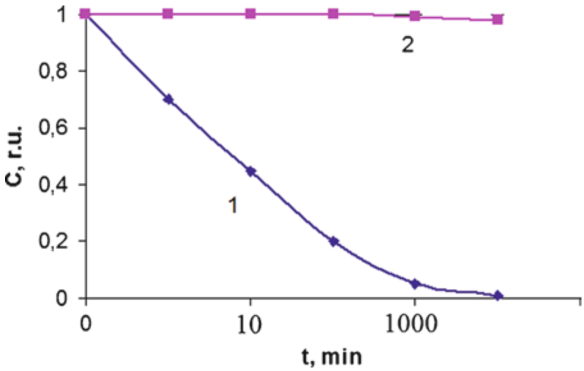

Fig. 17.5 MeO degradation degree under solar irradiation with (*1*) and without NCMC(Ti) (*2*)

containing water with cyanobacteria, placed under the sunlight at 8 a.m., and tested over a period of 24 h. Concentration of NCMC(Ti) in the mixed solution was 1 ug/l. Dependences of living cyanobacteria concentration in water samples irradiated by sunlight with and without NCMC(Ti) against a time are presented in Fig. 17.6. Photodegradation of cyanobacteria was not observed in the sample with NCMC(Ti) which was not irradiated by sunlight. These results demonstrate the efficacy of NCMC(Ti) photocatalysts to degrade cyanobacteria.

Field tests of the described technology were conducted on a 4 ha lake. The surface of the lake was treated using a 200 mg/l colloidal solution of NCMC(Ti) to achieve a 10 g/ha consumption of nanocompositions. At 8 am, the solution was dispersed for 30 min over the surface of the lake using a sprayer installed on a motor boat. Because the UV-light penetrates water to a depth of ~10 cm, the formation of OH-radicals was restricted to the upper water layers where cyanobacteria grow.

Nanocompositions in the water interacted with salt ions, organic molecules, and different organic and inorganic particles resulting in gradual coagulation and

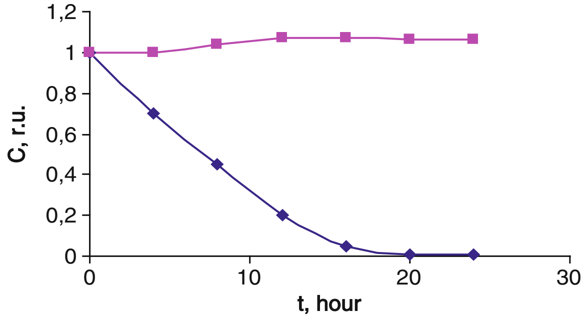

Fig. 17.6 Dependences of living cyanobacteria in water samples irradiated by sunlight with (*diamonds*) and without NCMC(Ti) (*squares*) against a time

precipitation in the form of large harmless water-insoluble particles. The rate of their sedimentation depends on water quality but usually is in the range of about 1–3 cm/h. Thus, during daylight hours, photonanocompositions can produce radicals within 3–8 h. Therefore the consumption of nanocompositions is low, about 10 g/ha or 50 l of aqueous solution of the nanocomposition with concentration of 200 mg/l.

During the second day, dead cyanobacterial clumps were found floating on the surface of the lake. After using a motor boat to break up these clumps, this material settled to the bottom over a 3–5 h period. During the next day, the transparency of lake water increased from 10 (initial) to 1,500 mm. These tests demonstrated that the efficacy of this new technology to removed cyanobacteria from water and regulate its concentration in open reservoirs over 2–3 days.

17.5 Conclusion

Electrochemically synthesized NCMC(Ti) colloidal solutions are highly efficient photocatalysts. Photodegradations of MeO can be done at NCMC(Ti) concentration of about 1 ug/l. The time of MeO degradation in the pH interval of 1–4.4 under a UV lamp is about 3–5 min and under sunlight is 2–3 h. This nanocomposition destroys cyanobacteria in water under the UV lamp in 8–10 min and under sunlight in 3–4 h. Under field test conditions, the consumption of nanocompositions is low (about 10 g/ha or 50 l of aqueous solution of the nanocomposition at a concentration of 200 mg/l); OH-radicals formed in the upper water layers where cyanobacteria grow; nanocompositions coagulate precipitating harmless water-insoluble particles within 1 day; and the transparency of water increased from 10 to 1,500 mm within 2 days. This new approach will provide a means to cope with cyanobacteria blooms occurring in response to global warming.

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Chapter 18
Risk Characterization of Contaminated Water Pathways and Toxicity Determination

Namik M. Rashydov

Abstract Radionuclide contaminants of most environmental significance are those taken up by plants; and have high rates of transfer to vegetable and animal products, such as crops, milk and meat, and have relatively long radiological half-lives. Soil type (particularly clay mineral composition and organic matter content), tillage practice, and climate affect radionuclide transport to rivers and groundwater. Prior to the Chernobyl accident, the respective concentrations of the ^{90}Sr and ^{137}Cs in the Pripyat water averaged 0.011 and 0.007 Bq/l. After some rainfalls, the respective concentrations of ^{90}Sr and ^{137}Cs in the Dnipro and Pripyat rivers ranged from 1.59 to 2.70 Bq/l and from 3.35 to 5.95 Bq/l. In contrast to ^{137}Cs, the radionuclide ^{90}Sr is transported by streams as a soluble compound (50–99%). Rainfall exacerbated contamination at the Chernobyl site by the addition of airborne radioactive particles (micro- and/or nano-sizes) to surface and ground-water system increasing genotoxicity to plants.

Keywords Climate • Radionuclide contamination • Autoradiography • Genotoxicity test-assay • Transfer coefficient • Micro- and nano- size radioactivity particles

18.1 Introduction

Increasing temperatures are attributed to climate change at various scales. The Caspian Sea is a valuable place to study climate change cause-and-effect on water levels, because they are related to atmospheric conditions in the North Atlantic Ocean thousands of kilometers to the northwest. The Caspian Sea levels changed in synchronicity with the estimated discharge of the Volga River, which in turn

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Table 18.1 The water levels of the Caspian Sea

Period	Environmental condition
79–70 B.C.	Transgression of the Caspian Sea
121–30 A.D.	Rise sea level from −36 m till −34 m
261–270	Within narrow limits risen sea level −32 m
311–320	Narrow fallen sea level −33 m
361–370	Formation delta of the Volga River
571–580	Sea level risen from −34 till −33 m
871–880	Risen sea level −29 m
1051–1060	Suspended process risen sea level
1929–1977	Sea-level fall of 3 m
1977–1995	Risen sea level of 3 m
2004	−28 m

depends on rainfall levels in its catchment. Levels of the Caspian Sea have risen and fallen many times over past centuries (Table 18.1) [1]. The last short-term sea-level cycle started with a sea-level fall of 3 m from 1929 to 1977, followed by a rise of 3 m from 1977 until 1995. Since then shorter oscillations have occurred. In 2004, the water level stabilized at about 28 m below sea level. Our data indicate that temperature is not the only critical environmental factor. Other factors, for example, radionuclide accumulations, are more dangerous in the environment than global temperature change because they may be irreversible.

The most important radionuclide contaminants are those taken up by plants; have high rates of transfer to animal products, such as milk and meat; and have relatively long radiological half-lives. The ecological pathways leading to plant contamination and environmental behaviour of radioactive isotopes are complex. The transport and fate are affected not only by physical and chemical properties of the radionuclide, but also by factors such as soil type and its tillage, species and cropping system of plants, seasonal climatic conditions, and where relevant, biological half-life within plants and animals. Direct radionuclide deposition on plants is the primary source of contamination in several temperature regimes. The ^{137}Cs and ^{90}Sr are relatively immobile in soil, and uptake by roots is of less importance compared with plant deposition. However, soil type (particularly with regard to clay mineral composition and organic matter content) and climate affect their transport to river and groundwater systems.

Contamination of aquatic ecosystems by radionuclide components follow: underwater layer of bottom sedimentation > aquatic hydrobionts > water. Whereas plants up take ^{137}Cs and ^{90}Sr by the same mechanisms as K and Ca respectively, the extent of their uptake depends on the availability of these elements. In contrast to ^{137}Cs, 50–99% of the radionuclide ^{90}Sr migrates in streams as a soluble compound. After the 1986 Chernobyl nuclear power plant (ChNPP) accident, radioactivity contaminated the Dnipro and Pripyat catchments and cooling pond of the ChNPP. The water was contaminated along several pathways by ^{141}Ce, ^{144}Ce, ^{103}Ru, ^{140}Ba, ^{131}I, ^{95}Zr, ^{95}Nb, ^{140}La, ^{134}Cs, ^{137}Cs, ^{90}Sr and other uranium fission and transuranium products. Since 1987, ^{137}Cs, ^{90}Sr and other transuranium radionuclide have contributed to the contamination. Before the Chernobyl accident, the respective concentrations of the ^{90}Sr

and ^{137}Cs in the river Pripyat averaged 0,011 and 0,007 Bq/l. Now the respective radionuclide concentrations of ^{90}Sr and ^{137}Cs in water range from 1.59 to 2.70 Bq/l and from 3.35 to 5.95 Bq/l.

The Chernobyl nuclear power plant is located close to the cooling pond and river Pripyat which discharge to the Dnipro river and reservoir system, one of the largest surface water systems in Europe. After an initial period, the radioactivity in rivers and reservoirs was generally below guideline limits for safe drinking water. The longer-lived radionuclides, such as ^{90}Sr, ^{137}Cs and transuranium isotopes, were adsorbed to surface soils preventing their transport to the groundwater system. However, significant transfers of radionuclides to the groundwater have occurred from waste disposal sites in the 30-km zone around Chernobyl. Although there is the potential for transfer of radionuclides from these disposal sites off-site, it is not significant in comparison to current levels of surface-deposited radioactivity wash-out. In case of migration of ^{137}Cs and ^{90}Sr, runoff played an extremely important role in transferring solid suspensions. When flooding occurred, the high level radioactivity associated with bottom sedimentation became mixed resulting in a multiple-fold increase of river water concentrations. In the 30-km radius surrounding Chernobyl, radioactivity was added by contaminated dust with very small sizes from nanometre to micrometer particles. After a rainfall, contaminated solids increased the radioactivity level of surface soil and water reservoirs which eventually settled as bottom sediment in the Pripyat and Dnipro rivers and cooling pond of the ChNPP. During the flood, the reverse process – transfer of high-sediment-suspension, this leads to a multiple increase in radioactivity of river waters. In this study, estimates and distribution of small-size radionuclide contaminates of the surface plant, soil and water was studied using autoradiography [2].

18.2 Materials and Methods

Plant samples collected from the contaminated Chernobyl region (*Erophila verna* (L.) *Bess)* and a controlled laboratory setting (*Arabidopsis thaliana)* were dried between paper sheets and then glued to glass slides. All slides were coated with a photo emulsion LM-1 in gel (Amersham – Biosciences, UK) and exposed for 20 days to a temperature +4^0 C. Afterwards, the slides were inspected for α-particle tracts using a light microscope (firm “Jenaval”, Germany) [2]. To study genotoxicity, we used three lines of the transgenic plant *Arabidopsis thaliana* L.; *RPD3-* gene histonedeacetylase, *SIR2*-gene coded protein deacetylate histones, *SU(VAR)* – gene suppressor variation and as reporter marker *GUS* – gene [3]. The seeds were soaked and grown in water from several lakes and rivers. Water genotoxicity in *Allium*-assay on induction of chromosome aberration was estimated and soils genotoxicity in *Tradescantia*-stamen-hair (*Tradescantia*-SH) assay on gene mutations was evaluated.

The study of mutagenic activity in water samples was carried out on *Allium cepa* L. seeds (Rashydov et al. 2004; [4]). The frequency of aberrant ana-telophases and mitotic index were scored in percent. Evaluation of total mutagenic activity of soils was performed with *Tradescantia clone 02* that is heterozygous for blue/pink alleles in their floral parts [5, 6]. All results were statistically processed, and a comparison between experimental variants and controls were conducted by χ^2-method. Plants also were collected from Chistogalovka and Chernobyl district villages where we discovered radioactive contamination by isotopes ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am up to 30 kBq/m^2. Measurement of the radionuclide ^{90}Sr was done using the method of settling and extinction analysis [7]. Measurements of specific activity ^{137}Cs in the soil and biological material samples was carried out using the gamma-spectrometry method. Spectrometry calibration was done using a standard loose gage EM66 with poured consistence 1.1 g/cm^3 with uncertainty of the specific activity radionuclide ^{137}Cs was 7% 2σ.

18.3 Results

We detected the distribution of decay tracks from several radioactive isotopes of small sizes on surface of soil and plants collected in a 30-km radius of Chernobyl (Fig. 18.1) and distribution ^{241}Am by tissues of the plant *Arabidopsis thaliana* which grown at contaminated ^{241}Am soil with specific radioactivity 10^5 Bq/kg in laboratory conditions (Fig. 18.2). The number of radiation tracks appearing on upper leaves (Figs. 18.1a and 18.2a) of phase rosette differed from leaves of the top apex (1b and 2b) of the plants white blow (*Erophila verna* (L.) *Bess.*) from Yaniv (1) and Chistogalovka (2), respectively. As shown in Fig. 18.2, the experiments under laboratory conditions reveal alpha-tracks from ^{241}Am decay in apical meristem of the *Arabidopsis thaliana*.

The transfer coefficient (TC) is a ratio of specific plant activities (kBq/kg) to specific activity of soil (kBq/kg). It characterizes movement of a radionuclide from the plant root to its vegetative parts. The TC calculated for radionuclide ^{137}Cs and ^{90}Sr revealed that fallout of these isotopes in the environment introduces additional contamination for top plants and those grown under laboratory conditions (Table 18.2). These experiments with soybean seedlings indicate that the TC for a vegetative plant path (0.008) was less than for top soybeans (0.019) under Chernobyl conditions. But for plants grown at Chistogalovka, the TC for radionuclide ^{137}Cs was 9.2 times greater than the Chernobyl samples. This is possible by foliar uptake of plant radioactivity micro- or nano-particles on leaves which move freely in the environment. There may be some dissipation of "hot" particles following the Chernobyl accident under influence of biotic and abiotic factors in soybean seedling resulting in uptake of radionuclide by foliar pathway in plants grown at Chistogalovka [8]. Our experimental data confirms that radioactivity fallout in the environment influenced the TC. As a result, the tracks reserve amount on the apex of a shoot and flower were observed.

After rainfall, isotopes accumulate on the surface of plants, soil, and water. In time, the dead plants and contaminated soil may be transported by erosion and settle with fallout to the bottom of the reservoirs. We conducted a risk assessment

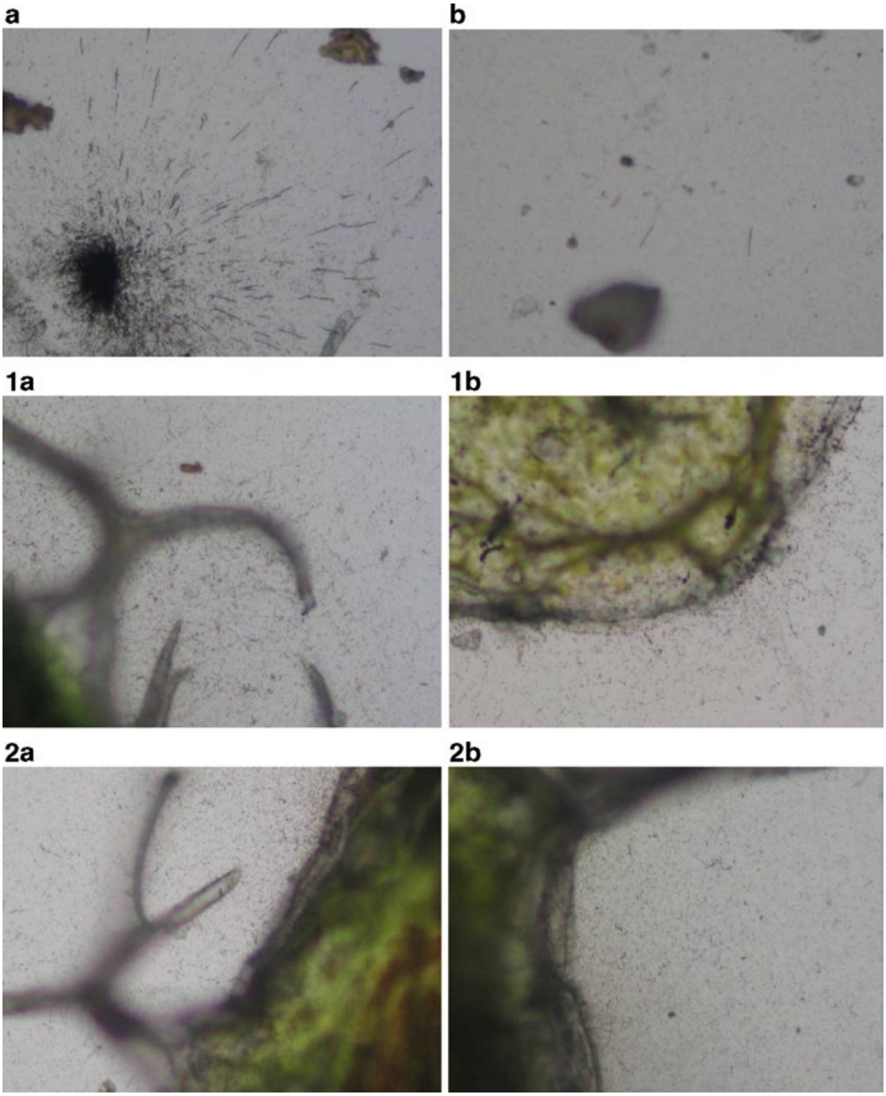

Fig. 18.1 Detection of radionuclide nano- and micro- sizes particles from soil Yaniv (**1**), from Chistogalovka (**2**), on surface of leaves (**a**) and top shoot apical meristem (**b**) of the plant white blow *Erophila verna* L.

based on genotoxicity effects of contamination with radionuclide ^{137}Cs and ^{90}Sr water and soil on transgenic lines *Arabidopsis thaliana* L. and compared this data with *Allium-assay* and *Tradescantia-stamen-hair- assay* (Table 18.3). Three plant assays (*Arabidopsis GUS-gene, Allium chromosome aberrations and Tradescantia stamen hair* mutations) are used to evaluate the genotoxicity of water reservoirs and soil sites from Chernobyl and Kyiv regions [5, 9].

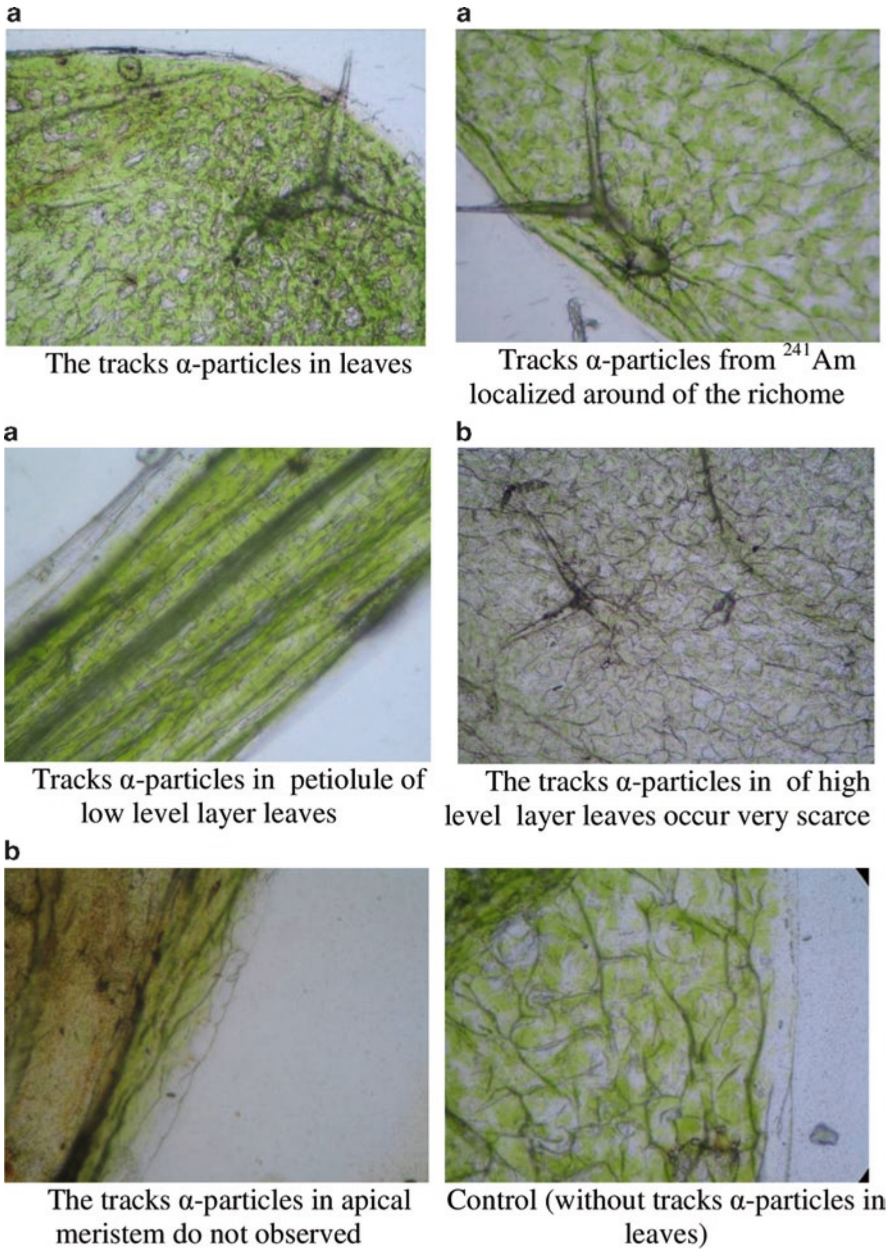

Fig. 18.2 Alpha-track distribution in low level layer of the leave tissues (**a**) top shoot apical meristem, (**b**) of the plant *Arabidopsis thaliana* grown in contaminated soil with radionuclide ^{241}Am in laboratory conditions where fallout of radionuclide contaminated dust was absent

Table 18.2 Measurement of radionuclide ^{137}Cs (Bq/kg) and ^{90}Sr (Bq/kg) for soil and soybean plants grown at the Chistogalovka village field experimental area, Chernobyl site, and under laboratory conditions. TC is the transfer coefficient for isotopes ^{137}Cs and ^{90}Sr

Site grow soybean plant	Content of radionuclide, Bq/kg		TC for ^{137}Cs	TC for ^{90}Sr
	^{137}Cs	^{90}Sr		
Top soybean (Chernobyl)	27 ± 2	1,720 ± 170	0.019	3.13
Chernobyl soil activity	1,414 ± 71	550 ± 55	–	–
Top soybean (Chistogalovka)	3,600 ± 144	54,000 ± 2,800	0.174	10.43
Chistogalovka soil activity	20,650 ± 1,050	5,180 ± 550	–	–
Top soybean (laboratory experiments)	13 ± 5	12 ± 2	0.008	0.021
Soil activity in laboratoryCondition	1,622 ± 71	560 ± 58	–	–

Table 18.3 Comparison of radioactivity in lakes, river, and soil using three test-systems (1) *Arabidopsis GUS-gene-assay*, (2) *Allium-chromosome aberration-assay,* and (3) *Tradescantia-stamen-hair- assay*

Samples	Radioactivity ^{137}Cs, Bq/l (Bq/kg)	Yield mutation, %	Level of reliability, P
GUS-gene activity in transgenic line *BAR/BinAR/RPD3-9/5 of Arabidopsis thaliana* L.			
Glyboke Lake	6.27	1.97 ± 0.10	<0.01
Pripyat River	0.07	0.25 ± 0.05	<0.05
Dnipro River (control)	0.02	0.21 ± 0.05	<0.05
Control (soil from Kyiv region)	110	0.21 ± 0.05	<0.05
Soil from Chernobyl	1,528	0.25 ± 0.05	<0.05
Soil from Kopachi	30,727	2.05 ± 0.15	<0.01
Soil content only ^{241}Am	10^5 Bq/kg	0.53 ± 0.08	<0.05
Level of chromosome instability *Allium cepa* L. cells induced by waters from reservoirs			
Control	0.01	1.93 + 0.45	<0.05
Telbin Lake	0.06	3.52 + 0.57	<0.05
Verbne Lake	0.02	5.85 + 0.75	<0.001
Berizka Lake	0.02	2.35 + 0.56	<0.05
Pushcha-Vodycja Lake	0.02	3.65 + 0.65	<0.05
Dnipro River	0.02	2.54 + 0.71	<0.05
Mutations induced in *Tradescantia-SH assay*			
Control 1	0.02	0.025 ± 0.024	<0.05
Telbin Lake	0.06	0.296 ± 0.082	<0.01
Verbne Lake	0.02	0.018 ± 0.018	<0.05
Berizka Lake	0.02	0.249 ± 0.051	<0.01
Dnipro River	0.02	0.109 ± 0.045	< 0.01
Dnipro River 1	0.02	0.104 ± 0.035	< 0.05

All samples taken from lakes revealed mutagenicity in *Arabidopsis GUS-gene, Allium* or *Tradescantia* assays. At the same time, only two of six probes of river soils were mutagenic. We supposed that local chemical pollution or relief features determined these effects. Studying the *Arabidopsis GUS-gene*-assay we found genotoxicity in water samples from lakes Glyboke and Telbin. By contrast, the samples taken from the Dnipro river did not show any mutagenic effects. Our experiments demonstrate that the lakes are more polluted by mutagens than river sites.

18.4 Conclusions

We found that transfer of the radionuclide ^{241}Am isotope from roots to top of the *Arabidopsis thaliana* plant was comparatively slow because the membranes served as an osmotic barrier [10]. Runoff played an important role in radionuclide transport. During flooding the radioactivity of bottom sediments was incorporated into the water column increasing the radioactivity by a many-fold increase. Radioactivity added from air-contaminated Chernobyl dust (nanometre to micrometer particles) too. Following rainfall, the deposition of this dust onto the surface of soil and water reservoirs increased radioactivity levels. By contrast, the radioactivity levels decreased in the Pripyat and Dnipro rivers and ChNPP cooling pond.

These data allowed us to develop a risk assessment approach for testing wastewater of Glyboke Lake, where radionuclide contamination with was considered high. We used sensitive plant assays to evaluate the genotoxicity of waters with different levels of radioactive pollution. Strong mutagenic effects were determined in water taken from Glyboke and Telbin lakes. Results obtained in all assays were related to the contaminated site levels.

Among scientists, there is a debate about the ChNPP cooling pond future. The problem is that the cooling reservoir surface is 7 m above the Pripyat river. This situation promotes annual discharge of about 100 million cubic meters of cooling water to the river. One solution being considered is the gradual draining of the reservoir. This will contribute to the formation of stable plant communities preventing dust transport in the form of micro-and nano-sized radioactive substances.

Radionuclide transformation in river water is a synchronous reflection of mobile species dynamics in soils that testifies to geochemical mechanisms controlling contaminant transport in the natural environment. For example bottom deposits of the Dnipro river reservoir system control the exchange of ^{137}Cs. Dynamic transformation of the ^{137}Cs from the solid phase in bottom sediment to water soluble form is described by logarithmical normal regularity, but the leaching of the ^{90}Sr from sediments occurs according to a first-order kinetic law. Total radionuclide transport into the Black Sea basin during 15 years is assessed as 200 TBq of ^{90}Sr and 20 TBq of ^{137}Cs [11]. There are times after a rainfall that Dnipro and Pripyat river concentrations for radionuclide ^{90}Sr and ^{137}Cs ranges from 1.59 to 2.70 Bq/l and from 3.35 to 5.95 Bq/l. In contrast to ^{137}Cs, the radionuclide ^{90}Sr migrates in river water as a soluble compound within the range of 50–99%. The increased genotoxicity of plant test-assays suggest that there also was significant radionuclide contamination In the Chernobyl area was added to surface water by rainout of atmospheric dust (micro- and/or nano-sizes).

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Chapter 19
Improved Methods for Conducting the Cadastre of Meliorative Condition in Irrigated Areas Subject to Climate Change

Rakhimdjan K. Ikramov, A.M. Samiev, and V. Muhtarova

Abstract In 1982, the Ministry of melioration and water industry (now called the Ministry of agriculture and water industry) began conducting the cadastre of meliorative condition of irrigated areas and technical condition of hydrameliorative systems. This cadastre is still performed according to methods created during the former USSR. Today, these methods do not meet requirements of practice under conditions of increasing deficiency of water resources, their deterioration, and climate change. In this study, the acceptable depth to ground water (LGW) for different hydrogeologic and soil conditions is investigated. Methods for ensuring that a sufficient water supply exists for irrigated areas are developed based on irrigation and climatic factors and degree of area drainage. In the assessment of meliorative condition indicators, we suggest that investigators analyze the evolution over the most recent 3–5 years taking into account their degree of stability during and crop capacity. To justify the repair-and-renewal operations and construction work on irrigational-drainage systems, the new methods are based on actual fluid-and-electrolyte balances and engineering of the hydraulic structures.

Keywords Climate change • Management • Water resources • Irrigated area • Cadastre • Assessment • Ground water • Sufficiency of water supply • Degree of drainage

19.1 Introduction

Since 1982, an annual cadastre has been compiled by the Operational-Hydroeconomic Services. The cadastre is a tool for water resources management on irrigated areas and hydrameliorative systems (HMS). Today, this cadastre does not meet current requirements because of several drawbacks. First, the meliorative condition of irrigated

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areas (MCIA) is assessed by comparing actual average depth to groundwater (LGW) during the vegetation period and degree of soil salinization in autumn with their acceptable value (even though the meliorative well-being may be reached over a range of LGW and different infiltrations). Second, of the factors directly influencing MCIA, only the infiltration for vegetation is considered. The mineralization and quality of water are not taken into account. The degree of drainage is not determined and assessed at all. Third, the necessity of capital repairs and reconstruction of water facilities and drainage system is established only by comparing actual depth of LGW against an acceptable value without taking into account cause effect relation.

We suggest that the cadastre be used for the following problems: (1) guaranteeing a favorable water-salt regime of soil and ground water; (2) reaping a good harvest; (3) maintaining a sufficient water supply during the vegetation period; and (4) providing safety of hydrameliorative systems; that is, minimizing negative ecological implications of meliorative activities and creating the required economic and social conditions on HMS (agricultural products) on meliorated areas. To solve these problems, it is necessary to ascertain assessment criteria of the meliorative activities, structure and assessed value of indices (which can vary spatially and temporally).

19.2 The Assessment of the MCIA

Meliorative condition of the area is assessed according to categories: good, satisfactory, and unsatisfactory; depth to ground water, and soil salinity. The area is assessed unsatisfactory by meliorative condition under the following criteria:

$$h\varphi<[h];\ S\varphi>[S]\ \text{И}Ece_{\text{ф}}>[Ece] \tag{19.1}$$

where $h_{\text{ф}}$, $\lceil h \rceil$ is the actual and acceptable depth to ground water; $S_{\text{ф}}$, $\lceil S \rceil$ is the actual and acceptable degree of soil salinization; and $Ece_{\text{ф}}$, [Ece] is the actual and acceptable soil conductivity. Acceptable values were established for different soil-climatic zones by the Ministry of melioration and water industry [1]. Under modern conditions, however, sufficiency of the water supply in irrigated areas depends on the quality of water and structure of the crops. Taking into account these factors according to the methods of Ikramov, R. [2] and actual observations, the acceptable depth to ground water was determined for irrigated areas of Uzbekistan (Table 19.1).

Assessment methods of MCIA, taking into account the directivity of its values, were developed to improve the conducting of the cadastre. The dynamics of values during the last 3–5 years is analyzed and assessment specified taking into account their “stability” or “instability” from past to modern times. Assessment categories of the meliorative process are suggested (good, satisfactory, and unsatisfactory), and it may be considered stable if MCIA meets the requirements of the criteria of these categories. The MCIA is considered unstable if the meliorative process does not meet requirements of the criteria or if it varies. A computer program is used to assess the MCIA taking into account directivity of value changes. Extra meliorative activities are not recommended on the areas with good and satisfactory MCIA.

Table 19.1 Zonal meaning of acceptable midvegetation depth of the bedding level of groundwater on irrigated area (for conducting cadastre of land reclamation condition of irrigated area)

No.	Genetic type of relief	Climatic zones and moistening zones	Types of soil covering	Regions, areas irrigation system	Granulometric composition of the soil and the basement rock (in the layer up to 4 m)								Note
					Clay sand, sand				Loam, clay and layered				
					Midvegetation depth of groundwater occurrence (in m,) by mineralization								
					Less than 1 g/l	1–3 g/l	3–5 g/l	5–10 g/l	Less than 1 g/l	1–3 g/l	3–5 g/l	5–10 g/l	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Turan lowland the delta and the lower reaches of the Amudarya river	Desert zone, very dry K_y=0.12	Meadow, marsh flood-plain	Karakalpak ASSR	–	1.1–1.3	1.5–1.6	1.6–1.7	–	1.3–2.2	1.8–2.8	2.0–3.1	Minimal value of acceptable depth is used for chloride and sulphate-chloride types of aeration zone salinization: Maximal value is used for chloride-sulphate and sulphate types of salinization
2	Turan lowland the lower reach of the Amudarya river	Desert zone, very dry K_y=0.12	Outdated irrigated meadow	Khorezm region	–	1.2–1.4	1.5–1.6	1.7–1.8	–	1.5–2.3	1.8–2.8	2.0–3.2	
3	Turan lowland	Desert zone, very dry K_y=0.12	Desert takyr alkaline brown-grey	Bukhara region	1.2–1.3	1.2–1.4	1.5–1.6	1.7–1.8	1.5–1.7	1.5–2.4	1.8–2.9	2.1–3.2	
4	Turan lowland foothills and intermontane region	Desert zone, very dry K_y=0.12 semidesert zone, semidry K_y=0.12, 0.33	Meadow and desert takyr, Sierozem	Surkhandarya region	1.3–1.4	1.3–1.4	1.5–1.6	1.7–1.8	1.5–1.7	1.5–2.4	1.9–2.9	2.1–3.2	
5	Foothills and intermontane region	Desert zone, very dry K_y=0.12	Sierozem meadow and meadow marsh	Syrdarya region	1.0–1.1	1.0–1.3	1.4–1.5	1.6–1.7	1.2–1.6	1.2–2.1	1.7–2.6	2.0–3.0	

Operational and capital activities on HMS are necessary on areas where the MCIA is unsatisfactory.

It is suggested to assess the MCIA using characteristics of critical meliorative regimes because in practice we deal with meliorative systems of different and very often nonoptimal characteristics. By critical meliorative regime, we mean a set of soil conditions, such as irrigation, washing, agrotechnology, drainage, which provide high fertility and maximal crops by large depth intervals LGW (lower than root-inhabited layer). The characteristics of critical meliorative regimes are based on meliorative process modeling and hydromeliorative system operation by water-salt balance of the area under crops, efficiency of the irrigating system, the coefficient of irrigation area, values II-O and water escape [2].

When assessing a meliorative condition, it is suggested to use data on the crop capacity of cotton and wheat. Categories for crop capacity of cotton are more than 32 c/ha, high 24–32 c/ha, low 16–24 c/ha, and very low fewer than 16 c/ha. Categories for crop capacity of winter wheat are more than 48 c/ha, high 36–48 c/ha, low fewer than 24–36 c/ha, and very low fewer than 24 c/ha. If LGW depth and soil salinization are unsatisfactory, but the crop capacity is high then the final assessment of MCIA is considered satisfactory. At the next stage, we determine the factors which form the MCIA (with the help of analyses of main factors influencing on it by serial exclusion); and the reason and types of activities which must be done to guarantee meliorative well-being of the areas (Fig. 19.1).

19.3 Efficiency of Water Supply Assessment

Scientific basis for efficiency of water supply assessment is the empirical dependence of crop capacity on water consumption under different climatic regions. Under the condition of water resource deficiency, low water and land efficiency, it is suggested to take into account the sufficiency of water supply not only during the vegetation period but also its distribution within this period (that is, the regime of crop irrigation), and also the mineralization of irrigating water, which is not done when conducting the present cadastre.

Efficiency of the water supply assessment for an irrigated area is calculated for every farm area. It consists of an average assessment over 3–5 years of actual water infiltration for crops conforming to the conditions of maximal crop growing. The irrigated area is considered supplied with water if:

$$M_{\phi} \cdot \eta_c \prec K_B \cdot M_p^{C.B.} \tag{19.2}$$

where M_{ϕ} is the water abstraction over a 5 year vegetation period (1,000 m^3/ha); η_c is the coefficient of efficiency of irrigation system; K_B is the coefficient of acceptable decrease in average irrigation rate by which crop capacity decreases on and more than 10% of maximal crop capacity, which value is 0.83 (according to the general conclusion made by scientific production association CASRI); $M_p^{C.B.}$ is the

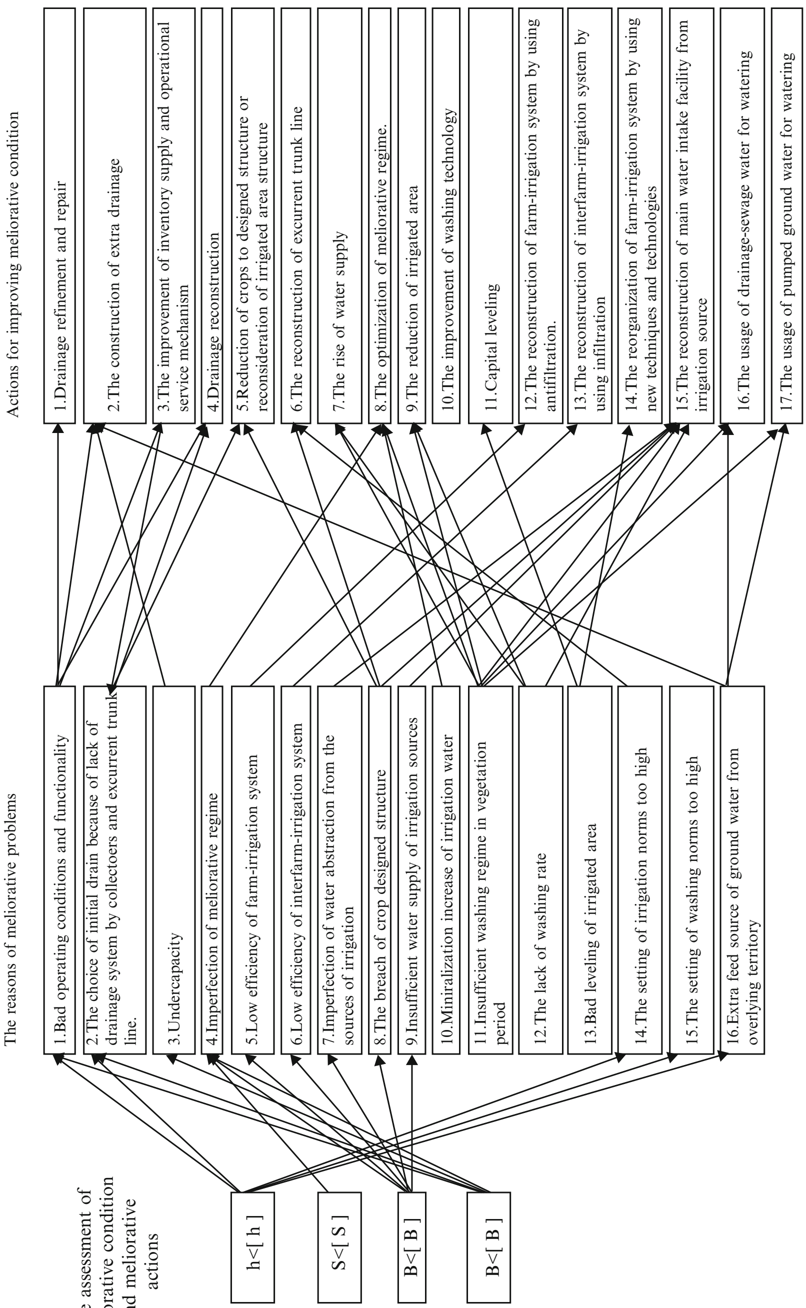

Fig. 19.1 The scheme of analysis and the choice of actions conducting the meliorative cadastre

value of calculated weight average irrigation rate with actual structure of crops taken into account (in favorable land conditions with water mineralization up to 1 g/l of unsalted land and ground water).

Depending on water mineralization and indices of the meliorative land condition, a correction is introduced into the equation as follows:

$$M_{\phi} \cdot \eta_{c} \prec K_{B.} M^{C.B.} \cdot \psi \qquad (19.3)$$

where the coefficient value $\psi \rightarrow$ psi is accepted according to the recommendations of Ikramov, R [2].

Under the condition of water resource deficiency and in the presence of large areas inclined to salinization, it is necessary to determine the efficiency of water supply over the period between vegetation (from November to April) using:

$$B_{З}^{MВ} \eta + B_{КДВ} < K_{B}^{MB} [B]^{MB} \psi^{CC} \qquad (19.4)$$

where B_{3}^{MB} is the specific water abstraction for the period between vegetation, 3/га; and $B_{КДВ}$ is $_{\text{the}}$ supply for collector-drainage water irrigation, м³/га.

Water feed is necessary during the period between vegetation and is calculated using:

$$\left[B^{MB}\right] = \sum_{i-S_O}^{S} \sum_{0}^{F} N_{ij} f_{ij} + \sum_{i-1}^{n} m_{j}^{B3} f_{j}^{B3} \qquad (19.5)$$

where N_{ij}, f_{ij} is the washing rate and area with i-level of salinization; j is the mechanical structure; S, S_O is the initial and acceptable degree of soil salinization; m_{j}^{B3} is the rate of moisture filled watering for soil with i mechanical structure; f_{j}^{B3} is the area with i mechanical structure, which requires moisture filled watering; K_{B}^{MC} is the coefficient of acceptable water feed reduction in the period between vegetation.

19.4 The Assessment of Irrigated Area Drainage

Drainage area in the arid zone is an important condition of melioration (not currently determined when conducting the cadastre). It is almost impossible to reveal the influence of only one drainage factor on the harvest. The following dependence for Golodnaya steppe was revealed on the basis of mathematical models for the meliorative process and empirical connections of cotton harvest from soil salinization [3, 4] (Fig. 19.2).

For assessing artificial land drainage, it is necessary to divide the actual drainage of the collector network into components: irrigation escape water ($C_{П,} C_{Э}$) and ground water drainage (D_g); that is:

$$\text{Ddcn} = \text{Dg} + \text{CП} + \text{C э} \qquad (19.6)$$

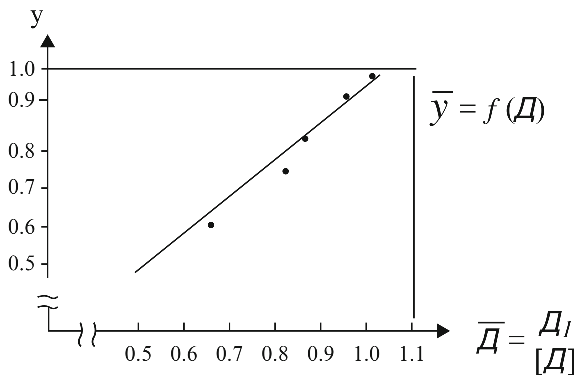

Fig. 19.2 The dependence of relative crop capacity on drainage decreases in comparison with "critical" value for the Golodnaya steppe

The contributions of these drainage collector network components are based on the physical method of Kudelin, hydrochemical method of Engulatov, and empirical method of Ikramov [2].

The following method is suggested to assess drainage. Two cases are provided on the basis of the degree of artificial drainage dependency, and on the technical condition of drainage facilities. In the first case, the efficiency of water supply of irrigated areas is normal; that is

$$B_{\Phi} = [B] \tag{19.7}$$

where $B_{\Phi,}$ [B] is the actual and necessary conformity with water abstraction norms, м^3/га. The territory is considered to have enough drainage if

$$D_{\Phi} \geq K_d[D] \tag{19.8}$$

where D_3 [D] is actual and necessary land drainage, м^3/га; K_d is the coefficient of acceptable drainage decrease. It may also be accepted under conditions of crop capacity decreasing no more than 10% of maximal crop capacity by analogy with K_B **.** In accordance with Picture 2 K_d=0,9. In the second case, the efficiency of water supply of irrigated areas is insufficient:

$$B_{\Phi} < K_B\,[B]\cdot \tag{19.9}$$

The territory is considered to have enough drainage if

$$D^{\Phi} > 0.8[D]^* \tag{19.10}$$

where *[D]** is determined as a characteristic of critical meliorative regime by concerned water infiltration.

19.5 Conclusions

A new approach to the MCIA assessment is presented that considers water infiltration and artificial land drainage under climate change conditions. To reveal areas on hydromeliorative systems which need capital irrigation and drainage network repairs, the calculations of Ikramov [2] are used. The introduction of these aspects into the cadastre work is now possible given the speed and memory of modern computers. The transition of hydroeconomic organizations to this approach will be possible by training their staff. For these purposes, the author prepared the project "The guide on the control methods, the assessment criteria and conducting the cadastre of meliorative condition of irrigated areas of Republic of Uzbekistan".

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Chapter 20
Trends of Irrigation Development in the Kyrgyz Republic Within the Context of Climate Change

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Abstract The climatic change hazard in the Kyrgyz Republic is the potential reduction of mountain runoff to rivers. This is because agriculture, a basis of state economy, depends on irrigation water from mountainous rivers. The current shortage in surface water resources provides a motivation for increasing the irrigation system efficiency and use of ground waters for irrigation. The surface and ground waters of intermountain valleys of Kyrgyzstan are interdependent. The efficiency improvement of irrigation systems reduces recharge of ground waters and, from the point of view of their budget, is the same as using ground waters for irrigation. These factors reduce flow of ground waters into downstream areas, where they discharge into surface water sources. That is, the replenishment of surface water resources at the expense of ground waters leads to reduction of surface and ground water resources in the underlying areas. This paper shows demonstrates the mentioned process occurs but with a long time delay. The periods of delay may be more than 20 years, giving time for the introduction of agriculture technologies intended for use of smaller quantities of water. The equations suggested here can be used for similar calculations in other intermountain valleys of Central Asia.

Keywords Ground water flow • Influence of irrigation development • Climate change protection • Kyrgyz Republic • Chu Valley

20.1 Introduction

Irrigation farming is the basic source of foodstuffs for the Kyrgyzstan population. Because the mountainous rivers provide water resources for irrigation, any persistent change in climate will influence discharge resulting in a threat to food safety and security of the country.

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Sources providing water to rivers in the study area are melt-waters of snow and glaciers, demonstrating the dependence of runoff to climate warming. Even now, rivers of the glacier-and-snow type are characterized by increases in runoff and discharge along with corresponding reductions in low-hill regions. This is due to the intensity of deglaciation and reduction of snow areas. The current average rate of glacial retreat is about 6–8 m per year. The continuation of this retreat process will result in decreasing streamflow that will become appreciably notable. To mitigate these consequences, the following groups of problems are to be studied.

1. Water loss reduction and implementation of water-efficient irrigation processes. Now, water losses both in the irrigation network and on the farmlands is about 70% of the total water draw-off at the irrigation source.
2. Design and construction of additional reservoir storage to accumulate the river run-off for subsequent irrigation.
3. Use of waste and drainage water for irrigation.
4. Use of groundwater for irrigation.
5. Effective monitoring of ground and surface water resources, as well as of reclamation conditions of irrigated lands.

20.2 The Impact of Irrigation Development on Changes in the Groundwater Balance

This section considers irrigation development examples in the Chu valley of Kyrgyzstan. In these examples, the consequences of groundwater use for irrigation and increase of the irrigation system efficiency in the context of climatic change are addressed. The effect of the mentioned factors on changing groundwater budget also is addressed.

20.2.1 The Western Part of the Chu Valley

In the area of groundwater recharge (Fig. 20.1), a reconstruction of the irrigation system was carried out. As a result, the inflow of groundwater at the expense of irrigational losses has decreased significantly. For this reason, it is necessary to assess changes in the reduction of groundwater flow to subjacent areas of the Chu valley. See a typical cross section in Fig. 20.2.

This problem can be solved by means of ground water modeling. However, a more convenient approach is to derive an approximation formula in which parameters are defined by means of a one-off simulation [1]. This formula can then be used to assess various problems in connection with the effect of groundwater recharge on adjacent hydro-geological areas. A general groundwater flow equation can be written as

$$Q(t) = Q_e + (Q_s - Q_e) \cdot e^{-t \cdot \beta(t)} \tag{20.1}$$

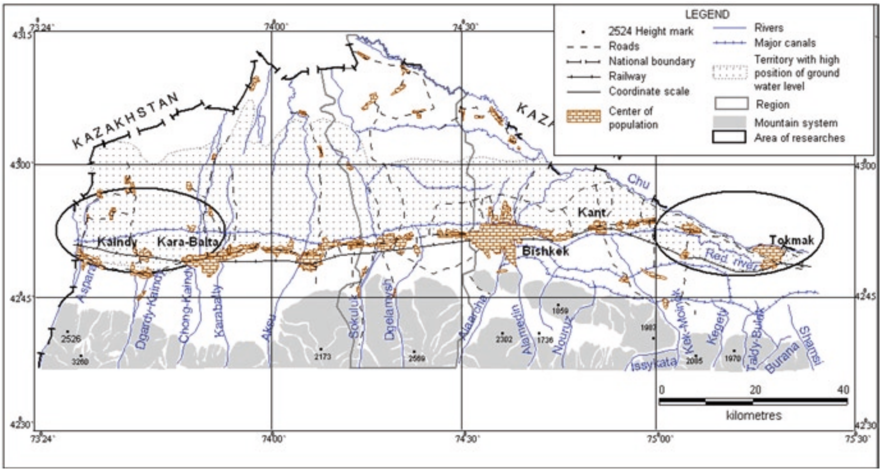

Fig. 20.1 Map of the Chu Valley, northern Kyrgyzstan

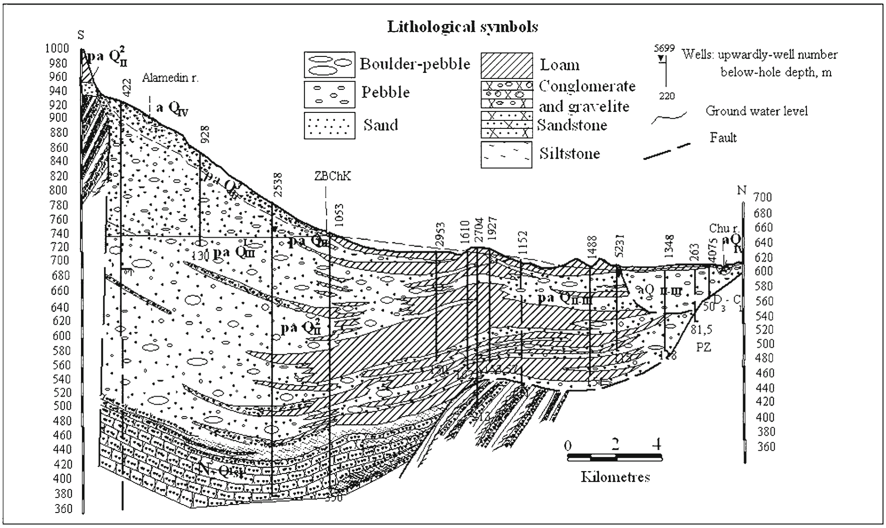

Fig. 20.2 Typical cross section of the western Chu Valley

where Q(t) is the groundwater outflow from the groundwater recharge area into downstream areas of groundwater discharge (assessed value), m^3/day; Q_s, Q_e are the initial and final steady state groundwater outflows (assessed by mass balance), m^3/day; e is the base of natural logarithm; t is the period of time, days;

$$\beta(t) = \frac{a}{L^2} \cdot \gamma(t) \quad a = \frac{T}{\mu} \tag{20.2}$$

T is the transmissivity (characterizes both groundwater recharge and discharge areas, m^2/day; μ is the storage coefficient; L is a representative distance from a mountain framework to the border of a discharge area, m; and γ(t) is a dimensionless parameter characterizing the specific natural settings of the considered hydrogeological areas, it is assessed by the results of simulation of the area of interest, and it can be time dependent.

The following approach is suggested to estimate γ(t) conditions in central and western parts of the Chu valley. In the beginning, the outflow from the area of groundwater recharge within specific periods is estimated based on the simulation results: t1 = 1 year, t2 = 3 year, t3 = 5 years, t4 = 10 years, and t5 = 25 years. By summing up the results, the dependence for γ (t) can be computed as follows:

$$\gamma(t) := \begin{cases} \gamma 1 & \text{if } t \le t_4 \\ \gamma 2 & \text{if } t \ge t_5 \\ \gamma 1 + (\gamma 2 - \gamma 1) \cdot \dfrac{t - t_4}{t_5 - t_4} & \text{if } t > t_4 \wedge t < t_5 \end{cases} \tag{20.3}$$

γ_1 is evaluated by minimization of the function

$$F(\gamma) = \sum_{i=1}^{4} (Q\,(t_i) - \overline{Q}_i)^2 \tag{20.4}$$

where $Q(t_i)$ is set by expression (20.1) at the time point t_i, m^3/day; Q_i is an outflow of groundwater from a groundwater recharge area into a groundwater discharge area at time t_i, m^3/day; and γ2 is defined by the following dependence:

$$\gamma_2 = \frac{L^2}{\alpha t_5} \,\mathrm{Ln}\, \frac{Q_S - Q_E}{Q_5 - Q_E} \tag{20.5}$$

Estimates using the above equations were done for the western Chu valley. The following parameters were used: T = 3,000 m^2/day; L = 12,000 m; μ = 0.2; γ_1 and γ_2 equal to 2.175 and 1.320, respectively. In accordance with one possible development scenario, QS = 3.88 m^3/s, QE = 0.93 m^3/s [2].

The change of groundwater outflow from the groundwater recharge area in response to reduction of filtration losses is shown in Fig. 20.3. This graph indicates that within about 8 years, the outflow of groundwater into adjacent areas will be reduced to a value of 0.5 ($Q_S - Q_E$). The expected reduction of outflow to a value $Q_S - Q_E$ will occur within 30–40 years. These results suggest that a reduction of groundwater in the area of recharge resulting from climate change will not trigger an immediate change to the hydrologic budget; thereby allowing time for making necessary decisions and system adjustments. Multiple estimates of the response time also can be made with the use of Eqs. 20.1–20.5. As far as the central and western parts of the Chu valley are concerned, the values γ_1 and γ_2 can be used in calculations.

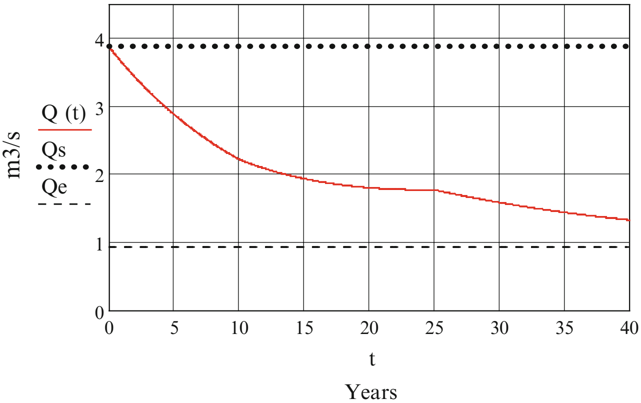

Fig. 20.3 Changes of groundwater inflow from the groundwater recharge area into the discharge area at reduction of filtration losses from value Q_S to value Q_E

20.2.2 The Eastern Part of the Chu Valley

A primary irrigation development challenge, during conditions of climate induced streamflow reduction, is to prevent filtration losses from the river Chu at a reach 48 km along the river entry into the Chu valley. An estimate of losses in this area (the so-called crevasse zone) is about 20 m^3/s. One potential solution is to construct a second bypass canal that is lined by concrete.

It is necessary to point out that filtration losses are discharged into the river Chu downstream (below town Tokmak). Reduction of filtration losses will result in a reduction of discharge into downstream areas. One consideration to address prior to the construction of a bypass canal is the time interval within which the reduction of losses will influence groundwater discharge to the riverbed. A section of the area of interest along the riverbed is provided in Fig. 20.4.

Alteration of discharge downstream of Tokmak is characterized by the change of groundwater flow near Tokmak ΔQ(t). To estimate the required amount, we use the analytical equation of S. F. Averyanov [3] given by

$$\Delta Q(t) := \Delta QN \cdot \left[1 - \frac{8}{\pi^2} \cdot \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{(2 \cdot n - 1)^2} \cdot \sin\left[\frac{\pi}{2} \cdot (2 \cdot n - 1)\right] \cdot \exp\left[\frac{-\pi^2 \cdot (2 \cdot n - 1)^2}{4} \cdot \frac{a \cdot t}{L^2}\right]\right] \quad (20.6)$$

where ΔQN is the amount of filtration losses change in the crevasse zone of the river Chu, m^3/day; t is a period of time from the moment of the filtration losses change, days; $a = T/\mu$ is a ratio; T is the hydraulic transmissivity, m^2/day; and μ is the storage coefficient.

Hydrogeologic investigations of this area [4, 5] provided the following parameter values: $T = 10{,}000$ m^2/day, $\mu = 0.18$, and $L = 48{,}000$ m. Typical value of filtration

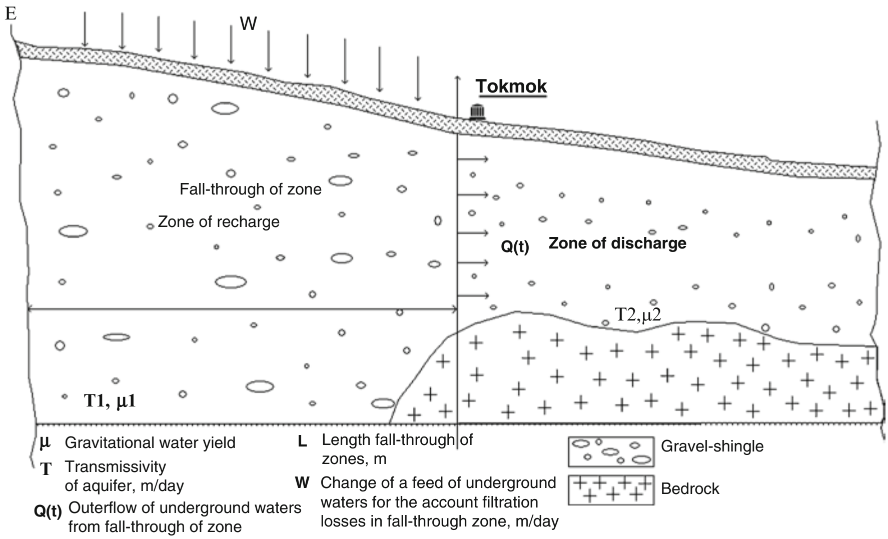

Fig. 20.4 Cross section of the Chu River located in the east part of the Chu valley

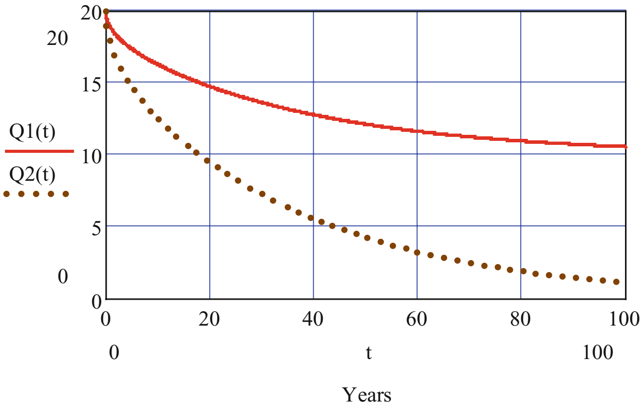

Fig. 20.5 Alteration of the groundwater flow near Tokmak in response to filtration losses (Q1(t) – decrease of losses by 10 m^3/s; Q2(t) –decrease of losses by 20 m^3/s)

losses in the crevasse zone were determined to be about 20 m^3/s [5, 6]. Using these data we considered loss events (1) losses decreased by 10 m^3/s, and (2) losses decreased to zero (reduction by 20 m^3/s). The results of calculations in are presented in Fig. 20.5. The results indicate that a reduction of filtration losses will result in decreased discharge, however, it be delayed over many years. For example, within the period of 20 years, the outflow into the groundwater discharge area will decrease only 50% of the filtration losses reduction volume.

20.3 Conclusions

As it is stated above, the major potential hazard to conditions of the Kyrgyz Republic from the climatic change is reduction of the mountain rivers runoff. This statement is correct as agriculture (being a basis of economy of the state) is based on irrigation farming. Mountainous rivers are the main source of irrigation. Because of shortage of surface water resources, the problem arises as to increase of the irrigation systems efficiency and use of ground waters for irrigation.

It is necessary to keep in mind, that surface and ground waters of intermountain valleys of Kyrgyzstan are closely interdependent. The increase of the efficiency of irrigation systems reduces recharge of ground waters and, from the point of view of their balance, is the same as using ground waters for irrigation. The mentioned factors reduce flow of ground waters into downstream areas, where they discharge into surface water sources. That is, replenishment of shortage of surface water resources at the expense of ground waters leads to reduction of surface and ground water resources in the underlying areas. The present paper shows that the mentioned process occurs but with a big delay. The periods of delay may more than 20 years, and this gives time for introduction of agriculture technologies intended for use of smaller quantities of water. The dependences suggested in this paper can be used for similar calculations as far as other intermountain valleys of the Central Asia are concerned.

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Chapter 21
Groundwater Evapotranspiration – Underestimated Role of Tree Transpiration and Bare Soil Evaporation in Groundwater Balances of Dry Lands

Maciek W. Lubczynski

Abstract This paper analyzes and emphasizes the importance of groundwater evapotranspiration (*ETg*) in groundwater balances. The *ETg* diminishes the net groundwater recharge that constrains groundwater flow and replenishment of groundwater resources. The *ETg* consists of two different components, groundwater transpiration (*Tg*) and groundwater evaporation (*Eg*), both not yet well identified in hydrogeology. The *ETg* values are the largest in dry locations with shallow groundwater table. The significance of the *ETg* however is the largest when its relative contribution to groundwater balance is high i.e. when its rate is comparable with groundwater recharge.

Keywords Groundwater balance • Transpiration • Evaporation • Dry lands • Modeling

21.1 Introduction

Groundwater represents more than 95% of fresh water resources of the earth, so it is the most reliable source of usable water. The abstraction of groundwater however is not the easiest and the cheapest but its quality is usually by far the best. As such, the management of this precious resource should be done carefully. The management of groundwater resources is typically realized by groundwater models which rely on groundwater balances. It is therefore imperative that the groundwater balance

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components (groundwater fluxes) are defined in reliable way so that groundwater balance can be closed accurately. For the elementary unit of an aquifer, groundwater balance equation is:

$$Q_{Gin} + R = Q_{Gout} + ET_g + / -DS + / - Q_{ext} \tag{21.1}$$

where: Q_{Gin} : groundwater inflow (in case of 2-D solution this would be lateral inflow), R : groundwater recharge, Q_{Gout} : groundwater outflow (in case of 2-D solution this would be lateral outflow), ET_g : groundwater evapotranspiration, ΔS – change of groundwater storage; Q_{ext} : external groundwater sink and sources (for example well abstraction).

It is widely assumed that the main and the most common driving force of natural groundwater flow is groundwater recharge. However, in many places of the world, particularly in dry, water limited environments (WLE) defined by Abrahams and Parsons [1] as areas where yearly $P/PET < 0.75$, the recharge is reduced in dry seasons by the influence of groundwater evapotranspiration (ET_g). The ET_g represents in situ water loss from saturated zone or its capillary fringe hydraulically linked with an aquifer [2]. When ET_g is present and significant, the driving force of groundwater flow is the net recharge (R_n). The R_n is defined as:

$$R_n = R - ET_g \tag{21.2}$$

It is the R_n, and not the R, that is responsible for the replenishment of groundwater resources. Therefore quantifying ET_g is important particularly in groundwater management of dry lands. This paper aims at emphasizing this importance by presenting the ET_g and discussing its role in groundwater balances.

21.2 Groundwater Evapotranspiration

The groundwater evapotranspiration (ET_g) which is part of total evapotranspiration, represents two different processes and therefore consists of two different components, groundwater transpiration (T_g) and groundwater evaporation (E_g):

$$ET_g = T_g + E_g \tag{21.3}$$

Groundwater transpiration (T_g) is defined by Lubczynski and Gurwin [3] and Lubczynski [4] as the root water uptake from groundwater or the capillary fringe while groundwater evaporation (E_g) as the liquid and/or vapor water loss from groundwater or the capillary fringe. The capillary fringe is indicated in both definitions because when linked with groundwater, its local loss, for example due to root water uptake or direct evaporation from water table, is replenished by water originated from the aquifer so such process occurs at the expense of groundwater. The ET_g affects mainly dry, water limited environments during dry seasons when there is large potential evapotranspiration (PET) and large air vapor pressure deficit (VPD).

21.3 Groundwater Transpiration

Many studies documented already cases where plants called phreatophytes, mostly trees with deep roots, uptake groundwater. That amount of groundwater is known as groundwater transpiration (T_g). The estimate of T_g is not an easy task because standard methods of transpiration measurements can handle determination of total transpiration (T_t) which next to T_g includes also unknown water uptake by shallow roots from unsaturated zone moisture (T_u).

$$T_t = T_g + T_u \quad (21.4)$$

Water limited environments are characterized by long dry seasons that enforce various plant adaptations to overcome shortage of water resulting in water stress. Some of these adaptation strategies involve use of groundwater (T_g) when other sources of water are unavailable. The phreatophyte groundwater uptake is hydrogeologically relevant in locations, where phreatophytes are abundant and their T_g is significant as compared to other groundwater fluxes. The significance of T_g in water balances is the largest in very dry environments with shallow aquifers.

The exact mechanism of water uptake by plants is not known yet. There are two theories in that respect, cohesion-tension theory [5] and multi-force theory [6]. The common aspect of the two theories is the importance of plant water potential in upward (ascent) or downward (descent) bi-directional water movement, depending on the water potential gradient. The tree water management ability of the passive redistribution of water through the system of roots which act as conduits transferring water from moist to dry soils is called hydraulic redistribution (HR) [7]. HR ascent (also known as hydraulic lift) towards canopy occurs when soil water potential is larger than the leaf water potential and HR descent away from the canopy takes place when the leaf water potential is larger than the soil water potential [4].

Although HR is commonly attributed to phreatophytes, the hydraulic lift may also source deep soil moisture, not groundwater [8, 9]. In dry season (Fig. 21.1),

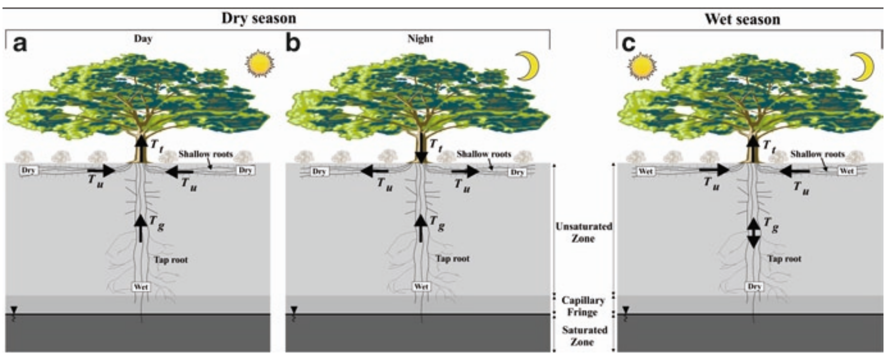

Fig. 21.1 Hydraulic redistribution: (**a**) during day time of the dry season; (**b**) during night time of the dry season; (**c**) during wet season (*day* and *night*) (After Lubczynski [4])

during day time, the water from underneath is lifted up through tap roots (sinkers) towards transpiring leaves thanks to large air *VPD*. Also during night time considerable quantities of water, amounting to an appreciable fraction of daily transpiration, are lifted up and that water is redistributed through shallow lateral roots into the soil dried up during preceding days [10]. In dry seasons, in case of fog [11] or substantial night moisture in the air [12], water can also be absorbed through leaf surfaces resulting in reverse flow direction in the stem. In wet seasons, during sunny days the direction of flow is typically upward but in rainy days, some tree species can send water downward to increase unsaturated zone water storage. That water is utilized later in water shortage periods, also indicating water stress adaptation mechanism.

The assessment of transpiration in hydrology and hydrogeology involves three main tasks: (i) measurements of total transpiration (T_t); (ii) extraction of groundwater transpiration (T_g) through partitioning of (T_t); (iii) upscalling of individual T_t and T_g to plot or catchments scale.

21.3.1 Measurements of Transpiration

Total transpiration of plants, mainly trees, can be nowadays estimated or even monitored in time by in-situ sap flow measurements. The sap flow (Q_s), represents the passage of water containing inorganic ions through the system of very thin, plant structural pipes called tracheids and vessels within the conductive sapwood area (xylem) of the stems and branches. The Q_s is calculated as a product of sap velocity which is also known as sap flux density (v) and sapwood (xylem) area (A_x). The v is typically estimated with thermal methods that apply heat transfer. The popularity of thermal methods is due to their simplicity, cost effectiveness and easy adaptation to logger based monitoring. The thermal methods such as thermal dissipation probe (TDP) and heat pulse (HP) methods are the most frequently used ones (probably because of relatively low cost) although they have some limitations [13, 14]. The newly developed heat field deformation (HFD) method [15] seems to overcome most of these limitations but its commercial implementation which is distributed by ICT Instruments is expensive. The sapwood area is the area between bark and non-permeable central part of stems called heartwood. The most common method of assessing A_x is coring of the stem across the sapwood to determine its depth. Other more rigid method requires cutting off branches or even whole trees. Many species show clear visual difference between sapwood and heartwood. Otherwise the staining of the conductive xylem can be applied.

21.3.2 Partitioning of Transpiration

The easiest determination of T_g is when $T_u = 0$ resulting in $T_g = T_t$ where T_t can be defined by sap flow measurements. However, the $T_u = 0$ is likely only in dry seasons of arid or semi-arid locations with shallow aquifer. In all other cases, i.e. when

$T_u \neq 0$, the partitioning of transpiration into T_u and T_g is needed. This can be done by combination of in-situ sap flow and stable isotope measurements [16] although this method is only successful if there is sufficient isotopic contrast between groundwater and unsaturated zone water [4].

21.3.3 Upscalling of Transpiration

In hydrogeological assessment, groundwater balances are usually carried out at catchment scales. T_t and T_g can be upscalled to the catchment scale using high resolution remote sensing. The upscalling of T_t at the plot scale uses biometric relation between stem area and xylem area and at the catchment scale between canopy projection area and xylem area. The canopy areas can be identified using very high resolution multiband images such as QuickBird and Ikonos. Applying biometric relations, they can be converted to xylem areas. The xylem areas are then multiplied by species dependent sap flux densities which are categorized with regard to species type and eventually size of a tree. Obtaining T_g map in the catchment scale is pretty similar to obtaining T_t although it requires additional species dependent partitioning transfer functions (PTF) which represent relations between T_t and T_g [4].

21.4 Groundwater Evaporation

Groundwater evaporation represents groundwater loss by direct evaporation from water table. This process takes place in bare soil environments and it is the most distinct in dry lands with shallow water table and coarse unsaturated zone material. Groundwater evaporation (E_g) is part of the subsurface water evaporation (E_{ss}), often also called bare soil evaporation.

$$E_{ss} = E_g + E_u \tag{21.5}$$

During wet seasons (Fig. 21.2) the unsaturated zone contains large volume of soil moisture usually above field capacity. This moisture evaporates (E_u) whenever appropriate *PET* and *VPD* conditions occur. Towards dry season, the same aquifer looses unsaturated zone moisture, after some time to start evaporating groundwater (E_g). With large *PET* and large *VPD*, this process changes from capillary transport into vapor transport once unsaturated zone moisture is removed. In locations with deep water table, during dry seasons, the unsaturated zone moisture cannot be entirely dewatered, so the evaporation process involves always both, capillary and vapor transport. The depth at which soil abruptly changes its moisture status delineates evaporative front above which water transport occurs mainly in the vapor form.

The E_{ss} can be accessed through various methods such as eddy flux towers or lysimeters. However, its partitioning into E_g and E_u and the extraction of E_g is difficult. The partitioning of E_{ss} is relatively easier if $E_u = 0$, i.e. when the unsaturated zone is dry so that the assumption $E_g = E_u$ can be made. This happens only in dry seasons in

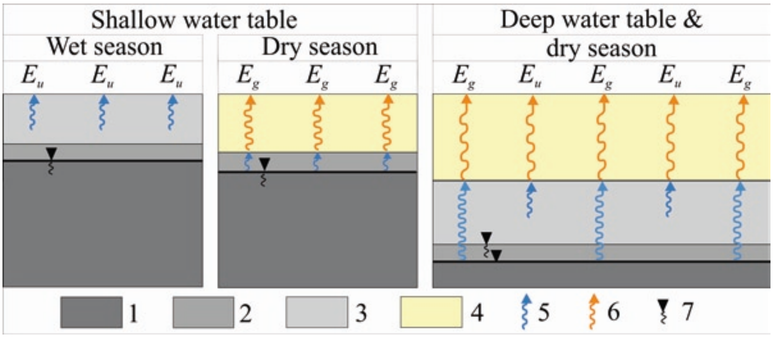

Fig. 21.2 Groundwater evaporation in dry lands: *1* – aquifer; *2* – capilary fringe; *3* – unsaturated zone with prevailing capillary flow; *4* – unsaturated zone with prevailing vapor flow; *5* – capillary flow; *6* – vapor flow; *7* – water table

dry climatic zones. Otherwise the procedure of separating E_g is complex because the evaporation process takes place either through liquid or vapor transport. Furthermore, as pointed out earlier, vapor is not directly measurable. Because of these difficulties, the partitioning of subsurface evaporation has not been developed yet.

21.5 Discussion and Conclusions

Groundwater evaporation is an important component of groundwater balance in locations with dry climate and shallow water table. In two such study areas in which the author was involved, i.e. in weathered and fractured granitic Sardon catchment in Spain [3] and weathered and fractured gabroic Pisoes catchment in Portugal characterized by thin 0–2 m top clay layer, [17], the ET_g represented 30–40% of the recharge. In such study areas, disregarding ET_g in groundwater balances carries the risk of mismanagement of groundwater resources.

Groundwater evapotranspiration consists of two different components, groundwater transpiration (T_g) and groundwater evaporation (E_g). The former refers to groundwater uptake by phreatophytes whereas the latter to direct evaporation of groundwater from water table or its hydraulically connected capillary fringe. Both components can be relatively easily assessed by the standard transpiration and evaporation measurements when moisture of unsaturated zone can be neglected. Such conditions however are rare because they only occur in shallow water table locations in dry seasons. In all other cases, transpiration and/or evaporation measured at the surface have to be partitioned.

Importance of groundwater transpiration at the catchment scale depends on the amount of phreatophytes, their species type and age and the hydrogeological and climatic conditions of the catchment. The importance of *Tg* is the highest in dry areas with shallow water table and large density of phreatophytes.

The extraction of T_g from T_t is possible by combination of sap flow measurements and stable isotope analysis, provided there is sufficient isotopic contrast between groundwater and unsaturated zone moisture. In case it is not, the groundwater isotopic content can be enriched although not in every country this is permitted. The partition of T_t is cumbersome, expensive and time consuming. It is also species-dependent, therefore the results of each individual experiment have to be well documented to create data base corresponding to different phreatophyte species. In parallel models optimizing this work should be developed.

The importance of subsurface evaporation in bare lands is the largest in dry climatic zones with shallow water table, coarse material of unsaturated zone and lack of vegetation. In Sardon study area [3] with savannah type of vegetation of sparsely distributed oak trees, the dry season E_g represented ~70% of ET_g that varied from 0.55 to 0.70 mm/d over 3–4 months of different dry seasons. In other, Pisoes catchment in Portugal without phreatophytes ($T_g = 0$) but with top surface 0–2 m clay layer restricting evaporation, E_g was also significant and ranged from 0.28 to 0.70 mm/d over 4–5 months in different dry seasons.

When E_u cannot be neglected, the extraction of E_g from the subsurface evaporation (E_{ss}) measurements creates problem that does not have scientific solution as yet. The difficulty is because of: (i) continuous interaction between evaporation originated from groundwater (E_g) and the evaporation originated from soil moisture of unsaturated zone (E_u); (ii) interchange between liquid and vapor phases during water transport whereas the latter cannot be directly measured; (iii) difficulty of non-invasive and in-situ quantitative assessment of these processes in subsurface. Considering all these difficulties, the most realistic way to assess *Eg* seems to be modeling based on depth-wise profile measurements, characterizing not only capillary water transport but also vapor transport. This way for example Scanlon et al. [18] show that evaporation may originate from large depth. However, none of such studies provides explicit partitioning of E_g and E_u despite of large hydrogeological importance.

If E_g and T_g are defined then the ET_g can be calculated by Eq. 21.3. In dry conditions and shallow water table, ET_g is usually a significant component of groundwater balance. It is also a critical input in groundwater modeling and groundwater management. ET_g is part of the net recharge which is a driving force of groundwater flow. Thus, its omission or underestimation in calibration of groundwater models leads to overestimation of aquifer transmissivities, overestimation of groundwater resources and mismanagement of groundwater resources.

Groundwater balance components are vulnerable to ongoing climatic and land cover changes. The majority of climatic models predict that the dry lands will become drier, dry seasons longer and rains more intense but less temporally distributed. With such changes, E_g will certainly increase and T_g possibly too. Land cover changes, such as expansion of urbanization, will reduce ET_g whereas forestation impact on groundwater balance components is not that clear. Deforestation certainly will reduce transpiration and cloud formation but on the other hand it will also increase infiltration, runoff and subsurface evaporation. The available knowledge indicates that in dry lands, deforestation typically results in rise of water table which, in turn, results in the increase of subsurface evaporation causing the unwanted salt deposition.

With current tendency of climate change and land desertification, the importance of ET_g in groundwater balances will increase, not only in arid and semiarid areas, but also in moderate climates, which experience nowadays increasingly long drought periods and frequent heat waves. Therefore the significance of ET_g in these environments has to be evaluated as well.

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Chapter 22
Modeling Water Stress Effect on Soil Salinity

Gokmen Tayfur

Abstract As it is widely known the earth is experiencing a climate change. The primary effect of this change is the increase trend in global temperature. This, in turn, results in increased number of events in flooding, and drought in different parts of the world. A secondary effect is the change in water and soil salinity. A considerable portion of the cultivated land in the world is affected by salinity, limiting productivity potential. About 20 million ha of total 230 million ha of irrigated land in the world are salt affected. The climate change is expected to worsen this situation. This study explores the water stress effect on soil salinity. For this purpose, a model is developed to simulate salt transport in a layered soil column. The soil salinity transport model development involves two parts: (1) modeling salt movement through sail layers due to runoff, percolation, and lateral subsurface flow, and (2) modeling dissolution and precipitation of gypsum which acts as sink or source for salts in soil. The model is calibrated and validated with measured data. The soil is irrigated under optimal and water stress irrigation conditions. The major model parameters affecting the soil salinity are found to be wilting point, field capacity, hydraulic conductivity, initial soil salinity, and soil gypsum concentration. The results have revealed that water stress results in high concentration of salt accumulation in soil columns.

Keywords Modeling • Water stress • Salinity • Soil

22.1 Introduction

It is clearly known that the increasing of carbon dioxide and other greenhouse gases will raise global temperatures, resulting in global warming. This, in turn, will result in climate change which is expected to impact the world by affecting winter snow-

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fall and snowmelt, minimum water temperature, summer average temperature, and growing season rainfall amounts and intensities [1]. Temperature changes are expected to alter precipitation and evapotranspiration which are the prime drivers of water availability and agricultural production. Agriculture is an important economic activity in the world and the global warming is expected to have a great impact on water resources and agriculture [2].

Elgaalin and Garcia [2] investigated the impact of climate change on water supplies in Arkansas River Basin of Colorado under two transient climate change scenarios, employing artificial neural network method. Since monthly runoff is the primary factor in determining the amount of water available for irrigation, they linked the available potential water for agriculture to climate change on a monthly scale. They employed the two general circulation models (GCM) – HAD (Hadley Center for Climate Prediction and Research), and CCC (Canadian Climate Center) – to generate future climate projections assuming a progressively 1% annual increase in carbon dioxide concentrations [2]. Minville et al. [3] investigated the impact and uncertainty of climate change on water resources management in the Perobonka River System, Canada. They evaluated the impact of the change on medium-term reservoir operations for the Perobonka water resources system (Quebec, Canada) with annual and seasonal hydropower production indicators and flood control criteria.

Agricultural systems are more sensitive to the climate change due to the common lack of buffering capability in agricultural response to climate events. For example, a single month of extremely low rainfall may affect a reservoir by decreasing storage over the course of a few months, but the reservoir system might be able to recover quickly with single large rainfall. On the other hand, extremely low rainfall period of a month will cause death of a region's crops with no hope of growing new crops until next growing season. Hence, agricultural water resources planning must consider the variability in agricultural systems over time and the primary cause for temporal variation in climate [4].

Irrigation is a principal adaptation mechanism to climatic variability and economic studies have shown that climatic variability can be a factor in determining private investment in irrigation infrastructure more important than any others including credit availability, governmental price policies, and local violence [4]. Already irrigated agriculture takes place under water scarcity. This situation definitely will worsen in future. To cope with scarce supplies, deficit irrigation, i.e. application of water below full crop-water requirements, is an important tool to achieve the goal of reducing irrigation water use [5].

One of the major adverse effects of deficit irrigation, on the other hand, is the salinisation of the soil. Salinisation, which is also known as alkalisation or sodification, is the process that leads to an excessive increase of water-soluble salts in the soil. The accumulated salts include sodium, potassium, magnesium, calcium, chloride, sulphate, carbonate and bicarbonate that lead to severe deduction of soil fertility. Primary salinisation involves salt accumulation through natural processes due to a high salt content of the parent material or in groundwater. Secondary salinisation is caused by human interventions such as inappropriate irrigation practices, e.g. with salt-rich irrigation water and/or insufficient drainage. Salinisation is often associated with irrigated areas where low rainfall, high evapotranspiration rates or soil textural characteristics impede the washing out of the salts which subsequently build-up in the soil surface layers. Irrigation with high salt content waters dramatically worsens the problem.

Salinity is one of the most widespread soil degradation processes on the Earth. According to some estimates, the total area of salt affected soil is about one billion hectares. They occur mainly in the arid–semiarid regions of Asia, Australia and South America. In Europe, salt affected soil occurs in the Caspian Basin, the Ukraine, the Carpathian Basin and on the Iberian Peninsula. Soil salinity affects an estimated one million hectares in the European Union, mainly in the Mediterranean countries, and is a major cause of desertification. In Spain 3% of the 3.5 million hectares of irrigated land is severely affected, reducing markedly its agricultural potential while another 15% is under serious risk. The Euphrates, Tigris and Van basins are presenting an alarming situation with over 75,000 ha facing salinity-alkalinity problems [6]. Accordingly Kendirli et al. [7], 1.5 million ha of land in Turkey is salt effected and about 74% of barren land is saline soils.

The accumulation of salts, particularly sodium salts, is one the main physiological threats to ecosystems. Salt prevents, limits or disturbs the normal metabolism, water quality and nutrient uptake of plants and soil biota. When water containing a large amount of dissolved salt is brought into contact with a plant cell, the protoplasmic lining will shrink. This action, which is known as plasmolysis, increases with the concentration of the salt solution. The cell then collapses. In addition, sodium salts can be both corrosive and toxic to organic tissue. The nature of the salt, the plant species and even the individuality of the plant (e.g. structure and depth of the root system) determine the concentration of soil-salt levels at which a crop or plants will succumb. Examples of plants and crops with a high tolerance to salt include bermuda grass, cotton, date palm, peas, rape and sugar beet while apples, lemons, oranges, potatoes and most clovers have a very low tolerance.

Salinization processes are near to irreversible in the case of heavy-textured soils with high levels of swelling clay. Although a combination of efficient drainage and flushing of the soil by water is often used, the leaching of salts from the profile is rarely effective. Because the reclamation, improvement and management of salt affected soils necessitate complex and expensive technologies, all efforts must be taken for the efficient prevention of these harmful processes. Permanent care and proper control actions are required. Adequate soil and water conservation practices, based on a comprehensive soil or land degradation assessment, can provide an "early warning system" that provides possibilities for efficient salinity control, the prevention of these environmental stresses and their undesirable ecological, economical and social consequences.

This study presents a mathematical model for simulating salt transport in saturated/unsaturated soil. The effect of deficit irrigation on the salt accumulation in the soil column is quantitatively investigated and tested against measured data.

22.2 Salt Transport Model

The model simulates salt transport downward and upward. Downward movement involves two parts – (1) modeling movement in the top layer of 10 cm thickness; and (2) modeling the movement under the layers below the top layer (Fig. 22.1). In the top layer, total water flow leaving the surface layer consists of rainfall, lateral subsurface flow, and vertical percolation (Fig. 22.2). In other soil layers, the total water flow consists of only lateral subsurface flow and vertical percolation (Fig. 22.3).

The downward salt movement can be formulated as follows [8]:

$$S = S_i\left[1 - \exp\left(\frac{-W_t}{n-\theta_w}\right)\right] \tag{22.1}$$

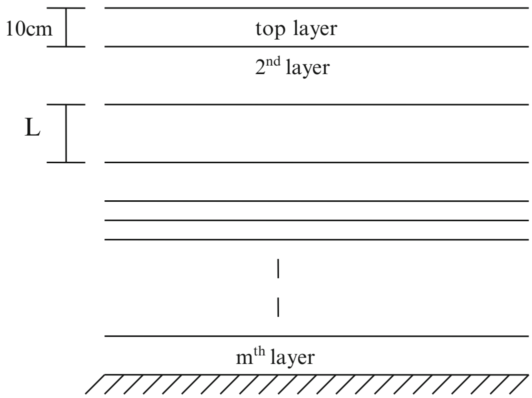

Fig. 22.1 Schematic representation of layers in a soil column

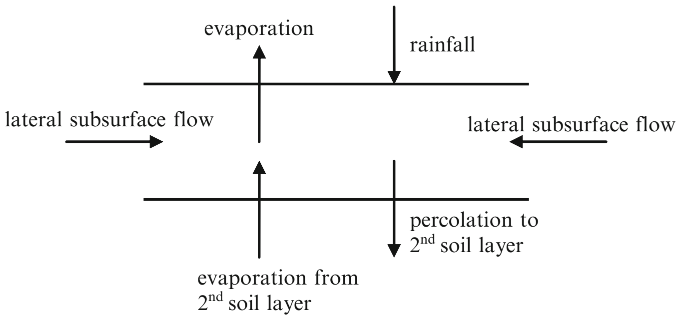

Fig. 22.2 Schematic representation of flow and evaporation mass transport in the top soil layer

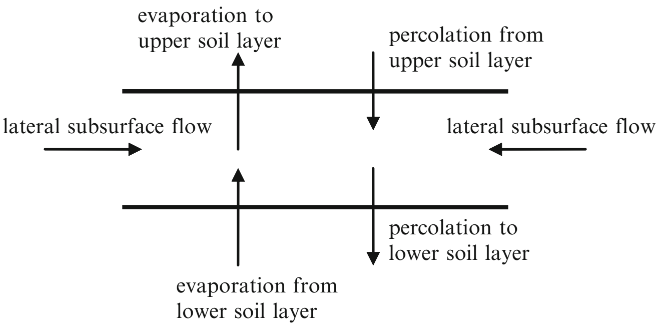

Fig. 22.3 Schematic representation of flow and evaporation mass transport in an inner soil layer

where S is salt mass in total water flow, S_i is initial salt mass in the soil layer; W_t is total water flow, n is soil porosity, and θ_w is the wilting point water content. The final salt mass contained in the soil layer is expressed as $S_f = S_i - S$ and the average salt concentration is expressed as $C_s = S/W$ where C_s is the average salt concentration associated with the total water flow. Hence, salt mass contained in runoff, lateral flow, and percolation is found by the product of corresponding water flow and salt concentration.

The upward salt movement is due to water evaporation from the spoil. When water is evaporated from the soil surface, salt is moved upwards into the top soil layer by mass flow. The equation for estimating this salt transport is expressed as [8]:

$$S_{ev} = \sum_{l=2}^{m} E_{vl} C_{sl} \tag{22.2}$$

where S_{vl} is salt mass moved from lower layers to top layer by soil water evaporation and E_{vl} stands for soil water evaporation amount in the contributing layers. Subscription l refers to soil layer and m represents the number of layers contributing to soil water evaporation.

Other major source of salt in a soil column comes from gypsum dissolution. The time dependent gypsum dissolution is defined by Kemper et al. [9] as:

$$\frac{dC_g}{dt} = K_d (C_{gs} - C_g) \tag{22.3}$$

where C_g is solution concentration at any time, C_{gs} is solution concentration at gypsum saturation which is taken as 4% (g of gypsum/g of soil) or 2.63 g/L in soil solution [10] and K_d is the dissolution coefficient.

Integrating Eq. 22.3 from $t = 0$ (water enters the soil layer) to $t = t_c$ (water leaves the soil layer) yields $K_d t_c = ln(C_g/C_{gs} - 1)$. Keren and O'Connor [11] conducted a gypsum dissolution study using soil samples amended with 2% and 4% gypsum under different water flow velocities and concluded that $K_d t_c = \alpha t_c^{0.5} + \beta$ where α and β are coefficients. According to Kemper et al. [9], $t_c = L/W$ where L is thickness of soil layer and W is actual flow velocity which is the Darcy velocity divided by the porosity. Assuming that soil porosity is equal to the saturated soil moisture content (θ_s) [12], the dissolution coefficient can be expressed as:

$$K_d = \alpha\sqrt{\frac{W}{L\theta_s}} + \beta\left(\frac{W}{L\theta_s}\right) \tag{22.4}$$

Hence, gypsum dissolution at any time can be computed as [12]

$$C_g(t) = K_d(t)\theta(t)C_g(t-1) \tag{22.5}$$

where t and $(t-1)$ stand for present and previous time steps, respectively, and θ is soil moisture content. The dissolved gypsum mass is the product of $C_g(t)$ and water flux, W. The values of the α and β coefficients obtained by Keren and O'Connor [11] are as follows:

$$\begin{aligned} &\alpha = 1.2h^{-0.5} \\ &\beta = 0.0 \end{aligned} \qquad \text{for } 0\% \le gypsum \le 2\%$$

$$\begin{aligned} &\alpha = 2.55h^{-0.5} \\ &\beta = 0.0 \end{aligned} \qquad \text{for } 2\% < gypsum \le 4\%$$

Gypsum precipitation due to the soil water evaporation can be expressed as [8]:

$$G_p = \sum_{l=2}^{m} E_{vl}C_{gl} \tag{22.6}$$

where G_p is the mass of calcium and sulfate ions that are evapoconcentrated and precipitated back to gypsum as a result of the soil water evaporation from lower layers towards top layer.

The total salt mass balance at any soil layer (l) can then be expressed as [8]:

$$T_{sl} = S_{il} - (S_l + G_{dl}) + (S_{evl} + G_{pl}) \tag{22.7}$$

where T_{sl} and S_{il} are final and initial salt mass in a soil layer l, respectively. S_l is salt mass lost from soil layer l due to total water flow leaving the layer. G_{dl} is mass of dissolved components (calcium and sulfate ions) of gypsum lost from soil layer l due to the total water flow leaving the layer. S_{evl} *is* salt mass moved to the layer l from contributing lower layers due to soil water evaporation. G_{pl} is mass of precipitated components (calcium and sulfate ions) of gypsum moved to the soil layer l due to the soil water evaporation. The total salt mass, Tsl (t/ha) and soil saturation extract Ece (dS/m) in a soil layer l can be expressed as [8]:

$$T_{sl}\left(t/ha\right) = EC_e \cdot 640\,(g/m^3) \cdot \theta \cdot L(m) \cdot 1x10^4(m^2/ha) \cdot 1x10^{-6}(g/t) \tag{22.8}$$

where L is the thickness of a soil layer l (see Fig. 22.1).

22.3 Model Calibration and Validation

The model is calibrated and validated with soil EC_e data obtained by Champion et al. [14] at the Fruita Research Center in Grand Valley in Coloroda. The soil in the Center contains gypsum and soluble salts. The topsoil thickness is 74 cm of loam and sandy loam. The underlying material to a depth of 150 cm is stratified loamy fine sand, silt loam, silty clay loam and very fine sandy loam. The experimental site contained six lysimeters of 1.55 × 1.22 × 1.22 m deep. The weather data consists of daily maximum, minimum temperatures, solar radiation, wind speed, and precipitation. The soil data consists of soil moisture and ECe and the irrigation data contained the dates and rates of applied water. The lysimeters were surface irrigated with water from Colorado River having an average ECe of 0.65 dS/m. Alfalfa was grown in the lysimeters. The lysimeters were applied a total of 796 mm irrigation water from April 15 to September 23, 1986.

Data from one of the lysimeters is used for the model calibration. Table 22.1 shows the measured versus predicted ECe values in time along a soil depth. The computed mean absolute error (MAE) and mean relative error (MRE) for the results in Table 22.1 are, respectively, 1.17 dS/m and 34.9%. Table 22.2 shows the calibrated values of the model parameters that resulted in the simulations summarized in Table 22.1. The calibrated model was then applied to simulate salt variation in a soil column experiment of the same lysimeter in Fruita Research Center in

Table 22.1 Measured versus predicted ECe values as a result of the calibration procedure

Soil layer depth (cm)	Measured ECe (dS/m)	Predicted ECe (dS/m)	Date
1.17	30.0	1.00	May 23, 1986
1.69	60.0	4.26	
7.12	90.0	6.23	
1.20	30.0	1.00	June 12, 1986
1.72	60.0	3.25	
7.05	90.0	6.75	
1.38	30.0	1.50	September 9, 1986
1.72	60.0	3.30	
6.55	90.0	3.35	

Table 22.2 Parameter values as a result of the calibration procedure

	Soil layer depth (cm)		
Parameter	0–30	30–60	60–90
Wilting point water content	0.116	0.120	0.059
Field capacity	0.398	0.418	0.359
Saturated conductivity (mm/h)	2.500	5.500	8.200
Initial gypsum concentration (mg/L)	1.100	4.600	8.800
Initial measured ECe (dS/m)	8.850	8.850	8.850

Table 22.3 Measured versus predicted ECe values as a result of the validation procedure

Date	Measured ECe (dS/m)	Predicted ECe (dS/m)
March 10, 1988	3.05	3.05
March 25, 1988	4.60	4.70
April 10, 1988	4.82	4.65
April 25, 1988	5.00	4.75
May 10, 1988	5.70	5.10
September 30, 1988	3.25	4.85

1988. Alfalfa in the same lysimeter received about 841 mm irrigation rate from April 20 to September 16, 1988. Table 22.3 shows the validation model results in predicting ECe in time in the 90 cm soil profile. The computed MAE = 0.45 dS/m and MAE = 11.7 implying satisfactory performance of the model.

22.4 Water Stress Effects on Salt Movement

The effect of irrigation water stress that is already seen in some parts the world as a result of water shortage and it will surely be employed in near future in most part of the world due to global warming effects is investigated in this study. The calibrated and validated salt transport model, in order to see the effects of the water stress on salt transport, is applied to a 1992 study of Robinson et al. at the Desert Research and Extension Center, University of California, in the Imperial Valley of California. Table 22.4 presents four different irrigation treatment – optimum check, minimum stress, short stress, and long stress. The irrigation water which is diverted from Colorado River into All American Canal had an average ECw of 1.25 dS/m (850 mg/L) about twice of the one used at the Fruite Research Center, CO. The soil in the Imperial Valley is Holtville clay extending 60–90 cm in depth overlying sandy clay. The observed ECe in 1991 was assumed as initial ECe values.

Table 22.5 summarizes observed versus predicted salt concentrations along the soil depth of 120 cm. The measured salt concentration data clearly show that under stress conditions, salt concentration increases along the soil depth in time. For example, in between 60 and 120 cm zone, on the average, the measured ECe on October 16, 1991 was around 6.08 dS/m under optimum conditions, it then became 6.93 under minimum stress, 8.38 under short stress, and 9.88 dS/m under long stress conditions. The salt concentration increase is, on the average, 14%, 38%, and 63% under minimum, short, and long stress conditions, respectively. The results in the table show that the developed salt transport model shows good performance in predicting concentrations under optimum and minimum stress conditions along the soil depth. Under short and long stress conditions, the model performs poorly in predicting salt concentrations especially in the lower zone. The computed error measures, on the average, for the results in Table 22.5 are MAE = 1.15 dS/m and MRE = 25.4%.

Table 22.4 Water stress irrigation treatments in 1991 in the Imperial Valley, CA

	Number of total applied type irrigations water				
Treatment type	July	August	September	October	
Optimum	3	2	2	2	1,269
Minimum stress	3	1	1	2	1,203
Short stress	3	0	0	2	991
Long stress	0	0	0	2	821

Table 22.5 Measured versus predicted ECe values under four different stress conditions

Date	Soil layer depth (cm)	Measured ECe (dS/m)	Predicted (dS/m)
Optimum treatment			
June 4, 1986	30.0	2.60	4.10
	60.0	3.30	3.95
	90.0	6.40	5.75
	120.0	5.85	5.70
September 4, 1986	30.0	2.90	4.85
	60.0	3.40	4.40
	90.0	6.95	5.75
	120.0	5.90	5.70
October 16, 1986	30.0	3.20	5.05
	60.0	3.45	4.55
	90.0	6.30	6.90
	120.0	5.85	5.70
Minimum stress treatment			
June 4, 1986	30.0	2.30	3.55
	60.0	3.20	3.45
	90.0	6.30	6.55
	120.0	6.90	7.10
September 4, 1986	30.0	2.55	4.10
	60.0	3.90	3.80
	90.0	6.60	6.60
	120.0	6.85	7.10
October 16, 1986	30.0	2.65	4.55
	60.0	4.55	4.00
	90.0	7.45	6.60
	120.0	6.40	7.00
Short stress treatment			
June 4, 1986	30.0	2.55	4.10
	60.0	4.75	4.35
	90.0	7.05	6.10
	120.0	6.10	6.30
September 4, 1986	30.0	2.80	4.15
	60.0	5.40	4.45
	90.0	8.70	6.00
	120.0	5.75	6.10

(continued)

Table 22.5 (continued)

Date	Soil layer depth (cm)	Measured ECe (dS/m)	Predicted (dS/m)
October 16, 1986	30.0	3.00	5.00
	60.0	5.50	4.35
	90.0	10.20	6.00
	120.0	6.55	6.20
Long stress treatment			
June 4, 1986	30.0	2.20	3.68
	60.0	3.20	3.70
	90.0	5.65	5.45
	120.0	6.30	6.32
September 4, 1986	30.0	2.45	3.55
	60.0	3.75	3.70
	90.0	9.25	4.74
	120.0	8.95	6.25
October 16, 1986	30.0	2.75	4.05
	60.0	4.05	3.80
	90.0	10.80	5.20
	120.0	8.95	6.50

22.5 Concluding Remarks

Climate change as a result of global warming will have a deep impact on surface and groundwater systems and, as a result, on the agriculture which is very responsive the climate change in a very short period time. Irrigation is a way of adaptation to the climate change and the deficit irrigation is a practical tool for the adaptation. However, the impact of such management results in salt accumulation in the soil zone reduces the fertility of the soil, as presented in this study. The reclamation of such soils is very expensive and requires complex technology. It is therefore essential to find a balance between deficit irrigation and its consequence of salt accumulation. The model measured results show that long stress treatment is not a viable solution. Short stress treatment is a delicate. Minimum stress treatment can be confidently employed. The transport model can satisfactorily simulate salt transport under optimum and minimum stress conditions. However, it does not perform well in predicting the concentrations in prolonged stress periods especially in the lower zones. Hence, the model should be improved to overcome this shortcoming or it should be used with care for the stress periods.

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Chapter 23
Climate Changes in Republic of Macedonia

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Abstract The chapter comprises updated results from research on projected climate change in Republic of Macedonia in the course of twenty-first century related to previously elaborated National Communications on Climate Change as obligation under the United Nation Frame Convention on Climate Change. The results refer to air temperature and precipitation analysis on seasonal and annual base according to various emission scenarios for years 2025, 2050, 2075 and 2100 for the entire country as well as for diffe rent climatic regions of Macedonia. Also, presented are first estimations of the water resources vulnerability assessment and the status of the available information on the transboundary aquifers in Republic of Macedonia.

Keywords Climate change • Climate change scenarios • Water resources

23.1 Introduction

Republic of Macedonia has ratified the United Nation Framework Convention on Climate Change (UNFCCC) on December 4, 1997. As a Party to the Convention, there is an obligation for regular preparation of National communications on climate change. Two National communications on climate change, prepared in 2003 and 2008, comprise elaboration of different scenarios for the changes of the main climatic elements (air temperature and precipitation) in the twenty-first century.

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23.2 Climate Change Scenarios for the Territory of Republic of Macedonia in the First National Communication on Climate Change

Six climate models were used for investigation of climate change in the twenty-first century using software packages of MAGICC SCENGEN (version 2.4 dated 2000) [1–3]. Climate change scenarios for Macedonia were performed assuming that the current policy of increasing CO_2 concentration is kept. Two projections of socio-economic development (emission scenarios) – IS92a and IS92c (Tables 23.1 and 23.2) – were chosen as IS92a is a scenario of "the best estimation" of climate sensibility and IS92c is a scenario of "low" climate sensibility [4].

23.3 Results of the Climate Change Scenarios According to the Second National Communication on Climate Change

For the needs of preparation of the Second National Communication on climate change, calculations were made to estimate the main meteorological variables for the entire territory of Republic of Macedonia for years 2025, 2050, 2075 and 2100. Also, the method of statistical downscaling was applied for the purpose of regional estimation of the climate change [5]. As representative for different climate and geographical regions, meteorological stations that have long-term records of quality data were selected.

Table 23.1 Changes of air temperature (°C) in the twenty-first century (mean projection), according to the emission scenario IS92a and IS92c for winter-DJF, summer-JJA and annual

	DJF				JJA				Annual			
	2025	2050	2075	2100	2025	2050	2075	2100	2025	2050	2075	2100
IS92a	1.0	1.8	2.5	3.3	1.1	2.0	2.8	3.6	1.0	1.7	2.5	3.2
IS92c	0.9	1.3	1.6	1.7	0.9	1.4	1.8	1.9	0.8	1.3	1.6	1.7

Table 23.2 Changes of precipitation during twenty-first century (mean projection), according to the emission scenario IS92a and IS92c for winter-DJF, summer-JJA and annual

	DJF				JJA				Annual			
	2025	2050	2075	2100	2025	2050	2075	2100	2025	2050	2075	2100
IS92a	1	2	2	3	−5	−10	−14	−18	−1	−2	−3	−4
IS92c	1	1	2	2	−5	−7	−9	−9	−1	−2	−2	−2

23.3.1 Results of Direct GCM Output for the Entire Territory of the Country – First Estimate

The projected changes of average daily air temperature (°C) and precipitation (%) for Macedonia were based on direct GCM output interpolated to geographic location 21.5°E and 41.5°N with regard to the period 1961–1990. The values were presented separately for different seasons and based on projections of results from four GCMs (CSIRO/Mk2, HadCM3, ECHAM4/OPYC3, NCAR-PCM) scaled to six emission scenarios (SRES A1T, A1Fl, A1B, A2, B1, and B2). The Mean values were calculated as average across different emission scenarios and different GCMs; the Low/High values were minimum/maximum across different scenarios and averaged across different GCMs.

As a first estimate of expected climate change over the territory of the entire country, the results of selected GCMs were interpolated to the geographic location 21.5°E and 41.5°N, i.e., approximately to the middle of the country. The results of such approach, called direct GCM output, showed the highest increase in air temperature until the end of this century to be in the summer season together with the most intensive decrease in precipitation. In the case of precipitation, practically no change was expected in the winter but a decrease in all other seasons. Details on the direct GCM output projections can be found in Table 23.3.

The direct GCM output method provides only a rough description of the expected climate change in the twenty-first century in Macedonia, mostly about changes of the average conditions over the territory of entire country. The spatial variability of meteorological parameters, as well as heterogeneous climate regions and topography of the country should also be kept in mind. Thus, the direct GCM output approach can present a benchmark for more detailed and complicated methods like empirical downscaling for the purpose of regional projection of future climate change [5, 6].

23.3.2 Results of the Empirical Downscaling Method

Generally, the results of the empirical downscaling show stronger increase of the air temperature in the winter and summer, and weaker decrease of precipitation in the winter than the results estimated by GCMs. The projections for temperature and precipitation are compatible for the other seasons.

Table 23.3 Projected changes of average daily air temperature T (°C) and precipitation RR (%) for the entire territory of Republic of Macedonia according SRES scenarios

	DJF				JJA				Annual			
	2025	2050	2075	2100	2025	2050	2075	2100	2025	2050	2075	2100
T	0.8	1.7	2.3	3.0	1.4	2.5	4.1	5.4	1.0	1.9	2.9	3.8
RR	0	1	2	−1	−7	−17	−27	−37	−3	−5	−8	−13

23.3.2.1 South-Eastern and Central Parts of Republic of Macedonia/Sub-Mediterranean Climate Regions

If the empirical downscaling projections for the region of south-eastern Macedonia (with prevailing influence of sub-Mediterranean climate) and for the central parts of Macedonia (with a combined influence of continental and sub-Mediterranean climate) are compared, a less intensive temperature change is evident for the first one in the winter and more intensive – in the summer and autumn. Changes of the air temperature in the spring are comparable in both sub-regions and also, the highest increase of air temperature is expected in the summer. The difference between winter and summer increase of the air temperature is especially evident for the south-eastern region. The expected changes in precipitation are similar for both sub-regions as practically no change in precipitation is expected in the winter season and a decrease in precipitation – in all other seasons (Table 23.4).

23.3.2.2 Southern and South-Western Part of Republic of Macedonia/Continental Climate Region

Both parts of Macedonia are under the prevailing influence of continental climate [7, 8]. The climate change projections for these two regions are quite different although not very remote to each other. In the case of southern region, the projections of precipitation change are very similar to the regions with prevailing or partial influence of sub-Mediterranean climate.

Almost no change of precipitation is expected in the winter and decrease in the other seasons, the strongest decrease being in the summer. A slightly stronger signal in the temperature change is expected for this region in comparison to regions with sub-Mediterranean climate influence. The difference is especially evident in projections for the winter period. On the contrary, projections of temperature changes for the south-western region are much lower than those for the region represented by Bitola and Prilep. Additionally, even a slight increase of precipitation is expected for the winter but an evident decrease in the other seasons. The different response of

Table 23.4 Projected changes of average daily air temperature (°C) and precipitation (%) for (**a**) central part of Macedonia under a combination of sub-Mediterranean and continental climate impacts (represented by locations Veles, Strumica, Skopje-Petrovec, Štip) and (**b**) south-eastern part of Macedonia under the sub-Mediterranean climate impacts (represented by locations Gevgelija and Nov Dojran)

	DJF				JJA				Annual			
	2025	2050	2075	2100	2025	2050	2075	2100	2025	2050	2075	2100
(a)												
T	1.0	2.3	3.2	4.3	1.4	2.6	4	5.4	1.1	2.2	3.3	4.5
RR	0	1	2	−1	−6	−11	−18	−23	−3	−6	−9	−13
(b)												
T	1.0	2.1	2.9	3.8	1.5	2.9	4.5	6.0	1.2	2.3	3.4	4.6
RR	−2	0	−1	−3	−4	−9	−14	−19	−3	−5	−9	−12

Table 23.5 Projected changes of average daily air temperature (°C) and precipitation (%) for (**a**) southern part of Macedonia under continental climate impacts (represented by locations Bitola and Prilep) and (**b**) south-western part of Macedonia under the continental climate impacts (represented by locations Ohrid and Resen)

	DJF				JJA				Annual			
	2025	2050	2075	2100	2025	2050	2075	2100	2025	2050	2075	2100
(a)												
T	1.2	2.7	3.9	5.3	1.5	2.7	4.3	5.7	1.2	2.5	3.8	5.1
RR	−1	−1	−1	−3	−5	−12	−17	−22	−3	−5	−9	−13
(b)												
T	0.9	2.0	2.9	3.9	1.1	2.0	3.1	4.2	0.9	1.9	2.9	3.9
RR	2	3	7	5	−3	−9	−13	−18	−2	−3	−5	−8

these two regions to large-scale climate variability could be related to the proximity of large water bodies (Lake Prespa and lake Ohrid) in the case of Resen and Ohrid stations (see Table 23.5).

23.3.2.3 Eastern Part of Republic of Macedonia/Continental Climate Region and North-Western Part of Macedonia/Alpine Climate Region

The annual pattern of expected temperature change in this region is similar to the pattern for the continental region in Southern Macedonia but the intensity of change is slightly lower. A comparison with stations Bitola and Prilep also shows that a slight increase of precipitation is expected in the winter but decrease in all other seasons, being most intensive, in relative sense, in the summer. In the summer and autumn, an increase in the daily air temperature is expected.

For all the three climate sub-types under the mountainous influence (mountain/continental, sub-Alpine, Alpine) that can be found in the north-western part of Macedonia, the projections for the change in air temperature and precipitation are very similar. An increase of few percent in the precipitation is expected in the winter and a more intense decrease in all other seasons. The expected air temperature change is the strongest in this region of the country. The highest increase in air temperature is expected in the summer but the difference between seasons is not significant (see Table 23.6).

23.4 Comparison of Results of Direct GCM Output

The estimates for temperature and precipitation change in the twenty-first century are more dramatic than the estimates based on IS92a and IS92c emission scenarios used in previous study. The direction of expected changes (e.g., strongest increase in air temperature and precipitation decrease in the summer) is the same but their intensity is different.

Table 23.6 Projected changes of average daily air temperature (°C) and precipitation (%) for (**a**) eastern part of Macedonia under continental climate impacts (represented by locations Kriva Palanka and Berovo) and (**b**) north-western part of Macedonia under the prevailing Alpine impacts (represented by locations Lazaropole, Popova Sapka, and Solunska Glava)

	DJF				JJA				Annual			
	2025	2050	2075	2100	2025	2050	2075	2100	2025	2050	2075	2100
(a)												
T	1.1	2.4	3.4	4.6	1.3	2.5	3.9	5.2	1.1	2.2	3.4	4.6
RR	2	4	8	6	−4	−10	−14	−20	−2	−5	−7	−10
(b)												
T	1.2	2.7	3.8	5.2	1.5	2.8	4.5	5.9	1.3	2.6	3.9	5.3
RR	2	4	7	5	−4	−9	−13	−18	−2	−3	−5	−8

The difference is probably related to the fact that IS92 emission scenarios proposed by the IPCC in 1995 are more optimistic than SRES scenarios proposed in 2001. This can be seen also in the projections for global temperature change based on IS92 emission scenarios which are lower than those based on SRES scenarios. Another reason could be the different GCMs were used in both studies (Fig. 23.1) [4–6].

23.5 Climate Change Impact on the Water Resources

According to climate change vulnerability assessment for water resources sector, reduction of outflows in the country is primarily caused by the climate change (Fig. 23.2) [9]. Current overall annual water demand is 2.3×10^6 m^3 mil and projected for the year 2020 is 3.5×10^6 m^3. On the other hand, developed scenarios for climate change impact on the water resources indicate that;

- Groundwater recharge for Vardar River catchment would continuously decrease in the future reaching about 57.6% of the current recharge quantity in 2100
- Annual discharges for the rivers Vardar, Treska and Bregalnica would show decreasing trend
- Eastern part of the country shall experience more severe and longer water deficiency than the western part. The predicted average reduction in water availability for year 2100 for Bregalnica river basin is almost 24%, while it is 7% for Treska river basin and
- The overall water availability in the country (Vardar river basin) for year 2100 is expected to be reduced by 18% (estimate ranging from 13 to 23%) (Table 23.7) [9].

23.6 Water Monitoring in Republic of Macedonia

The Republic Hydrometeorological Service performs systematic monitoring of the surface, ground water and springs. There is a network of 110 stations (68 active) for river hydrometric measurements. For groundwater levels, temperature and quality,

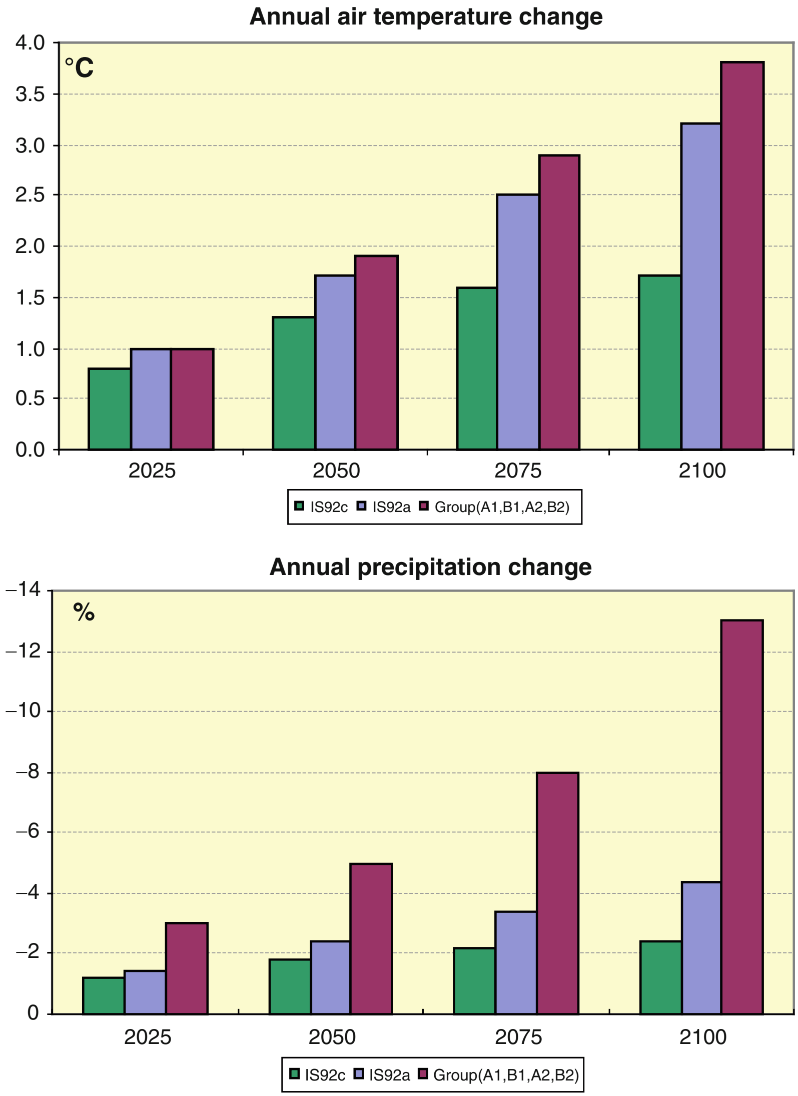

Fig. 23.1 Comparison results for different GCM and scenarios

monitoring stations exist in several regions (Polog, Skopsko Pole, Kocansko Pole, Stipsko Pole, Strumicko Pole and Strusko Pole). However, due to present financial limitations, the monitoring activities are limited and the data availability is decreasing by the year, from 115 to presently 38 (Fig. 23.3) [10]. Organized groundwater data collection and management is missing, as well as the user cadastre, analysis of the balance of inflow-outflow from the groundwater sources as the function of the natural hydrological conditions.

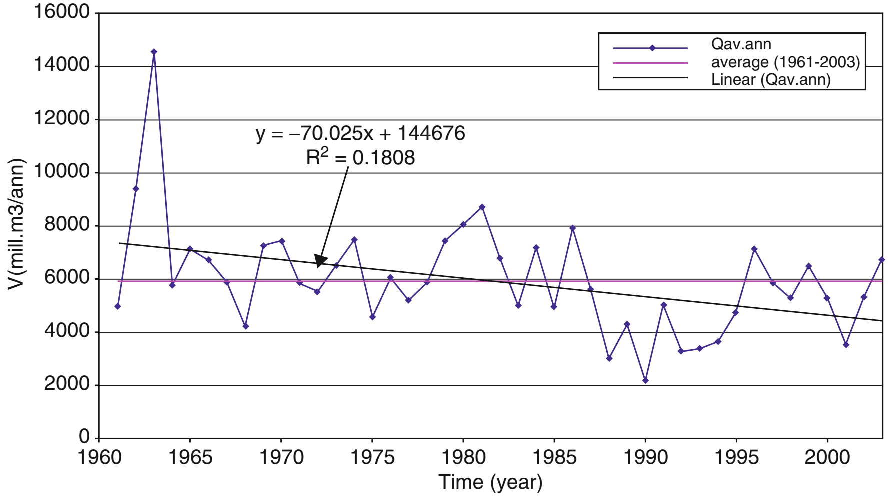

Fig. 23.2 Outflow from Republic of Macedonia

Table 23.7 Model predictions of the % of annual decrease in 2025, 2050, 2075 and 2100, assuming 100% discharge in 2000

	2025	2050	2075	2100
Vardar	92.4	88.6	85.6	81.8
Treska	97.6	96.6	95.2	93.0
Bregalnica	90.0	83.9	80.7	76.2

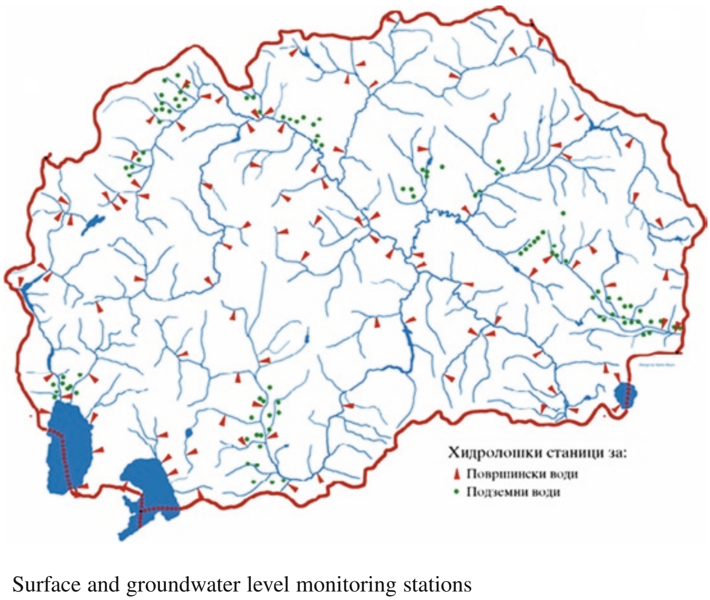

Fig. 23.3 Surface and groundwater level monitoring stations

Table 23.8 Inventory of internationally shared aquifers [11]

Aquifer	Type	Countries	Boundary length (km)	Area (km^2)
RM-SW Serbia	Karst	RM/Serbia	N/A	300
RM-Central Serbia	Karst	RM/Serbia	50	100
Tetovo-Gostivar	Karst	RM/Serbia	15	50
Korab/Bistra – Stogovo	Karst	RM/Albania	25	140
Jablanica/Golobordo	Karst	RM/Albania	50	250
Ohrid Lake	Karst	RM/Albania	N/A	0
Prespes and Ohrid Lakes	Karst	RM/Greece/Albania	52	750
Galicia	Karst	Albania/Greece	N/A	0
Pelagonia/Florina/Bitolsko	Alluvial	RM/Greece	N/A	607
Gevgelija	Alluvial	RM/Greece	N/A	0
Dojran Lake	Alluvial	RM/Greece	N/A	190
Sandansky Petrich	Alluvial	RM/Bulgaria /Greece	18	764

23.6.1 Transboundary Water Resources

In general, Macedonia is an upstream country. All Macedonian rivers flow into neighboring countries (Table 23.8). Transboundary river catchments in Macedonia are: Crn Drim catchment including Ohrid and Prespa Lakes (MK-AL-GR), Vardar/Axios catchment (MK-GR) where small part inflows from Yugoslavia (Lepenec and Pcinja rivers) (MK-SRB), Strumica/Struma catchment (MK-BG) and Lake Dojran catchment (MK-GR) (Table 23.8) [11, 12].

Regarding shared groundwater resources, the Prespa – Ohrid lake system and Lake Dojran are examples of a groundwater – surface water interaction with influence on the catchment environment. In the last decade, dramatic decrease of the water surface level in lakes Prespa and Dojran has occurred. Dojran Lake, being a shallow warm-water lake experiences extreme pressure from its environment, because three quarters of the volume of water disappeared in the period 1988–2002. Some recovery is noted due to two wet years and the construction of supplementary supply system from wells in Gjavato region. Prespa Lake and Ohrid Lake are hydraulically connected through karstic massif of Galicica Mountain. Exploration of this connection is necessary in order to re-establish the water balance in the catchment. There is a requirement for a general planning and management of shared water resources in the region. Regarding Prespa and Ohrid Lakes, several projects are already under way. Regarding Lake Dojran, international cooperation in research, investigations and management is of utmost importance [12].

23.7 Conclusion

Under the requirements of the UNFCCC, valuable research has been carried out in the Republic of Macedonia in order to provide estimations for future changes in the climate conditions for the twenty-first century. Significant progress has been achieved with the Second National Communication for which not only general assessment of the climate change for the territory of entire country has been made in accordance with the latest GCMs and emission scenarios but also first estimations for the regional changes of the basic climate parameters are made.

The direct GCM output projected for Macedonia show more intensive increase of the air temperature in the summer than in the winter season. The expected change of air temperature in the country during the twenty-first century is much higher than the expected global temperature change but the results of our study are consistent with other available studies for regions that include Macedonia.

The local projections of climate change indicate that different climatic regions of Macedonia would respond slightly different to the large-scale climate changes. The continental climate region in the south-western part of Macedonia – close to the Ohrid and Prespa lakes – seems to have the weakest response to large-scale climate change in sense of absolute temperature and precipitation changes whereas the north-western part being under the prevailing mountain/Alpine climate influence would have the strongest response.

The obtained differences between results from different GCMs show the need for further investigations and application of various methods and tools (e.g., PRECIS, dynamical downscaling, etc.) for critical review of present results about the future climate change on the territory of Republic of Macedonia.

According to climate change vulnerability assessment for water resources sector, reduction of outflows from the country is primarily caused by climate change. It is likely that larger water bodies (lakes Ohrid, Prespa and Dojran and rivers) in three catchments areas (river Vardar, river Crni Drim and river Strumica) would suffer serious water stress in the next century. This would lead to raise transboundary water management issues.

Overcoming the permanent problems in operation and reduction of water monitoring network, modernization of equipment, and provision of results of further research would enable to identify the most vulnerable regions in Republic of Macedonia and to implement adequate adaptation measures.

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Chapter 24
Water Governance in Bulgarian Agriculture

Hrabrin Bachev

Abstract This paper analyzes evolution and efficiency of water governance in Bulgarian agriculture during post-communist transition and EU integration. First, it defines the water governance and the scope of analysis. Next, it presents the process of transformation of agricultural water governance embracing all mechanisms and modes including institutional environment, market, private, public, and hybrid. Third, it assesses impacts of newly evolved system of governance on efficiency and sustainability. Finally, it suggests recommendations for improvement of public policies.

Keywords Agricultural water governance • Market, private, and public modes • Bulgarian agriculture

24.1 Introduction

There has been a fundamental transformation of policing, property rights and organizational structure of agricultural water management in Bulgaria since 1989 when transition from a centrally planed to a market economy started [1]. That has profound effects on efficiency and sustainability of waters exploitation and agricultural impact on water resources. *This paper analyzes the evolution and efficiency of water governance in Bulgarian agriculture during post-communist transition and EU integration. First,* it defines the water governance and the scope of analysis. *Second,* it presents the process of transformation of agricultural water governance embracing all mechanisms and modes – institutional environment, market, private, public, and hybrid. *Third,* it assesses impacts of newly evolved system of governance on efficiency and sustainability. *Finally,* it suggests recommendations for improvement of public policies.

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24.2 Definition and Scope of Analysis

Water governance refers to the specific system of social order regulating relations related to water (suppliers, users, polluters, interest groups etc.) and stimulating appropriate behavior for sustainable exploitation of water resources. Agricultural water management is studied as integral part of the systems of water management, farm management and environmental management (Fig. 24.1). The analysis takes into account all critical factors affecting specific management choice related to water – natural, institutional, economical, technological, behavioral, international etc.

Furthermore, the analysis embraces all mechanisms and modes of governance affective individual, collective and social behavior including: (a) *institutional environment* – distribution of formal and informal property rights and rules, and system(s) of enforcement of these rights and regulations; (b) *private modes* (private and collective order) – diverse voluntary initiatives and specially designed contractual and organizational arrangements of private agents such as codes of behavior, contracts, cooperatives, associations, business ventures etc; (c) *market modes* – various decentralized initiatives governed by free market price movements and market competition; (d) *public forms* (public order) – different forms of a third-party public (Government, international etc.) intervention in market and private sectors such as public information, regulation, assistance, funding, taxation, control, provision etc; (e) *hybrid modes* – some combination of above three.

Individual governing modes have different potential to induce effective and sustainable exploitation of water resources and reconcile water related conflicts since they give unlike incentives (benefits) and impose different costs to agents associated with water.[1] Depending on the specific system of water governance in a particular industry, region, country etc, the efficiency and sustainability of exploitation of water resources is quite different.

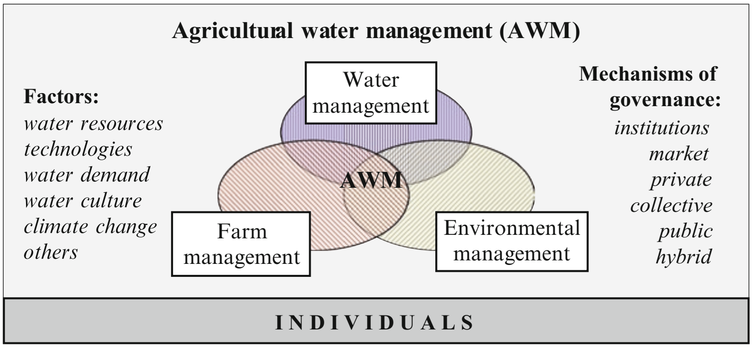

Fig. 24.1 Framework for analysis of agricultural water management

[1] While *market prices* could coordinate well relations between water suppliers and users, regulation of relations of water polluters and users require a special *private* or *public order.*

24.3 Post-Communist Evolution of Agricultural Water Management

During 1990s most agricultural lands and assets of dominating public farms were privatized, and entire farming activity transferred into newly evolving unregistered farms, cooperatives and agri-firms.[2] For a long-period of time the rights on major recourses (farmland, irrigation facilities) and the diverse environmental rights (on use and preservation of natural resources) were not defined or were badly defined and enforced [1]. Most agrarian activities were carried out in less efficient and unsustainable structures[3] with little incentives or capability for effective exploitation and conservation of water infrastructure and resources (Table 24.1).

State monopoly Irrigation Systems (IS) was reorganized into a Joint-stock company owned by the Ministry of Agriculture (MA) responsible for the management of state assets, provision of irrigation and drinking water, drainage and flood protection. Union of Water Users (UWU) was initiated and 176 Water User Associations (WUA) emerged. This collective form was unable to improve efficiency (low incentives, lack of ownership) and deal with monopoly position of 21 semi-autonomous regional branches of IS. Since 2001 the user-rights on irrigation assets of IS have been freely transferred to newly-registered WUA. Around 70 WUA are formed servicing 30% of the total irrigation area. Expected "boom" in efficiency from collective management of irrigation has not materialized because of semi-monopoly situation (terms, pricing) of regional water suppliers, few incentives for water users to innovate facilities and expand irrigation, and uncompleted privatization of state assets. Evolution of farmers and eco-associations in the country has been hampered by the big number and diversified interests of agents – different size of operation, type of farming, water needs, water impacts, preferences, age and horizon etc.

During transition public eco-policies, regulations, monitoring, and support were inefficient, inconsistent, reactive and sectoral with different agencies responsible for various aspects of water management. Investment Fund Melioration (FM) was established (disappeared in 1998) and subsidies to IS costs applied until 2004. However, the overall level of public support to agriculture and water sector has been very low. EU Special Assistance Program for Agrarian and Rural Development (SAPARD) introduced "Agro-environmental" measures but they were approved too late (end 2006) and only few pilot projects were actually supported.[4]

[2] Until 1989 farming was carried by small number of large public farms averaging thousands of ha and livestock. By 1995 almost 1,8 million new farms appeared most of them being small-scale and (semi) subsistent. Since 1995 unregistered farms and cooperative decreased 75% and 52% while agri-firms increased 2,4 times. Currently 1,4% of farms manage 68% of farmland.

[3] organizations under privatization, liquidation or reorganization; small part-time and subsistence farms; production cooperatives; huge agri-firms based on short-term lease contracts.

[4] due to mismanagement SAPARD was suspended by EC (2008) and considerable funding lost.

Table 24.1 Evolution of agricultural water management in Bulgaria

Periods	Public modes	Private modes	Market modes
Transition (1990–2000)	Organizations under privatization and reorganization; (IS); regional branches of IS; MA; FM; MA subsidies to IS; water use and protection rules	Cooperatives; unregistered farms; agri-firms; UWU; WUA	Short-term lease contracts; free (monopoly) pricing
Pre European Union (EU) accession (2001–2006)	Ministry of Environment and Waters (MEW); MA; Executive Environment Agency (EEA); Executive Hydro-melioration Agency (EHMA); assistance in WUA formation; free transfer of state irrigation assets to WUA; MA investment in IS; MA subsidies to IS; SAPARD; good agricultural practices; water user regulations, bans; eco-monitoring, information, assessment; compensation for natural disasters	Cooperatives; unregistered farms; agri-firms; newly-registered WUA; private and collective rules for water use; vertical integration of eco-system services; interlinked contracts; environmental NGO's	Free (monopoly) pricing; organic farming; eco labeling; trade with origins, brands, and specific products; trade with eco-system services; insurance against droughts and floods
EU membership (since 2007)	EU common policies and standards; cross compliance; National Plan for Agrarian and Rural Development (NPARD); long-term public eco-contracts; eco-training; emergency free irrigation; compensation for natural disasters	Cooperatives; unregistered farms; agri-firms; WUA; private and collective rules for water use; vertical integration of eco-system services; interlinked contracts; environmental NGO's	Free (monopoly) pricing; organic farming; eco labeling; trade with origins, brands, and specific products; trade with eco-system services; insurance against droughts and floods

In recent years, a number of national programs have been develop,[5] a system of eco-monitoring and information set up, and mandatory eco-assessment of public programs introduced. Laws, standards and institutions were harmonized with EU which introduced a modern framework for eco-governance including new rules for

[5]For Preservation of environment; Development of water sector; Combating climate change; Management of lands and fights against desertification; Agrarian and rural development etc.

environment protection, integrated water management, polluter pay principle etc, and relevant institutions for controlling, monitoring and assessment (EEA, EHMA etc.). Needs to reconcile interests, share and sustain natural resources bring about special governance at watershed, regional, national and transnational scales. However, deformation of public choices by strong private interests, slow and inefficient eco-actions, and poor eco-monitoring has been common.

EU Common (agricultural, water, environmental, rural etc.) policies implementation provides considerable support for farming modernization, infrastructural development, and eco-measures.[6] There is also a mandatory "cross compliance requirement" for receiving public support. That leads to enhancement of sustainability of many farms. There has been a considerable progression in implementation of public measures but it is still far below the targets.[7] The state stepped in providing free irrigation in 2007 drought and compensating for flood damages (2007, 2010). Most farms cannot participate in public schemes,[8] due to poor design, restricting criteria, little awareness, complicated procedures, and high related costs. Poor coordination, ineffective enforcement, and corruption are still typical for public forms.[9]

The restructuring of farms continues as most of them apply survival tactics rather than a long-term strategy for improving efficiency [1]. Also, a great portion of subsistence, small commercial farms, and farming cooperatives are unable to adapt to evolving market, institutional and natural environment.[10] There have been emerging private modes introducing incentives and possibilities for effective water and integral eco-management (codes of behavior, cooperation, vertical integration, classical or inter-linked contracts) profiting from inter-dependent activities such as farming, water use and protection, fishing, recreation, processing, marketing etc. There are good examples for introduction and enforcement of private rules for use and protection of natural resources by farmers and users, and top eco-standards by individual farms or a vertical integrator. In recent years market-driven organic farming and trade with eco-products and services appeared but it is restricted or just a part of the marketing strategy rather than a genuine eco-action. Private management is associated with improved environmental stewardship on owned and marketed resources, but less concern to manure and garbage management, over-exploitation of leased and common resources, contamination of soils and waters etc. Furthermore free market management of giant and semi-monopoly water supply, servicing and insurance companies usually comes with unfavorable pricing and terms for farmers. Consequently, only few farms purchase insurance against natural disasters (such as, draughts and floods).

[6] Environmental measures account for 27% of the overall budget of NPARD (MAF).

[7] In NPARD are opened 6 out of 24 measures. Target achievement for support to unfavorable regions is good, but for agri-environmental payment it is only 6% and the rest none (MAF).

[8] e.g. around 16% of all farms receive area based payments and 13% get national top-ups (MAF).

[9] E.g. due to organizational and financial reasons implementation of EU water monitoring programs is delayed as EEA gets no water information from Bulgarian Academy of Sciences.

[10] Market competition, and new EU quality, safety, and eco-standards [1] as well as challenges associated with the climate change [2].

24.4 Impacts on Efficiency and Sustainability

The newly evolved system of agrarian governance (market and private incentives, smaller size and owner operating nature of farms, etc.) let avoid certain problems of large public enterprises from the past.[11] It has also led to a sharp decline in all crop (except sunflower) and livestock (except goat) productions.[12] The share of water intensive crops like vegetables, rice and maize considerable decreased, while some traditional and more sustainable technologies, varieties and breeds introduced. A large portion of agricultural lands have been left abandoned for a long period of time and the average yields for all major products shrunk 40–80% of the pre-reform level. All of this has relaxed the overall agricultural pressure on environment and water issues.

Since 1989, there has been more than a 21-fold decline in water used in agriculture[13] (Table 24.2). In recent years sector "Agriculture, hunting, forestry and fishery" comprises merely 3.17% of total water use and 0.34% of generated waste waters (NSI).

Table 24.2 Evolution and agricultural use of water resources in Bulgaria (Source: FAO, AQUASTAT)

Indicators	1988–1992	1993–1997	1998–2002	2003–2007
Total water resources (10^9/m^3/year)	21	21	21	21
Water resources per capita (m^3/inhabitant/year)	2,427	2,562	2,661	2,748
Total water withdrawal (10^9/m^3/year)	14.04	na	8.67	na
Agricultural water withdrawal (10^9/m^3/year)	3.06	0.14	0.14	0.14
Share of agricultural water withdrawal in total (%)	21.78	–	1.66	–
Share of total actual renewable water resources withdrawn by agriculture (%)	14.36	0.66	0.68	0.67
Area equipped for irrigation (1,000 ha)	1,263	789	622	104.6
Share of cultivated area equipped for irrigation (%)	29.17	17.55	17.36	3.18
Area equipped for irrigation actually irrigated (%)	Na	5.42	4.96	51.29

[11] Over-intensification of production, intensive and inefficient water use, chemical contamination of soils and waters, livestock and manure concentration, uncontrolled erosion [1].

[12] Potatoes 33%, wheat 50%, corn and burley 60%, tomatoes, Alfalfa hay and table grape 75%, apples 94%, pig meat 82%, cattle meat 77%, sheep and goat meat 72%, poultry meat 51%, cow milk 45%, sheep milk 66%, buffalo milk 59%, wool 85%, eggs 45%, honey 57% (NSI).

[13] The main sources of water supply in the sector are large dams and rivers. Ground water is a supplementary source while utilization of sludge from purified waste waters in insignificant. Irrigation water accounts for the major share in total agricultural water use (74%).

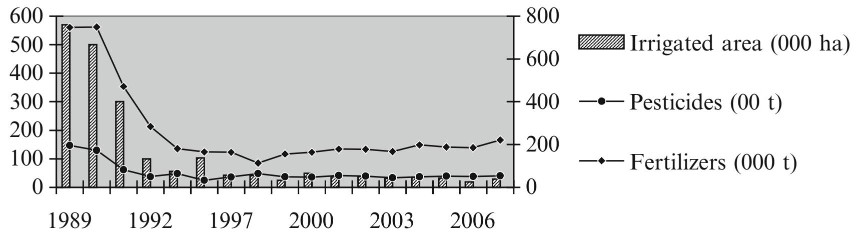

Fig. 24.2 Irrigation and chemical application in Bulgarian agriculture (Source: National Statistical Institute)

The later contributes to reduction of water stress in the country.[14] Restructuring of farms and agricultural production has been also accompanied with a sharp reduction in irrigated farmland (Fig. 24.2). What is more, a considerable physical distortion of irrigation facilities has taken place affecting 80% of the internal canals (MAF). Furthermore, water losses in the irrigation system amount to 70% as a result of poorly maintained facilities, low efficiency, and water stealing.

The negative impact of intensive irrigation on overall erosion and salinization has diminished significantly after 1990 (EEA). Erosion has been a major factor contributing to land degradation in Bulgaria. Its progressing level is a result of extreme weather but it has been also adversely affected by dominant agro-techniques, deficiency of anti-erosion measures, uncontrolled deforestation and recultivation of permanent grasslands. Due to ineffective management around one-third of the arable lands are subjected to wind erosion and 70% to water erosion as total losses varies from 0.2 to 40 t/ha in different years (EEA). Annual losses of earth masses from water erosion are estimated at 145Mt and two-third of it comes from the arable land.[15] The fraction of salinized land doubled after 1989 but it is merely 1.1% of the total farmland (EEA).

The widespread application of primitive irrigation techniques, and inappropriate crop choice, rotation and agro-techniques augment inefficiency of water use and local soil erosion. The decline in irrigation has also had a direct harmful effect on crop yields and structure of rotation. The level of irrigation depends on the humidity in each year, kind of irrigated crops and water prices. Nonetheless, irrigation has not been effectively used to correct inappropriate seasonal and regional distribution of rainfalls, and mitigate effect of climate change[16] on farming and land degradation. Farms meager capability for adaptation resulted in huge crop, livestock and property losses during recent droughts and floods.

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[14] Depending on year's humidity territory accumulates 9–24 billion m^3 water (EEA). In 2006 total water withdrawal was 6559054 out of which 92.8% surface and 7.2% ground water. Since 1990 Water Exploitation Index decline considerably from 55% (2d in Europe) to 33%.

[15] Soil losses range from 8 t/year for permanent crops to 48 t/year for arable lands (EEA).

[16] Temperature increases, rains quantity decreases, and more extreme events occurs (EEA). By 2030 water availability on more than 50% of the territory will decrease 5–10%, a severe water stress is projected for South-Eastern parts and a medium in some other places.

There has been a considerable amelioration of the quality of surface and ground water as a result of an unintended decrease in the negative effects of agriculture. The total amount of fertilizers and pesticides used has declined with respective applications representing merely 22% and 31% of the 1989 level (Fig. 24.2). The respective unbalanced N, P and K fertilization is currently applied based on 37.4%, 3.4% and 1.9% of the Utilized Agricultural Area (UAA). This trend has diminished pressure on the environment and risk of chemical contamination of soils and waters. Nitrate and phosphate content in surface water decreases over the transition has resulted in only 0.7% of samples exceeding the Ecological Limit Value (ELV) for nitrate (EEA). Despite improvement, many water eco-systems are at risk caused by agricultural emissions in water and increasing application of chemicals.

In drinking water about 5% of analyses show concentrations of nitrate up to five times above appropriate level (EEA). The later is mostly restricted to 400 small residential locations, but it also is typical for almost 9% of the large water collection zones. Improper use of nitrate fertilizers, inappropriate crop and livestock practices, monoculture, and non-compliance with specific rules for farming in water supply zones, are responsible for that problem.

Monitoring of water for irrigation shows that in 45% of samples, nitrate concentrations exceed the contamination limit value by factors of 2–20 (EEA). Nitrates are also the most common pollutants in ground water with N levels only slightly exceeding the ecological limit in recent years. Around the country a trend for reduction in pesticides concentration in ground water is reported with occasional cases of triasines over the ELV since 2000.

Nitrate Vulnerable Zones cover totally or partially 53% of the territory of the country and 68% of UAA. The lack of effective manure storage and sewer systems in majority of farms contributes to the persistence of this problem. Only 0.1% of the livestock farms possess safe manure-pile sites, around 81% of them use primitive dunghills, and 116 thousands holdings have no facilities at all (MAF). A serious environmental challenge also has been posed by inadequate storage and disposal of expired and prohibited pesticides,[17] as 28% of all polluted localities in the country are associated with these dangerous chemicals (EEA). Furthermore, the number of illegal garbage dumps in rural areas has noticeably increased reaching an official figure of 4,000; and farms contribute extensively to waste production bringing about air, soil and water pollution (EEA).

24.5 Conclusions

Based on our findings, the following recommendations should be implemented.

1. Better integrate eco- and water (including the neglected ground water) policy in agrarian regions; develop policies to enforce long-term eco-measures.

[17] There are still 333 abandoned storehouses in 324 locations for 2,050 t pesticides (EEA).

2. Apply integral approach of soil, water and biodiversity management in planning, funding, management, monitoring, controlling and assessment at all levels with involving all stakeholders in decision-making process. Eco-system services, life-cycle, water accounts, and other modern approaches need to be incorporated into program management.
3. Improve coordination and efficiency of actions between various public and private agents involved in water and eco-management.
4. Better define, regulate, and further privatize (collectivize) property, user, management, trading, discharge rights and assets related to water resources, eco-system services, and diverse emissions and wastes.
5. Employ a greater range of instruments including appropriate pricing, quotas, public funding and insurance, taxing, and interlinking to improve water use efficiency and risk sharing, prevent over-intensification and the negative effect on water resources, and support farms adaptation to changing environment.
6. Ensure adequate water and eco-data collection, monitoring, and independent assessment including agricultural benefits and effects; waters quality; total costs; water-foot prints; effects of climate change; existing and likely risks etc. Assure mechanisms for timely disclosure and effective communication to decision-makers, stakeholders and public at large.
7. Better adapt CAP instruments to specific Bulgarian conditions supporting farm modernization and adaptation, and irrigation, drainage and flood protection innovations; relaxing EU criteria for semi-market and young farmers; directing funds to prospective (Farm modernization and adaptation, Young farmers) and unsupported (Organic livestock) measures; and better implementing planed environmental measures.
8. Employ hybrid (public-private, public-collective) modes given coordination, incentives, and control advantages. Public organization and enforcement of most eco-standards is very difficult (especially in huge informal sectors and remote areas). Public support to voluntary initiatives of professional, community and non-governmental organizations (informing, training, assisting, funding, risk-sharing), and assistance in cooperation at eco-system, watershed, trans-regional and trans-border levels will be more efficient. Effective (real) participation of farmers and stakeholders in priority setting, management, and assessment of public programs and regulations at all levels is to be institutionalized.
9. Improve eco- and water education and training of farmers, administrators, and public modernizing Agricultural Education and Advisory Service which are to reach all agents through effective methods of education, advice and information suited to their specific needs; set up a system for continued training and sharing of experiences; include eco and water management and climate change issues; cooperate closely with other academic institutions and private organizations.
10. Improve the overall institutional environment and public governance perfecting property rights protection and laws and contracts enforcement, combating mismanagement and corruption in public sector, removing restrictions for market, private and collective initiatives.

11. Give more support to understanding agricultural water use and effects,[18] and multidisciplinary research on various aspects, factors and effects of eco- and water governance. Currently, efforts of Ecologists, Technologists, Climatologists, Economists, Layers, Behavioral Scientists are rarely united; most studies focus on individual aspect of sustainability or formal modes; normative (ideal or model in other countries) rather comparative (between feasible alternatives) approach is employed; and significant social (third-party, recovery, transaction etc.) costs ignored.

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[18] Agricultural and water research has been severely underfunded for the last 20 years.

Chapter 25
Influence of Climate Change on Shallow Groundwater Resources: The Link Between Precipitation and Groundwater Levels in Alluvial Systems

Orhan Gunduz and Celalettin Simsek

Abstract Alluvial groundwater systems are extremely vulnerable to changes in precipitation amounts as they are typically recharged from above. Thus, any change in precipitation patterns due to climate change is likely to influence such systems first. Dynamic behavior of these systems is clearly seen from large fluctuations in the declining and rising curves of groundwater level time series graphs. An example of such a system is analyzed within the scope of this study that is located in Western Anatolia near Izmir, Turkey. Data collected from 21 monitoring wells were used to assess the long term general trend in the groundwater levels of Torbali-Bayindir plain, an alluvial system near Izmir city. The results demonstrated an average declining pattern of 0.75 m/year in groundwater levels where strong seasonal fluctuations in some wells could reach as high as 30 m. Considering this dynamic behavior, such systems, which are highly dependent on timing, persistence and total amounts of precipitation, are extremely vulnerable to changes in precipitation patterns, particularly in areas where climate change effects are towards increased temperature values and reduced precipitation totals.

Keywords Alluvial surface aquifer • Precipitation • Groundwater level • Climate change

25.1 Introduction

Alluvial aquifer systems are typically considered to provide significant amounts of groundwater in many parts of the world. Being mostly composed of sand, silt and gravel, these systems serve as ideal locations for drilling wells for domestic,

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agricultural and industrial water supply. Based on their lithological characteristics, alluvial systems are usually situated in lowland areas, particularly on plains and floodplains of river systems, which are also under the influence of anthropogenic stresses due to settlement, agricultural production and industrial development. Morphologically, these systems are generally surface aquifers that are characteristically recharged from surface infiltration. Consequently, water in surficial alluvial aquifers is typically short-circulated groundwater that has a fairly short recharge-discharge cycle. In addition, alluvial systems are not only the mostly used groundwater resources of the world but also rank very high in the list of water resources that is influenced from variations in precipitation patterns as a result of climate change.

The relationship between recharge and discharge in alluvial aquifers is quite dynamic. Many times, water level fluctuations in these systems demonstrate cycles not longer than one season. The decline and rise of water levels resemble a characteristic sinusoidal pattern. The slopes of the declining and rising curves as well as the difference between their crest and base are strongly related to aquifer characteristics (i.e., hydraulic conductivity, specific yield), recharge characteristics (i.e., precipitation-infiltration ratio, land use and land cover) and water extraction characteristics (i.e., number, capacity and configuration of wells, withdrawal rates). The changes in climatic pattern particularly influence the amount and extend of precipitation, which in turn affects the infiltration rates and ultimately the recharge amounts. Furthermore, the increasing dependency of communities on relatively more stable groundwater resources is also creating an extra pressure on groundwater thru ever-increasing extraction patterns. Hence, changes in climatic patterns and precipitation amounts influence alluvial groundwater systems not only from a decreased supply rate perspective, as occurs in many parts of the world, but also from an increased demand point of view.

Based on these fundamentals, this study focuses on the Torbali-Bayindir Plain that is situated in Kucuk Menderes River Basin to the south of Izmir-Turkey (Fig. 25.1) to analyze the trends in precipitation and groundwater levels. The plain is a part of a larger east-west directed graben system, on which intense agriculture and industrial development is currently present [1]. The water demand in this region is completely supplied from shallow groundwater through wells drilled in the alluvial aquifer, whose thickness could reach up to 100 m. A total of 20 groundwater monitoring wells with monthly level data extending back to 1970s are used to assess the fluctuations in groundwater levels. A more intensive monitoring activity is also conducted in one well equipped with automatic level recorder, which provided an inside look into more intermittent data from other wells. Moreover, daily precipitation data from Izmir and Adnan Menderes Airport meteorological stations are used to compute monthly and yearly precipitation totals that would mostly characterize the precipitation patterns in the study area. Groundwater level data is used to detect the general annual declining pattern in the plain. The relationships between precipitation and groundwater

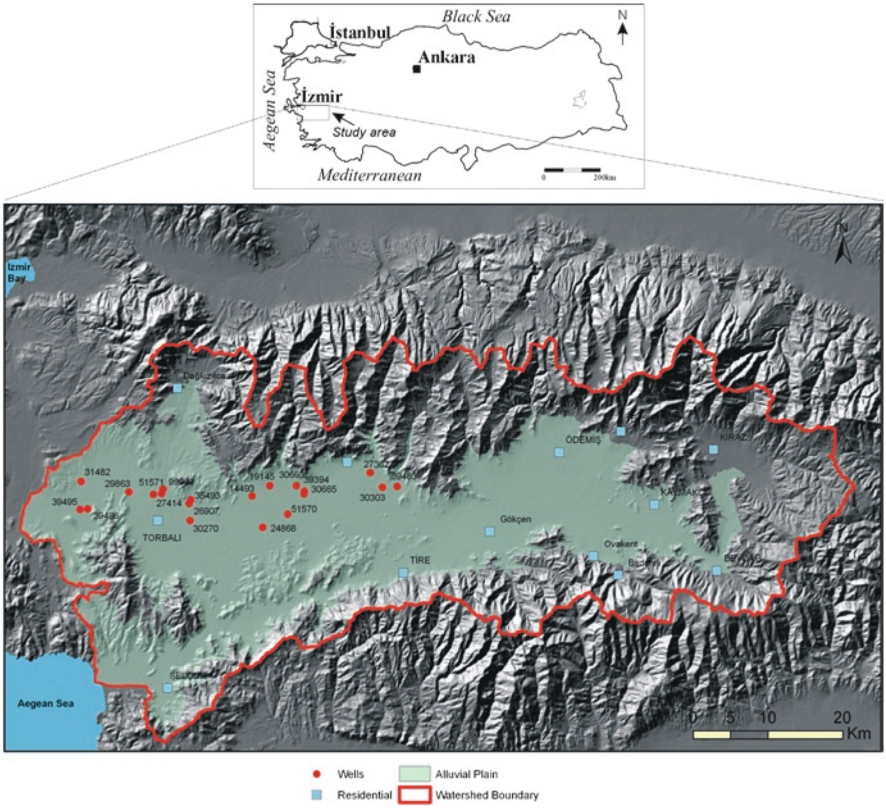

Fig. 25.1 Location map of the study area

level are then used to evaluate the response of the alluvial aquifer system in Torbali-Bayindir plain.

25.2 General Characteristics of the Study Area

The study area is located within the boundaries of the districts of Torbali and Bayindir in Izmir Province of Turkey. It is situated about 50 km south of the city of Izmir in western Anatolia (Fig. 25.1). Torbali-Bayindir Plain forms northern portions of Kucuk Menderes River Basin and is located in a wide alluvial zone (Fig. 25.1). Within the plain, Torbali, Bayindir, Caybası, Ayrancilar, Subası, and Kuscuburun are main population centers. Agriculture is the main economic activity of the area due to fertile soils and suitable climatic conditions. Both settlements and these agricultural fields supply their drinking and irrigational water demands from wells drilled in the alluvial aquifer.

The plain is located within a graben zone where Mesozoic-aged Menderes metamorphic rocks form the basement and are observed outcropping in the eastern and western parts of the plain [2]. The Menderes metamorphic rocks consist of mica and chlorite schists in their lower levels and dolomitic marble in their upper sections. This formation is widely observed in westerns part of the project area. These schists are nearly impermeable and thus do not supply significant amounts of groundwater. The Neogene Visneli Formation, of limestone and claystone, overlies basement rock. This formation is widely observed in northern parts of project area. Finally, Quaternary alluvial layers overlie the basement and Visneli Formation in the study area. The thickness of alluvial layer ranges 30–100 m in the plain.

The evaluation of regional geology revealed that the most important water bearing units in the study area is the alluvial aquifers. The Quaternary surfacial aquifer is composed of the alluvial deposits of Kucuk Menderes River and its tributaries. It is the main water-supplying strata within the study area. This aquifer is divided into two zones according to material properties. Granular material such as sand and gravel are mainly located along the creek beds, while silty sand and clayey material are located elsewhere [3, 4]. This sandy formation is widely used to supply groundwater for domestic agricultural and industrial demands. This aquifer is recharged from surface infiltration and from water seeping along the creek beds. Average conductivity of sandy and silty aquifers are 1.9×10^{-4} and 4.5×10^{-6} m/s, respectively [7].

25.3 Climatic Conditions

Climate change is currently considered to be one of the greatest environmental problems that mankind faces today. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) shows that the global mean surface temperature has risen by 0.74°C over a period of 1906–2005 [5]. Around the world, many scientists are actively working to understand and mitigate the effects of climate change on the environment and on human life style. In many areas including the project site, which is typically under the influence of characteristic Mediterranean climate with hot dry summers and wet warm winters, climate change is likely to create hotter and drier summers [5]. The intensity of extreme events that create catastrophic consequences is also likely to increase globally.

Based on 80-year data collected between 1929 and 2009 in Izmir meteorological station [6], there is a decreasing trend in precipitation with an approximate rate of about 1 mm/year (Fig. 25.2) that is significantly higher than the national average of 0.29 mm/year. Of this 80 year period, the number of years that received

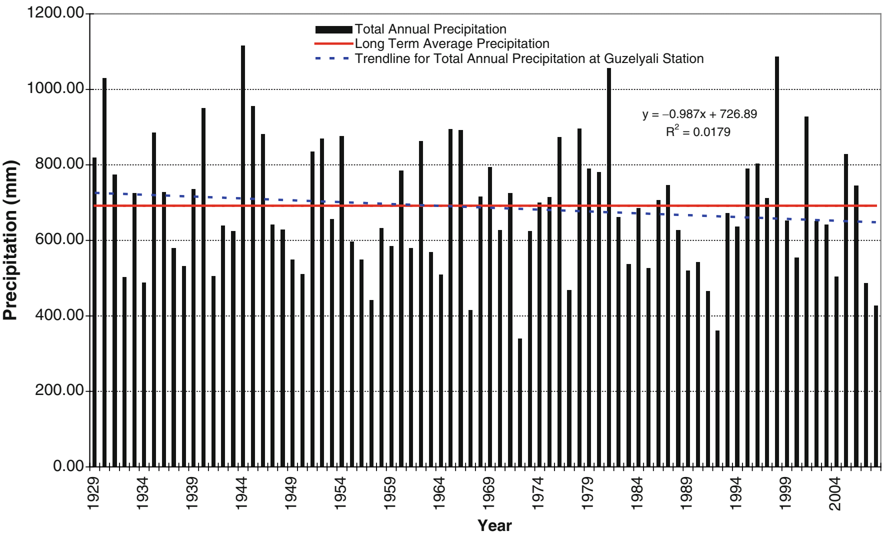

Fig. 25.2 Total precipitation at Izmir (Guzelyali) meteorological station and long-term trend

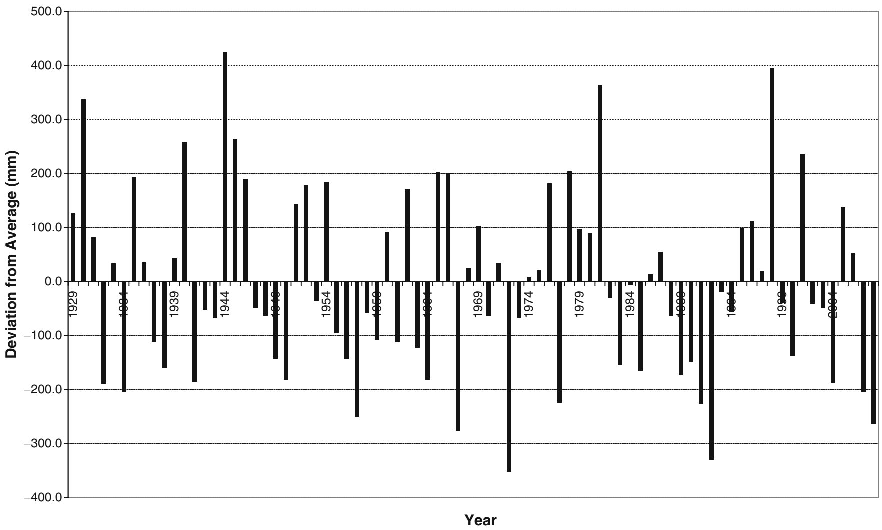

Fig. 25.3 Deviation of total annual precipitation from long term average

above average precipitation value is 37, which is another indication of the decreasing precipitation trend in the region. When the deviations from the long term average value of 687 mm are concerned, one could detect consistent drought periods that typically last 3–4 years and repeat nearly every 8–12 years (Fig. 25.3). For a city that supplies approximately 65% of its domestic water demand from groundwater resources, this declining trend in precipitation patterns and the associated reduced recharge rates poses an imminent threat to the security of water supply and to public health.

25.4 Groundwater Levels

Considering the strong groundwater dependent nature of the area, the groundwater levels in Torbali-Bayindir plain is monitored by State Hydraulic Works on a monthly basis since 1960s. Considering the large time period between two consecutive data, the information from these wells could best be used in assessing the long-term general trend in groundwater levels in the plain. An example of such change in a well is presented in Fig. 25.4. In this study, the long-term data from 21 such wells are analyzed and statistical summary of the results are presented in Table 25.1. As seen from the table, all wells but one represents a declining pattern which is mostly associated with increased extraction from the aquifers. Overall, the data from these 21 boreholes has an average declining rate of 0.75 m/year with an average R^2 value of 0.54. The declining rate reach to levels of 1.3 m/year with a R^2 value of about 0.9 in some wells.

While the average groundwater level in the plain is calculated to be 23.4 m, minimum level recorded is found to be 64.3 m in a well near Bayindir. A more specific result is the seasonal decline and increase in a well as a function of the

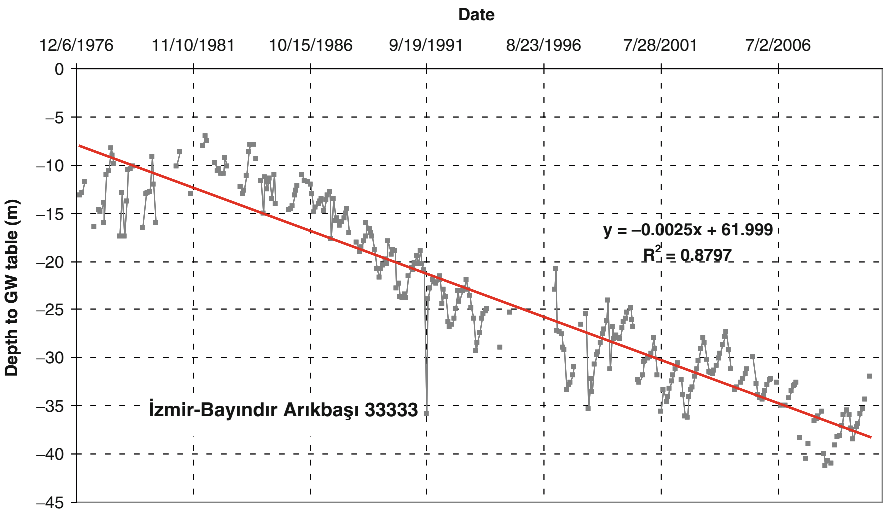

Fig. 25.4 Change in groundwater levels in a monitoring well in Torbalı-Bayindir plain

Table 25.1 Statistics for groundwater level data

District	Well name	X	Y	Date range	Min GW level	Maximum GW level	Average GW level	Decline/ day (m)	Decline/ year (m)	R2
Bayindir	Yakacik	561,493	4,227,277	06/1983–05/2010	–46.70	–1.19	–26.60	–0.0035	–1.2775	0.8935
Bayindir	Haskoy	545,486	4,221,940	06/1978–05/2010	–54.65	–0.12	–13.51	–0.003	–1.0950	0.6780
Bayindir	Arikbasi	544,074	4,226,112	01/1977–05/2010	–41.20	–7.00	–23.87	–0.0025	–0.9125	0.8797
Bayindir	Kizilcaova	546,429	4,227,472	01/1985–04/2003	–33.90	–10.35	–21.99	–0.0029	–1.0585	0.7419
Bayindir	Kizilcaova (19141)			05/1975–05/2010	–49.50	–14.53	–36.65	–0.0023	–0.8395	0.8011
Bayindir	Yusuflu	559,856	4,229,224	01/1985–05/2010	–64.30	–13.37	–43.37	–0.0033	–1.2045	0.8700
Bayindir	F1r1nl1	551,058	4,226,751	01/1985–05/2010	–53.15	–0.60	–17.339	–0.0025	–0.9125	0.6257
Bayindir	F1r1nl1	551029	4,226,400	01/1985–05/2010	–34.70	–0.25	–13.58	–0.0029	–1.0585	0.5165
Bayindir	Zeytinova	563,444	4,227,368	01/1991–05/2010	–55.40	–24.15	–42.07	–0.0022	–0.8030	0.5519
Bayindir	Elifli	549,991	4,227,482	01/1991–04/2010	–47.40	–9.75	–28.26	–0.0014	–0.5110	0.1914
Bayindir	Ciplak (Canli)	548,848	4,223,693	01/1985–06/2004	–24.90	–0.18	–12.13	–0.0023	–0.8695	0.7258
Torbali	Sehitler	535,825	4,222,837	06/1987–04/2010	–34.50	–3.27	–14.60	–0.0017	–0.6205	0.3381
Torbali	Torbali	527,639	4,226,632	03/1985–04/2010	–339.50	–0.25	–16.09	–0.0013	–0.4745	0.2042
Torbali	Torbali	530,918	4,226,340	09/1972–04/2010	–52.45	–6.85	–25.29	–0.0024	–0.8760	0.8318
Torbali	Pancar	521,261	4,228,044	01/1985–04/2010	–10.70	–0.40	–4.19	4.00E-05	0.0146	0.0023
Torbali	Pancar	522,173	4,224,376	01/1992–04/2010	–43.70	–3.70	–24.36	–0.0001	–0.0365	0.0005
Torbali	Pancar	521,125	4,224,308	01/1992–04/2010	–48.10	–3.40	–25.88	–0.0011	–0.4015	0.0538
Torbali	Mandra	532,182	4,227,015	09/1968–04/2010	–61.80	–11.64	–27.89	–0.0016	–0.5840	0.6183
Torbali	Arslanlar	535,684	4,225,108	09/1979–04/2010	–36.80	–3.70	–13.93	–0.002	–0.7300	0.5839
Torbali	Arslanlar	535,936	4,225,606	01/1987–04/2010	–41.50	–9.70	–19.10	–0.0024	–0.8760	0.6395
Torbali	TMYO-1	532,025	4,226,423	04/2007–10/2009	–46.50	–28.83	–40.91	Insufficient data	Insufficient data	Insufficient data
				Minimum	–64.30	–28.83	–43.37	–0.00350	–1.27750	0.00050
				Maximum	–10.70	–0.12	–4.19	0.00004	0.01460	0.89350
				Standard Dev.	12.32	7.95	10.63	0.0010	0.3472	0.3004
				Average	–43.85	–7.30	–23.41	–0.00207	**–0.75482**	**0.53740**

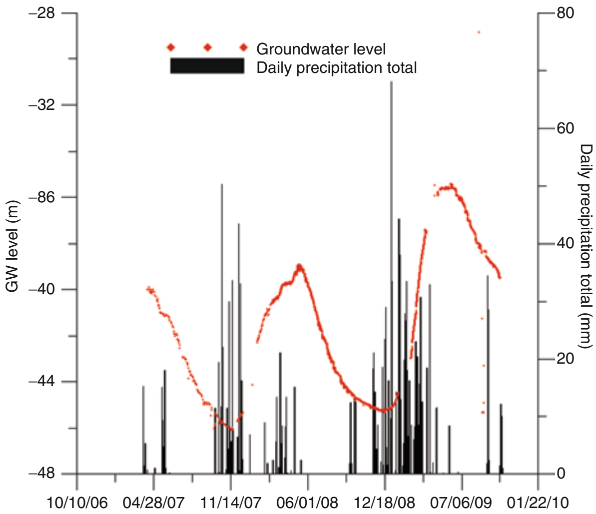

Fig. 25.5 Relationship between precipitation and groundwater levels

infiltration results (Fig. 25.5). Seasonal decline and recovery could sometimes reach to levels as high as 30 m representing the extremely dynamic pattern of groundwater flow pattern in this alluvial system.

25.5 Conclusions

Being the primary source of recharge for shallow groundwater systems, precipitation is of utmost importance for groundwater sustainability, particularly in semi arid to arid regions of the world. Although it is very difficult to set a concrete relationship between groundwater levels and precipitation totals due to many reasons including but not limited to overexploitation and unaccounted extraction patterns, it is still very important to find ways to understand the major mechanisms and details of the decreasing groundwater levels. One such way is to examine the long term trends of precipitation and groundwater levels in shallow aquifer systems.

The Torbali-Bayindir aquifer is mostly of alluvial in origin and is under the influence of declining precipitation totals and anthropogenic stress. Long term analysis of the data demonstrated a general declining pattern in groundwater levels at an average rate of about 0.75 m/year, which is partly associated with decreasing precipitation patterns and partly with overexploitation of the aquifer. The results further indicated a very fast response of the groundwater levels to precipitation events. This finding strengthens the fact that alluvial systems in this region are short-circulated with an extremely dynamic structure. The slopes of rising and falling limbs of well level curves indicate the high conductance of the system, which also is a clue for the fact that systems similar to the one in Torbali-Bayindir plain are among the ones that will be severely impacted from the consequences of climate change.

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Chapter 26
Evaluation of Four Climate Changes Scenarios on Groundwater Resources of the Escusa (Castelo De Vide) Aquifer, Central Portugal

José Paulo Monteiro and António Chambel

Abstract In countries with advanced environmental management systems, numerical models are often used in the planning and management of sustainable groundwater resources. Toward that end, we evaluated the influence of climate change on karstic groundwater resources of the Escusa (Castelo de Vide) aquifer using a finite-element discrete continuum flow model, allowing the use of 1-D, 2-D and 3-D finite elements in the same computational mesh. The model was calibrated by the regional field measurements. Since this coupled model simulates fluid movement in, and exchange between, multiple domains, it was possible to monitor flow processes such as recharge (diffuse and concentrated infiltration), flux inside the aquifer (quick in caves and conduits and slow in the rock mass), and concentrated discharge (karstic springs) and diffuse discharge to wetlands and other porous hydrogeological units. Four different climate scenarios were analyzed with respect to their influence on future aquifer discharge rates. These scenarios (by the Hadley Centre for Climate Prediction and Research) reflected global and regional climate predictions for 50 and 100 year periods. The variation in groundwater discharge rates from the Escusa aquifer was evaluated in relation with discharge to the Sever River and granitic rocks in contact with the aquifer in its northern part. All the climate-based simulations show a decline in the discharge rates of the groundwater aquifer. Another important finding is that the discharge rates per month change and sometimes it is possible to have an increase in the discharge during the first half of the year and a reduction in the second half of the year.

Keywords Karstic aquifer • Modelling • Climatic changes

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26.1 Introduction

One possible way to evaluate the influence of the climatic changes on the groundwater flow regime is the use of numerical models based on distributed parameters. This kind of models can be used to investigate the aquifers hydraulic behaviour and, additionally, after calibration and validation, to simulate the pollutant or heat transport associated to a vector flux field.

The existence of a numerical model, which was calibrated using the field data for the karstic aquifer of Escusa, also called Castelo de Vide, in the central part of Portugal (Fig. 26.1), created a possibility to evaluate the impacts of different climate change scenarios for this aquifer. The model using the finite element numerical technique has some new potentialities when compared with the most commonly used ones to simulate the groundwater flux in a very heterogeneous media, as it is the case of karstic systems. This model permits the simulation of fluid fluxes simultaneously in one-dimensional, bi-dimensional and tri-dimensional domains. This potential permits the simulation of the duality of flow processes in karstic environments, reflected in the processes of recharge (diffuse and concentrated infiltration), in the vector flux field inside the aquifer (quick in caves and conduits and slow in the rock mass) and, finally, in the occurrence of concentrated discharge (karstic springs) and diffuse discharges in contact with wetlands or with porous hydrogeological unities connected with the karstic system [5].

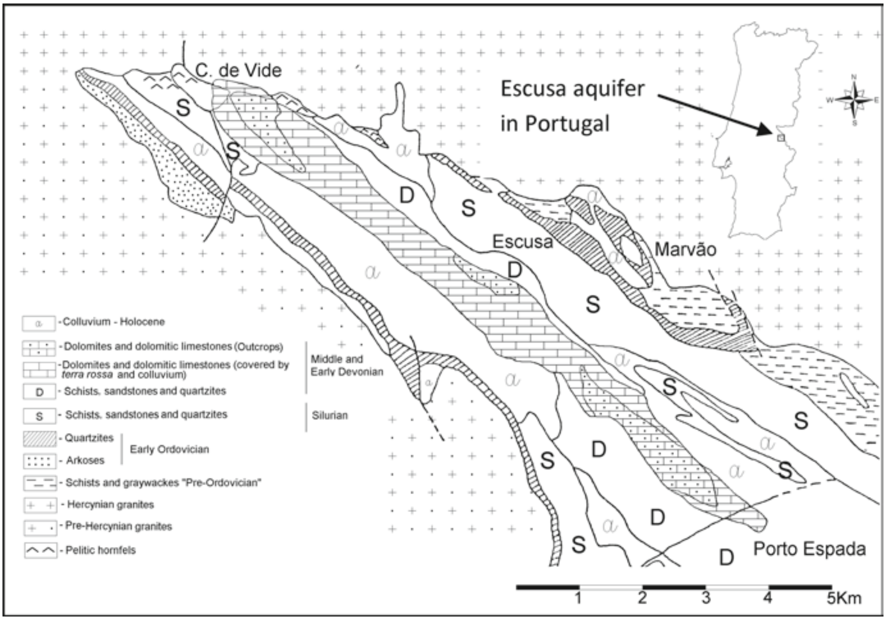

Fig. 26.1 Local geology and structure of the Castelo de Vide syncline (where the aquifer of Escusa is settled) and its location in Portugal. The general basis was adapted from Fernandes et al. [2] and Perdigão & Fernandes [17], adjusted by field work (geometry of carbonate rocks)

Four different scenarios were analysed with respect to the influence of climatic changes on the aquifer discharge rates in the future. The climatic models used were based on different scenarios created by the Hadley Centre for Climate Prediction and Research, with predictions for 50 and 100 years, using global and regional models defined for the latitude of Portugal. The study was based on the 40 years of climatic measurements, with evaluation of monthly recharge rates to the aquifer. Then, the expected variation of the discharge rates to the main stream crossing this aquifer, the Sever River, depending mainly on its groundwater, was studied according the four different future scenarios, as well as the variation in groundwater discharge rates from the aquifer to the granitic rocks in contact with the aquifer in its northern part.

26.2 Geologic Setting

The Castelo de Vide syncline is a periclinal structure with an axis oriented in NW-SE direction (Fig. 26.1). The length of the structure along its axis is about 40 km; the maximum width perpendicular to the axis is about 10 km. The contact of the syncline with the surrounding rocks is marked by Ordovician quartzites (Arenig). Towards NE these quartzites are in direct contact with the Hercinian intrusive Nisa granites, marked by metamorphic contact rocks (hornfels), whereas toward SW they overly the Pre-Hercinian Portalegre granites, with arkoses in the basis marking the transgression of the early Ordovician rocks over the granites. Locally, rocks of the "slate and greywacke complex" are present beneath the NE limit of the Arenig quartzites. The geostructure of this syncline was described by Teixeira [21], Gonçalves et al. [4], Perdigão & Fernandes [17], Fernandes et al. [2]; Perdigão [16], Perdigão [15], Perdigão [14] and Silva and Camarinhas [19].

The carbonate rocks that form the aquifer of Escusa in the centre of this pericline are predominantly dolomites [19] which are classified as dolostones. The effects of active karstic processes at field scale are responsible for the presence of lapiaz, swallow holes, sinking streams, flowing from the neighbouring low permeability schists, and frequent collapse of the roof of shallow dissolution cavities. The thickness of the carbonate formation is about 200 m, but the maximum depth drilled up to now is 139 m. The area corresponding to the limits presented in the map in Fig. 26.1 is of 7.9 km^2.

The carbonate formation is covered in most of its extension by *terra rossa* and colluvium deposits resulting, respectively, from the weathering of the carbonate rocks and from the mechanical weathering of the surrounding crystalline rocks (predominantly fragments of the Ordovician quartzites).

26.3 Hydrogeologic Setting

The highly fractured Ordovician quartzites that form the flanks of the Castelo de Vide Syncline are present in two divergent branches. A group of few wells screened in this aquifer supply a private water plant. The waters have a very low TDS (always lower than 50 mg/l) with Ca-Na-Cl facies. The recharge of this aquifer occurs trough the quartzites and arkoses. The characterization of their hydraulic parameters is presented in Oliveira [13].

The Silurian and Devonian schists, sandstones and quartzites (schists are largely predominant), with a thickness of more than 200 m, are in direct contact with the underlying Ordovician fractured aquifer. In hydrogeological terms these rocks are of very low permeability, defining both the confining layer of the Ordovician fractured aquifer and the "impermeable" substratum of the carbonate aquifer of Escusa, which represents the uppermost aquifer in this sequence, in the nucleus of the syncline (top of the Devonian sequence). A very simplified schematic cross section showing the aquifers in the Castelo de Vide System is presented in Fig. 26.2. The hydrogeology of the Escusa carbonate aquifer was described in Monteiro [9, 10].

The artesian well presented in Fig. 26.2 was built by the private water plant and the quartzite aquifer was found at a 100 m depth and the arkoses at 205 m. Screened only over the entire thickness of the Ordovician quartzites, the hydraulic head at the time of drilling was 15 m above the ground level.

As also can be seen in Fig. 26.2, the carbonate aquifer is located in the bottom of a "U" shaped valley. This is important for the control of the recharge processes related with swallow holes developed near the contact with the schists that are responsible by concentrated recharge. Another recharge process is related to lateral diffusive infiltration from the colluvium deposits existing in some areas near its lateral limits (frequently referred as "allogenic drainage"). This is a secondary process due to the limited extension of these deposits.

In the rare zones where other lithologies contact with the carbonate rocks at lower altitudes, the water transfers towards the adjacent hydrostratigraphic units. These conditions occur only at the NW extreme of the aquifer. During precipitation events, the stream water infiltrates when the limits of the carbonate aquifer are met.

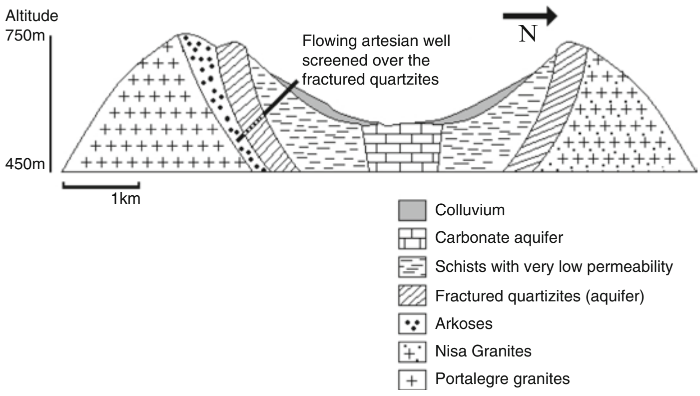

Fig. 26.2 Schematic N-S cross-section of the aquifers present in the Castelo de Vide Syncline. The carbonate rocks correspond to the aquifer of Escusa. Note that the scales are approximate and aspects as the thickness and depth of the formations are completely fictive

This is true for the entire stream network, except for the Sever River, which corresponds to the main discharge area of the aquifer. The drainage density over the carbonate aquifer is almost zero, and, in practical terms, infiltration equals the average precipitation values minus the evapotranspiration in addiction to the runoff generated laterally in the low permeability slopes surrounding the aquifer. It seems also that the NW limits of the aquifer, where the streams diverge from the limits of the carbonate rocks, correspond to a zone where water transferences take place from the carbonate aquifer toward the adjacent lithologies. In this area, the carbonate rocks are in contact with granites and tectonized hornfels, having a higher permeability than the schists limiting the aquifer in almost its entire extension (Fig. 26.3).

26.4 Conceptual Flow Model and Hydrogeological Analysis for Several Scenarios of Future Climatic Changes

As seen in Fig. 26.3, three sectors, as well as the discharge areas, are identified inside the Escusa aquifer. In the area of Escusa, the flow diverges toward Castelo de Vide and toward the Sever River (Rio Sever). In the Porto Espada sector, the predominant flow is toward the Sever River. Therefore, the flow from the Porto Espada and Escusa sectors contributes to the major discharge area of the aquifer, and the Sever River. Near Castelo de Vide, discharge is towards the low permeability lithologies in contact with the carbonate aquifer in that area. The remaining area of contact of the aquifer with adjacent lithologies is with "impermeable" series and thus no more outflow areas are considered. According the variation of recharge values, the groundwater divides are displaced toward the area of the river or the area of Castelo de Vide.

The average annual recharge for aquifer long-term water balance is about 450 mm/year. Considering that hydraulic head values in the discharge areas are also well-known, the conceptual flow model [6] can be expressed in terms of a steady state flow problem, for which only one unknown variable exists and that is the hydraulic conductivity. This problem can be solved using a numerical flow model. The solution provides a homogeneous equivalent hydraulic conductivity value [7] allowing a steady state characterization of the flow domain at a regional scale. This accommodates the long-term mass balance of the aquifer and sectors expressed in the conceptual flow model presented in Fig. 26.3.

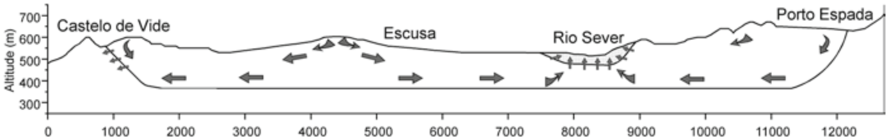

Fig. 26.3 Schematic cross-section showing the predominant flow directions and discharge areas of the Escusa (Castelo de Vide) carbonate aquifer. The distances along the axis are given in meters. The biggest arrows represent the predominant flow directions. The small arrows, crossing the aquifer boundaries represent the position of discharge areas

The hydraulic conductivity values calculated by the numerical and analytical solutions were compatible with a steady state description of the aquifer at the regional scale in terms of the existence of the defined sectors and in terms of the long-term water budget. The presented formulation to calculate hydraulic conductivity circumvents the need of knowing values that quantify the outflow volumes in the discharge areas of the aquifer.

The hydraulic conductivity values were calculated by means of two distinct theoretical conceptions for the interpretation of the aquifer hydraulic behaviour. In both cases, the known variables were the flow domain geometry and average hydraulic head values in discharge areas. The first solution was based on a numerical flow model where hydraulic conductivity was independent of hydraulic head and thus treating the aquifer as confined. The second solution which is analytical considers the aquifer whose water table is bounded by a free surface having a shape defined by the equilibrium between infiltration and hydraulic parameters characterizing each of the aquifer sectors.

The calculated values must be regarded as an equivalent hydraulic conductivity characterizing the entire flow domain [7]. A complete equivalence between the real heterogeneous medium and the idealized one is impossible. Therefore, the relation between the calculated equivalent hydraulic conductivity and the real values is defined, in a limited sense, according to certain criteria that must be equal for both media [18]. In the present case, the used criteria was based on flow equivalence and, additionally, on the definition of the global flow pattern of the aquifer.

The calculated values of hydraulic head using both the methods cannot be used in any other context other than the characterization of the aquifer steady state flow pattern at a regional scale. The description of the aquifer behaviour under specific stress conditions that are different from the average recharge values is impossible without a characterization of a parameter distribution considering the flow domain heterogeneity.

However, the obtained solutions allow the analysis of some crucial basic questions that shall be answered before the decisions required to build a more sophisticated model. This allows the analysis of more complex problems related to the parameters distribution in a flow domain where transient and diffuse flow are overlapped in a very complex pattern. First of all, it is possible to confirm the possible existence of the aquifer sectors proposed for defining the conceptual flow model. These sectors are present in an "artificial flow domain" similar to the real aquifer in terms of geometry, location of discharge areas and average water balance. Moreover, the global flow pattern can be described by different solutions based on a confined or unconfined description of the system.

Point values of hydraulic conductivity were calculated by the interpretation of pumping tests [8], which had permitted the estimation of hydraulic conductivity values characterising the fractured carbonate rock matrix and the nonfractured rock matrix. For the dissolution channels present in the carbonated rocks it is only possible to determine orders of magnitude for hydraulic conductivity in a simplified theoretical framework.

Groundwater undergoes geochemical evolution as it moves throughout flow systems. Therefore, hydrochemical and isotopic trends [1, 3] in each of the three sectors were also identified [11, 12, 20]. The results show that the predominant hydrochemical processes affecting water composition in the carbonate aquifer are the dissolution of carbonate rock minerals, mainly dolomite and accessory calcite. The saturation index (SI) values show that the Castelo de Vide sector tends to show a less accentuated trend to undersaturation with respect to calcite and dolomite than waters collected in the other two aquifer sectors (Fig. 26.4). At the same time, the TDS of samples taken in the Castelo de Vide sector are characterised by the highest values in the aquifer. This is reflected by the electrical conductivity (EC) values of water in this sector, whose average values are about 100 μS/cm higher than the values registered in the Escusa and Porto Espada sectors.

The described trends in the spatial distribution of EC and SI related with calcite and dolomite reflect the regional flow pattern defined in the conceptual flow model. Also, the observed hydraulic behaviour of the aquifer in the identified hydrochemical trend seems to be related to the time residence of water which must be longer in the Castelo de Vide sector due to the fact that the secondary outflow controlling the flow pattern in the NW area is toward relatively low permeable lithologies, that have a limited capacity to assimilate the transference's from the carbonate rocks. On the other hand, the flow toward the Sever River is more effective and thus the residence time of water flowing from the Escusa and Porto Espada sectors must be shorter, as shown by the presence of less mineralised waters and lower values of the SI with respect to calcite and dolomite.

In the Castelo de Vide sector, the residence time of water is longer due the low permeability of the lithologies receiving outflow from carbonate rocks in the secondary discharge area of the aquifer near Castelo de Vide. Therefore, the amount of total dissolved solids in water is more important than in the other aquifer sectors because the chemical processes of carbonate dissolution are closest to equilibrium. This is reflected by the highest values of EC in the Castelo de Vide sector. Due to the rapid outflows toward Sever River (Rio Sever), residence times are shorter in the Escusa and Porto Espada sectors. Here, the water is more undersaturated with respect to the dissolution of carbonate minerals than in Castelo de Vide sector, and the EC is also lower. The elevation of the recharge area in the Porto

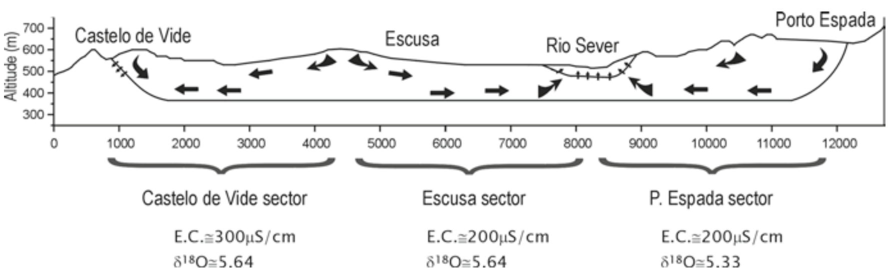

Fig. 26.4 Hydrochemical trends identified in the aquifer and aquifer sectors

Espada sector is about 100 m higher than in the other sectors. Depletion in ^{18}O is observed allowing distinguishing the isotopic composition of water in this sector.

Another hydrochemical trend identified in the aquifer is related to $\delta^{18}O$ ratio values. Lower values of $\delta^{18}O$ represent a depletion of the ^{18}O which is the heaviest isotope in relation with the lighter isotope ^{16}O. This property is of particular utility in diverse hydrologic applications, namely in the identification of groundwater origin in aquifers characterised by the existence of recharge areas with different altitudes. That altitude effect was detected in the Castelo de Vide Aquifer, where measured values of $\delta^{18}O$ show that in the Porto Espada sector water is depleted about 0.3‰ in ^{18}O with respect to the Castelo de Vide and Escusa sectors [12]. Those changes in values of $\delta^{18}O$ are related to the fact that average altitude in the Porto Espada sector is around 650 m, and about 520–550 m in Castelo de Vide and Escusa sectors.

The identified trends of hydrochemical processes at regional scale which allow an indirect confirmation of the defined conceptual flow model for the aquifer are summarised in Fig. 26.4. Based on the conceptual model in Fig. 26.3 and the recharge-infiltration balance which varies from year to year, a simulation for the next 50 and 100 years was performed based on four climatic scenarios defined by the Hadley Centre for Climate Prediction and Research. Table 26.1 reflects the expected modifications in the precipitation values according the four scenarios, two of them for 50 years and the other two for 100 years. The values can be compared with the averages of a 40 years series (1959–1998), as shown in the same table. Figure 26.5 presents the average transference volumes from the aquifer to Sever River (upper diagram) and for the granitic rocks in contact with the aquifer in the area of Castelo de Vide (down diagram). In this figure, it can be noticed that the

Table 26.1 Monthly precipitation considering four scenarios defined by the Hadley Centre for Climate Prediction and Research for the latitude of the Escusa aquifer, two for the year 2050, two for the year 2100

	Observed values (mm)	Previewed monthly average (mm)			
		2050		2100	
	Average of 40 years	HadCM3 B2a	HadCM3 A2c	HadCM3 B2a	HadRM2
Jan	117.02	117.21	106.84	81.43	44.38
Feb	105.40	117.10	81.48	108.20	58.27
Mar	72.83	91.47	55.13	98.41	94.72
Apr	72.43	75.69	70.91	84.98	101.91
May	68.59	83.34	65.44	76.82	102.88
Jun	34.13	41.16	32.56	38.23	32.44
July	7.19	6.16	5.46	6.27	6.15
Aug	8.25	6.06	5.30	6.05	4.45
Sept	45.13	30.69	29.96	30.05	13.74
Oct	93.53	66.31	61.26	54.90	32.28
Nov	114.39	88.19	73.44	54.90	35.57
Dec	120.21	105.78	112.03	67.32	46.67
Total	859.08	829.16	699.80	707.57	573.47

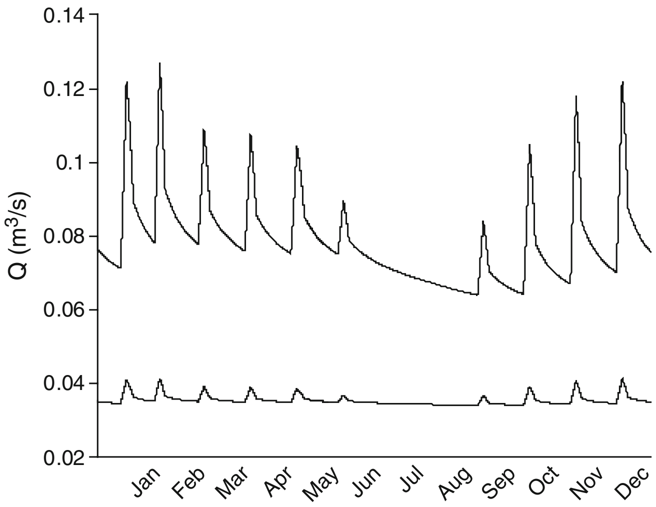

Fig. 26.5 Average transference values from the aquifer to the Sever River (upper diagram) and for the granitic rocks in contact with the aquifer in the area of Castelo de Vide (down diagram). Simulation based in the monthly average recharge volumes of 40 years (period 1959–1998)

discharge to the Sever River, when compared with the discharge to the granitic rocks is significant. Even so, the more abundant vegetation in this area is surely related with this water transfer.

In order to evaluate the impact of the future climatic scenarios, a simplification was made, considering that the recharge episodes in each month happen in a period of a quarter of the month, about a week. The representation of the discharge in the two areas (river and granitic rocks) was then compared with the four different future scenarios: (1) HadCM3 B2a (50 years), (2) HadCM3 A2c (50 years), (3) HadCM3 B2a (100 years) and (4) HadRM2 (100 years). The results are represented in Fig. 26.6 and the differences found between the actual discharge regimen and the simulated scenarios are more important than it seems by the observation of the figure.

Respecting scenario 1 (HadCM3 B2a), for 50 years (see Table 26.1), there is a slight trend to an intensification of recharge in the first semester (January-July), which can represent an increment in the reserves in the dry period (June-September), with more capacity for abstractions, and a slight reduction in the transferences to the Sever River between September and December. There are not significant transfers of waters toward the granitic rocks in the Castelo de Vide area in this scenario.

Concerning scenario 3 (HadCM3 B2a), for 100 years, it presents some similarity with scenario 1, but the increment of recharge in the beginning of the year only begins in the second half of the first semester. In this case, the increment of storage in the aquifer in the driest period is almost no sensitive. On the other hand, the decrease in the outputs between September and December is more evident on the water transfers to Sever River, which can be significantly affected in the last part of the year. Also in the last part of the year, the transfers to the granitic rocks decrease slightly.

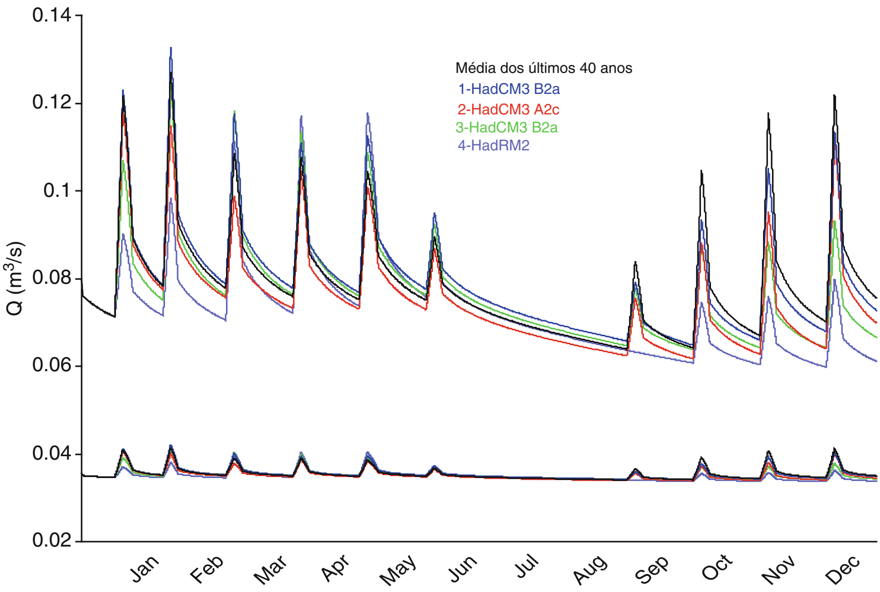

Fig. 26.6 Average transference values from the aquifer to Sever River (upper diagram) and for the granitic rocks in contact with the aquifer in the area of Castelo de Vide (down diagram). Simulation based in the monthly average recharge volumes for 40 years (1959–1998) and in the four established hypothetic future scenarios

Concerning scenario 2 (HadCM3 A2c), for 50 years, there is a general trend to a reduction in the recharge. The same is true as the previous ones, the tendency increases in the end of the year. In this case, the storage in the aquifer during the driest months tends to a reduction.

Scenario 4 (HadRM2), for 100 years, is the one that shows more differences in relation with the actual average trends. Excepting the period between March and May, in which a slight increment of recharge is expected, in all the other parts of the year there are a strong reduction in the flow of the Sever River, changing clearly the transfers from the aquifer (by less than half). Also the transfers to the granitic rocks in the area of Castelo de Vide are negligible when compared with the actual ones.

26.5 Final Remarks

The analysis of the evolution of water resources with expected future climatic changes is of high importance for the planning and management in the future. The application of modelling to predict the evolution of the Escusa (Castelo de Vide) aquifer with four different climatic change scenarios defined by the Hadley Centre for Climate Prediction and Research resulted in different predictions but with the common conclusion: With changes in all the analysed scenarios, all the simulations show a decline in the discharge rates of the aquifer groundwater. Other important conclusion is that the discharge rates per month change and sometimes it is possible to have an increment of the discharges in the first half of the year and a reduction in the second half of the year. Some scenarios affect the water resources and the environment more than others. One can also benefit from the water storage in the dry period of the year, even if it causes a reduction in the aquifer recharge rates.

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Chapter 27
Classification of Groundwater Quality Based on Variability of Hydrogeochemical Environment

Jarosław Kania, Stanisław Witczak, and Kazimierz Różański

Abstract Groundwater quality is becoming an important issue in many parts of the world. The status of groundwater quality in the given groundwater system can be addressed through quantitative analysis of its hydrogeochemical field in temporal and spatial domain. A quantitative, multi-stage classification of groundwater quality adopted in Poland is presented and compared with the approach recommended by EU. It helps to guard pristine water quality and to detect early stages of deterioration of groundwater quality, thus allowing timely measures to achieve trend reversals.

Keywords Hydrogeochemical field • Chemical status of groundwater • Classification of groundwater quality

27.1 Introduction

Groundwater quality can be affected by both natural and anthropogenic factors, including evolution of climate. In order to quantify and evaluate these changes in groundwater quality appropriate methodology is required.

Groundwater is generally in perpetual motion and its physico-chemical composition evolves in space and time, adapting to changing geological environment as well as physico-chemical conditions along the flowpath. This changing geological environment can differ in terms of mineral and chemical composition, the presence of organic substances, etc., both at micro and macro scale. Groundwater movement

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is usually slow enough (flow velocity ranges from few to hundreds of meters per year), to allow for chemical quasi-equilibrium controlled mainly by lithology and environmental conditions (e.g. pH, redox). This might not be true for karstic aquifers, where flow velocities of water could be much higher.

27.2 Hydrogeochemical Field

The variability of geological environment together with changes of physico-chemical conditions and the slow movement of groundwater are the main factors leading to formation of the spatially variable hydrogeochemical field in the groundwater reservoir (aquifer). The term "hydrogeochemical field" was introduced by Stilmark [1]. It defines the spatio-temporal distribution of physico-chemical properties and concentration of dissolved constituents in the given groundwater system.

Regions with sharp spatial changes of the hydrogeochemical field are usually associated with regions of strong changes of the redox conditions. Example of such changes is shown in Fig. 27.1 where iron concentration in the vertical profile representing shallow, unconfined aquifer in the Vistula River valley increases from less than 1 mg/L up to 50 mg/L across the distance of ca. 7 m. This abrupt change is clearly linked to changes of Eh and pH. The wide range of the measured changes of Fe concentrations is comparable with the concentration range of this element being observed in Quaternary aquifers in Poland.

In shallow, unconfined aquifers the variability of the hydrogeochemical field is mainly linked to anthropogenic influences of various nature. Figure 27.2 shows an

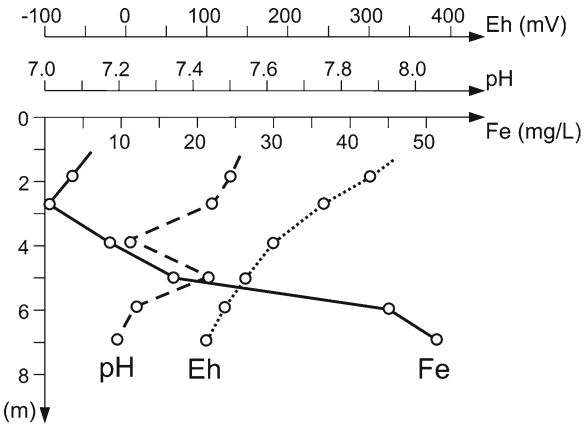

Fig. 27.1 Changes of Fe, pH and Eh in vertical profile in the Quaternary deposits of the Vistula River valley [2]

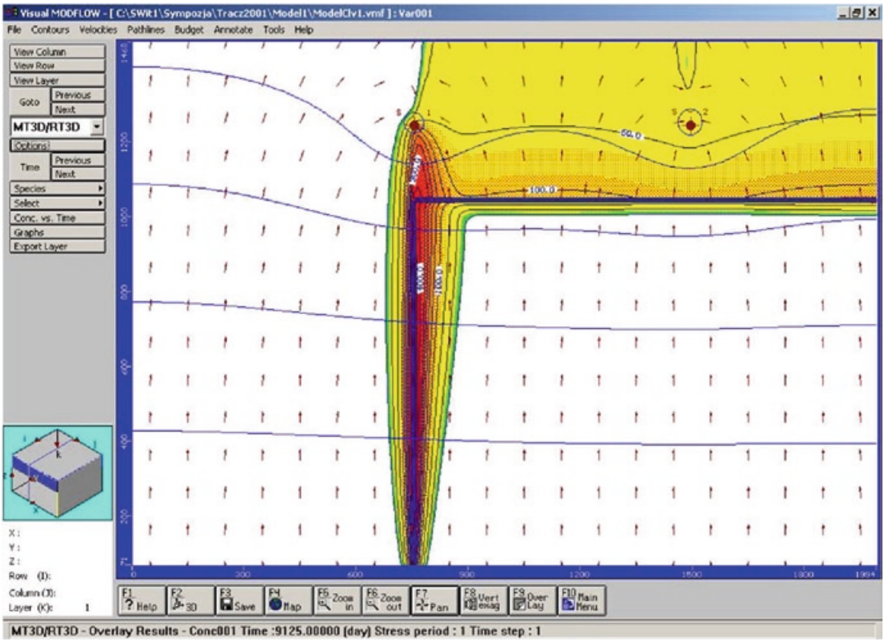

Fig. 27.2 Modelled distribution of chlorides in groundwater along a road subject to deicing during winter (example of MT3D results)

example of the influence of anthropogenic activities on the surface (road deicing) on the concentration of chloride in near-by groundwater system.

Under natural conditions, the hydrogeochemical field is usually variable in space but stationary or quasi-stationary in time. Groundwater chemistry may reveal some seasonal variations but typically it does not show any persistent temporal trend. Example of the spatial variability of hydrogeochemical field is presented in Fig. 27.3 which shows the distribution of calcium concentration in small Neogene sandy aquifer in southern Poland. This kind of spatial variability of the hydrogeochemical field is typical for most of major ions in confined aquifers.

As a rule, contamination of groundwater or strong changes of the hydrodynamic field result in temporal evolution of the hydrogeochemical field. Example of long-term temporal variability of the hydrogeochemical field is shown in Fig. 27.4, which presents changes of Fe concentration in groundwater pumped from a well-field located in south-western Poland, over the period from 1965 to 2000. High withdrawal of water and lowering of water table in the late 1960s induced the transition from reducing to oxidizing conditions. The resulting oxidation of pyrite (iron sulphides) in this groundwater system, lead to increase of Fe concentration. Subsequently, due to depletion of pyrite reserves in the oxidised zone, Fe concentration gradually decreased and the system reached new, quasi-equilibrium stage with respect to this element.

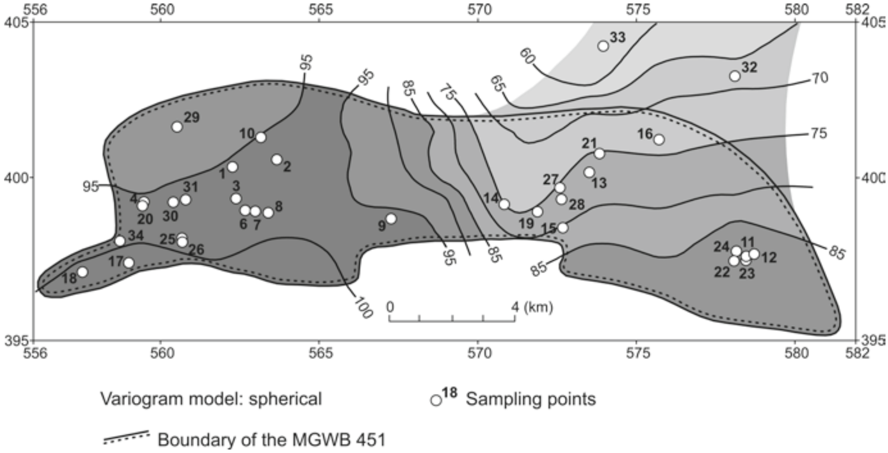

Fig. 27.3 Spatial distribution of Ca concentrations [mg/L] in the Bogucice Subbasin (MGWB 451) Poland. (The measured concentrations of calcium were interpolated using kriging technique)

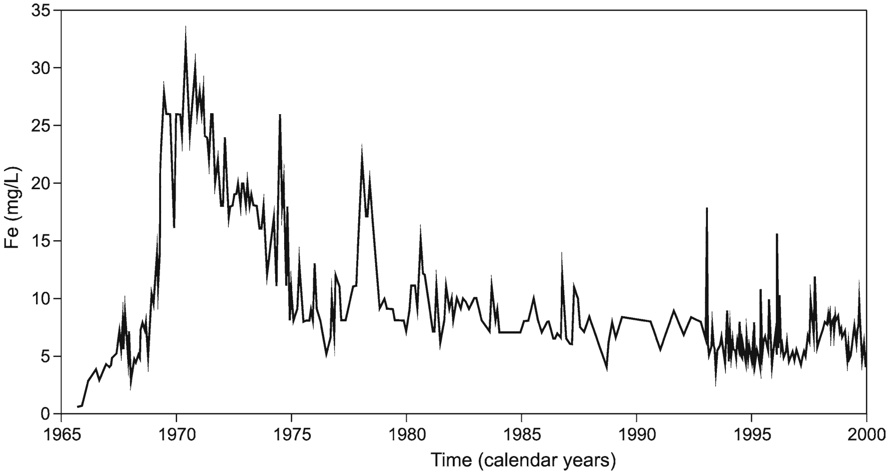

Fig. 27.4 Long-term changes of Fe content in water of the Zawada well-field, south-western Poland [3]

27.3 Characterisation of Hydrogeochemical Field

The hydrogeochemical field is typically characterised by a wide range of concentrations of specific elements forming a distribution. It could be a simple Gaussian distribution or log-normal distribution or it may have a more complex shape. Consequently, characterisation of hydrogeochemical field can be performed in several ways. One way is via cumulative frequency curves of the concentrations of

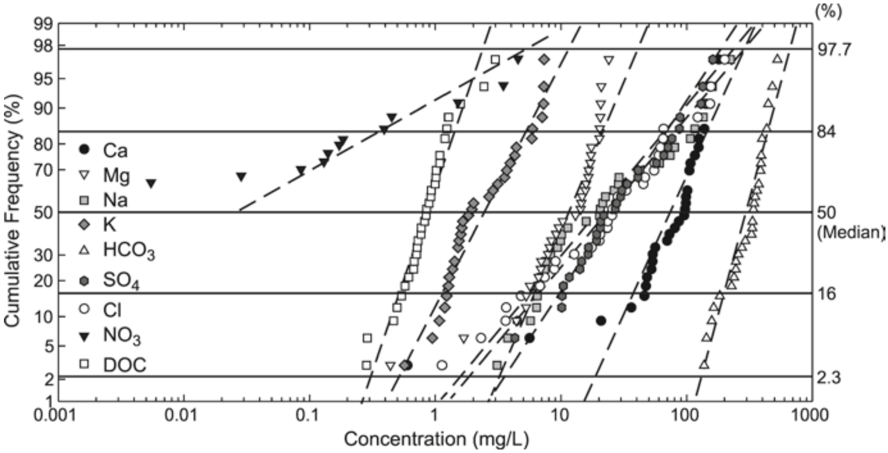

Fig. 27.5 Cumulative frequency diagrams of major ion concentrations in the Bogucice Subbasin (MGWB 451) [4]

specific elements present in the system [5]. In the cumulative probability plots the normal or log-normal distribution of concentration appears as a straight line (Fig. 27.5). The quality of fitting of the measured concentrations varies from element to element. The value of 50% corresponds to median of the distribution. The slope of the straight line is a qualitative measure of the variability of the given component concentration in the studied system.

Sometimes, the observed distribution of the measured element does not fit the Gaussian or log-normal distribution function. This situation is presented in Fig. 27.6 where the distribution of SO_4 concentration in the Kedzierzyn aquifer in southern Poland is presented. It is apparent in Fig. 27.6 that SO_4 data obtained for this system, when presented in the form of cumulative probability plot, cannot be fitted by a straight line. In such situations a more appropriate solution could be a subdivision of the entire dataset into smaller groups, guided by careful analysis of the investigated groundwater system (regionalization of data).

A more complex shape of the distribution of dissolved constituents is usually caused by anthropogenic influence. Kunkel et al. [6] considered complex distributions as a superposition of distributions representing natural and anthropogenic components (Fig. 27.7). They proposed the separation of these two components using appropriate statistical tests.

27.4 Quantification of Groundwater Quality – A Polish Case

The above-discussed different methods of characterisation of hydrogeochemical field can be adopted to assessment of groundwater quality in the framework of national (European) legislation. In order to achieve appropriate protection of

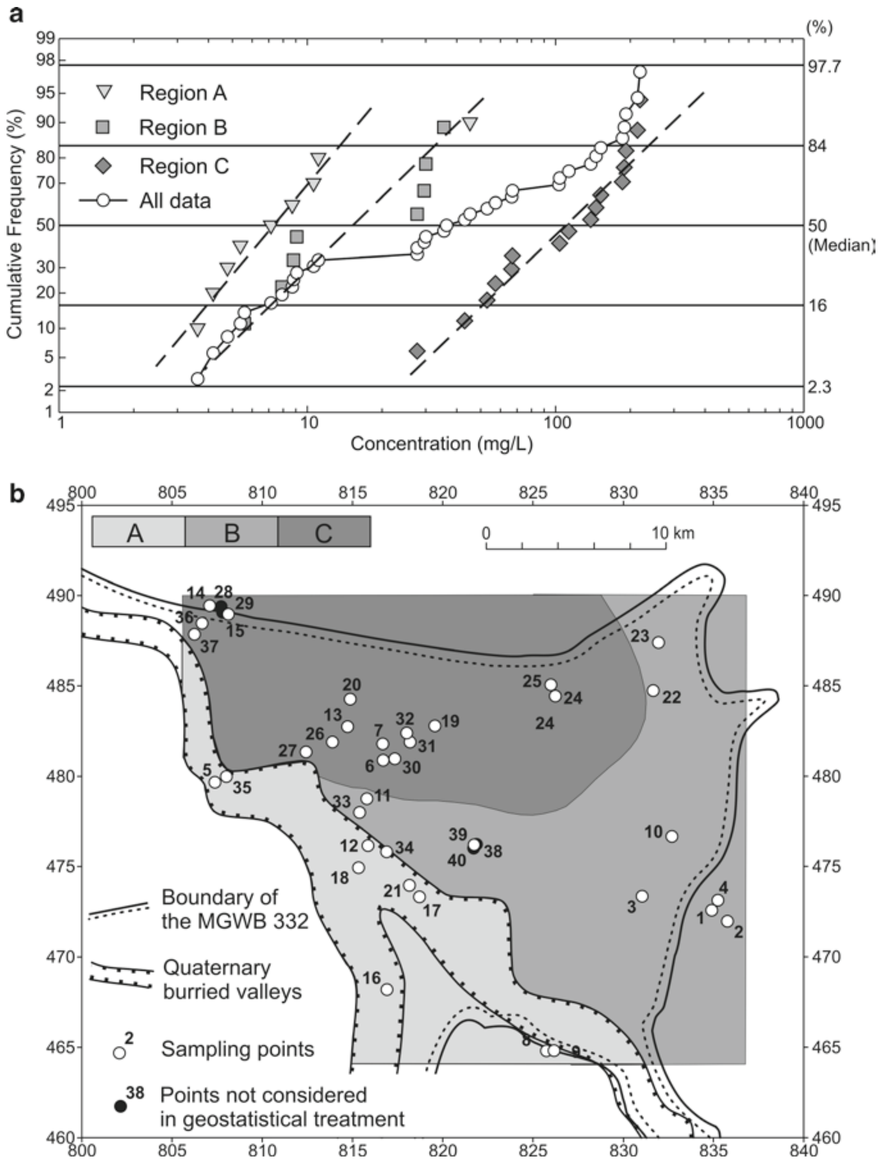

Fig. 27.6 Cumulative frequency diagrams of SO_4 (**a**) and regionalization of SO_4 distribution (**b**) in the Kędzierzyn aquifer (the NE region of MGWB 332) in southern Poland [7]. A – 4 to 10 mg/L, B – 5 to 50 mg/L, C – 30 to 200 mg/L

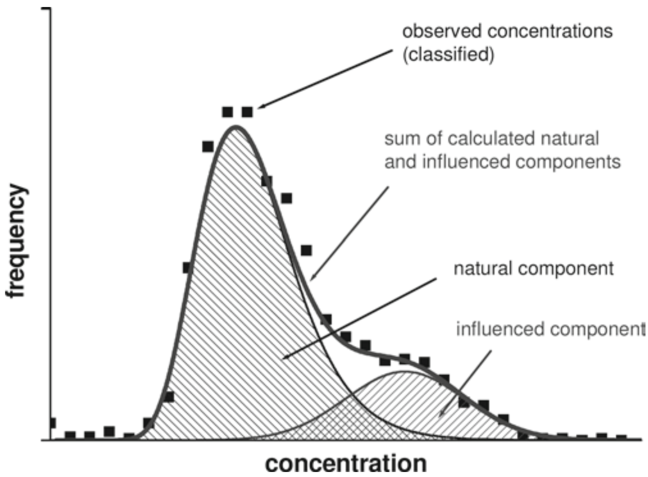

Fig. 27.7 Separation of natural and anthropogenic contribution to the observed complex-shape distribution of the given element in groundwater [6, 8]

groundwater, the EU Member States have to establish threshold values for pollutants, groups of pollutants and indicators of pollution, which will be used in the assessment of chemical status of groundwater bodies [9]. Below, the Polish approach to this problem is presented.

Considerable experience exists in Poland with respect to setting up threshold values for pollutants present in groundwater. Groundwater quality criteria leading to several quality classes are in use in Poland since the 1980s. Numerous studies have been accomplished since that time, focusing on the evaluation of natural background levels of chemical constituents in groundwater (e.g. [10, 11]). In the framework of this approach, the process of derivation of thresholds for specific constituents in groundwater includes the assessment of the following aspects of groundwater quality: (i) typical natural background, (ii) the origin of constituents (natural and/or anthropogenic), (iii) the reasons of introducing specific constituents and thresholds into the adopted classification as well as the receptors on which they are acting. The Polish approach towards the assessment of groundwater quality is focused on human health as a main risk receptor, and contains also other elements of aquatic and terrestrial ecosystems dependant on groundwater. The approach proposes classification of groundwater quality into five classes (Table 27.1). The first three classes represent a good chemical status of a groundwater body. They help to protect the pristine water quality and allow to draw attention to the anthropogenic changes in the early stages of groundwater contamination. The last two classes include waters having poor chemical status.

The list of parameters and constituents used for determining the chemical status of groundwater within the Polish approach includes obligatory part, necessary for

Table 27.1 Groundwater quality classes according to Polish classification [12]

Quality classes	Description
Class I: Groundwater of very good quality	Chemical composition derived exclusively from natural sources. None of the components exceeds maximum permissible level of a parameter in drinking water (MPL). No treatment is required. Lack of indications of anthropogenic influences.
Class II: Groundwater of good quality	Chemical composition derived exclusively from natural sources. One or more dissolved constituents exceed MPL due to natural processes. Some treatment may be required in case of the use of such waters for drinking purposes. No indications of significant anthropogenic influences.
Class III: Groundwater of acceptable quality	Chemical composition derived mainly from natural sources, with elevated concentrations of some natural and/or anthropogenic components, without discernible trends. The use of such waters for drinking purposes requires treatment.
Class IV: Groundwater of poor quality	Chemical composition derived from natural and anthropogenic sources, with elevated and variable concentrations of some components. The use of such water for drinking purposes requires advanced treatment. These waters usually occur in unconfined aquifers in areas of intensive human activity.
Class V: Groundwater of poor quality	Chemical composition derived from natural and/or anthropogenic sources, with high concentrations of some components which makes treatment of such water uneconomical at present stage of technology.

typical groundwater quality assessment as well as specific parameters which may be found in contaminated areas of groundwater body at risk.

In the framework of Polish classification, the pollutants and pollution indicators (55 in total) are subdivided into four groups:

- general indicators (pH, TOC/DOC, conductivity, temperature, DOX);
- major inorganic species (necessary for ionic balance calculations: Ca, Mg, Na, K and Cl, SO_4, alkalinity);
- secondary and trace inorganic species (Ag, Al, As, B, Ba, Be, Cd, CN, Co, Cr, Cu, F, Fe, Hg, Mn, Mo, Ni, NH_4, NO_2, NO_3, Pb, PO_4, Sb, Se, Sn, Ti, Tl, U, V, Zn);
- organic substances (AOX, BTX, petroleum hydrocarbons, PAH, individual Pesticides, total Pesticides, anionic surfactants, anionic and non-ionic surfactants, phenols, benzene, BaP, trichloroethylene, tetrachloroethylene).

The Polish classification differs from the approach proposed by EU, which is based on the concept of single threshold value. By introducing five classes of water quality it allows a deeper insight into the quality status of groundwater bodies. If only single threshold value is used, groundwater body which is subject of quality assessment can be characterized only by two values of chemical status: good or poor.

Figure 27.8 shows the application of both approaches (recommended by EU and the Polish one) to a small river catchment in southern Poland. The quality

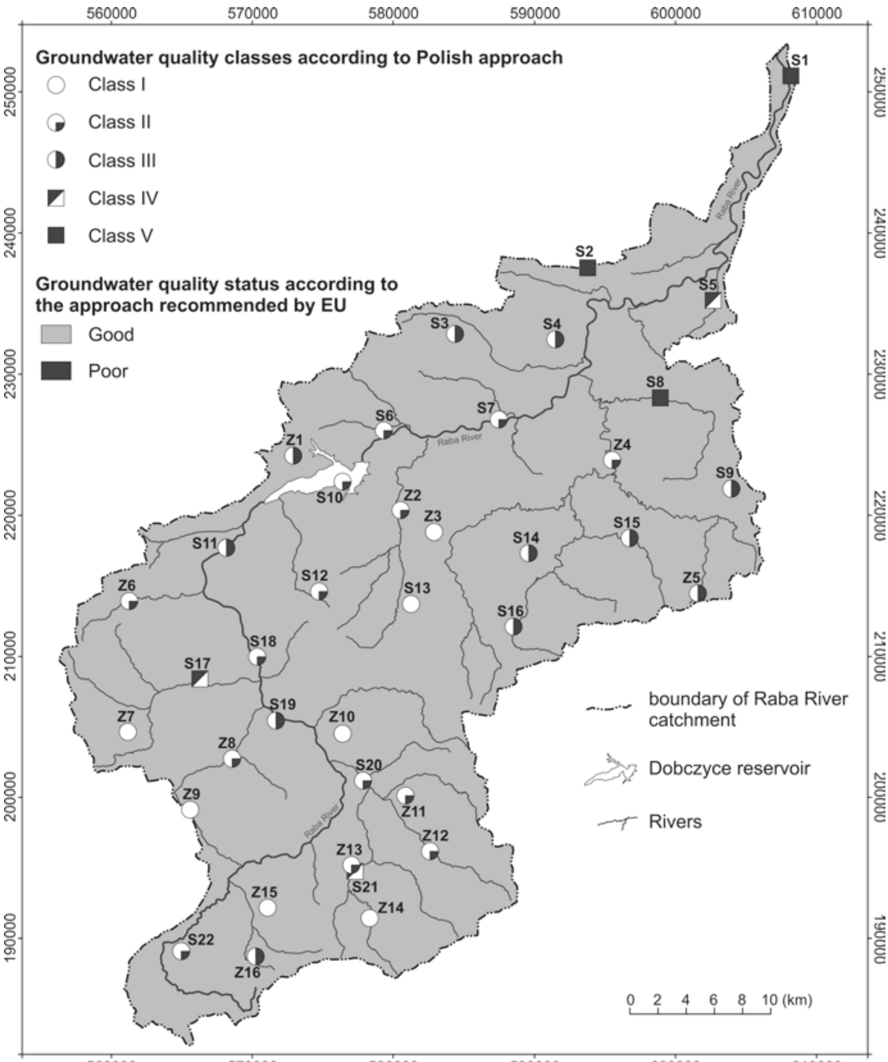

Fig. 27.8 Chemical status of groundwater in Raba river basin, Poland ([13], modified)

classes can be presented on maps, either for individual points or in a generalized way for the entire aquifer. It is apparent from Fig. 27.8 that although the whole river basin is characterized by a good status, the quality of water varies with the region, including areas with poor quality status. This allows a more flexible management of groundwater body and early reaction to any undesirable trends in groundwater quality.

27.5 Conclusions

Each groundwater body can be characterized by specific hydrogeochemical field. Typically, it varies in space in response to changing lithology of the aquifer and varying pH and redox conditions, but is stationary or quasi-stationary in the temporal domain. Temporal changes of the hydrodynamic field are usually the result of anthropogenic influences.

Characterization of the given hydrogeochemical field can be accomplished by presenting different types of frequency or probability distributions of the observed concentrations of the dissolved constituents. They reflect different processes taking part in the investigated groundwater system, and help to establish groundwater quality criteria.

Quantitative, multi-stage classification of groundwater quality presented in this paper allows a more detailed insight into the chemical status of groundwater and, in consequence, a more flexible management of groundwater bodies. It helps to guard pristine water quality and to detect early stages of deterioration of groundwater quality, thus allowing timely measures to achieve trend reversals.

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Chapter 28
Climate Change and the Hydrogeologic Framework in Constanta City, South Dobrogea, Romania

Glicherie Caraivan, Irina Dinu, Costina Fulga, and Daniela Popescu

Abstract Constanta city is located on the Black Sea coast in the eastern part of the Romanian South Dobrogea region. Global warming in the Dobrogea region promotes drought conditions that decrease groundwater levels and increase abstraction rates in the shallow unconfined aquifers (loess deposits and karstified Sarmatian limestones) being used for public supply. This study advocates using an alternative confined and high quality groundwater source in the zone adjacent to the tectonic blocks 5 and 10, where the Senonian aquitard ensures delays to climate change and provides protection from potential anthropogenic contaminants. Our review of the hydrogeologic and technical conditions further suggest that abstraction wells need to be developed within the Constanța city limits and Upper Jurassic–Lower Cretaceous aquifer (400–1,200 m thick). Suggested optimal exploitation characteristics are proposed.

Keywords Climate change • Global warming • Aquifer • Coastal area • Tectonic block • Abstraction well

28.1 Introduction

Over the years, the water supply of Constanța city has been dependent on the Autonomous County Water Enterprise. The increasing price of drinking water delivery motivated private companies to evaluate alternative drinking water sources such as groundwater, even in the harbor area. Here we analyze existing data and data from recent field investigation.

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28.2 Regional Geomorphological and Geological Framework

The Constanta Metropolitan area occupies about 60 km along the Black Sea shoreline (Fig. 28.1). The coast is mainly erosional, with cliffs, and barrier beaches as well. The climate is typical continental with a marine influence along

Fig. 28.1 Constanta city drillings wells location

a 10–15 km wide littoral strip. The average annual temperature is 11.2°C. Precipitation is low (<400 mm per year) and unevenly distributed throughout the year. Constanța city domain is located in the South Dobrogea geological unit, bounded to the north by the Capidava – Ovidiu fault (Fig. 28.2). South Dobrogea has specific plateau features with a Pre-Cambrian crystalline basement and a Paleozoic – Quaternary sedimentary cover. (Fig. 28.3). The Upper Jurassic – Lower Cretaceous carbonate rocks [1, 4] outcrop along the Capidava – Ovidiu Fault (Fig. 28.4). The Upper Cretaceous (Cenomanian – Senonian) is represented by conglomerates, sandstones, silty marls (Cenomanian + Turonian) and chalk with concretionary chert, sandstones, and conglomerates in the basal part (Senonian). The Sarmatian deposits are well represented consisting mainly of limestones. The Quaternary deposits at the lowest level are reddish in color argillaceous in composition (Lower Pleistocene); overlying this material are about 40 m of loess deposits (Middle – Upper Pleistocene). Recent alluvial sediments are present along the main river valleys.

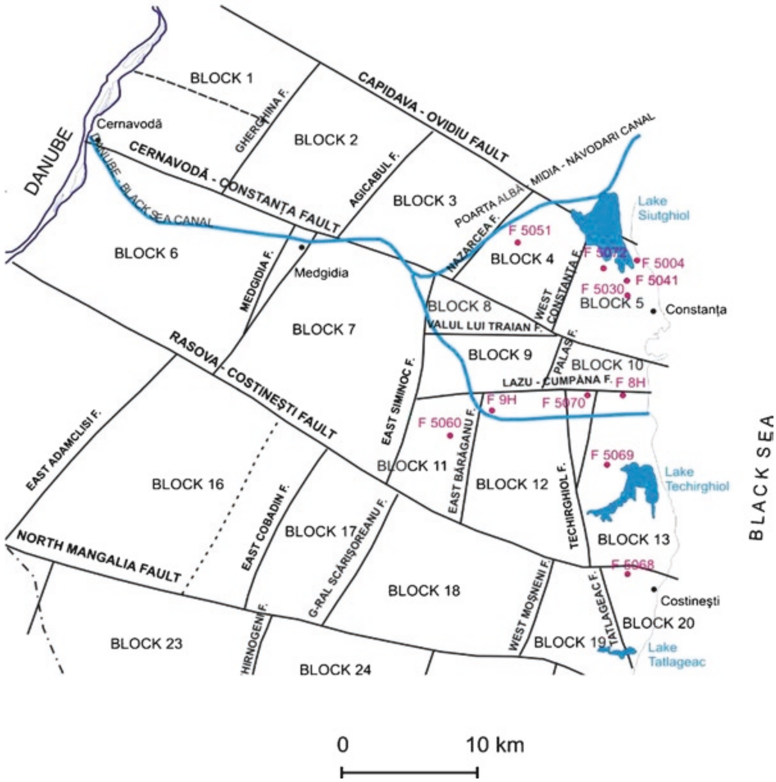

Fig. 28.2 Fault system and tectonic blocks of South Dobrogea

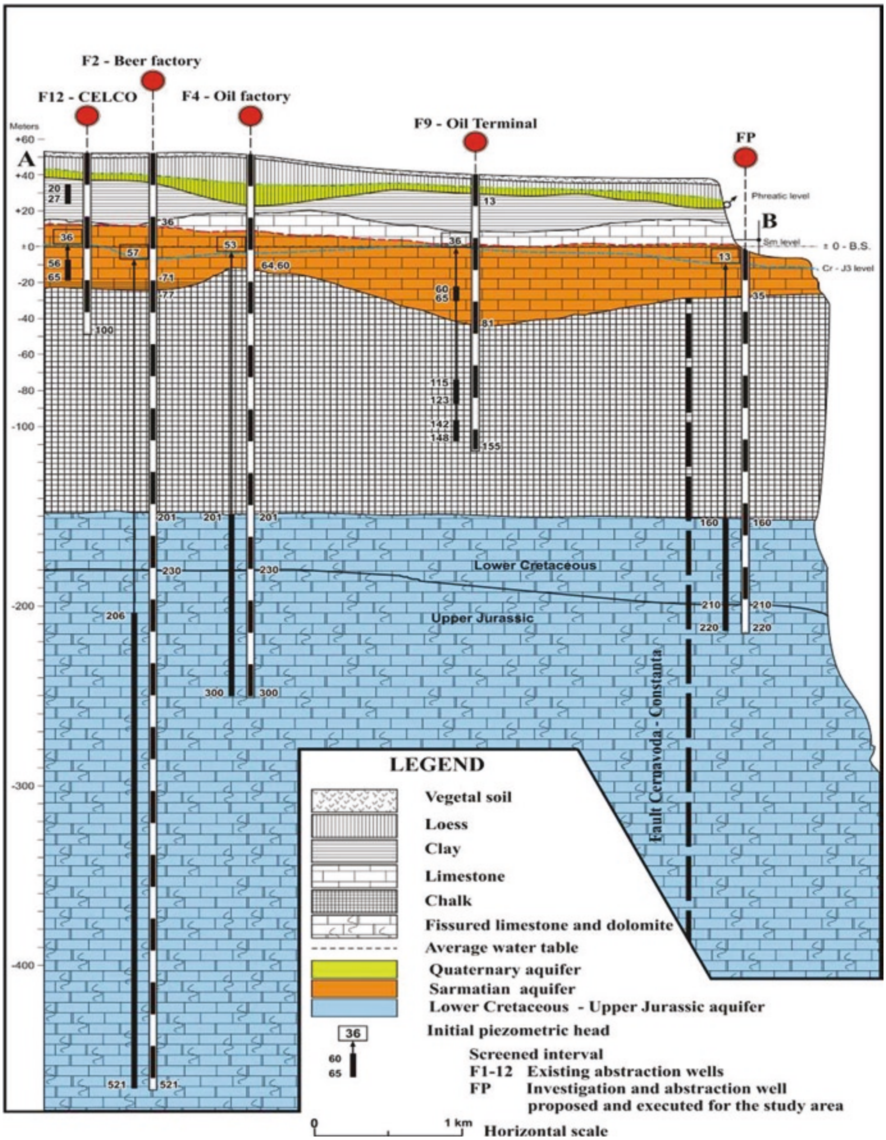

Fig. 28.3 Hydrogeological cross-section *A–B* (see Fig. 28.1)

28.3 Tectonic Framework

Regional WNW–ESE and NNE–SSW fault systems divide the South Dobrogea structure into tectonic blocks with uneven thickness and differing positions of the stratigraphic limits. Constanta domain is located on the following tectonic blocks (Fig. 28.2): Block 5 (Constanța); Block 10 (South Constanța); Block 13 (Eforie – Techirghiol).

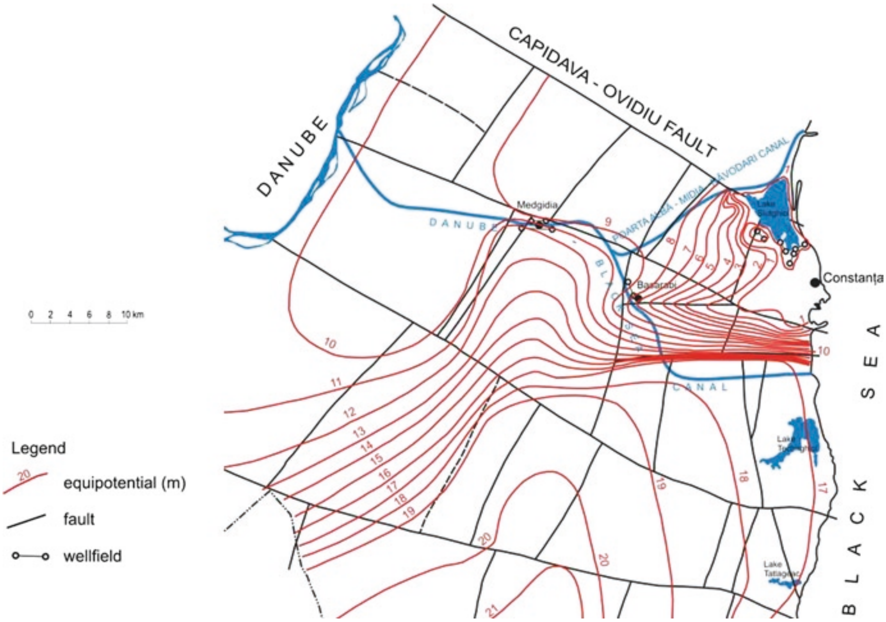

Fig. 28.4 Piezometric map of the Upper Jurassic – Lower Cretaceous aquifer complex (modified after [2])

28.4 Hydrogeologic Considerations

Four types of water are present in the study area: surface water, phreatic water, medium-depth groundwater (Sarmatian aquifer), and deep groundwater (Upper Jurassic – Lower Cretaceous aquifer). Surface water occurs in response to several springs occurring at the base of the slope of Constanța cliffs (showing slight influences from the sewerage system). The phreatic (unconfined) aquifer occurs at the base of the loessoid deposits which are underlain by impervious red clay overlapping the Sarmatian limestones (Fig. 28.3). Groundwater is mainly potable, but the pumping rates are low, around 1 l/s.

28.4.1 The Medium Depth Aquifer

The medium depth aquifer is located in the altered and karstified Sarmatian limestones, locally covered by bentonitic clay. The aquifer is locally unconfined, in the zones where it is covered by loess deposits, or locally confined, in zones where it is covered by clayey loess deposits [2]. The aquifer is supplied from the Bulgarian territory, where the whole structure is at higher elevations, and by recharge from precipitation. The aquifer discharges to the east to the Black Sea, and to the Danube – Black Sea canal (Fig. 28.3).

The water table in the abstraction wells from the Sarmatian aquifer is, usually, mainly ascending. The pumping rates at the installation are between 3.33 and 6.25 l/s, the estimated average hydraulic conductivities being between 3.48 and 6.90 m/day, corresponding to 16–30 m thick total screened intervals.

Groundwater from the Sarmatian aquifer exceeds the standard for nitrate content (80 mg/l) and for filtrate residual (over 2,000 mg/l), and the standard for total coliforms and fecal coliforms as well.

28.4.2 The Deep Upper Jurassic – Lower Cretaceous Aquifer

The main aquifer in the study area is the Upper Jurassic – Lower Cretaceous aquifer complex, located in the limestone and dolomite deposits. It is generally confined and affected by the regional WNW – ESE and NNE – SSW fault systems mentioned above (Fig. 28.2). In the southern and eastern parts of South Dobrogea, the deep aquifer complex is separated from the Sarmatian aquifer by a Senonian aquitard consisting mainly of chalk and marl. The natural boundary of the Upper Jurassic – Lower Cretaceous aquifer is the Capidava – Ovidiu Fault (Fig. 28.4). The piezometric surface indicates that the Upper Jurassic – Lower Cretaceous aquifer is supplied from the Bulgarian territory, where the Upper Jurassic deposits out crop [3]. The aquifer discharges eastward to the Black Sea and northeastward to Lake Siutghiol. It is also supplied by vertical percolation from the Sarmatian aquifer in the western part of South Dobrogea. Along the coast, the piezometric surfaces of the Upper Jurassic – Lower Cretaceous aquifer are higher than those of the Sarmation aquifer resulting in upward vertical flow.

The abstraction rates at the installation of the wells are around 22 l/s in the tectonic block 5, around 7.5 l/s in the tectonic block 10 and around 6.6 l/s in the tectonic block 13.

28.5 Conclusions

Global warming promotes drought conditions in the Dobrogea region that decrease groundwater levels and increase abstraction rates in the unconfined aquifer. This study advocates the exploitation of groundwater in the zone adjacent to the tectonic blocks 5 and 10, where the Senonian aquitard ensures delays to climate change and provides protection from potential anthropogenic contaminants. Our review of the hydrogeologic and technical conditions further suggest that abstraction wells need to be developed within the Constanța city limits and Upper Jurassic–Lower Cretaceous aquifer. The characteristics are as follows: depth of the proposed screened interval is 183–212 m, hydraulic conductivity is 6.5 m/day, and optimal abstraction rate is 6.92 l/s.

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Chapter 29
Using Numerical Modeling for Assessment of Pollution Probability of Drinking Water Resources in Borjomi Region (Southern Georgia)

George I. Melikadze, Tamaz Chelidze, Natalia Zhukova, Peter Malik, and Tomas Vitvar

Abstract Borjomi mineral waters field is a source of famous mineral water, which is exported to dozens of countries and forms a significant part of budget of Georgia. Currently, in connection with construction of Baku-Tbilisi-Ceyhan pipeline by British Petroleum (BP), serious concerns arise with respect to vulnerability of water supply of the city of Borjomi to possible oil spills related to operation of the pipeline. In this paper, we consider mainly the interaction between surface water and groundwater of the Bakuriani-Borjomi lava flow and the possibility of their pollution with hydrocarbons in case of oil spilling. In order to define the possible pollution propagation, we apply stable isotope technology and other modern hydrogeophysical methods that we have created.

Keywords Water resources • Numerical model • Pollution • Georgia

29.1 Introduction

The Tbilisi-Baku-Ceyhan pipeline is of course very beneficial for the country of Georgia. At the same time, even after its opening, there are intensive discussions on the possibility of ecological catastrophe in the case of its damage (spilling) at some areas.

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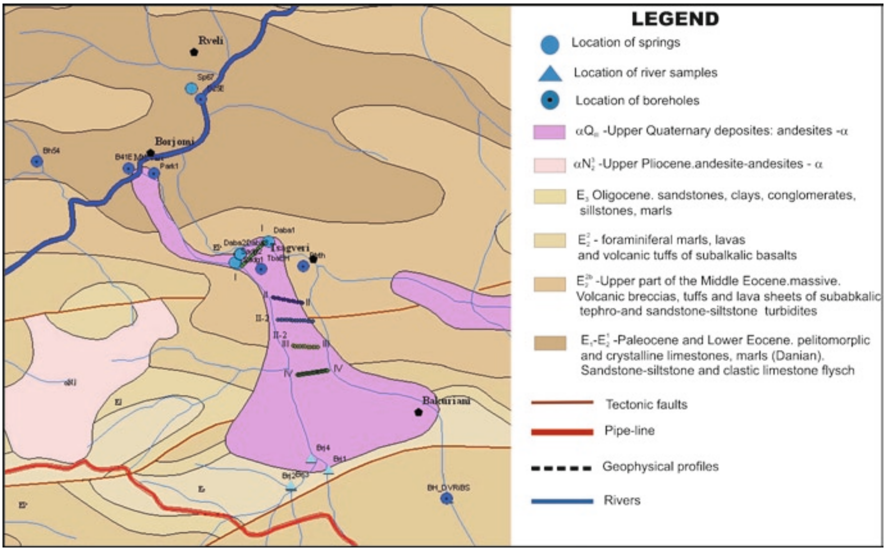


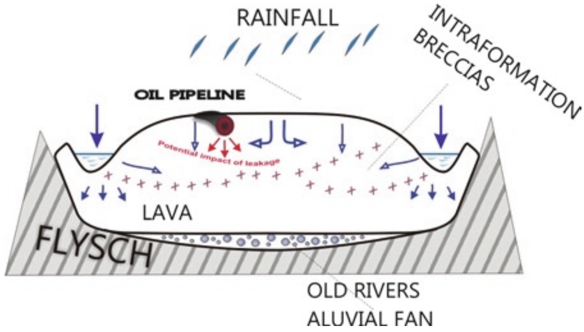
Fig. 29.1 Geological map of study area

One of such most complicated and extremely responsible sections lies within the geomorphologically dangerous Borjomi area, where the problem is connected with possible pollution of drinking groundwater source from lava layer at Bakuriani-Tsikhisjvari area by oil-products.

The section of the pipeline, situated on the southern periphery of the village Tsikhisjvari, is about 0.5 km apart of the stripe where the Quaternary lava formation comes out into the surface (Fig. 29.1). This is the recharge area for the breccias aquifer formation, which underlies the lava formation [1–3]. The precipitated surface waters are released in the form of a group of large springs in the areas of the villages Sadgeri, Daba and Tsemi [4–6]. The resort Borjomi is mainly supplied with water from a large spring situated on the right part of the deep and narrow gorge of the river Borjomula. It is about 7 km from the centre of the resort. The local name of the spring is “Tsisqvilis Tskaro” (the mill spring) and it is also called “Sadgeri spring”.

The earlier data of the electric prospecting show that the main water flow under the lava takes place 180 m below the surface, within the early Quaternary alluvial sediments of the paleo-channel of the river Borjomula [7]. Two opinions are considered about ecological situation of this area. First, presented by expert of PB, professor J. Lloyd [8], the part of the water, infiltrated in the andesite-basalts of the lava is, naturally, discharged in the Borjomula, Gujareti and Tsemula river-beds and its outflows are on the slopes of river gorges, as shown on the diagram (Fig. 29.2). Second, presented by Prof. of Georgian Polytechnic University U. Zviadadze [9], the bulk of the infiltrated water that moves further down reaches the waterproof layer (in this case the Upper Oligocene – Lower Miocene clay layer) and then moves towards the large Borjomula-Gujareti interfluves sheet.

Fig. 29.2 Hydrodynamical scheme



29.2 Data Analyses

In order to study the possibility of spoiling of drinking water in Borjomi area, the International Agency of Atomic Energy (IAEA) delivered the grant to Institute of Geophysics. The main objectives of the project were to develop a conceptual model of water flows in the target area, with special focus on the interactions of the rivers and mineral springs with the surrounding aquifers; use nuclear technologies (natural isotopes) and geophysical prospecting in selected areas for investigation of the recharge and discharge areas of the groundwater and possible propagation directions of pollution; compile numerical hydrogeological model of catchments and organize the control system against possible drinking water pollution.

29.2.1 Geophysical Prospecting

For defining the thickness and contours of lava formation geophysical prospecting was carried out along five profiles, where magnetic measurement has been carried out earlier. The new surveys were carried out by the modern geophysical equipment Multi-Electrode Array Resistivity System- "SARIS".

By the complex geophysical prospecting works, several water-bearing horizons were revealed. From the water supply point of view, the particular interest attracts groundwater located under Quaternary andesites. The recharge area of the mentioned horizon is large and covers the whole territory of plateau. The groundwater accumulation occurs at the bottom of the ancient river bed.

29.2.2 Stable Isotope and Hydrochemical Sampling

With a purpose of investigation of pollution's possibility transfer by water flows, hydrochemical compounds of all hydrogeological formations and their connection in the region have been studied: mineral water of Eocene-Paleocene flysch formation (5 boreholes), fresh waters (5 springs and 1 boreholes) – of lava formation and surface waters – rivers (5 sampling points). Totally, 16 sampling points have been selected within the study area to collect information on chemical and isotopic composition of water.

From May 2007 untill November 2009 ten sampling campaigns were carried out. The main hydrochemical macro- and microcomponents of water sources were tested by the field hydrochemical laboratory (Multi-340i/SET and Spectroquant® Colorimeters), which was also purchased by the IAEA. Stable (^2H and ^{18}O) isotopes and tritium content were measured in the several laboratories of Europe (Austria, Poland, Slovak etc.).

29.2.2.1 Hydrochemistry

Results were analyzed by AquaChem computer program. All water types were analyzed separately. Mineral water from boreholes №54, №41, №1, №25 in Borjomi belong to sodium-carbonate type with high total dissolved solids (T.D.S.) (Figs. 29.3 and 29.4).

Springs by composition are richer in magnesium that also points to the groundwater flow in contact with lava bodies along a way of water movement from lava breeds.

In conclusion we can summarize that there are three groups of water by chemical composition: first group of mineral water, second group of fresh water from the rivers and the last one from the springs, which is genetically connected with the second groups.

29.2.2.2 Isotopes

The $\delta^2H - \delta^{18}O$ relationship (Fig. 29.5) reveals several distinct features of the sampled waters (Table 29.1). All collected river samples (Borjomula river and its three branches, Bakurianischali river) form a tight cluster of points located above the GMWL.

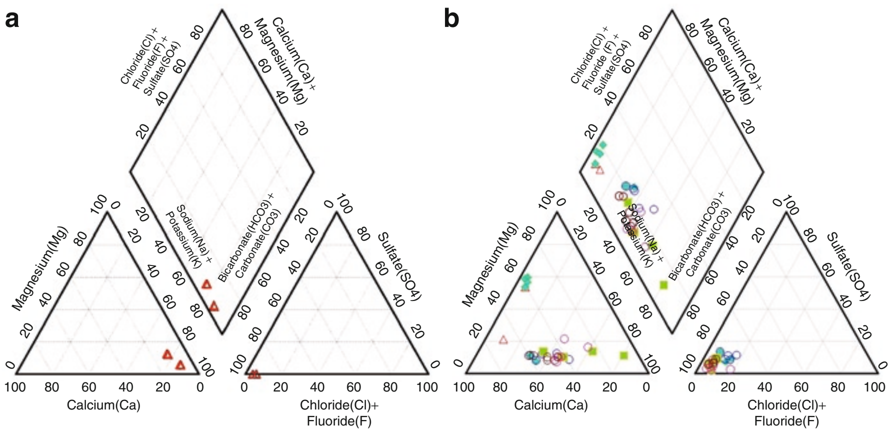


Fig. 29.3 Summary plot of chemical composition for all mineral water (**a**) and rivers (**b**)

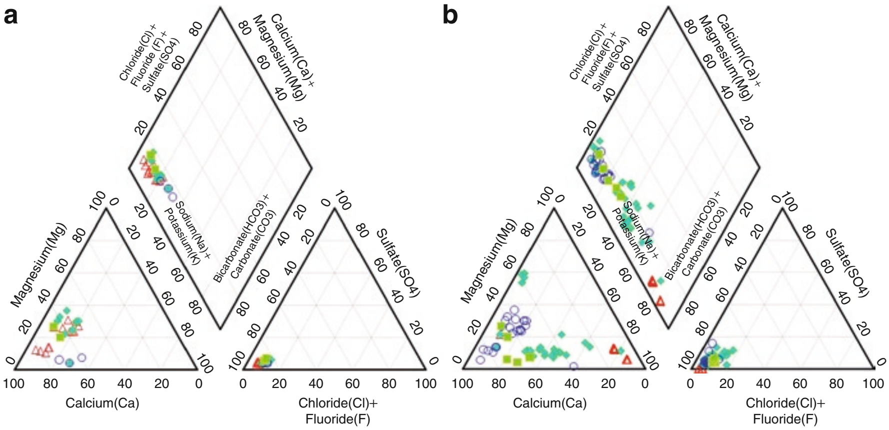


Fig. 29.4 Groups of springs (**a**) and all water groups (**b**)

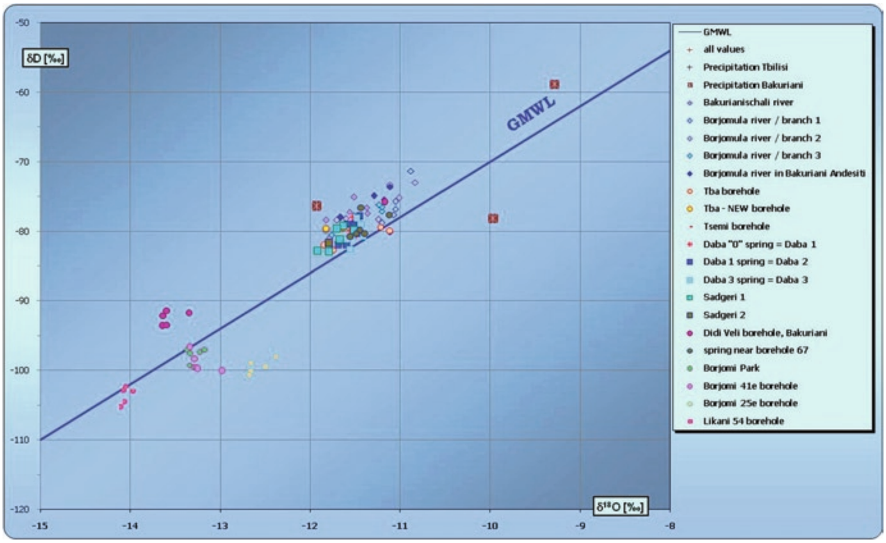


Fig. 29.5 All data: $\delta^{18}O$ [‰] & δD [‰] vs SMOW

River and spring samples reveal generally high, although quite variable tritium concentrations. Average tritium content in river samples is equal 14.3 ± 0.9 TU. For springs (Daba 0, 1 and 3; Sadgeri spring) the average tritium content is significantly smaller (9.9 ± 0.5 TU) (Fig. 29.6). The deep boreholes most probably do not contain any tritium although, again, the reported data scatter considerably.

Somewhat lower tritium value in springs when compared to rivers, combined with slightly lower $\delta^{18}O$ and $\delta^{2}H$ values, might indicate the presence of additional

Table 29.1 Isotopic composition of water measured in 16 sampling sites of the study area

No.	Sampling site	$\delta^{18}O$*(‰)	$\delta^{2}H$*(‰)	D-excess**(‰)	Tritium**(TU)
1	Borjomi park	−13.30 ± 0.05	−98.5 ± 1.1	7.9 ± 0.5	<1
2	Daba 0 spring	−11.52 ± 0.03	−79.8 ± 1.1	12.4 ± 0.5	8.7 ± 1.2
3	Daba 1 spring	−11.56 ± 0.09	−80.5 ± 1.5	12.0 ± 0.5	10.5 ± 1.9
4	Daba 3 spring	−11.48 ± 0.09	−80.5 ± 1.6	11.3 ± 0.6	11.1 ± 2.2
5	Bakuriani Didi Veli borehole	−13.54 ± 0.13	−92.5 ± 1.2	15.8 ± 0.5	<1
6	Bakurianischali river	−11.58 ± 0.22	−78.1 ± 1.7	14.5 ± 0.5	13.1 ± 1.9
7	Borjomula river Branch 1	−11.20 ± 0.20	−77.6 ± 1.4	12.0 ± 0.7	13.6 ± 3.0***
8	Borjomula river Branch 2	−11.39 ± 0.32	−77.5 ± 1.5	13.6 ± 0.8	12.4 ± 1.9
9	Borjomula river Branch 3	−11.33 ± 0.29	−77.5 ± 2.1	13.4 ± 0.6	16.6 ± 1.1
10	Borjomula river-Bakuriani andesiti	−11.39 ± 0.23	−78.1 ± 1.7	13.0 ± 1.1	15.2 ± 1.4
11	Tba borehole	−11.54 ± 0.35	−81.2 ± 1.4	11.2 ± 0.7	9.2 ± 0.9
12	Spring near borehole 67	−11.38 ± 0.18	−79.6 ± 1.4	11.4 ± 0.2	13.2 ± 3.3***
13	Borjomi 25e borehole	−12.62 ± 0.09	−99.8 ± 0.8	1.2 ± 0.4	<1
14	Borjomi 41e borehole	−13.20 ± 0.11	−99.4 ± 0.8	6.1 ± 0.9	<1
15	Likani 54 borehole	−14.05 ± 0.06	−103.9 ± 1.1	8.5 ± 0.5	<1
16	Sadgeri spring	−11.71 ± 0.15	−80.9 ± 2.1	12.8 ± 0.7	9.3 ± 0.9

*Reported uncertainty of single measurement.
**Reported uncertainty of the mean.
***Doubtful result (unacceptable scatter of the data).

water component, recharged at higher elevation and with longer mean transit time of water to the springs.

29.3 Modelling

The steady-state model calibration was carried out to minimize difference between the simulated and observed water levels. Model has been calibrated by head and deuterium observation data. Head data were collected on the rivers Borjomula and Gujaretis-tskali, in Daba and Tba boreholes during 2 years. Together with head observation, isotope data (deuterium observation) were used. Deuterium data showed different values for Bakuriani and Borjomi regions, indicating possibility of using deuterium for improving calibration process. Deuterium samples from Borjomula river, Tba, Sadgeri, Borjomi park were added into model as concentration observation points. The concentration was added into model by using particles tracking package. Each particle represents mass of concentration, which is transported by groundwater flow.

As a final result, we got the path ways of possible pollution's movement. Here, we can say that movement along left path way is faster. Three flow path ways inside

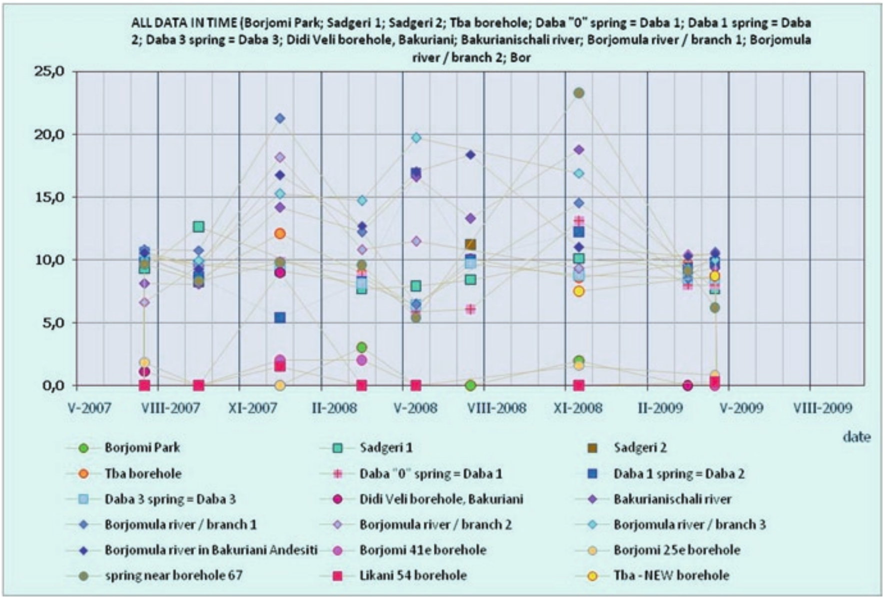


Fig. 29.6 All data: ^{3}H [TU] vs. TIME

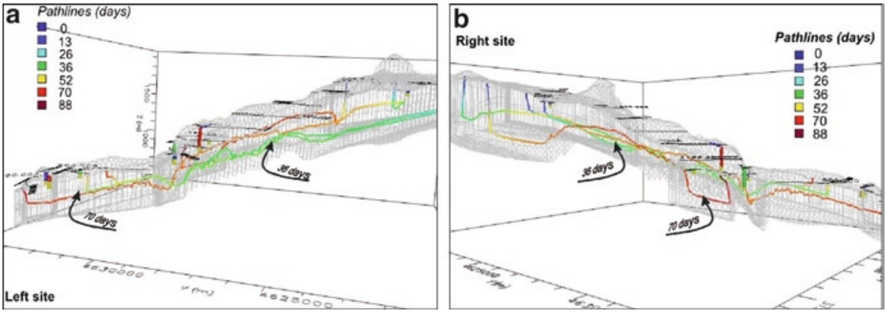


Fig. 29.7 Vertical view of movement of adjective transport (**a**) Shows veridical direction of particles' movement from the left site of model; (**b**) Shows vertical direction of particles' movement from the right site of model

and under lava were determined by the model (Fig. 29.7). Movement of water streams in different directions takes different time. First stream flowing coincides with old river bed in breccia's rocks. This stream has direction on the western site of lava stream and passes area near Tba borehole and runs up to Sadgeri springs. For reaching from recharge area to the Tba borehole, approximately 80 days are necessary to reach Sadgeri springs. Second stream found path on the right eastern site of lava and takes about 70 days to run up to the central part of Lava body near Tba village (red-brown segment of path line). Flowing from recharge area to the central part of area, not along old riverbed, takes about 50 days. Twenty-six days of flowing is marked by blue colour of line. It means that contaminant could reach central area where Tba and other boreholes are located at least in 26 days.

29.4 Conclusions and Recommendations

According to geological, hydrogeological, geophysical, hydrogeochemical, isotope and other investigations, carried out in the Borjomi-Bakuriani test area, we conclude that the waters of rivers Borjomula and Gudjaretis-tskali are formed simultaneously in the same recharge area, namely, Bakuriani-Tsikhisjvari lava plateau. After infiltration in lava sheet, “spring water” flows along ancient river valley in Quaternary alluvial and dicharges as Sadgeri and Daba springs. This is confirmed by isotope data- the stable isotope data presented above reveal that Sadgeri spring which supplies the Borjomi resort with potable water, as well as Daba springs, carry essentially fresh water, isotopically and chemically similar to that of Borjomula river and Tba borehole drilled in the lava bed. Stable isotope data also suggest that all springs mentioned above contain additional water component, recharged at higher elevation, with longer mean transit time to the discharge points. This hypothesis is supported by significantly lower tritium content in springs compared to rivers.

Water flows along breccia rocks and that is why their pathway to surface is longer than the route of waters flowing to rivers. This is confirmed by chemical data- the springs’ waters are richer in magnesium than river waters. By monitoring data, maximum of season variation in the Daba spring is fixed later (30–40 days) then in river Mtkvari. It means that the pathway of water from recharge area to spring-discharge area is longer then pathway to the river. Hydrodynamic modelling reveals the difference between durations of water flow for above two pathways, equal from 70 to 30 days. Thus the possibility of Borjomi city drinking water pollution in case of pipeline accident is very possible, and realistic. In this connexion, it is necessary to take effective measures for protection of water source areas.

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Chapter 30
Modeling of the Tbilisi (Georgia) Geothermal Deposit Under Climate Change Conditions

Nino Kapanadze, George I. Melikadze, and Genadi Kobzev

Abstract Georgia is rich with natural thermal waters and has a long tradition of their exploitation. Approximately 250 thermal springs and artificial wells are known, as well as spring clusters with water temperatures between 30°C and 108°C. The majority of these thermal water deposits have decreased well pressures due to irrational exploitation and climate change effects. In some cases, the complete termination of outflow has been observed. Based on the number of observed resources and their thermal potential, exploitation of thermal water deposits in the Tbilisi region is the most promising; thus, the assessment of its conditions are regarded as an important national priority. This paper summarizes the geothermal potential of the Tbilisi region based on development and application of a coupled 3D groundwater model using existing and newly obtained geologic, hydrogeologic, and geophysical data. Our modeling work resulted in a 10 year exploitation perspective of Tbilisi thermal deposits.

Keywords Climate change • Hydrodynamic numerical model • Geothermal resources

30.1 Introduction

The world Energy crisis and continued rise in fuel prices makes the search and exploitation of renewable, inexpensive, and environmentally clean energy resources an important priority. One promising resource is the Earth's thermal heat (Geothermal Energy). Geothermal energy can be observed at the Earth's surface in the form of thermal waters. This resource is renewable, exploitable, and cost-effective from economic and environmental points of view. Moreover, hydrothermal reservoirs

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have a wide range of applications that include agriculture, electricity, heating, perfumery, health spa, sanitation, and other purposes.

Georgia is rich in natural thermal waters and has long tradition of its use. There are many historic documents, archeological excavations, as well as names of rural settlements and towns (for example, Tbilisi, Tskhaltubo, Tskhal Tbila, abano, etc; the word “Tbilisi” means warm in the Georgian language), which point to a long practical experience with exploitation of thermal waters.

At the moment, there are about 250 natural thermal springs, artificial wells, and spring clusters with water temperatures in the range of 30–108°C. Given the number and thermal potential of observed resources, geothermal deposits in the Tbilisi region are the most promising; thus, the assessment of their conditions are regarded as an important national priority.

30.2 Tbilisi

Tbilisi is situated in the Achara-Trialeti mountain system, which is divided by seismoactive geological faults. Part of this system represents drainage of a sulphur water spa resort located in the central part of Tbilisi. The natural hot springs of this spa resort are connected to the outcropping Middle Eocene sediments occurring along the Mtkvari river valley with the discharge area located in the mountains to the west. Water from the springs has temperatures ranging from 40°C to 50°C and hydrogen-sulfide mineralization of 0.4–1.0 g/l. In the northwest part of the city, known as the Lisi district, several boreholes were drilled and water with temperatures ranging from 60°C to 70°C is being used for heating purposes. Future drilling is expected to exploit 30–40% of the geothermal deposit.

Three main districts are identified in the Tbilisi geothermal deposit; these are (from West to East): (1) Lisi-Saburtalo district, (2) Central – bathes or old thermal district, (3) Samgori- Sartichala district. Hydraulic connections were identified between the central and Samgori-Sartichala districts. Less clear are hydraulic connections between the Lisi-Saburtalo and other districts. Nowadays low temperature water of the Central district is used for spa and hygienic purposes. About 3,800 m^3/day of the high temperature (57–74°C) waters from “Lisi” (wells 5, 7, 8) and Saburtalo (wells 1, 4, 6) are used for heating and hygienic purposes. The composition of this water is similar in all three districts: low-mineralized 0.19–0.26 g/l, alkaline, sulfate-chloride-carbonate type, containing hydrogen sulfide.

Until now, the hydrodynamic relations between these three geothermal districts (“Lisi”, “central” and “oil” deposit) was not properly investigated. The absence of detailed hydrogeothermal observations makes it impossible to develop a rational environmentally reliable exploitation plan for these three deposits (Fig. 30.1).

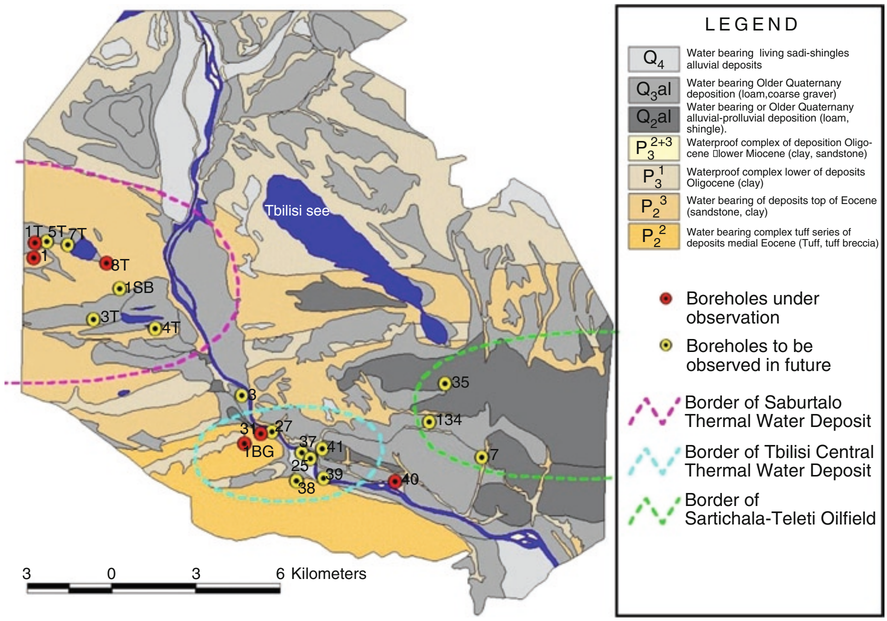

Fig. 30.1 Hydrogeological map

30.3 Hydro-Dynamical and Micro-Temperature, and Metrological Monitoring

To define hydrodynamic parameters, water levels and temperatures in wells were continuously monitored. Borehole devices [1] were used for permanent micro-temperature monitoring of wells. Accuracy of the water level monitoring device is about 0.1 cm (or pressure −1%). Four temperature sensors were installed in wells using a 200 m cable. They automatically measure water temperature with accuracy 0.5 mK. Both devices (water level and temperature) measure parameter values at 1, 2, 5, 10 and 20 min intervals and with a single battery can store data for up to 2–3 months.

Field temperature measurements were recorded in the Tbilisi geothermal wells "Lisi" 1, 2-T, and 3-T [2]. Other well measurements also were carried out under perturbed conditions (Table 30.1). A review of Mtkvari river discharge and precipitation in the recharge area revealed a temporal relation with decreasing precipitation corresponding to decreasing river stage and discharge to the Lisi well # 5 (Fig. 30.2). The decrease of Tbilisi thermal water outflow together with intensive and not correct exploitation of the wells is a result of regional climate change processes.

The exploitation of thermal waters in the Tbilisi region remains primitive; that is, hot water goes from the well to user and from the user to sewerage. Unfortunately,

Table 30.1 Temperature gradients measured in three Tbilisi geothermal wells

Rock age	Well Lisi 1 °C/100 m	Well 2 techn. °C/100 m	Well 3 techn. °C/100 m
Oligocene	–	2.50	1.66
Upper Eocene	2.37	3.30	1.88
Middle Eocene	2.04	2.97	–
Lower Eocene	2.10	–	–
Average value	2.17	3.86	1.71

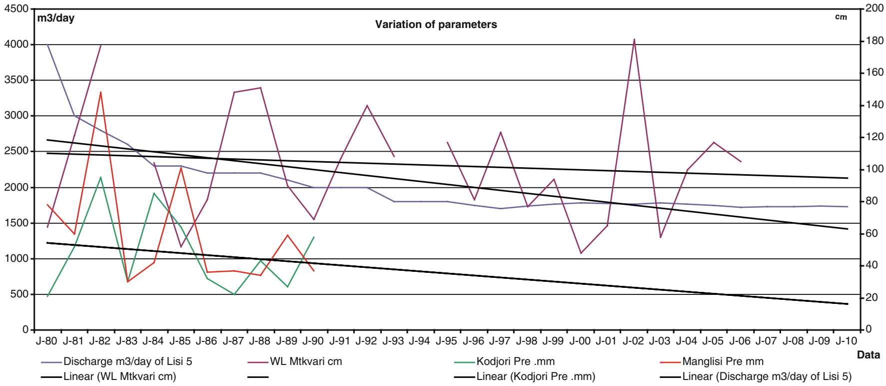

Fig. 30.2 Variation of parameters

there is no coordinated plan for optimal resource extraction and consequently water levels in wells change randomly. The lack of well monitoring and related research about hydrodynamic relations has a negative effect on its exploitation. To mitigate the decrease of pressure and water levels in wells, we propose the creation of an artificial geothermal circulation system (GCS). A GCS would prevent over exploitation of the deposit, protect the environment from pollution (bogging, thermal pollution), and decrease the amount of carbon dioxide emissions. This is particularly important as is directly connected to climate change observed in the southern Caucasus and across the world.

30.4 Establishment of Boundary Conditions for Targeted Area and Creation of Conceptual Model

A conceptual geothermal deposit model was created based on available geologic, geophysical, and hydrogeologic data. This model assumes that most of the Tbilisi hydrothermal basin is impermeable including the Upper Eocene thereby creating artesian conditions. Another assumption is that there is little or no hydraulic connection between the Tbilisi Central and Lisi districts. Several factors convince us that this is true. For example, hydraulic gradients in the "Lisi" thermal field are much larger than in the Central district suggesting the possibility of lower transmissivity. Low values of transmissivity might be caused by greater depths in the "Lisi" aquifer and because lithostatic pressure of upper rocks leads to decrease the size and total volume of permeable fractures. Conversely, decreasing pressure leads to the opening of cracks and thus to an increase in the fracture permeability.

30.5 Results

The conceptual model was converted to a numerical model for simulating the regional fluid and energy balance; identify areas for exploitation; and evaluate alternative exploitation scenarios. The Tbilisi deposit simulation was carried out over a 10 year period assuming current exploitation conditions. Results indicate that future water pressures will decrease at all wells resulting in subsidence (Fig. 30.3). Balance calculations also show energy losses at the thermal field boundaries resulting in an overall negative balance for the deposit. Similar results were obtained for wells in the "Lisi" district. A second "Lisi" district scenario evaluated the exploitation with reinjection into the deposit. This involved the simulated reinjection of hot water using wells 1 and well 5 over a 10 year period. Results indicated that the "Lisi" well pressure decreases were moderate (compared to the Tblisi deposit) with increases of water temperature in well 5 (Figs. 30.4 and 30.5). As a consequence, the total thermal balance for the "Lisi" district, where reinjection was simulated, became positive (Fig. 30.6) [3].

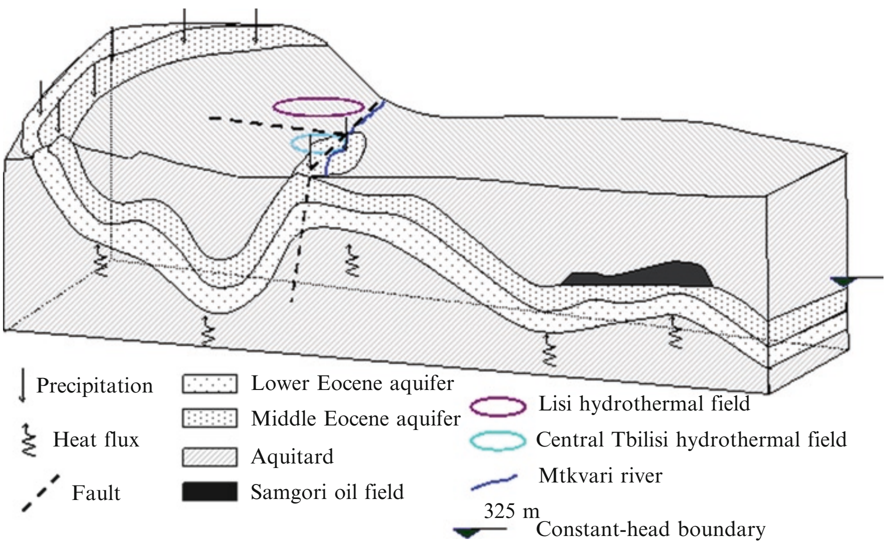

Fig. 30.3 Block diagram of conceptual model

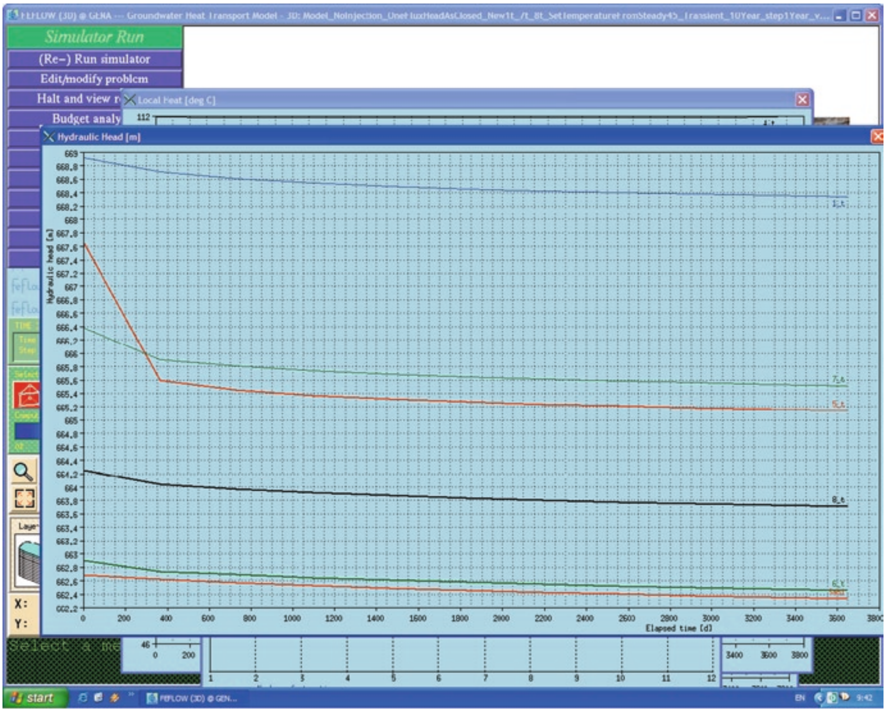

Fig. 30.4 Variation of pressures for 10 year

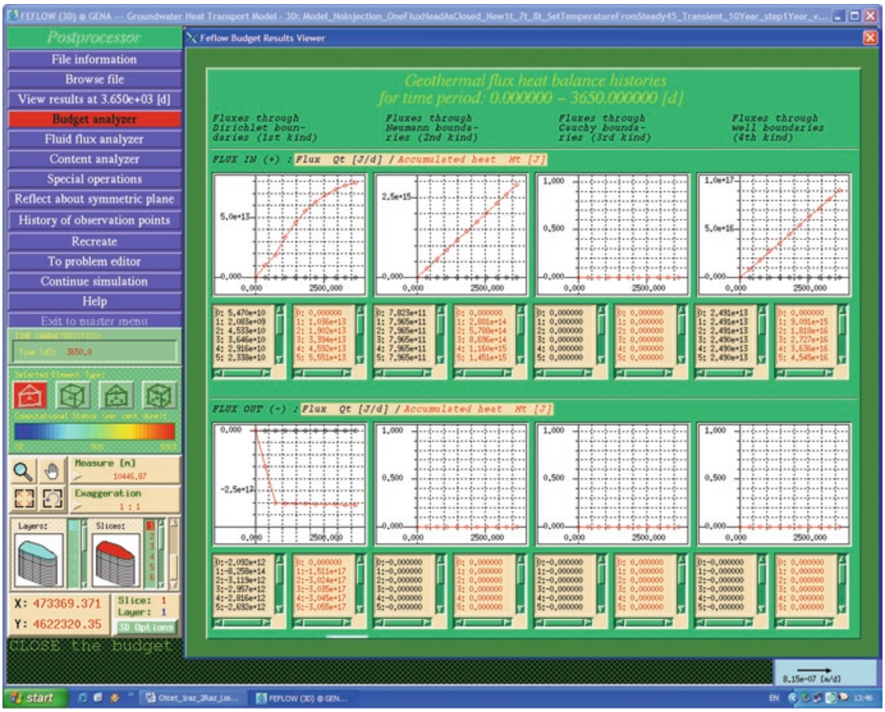

Fig. 30.5 Thermal balance for 10 year without reinjection

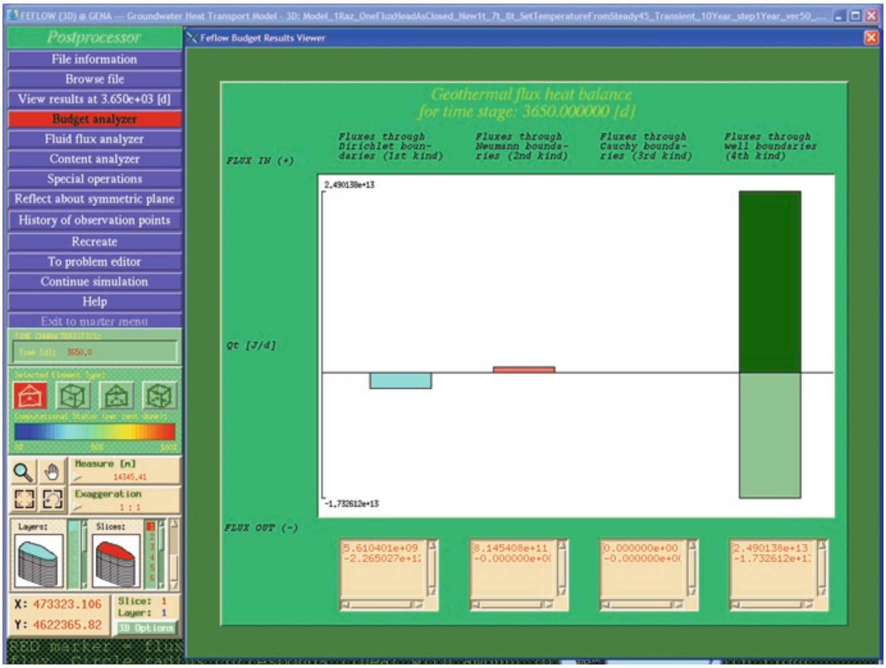

Fig. 30.6 Thermal balance for reinjection during 10 years

30.6 Conclusions

Field hydrogeophysical investigations (hydraulic testing, hydraulic and microtemperature observations) provided sufficient information for the development of a conceptual thermo-hydrodynamical models of the Tbilisi and Lisi deposits [4]. Their subsequent conversion to numerical models provided a means for simulating the regional fluid and energy balance; identify areas for exploitation; and evaluate alternative exploitation scenarios. Simulations confirmed that decreasing thermal waters occurs due both to exploitation and global climate change processes. Also, the combination of 10 more years of Tbilisi deposit exploitation under current climate change will result in cooling with a tendency for subsidence. To mitigate these effects, we recommend the creation and implementation of a geothermal circulation system. This system will help achieve economical and ecologically reasonable exploitation of our geothermal resources.

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Chapter 31
Future of Water Resources and Wastewater Reuse in Turkey

Idil Arslan-Alaton, Ayşen Türkman, and Derin Orhon

Abstract Having a water potential of 1,500 m^3/capita-year, Turkey cannot be classified as a water rich country. It is estimated that in 2030 the population will reach 100 million and consequently the water potential will drop down to 1,000 m^3/capita-year. Considering the predictions about regional and global climate change trends these figures obviously indicate a probable water scarcity in the nearest future and the importance of efficient wastewater reuse in Turkey. In Turkey, wastewater reuse for irrigation purposes was done in the past by direct use or after mixing with river water. But, recently, more conscious wastewater reuse applications are practiced, considering the predictions and protection of water resources from pollution. In this paper, a general view of current water resources and wastewater reuse activities in Turkey are given. Also the future predictions and planned activities are mentioned.

Keywords Wastewater treatment • Water reuse • Turkey • Water resources • Agricultural irrigation

31.1 Introduction

The global water crisis is getting more and more serious every day due to the global warming and other environmental changes in the world. Facts about the global water crisis are given below [1].

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- More than one billion people lack access to a safe supply of drinking water.
- Water related diseases are one of the leading causes of disease and death in the world.
- Eighty-eight percent of all diseases are caused by unsafe drinking water, inadequate sanitation and poor hygiene.
- At any given time, half of the world's hospital beds are occupied by patients suffering from a water-related disease.
- Compounding the problem is the fact that approximately 50% of the water supply projects in the developing world fail.

Countries can be classified according to their water wealth [2]:

- Poor: Annual water volume per capita is less than 1,000 m^3.
- Insufficient/Water Stress: Annual water volume per capita is less than 2,000 m^3.
- Rich: Annual water volume per capita is more than 8,000–10,000 m^3.

Experts at the World Water Council, based in Marseilles (France), postulate that 20% of the world's population in 30 countries faced water shortages in the year 2000. They warn that unless action is taken, the number of people living under the threat of water scarcity will rise to 2.3 billion in 2025 [3]. The ten top water-poor countries are Haiti, Niger, Rwanda, Ethiopia, Eriteria, Malawi, Djibouti, Chad, Benin, and Burundi, and the ten top water-rich countries are Finland, Canada, Iceland, Norway, Guyana, Suriname, Australia, Ireland, Sweden, and Switzerland. Considering the annual volume of available water per capita, Turkey is a country facing water stress. The annual exploitable amount of water has recently been estimated as approximately 1,500 m^3 per capita [2].

31.2 Future of Water Resources in Turkey

Of 501 billion m^3 of annual precipitation in Turkey, 274 billion m^3 is assumed to evaporate from surface and transpire through plants. 69 billion m^3 of precipitation directly recharges the aquifers, whereas 158 billion m^3 forms the precipitation runoff. There is a continuous interaction between surface runoff and groundwater, but it is estimated that a net 28 billion m^3 of groundwater feeds the rivers. So, average annual surface water potential is 186 billion m^3, with the surface runoff of 7 billion m^3 coming from neighboring countries, total surface runoff within the country reaches 193 billion m^3.

However, not all of the renewable water resources can be utilized because of economic and technical reasons. Exploitable portions of surface runoff, inflow from bordering countries, and groundwater are 95, 3, and 12 billion m^3, respectively. Thus, the total of exploitable water resources amount to 110 billion m^3.

The State Institute of Statistics (SIS) has estimated Turkey's population as 100 million by 2030 [4]. Consequently, the annual available amount of water per capita will be about 1,000 m^3 by 2030 (Fig. 31.1). The current population and economic growth rate will alter water consumption patterns. As population increases, annual allocated available amount of water per person is expected to steadily decrease.

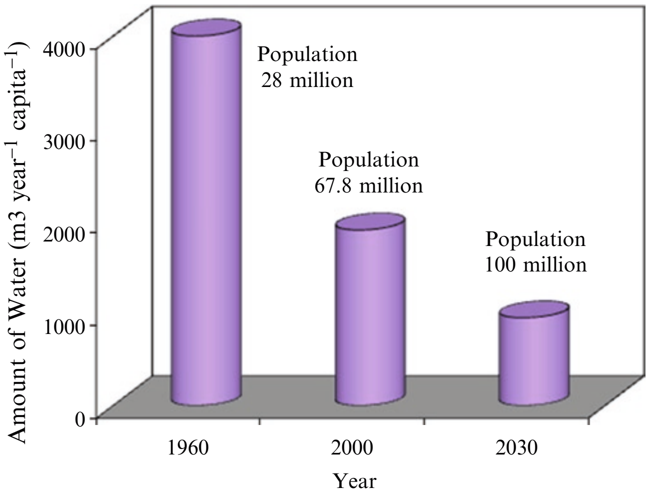

Fig. 31.1 Annual available amount of water per capita in Turkey (Adopted from SIS [7])

The projections for future water consumption would be valid on the condition that the water resources are protected from pollution at least for the next 25 years. It is imperative that available resources have to be evaluated rationally so as to provide clean and sufficient water resources for the next generation.

Because of the climatic conditions of Turkey, the precipitation-flow relationships can change not only seasonally but also from year to year and natural water supply can falls to minimum levels in summer time, when the demands are at the highest levels. The country's water resources are very sensitive to climatic conditions, and droughts are generally present in periods of every 15 years. In these dry periods the mean annual water yield decreases to one third of the annual average long period value [5].

Climate change is also one of the important factors effecting water resources in all the Mediterranean Region. Precipitation in the Mediterranean Basin as a whole has decreased by 20% in the last 25 years. It is also expected that decreasing trend will continue and a serious drop in precipitation is predicted in Turkey's semi-arid Mediterranean, Aegean and Central Anatolian regions [6].

It is estimated that summer temperatures in Turkey will rise by 3°C and winter temperatures by 1–2°C. According to results from the General Circulation Model (GCM), winter precipitation in southern areas will considerably decrease. A project concerned with the climate change effects on agricultural production in arid areas predicted that winter precipitation in Turkey would fall by 42–46% by the 2070s, at the same time that crop requirements would rise by 5–10% [5]. In Turkey, water problems are increasing due to the following reasons:

- In the last few years, Turkey has lost some of its wetlands an area as large as the triple surface area of the Lake Van, i.e. the largest lake of the country, with a surface area of 3,713 km^2.
- So far, no detailed and thorough environmental feasibility study has been conducted in Turkey.

- Only 36% of Turkey's total water potential is used for irrigation, as well as for industrial and domestic activities [5, 8].
- 75% of Turkey's available water sources are used for agricultural irrigation, 94% of this water is used as surface irrigation water [7, 9, 10].
- Water resources are getting more contaminated due to urbanization, industrialization and agricultural activities.
- Global warming affects the water resources, and desertification is observed in some areas of Turkey.
- Water demand increases due to the population increase.
- Natural pollution has also been recently identified in many places in Turkey. For example arsenic pollution has been detected in groundwater supplying water to the cities of Ankara and Izmir.

According to UNDP [11], Turkey, due to its physiographic environment combined with its past cultural and economic heritage and the current socio-economic situation of land users, is highly vulnerable to desertification, with 86.5% of its total land area, and 73% of its arable land at risk of erosion, land degradation and desertification. Regarding climatic factors and sparse and vulnerable vegetation cover, Southeastern Anatolia and continental interiors of Turkey appear to be the arid lands that are prone to desertification. When natural and anthropogenic factors, such as high topography, unsustainable use of agricultural land and forest fires are taken into account, the Mediterranean and Aegean regions could be considered as areas that may be more vulnerable to the desertification process in the future [11].

31.3 Urban Wastewater Treatment in Turkey

The Ninth National Development Plan established for the period 2007–2013 [11]. On the other hand states that, according to the statistical information gathered from 1,911 municipalities out of the total number of 3,225, 80% of the population benefits from sewer systems, 47% are provided with wastewater treatment, whereas 93% of the total population is supplied with drinking water, but only 42% is being served by drinking water treatment facilities. The development plan also stipulates that European Union (EU) legislations will be adopted and applied, reliable and integrated information systems will be established and tracking, auditing and reporting infrastructure will be further developed.

Based on a nationwide data inventory accomplished in the years 2003 and 2006 within the scope of an EU-funded MEDA-Water project [12], in Turkey there are currently around 131 urban wastewater treatment plants in operation, out of which 41 are located in settlements with less than 10,000 inhabitants and 28 in settlements with more than 100,000 inhabitants ([13] and 2006). Among the 131 treatment plants, 51 apply preliminary (physical) treatment, 73 operate secondary (biological) treatment units, and the remaining 7 treatment plants practice tertiary treatment for advanced nitrogen and phosphorus removal. Actually, only 55% of the total Turkish population is served by the state-owned sewage treatment works [13].

Table 31.1 Discharge limits values foreseen in the National Urban Wastewater Treatment Directive [14]

Parameter	Maximum concentration (mg/L)	Minimum required treatment efficiency (%)
BOD_5 (nitrification excluded)[b]	25	70–90
		40[a]
COD	125	75
TSS	35	90[c]
	35[a]	90[a]
	(P.E. > 10,000)	(P.E. > 10,000)
	60[a]	70[a]
	(P. E. = 2,000–10,000)	(P. E. = 2,000–10,000)

[a]At locations that are 1,500 m or higher above the sea level and where temperatures are often too low for efficient biotreatment, urban wastewater discharge can be carried out at higher effluent parameter values

[b]In case that a correlation can be established between a parameter that can be used instead of the BOD_5 parameter such as total organic carbon, TOC, or total oxygen demand, TOD, a parameter replacement is possible

[c]This condition is population-dependent

In order to meet the requirements of the Urban Wastewater Treatment Directive 91/271/EEC, the national wastewater directive for the discharge of urban wastewater to the municipal sewage system has been recently published as an amended by-law on urban wastewater treatment in 2006 [14, 15] (Table 31.1).

This legislation covers the discharge of urban wastewater into receiving water bodies as well as the design, construction and collection of municipal sewage, with special emphasis on treatment principles that have to be applied according to the population equivalencies and sensitivity of the receiving water body [14]. Additionally, time frames have been allocated to construct and operate wastewater treatment plants and sewer collectors, as well as to meet the requirements of the amended by-law on population equivalencies (P.E.) changing between less than 2,000 to more than 100,000 P.E [15].

31.4 Wastewater Reuse Applications in Turkey

Although the Turkish legislation on wastewater reuse in agriculture has already been established in 1991, there is no major improvement in its application since that time. In Turkey, only few wastewater reuse applications exist in small communities, where wastewater of domestic nature is used for irrigation of forest areas, gardens and parks [16]. Besides, there are several nationwide medium-to-large scale project activities planned for the treatment of urban wastewater and its reuse for agricultural irrigation purposes [17]. For instance, treated effluent originating from Ankara Metropolitan Sewage Treatment Works is used for irrigation of several crops. Currently there are planning efforts in Konya province, which is particularly known as the "grain cellar" and is the largest agricultural area of the country, to use secondary (biologically) treated urban wastewater for the irrigation of cereals. A comprehensive, regional project known as the Southern Anatolia Project (in Turkish: Guneydogu Anadolu Projesi, abbreviated as GAP) also features wastewater treatment and reuse for agricultural irrigation purposes. Another example for the few case studies on urban wastewater reuse in Turkey is the irrigation of edible and other type of crops with secondary treated domestic effluent originating from the Metropolitan Gaziantep Sewage Treatment Plant, with a total wastewater volume of 73 Mm^3/year [18].

On the other hand, it has been reported that the indirect use of domestic wastewater as irrigation water is eventually illegally practiced in Turkey. The above mentioned and recently completed MEDA-Water project demonstrated that in most cases the quality of even secondary treated urban wastewaters sampled from different Turkish urban wastewater treatment plants is not suitable for agricultural use, mainly because these effluents do not meet most of the irrigation water quality criteria, such as total Coliform, sodium absorption ratio (SAR), conductivity, and salinity values given by the National Water Pollution Control Regulation Technical Aspects Bulletin shown in Table 31.2 [19].

Table 31.2 Turkish water quality criteria for irrigation [19]

	Quality classes of irrigation water				
	Class I	Class II	Class III	Class IV	Class V
Quality criteria	(Perfect)	(Satisfactory)	(Usable)	(Usable with care)	(Harmful)
EC_{25} (μmhos/cm) × 10^6	0–250	250–750	750–2,000	2,000–3,000	>3,000
Sodium (%)	<20	20–40	40–60	60–80	>80
SAR[a]	<10	10–18	18–26	>26	
SCR[b] (meq/L or mg/L)	>1.25 <66	1.25–2.5 66–133	>2.5 >133		
Cl^- (meq/L or mg/L)	0–4 0–142	4–7 142–249	7–12 249–426	12–20 426–710	>20 >710
SO_4^{2-} (meq/L or Mg/L)	0–4 0–192	4–7 192–336	7–12 336–575	12–20 575–960	>20 >960
TDS (mg/L)	0–175	175–525	525–1,400	1,400–2,100	>2,100
Boron (mg/L)	0–0.5	0.5–1.12	1.12–2.0	>2.0	–
Class of irrigation water[c]	C_1S_1[d]	C_1S_2, C_2S_2, C_2S_1	C_1S_3, C_2S_3, C_3S_3, C_3S_2, C_3S_1	C_1S_4, C_2S_4, C_3S_4, C_4S_4, C_4S_3, C_4S_2, C_4S_1	–
NO_3^- N or NH_4^+-N (mg/L)	0–5	5–10	10–30	30–50	>50
Fecal coliforms (100 CFU/mL)	0–2	2–20	20–100	100–1,000	>1,000
BOD_5 (mg/L)	0–25	25–50	50–100	100–200	>200
TSS (mg/L)	20	30	45	60	>100
pH	6.5–8.5	6.5–8.5	6.5–8.5	6.5–9	<6 or >9

[a]Sodium adsorption ratio
[b]Sodium carbonate residue
[c]Depends on the plant type
[d]C_n = Conductivity; S_n = SAR

This issue can also be due to the fact that some of the Turkish urban wastewater treatment plants regularly receive brackish water (seawater), or industrial wastewater (for instance textile industry wastewater). Eventually these factories don't have disinfection units or these units are not maintained and/or operated properly, namely as consequence of high electrical energy consumption and/or costs of disinfecting chemicals. Surprisingly, boron (another significant water quality parameter indicated in the national irrigation standards) generally doesn't reach significant levels in the effluents of sewage treatment plants and hence it doesn't create any serious environmental problem if reuse for agricultural irrigation is envisioned.

31.5 Conclusions

Although Turkey doesn't currently face any severe water scarcity problems, since water resources have shown the first signs of quality deterioration, it is evident that Turkey is among the countries that may expect water stress in the nearest future.

Reuse of wastewater for irrigation purposes in agriculture has been a widely applied practice all around the world, especially in regions with serious water shortage problems. In most of the developing countries, the high costs of sophisticated, advanced wastewater treatment technologies motivate the direct reuse of raw or partially treated sewage water in irrigation, despite the socio-cultural objections in some countries regarding religious rituals towards consuming wastewater.

In Turkey, wastewater reuse applications in agriculture are done rather indirectly by withdrawing river or lake water downstream from sewage treatment plants. Such improper practices will result in the deterioration of Turkish surface water resources and soil contamination. However, with the efficient operation of recently constructed urban wastewater treatment plants, some more conscious and planned reuse activities in agriculture have recently started. From the above mentioned facts it is obvious that the reuse of biologically treated urban wastewater in Turkey should be applied systematically in the nearest future. This will ensure new water sources in an attempt to contribute to the sustainable environmental protection.

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Chapter 32
Reuse of Urban Wastewater in Environmentally Protected Areas: The Case Studies of Messolonghion Lagoon, Greece

Ioannis K. Kalavrouziotis and Dimitrios Kalfountzos

Abstract The lagoon of Messolonghion is a fragile ecosystem that is protected as a Nature wetland under the Ramsar Treaty. The need for environmental protection of the wetlands has proven to be necessary because of continued human interference as well as climate changes recorded in recent years. Studies show that the lagoon of Messolonghion is an ecosystem that has been burdened by human activities (pesticides, fertilizers, overexploitation of underground aquifers, intrusion and land use change), and also by climatic changes (temperature, precipitation, sea level). Human activities and climatic changes together adversely affect the hydrodynamic and ecological balance of the entire ecosystem. The Messolonghion lagoon ecosystem is also the recipient of the effluent output of the locally operating Wastewater Processing Plant (WWTP), and has been over-enriched in macro-nutrients N, P, K. The potential of urban wastewater reuse for soil and crop irrigation in the protected area appears to be an environmentally acceptable solution for alleviating the natural water shortage, since it will save significant amounts of irrigation water, as well as it will reduce the adverse effects of the treated effluents discharged into the aquatic ecosystem. A prerequisite for safe reuse of urban wastewater is a series of studies of parameters that have to do with the geotechnical characteristics (geology, hydrology, soil characteristics of the reuse area) and climatic factors (temperature, humidity, sunshine, precipitation). The study of cultivated areas and the soil parameters for each crop will allow us to calculate the water requirements of crops and the final percentage of reuse of effluent water on soils and crops. The implementation of the methodology is important for the countries of the southern Mediterranean, especially in coastal areas, facing environmental problems and threatened by declining of the irrigation water resources due to climate changes.

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32.1 Introduction

The problem of crop irrigation in Greece is becoming very serious due to the water shortage that is being faced more frequently. In fact it is slowly and steadily becoming more acute with time and it is expected to constitute an important constraint in agricultural production.

The volume of available natural water resource in Greece is estimated to about 14,340 hm^3. Greece has suffered seriously lack of water for the last 40–45 years, and periodical cycles of water shortages every 5–7 years due to droughts. About 40% of the total land area of Greece is being irrigated [1]. On an annual basis, the total water demand for crop cultivation is approximately equal to 5,500 hm^3 [1]. The total water demand per year in Greece is estimated to be 8,243 hm^3, of which 83% is used for crop irrigation, 1% for animal husbandry, 13% for potable use (10% public water supply and 3% for industry and energy production).

Presently, the reuse of TMWW is in a stage of research, aiming at establishing the necessary basis for the safe of this marginal water with the view to protect both human life and environmental quality. However the reuse is starting to be applied in Northern Greece, basically in fibber crop (cotton) not as a routine practice, but as a tentative solution to reduce the effects of recurring drought problems, which appear in Greece every 5–7 years [1].

The investigations on the reuse which have started for the last 10 years include the followings:

(a) Tolerance of forest plant species *Myoporum* sp., *Nerium oleander,* and *Geranium* sp. to heavy metals from treated waste water and of water enriched with high levels of Mn, Zn and Cu [2].
(b) Estimation of crop water needs of various region in Greece and calculation of the quantities of treated wastewater needed in the context of the future exploitation of the wastewater treatment plants (WWTP) in Western Greece.
(c) Several research and pilot projects dealing with wastewater recycling and reuse in Greece [3].
(d) The capacity of the Mediterranean forest species to absorb Mn2+ when irrigated with treated municipal wastewater ([4])
(e) The effect of the treated municipal wastewater (TMWW) on some forest species growth characteristics such as: *Eucalyptus* spp, *Medicago arborea, Buddleia variabilis* and *Nerium oleander* [5]
(f) Effects of TMWW on the accumulation of nutrients and heavy metals in soil and plants, studied in a series of experiments using *Alium cepa* (onion) and *Lactuca sativa* (lettuce) as test plants [6].
(g) Interactions between plant macro, micronutrients and heavy metals in soil and in some vegetables (*Brassica Oleracea* var Italica (Broccoli) and *Brassica oleracea* var Gemmifera (Brussels sprouts), and *Brassica oleracea* var, Capitata).

Quantification of the elemental contribution to roots, stems, leaves and sprouts or heads (edible parts). Contribution of the elemental interactions to the accumulation of heavy metals in the edible plant parts [7].

(h) Interactions related to the consumers health such as ClxCd [7]. The relevant research work is under progress.

32.2 Materials and Methods

32.2.1 Research Site

The physical location of the research site is situated around the vicinity of the biological waste treatment station of Messolongi, adjacent to the torrent of "Koukos" and north of the lagoon of "Kleisova". The demarcation of the area includes to the west the eastern city limits of Messolongi, to the north it extends to the Highway Antirio – Ioannina, to the east it reaches the west bank of the river Evinos, and lastly to the south it runs parallel to the shoreline of the lagoon "Kleisove" and ends at the mouth of the river in Patras Bay. The Messolonghion, Greece area is shown in (Fig. 32.1a). The research site is divided in the following zones:

1. PP2 region, area 2,502.4 ha
2. PF2G area, 88.8 ha
3. PF2V area, 237 ha

These zones are shown in Fig. 32.1b. The remaining area covers 992.2 ha, while the overall area of the present study is 3,820.5 ha. The PF2V, PF2G and regions are areas characterized as nature conservation in land area.

The PP2, which has been characterized as an approved peripheral zone, is located outside of the approved general development plan and outside the demarcated settlements of less than 2,000 inhabitants.

32.2.2 Geomorphology, Tectonics and Seismicity

The broader region includes metalpine, alpine formations, and deposits. The alpine formations belong to the Ionian zone, with the exception of the limestone mass "Varasova": to the east of the lagoon, which belongs to the Zone of "Gavrovo". Specifically for the study however, what concerns us mostly is the geomorphology of the delta region of Evinos. Faults and tectonic lines follow the general direction NW – SE of Pindos Mountains. An exception to the transverse trend is the axis of lakes Lysimachia and Trichonis. The system of lagoons "Aitolikou – Messolongi" is the result of tectonic faults. The eastern and north-east coast of the system is determined by fault direction NNW – SSE whereas a fault parallel to this passes through the islands of the West Coast. The area of study

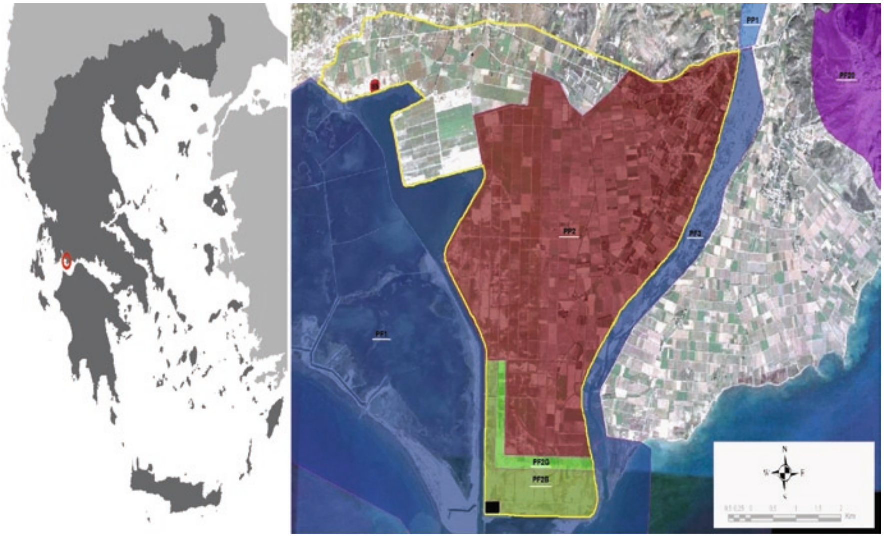

Fig. 32.1 (**a**) Messolonghion area generally (**b**) Messolonghion study area (• WWTP Messolonghion)

(lagoon of Mesolonghi – Etoliko – Kleisova) as well as most of the surrounding area is located in high seismic risk Zone III according to the Greece's the Seismic Risk Zones map. This is because this region is adjacent to seismically active areas of Ionion.

32.2.3 Hydrogeology and Surface Water

In the region, the hydrogeological formations vary significantly. Thus, layers appear with high, low or minimum permeability.

High permeability characterizes the Cretaceous and Eocene limestone formations, the land and river silting of the modern landfils, and the lenticular sand layers of the landfills in the lagoon, as well as the formations of the Triadikos. Permeability is relatively high and micaceous sandstones and conglomerates exist in northeastern Aitolikon lagoon.

Low permeability is present in the pleistocene deposits to the north of the Messolongi lagoon. Practically, water impermeable layers can be considered as the flysch, the marly lacustrine deposits as well as the recent stage lagoon sediments.

The above characteristics of the hydrogeological formations contribute to the creation of karst aquifer systems and coastal alluvial aquifers. In the wider region, and specifically in the watersheds of the rivers Acheloos and Evinos, the drainage appears to be quite low with increased surface runoff, providing the river Achelous with 500–900 m^3/s, the minimum flow of the river Evinos being 7 m^3/s.

Also in the lagoon terminate the streams developed in the mountain east of the lagoons. These creeks (about 10) on their way to the alluvial coastal area of the lagoons present steep slopes and carry large quantities of water, especially during the rainy months. The total surface runoff is estimated to be 26 million m^3 per year. These four tributaries end in the central part of the lagoon of Messolongi and in the lagoon of Etoliko.

32.2.4 Soil Classes

The variety of geological formations in the region determines a multiplicity of soil types:

(a) Deep soils with high levels of underground water (clay (C), sandy loam (SL).
(b) Deep soils of medium mechanical properties with moderate to good draining characteristics (loam, (L), Clay loam (CL), Silty loam, clay (SiCL)).
(c) Deep soils of medium to high mechanical properties with good draining properties clay loam (CL), sandy clay loam (SCL), and silty clay loam (SiCL)).
(d) Deep soils of medium to high mechanical analysis (clays (C), silty clay (SiC), and clay loam (CL)
(e) Saline soils in coastal areas.

32.2.5 Soil Mechanics Elements of Modern Lagoon Sediments

The bottom as well as the inshore zone of the lagoon consists of modern deposits of silty clay or argilic clay silt, with the presence of fine sand and shellfish layers. These deposits are characterized by very low carrying capacity and are generally problematic in terms of ground mechanic properties.

32.2.6 Flora – Fauna

The area belongs to the estuaries of the wetland system "Mesolonghi – Achelous – Evinos", areas where rich flora and fauna can be found. It is one of the most important habitats of Greece protected by the RAMSAR Treaty. The same region and the mountains to the north and east of Mesolonghi and Arakynthos Varasova, have been characterized as protected areas in the context of NATURA 2000. This is also a very important wetland for birds (amongst the 11 considered of international importance by the Treaty RAMSAR). Migratory birds use the lagoon for rest and refueling station, while the area has seen over 200 different species, of which 70 are rare or endangered. The most rare and highly protected slender gull and also the famous wild ducks in the region are included amongst these species.

32.2.7 Demographıc Data of Messolonghi

The prefecture of Aitoloakarnanias is the westernmost prefecture of Sterea Hellas and extends between 38°18' 20°43" N and 22°02' 18 91" E. It has an area of 5,450 km^2, which corresponds to 4% of the total area in Greece. According to the 2009 census of the ESYE, it has a population of 228,069 (2.3% of the total population of the country). The population of Mesolonghi is 13,791 (6% of the total population of the prefecture Aitoloakarnanias).

32.2.8 WWTP of Messolonghion

The installations of Messolonghion are located near the torrent of Koukos, North of Kleisova lagoon. The area covered by installations is about 1 ha. The altitude is 0.8 m and geographical continents are N 38°22 08 and E 21°2731 in HATT system.

The treated wastewaters are drained into the torrent of Koukos, which terminates in the Kleisova lagoon, which in connected to the Patras Gulf.

The WWTP has been designed to serve 16,000 people with the future extension capacity by 50% with a mean daily production 4.630 m^3/day. The treatment method applied consists of active sludge subjected to continuous aeration, nitrification-denitrification and dephosphoration.

32.2.9 Chemical Analyses

Both TMWW, and the well irrigation water samples, were analyzed by means of internationally accepted methods and the results have been reported by Kalavrouziotis et al. [8]. The concentrations of the elements obtained were within the limits set for by WHO [9].

32.3 Results and Discussion

32.3.1 Water Consumption by Crops in the Protected Area of Messolonghion, Greece

In order to determine the water needs of the cultivations of the Messolonghion area, first the mean daily rate of the reference evapotranspiration was calculated employing the Penman-Monteith equation according to FAO-56 [10].

$$ET_o = \frac{0,408\Delta\left(R_n - G\right) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0,34u_2)} \tag{32.1}$$

where; ETo is the reference evapotranspiration (mm/day), Rn is the net radiation at the crop surface (MJ m^{-2} d^{-1}), G is the soil heat flux density (MJ m^{-2} d^{-1}) which, for daily intervals, may be ignored, T is the mean daily temperature at 2-m height (°C), u2 is the wind speed at 2-m height (m s^{-1}), es is the saturation vapour pressure (kPa), ea is the actual vapour pressure (kPa), es – ea is the saturation vapour pressure deficit (kPa), – is the slope saturation vapour pressure curve at temperature T (kPa $°C^{-1}$) and – is the psychrometric constant (kPa $°C^{-1}$).

The daily reference evapotranspiration was calculated by considering meteorological data from Messolonghion station for the last 42 years (1967–2009) as provided by the National Meteorological Service (NMS).

The estimation of crop evapotranspiration, ETc, incorporates the single or the dual crop coefficients in the following equation:

$$ET_c = K_c \cdot ET_o \quad (32.2)$$

where; K_c is the single crop coefficient, which averages crop transpiration and soil evaporation. The crop evapotranspiration, (ET_c), for the crops of Messolonghion valley for the irrigation period of year 2009 was calculated.

The cropping land covers an area of approximately 3,820 ha as shown Table 32.1.

The mean plant coefficients for maize, citrus fruits, and olives in development stage (K_c) were obtained from Papazapheiriou [10] who determined them for the climatic conditions prevalent in Greece. For alfalfa and vegetables, for which the plant coefficients for the climatic conditions of Greece have yet to be determined, the crop coefficients by stage of growth K_c, were used as given by Allen et al. [1].

As it shown in Fig. 32.2, the greatest crop evapotranspiration was that of alfalfa, followed by those of citrus fruits, maize, olives, and vegetables.

Net water needs for the crops were determined according to the following equation:

$$In = ET_c - \left(P_e + G_w + S_m\right) \quad (32.3)$$

where; P_e refers to the portion of rainfall, which may be used by the crops and it is known as "effective rainfall", G_w is the contribution of the groundwater and S_m is the water stored in the topsoil layer of the soil at the beginning of the germinative period.

In this study, G_w was considered equal to zero, since the underground water table in the Messolonghion area plain is very low as a result of excessive pumping.

Table 32.1 Total cropped area in Messolonghion in 2009

Crop	Area (ha)
Maize	1,393.3
Alfalfa	1,612.2
Vegetables	40.5
Citrus	408.2
Olives	365.8
Total	3,820

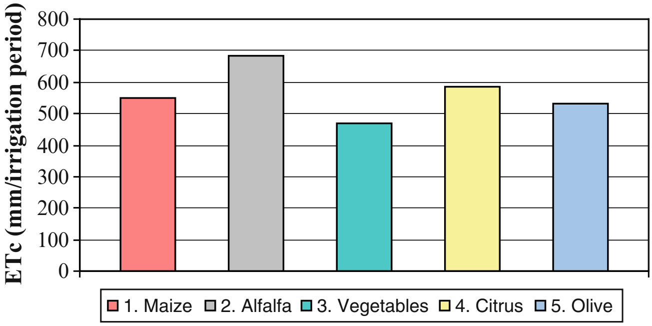

Fig. 32.2 Crop evapotranspiration (ET_c), in Messolonghion area (in mm/irrigation period)

The concession was also made that the soil moisture at sowing and at harvest time was the same, and the term S_m was, therefore, assumed to be zero. Beyond, however, the obvious need for water, which must be met through irrigation, is necessary for the leaching of salts, which are concentrated in the root-supporting layer of the soil.

Consequently, for the calculation of the net water requirements, the difference between the crop evapotranspiration of the cultivations minus the "effective rainfall" P_e was calculated.

The effective rainfall was calculated by the USDA [12] method, as follows:

$$P_e = f(D)\left[1.25P_t^{0.82416} - 2.93\right]10^{0.000955ETc} \qquad (32.4)$$

where; P_e = average monthly effective precipitation (mm), P_t = monthly mean precipitation, ET_c = average monthly crop evapotranspiration (mm), f(D) = soil water storage factor.

The soil water storage factor is defined by:

$$f(D) = (0.531747 + 0.295164\ D - 0.057697D^2 + 0.003804D^3) \qquad (32.5)$$

where D = the usable soil water storage (mm).

Finally, the total water demand of the crops for the 2009 irrigation season was calculated on the basis of the crop statistics (data) for the same year.

The calculation of the total water demand for each crop for the entire season of irrigation was obtained by multiplying the net needs of water for irrigation of the various crops by the corresponding areas presented in Table 32.2.

Among all crops, vegetables were the most demanding crop for irrigation water, whereas olive was the last one. Considerable demands were also found for alfalfa, maize and citrus.

The pie chart of Fig. 32.3 gives the irrigation requirement by each crop as a percentage of the total water for the year 2009.

Table 32.2 Total demand for irrigation water by the crops of the valley of Messolonghion, 2009

Crop	Net demand for irrigation water, I_n of the crops (mm/period of irrigation)
Maize	316
Alfalfa	382
Vegetables	469
Citrus	280
Olives	225

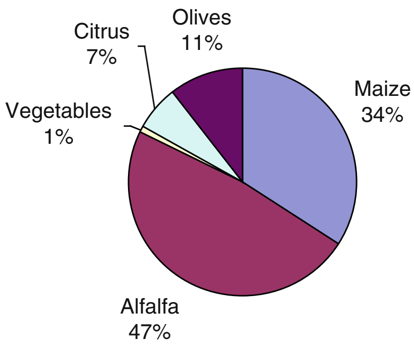

Fig. 32.3 Percentage of irrigation requirement for each crop

The total water requirements of these crops during the irrigation period of the year 2009 for the 3,820 ha of irrigated areas in Messolonghion are 12,697.033.33 m^3, with an average of 3,323.8 m^3/ha.

Given that the WWTP has a total of 1,689.950 m^3 effluents the percent of reuse is estimated to be 13.3%.

32.4 Conclusions

The treated wastewater from the WWTP of Messolonghion, Greece can cover the water demand of all the surrounding areas. The first crop, which is better to irrigate with processed wastewaters in the Messolonghion area is Alfalfa and the second is Maize. The research values of all geological, soil, water, geotechnical, agricultural, and meteorological parameters must be the most reliable ones in processing of liquid wastes, and optimised in order to be reused safely for environmental protected areas, mostly important for the people and also the environment. The reuse for irrigation is expected to contribute substantially to the prevention of any future degradation by heavy metals of the wastewaters final receiver, i.e. the lagoon of Messolonghion, with the ultimate goal of the environmental protection of the water receivers.

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