MODELING OF MOGAN AND EYMİR LAKES AQUIFER SYSTEM

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

BY

ÖZLEM YAĞBASAN

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

JUNE 2007

Approval of the Graduate School of Natural and Applied Sciences

Prof. Dr. Canan ÖZGEN

Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Doctor of Philosophy.

Prof. Dr. Vedat DOYURAN

Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Doctor of Philosophy.

Prof. Dr. Hasan YAZICIGİL

Supervisor

Examining Committee Members:

Prof. Dr. Nurkan KARAHANOĞLU (METU, GEOE)

Prof. Dr. Hasan YAZICIGİL (METU, GEOE)

Prof. Dr. Vedat TOPRAK (METU, GEOE)

Assoc. Prof. Dr. Zeki ÇAMUR (METU, GEOE)

Assist. Prof. Dr. Levent TEZCAN (Hacettepe Uni., HYDRO-GEOE)

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

Name, Last name : Özlem YAĞBASAN

Signature :

ABSTRACT

MODELING OF MOGAN AND EYMİR LAKES AQUIFER SYSTEM

Yağbasan, Özlem

Ph. D., Department of Geological Engineering

Supervisor: Prof. Dr. Hasan Yazıcıgil

June 2007, 163 pages

Mogan and Eymir Lakes, located 20 km south of Ankara, are important aesthetic, recreational, and ecological resources. Dikilitaş and İkizce reservoirs, constructed on upstream surface waters, are two man-made structures in the basin encompassing an area of 985 km^2. The purpose of this study is (1) to quantify groundwater components in lakes' budgets, (2) to assess the potential impacts of upstream reservoirs on lake levels, and (3) to determine effects of potential climatic change on lakes and groundwater levels in the basin. Available data have been used to develop a conceptual model of the system. The three dimensional groundwater model (MODFLOW) has been developed for the system. The model has been calibrated successfully under transient conditions over a period of six years using monthly periods. The results show that groundwater inflows and outflows have the lowest contribution to the overall lakes' budget. A sensitivity analysis was conducted to determine the limits within which the regional parameters may vary. Three groundwater management scenarios had been developed. The results show that the upstream reservoirs have a significant effect on lake stages but not on groundwater levels. A trade-off curve between the amount of water released and the average stage in Lake Mogan has been developed. The continuation of the existing average conditions shows that there would be declines in groundwater elevations in areas upstream from Lake Mogan and downstream from Lake Eymir. The results also indicated that very small, but long-term changes to precipitation and temperature have the potential to cause significant declines in groundwater and lake levels.

Keywords: Mogan and Eymir Lakes Basin, Lake and Aquifer Interaction, Simulation, Calibration, Groundwater Management

ÖZ

MOGAN VE EYMİR GÖLLERİ AKİFER SİSTEMİNİN MODELLENMESİ

Yağbasan, Özlem

Doktora, Jeoloji Mühendisliği Bölümü

Tez Yöneticisi: Prof. Dr. Hasan Yazıcıgil

Haziran 2007, 163 sayfa

Ankara'nın 20 km güneyinde yer alan Mogan ve Eymir Gölleri önemli estetik, eğlence ve ekolojik kaynaklardır. Yüzey sularının membasında inşa edilen Dikilitaş ve İkizce Göletleri, 985 km^2'yi kapsayan havzadaki insan yapımı iki yapıdır. Bu çalışmanın amacı: (1) göllerin bütçesindeki yeraltısuyu öğesinin miktarını belirlemek, (2) memba göletlerinin göl seviyeleri üzerine olan potansiyel etkilerini değerlendirmek ve (3) havzadaki potansiyel iklimsel değişimin göller ve yaraltısuyu seviyeleri üzerine etkilerini belirlemektir. Sistemin kuramsal modelinin geliştirilebilmesi için varolan veriler kullanılmıştır. Üç boyutlu yearaltısuyu modeli (MODFLOW) sistem için geliştirilmiştir. Model, kararsız akım koşullarında altı yıllık dönemde aylık süreler kullanılarak başarılı bir şekilde kalibre edilmiştir. Sonuçlar, yeraltısuyu giren ve çıkan akımlarının göllerin ayrıntılı bütçesi içinde en düşük katkı oluşturduğunu göstermektedir. Bölgesel parametrelerin değişebileceği sınırların belirlenebilmesi için duyarlılık analizi yapılmıştır. Üç yeraltısuyu yönetim senaryosu kurulmuştur. Sonuçlar, memba göletlerinin yeraltısuyu seviyeleri üzerinde değil de, göl seviyeleri üzerinde önemli bir etkisi olduğunu göstermiştir. Bırakılan su miktarı ile Mogan Gölü'ndeki ortalama seviye arasındaki değiş-tokuş eğrisi geliştirilmiştir. Mevcut ortalama koşulların devam etmesi, Mogan Gölü'nün membasındaki ve Eymir Gölü'nün mansabındaki alanlarda yeraltısuyu seviyelerinde düşmeler olabileceğini göstermiştir. Sonuçlar ayrıca, yağış ve sıcaklıktaki çok küçük ama uzun dönemli değişikliklerin, yeraltısuyu ve göl seviyelerinde önemli düşümlere sebep olabileceğini göstermiştir.

Anahtar Kelimeler: Mogan ve Eymir Gölleri Havzası, Göl ve Yeraltısuyu İlişkisi, Simülasyon, Kalibrasyon, Yeraltısuyu Yönetimi

To My Family…

ACKNOWLEDGMENTS

The author is grateful to her professor, Dr. Hasan YAZICIGİL for having provided the opportunity to work under his guidance. His encouragement, advice and interest in the present study have always been a constant source of inspiration for the author and are sincerely appreciated.

The author expresses her sincere thanks to Dr. Levent TEZCAN for his advice and critical comments during various stages of this study. His pleasant and enthusiastic disposition was a nice experience for the author to work with him. Thanks are also due to Dr. Nurkan KARAHANOĞLU for his comments, advice and encouragement.

Sincere appreciation and thanks are expressed to İsmail KÜÇÜK from EİEİ for providing available data for the study. Special thanks are due to the staff of V. District of DSİ, MTA and Turkish State Meteorological Service.

The author extends her gratitude to the İşlem Geographical Information System Company for the valuable support during the preparation of the base maps of the research.

Sincere appreciation and thanks are expressed to Ebru Vesile ÖCALIR for her encouragement and assistance.

Special thanks go to the author's parents, Aysun YAĞBASAN and Rahmi YAĞBASAN, whose patience, understanding and devotion greatly aided in successful completion of her thesis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Statement of Problem

Lakes are important surface water resources not only because they may serve as a source of water supply but also they provide recreational opportunities through fishing, boating and swimming as well as a scenic setting for lakeside estates and the surrounding communities. Some lakes may also have associated wetlands that provide housing for birds and various ecological resources. Mogan and Eymir Lakes, located approximately 20 km south of Ankara in Central Anatolia, are such lakes that provide aesthetic and recreational opportunities for the City of Ankara and the Town of Gölbaşı (Figure 1.1). These lakes, especially Lake Mogan, have wetlands housing to more than 200 different types of birds. Because of their values as an aesthetic, recreational and ecological resources, there is a growing concern about the possible impacts of various developments and global climatic changes on the long-term sustainability of these lakes.

In most of the semi-arid countries faced with increasing population and demand for development of new agricultural lands, aggressive policies have been adopted to develop and exploit their surface water resources. The environmental consequences of these engineering efforts and their impact on lakes and dependent ecosystems are too often overlooked. Dikilitaş and İkizce irrigation reservoirs, constructed in late 1980s on upstream surface water resources of Lake Mogan,

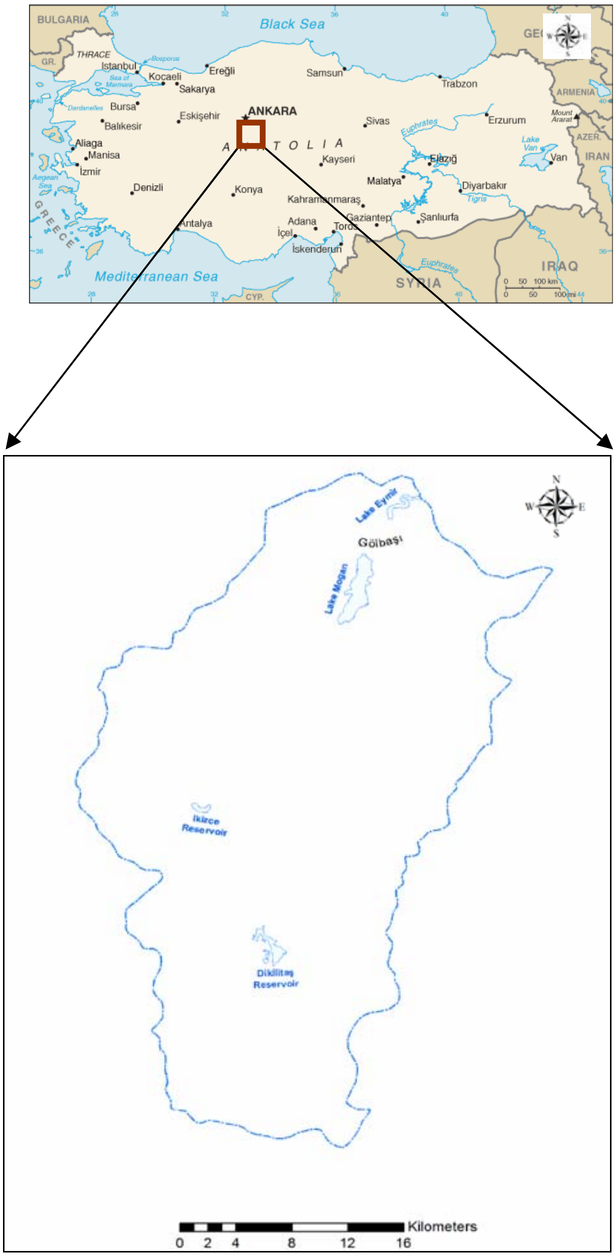

Figure 1.1. Location map of Mogan and Eymir Lakes Basin.

are such engineering structures and considered to have a significant impact on Lake Mogan (Figure 1.1). The recent awareness about climatic change has raised even greater concerns on the potential impacts of these reservoirs on the lakes and associated ecosystems. In regions where present water resources are constrained, such as the Central Anatolia, climatic change could have a detrimental impact on lakes and reservoirs. Therefore, it is important that the potential impact of the upstream reservoirs be assessed to determine if, and what type of water management programs should be implemented to insure long-term existence of the lakes. The objectives of long-term lake sustainability and demand for irrigation water are however, generally conflicting and non-commensurable. Hence, a trade-off that exists between these two objectives has to be identified.

Although not all of the lakes but most have some connection with the groundwater system. A great deal of effort has been spent over the past two decades to understand the interaction between lakes and groundwater systems. Understanding the interaction between lake and groundwater systems is essential for sound management of both resources. In most environments, these two components are in continuous interaction and development of or changes to one component inherently affect the other. Groundwater fluxes, while difficult to measure, may be important to the hydrology and chemistry of lakes. Stresses on the groundwater system and changes in groundwater fluxes affect lake water levels, which in turn affect groundwater levels in a dynamic feedback process. The exchange of water between the two systems can be highly variable over a range of spatial scales and highly dynamic in time. Understanding those patterns and dynamics can be crucial for efforts to manage both systems in an optimum manner. Hence the recognition and quantification of this feedback mechanism are prerequisite in lake-aquifer management studies.

Traditional estimates of groundwater inflow and outflow to a lake are based on a residual in the hydrologic budget of the lake, simple flow nets, one-dimensional Darcian calculations, and stable isotopes. The most sophisticated way of investigating lake-groundwater interactions however is by explicitly including lakes into groundwater flow models. Standard groundwater models assume that lake water levels are known inputs, and therefore do not recognize the true nature of the connection between lake and groundwater. Recognition of the need for improvement in the way in which groundwater models handle surface water inputs led to development of specialized software packages for MODFLOW (the industry's standard code for groundwater flow modeling) that address the dynamic exchange of groundwater with lakes, rivers and reservoirs. Thus, watersheds containing important lake and stream systems require models that include consideration of the dynamic exchange of waters among groundwater, lakes and streams.

1.2 Purpose and Scope

The purpose of this study is (i) to quantify groundwater components in lakes' budgets, (ii) to assess in a quantitative manner the potential impacts of upstream reservoirs on lake levels, and (iii) to determine effects of potential climatic change on lakes and groundwater levels in the basin. The focus of the study was centered on the quantity aspects of the effects rather than quality aspects.

The scope of work included:

- compilation and review of available literature in regard to the theoretical developments in modeling the interaction between lakes and groundwater systems, case studies where such methodologies have been applied to real-world problems, and previous studies conducted in the basin,

- compilation, review and analysis of available data on topography, climate and meteorology, geology, hydrology, and hydrogeology,

- development of conceptual model of the study area and construction of a numerical model,
- calibration of the numerical model under transient conditions and sensitivity analyses,
- assessment of the impacts of reservoirs and potential climatic changes on lake and groundwater levels,
- recommendations in regard to water management practices as well as future studies to be conducted in the basin.

1.3 Location and Extent of the Study Area

Mogan and Eymir Lakes are located approximately 20 km south of Ankara, Capital City of Turkey (Figure 1.1). The study area, located in the Central Anatolian Region, is within the bounds of 39°28'-39°53' north latitudes and 32°30'-33°00' east longitudes. The catchment area of Mogan and Eymir Lakes Basin is 985 km^2 and the perimeter of the basin is 159.14 km. There is a "Specially Protected Area by Law" within the basin which has been accepted by the Council of Minister in 1990. It covers both of the lakes and their surroundings within an area of 245 km^2.

Dikilitaş and İkizce reservoirs are located on the upstream surface water resources of Lake Mogan and both are used for irrigation purposes. There are no perennial rivers in the basin.

CHAPTER 2

LITERATURE REVIEW

The application of groundwater flow models to the solution of groundwater flow problems grew significantly during 1970s following the development of the computer technology. The U.S. Geological Survey (USGS) was a leader in the application of groundwater flow models. The early models developed were basically two dimensional (Pinder 1970, Prickett and Lonnquist 1971, Trescott et. al. 1976). Three dimensional models were also developed as computers became more powerful (Trescott 1975). In early 1980s the USGS developed a code which was originally called USGS Modular Three-Dimensional Finite Difference Groundwater Flow Model (McDonald and Harbaugh 1984). It is later known as MODFLOW. Since then MODFLOW has been used significantly all over the world and several packages have been added to it. With continued development of new packages, MODFLOW-96 (Harbaugh and McDonald 1996) and MODFLOW-2000 (Harbaugh et al. 2000) have been released. Cheng and Anderson (1993) was the first who developed a lake package, LAK1, for the MODFLOW. This package, improved over the years, allowed for fluctuating lake levels. In the following, the historical developments in numerical solution techniques for solving lake-groundwater interactions are summarized.

2.1 Historical Development of the Numerical Solution Techniques Related with Groundwater-Lake Interactions

Approaches for modeling lake-groundwater interactions have evolved significantly from early simulations. Early simulations employed cross-sectional models with fixed lake stages specified as specified head or head-dependent flux boundaries (Winter 1976; Anderson and Munter 1981). Areal models were also constructed with fixed lake stages using both finite difference and analytic element methods (Hunt et al. 1998). The main problem with this approach is the lake levels do not change unless the user specifies time-dependent lake stages a priori. In many applications, however, it is desirable to calculate lake levels as part of the head solution process. Such applications include simulating changes in lake level in response to pumping from the aquifer or to drought or other climatic changes.

Another approach for simulating lake levels is the introduction of a high conductivity feature or “high-K lake” (Lee 1996; Hunt and Krohelski 1996; Hunt et al. 2000, Anderson et. al. 2002). In this approach, the lake is represented by cells of high hydraulic conductivity in a finite-difference model, or as a high conductivity inhomogeneity in an analytic element model. In high-K lake approach, the lake is part of aquifer, and the model uses hydraulic conductivity and storage values assigned to the lake nodes to calculate the head in the lake (i.e., lake stage) as part of the finite-difference solution of groundwater flow equation. The method, however, is limited to seepage lakes only, i.e., lakes without surface water inflow and outflow. Furthermore, the approach may require a large number of iterations and thus long run times to converge if it is necessary to use a large contrast between the hydraulic conductivity of the lake nodes and surrounding aquifer (Anderson et al. 2002).

The third approach to solving for lake levels in a groundwater model is to compute changes in lake level from a mass-balance calculation. This is the approach used in a series of lake packages developed for MODFLOW. LAK1 developed by Cheng and Anderson (1993) was patterned after Özbilgin and Dickerman (1984). Limitations in LAK1's steady-state solver led Council (1998) to develop LAK2. Later, Merritt and Konikow (2000) developed LAK3 as an improvement over earlier packages. LAK3 has the capability to simulate solute transport and multiple lake basins. The transient solver was also improved. All three lake packages calculate changes in lake level from a water budget that includes groundwater flow, stream flow, precipitation, and evaporation from the lake. The calculated lake level is then used as a head-dependent boundary condition, similar to the way in which river levels are treated in MODFLOW's River Package, except that the volume of the lake is represented in the grid by inactive nodes. In transient simulations, changes in lake storage are computed as the difference between total inflow and outflow. All have comprehensive reporting of lake water budget. LAK3 has been used in this study.

Briefly, LAK3 allows the user to specify explicit, semi-implicit, or fully implicit transient lake stage solutions. LAK3 can simulate the transient separation of lakes into distinct basins as lake stage declines as well as the joining of separate lake basins into one lake as lake levels rise. Finally, LAK3 includes the ability to simulate average solute concentration in a lake and solute transport through a lake using the MODFLOW Ground-Water Transport package (MODFLOW_GWT). When using MODFLOW, LAK packages are superior to other methods (constant head, head dependent flux, or high conductivity lake), because they have powerful post simulation reporting features and allow for explicit inclusion of surface water flow to and from lakes.

2.2 Case Studies Related to Lake-Aquifer Interactions

Studies related to lake and aquifer interactions conducted in hypothetical as well as real world cases provided information for understanding the mechanisms between these systems. In the following, important findings and conclusions obtained from these studies are summarized.

Winter (1978) was probably the first who has applied a numerical approach for solving lake and groundwater interaction. He stated that the continuity of the local system boundary beneath a lake was the factor that controlled the interaction of lakes and groundwater. Further, for most settings modeled in the study the stagnation zone, key for the determination of the continuity of the boundary, underlie the lake shore and it generally followed its curvature. The boundary conditions of the system studied showed that the factors strongly influencing the continuity of the local system boundary were: the height of adjacent water table mounds relative to lake level, position and hydraulic conductivity of aquifers within the groundwater system, ratio of horizontal to vertical conductivity of the system, regional slope of the water table and lake depth.

Krabbenhoft et al. (1990a, 1990b) presented the results of a study in which stable isotopes and a numerical model were used independently to calculate groundwater inflow and outflow rates to the Sparkling Lake in northern Wisconsin in a two-part paper. In part one (Krabbenhoft et al. 1990a), the results of the isotope mass balance method was given. In part two (Krabbenhoft et al. 1990b), the results of application of a three-dimensional groundwater flow and solute transport model to an observed plume downgradient from the lake were presented. The flow model was calibrated to observed hydraulic gradients and estimated recharge rates. By employing both flow and transport models in the calibration process, assumed flow parameters were checked by calibration of the transport model and therefore greater confidence was placed in the validity of the flow model results. A favorable comparison between the results of the isotope method and a groundwater flow/transport model suggested that both were complementary, useful techniques for computing groundwater inflow and outflow rates.

Anderson et al. (1992) studied a 10 year record of water level fluctuations in a groundwater/lake system in northern Wisconsin. They showed that dynamics were strongly influenced by seasonal transient effects. Short-term transient effects in the form of seasonal groundwater mounds occurred on all sides of the lake, causing groundwater inflow, when regional groundwater levels were high. These observations pointed to the importance of a long-term record in assessing the significance of short-term effects. Short-term transience affected the groundwater component of the lake budget, because the mounds induced groundwater to flow toward the lake. In the absence of the mounds, water flowed away from the lake. Also, shifts in the groundwater regime would affect the lake's chemical budget in the long term.

The effect of climatic variability on lake levels, lake water quality, and groundwater resources in a lake-groundwater system has been studied by Crowe (1993). He developed a dynamic hydrologic model to provide insight into the effects of climatic variability on Wabamun Lake and its watershed in Alberta, Canada. The calibration of the lake-watershed model to the observed lake surface elevation fluctuations and lake salinity records indicated the importance of groundwater in the hydrologic balance of the lakes. Subsequently, the calibrated model was used to investigate the effects of climate variability on the watershed through a series of sensitivity analyses. The results of the sensitivity analyses indicated that small changes in temperature (1-2^{o}C rise) or precipitation (5-10 % decline) throughout the watershed may significantly impact the quality of lake water and the availability of the groundwater resources. The results of the analyses indicated that very small, but long term changes to temperature and precipitation, have the potential to cause decline in lake levels, a deterioration in the quality of the lake water, and a substantial loss of groundwater resources.

Cheng and Anderson (1994) studied the influence of lake position on groundwater fluxes in a hypothetical system. Groundwater flow around three hypothetical lakes, located in the upper, middle, and lower sections of a watershed, was numerically simulated under steady-state and transient conditions using MODFLOW package. The model simulated the effects of groundwater fluxes, precipitation, and evaporation on the lake and calculated lake level fluctuations as well as groundwater fluxes for both steady-state and transient conditions. The results of the simulations indicated the importance of the lake position within the regional flow system on the lake's water and chemical budgets. Steady state simulations showed that groundwater is likely to be more important to the water budgets of the lakes located lower in the flow system. Transient simulation results showed that groundwater flows around a lake located in the upper section of a watershed tend to be more variable than for lakes located lower in the watershed. The formation of downgradient mounds, causing a temporary net increase in groundwater inflow, accompanied by groundwater flow reversals are expected to be induced by high-intensity groundwater recharge (i.e. infiltration from spring snowmelt). Such effects were observed in the lakes located in the uppermost sections in a watershed.

Narayan et al. (1995) modeled the movement of salt from Lake Ranfurly West towards the River Murray and the associated groundwater interception scheme in cross-section using the variable density solute transport model SUTRA (Voss 1984). Density-dependent behavior was assumed to be important owing to the high salinity in Lake Ranfurly and seepage of the saline water to the underlying aquifer system. There was a significant density contrast between the seepage water from Lake Ranfurly and the native groundwater. The results of the management scenarios showed that salt load to the river was fully dependent on the pumping scheme and the nature of the aquifer material in which groundwater was intercepted.

Urbano et al. (2000) developed a free surface paleohydrologic model along a cross-section across the Murray Basin in the south eastern Australia to study the effects of groundwater flow on paleoclimate records in semi-arid environments, over millennial time scales. The groundwater code MWT3D (Knupp 1996) was used in the development of the numerical model. The equations for flow in a fully saturated porous medium were solved by deforming the numerical mesh to follow the motion of the water table. The method tracks the location of the water table and the formation of seepage faces. The groundwater system communicated regional effects between lake basins that were unconnected by surface water. This interaction could have a significant influence on the interpretation of paleoclimatic records, since lake-groundwater interactions are crucial to the formation of limnologic paleoclimatic indicators in arid environments.

Anderson et al. (2002) investigated the sensitivity of the solutions using high hydraulic conductivity (high-K) lake nodes to the value of K selected to represent the lake. The results of a test problem and the field application of a lake system in Wisconsin were compared with results obtained using LAK3 package (Merritt and Konikow 2000). The results compared favorably with each other. While the results demonstrated that the high-K method accurately simulated lake levels, the method had more complex post processing and longer run times (large number of iterations) than the same problem simulated using the LAK3 package.

Kim et al. (2002) constructed a two-dimensional groundwater flow model to investigate the long-term hydrologic impacts of Lake Nasser and the major land irrigation projects that use excess lake water in southwest Egypt. The model was developed by using MODFLOW code. In order to estimate recharge from the lake by employing the River Package module, the head-dependent flux boundary conditions were used. The model was successfully calibrated to temporal-observation heads from 1970 to 2000 that reflect variations in lake levels. The calibrated results showed good agreement with observed transient heads, which reflected variation in lake levels. Predictive analyses for the subsequent 50-year period were conducted by using the calibrated model.

Smerdon et al. (2005) determined the hydrologic controls on the interaction between a shallow lake and a groundwater flow system for the Boreal Plains of Canada. Lake-groundwater interactions were studied to provide an understanding of the near-surface hydrologic processes in a sub-humid climate, where annual precipitation is equal to, or less than potential evapotranspiration. After the designation of the piezometer network in the basin, the connection between the lake and groundwater system was studied and components of the lake water budget for two consecutive hydrologic years were quantified in order to determine the major controls on lake-groundwater interaction. Hydrometric measurements and stable isotopic analyses indicated that evaporation was the dominant hydrologic flux during ice-free months, and was primarily responsible for a 0.2 m decline in lake level during the study. The dynamic relationship between precipitation, groundwater interaction, and surface flow was mainly controlled by the evaporative flux from lake surfaces.

2.3. Previous Studies in Mogan and Eymir Lakes Basin

Previous studies conducted in Mogan and Eymir Lakes Basin provided data that were used in this study. In the following a summary of these studies as well as important findings pertinent to this study are presented.

Kalkan et al. (1992) conducted a geological and hydrogeological investigation study with the aim of protection of the Lakes Mogan and Eymir. They produced maps showing drainage and protection zones for the lakes system, geology, hydrogeology and geomorphology of the study area.

Dogramacı (1993) studied geohydrological characteristics of the Pliocene deposits in Gölbaşı Basin by collecting 101 samples from a depth of 30 cm. The laboratory results conducted on these samples showed that the hydraulic conductivity of the Pliocene deposits ranged between 7.5×10^{-5} cm/sec and 8.0×10^{-6} cm/sec. The porosity values ranged from a minimum of 34.7 % to 48.7 %. The specific yield values varied from 1.9 % to 6.0 %. The arithmetic mean values for porosity and specific yield are 41 % and 4 % , respectively. The porosity data showed strong negative and positive correlation with the specific yield (r=0.910), and specific retention (r=0.993), respectively.

Arıgün (1994) conducted a hydrogeological investigation for the western part of the recharge area of Lakes Mogan and Eymir. Several studies were conducted in order to determine the hydrogeologic characteristics of the stratigraphic units in the surroundings of Lakes Mogan and Eymir. The transmissivity and hydraulic conductivity values of the Quaternary alluvium aquifer were calculated as 6.39×10^{-4} m^2/sec and 4.37×10^{-6} m/sec by the evaluation of the pumping test data in the basin.

METU (1995) conducted a study to develop water resources and environmental management plan for Lakes Mogan and Eymir. A group of researchers from civil, environmental, and geological engineering departments of METU were participated in this project. For the period between July 1, 1993 and June 31, 1995, the lake systems were characterized by conducting detailed hydrological, hydrogeological, environmental and hydraulic studies. Pumping, recovery and tracer tests were conducted to estimate the hydraulic characteristics of the Quaternary deposits feeding the Lake Mogan. The storativity, hydraulic conductivity and transmissivity values were estimated as 2.9×10^{-4}, 40.4 m/day, 80.75 m^2/day, respectively. By the implementation of the Darcy's Law in the preparation of the lakes' water budget, the total groundwater inflow and outflow rates to Lakes Mogan and Eymir were determined as 20 lt/sec, 9 lt/sec and 17 lt/sec, 2 lt/sec, respectively.

Çamur et al. (1997) modeled the hydrogeochemical characteristics of spring, stream, wetland, and lake waters in the Lakes Mogan and Eymir Special Environmental Protection Area by using a reaction-path simulation method on the basis of water-rock interactions. The geochemical characteristics of surface waters and groundwater, mineralogical sources of ion concentrations in springs, and mixing and evaporation/dilution relationships between compositions of input flows and lakes and compositions of feeding flows and the wetland were quantitatively evaluated using the mass-balance reaction modeling of Plummer et al. (1991).

Özaydın (1997) studied the water balance of both lakes using the stable isotope mass balance approach. Monthly water budget (groundwater inflow and groundwater outflow) of Lakes Mogan and Eymir was determined by using Oxygen-18 and Deuterium isotopes. For 1994 and 1995 water years, the average groundwater inflow and outflow rates to Lake Mogan were determined as 13.39×10^6 m^3, 2.71×10^6 m^3 and 8.92×10^6 m^3, 1.27×10^6 m^3, respectively. Also, the average groundwater inflow and outflow rates to Lake Eymir were determined as 6.7×10^6 m^3, 1.94×10^6 m^3 and 5.79×10^6 m^3, 0.87×10^6 m^3, respectively. In addition, an approximate age of the groundwater was estimated as 6 years by means of the available tritium values from groundwater.

Canpolat et al. (2001) conducted a hydrogeochemical modeling study to evaluate the heavy metal loadings to waters and sediments by leachate from the Gölbaşı waste disposal site located between the two lakes. It has been determined that the groundwater of the waste disposal area, characterized by high concentrations of heavy metals, contaminated the waters and sediments in the down-gradient area, Lake Eymir and the swamp along the flow path. It has been shown that the amounts of contaminants removed from or added both to the downgradient groundwater and to surface waters through mixing, dilution, and evaporation processes were rather small. The amounts of ions in the waters were predominantly governed by exchange and dissolution/precipitation reactions.

Küçük et al. (2005) conducted a study in which hydrometric measurements conducted by EİEİ were presented. The purpose of the project was to evaluate the water resources in the Mogan and Eymir Lakes Basin. The recharge and discharge calculations were made and the lakes' budget in terms of water year were evaluated in this project.

CHAPTER 3

DESCRIPTION OF THE STUDY AREA

3.1 Physiography

The Mogan and Eymir Lakes Basin covers an area of 985 km^2 and has a rectangular shape that extends in northeast and southwest direction. The two lakes are located in the northeastern part of the basin (Figure 3.1). There are also two irrigation reservoirs, namely Dikilitaş and İkizce, located in the southern and western part of the basin, respectively.

In general, the basin has a very mild slope. The highest and the lowest elevation in the basin are 1560 m and 980 m, respectively. The magnitude of the regional slope is 20 % in north and east direction, 6-20 % in west and northwest direction. The elevation of 62 % of the total area is between 1050 m and 1250 m. The relief map, prepared by creating tin (triangulated irregular network) of the study area, shows the drainage pattern and morphological characteristics of the basin (Figure 3.1).

3.2 Climate

Continental climate is dominant in the basin with very cold and rainy/snowy days in winter but very hot and dry weather in summer. There are four meteorological stations in the basin, namely Culuk, Tepeyurt, Gölbaşı and Ankara University Agricultural Faculty Investigation Farm (Figure 3.2). Gölbaşı Station

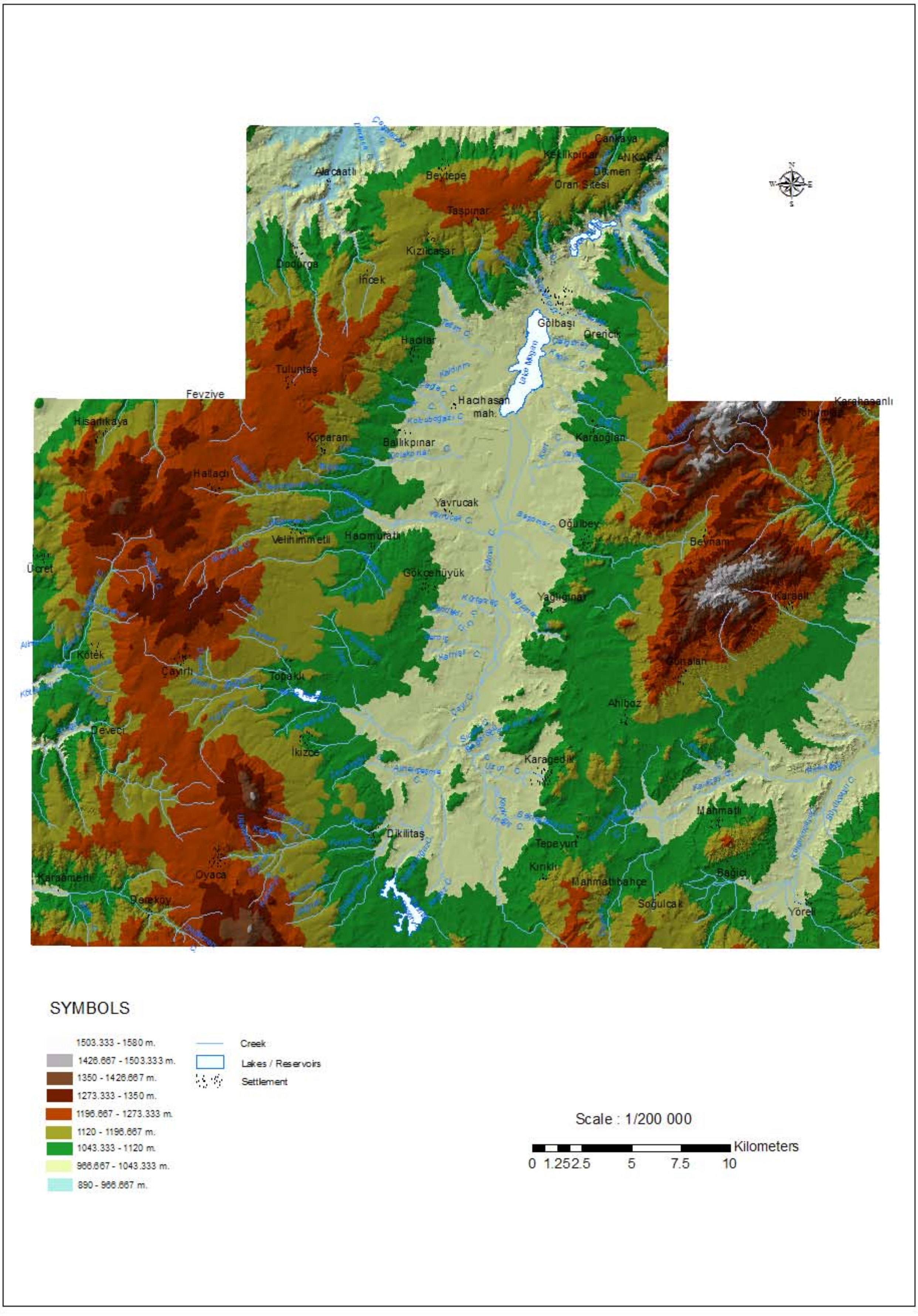

Figure 3.1. Relief map of the study area.

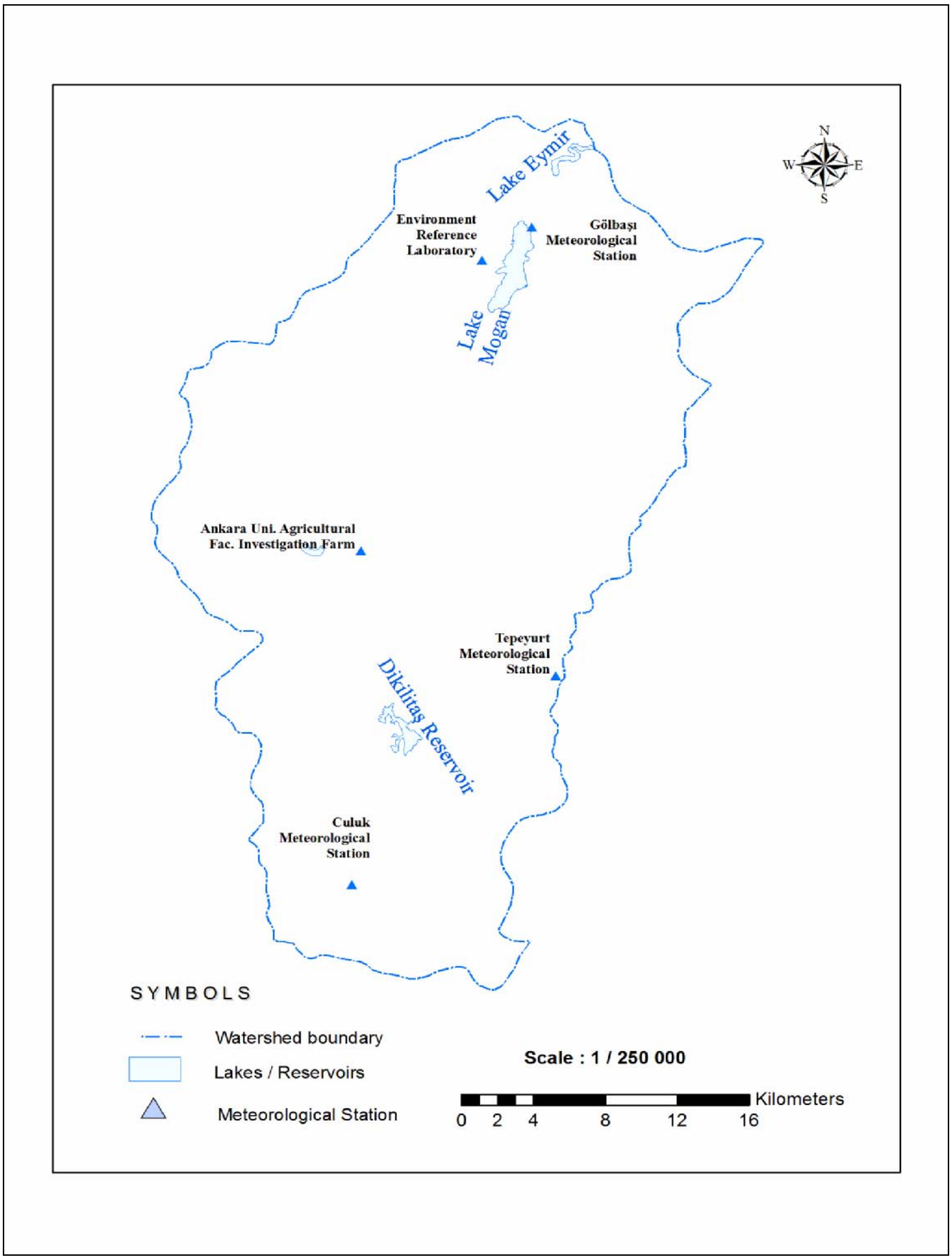

Figure 3.2. Location of the meteorological stations in the basin.

was moved to the Environment Reference Laboratory in March 2003. Measurement of daily precipitation is made at all of the meteorological stations. In addition to precipitation, temperature, evaporation, relative humidity, wind and radiation are also measured at Culuk and Gölbaşı (Environment Reference Laboratory) Meteorological Stations. The meteorological data for water years 1999 through 2004 have been analyzed herein to derive the climatological characteristics of the basin.

The average annual temperature measured at Culuk Meteorological Station is around 9.7 °C with monthly averages ranging from -2.9 °C in January to 22 °C in July. The basin can be identified as a semi-arid region in terms of precipitation, and as a steppe type in terms of vegetation cover.

The monthly precipitation data measured at these stations are given in Tables 3.1 through 3.5. The data continuity was poor due to maintenance problems, failure of the instrumentation, and relocation of the stations.

Table 3.1. The monthly precipitation (mm) measured in the Gölbaşı Meteorological Station.

Water year	October	November	December	January	February	March	April	May	June	July	August	September
1999	17.4	40.3	49.1	42.9	71.5	50	27.5	20.4	48.9	34.8	38	49.9
2000	44.6	165.9	49.1	42.9	71.6	50.6	31.8	15.4	50.3	33.4	38.1	49.8
2001	44.7	163.7	29.9	32.5	45.8	19.7	20.9	69.7	0.7	0.6	0.6	2.5
2002	5.6	32.6	28.6	45	59.8	20.9	4.1	18.1	34.6	12.1	26	22.0
2003	18	28.7	18.3	44	53.9							

Table 3.2. The monthly precipitation (mm) measured in the Environment Reference Laboratory Meteorological Station.

Water year	October	November	December	January	February	March	April	May	June	July	August	September
2003	Relocation of the Gölbaşı Meteorological Station					5.4	84	32.8	0	0	0.2	33
2004	50.1	12.2	68.1	68.1	34.3	23.7	49.9	55.5	37.3	10.1	28	6.4

Table 3.3. The monthly precipitation (mm) measured in the Ankara University Faculty of Agriculture Investigation Farm Meteorological Station.

Water year	October	November	December	January	February	March	April	May	June	July	August	September
1999	9.9	27.2	42.6	22.5	49.0	69.0	31.5	13.3	32.4	39.6	35.2	4.7
2000	5.6	25.6	19.6	19.0	24.4	21.6	60.6	27.0	50.4	0.0	10.6	10.6
2001	17.4	13.4	30.2	0.4	15.2	24.2	23.2	55.8	0.2	15.8	12.6	11.8
2002	47.6	57.2	113.0	5.4	16.4	39.4	65.8	0.2				
2003					38.3	11.6	59.2	54.4	1.1	5.1	0.3	13.0
2004	19.5	A	A	30.9	7.7	7.7	26.9	29.7	14.6	9.1	16.2	1.0

A: Data are not available due to maintenance problems.

Table 3.4. The monthly precipitation (mm) measured in the Culuk Meteorological Station.

Water year	October	November	December	January	February	March	April	May	June	July	August	September
1999	0.9	2.3	0.8	1.2	1.3	0.3	0.4	0.1	1.3	30.3	77.5	19.9
2000	64.6	31.0	0.7	0	0	0	97.3	8.9	28.4	0	15.9	6.3
2001	12.9	17.0	24.2	1.7	15.4	28.9	26.7	74.1	0	8.7	13.3	8.4
2002	0.1	75.5	138.1	8.5	8.7	38.1	84.5	31.0	0	0.2	26.4	33.9
2003	12.9	25.4	11.7	24.4	18.9	8.4	74.1	50.0	0	2.4	0	20.4
2004	20.5	4.3	67.2	45.8	10.7	8.4	39.3	23.0	17.5	6.2	12.8	0.1

Table 3.5. The monthly precipitation (mm) measured in the Tepeyurt Meteorological Station.

Water year	October	November	December	January	February	March	April	May	June	July	August	September
1999	23.0	25.4	102.9	32.4	42.2	80.5	32.8	26.5	81.6	48.5	51.7	17.3
2000	53.3	17.7	10.2	26.7	25.8	16.1	99.7	19.1	28.9	0.0	34.8	16.6
2001	18.3	27.2	43.4	0.6	15.5	12.0	24.6	98.3	0.0	4.2	21.4	9.0
2002	0.4	39.8	B	B	B	B	B	B	B	B	B	B
2003	B	B	B	B	B	B	B	B	B	B	B	B
2004	B	3.3	65.5	34.7	7.2	9.4	32.9	29.7	71.8	14.9	36.5	1.7

B: Data are not available due to the failure of the pluviograph in December 2002-October 2003.

According to the available measurements, the minimum average annual precipitation is measured as 260.6 mm in the Ankara University Investigation Farm Meteorological Station and the maximum annual precipitation is measured as 439.5 mm in the Gölbaşı Meteorological Station (together with the Environment Reference Laboratory). The arithmetic average obtained by using the average annual precipitation values obtained from the stations located in the basin is 333.9 mm (Table 3.6). The average monthly precipitation at the Gölbaşı Meteorological Station varied from 15.2 mm in July to a maximum of 73.9 mm in November. The average annual precipitation for the same period at the Culuk Meteorological Station is 261.7 mm with monthly averages changing between 9.2 to 40.5 mm in winter, whereas with an average of about 18 mm in summer. Thus, the Gölbaşı Meteorological Station received more rainfall than the Culuk Station, probably due to the micro-climatic effect of the Lakes.

Evaporation rates are measured with Class A land pan in the Gölbaşı and Culuk Meteorological Stations. After relocation of the Gölbaşı Meteorological Station, evaporation rates are measured in the Environment Reference Laboratory Meteorological Station. The monthly evaporation rates of the meteorological stations are given in Tables 3.7 through 3.9. According to the measurements obtained from these stations, the annual average evaporation is 1092.2 mm for Gölbaşı with monthly averages ranging from 47.1 mm in November to 246.5 mm in July. The annual average evaporation is 1297.4 mm for the Culuk Meteorological Station with monthly averages varying from a minimum of 57.2 mm in November to a maximum of 294.5 mm in July.

The monthly average relative humidity values at the Culuk Meteorological Station given in Table 3.10 show that the relative humidity varies from a minimum of 40.5 percent in July to a maximum of 83.6 percent in January. The mean annual relative humidity for the period of record is determined as 60 percent.

Table 3.6. The mean monthly and annual precipitation measured in the meteorological stations found in the Lake Mogan and Eymir Basin (mm).

Name of the Station	Years of Record	MONTH												Annual Precipitation
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Gölbaşı	1999-2004	45.9	56.2	28.4	36.4	35.3	28.6	15.2	21.8	27.3	30.1	73.9	40.5	439.5
Ank. Uni. Inv.Farm	1999-2004	15.6	25.2	28.9	44.5	30.1	19.7	13.9	14.9	8.2	20	30.9	51.2	260.6
Culuk	1999-2004	13.6	9.2	14.0	53.7	31.2	9.4	7.97	24.3	14.8	18.7	25.9	40.5	261.7
Tepeyurt	1999-2004	23.6	22.7	29.5	47.5	43.4	45.6	16.9	36.1	11.2	31.5	18.4	55.5	373.9
AVERAGE														333.9

Table 3.7. The monthly evaporation (mm) measured in the Gölbaşı Meteorological Station.

Water year	October	November	December	January	February	March	April	May	June	July	August	September
1999	68.4	41.6					95.6	118.9	89.5	146.5	122	87.5
2000	64.3	42.5				7.6	62.1	81.2	85.3	187	114.6	81.1
2001	79.8	18.8					98.8	140.3	263.5	219	157.1	123.9
2002	87.5						80.4	121.6	191.2	246.8	239.1	116.4
2003	65.9	37				3.4						

Table 3.8. The monthly evaporation (mm) measured in the Environment Reference Laboratory Meteorological Station.

Water year	October	November	December	January	February	March	April	May	June	July	August	September
2003							182.8	117.6	212.9	366.8	346	158.1
2004	125.2	95.4					62.1	97.5	247.2	312.6	291.6	151.4

Table 3.9. The monthly evaporation (mm) measured in the Culuk Meteorological Station.

Water year	October	November	December	January	February	March	April	May	June	July	August	September
1999	136.4	48.9					96.9	140.4	171.1	314.4	272.8	149.4
2000	125.6	66.9					102.1	147.5	186.0	336.8	260.9	167.2
2001	90.4	67.2					98.8	139.1	263.5	345.9	281.1	203.3
2002	131.0	42.1					101.4	76.9		151.5	256.2	139.0
2003	114.7	60.5					84.1	171.5	189.7	314.3	269.4	170.1
2004	83.3	57.5					105.4	143.8	190.2	304.2	260.7	154.3

Table 3.10. The monthly humidity (%) measured in the Culuk Meteorological Station.

Water year	October	November	December	January	February	March	April	May	June	July	August	September
1999	51.5	77.5	89.9	83.1	80.8	68.3	61.7	50.2	62.9	49.6	51.7	50.0
2000	61.8	68.2	71.7	87.7	86.6	70.5	66.2	61.6	56.1	33.7	46.3	46.5
2001	59.3	50.9	82.5	80.2	70.5	55.4	55.5	60.0	37.8	39.1	43.1	40.8
2002	45.5	76.5	87.5	85.0	65.2	57.9	72.5	57.7		37.2	48.0	55.3
2003	54.3	65.3	82.0	76.4	82.8	70.0	65.5	49.3	56.3	42.3	36.5	50.6
2004	53.9	70.6	85.5	89.2	73.5	54.8	54.9	56.5	52.7	40.9	45.2	46.0

Due to the poor coverage and discontinuity of the available short term meteorological data in the basin, an attempt was made to relate the available precipitation and evaporation data with the long-term (1981-2004) data of the Ankara Meteorological Station. No statistically acceptable relation could be obtained between the stations which may be due to the micro-climate effect produced by the presence of the lakes in the basin. For the water years 1999-2004, the Gölbaşı Station received 23 percent more rainfall per annum than the Ankara Station. The average annual temperature measured at Ankara Meteorological Station is around 11.7 °C with monthly averages changing between -0.1 to 7.0 °C in winter, whereas with an average of about 20.5 °C in summer. The annual average evaporation at Ankara Station is 1109.8 mm with monthly averages changing between 25.9 mm in November and 243.3 mm in July.

3.3 Geology

The geological studies in the basin are largely conducted by the MTA in regard to the Environmental Geology and Natural Resources Potential Studies for the City of Ankara. The following geological information is mainly summarized from the work of Akyürek et al. 1997. The geological map of the basin is given in Figure 3.3. The stratigraphic sequence in the basin is shown in the generalized columnar section given in Figure 3.4.

The sedimentary succession in the northern part of the basin begins with the products of the green-schist intensity of metamorphism of Early Triasssic age (the Emir formation (Trae): Erol 1956; Çalgın 1973; Norman 1973; Akyürek et al. 1983). The products comprise muscovite-quartz schist, cerrisite-chlorite-quartz schist, cerrisite-chlorite schist, phyllite and quartz-albite- chlorite schist. The lower boundary of the formation is not clear in the study area. Upward in the section the metamorphic rocks are followed by the metaclastic rocks consisting of metaconglomerate, metasandstone, mudstone, sandy limestone, limestone,

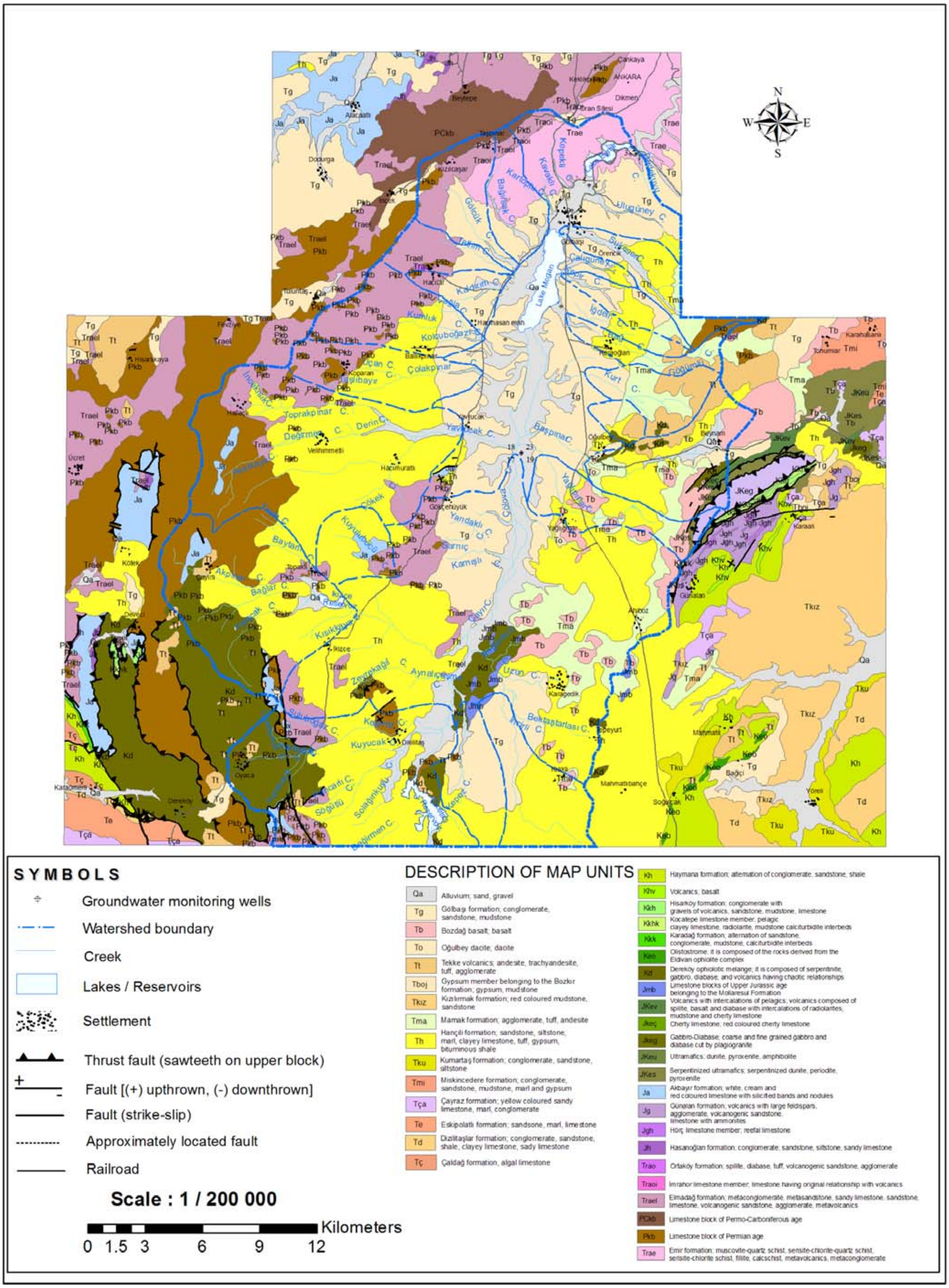

Figure 3.3. Geological map of the basin (MTA, 1997).

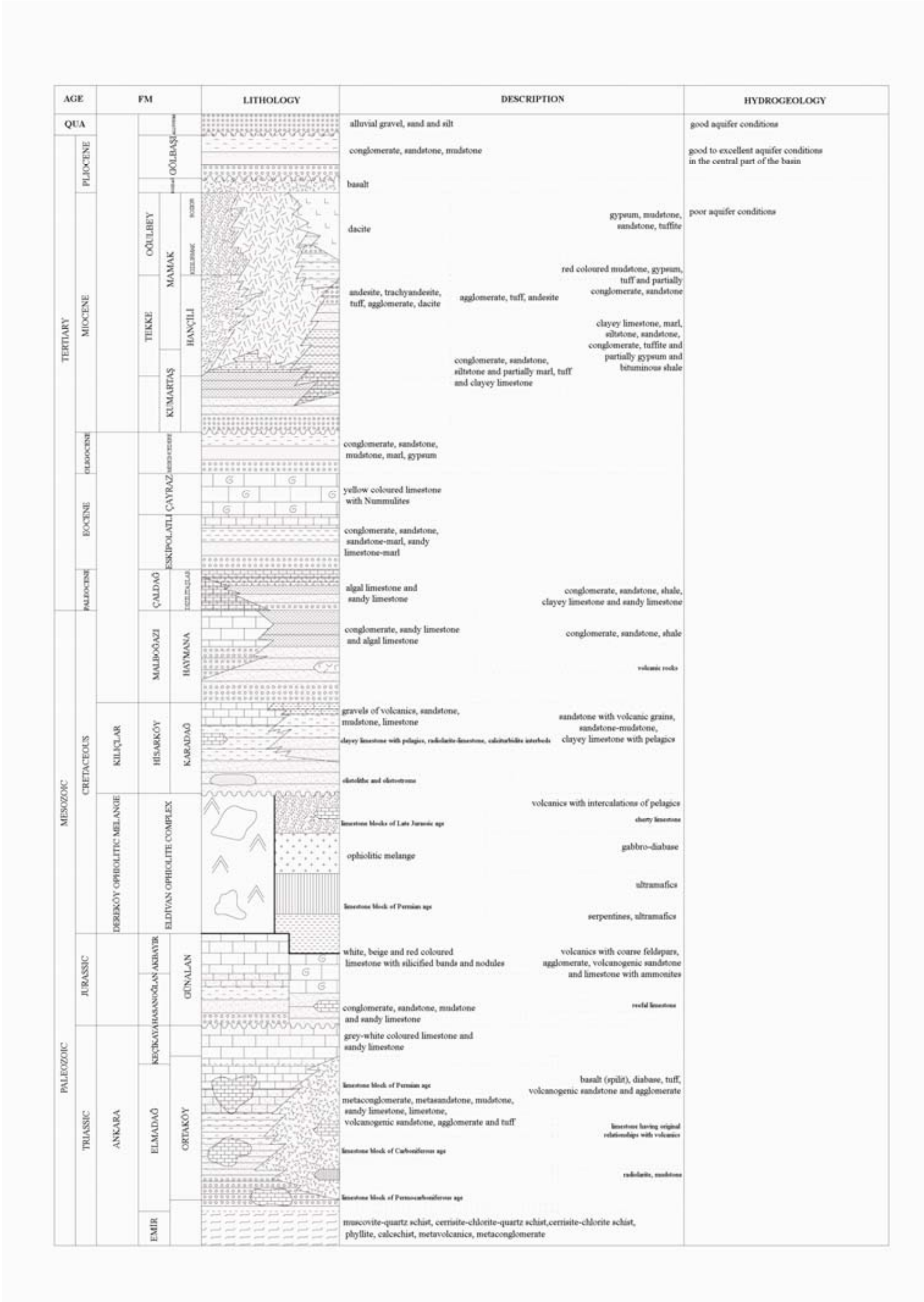

Figure 3.4. Generalized columnar section of the Mogan and Eymir Lakes Basin (MTA, 1997).

volcanogenic sandstone, agglomerate and tuff of Middle and Late Triasssic age (the Elmadağ Formation (Trael): Erol 1956; Schmit 1960; Norman 1973; Çalgın et.al. 1973; Bingöl et al. 1973; Batman 1978; Erk 1977, 1980; Akyürek et al. 1980). The formation includes limestone blocks of Permian age (Pkb) and Permo-Carboniferous age (PCkb) in different dimensions. These metaclastic rocks are in lateral transience with the Middle and Late Triasssic aged basalt (spilit), diabase, tuff and volcanogenic sandstone and agglomerate (the Ortaköy Formation (Trao): Bingöl 1973; Çalgın 1973; Akyürek et al. 1979, 1983). The limestones having original relationship with the volcanics and radiolarite-mudstone are differentiated as İmrahor limestone member (Traoi) and Radiolarite member (Traor) in the Ortaköy Formation, respectively. The grey-white coloured limestone and sandy limestone of Middle-Late, Late Triasssic age outcrops in transience with the Elmadağ Formation and the Ortaköy Formation (the Keçikaya Formation (Trak): Keskin et al. 1975; Akyürek et al. 1978, 1983). The Triassic age of Ankara group (comprising the Emir, Elmadağ, Ortaköy and Keçikaya formations) is unconformably overlain by the Lias volcanics with coarse feldspars, agglomerate, volcanogenic sandstone and limestone with ammonites (the Günalan Formation (Jg): Müller 1957; Akyürek et al. 1979, 1980). The limestone existing in the Günalan Formation is differentiated as Hörç limestone member (Jgh) according to the distinct lithologic character. The sequence of conglomerate, sandstone, mudstone and sandy limestone of Lias age unconformably overlies the Elmadağ Formation (the Hasanoğlan Formation (Jh: Akyürek et al. 1982). The white, beige, and red coloured limestone with silicified bands and nodules of Late Jura- Early Cretaceous age is in transience with the Hasanoğlan Formation (Akbayır Formation (Ja): Akyürek et al. 1982).

Unconformably above the sedimentary sequence, ophiolites of Late Jurassic-Cretaceous age are present. The ophiolites outcropping in the region according to the internal and stratigraphic characteristics are differentiated as partly preserved internal structured Jura-Early Berracien age of Eldivan ophiolite complex (JKe), Early Cretaceous age of Dereköy ophiolitic mélange (Kd) and Olistolithe and Olistostroms (Keo) derived from Dereköy ophiolitic mélange. The Eldivan ophiolite complex, comprising serpentinized ultramafics, ultramafics, gabbro-diabase and volcanics with intercalations of pelagics, exposed in the Middle Anatolia is considered as the internal structure preserved ocean crust material (Akyürek et al. 1979; 1981). The serpentinized ultramafics (JKes) are mainly composed of serpentinized dunite, peridotite, pyroxenite. The volcanics with intercalations of pelagics (JKev) generally in pillow type lava flows primarily consists of basalt, tuffites, volcanics composed of spilite, clayey limestone and radiolarite-mudstone. The red coloured cherty limestone in the volcanics with intercalations of pelagics is identified as cherty limestone (JKeç) in the Eldivan ophiolite complex. The Dereköy ophiolitic mélange, considered as the lateral transgressive to the Eldivan ophiolite complex, comprises serpentinite, gabbro, diabase, radiolarite, limestone block of Permian age (Pkb) and limestone blocks of Late Jurassic age belonging to Mollaresul Formation (Jmb).

In the southwestern part of the basin, the succession begins with the Cenomanian-Campanian age of sedimentary, volcano-sedimentary and volcanic rocks (the Kılıçlar group, comprising the Hisarköy and Karadağ (Kkk) formations: Akyürek et al. 1982, 1984). The Eldivan ophiolite complex is unconformably overlain by the sequence of the Cenomanian-Campanian age of gravels of volcanics, sandstone, mudstone and limestone (the Hisarköy Formation (Kkh): Akyürek et al. 1979, 1981). The sequence of the Cenomanian-Campanian age of clayey limestone with pelagics, radiolarite-limestone and calciturbidite interbeds is observed in the Hisarköy Formation as a distinct lithologic character (the Kocatepe limestone member (Kkhk): Akyürek et al. 1982, 1984). The sequence of the Cenomanian-Campanian age of sandstone with volcanic grains, sandstone-mudstone, clayey limestone with pelagics is laterally transgressive with the

Hisarköy Formation (the Karadağ Formation (Kkk): Norman 1972; Birgili et al. 1975; Ünalan et al. 1976; Akyürek et al. 1979, 1981). The succession continues upward across transience with the sequence of the Maastrichtian age of conglomerate, sandstone and shale (the Haymana Formation (Kh): Norman 1972; Birgili et al. 1975; Çapan&Buket 1975; Akyürek et al. 1982, 1984, 1988). The volcanic rocks outcropping in the Haymana Formation is differentiated as Volkanitler (Khv) according to the distinct lithologic character. The sequence of the Late Maastrichtian age of conglomerate, sandy limestone and algal limestone is laterally transgressive to the Haymana Formation (the Malboğazı Formation (Km): Ünalan et al. 1976; Hakyemez et al. 1986; Akyürek et al. 1988). Upward in the section, the sedimentary deposits are followed by the Monsian algal limestone and sandy limestone (the Çaldağ Formation (Tç): Yüksel 1970; Akarsu 1971). The sequence of the Paleocene age of conglomerate, sandstone, shale, clayey limestone and sandy limestone is laterally transgressive to the Çaldağ Formation (the Dizilitaşlar Formation (Td): Schmidt 1960; Çapan and Buket 1975; Ünalan et al. 1976). Conformably above them, the sequence of the Early Eocene age of conglomerate, sandstone, sandstone-marl, sandy limestone-marl is present (the Eskipolatlı Formation (Te): Yüksel 1970; Ünalan et al. 1976; Batman 1978). The sequence of the Late Eocene age of yellow coloured limestone with Nummulites indicating shallow marine deposition overlies the Eskipolatlı Formation (the Çayraz Formation (Tça): Norman 1972; Birgili et al. 1975; Ünalan et al. 1976; Yoldaş 1982; Akyürek et al. 1982,1984, Hakyemez et al. 1986). The sedimentary deposits are overlain by the sequence of Oligocene age of conglomerate, sandstone, mudstone, marl and gypsum (the Miskincedere Formation (Tmi): Norman 1972; Çalgın et al. 1973; Çapan&Buket 1975; Birgili et al. 1975; Akyürek et al. 1982, 1984). Unconformably above them, the sequence of Early-Middle Miocene age of conglomerate, sandstone, siltstone and partially marl, tuff and clayey limestone exists in the section (the Kumartaş Formation (Tku): Çalgın et al. 1973; Arıkan 1975; Ünalan et al. 1976; Akyürek et al. 1980, 1984). The sequence of clayey limestone, marl, siltstone, sandstone, conglomerate, tuffite and partially gypsum and bituminous shale is laterally transgressive to the Kumartaş Formation (the Hançili Formation (Th): Erol 1956; Çalgın et al. 1973; Akyürek et al. 1982, 1984). The deposition environment is of the deltaic-lacustrine type. The Late Miocene age of andesite, trachyandesite, tuff, agglomerate and dacite as the products of the volcanism are observed in the Kumartaş and Hançili formations (the Tekke volcanics (Tt): Çalgın 1973; Akyürek et al. 1980, 1982, 1984). Laterally transgressive with the Tekke volcanics and the Hançili Formation, the Late Miocene age of agglomerate, tuff and andesites outcrop in the basin (the Mamak Formation (Tma): Çalgın et al. 1973; Akyürek et al. 1980). The Late Miocene age of red coloured mudstone, gypsum, tuff and partially conglomerate and sandstone conformably overlie the Hançili and Kumartaş formations (the Kızılırmak Formation (Tkız): Birgili et al. 1975). Upward in the section, the Late Miocene age of the sequence of gypsum, mudstone, sandstone and tuffite is laterally transgressive to the Kızılırmak Formation (the Bozkır Formation (Tboj): Birgili et al. 1975). Forming the upper layers of the Tekke volcanics, the Miocene age of dacites cuts the Mamak and Hançili formations (the Oğulbey Dacites (To): Kalkan et al. 1992). The Miocene age of volcanic, sedimentary and volcano-sedimentary rocks are conformably overlain by the Pliocene age of the basalts with plenty of gas voids (the Bozdağ Basalt (Tb): Çalgın et al. 1973; Akyürek et al. 1980, 1982, 1984). Unconformably above them, the Pliocene age of conglomerate, sandstone and mudstone indicating a lacustrine-type environment is present in the basin (the Gölbaşı Formation (Tg): Çalgın et al. 1973; Akyürek et al. 1980, 1982, 1984). The succession ends with the Quaternary age of gravel, sand, and silt fragments observed in the lakebeds of Mogan and Eymir and delta of Çölova Creek (the Alluvium).

3.4 Water Resources

3.4.1 Surface Water Resources

The drainage network of the Mogan and Eymir Lakes Basin is shown in the drainage map given in Figure 3.5. The lakes are fed by several streams but the majority of these are ephemeral in nature; they do not have continuous flow in summer and early fall. The stream order and drainage density of the basin are 4^{th} order and 5.26, respectively.

The creeks which feed Lake Mogan are Çölova, Yavrucak, Sukesen and Başpınar and other nine small creeks. Permanent discharge measuring stations equipped with automatic water level recording instruments were constructed over the major creeks (Çölova, Yavrucak, Sukesen, Başpınar). Discharge rate gauging stations are shown in the drainage pattern map of the basin given in Figure 3.5. Discharges of the creeks have been measured on a regular basis by the technical staff of EİEİ (General Directorate of Electrical Power Resources Survey and Development Administration). The discharge volumes of the creeks flowing into Lake Mogan for water years 1999 through 2004 are given in Table 3.11. The discharge hydrographs of each gauging station for the same period are given in Appendix A. The discharge volumes varied from 3.09×10^6 m^3/year in 2004 to 17.4×10^6 m^3/year in 2000, the average volume being 10×10^6 m^3/year.

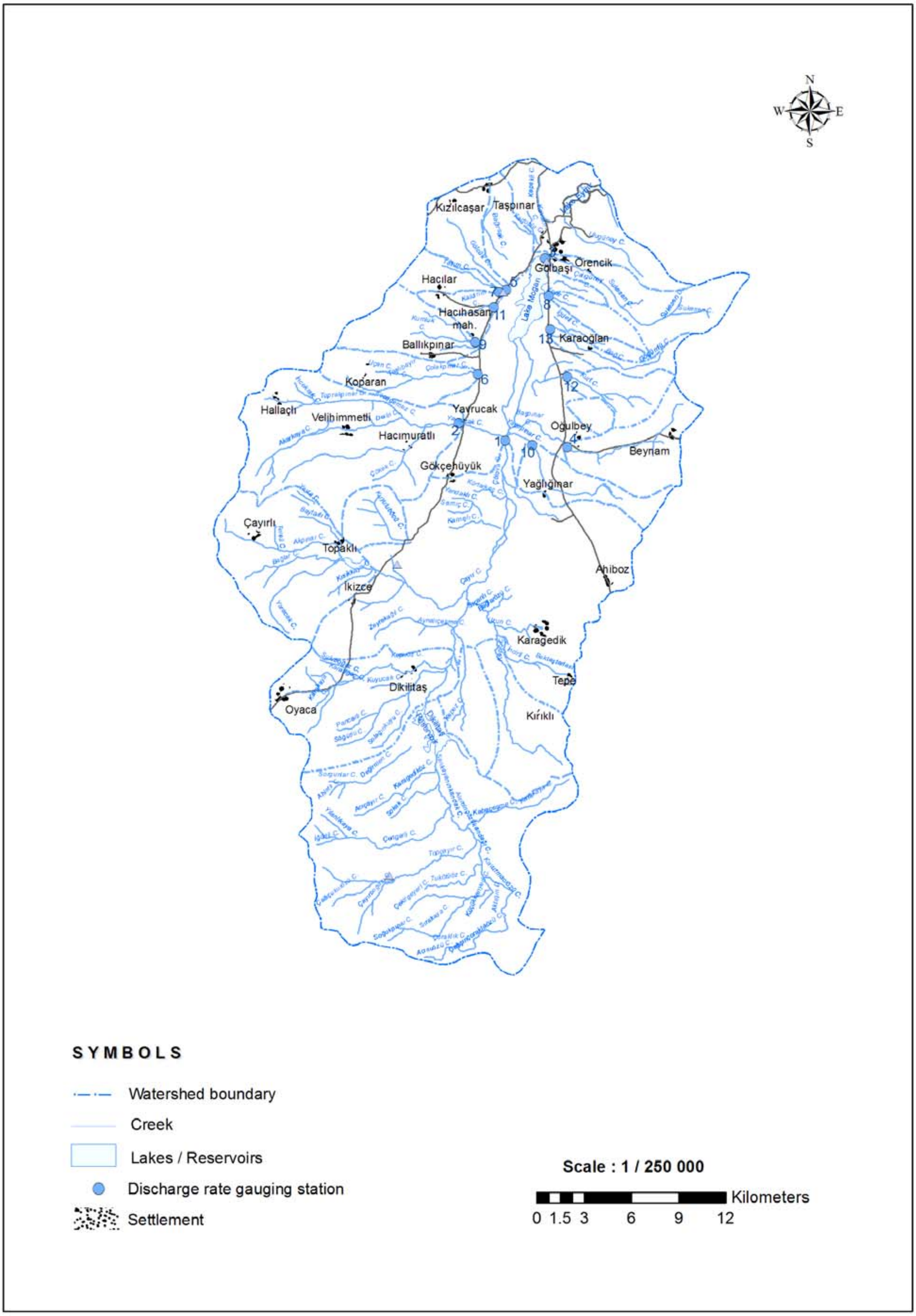

Figure 3.5. Drainage map of the basin.

Table 3.11. Discharge rates of the creeks flowing into Lake Mogan in terms of water year.

Number	Name of the creek	Catchment area (km^2)	1999 water year, $10^6 m^3$	2000 water year, $10^6 m^3$	2001 water year, $10^6 m^3$	2002 water year, $10^6 m^3$	2003 water year, $10^6 m^3$	2004 water year, $10^6 m^3$	Total Discharge, $10^6 m^3$
1	Çölovası Creek_Yavrucak	82.46	4.111	10.788	2.61	1.98	6.308	0.23	26.027
2	Yavrucak Creek_Yavrucak	88.57	3.658	4.364	0.914	5.591	3.243	1.614	19.384
3	Sukesen Creek_Gölbaşı	32.13	1.126	1.103	0.68	1.475	1.353	0.863	6.60
4	Başpınar Creek_Oğulbey	31.38	1.561	0.712	0.419	0.089	0.177	0.025	2.983
5	Gölcük Creek_Menfez 1	19.51	0.797	0.234	0.373	0.879	0.481	0.181	2.945
6	Çolakpınar Creek	24.10	0.318	0.064	0.076	0.053	0.035	0	0.546
7	Tatlım Creek_Hacılar	10.47	0.202	0.035	0.118	0.039	0.056	0.057	0.507
8	Kepir Creek	8.95	0.173	0.047	0.048	0.051	0.06	0.059	0.438
9	Kumluk_2 Creek	25.21	0.04	0.026	0.039	0.02	0.048	0.031	0.204
10	Yağlıpınar Creek_Yağlıpınar	19.27	0.1	0.021	0.009	0.022	0.019	0.012	0.183
11	Kaldırım Creek_Hacılar	9.04	0.054	0.022	0.055	0.011	0	0	0.142
12	Kurt Creek	15.12	0.008	0.008	0	0.002	0	0.009	0.027
13	Bağ Creek	9.66	0.002	0.008	0	0	0	0.004	0.014
	Total	375.87	12.15	17.43	5.34	10.21	11.78	3.09	60.00

3.4.2 Lakes and Reservoirs

Surface water bodies in the basin consist of two natural lakes, Mogan and Eymir, and two artificially constructed reservoirs, namely Dikilitaş and Ikizce (Figure 3.5). Mogan and Eymir Lakes are alluvial barrier lakes that are produced by the deposition of material from Sukesen and Alicin Creeks, respectively (METU, 1995). A wetland between these lakes is considered to be representative of this natural barrier where presently an abandoned municipal waste disposal site is located.

The surface area of the both lakes changes with respect to seasons as water levels in the lakes fluctuate. Lake Mogan occupies an area of approximately 6 km^2 with a perimeter length of 16 km. The width and the length of Lake Mogan are approximately 1 km and 6 km, respectively. Lake Eymir, located on downstream from Lake Mogan, is relatively small with a surface area of 1.25 km^2. It has a perimeter length of 9.4 km and a shape that looks like a widened river channel with a length and width of 4 km and 0.3 km, respectively. The characteristics of Lakes Mogan and Eymir are given in Table 3.12. The stages versus volume and area relationships for both lakes are given in Figures 3.6 through 3.9.

Table 3.12. General characteristics of Lakes Mogan and Eymir (METU, 1995).

Lakes	**MOGAN**			**EYMİR**		
Water level (masl)	Minimum	Normal	Maximum	Minimum	Normal	Maximum
	971	972	973.25	967	968.50	969.50
Volume ($10^6 m^3$)	5.04	9.47	16.12	2.16	3.88	5.2
Area (km^2)	4.77	6.08	7.65	1.05	1.25	1.39
Catchment Area (km^2)	942			942+43		
Lowest Elevation (m)	969.00			963.90		

The only natural outflow from Lake Mogan occurs by way of groundwater flows to the northeast where they feed the wetland with surface waters released from the regulator canal located at the northern end of the lake. The wetland, in turn, feeds Lake Eymir from the surface and underground to the north (METU, 1995). Lake Eymir is also fed by groundwater in other areas and outflows to the İmrahor Creek to the northeast through a collector canal. Water released from Lake Mogan feeds Lake Eymir by an artificial canal. The water level of Lake Mogan is approximately 3 m higher than that of Lake Eymir. Therefore, the flow direction is towards Lake Eymir.

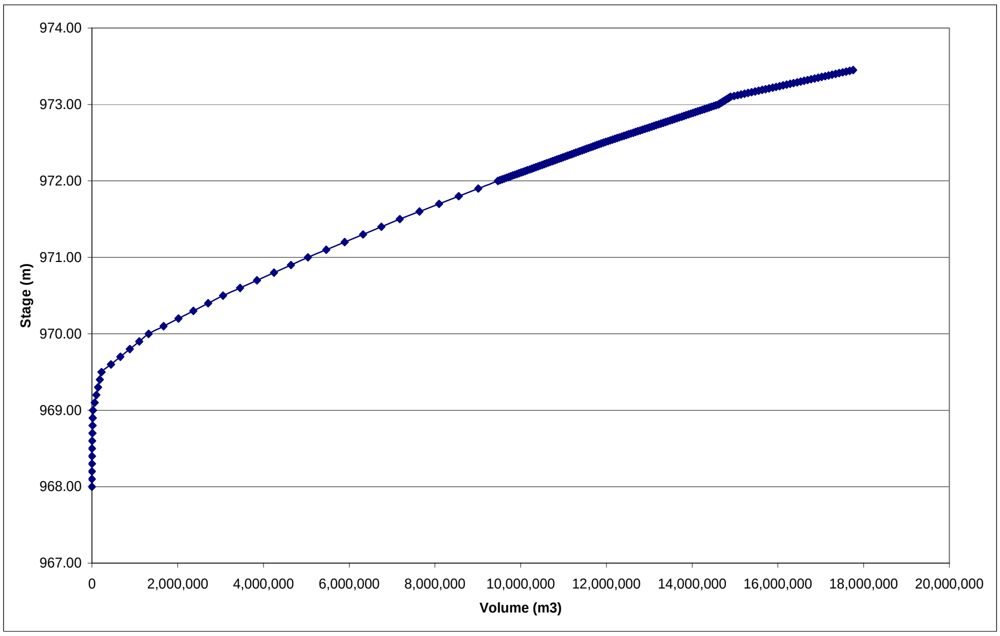

Figure 3.6. Stage versus volume relation for Lake Mogan.

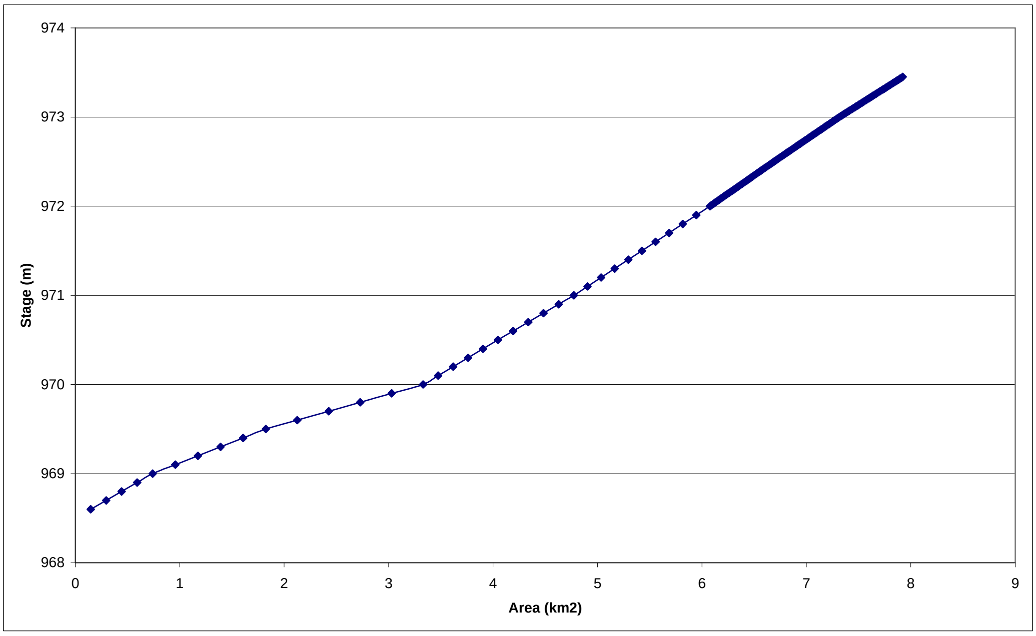

Figure 3.7. Stage versus area relation for Lake Mogan.

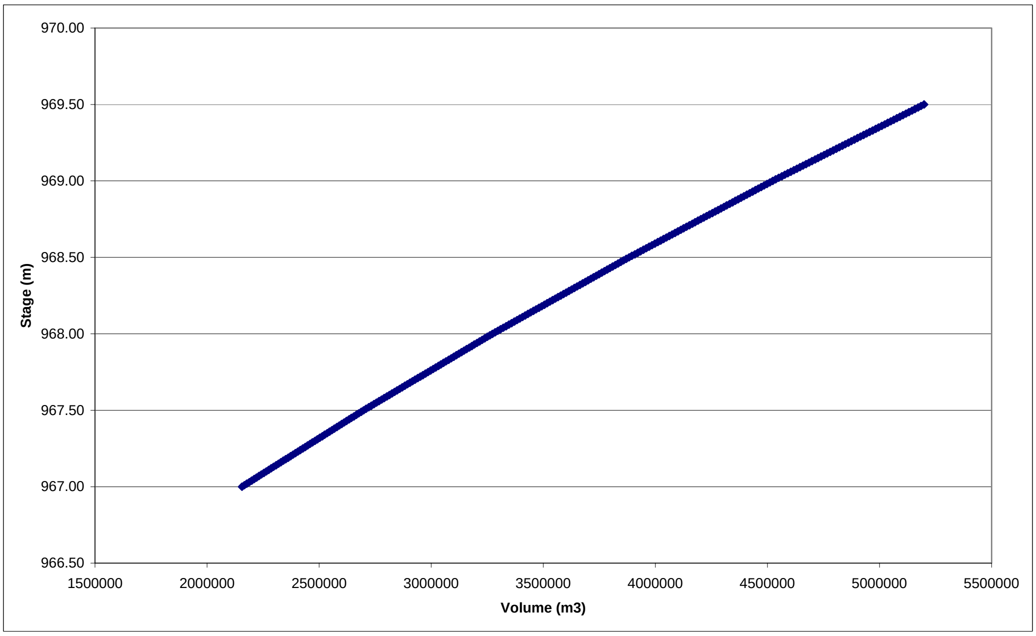

Figure 3.8. Stage versus volume relation for Lake Eymir.

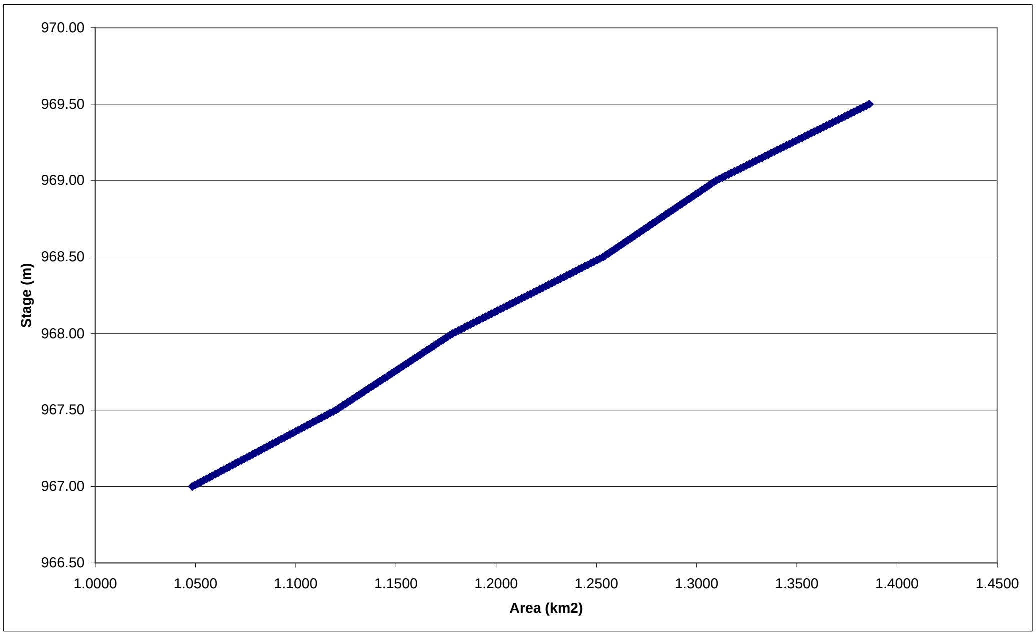

Figure 3.9. Stage versus area relation for Lake Eymir.

The water levels in both lakes are measured on a monthly basis by EİEİ. The stage hydrographs of the Lakes Mogan and Eymir for water years 1999 through 2004 are given in Figures 3.10 and 3.11, respectively. Examination of these hydrographs show that water levels in both lakes fluctuate seasonally. The average seasonal water level fluctuation in Lake Mogan is between 0.5 and 0.8 m whereas at Eymir it is between 0.5 m and 1.0 m. The maximum fluctuation occurred in 2002 water year with values of 1.4 m and 1.93 m at Lakes Mogan and Eymir, respectively. Two declining trends in water levels of the both lakes are noted with lowest levels occurring in water years 2001 and 2004 that correspond to the lowest surface water contributions to the Lake Mogan (See Table 3.11). This shows that surface water contribution is an important component in the water budget of the lakes.

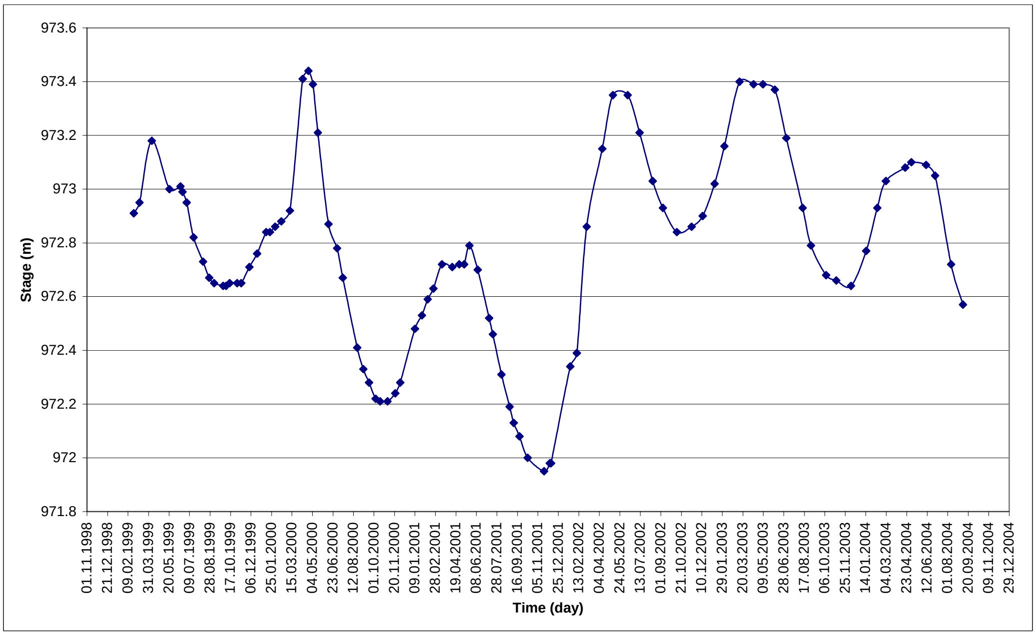

Figure 3.10. Stage hydrograph of Lake Mogan for water years 1999-2004.

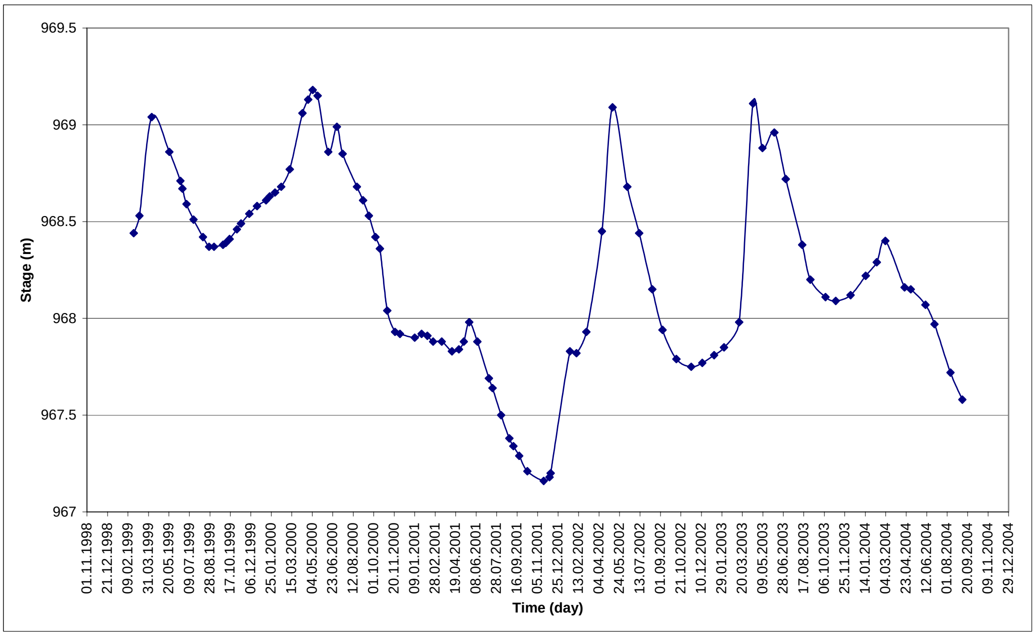

Figure 3.11. Stage hydrograph of Lake Eymir for water years 1999-2004.

The two artifical reservoirs, Dikilitaş and Ikizce, are located upstream of Lake Mogan (Fig. 3.5). The water from these reservoirs is used for irrigation. These upstream reservoirs have a significant impact on the inflow to Lake Mogan. The main characteristics of the reservoirs are given in Table 3.13. Dikilitaş reservoir is the larger of the two with an average surface area and a perimeter of 2.01 km^2 and 15.55 km, respectively. The İkizce reservoir has a surface area of 0.53 km^2 and a perimeter length of 3.88 km.

Table 3.13. Main characteristics of Dikilitaş and İkizce reservoirs.

Properties	Dikilitaş reservoir	İkizce reservoir
Catchment area (km^2)	182	63
Yearly water yield (m^3)	11 938 309	1 273 000
Total storage capacity (m^3)	10 000 000	1 273 000
Active storage (m^3)	9 079 099	1 100 000
Irrigable land (ha)	2400	400
Spillway capacity (m^3/s)	70	-

3.4.3 Groundwater Resources

3.4.3.1 Water Bearing Units

The evaluation of the lithologic character of the geological formations indicates that the basement schists (Emir Formation) outcropping in the northern part of the basin form a very poor aquifer. The Dereköy Formation consisting of ophiolitic mélange outcrops in the southwest and forms also a poor aquifer. The Hançili Formation consisting of alternations of sandstones, siltstones, marl, clayey limestone and tuffs covers large areas in the basin and form weak to medium aquifer. The Gölbaşı Formation cropping out in the central part of the basin consists of weakly cemented conglomerates, sandstone, and mudstones. It has a granular structure and forms an aquifer in the basin. Several wells have been drilled in this formation by private people. The Elmadağ Formation cropping out in the northwest of the basin consists of metaconglomerates, metasandstones, sandy limestones, sandstones, and limestones. This unit can also be characterized as an aquifer. The Quaternary alluvium consisting of sands, gravels, and clays crops out along the streams reaching the lakes and forms a good aquifer. This unit plays an important role in the recharge and discharge of the lake systems (METU, 1995). The Quaternary alluvium is highly heterogeneous in hydraulic character. The pumping, recovery and tracer tests conducted in a highly permeable portion of this unit by METU (1995) yielded a hydraulic conductivity of about 40 m/day in Çölova part of the basin. On the other hand, Arıgün (1994) estimated hydraulic conductivity as low as 0.4 m/day for an area in the west of the Lake Mogan.

3.4.3.2 Groundwater Pumping Wells

Groundwater in the basin is used for supplying the domestic and irrigation needs of the private people. Gölbaşı town obtains its domestic supply from the Ankara Greater Municipality pipeline system. Data corresponding to the registered private pumping wells have been examined at the Fifth District Office of the State Hydraulic Works. Approximately a total of 1100 wells are located within the basin (Figure 3.12). Most of these wells tap the Gölbaşı and Elmadağ formations. The well depths average to about 100 m with well yields generally ranging from 0.3 L/s to 2 L/s. However, well yields as high as 3 to 5 L/s are also noted in wells tapping the Gölbaşı Formation.

3.4.3.3 Groundwater Monitoring Wells

The information regarding groundwater levels in the basin is obtained from a set of monitoring wells drilled by METU (1995). Twenty-three wells with a total depth of 336 m were constructed along the perimeter of both lakes. Nested wells were also drilled at some critical locations to understand the vertical gradients. The construction activities that have taken place lately in the basin damaged most of these monitoring wells. Currently, there are only 11 wells available for monitoring. The existing 11 groundwater monitoring wells are numbered as: 1 (E0648588), 2 (E0648589), 3 (E0648590), 4 (E0648591), 5 (E0648592), 9 (E0648596), 17 (E0648604/A), 18 (E0648605), 19 (E0648606), 20 (E0648607), and 23 (E0648604/B). The location of the existing groundwater monitoring wells is shown in Figure 3.13 and the information related to the construction details of all monitoring wells is summarized in Table 3.14.

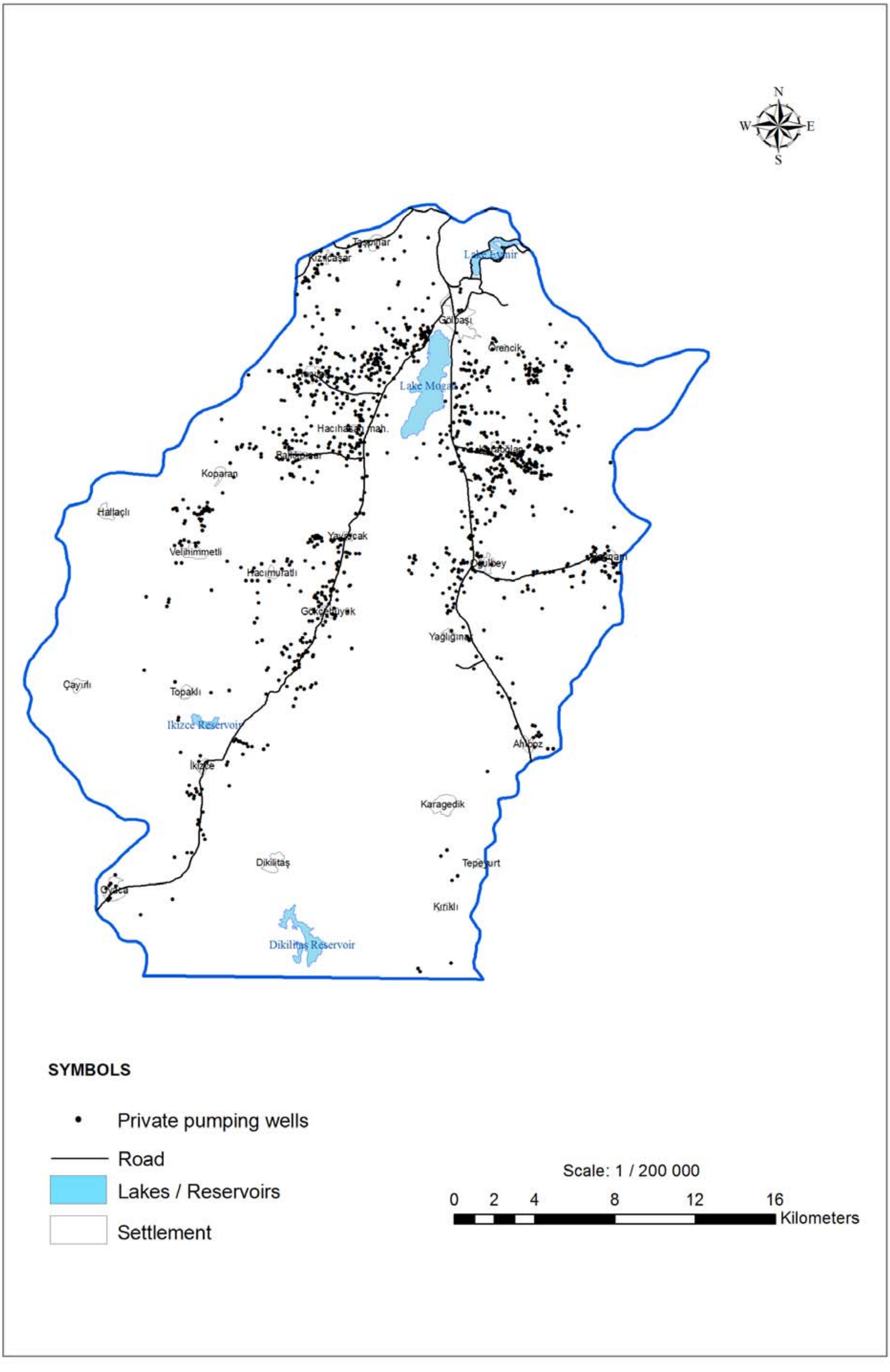

Figure 3.12. Location of the private pumping wells in the basin.

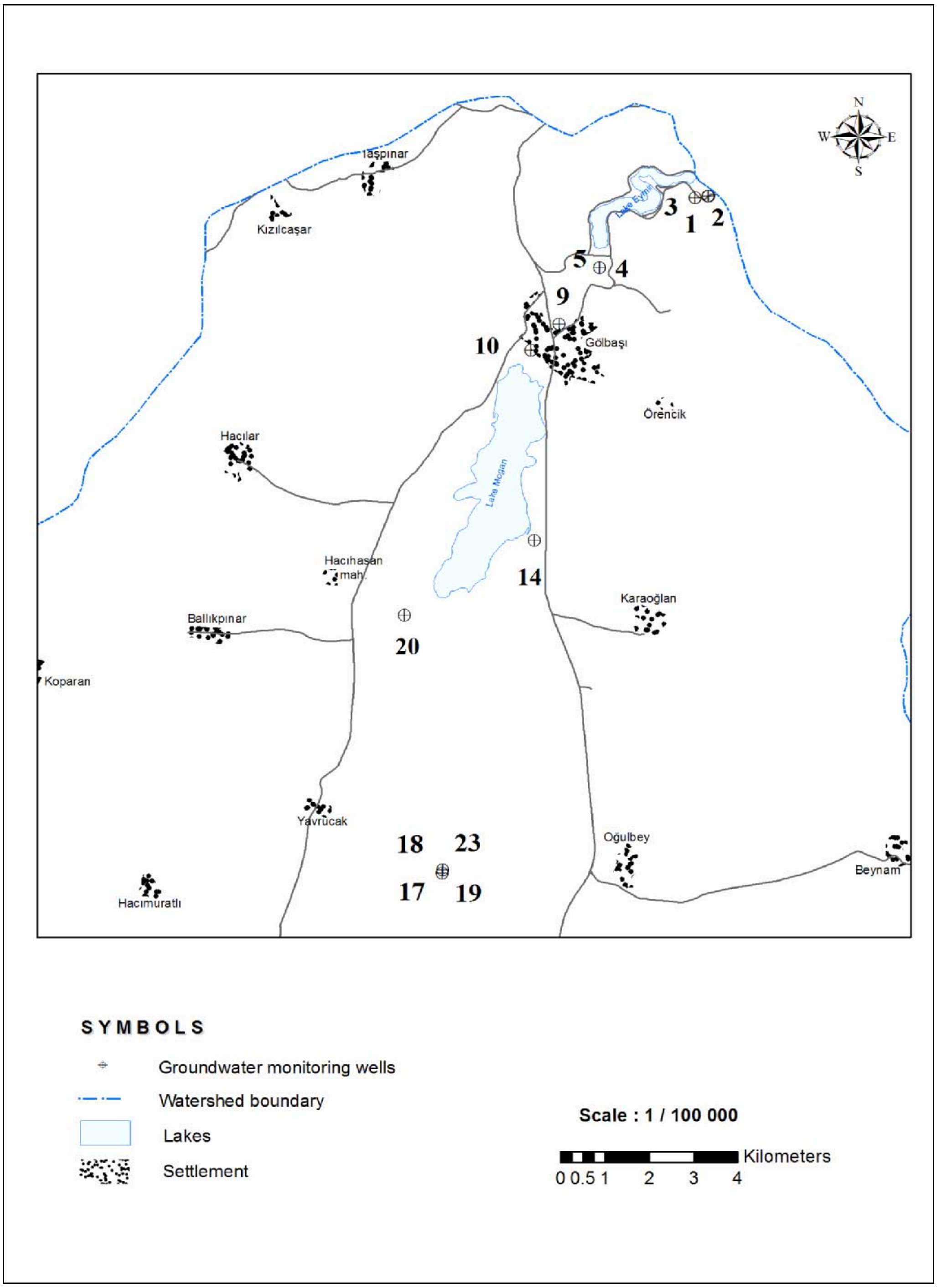

Figure 3.13. Location of the existing groundwater monitoring wells in the basin.

Table 3.14. Information about the groundwater monitoring wells (METU, 1995).

METU Well No:	DSİ Well No:	Ground Level (m)	Drill Depth (m)	Drill Diameter (inch)	Pipe Diameter (inch)	Screen Length (m)
1	E0648588	973.226	29.0	9 7/8	4	2
2	E0648589	973.243	10.0	12 1/4	8	2
3	E0648590	969.740	10.0	9 7/8	4	2
4	E0648591	971.219	4.0	9 7/8	4	2
5	E0648592	971.220	35.0	9 7/8	4	2
6	E0648593	971.770	6.0	9 7/8	4	2
7	E0648594	971.745	6.0	9 7/8	4	2
8	E0648595	973.703	10.0	9 7/8	4	2
9	E0648596	971.051	10.0	9 7/8	4	2
10	E0648598	973.321	10.0	12 1/4	8	2
11	E0648597	973.322	35.0	12 1/4	4	2
12	E0648599	-	15.0	12 1/4	-	-
13	E0648600	976.889	10.0	9 7/8	4	2
14	E0648601	974.077	9.0	9 7/8	4	2
15	E0648602	974.177	17.0	9 7/8	4	2
16	E0648603	973.344	10.0	12 1/4	4	2
17	E0648604/A	982.578	15.0	12 1/4	8	2
18	E0648605	982.621	35.0	9 7/8	4	2
19	E0648606	982.628	15.0	9 7/8	4	2
20	E0648607	974.376	10.0	9 7/8	4	2
21	E0648608	973.821	10.0	9 7/8	4	2
22	E0648609	976.708	10.0	12 1/4	4	2
23	E0648604/B	982.603	15.0	9 7/8	4	2

3.4.3.4 Groundwater Level Fluctuations

The response of groundwater system to various hydraulic mechanisms is best represented by the seasonal fluctuation of groundwater elevations. In the aim of specifying the groundwater fluctuations and the relation between the lakes and groundwater, the groundwater fluctuations with the lake levels are given in the

Appendix B for water years 1999 through 2004. Generally the fluctuations of groundwater levels are in good harmony with the fluctuations of lake levels.

A typical groundwater level hydrograph with the rainfall hyetograph is shown in Figure 3.14 for well no: 19. The groundwater level hydrographs together with rainfall hyetographs for all the other wells are given in Appendix C. The examination of these graphs show that generally groundwater elevations continuously rise with the beginning of the heavy rains in October and reach the highest levels in the middle of May. The decline in the groundwater elevations begin in June. It can be seen that the seasonal fluctuations in water levels vary between 0.5 m and 1 m. This is noted to be similar order of magnitude with the fluctuations of the lake levels. It is also seen that a declining trend is observed in most monitoring wells for the period of record.

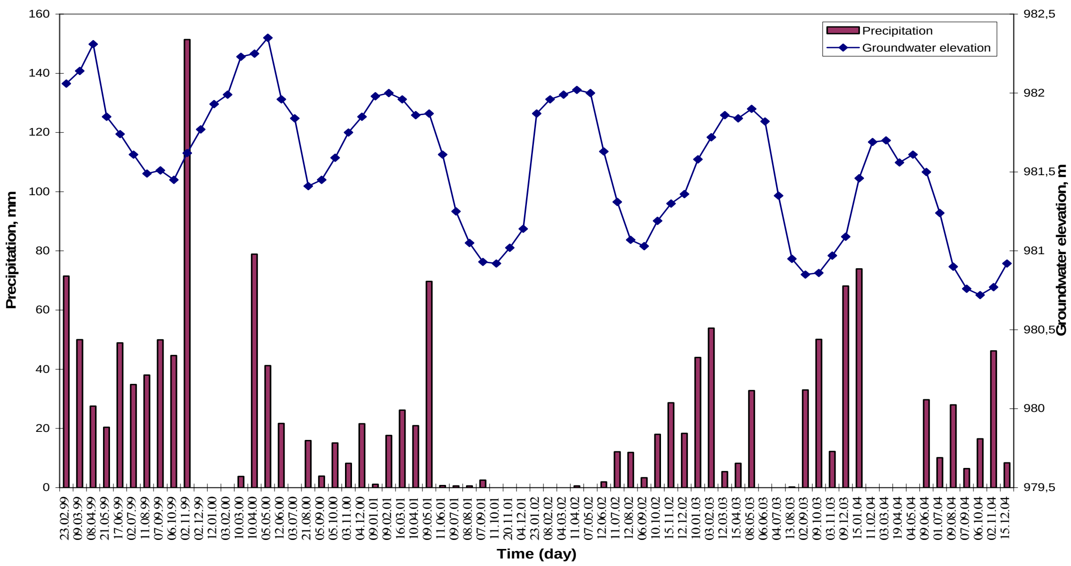

Figure 3.14. The relation between precipitation and groundwater elevation in Well no: 19.

CHAPTER 4

GROUNDWATER FLOW MODEL

4.1 Modeling Objectives

A numerical groundwater flow model of the study area has been developed to understand the groundwater flow patterns in the area, the interaction between the lakes and the aquifer system and to verify the conceptual hydrogeological understanding of the study area.

A numerical model is based on assumptions and approximations that simplify the actual system and cannot simulate exactly the inherent complexity of the geohydrologic frame-work. The results of the simulation are an approximation or an expectation of actual conditions and are only as accurate or realistic as the assumptions and data used in its development.

The numerical MODFLOW (Harbaugh and McDonald, 2000) model, which uses a finite difference approximation method, was used to simulate groundwater flow in the study area. Argus ONE (1997) software was used as pre- and post processor. The modeling process for the current study involved defining the conceptual model of the study area, model grid, model boundaries, aquifer and lake properties, recharge and discharge.

4.2 Conceptual Model of the Study Area

The conceptual understanding of the hydrogeologic system is the first step in developing a reliable groundwater model of the study area. The evaluation of the relationship between water levels in the lakes and the aquifer system would clarify the interaction between the two systems. To that end, the graphs showing the fluctuations of lake and groundwater levels are examined in various parts of the basin.

The relations between the groundwater elevations and the lake levels in the region extending from the upstream of Lake Mogan in the south to the downstream of Lake Eymir in the north are shown in Figures 4.1, 4.2, and 4.3. Figure 4.1 indicates the water levels of the wells located in the upstream of Lake Mogan in the Çölova subbasin (wells no: 17, 18, 19, 20, 23) and the Lake Mogan's water levels. The harmony between the groundwater elevations and the Lake Mogan's water levels reveals the relation between two systems and the discharge of the groundwater system to the Lake Mogan. The magnitude of this discharge is directly proportional with the head difference between the two systems and the lakebed lekance.

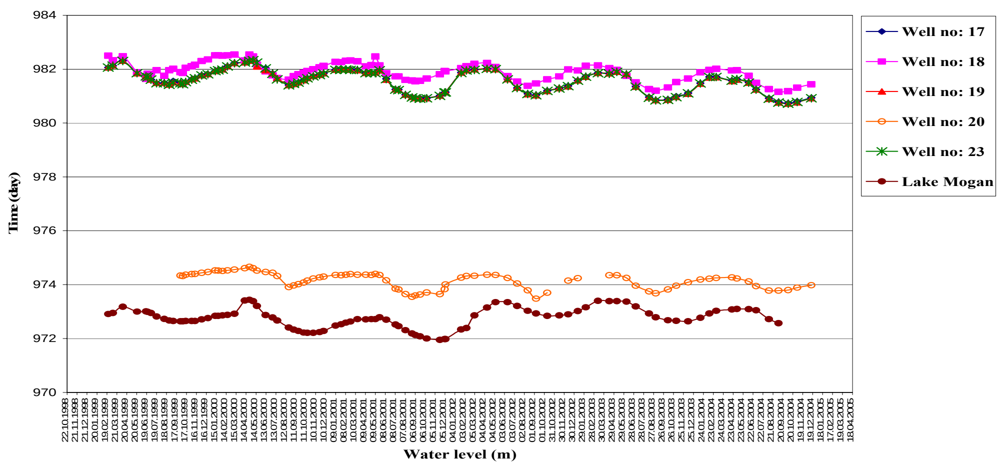

Figure 4.1. The relation between groundwater elevation of wells located in the upstream of Lake Mogan and Lake Mogan's water level.

Figure 4.2 shows the water levels of the wells located between Lake Mogan and Lake Eymir and the lakes' levels. The hydraulic heads observed in both systems delineate a discharge from Lake Mogan to Lake Eymir through the groundwater system.

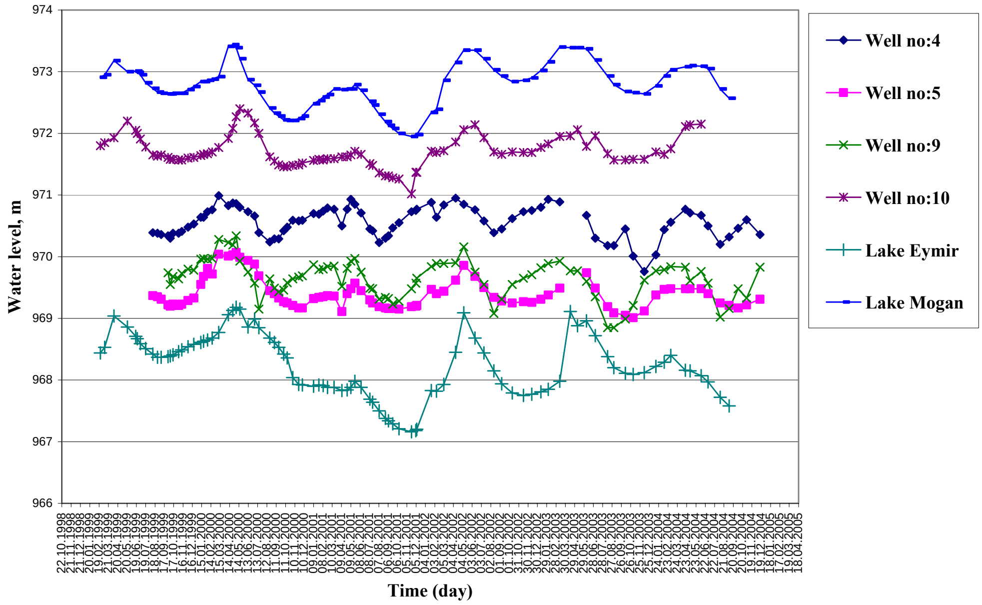

Figure 4.2. The relation between groundwater elevation of the wells located between Lake Mogan and Lake Eymir and lake water levels.

Figure 4.3 shows the water levels of the wells located in the downstream of Lake Eymir (wells: 1, 2, 3) and Lake Eymir's water levels. The higher heads observed in Lake Eymir indicates a discharge from the lake to the groundwater system in the northern part of the basin.

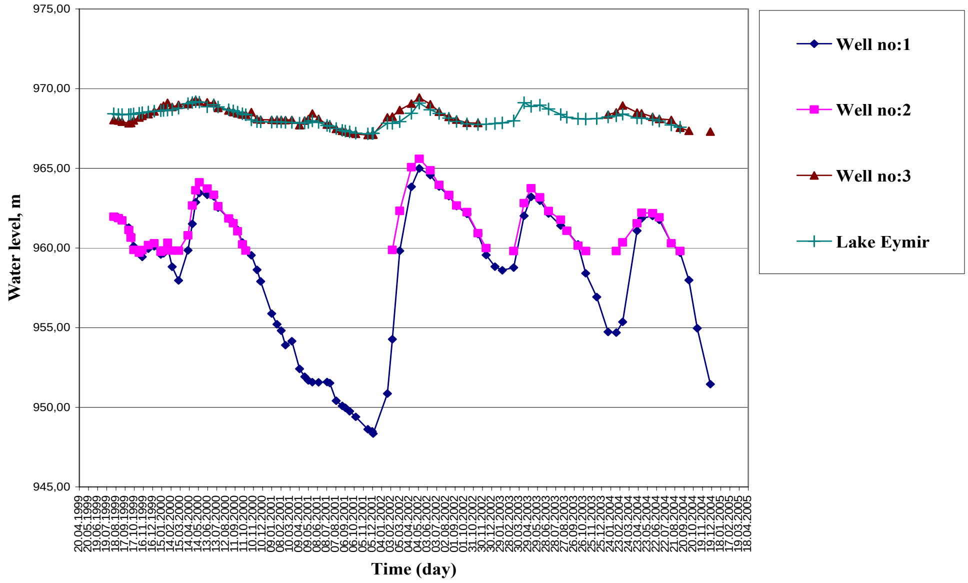

Figure 4.3. The relation between groundwater elevation of the wells located in the downstream of Lake Eymir and Lake Eymir's water levels.

In a similar way, the examination of the relation between the groundwater elevations in the nested wells and the lake levels clarifies the conceptual understanding of the study area better (Figure 4.4). In the upstream of Lake Mogan, the hydraulic heads in the deep well 18 and shallow well 19 are greater than the Lake Mogan's water level (Figure 4.5). Furthermore, the heads in the deep well 18 is greater than the shallow well 19, indicating an upward gradient. Thus, these relations delineate a discharge from the groundwater system to the Lake Mogan as postulated in Figure 4.4. In the downstream of Lake Mogan, lake level is

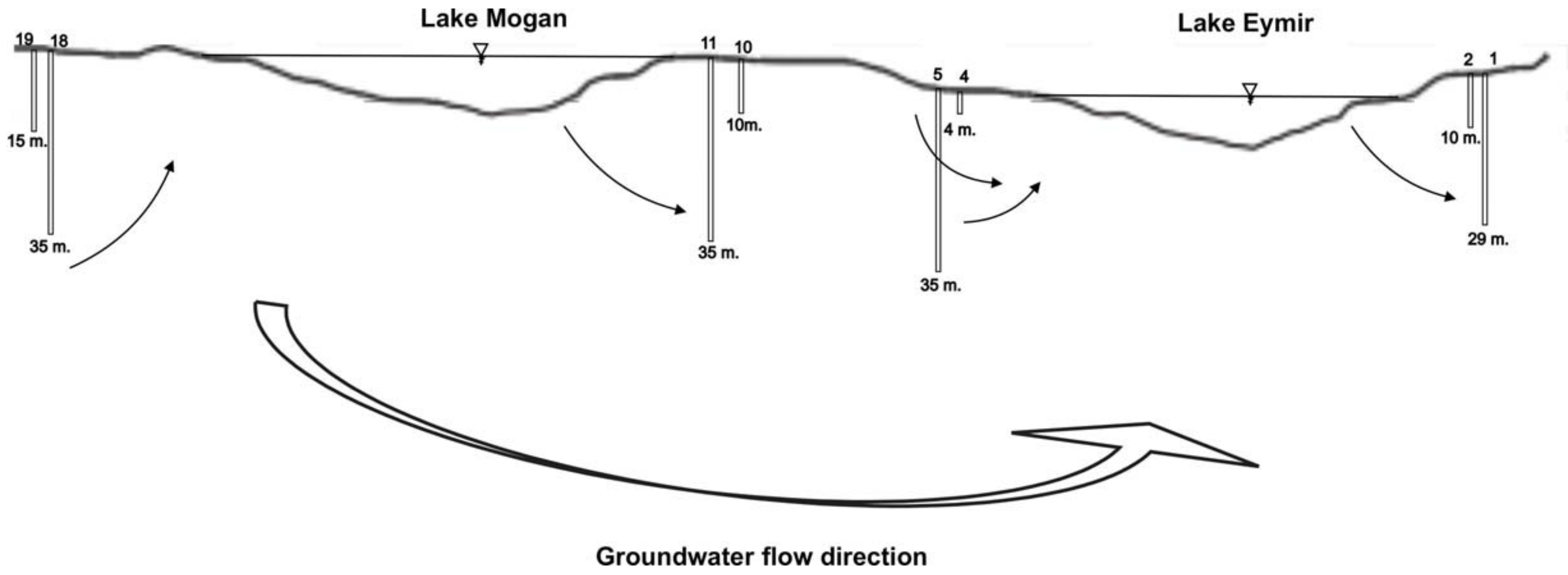

Figure 4.4. The conceptual model of the study area.

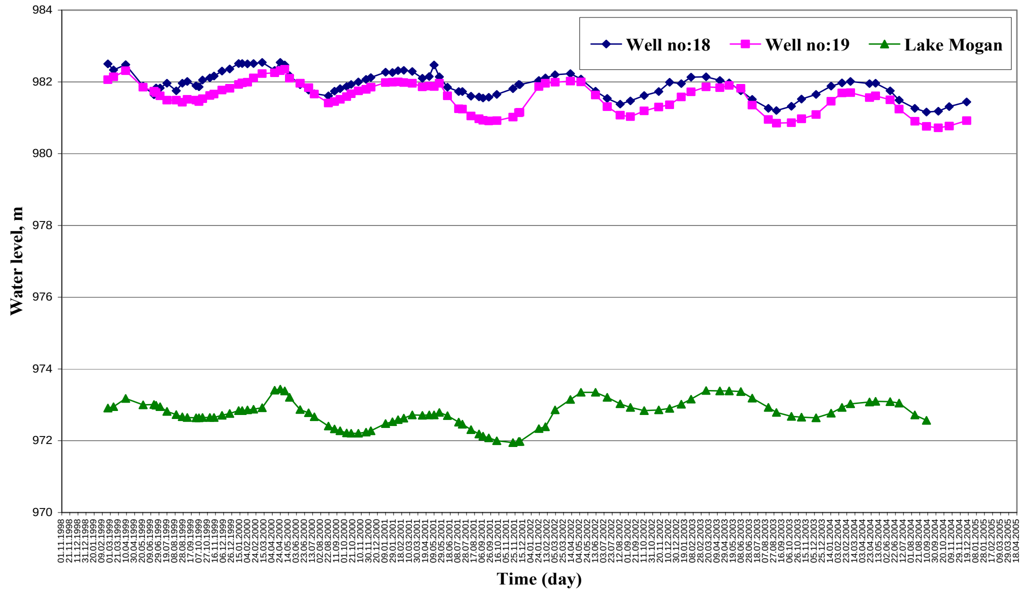

Figure 4.5. The relation between groundwater elevation of wells 18 and 19 and Lake Mogan.

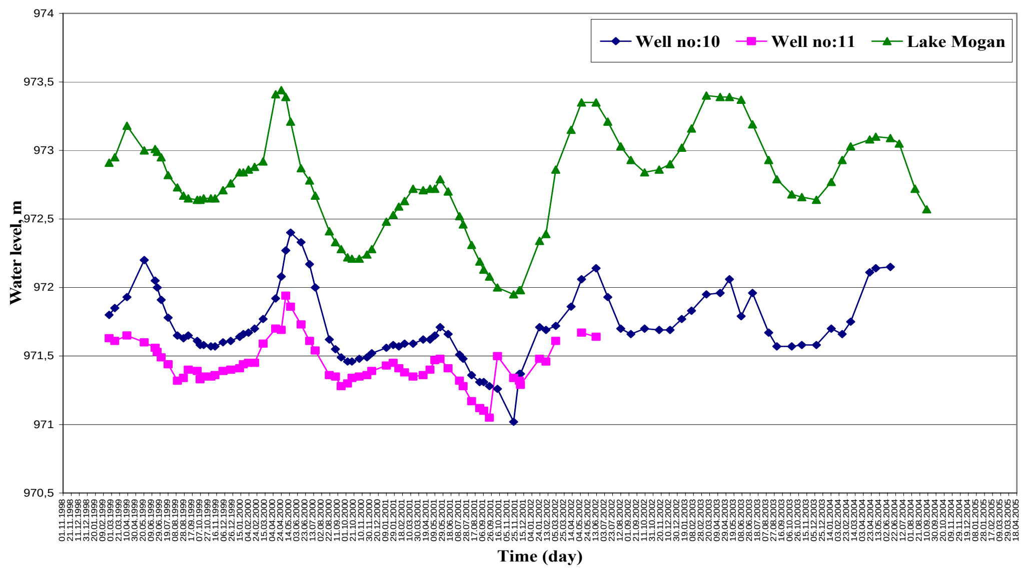

Figure 4.6. The relation between groundwater elevation of wells 10 and 11 and Lake Mogan.

greater than the hydraulic heads in the shallow well 10 and the deep well 11, respectively (Figure 4.6). In this section, Lake Mogan feeds the groundwater system, which is also supported by the downward vertical gradient observed between the shallow and deep wells, 10 and 11. In the upstream of Lake Eymir, the hydraulic head in the shallow well 4 is greater than that of the deep well 5, both of which are greater than Lake Eymir's water level (Figure 4.7). So the groundwater system feeds Lake Eymir. In the downstream section of Lake Eymir, lake level is greater than the hydraulic head in the shallow well 2 and of the deep well 1 (Figure 4.8). Thus, the Lake Eymir feeds the groundwater system in this part of the basin which is also proven by the downward vertical gradient observed between the shallow and deep nested wells 2 and 1. Therefore, the relations between the lake levels and the groundwater elevations in the nested wells prove the discharge from Lake Mogan to Lake Eymir through the groundwater system.

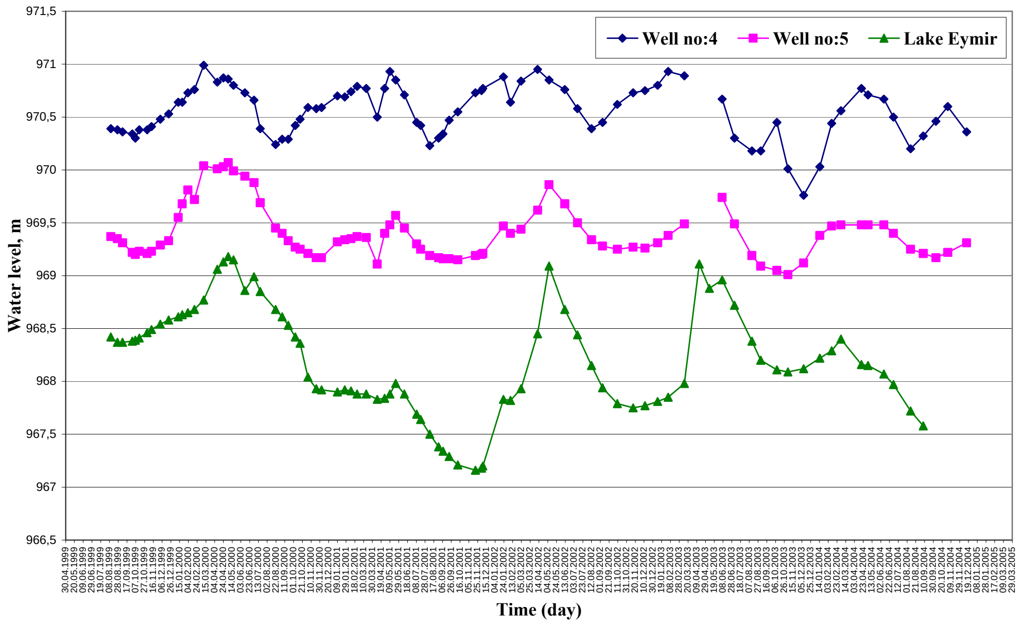

Figure 4.7. The relation between groundwater elevation of wells 4 and 5 and Lake Eymir.

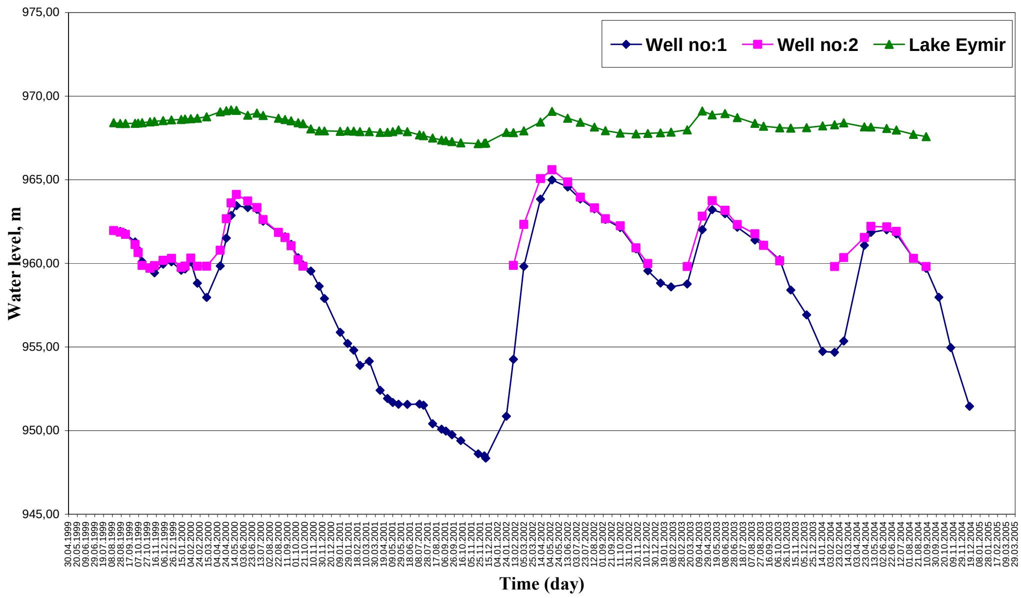

Figure 4.8. The relation between groundwater elevation of wells 1 and 2 and Lake Eymir.

The groundwater system is composed of various rock units, each having different hydraulic properties. Rock units outcropping in the basin are combined into various hydrogeologic units based upon their lithologic and hydraulic properties. Five different hydrogeologic units were identified, resulting in five different hydraulic conductivity zonation in the basin.

The source of most of the groundwater recharge in the basin is from areal precipitation. This areal recharge would vary according to the permeability of the hydrogeologic units. Due to shallow groundwater depths, evapotranspiration losses is sought to be the major discharge from the system. Groundwater pumped by private wells constitute only a small fraction of the discharge.

4.3 Computer Code Specification

The numerical model used for this study is the modular finite-difference groundwater flow model (MODFLOW-2000) developed by the U.S. Geological Survey (USGS) (Harbaugh et al., 2000). The program was constructed in the early 1980's and has continually evolved since then with development of many new packages and related programs for groundwater studies. Currently, MODFLOW is the most widely used program in the world for simulating groundwater flow. MODFLOW was selected based on the following considerations:

- MODFLOW can simulate a wide variety of hydrologic features and processes in 3 dimensions.
- MODFLOW is capable of simulating various geologic structures such as layering, heterogeneity and anisotropy. The code can simulate geologic structures (i.e., faults), tilted layers and sloping water tables.
- Steady-state and transient flow can be simulated in unconfined aquifers, confined aquifers, and confining units.
- A variety of features and processes such as lakes, rivers, streams, drains, springs, reservoirs, wells, evapotranspiration, and recharge from precipitation and irrigation also can be simulated.
- Each simulation feature of the MODFLOW has been extensively tested.
- MODFLOW has been accepted in many legal cases in the United States as a legitimate approach to analysis of groundwater systems.

4.4 Model Formulation

4.4.1 Mathematical Model

The three dimensional movement of groundwater of constant density through porous earth material may be described by the partial differential equation

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-Q=S_s\frac{\partial h}{\partial t} \qquad \text{Eq. 4.1}$$

where

x, y, z are the cartesian coordinates aligned along the major axes of hydraulic conductivity K_{xx}, K_{yy}, K_{zz};

h is the hydraulic head (L);

Q is the volumetric flux per unit volume and represents sources and/or sinks of water (t^{-1});

S_s is the specific storage of the porous material (L^{-1}); and

t is the time (t).

In general, S_s, K_{xx}, K_{yy}, K_{zz} may be functions of space [$S_s = S_s(x, y, z)$ and $K_{xx} = K_{xx}(x, y, z)$, etc.] and Q and h may be functions of space and time [$h = h(x, y, z, t)$, $Q = Q(x, y, z, t)$] so that Equation 4.1 describes groundwater flow under transient conditions in a heterogeneous and anisotropic media.

4.4.2 Numerical Model

In order to solve the Equation 4.1 aquifer system is discretized into a mesh of points termed nodes, forming rows, columns and layers (Figure 4.9).

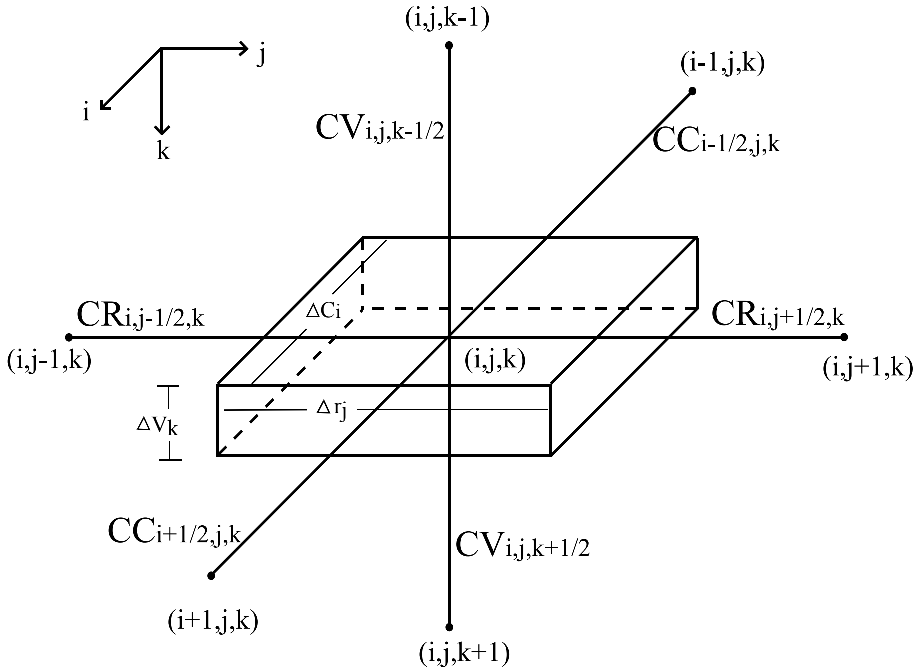

Figure 4.9. Definition of conductance terms between model cells.

The system described by Equation 4.1 is replaced by a finite set of discrete points in space and time, and the partial derivatives are replaced by differences between functional values at nodal points. Eventually, a system of N equations with N unknowns is formulated where the N unknowns are the heads at nodal points. N shows the number of blocks in the porous media. By using block centered finite difference grid Equation 4.1 can be rewritten (Domenico and Schwartz, 1998) as;

$$CR_{i,j-1/2,k}\left(h^n_{i,j-1,k}-h^n_{i,j,k}\right)+CR_{i,j+1/2,k}\left(h^n_{i,j+1,k}-h^n_{i,j,k}\right)$$
$$+CC_{i-1/2,j,k}\left(h^n_{i-1,j,k}-h^n_{i,j,k}\right)+CC_{i+1/2,j,k}\left(h^n_{i+1,j,k}-h^n_{i,j,k}\right)$$
$$+CV_{i,j,k-1/2}\left(h^n_{i,j,k-1}-h^n_{i,j,k}\right)+CV_{i,j,k+1/2}\left(h^n_{i,j,k+1}-h^n_{i,j,k}\right)$$
$$+Q_{i,j,k}=SS_{i,j,k}\frac{\left(\Delta r_j \Delta c_i \Delta v_k\right)\left(h^n_{i,j,k}-h^{n-1}_{i,j,k}\right)}{t_n-t_{n-1}} \quad \text{Eq. 4.2}$$

where the n superscript of h shows present time step while the superscript n-1 shows the previous time step and;

i, index in x dimension,

j, index in y dimension,

k, index in z dimension,

$SS_{i,j,k}$ is the specific storage of cell i, j, k (L^{-1}),

$Q_{i,j,k}$ is the flow rate into/out of cell i, j, k (L^3/T),

$\Delta r_j * \Delta c_i * \Delta v_k$ volume of i, j, k cell (L^3),

$$CR_{i,j-1/2,k}=KR_{i,j-1/2,k}\frac{\Delta c_i \Delta v_k}{r_{j-1/2}} \quad \text{Eq. 4.3}$$

$$CC_{i-1/2,j,k}=KC_{i-1/2,j,k}\frac{\Delta r_j \Delta v_k}{c_{i-1/2}} \quad \text{Eq. 4.4}$$

$$CV_{i,j,k-1/2}=KV_{i,j,k-1/2} * \Delta r_j * \Delta c_i / \Delta v_{i,j,k-1/2} \quad \text{Eq. 4.5}$$

Δr_j increase in length along j column in x direction (L),

Δc_i increase in length along i row in y direction (L),

Δv_k increase in length along k in z direction (L),

$KR_{i,j-1/2,k}$ hydraulic conductivity along the row between nodes i, j, k and i, $j-1$, k (L/T).

$KC_{i-1/2,j,k}$ hydraulic conductivity along the column between nodes i, j, k and $i-1, j, k$ (L/T).

$KV_{i,j,k-1/2}$ hydraulic conductivity in vertical direction between nodes i, j, k and $i, j, k-1$ (L/T).

Similar terms for other conductance terms can be written. The final form of the finite difference equation given in Eq. 4.2 can be expressed:

$$CV_{i,j,k-1/2}h^n_{i,j,k-1} + CC_{i-1/2,j,k}h^n_{i-1,j,k} + CR_{i,j-1/2,k}h^n_{i,j-1,k}$$
$$+(-CV_{i,j,k-1/2} - CC_{i-1/2,j,k} - CR_{i,j-1/2,k} - CR_{i,j+1/2,k}$$
$$-CC_{i+1/2,j,k} - CV_{i,j,k+1/2} + HCOF_{i,j,k})h^n_{i,j,k}$$
$$+CR_{i,j+1/2,k}h^n_{i,j+1,k} + CC_{i+1/2,j,k}h^n_{i+1,j,k} + CV_{i,j,k+1/2}h^n_{i,j,k+1} = RHS_{i,j,k} \quad \text{Eq. 4.6}$$

where

$$HCOF_{i,j,k} = P_{i,j,k} - \frac{SC1_{i,j,k}}{t_n - t_{n-1}} \quad \text{Eq. 4.7}$$

$$RHS_{i,j,k} = -Q_{i,j,k} - \frac{SC1_{i,j,k}\, h_{i,j,k}^{\;n-1}}{t_n - t_{n-1}} \quad \text{Eq. 4.8}$$

and

$$SC1_{i,j,k} = S_{si,j,k} * \Delta r_j * \Delta c_i * \Delta v_k \quad \text{Eq. 4.9}$$

$P_{i,j,k}$ and $Q_{i,j,k}$ represent the sum of constants related to N different inflow and outflow processes like pumping, induced recharge, etc.

Writing one of these equations for each of the nodes in the system yields a system of equations:

$$[A]\{h\} = \{q\} \qquad \text{Eq. 4.10}$$

where $[A]$ is the coefficient matrix

$\{h\}$ is the vector of unknown head values

$\{q\}$ is a vector of constant-head terms

Obtained finite difference equation is solved using numerical methods and eventually at the end of solution process at each time step a new array of heads and drawdowns are obtained for the end of the time step. Preconditioned- Conjugate Gradient method was used in this study to solve the finite difference equations with a convergence criterion of 0.1 m.

4.4.3 Seepage between Lake and Aquifer System

In the Lake Package used in this study, a lake is represented as a volume of space within the model grid which consists of inactive cells extending downward from the upper surface of the grid. Active model grid cells bordering this space, representing the adjacent aquifer, exchange water with the lake at a rate determined by the relative heads and by conductances that are based on grid cell dimensions, hydraulic conductivities of the aquifer material, and user-specified leakance distributions that represents the resistance to flow through the material of the lakebed. Parts of the lake may become “dry” as upper layers of the model are dewatered, with a concomitant reduction in lake surface area, and may subsequently rewet when aquifer heads rise (Merritt and Konikow, 2000).

The seepage rate calculation between a lake and the adjacent aquifer material is based upon the application of Darcy's Law:

$$q = K \frac{h_l - h_a}{\Delta l} \qquad \text{Eq. 4.11}$$

where

q is the specific discharge (seepage rate) (L/T)

K is the hydraulic conductivity (L/T) of materials between the lake and a location within the aquifer below the water table

h_l is the stage of the lake (L)

h_a is the aquifer head (L)

Δl is the distance (L) between the points at which h_l and h_a are measured.

In numerical models, it is convenient to further quantify the transfer of fluid as a volumetric flux Q (L^3/T).

$$Q = qA = \frac{KA}{\Delta l}(h_l - h_a) = c(h_l - h_a) \qquad \text{Eq. 4.12}$$

The quantity $c = KA/\Delta l$ is termed the conductance (L^2/T). Expressed per unit area, the quantity $K/\Delta l$ is referred to as a leakance (T^{-1}). In numerical models, A is usually the cross-sectional area of a grid-cell face in one of the horizontal (X-Y) or vertical (X-Z or Y-Z) coordinate planes (Figure 4.10). In the USGS Lake Package, conductances are computed for horizontal lake/aquifer interfaces based on parameter input before MODFLOW time steps are performed.

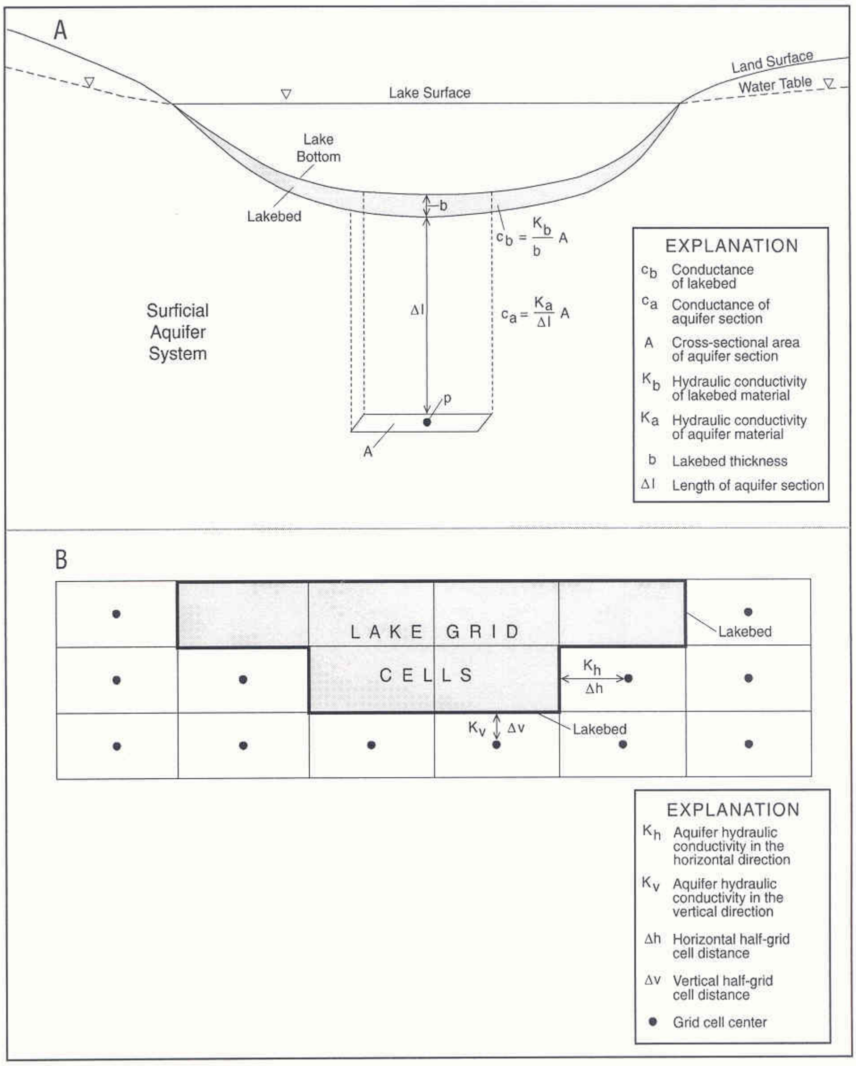

Figure 4.10. Concepts used in estimating seepage flux between the lake and some point in the surfacial aquifer.

Conductances per unit thickness for vertical interfaces are also computed at this stage, and are later multiplied by the current wetted thickness of the aquifer cells adjacent to the lake as part of the computation of seepage rates during simulation time steps.

The lakebed is defined by its assigned leakance value and is not specified to have an explicit dimension within the model grid.

The conductance of the lakebed is expressed as $c_b = \frac{K_b A}{b}$ Eq. 4.13

where

K_b is the hydraulic conductivity of the lakebed material

b is the lakebed thickness (Figure 4.10)

A is the common cross-sectional area.

The conductance of the aquifer segment is expressed as $c_a = \frac{K_a A}{\Delta l}$ Eq. 4.14

where

K_a is the aquifer hydraulic conductivity

Δl is the length of the travel path in the aquifer to the point where the aquifer head h_a is measured.

The equivalent conductance, c, of the entire path between the points in the lake and aquifer where the heads are measured is:

$$\frac{1}{c} = \frac{1}{c_b} + \frac{1}{c_a} \qquad \text{Eq. 4.15}$$

or

$$c = \frac{A}{\frac{b}{K_b} + \frac{\Delta l}{K_a}} \qquad \text{Eq. 4.16}$$

Seepage rates computed for each interface between a lake cell and a horizontally or vertically adjacent aquifer cell by the Lake Package implementation of Equations 4.11 and 4.12 are added to the appropriate elements in the *RHS* and *HCOF* matrices given in Equation 4.6 as follows:

$$RHS_{i,j,k} = RHS_{i,j,k} - c_m h_l^{n-1} \quad \text{Eq. 4.17}$$

for aquifer head (h_a) above lake bottom (h_{bot}) in the vertical column

$$RHS_{i,j,k} = RHS_{i,j,k} - c_m (h_l^{n-1} - h_{bot}) \quad \text{Eq. 4.18}$$

for h_a below h_{bot} , horizontal interface

$$RHS_{i,j,k} = RHS_{i,j,k} \pm 0 \quad \text{Eq. 4.19}$$

for h_a below h_{bot} , vertical interface

$$HCOF_{i,j,k} = HCOF_{i,j,k} - c_m \quad \text{Eq. 4.20}$$

for h_a above h_{bot}

$$HCOF_{i,j,k} = HCOF_{i,j,k} \pm 0 \quad \text{Eq. 4.21}$$

for h_a below h_{bot}

where

i, j, k designates the particular matrix term

m denotes a particular cell interface

c_m is the conductance across that interface

$n-1$ denotes the previous time step.

The *HCOF* and *RHS* matrices are used in the MODFLOW solution for new aquifer heads for the current time step. This procedure constitutes the link between the Lake Package and the MODFLOW solution for aquifer head values. The cell-by-cell seepage rates are integrated over the time step to calculate seepage volumes for the time step. These integrated cell-by-cell volumes are then summed to obtain a total seepage volume for the lake, which is then used for computing the new lake stage.

4.4.4 Lake Water Budget

The interaction between the lake and the surficial aquifer is represented in the Lake Package by updating at the end of each time step a water budget for the lake that is independent of the ground-water budget represented by the solution for heads in the aquifer. Implicit in the calculation of a lake water budget is the recomputation of current values of lake volume and stage. The lake stage is crucial in making the estimates of groundwater seepage to and from the lake that are used by MODFLOW.

Updating a lake water budget also requires that estimates be made of gains and losses of water from the lake other than by seepage, such as (1) gains from rainfall, overland runoff, and inflowing streams, (2) losses to evaporation and outflowing streams, and (3) anthropogenic gains and losses. Examples of the latter include withdrawals for water supply or augmentation with water from another source.

The water budget procedure incorporated in the Lake Package is implied by the equation used to update the lake stage. The explicit form of this equation (Merritt and Konikow, 2000) is:

$$h_l^n = h_l^{n-1} + \Delta t \frac{p - e + rnf - w - sp + Q_{si} - Q_{so}}{A_s}$$ Eq. 4.22

where

h_l^n and h_l^{n-1} are the lake stages (L) from the present and previous time steps

Δt is the time step length (T)

p is the rate of precipitation (L^3/T) on the lake during the time step

e is the rate of evaporation (L^3/T) from the lake surface during the time step

rnf is the rate of surface runoff to the lake (L^3/T) during the time step

w is the rate of water withdrawal from the lake (L^3/T) during the time step (a negative value is used to specify a rate of augmentation)

Q_{si} is the rate of inflow from streams (L^3/T) during the time step

Q_{so} is the rate of outflow to streams (L^3/T) during the time step

A_s is the surface area of the lake (L^2) at the beginning of the time step

sp is the net rate of seepage between the lake and the aquifer (L^3/T) during the time step (a positive value indicates seepage from the lake into the aquifer), and is computed as the sum of individual seepage terms for all M lake/aquifer cell interfaces:

$$sp = \sum_m^M c_m \left(h_l - h_{am} \right)$$ Eq. 4.23

where

h_{am} is the head in the aquifer cell across the m^{th} interface

c_m is the conductance across the m^{th} interface.

An alternative to the explicit computation of lake stage at the end of each time step is to consider $\overline{h_l}$, the estimate of lake stage used for seepage calculations during the n^{th} time step, to be a combination of the stage from the previous time step (h_l^{n-1}) and the unknown stage to be computed at the end of the present time step (h_l^n), that is:

$$\bar{h}_l = (1-\theta)h_l^{n-1} + \theta h_l^n \qquad \text{Eq. 4.24}$$

where

θ is a user-specified weighting factor, $0 \leq \theta \leq 1$.

The formulation shown above is the semi-implicit formulation. In this study, semi-implicit formulation with $\theta = 0.5$ is used. If $\theta = 0$, this formulation reverts to the explicit case described earlier. If $\theta = 1$, the stage from the previous time step is ignored-this is the fully-implicit case.

4.5 Model Construction

4.5.1 Model Domain

The modeled domain and the finite difference grid are shown in Figure 4.11. The model extends to the watershed divides in the northern, western and eastern boundaries. The southern boundary of the model is selected to coincide with the location of the Dikilitaş reservoir since it acts as an internal source and accumulates most of the flow coming from the upstream end of the basin.

The model grid consists of 185 rows and 99 columns with a total of 13532 active cells in one layer (Figure 4.11). In order to represent the lake systems in a detailed manner, a non-uniform grid size was used. In the vicinity of the lakes, a grid size of 100 m by 100 m has been used whereas a grid size of 500 m by 500 m has been used in the rest of the area.

The aquifer system was discretized vertically into 3 layers (Figure 4.12). However in order to obtain a fine discretization, each layer was further divided into sub-layers. There are a total of 9 sub-layers. Each model layer has 13532 active model cells.

The uppermost layer including Lake Mogan extends from the topographic surface to the elevation of 968 meters. This layer consisted of only a single sub-layer. The second layer which includes the Lake Eymir extends to a depth of 960 meters and represented by two sub-layers. Finally, the third layer consisted of six sub-layers with a thickness of 5 meters. Thus, this layer extended to a depth of 930 meters. Each layer is assumed to be convertible between confined and unconfined conditions.

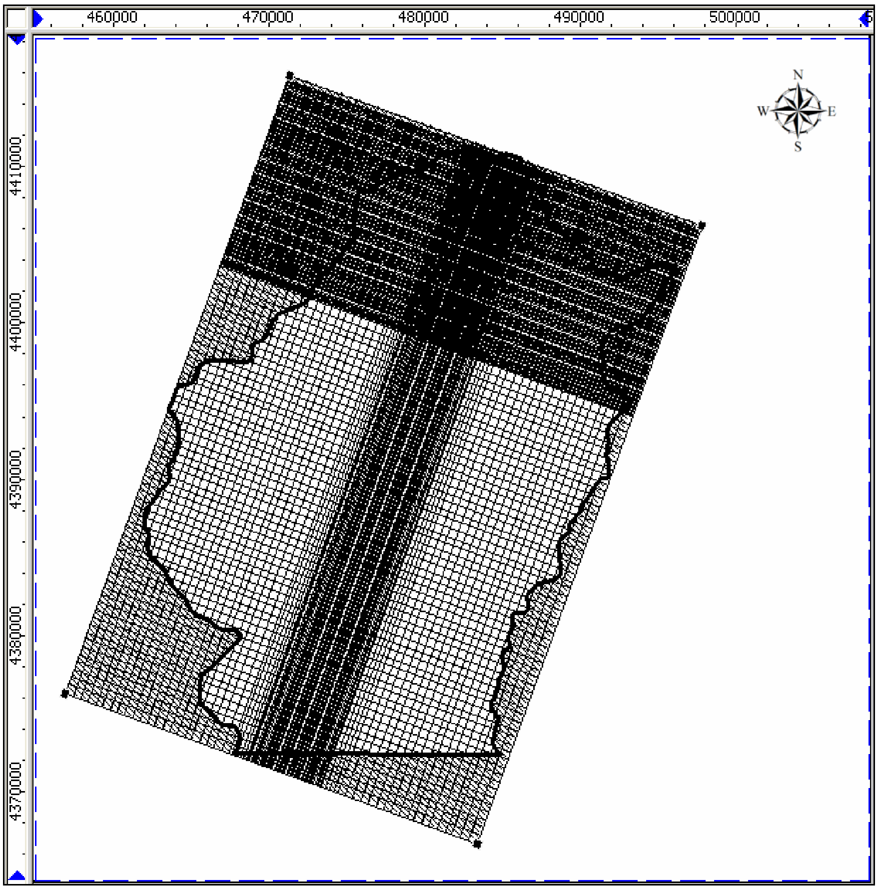

Figure 4.11. Model domain and the finite-difference grid.

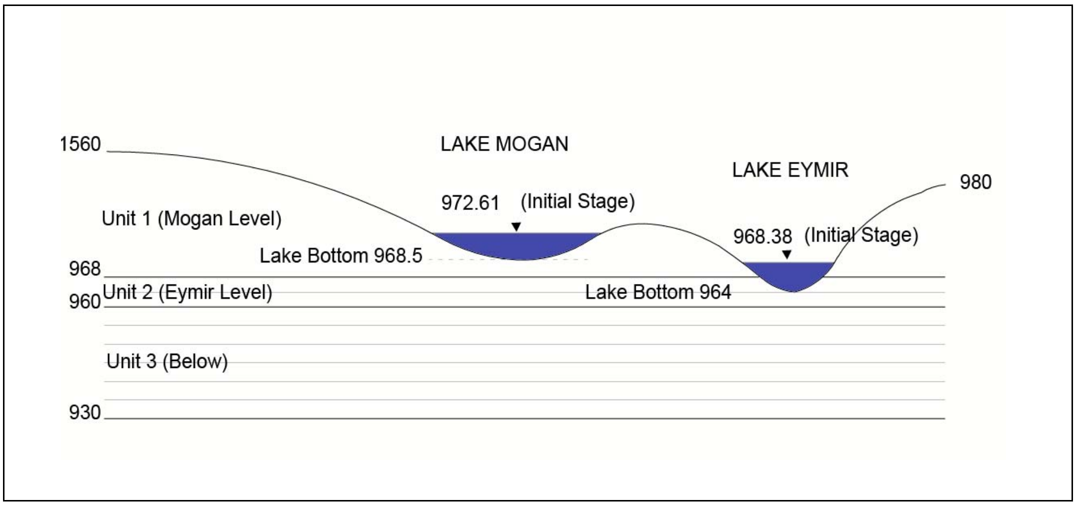

Figure 4.12. Vertical discretization of the study area.

4.5.2 Boundary Conditions

The external model boundaries have been selected as no-flow boundaries as they coincide with the watershed boundaries. However, the early runs indicated the necessity of the inclusion of a head dependent boundary along the northern part of the basin, at the exit of the Lake Eymir, to simulate the subsurface outflow through Quaternary alluvium. In addition to the external boundaries, the Dikilitaş and İkizce reservoirs have been assigned as internal boundaries using the head dependent boundary conditions to simulate the flux through these reservoirs. Mogan and Eymir Lakes were represented as internal lakes using the Lake Package.

The upper boundary of the model is simulated as free water surface (i.e., water table) that was allowed to move vertically in response to imbalances in the inflows and outflows of the model. The lower boundary of the model is an impervious no-flow boundary. This no-flow boundary is assumed to be located at a depth (i.e., 930 m) where the flow through the system has no impact on the lake systems.

4.5.3 Initial Conditions

The simulations conducted for the lake and aquifer systems were transient in nature. Transient simulations, in addition to boundary conditions, require the specification of the initial conditions in the aquifer as well as in the lakes. The model simulations have started at the beginning of October 1998, the water levels of which defined the initial conditions. Unfortunately the spatial distribution of the groundwater monitoring wells was not adequate to derive a water table map for the whole model domain. The water levels observed at monitoring wells at the beginning of October 1998 was augmented with the static water level information obtained from the archives of DSİ for the registered private wells. The water table map, thus, prepared represented the initial conditions as of October 1998. This map given in Figure 4.13 shows that the groundwater flow in the basin is from south to north and from basin boundaries in the east and west toward the central part where the lakes are located.

The initial lake stages for Mogan and Eymir represented the lake stages at the beginning of October 1998. These values were 972.61 m for Lake Mogan and 968.38 m for Lake Eymir (Figure 4.12).

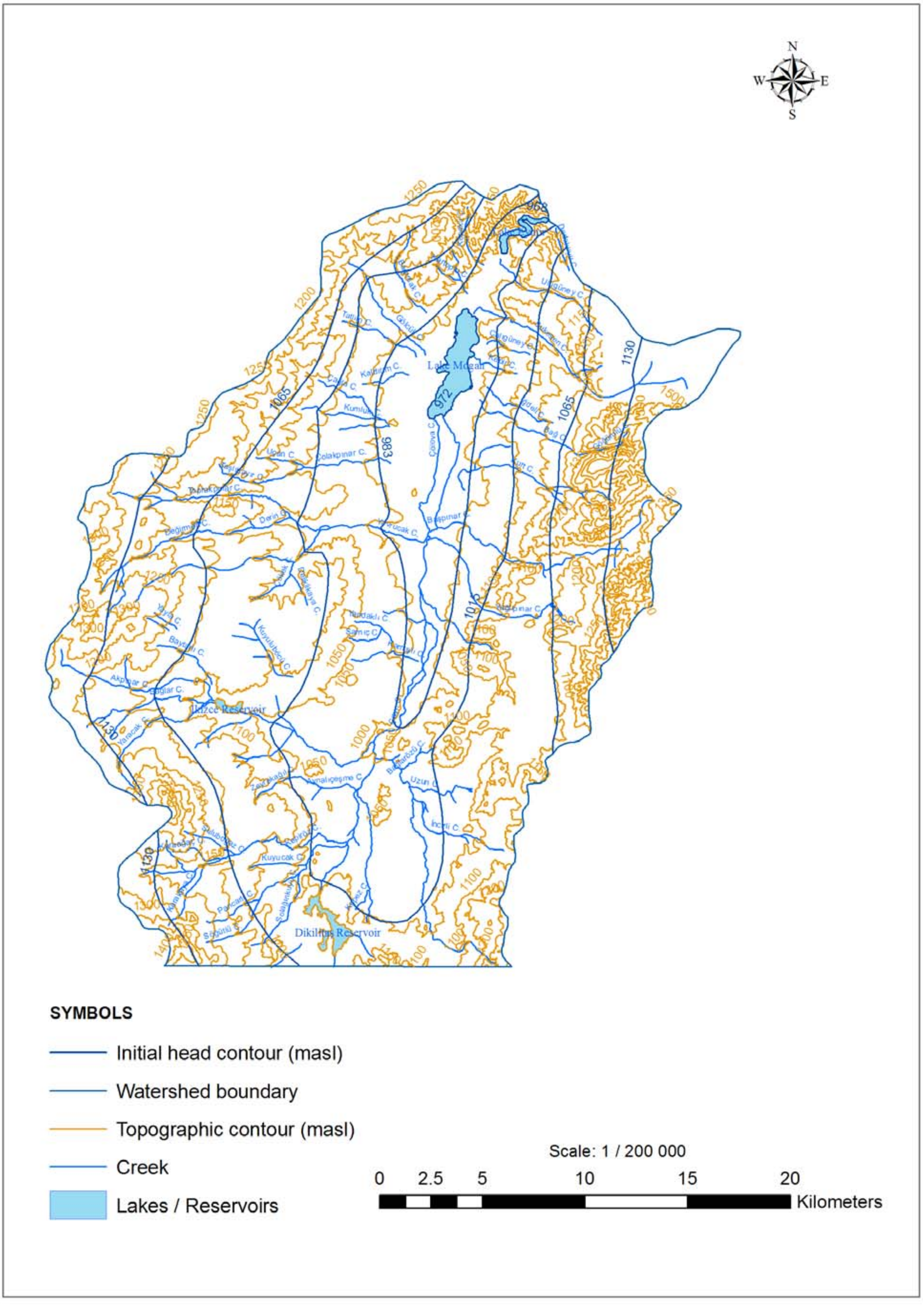

Figure 4.13. Initial head distribution over the basin.

4.5.4 Hydraulic Parameters

Simulation of the groundwater flow and lake stages requires specifying aquifer system and lakebed properties as well as sources and sinks. Aquifer system properties can vary considerably both horizontally and vertically and thus cannot be precisely represented in a numerical model. The aquifer system properties specified for each cell in the model are estimates of the average conditions in the area represented by each cell. Similarly, sources and sinks applied to the aquifer system (recharge and discharge) are estimates for the area represented by each cell. The initial values of the aquifer system hydraulic properties were obtained by evaluating the lithologic characteristics. Recharge from precipitation was estimated by simulating the changes in soil moisture storage. The discharge from the model area is taking place in the exit of the Lake Eymir, evapotranspiration losses, and well discharges.

The basic parameters that define the geohydrologic properties of the aquifers are hydraulic conductivity, storativity, and leakance between layers. The hydraulic parameters needed for the simulation of the lakes include lakebed hydraulic conductance, the lake bottom elevation and the lakebed thickness.

4.5.4.1 Hydraulic Conductivity

The initial distribution of the hydraulic conductivity used in the model was decided based upon the previous pumping test data and the lithologic characteristics of the major geological units. Initially, the model domain is divided into five hydraulic conductivity zones by combining some of the geological units having similar lithologic characteristics. The permeability zones shown in Figure 4.14 vary from highly permeable (Zone 1) to almost impermeable (Zone 5). For example, the Quaternary alluvium was included in Zone 1 whereas Emir Formation consisting of schists was put in Zone 5.

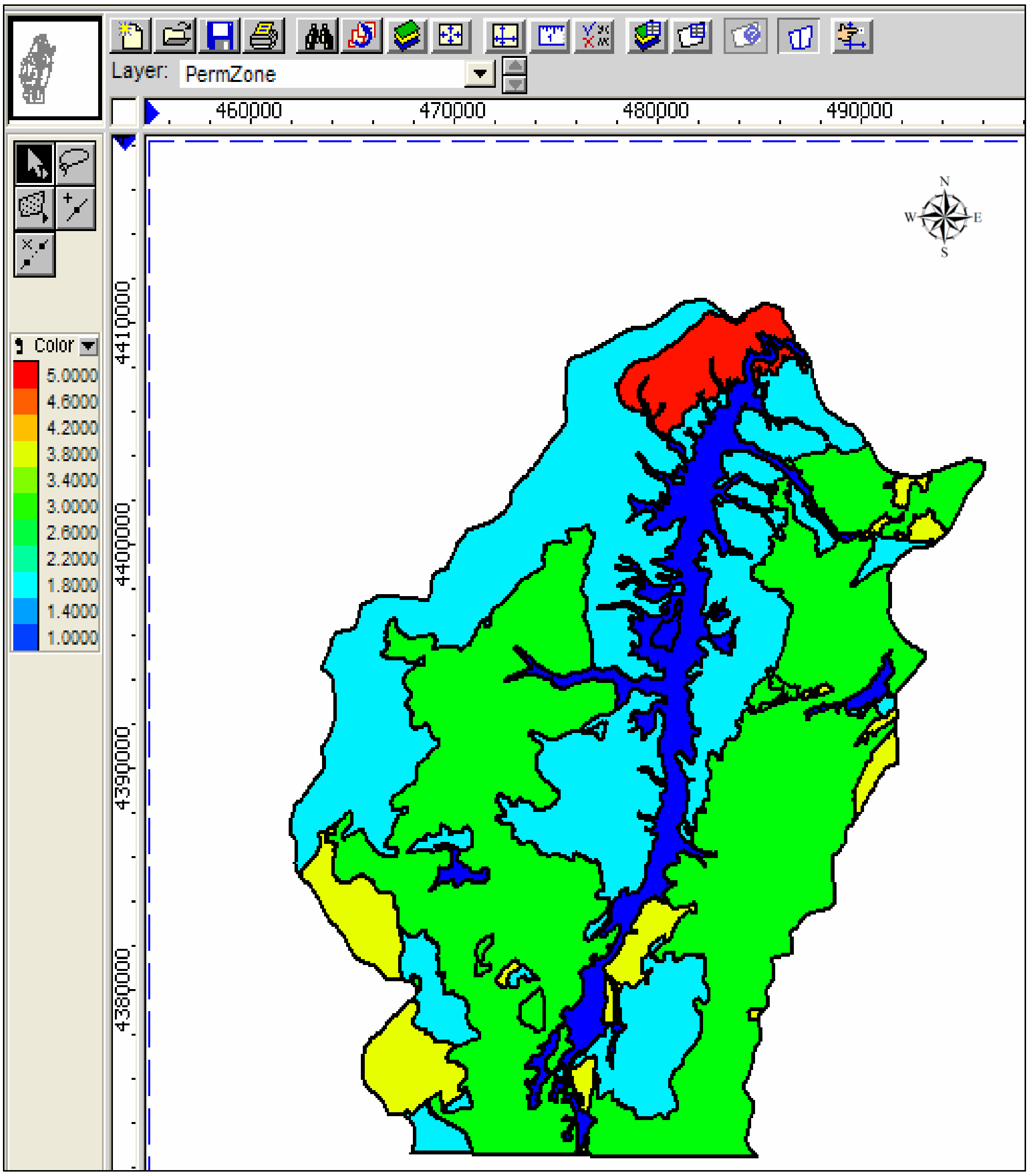

Figure 4.14. Hydraulic conductivity zonation of the model.

The vertical hydraulic conductivity in each layer is assumed to be equal to the 1/10th of the horizontal hydraulic conductivity in that layer. No horizontal anisotropy was assumed. The initial estimates were modified during the calibration of the model until the final distribution of hydraulic conductivity for the layers was derived.

4.5.4.2 Storativity

The storativity (specific yield or storage coefficient) of a water-bearing material is the quantity of water released from storage per unit area per unit decline in hydraulic head. This parameter, needed for transient simulations, indicates how quickly the water levels respond to stresses. No information was available from pumping test data on specific yield except a storage coefficient value for a confined section in Çölova part of the basin. The pumping test conducted by METU (1995) gave a storage coefficient value of 3×10^{-4} for a two meters thick aquifer section. The specific yield values for the Gölbaşı Formation obtained as a result of laboratory tests by Dogramaci (1993) ranged from 1.9 % to 6.0 %, the average being 4 %. Initially, a specific yield value of 10 % and a specific storage value of 1×10^{-4} were uniformly assigned for all layers for the unconfined and confined conditions. The initial estimates were modified during the calibration.

4.5.4.3 Lake Parameters

Because of the absence of the information related to the hydraulic conductivity of the lakebed sediments, a lakebed hydraulic conductivity value of 1 m/d and a lakebed thickness of 1 m have been assigned to both lakes. These initial values have been modified during the model calibration. The lake bottom elevations were assigned as 968.5 m and 964.0 m for Lake Mogan and Lake Eymir, respectively.

4.5.5. Sources and Sinks

4.5.5.1 Areal Recharge

The source of most of the groundwater recharge in the study area is from areal precipitation. The spatial and temporal distribution of recharge from precipitation had to be quantified. The temporal distribution of recharge for the Quaternary alluvium was determined by conducting a hydrologic simulation for water years 1998 through 2004, tracing monthly changes in soil moisture by using precipitation and evaporation data of the Gölbaşı Meteorological Station and excess water from effective rainfall in plain areas. This recharge series given in Figure 4.15 represented the areal recharge assigned to the Quaternary alluvium having the highest hydraulic conductivity (i.e., Zone 1 in Figure 4.14) distribution. The recharge series applied to the other zones assumed to have the same pattern except that their values were decreased in proportion to the hydraulic conductivities of the zones by multiplying them with 0.8, 0.6, 0.4 and 0.2 for Zone 2 to Zone 5, respectively. These initial estimates were later adjusted during the transient calibration of the model.

4.5.5.2 Evapotranspiration

Evaporation from bare-soil and transpiration by phreatophytes in areas where the water table was near the land surface (less than 2 m) can be simulated using the evapotranspiration package in MODFLOW. The monthly actual evapotranspiration series obtained from the hydrologic simulation given in Figure 4.16 were used as the maximum rate when the water table occurred at the land surface and decreased linearly to zero when the table reached a depth of 2 meters below the land surface.

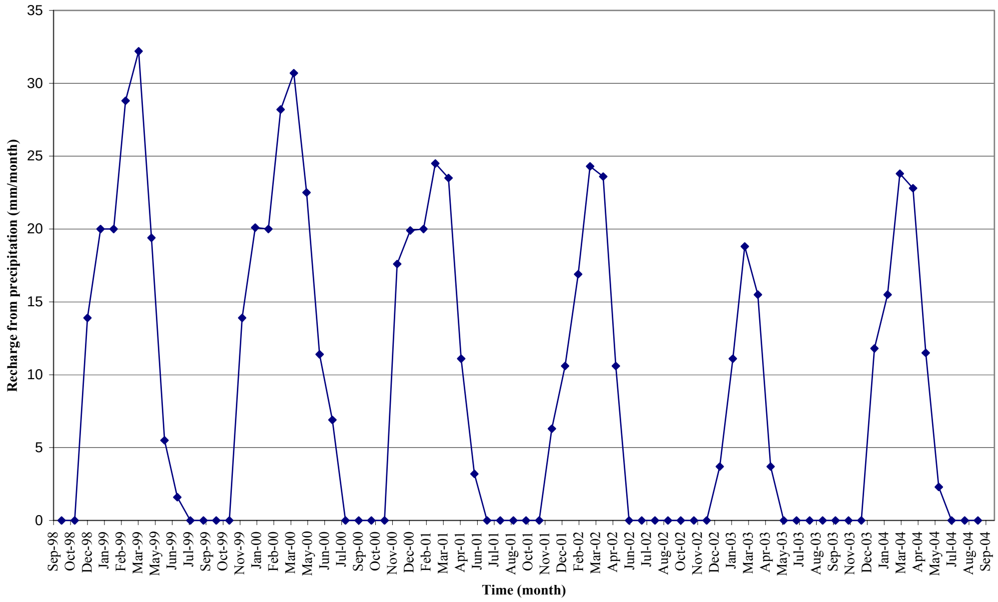

Figure 4.15. Recharge from precipitation for the Quaternary alluvium.

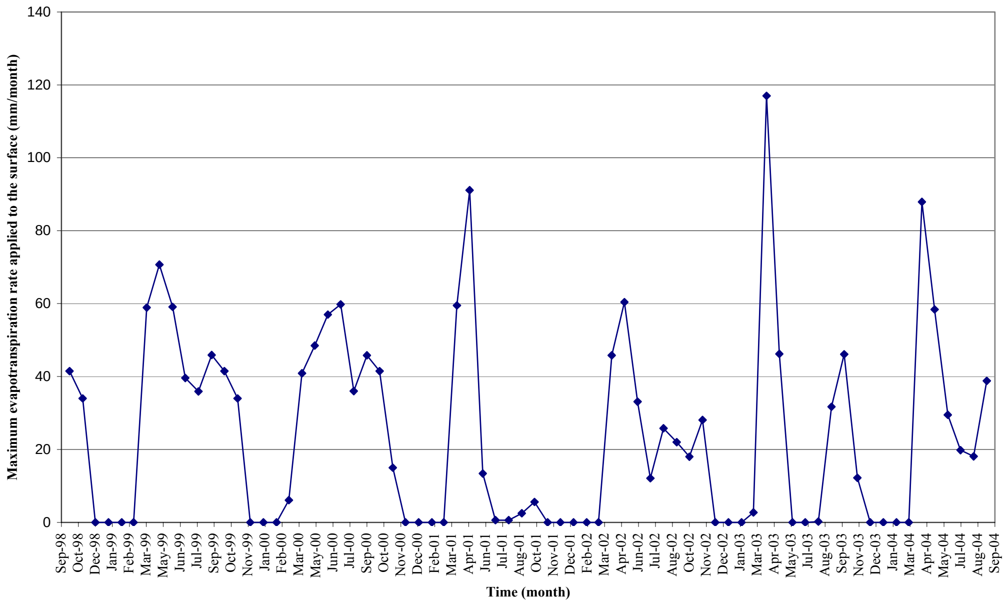

Figure 4.16. The maximum evapotranspiration applied to the land surface.

4.5.5.3 Pumpage from Wells

Groundwater pumped in the basin is used for supplying the domestic and irrigation needs of the private people. Data corresponding to the registered private pumping wells have been examined at the Fifth District Office of the State Hydraulic Works. Approximately a total of 1100 wells are located within the basin (Figure 3.12). Most of these wells tap the Gölbaşı and Elmadağ formations. The well depths average to about 100 m with well yields generally ranging from 0.3 L/s to 2 L/s. However, well yields as high as 3 to 5 L/s are also noted in wells tapping the Gölbaşı Formation. No information was available regarding the actual amount of groundwater pumped by these wells. Since most is used for irrigation purposes, it is assumed that these wells have operated only in summer months, June through September. Assuming each well operated only two hours per day with a pumping rate of 2 L/s, the number of wells falling in each model cell was used to derive a pumpage series for each model cell. The total amount of pumpage calculated in this manner amounted to 1.8×10^6 m^3/year. The pumping rates were proportionally distributed to various model layers by assuming an average depth of 100 m with a filter located at the bottom one-half of the depth.

4.6. Hydrologic Inputs and Outputs for Lakes

The calculation of lake budgets in the model required information regarding direct precipitation, evaporation, surface water inflows and water released from the lakes on a monthly basis.

The monthly precipitation and evaporation data measured at the Gölbaşı Meteorological Station for water years 1998 through 2004 were directly used. Figure 4.17 displays the monthly precipitation and evaporation series used in the model.

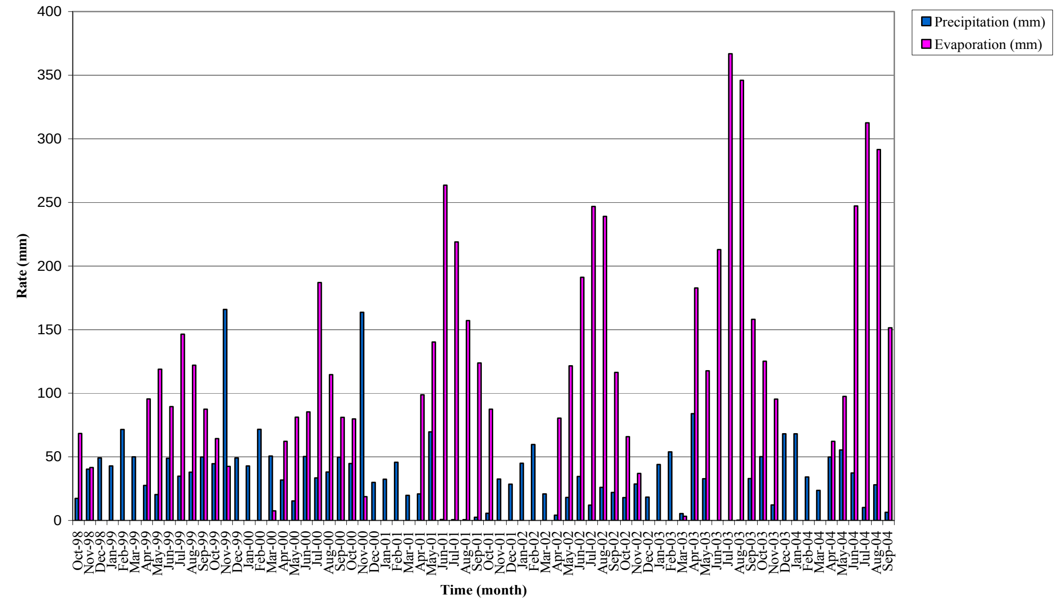

Figure 4.17. Monthly precipitation and evaporation data at the Gölbaşı Meteorological Station.

The surface water inflow to Lake Mogan has been calculated by summing the monthly streamflow discharges at 13 creeks given in Appendix-A. The surface water inflow series generated in this manner is given in Figure 4.18 for Lake Mogan. The water released from Lake Mogan for water years 1998 through 2004 is also given in Figure 4.18. It is noted from this figure that the amount of water released has been decreased significantly in water years 2000 through 2004. None has been released in 2004 due to low water level in Lake Mogan. The water released from Lake Mogan mainly constituted the surface water inflow to Lake Eymir as given in Figure 4.19. Water released from Lake Eymir was essentially the same as the surface water inflow, indicating a low storage capacity of this lake.

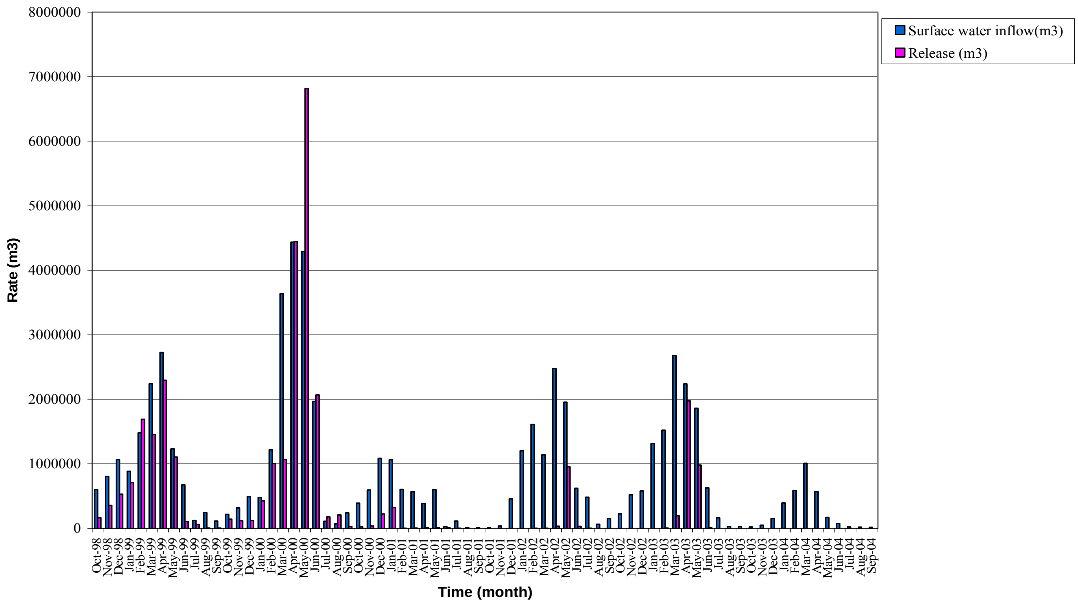

Figure 4.18. The surface water inflow to and release from Lake Mogan.

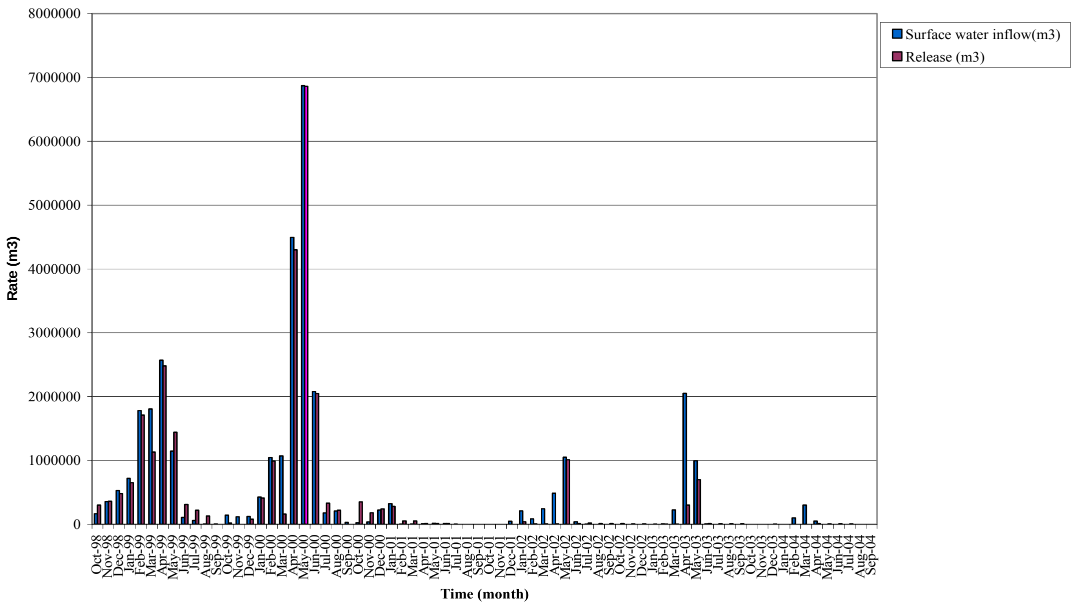

Figure 4.19. The surface water inflow to and release from Lake Eymir.

CHAPTER 5

CALIBRATION OF THE GROUNDWATER FLOW MODEL

5.1 Introduction

Model calibration is the process of making adjustments, within justifiable ranges, to initial estimates of selected model parameters and stresses in order to obtain reasonable agreement between simulated and measured values. As the model was iteratively calibrated, the initial estimates of the aquifer properties were adjusted to improve the match between the simulated and measured groundwater and lake levels. Simultaneously, the water budget items of the aquifer and the lakes were also reviewed. In addition, during calibration the Root Mean Square Error (RMSE), Mean Error (ME) and Mean Absolute Error (MAE) were continuously checked. Modifications were made to the initial estimates of the aquifer hydraulic conductivity, areal recharge, evapotranspiration, lakebed hydraulic conductivity, specific yield and specific storage. The initial estimates were adjusted within reasonable limits of the geologic and hydrologic properties of the aquifer systems.

Calibration of the model was performed through trial-and-error changes to regional hydrologic parameters to minimize the differences between simulated and measured hydraulic heads at nine monitoring wells and lake stages at two lakes. Regional parameters included groundwater recharge, hydraulic conductivity, storativity, lake seepage rates, and evapotranspiration losses. Local changes to these parameters have not been conducted to remove subjectivity.

During this calibration process, three error statistics used as the goodness of fit between simulated and measured water levels defined as:

1. The Root Mean Square Error or the standard deviation is the average of the squared differences in measured and simulated heads.

$$RMSE = \left[1/n \sum_{i=1}^{n} (h_m - h_s)^2 \right]^{0.5} \qquad \text{Eq. 5.1}$$

where n is the number of observations

h_s is the simulated hydraulic head

h_m is the measured head

2. The Mean Error (ME) is the mean difference between measured heads and simulated heads.

$$ME = 1/n \sum_{i=1}^{n} (h_m - h_s)_i \qquad \text{Eq. 5.2}$$

3. The Mean Absolute error (MAE) is the mean of the absolute value of the differences in measured and simulated heads.

$$MAE = 1/n \sum_{i=1}^{n} \left| (h_m - h_s)_i \right| \qquad \text{Eq. 5.3}$$

5.2 Transient Calibration

The calibration of model parameters during the transient phase of simulations primarily involved the estimation of the hydraulic properties of the aquifer and the lakes. The groundwater flow model was calibrated between October 1998 and September 2004 with monthly stress periods under transient conditions. Transient model covered 72 months, i.e. stress periods. The transient state model was calibrated using the water level data from the monitoring wells and lakes. Water level data from nine wells (Wells no (METU): 3, 4, 5, 9, 10, 14, 18, 19, 20) and lakes were used to compare measured and simulated water levels over time. The locations of these wells were shown in Figure 3.13.

The transient state model was assumed to be calibrated when the simulated water levels matched the general trend of the measured water levels, the general flow directions inferred from the contours of the simulated water levels matched flow directions inferred from the contours of measured water levels, and the model parameters were within the reasonable limits supported by the available hydrogeologic data.

In performing a transient simulation, it is necessary to specify the parameter of storativity (storage coefficient and specific yield) describing the capacity of an aquifer to transfer water to and from storage (Anderson and Woessner, 1992). Because of the lack of adequate data on the spatial distribution of storativity, the areal distribution of this parameter was kept uniform at values achieved at the end of transient calibration.

Some of the hydraulic parameters explained in Chapter 4 were modified several times to reach a calibrated transient state model and after each run error statistics given in Equations 5.1, 5.2 and 5.3 were checked continuously. Final values of the parameters at the end of the transient calibration are given in Table 5.1 together with initially assigned values. The initially assigned values of the hydraulic conductivities of Zones 1 through 5 were increased while recharge rates (i.e., multiplier) were decreased. Otherwise, the simulated heads remained significantly greater than their field counterparts. As mentioned earlier, local modifications to these parameters were not allowed to remove subjectivity in model calibration. In the absence of adequate spatial data coverage, the regionally

Table 5.1. Initial and calibrated parameter values.

Parameter Name	Initial values	Calibrated values
Hydraulic conductivity of Zone 1 (m/d)	10	20
Hydraulic conductivity of Zone 2 (m/d)	5	10
Hydraulic conductivity of Zone 3 (m/d)	1	5
Hydraulic conductivity of Zone 4 (m/d)	0.1	2
Hydraulic conductivity of Zone 5 (m/d)	0.001	1
Recharge multiplier to Zone 1	1	0.8
Recharge multiplier to Zone 2	0.8	0.7
Recharge multiplier to Zone 3	0.6	0.6
Recharge multiplier to Zone 4	0.4	0.3
Recharge multiplier to Zone 5	0.2	0.15
Evapotranspiration multiplier	1	0.4
Specific yield	% 10	% 10
Specific storage	0.0001	0.005
Lakebed hydraulic conductivity for Lake Mogan (m/day)	1	0.25
Lakebed thickness for Lake Mogan (m)	1	1
Lakebed hydraulic conductivity for Lake Eymir (m/day)	1	0.1
Lakebed thickness for Lake Eymir (m)	1	1

assigned parameter values were assumed to best represent the modeled system. The calibrated hydraulic conductivity value of Zone 1 (i.e., Quaternary Alluvium) was in between the range of values obtained from pumping tests (METU, 1995; Arıgün, 1994). Evapotranspiration multiplier was reduced by 60 % because the initial values removed significant amount of groundwater from storage. Initially assigned specific yield was not changed during model calibration. Specific storage value was however increased from the initial values. The lakebed hydraulic conductivities were reduced in order to match the lake levels because the initial values have given higher lake stages than observed.

The simulated groundwater levels at the end of the simulation period (i.e., end of September 2004) are given in Figure 5.1. A comparison of this map with the map of initial heads (Figure 4.13) shows good agreement in general.

The simulated heads and the measured water levels for the monitoring wells and the lakes for average monthly conditions are plotted for comparison purposes in Figures 5.2 through 5.12. As it can be seen from the examination of these figures, the simulated water levels matched the general trends of the measured water levels. However, the simulated seasonal fluctuations were not exactly reproduced. This may be attributed to the high specific storage value used in the model. The lower values, however, resulted in increase in the error statistics. The overall Root Mean Square Error (RMSE) for the calibrated model equals 0.5 m and 0.24 m, Mean Error (ME) equals 0.08 m and 0.03 m and the Mean Absolute Error (MAE) equals 0.43 m and 0.20 m for the wells and the lakes, respectively. These errors are within acceptable ranges considering the regional parameter values used in the model.

When the calculated versus observed groundwater and lake level elevations for October 1998- September 2004 are examined (Figure 5.13 and 5.14), most of the points lie within or close to the line in which the calculated and observed groundwater and lake level elevations are equal to each other, indicating good agreement. The correlation coefficient between the simulated transient-state hydraulic head and the measured water levels for the monitoring wells and the lakes are 0.9861 and 0.9898, respectively.

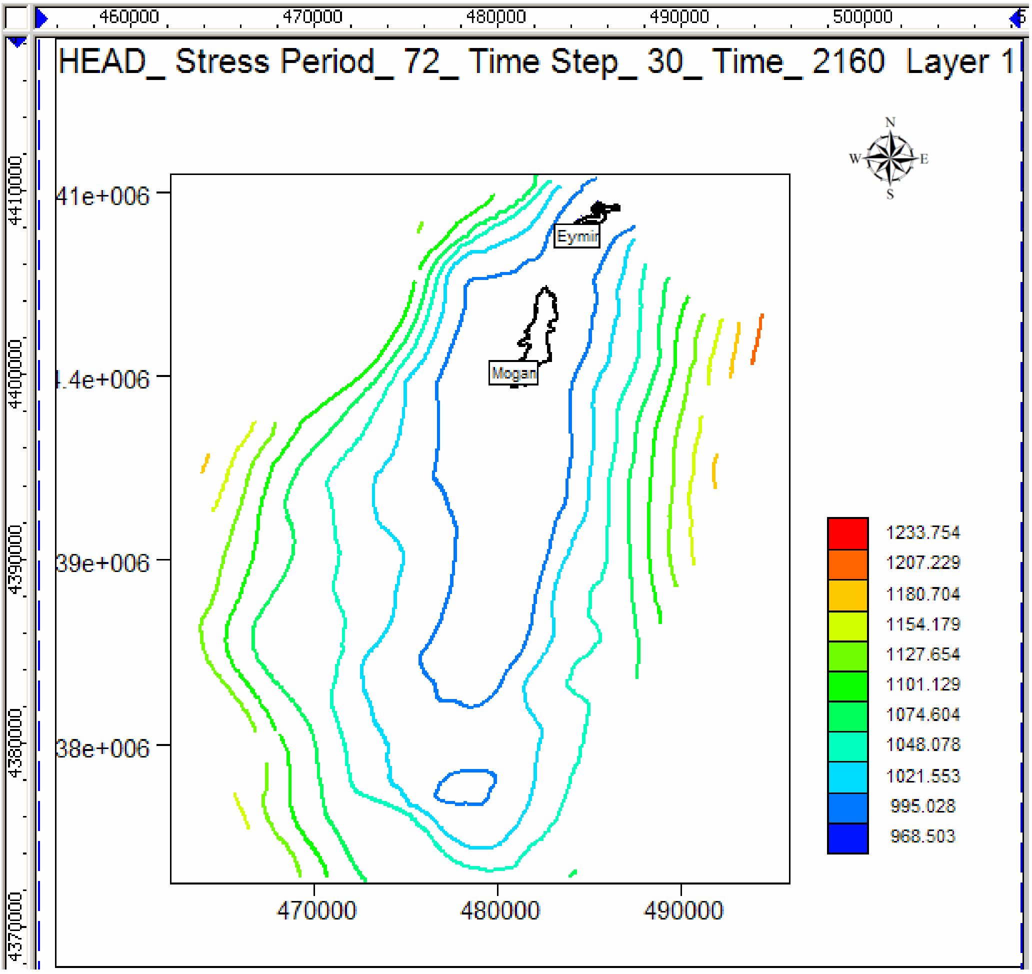

Figure 5.1. Groundwater level elevation map of the basin for September 2004 obtained by transient calibration.

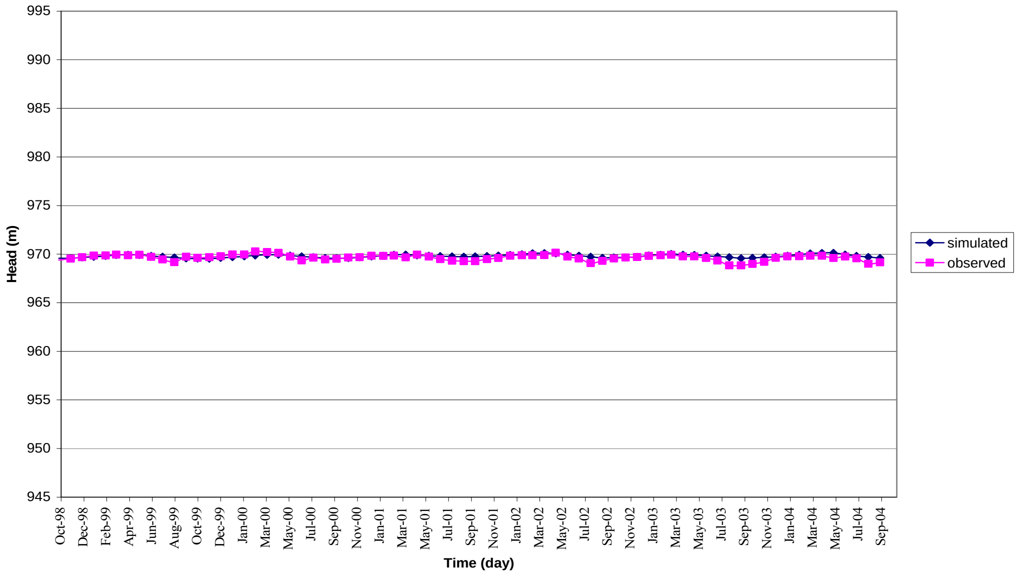

Figure 5.2. Observed and predicted hydrographs for Well no: 3 under transient conditions. (RMSE= 0.78, MAE= 0.61, ME= -0.42)

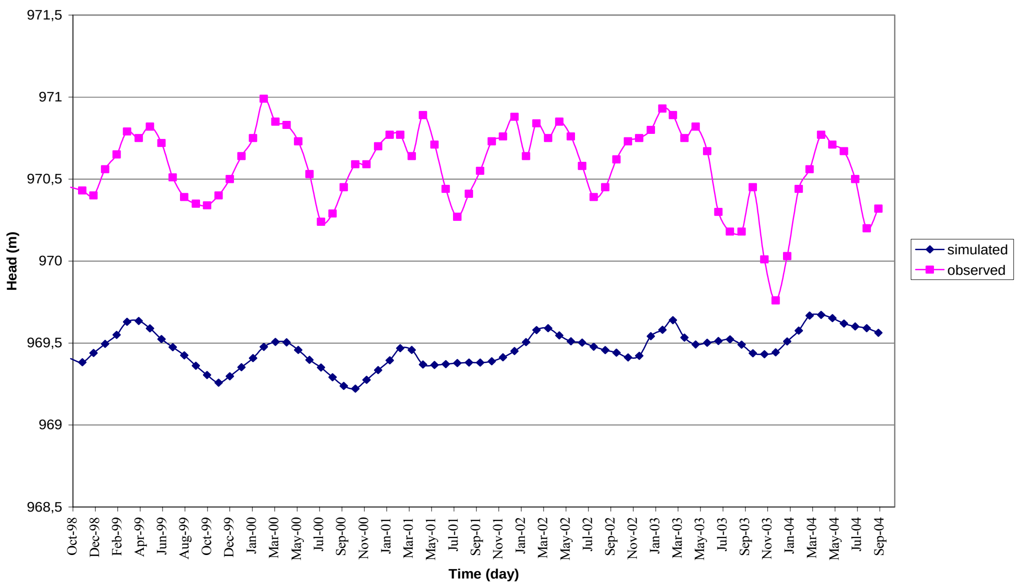

Figure 5.3. Observed and predicted hydrographs for Well no: 4 under transient conditions. (RMSE= 1.14, MAE= 1.11, ME= 1.11)

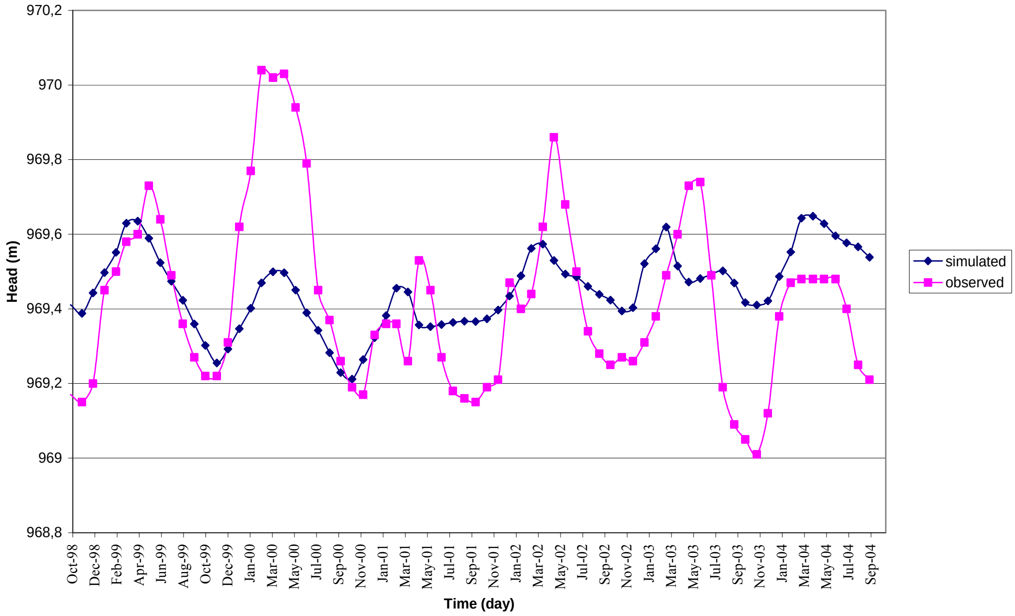

Figure 5.4. Observed and predicted hydrographs for Well no: 5 under transient conditions. (RMSE= 0.22, MAE= 0.18, ME= -0.03)

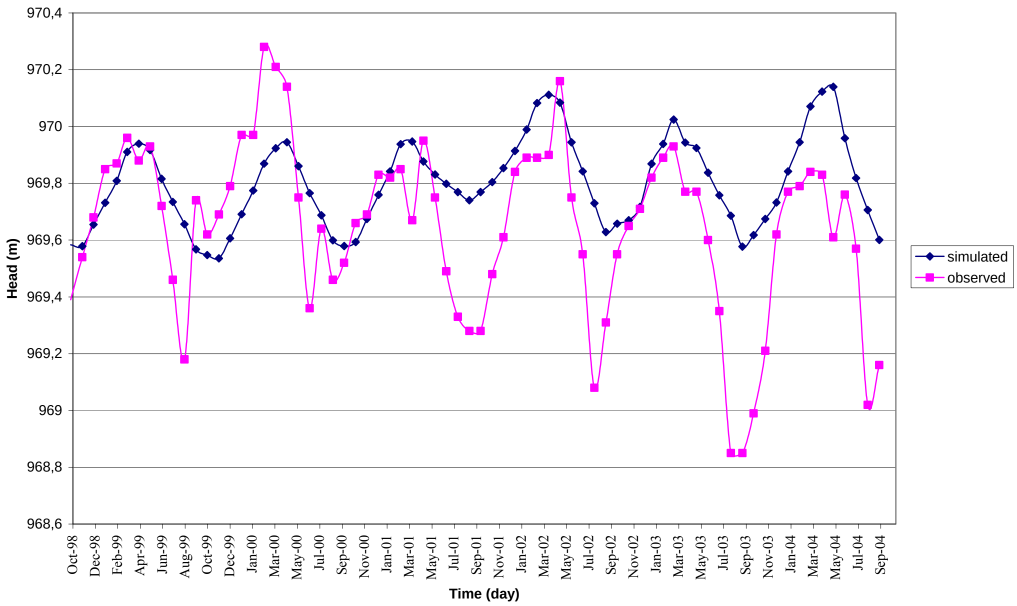

Figure 5.5. Observed and predicted hydrographs for Well no: 9 under transient conditions. (RMSE= 0.29, MAE= 0.22, ME= -0.15)

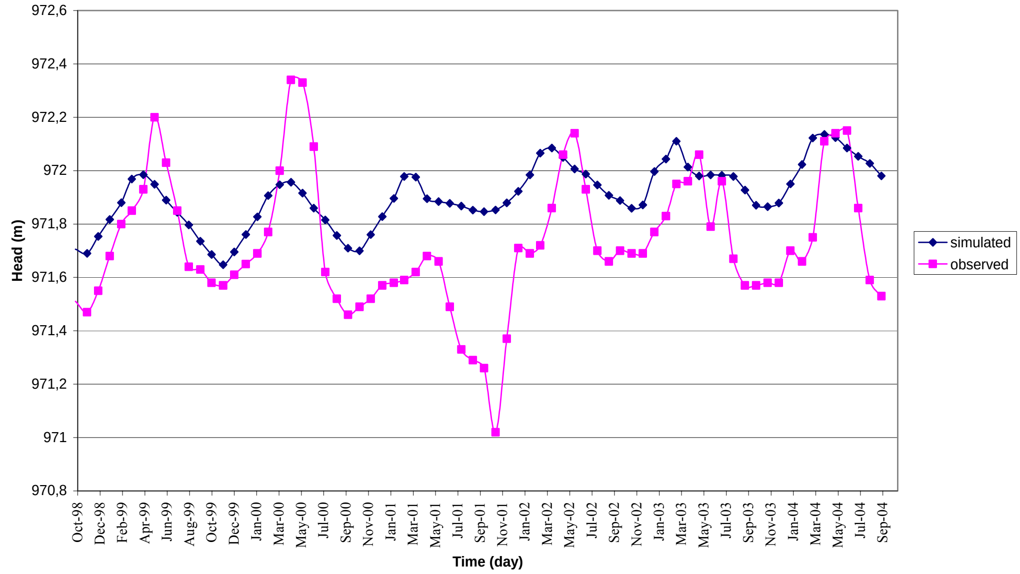

Figure 5.6. Observed and predicted hydrographs for Well no: 10 under transient conditions. (RMSE= 0.28, MAE= 0.23, ME= -0.18)

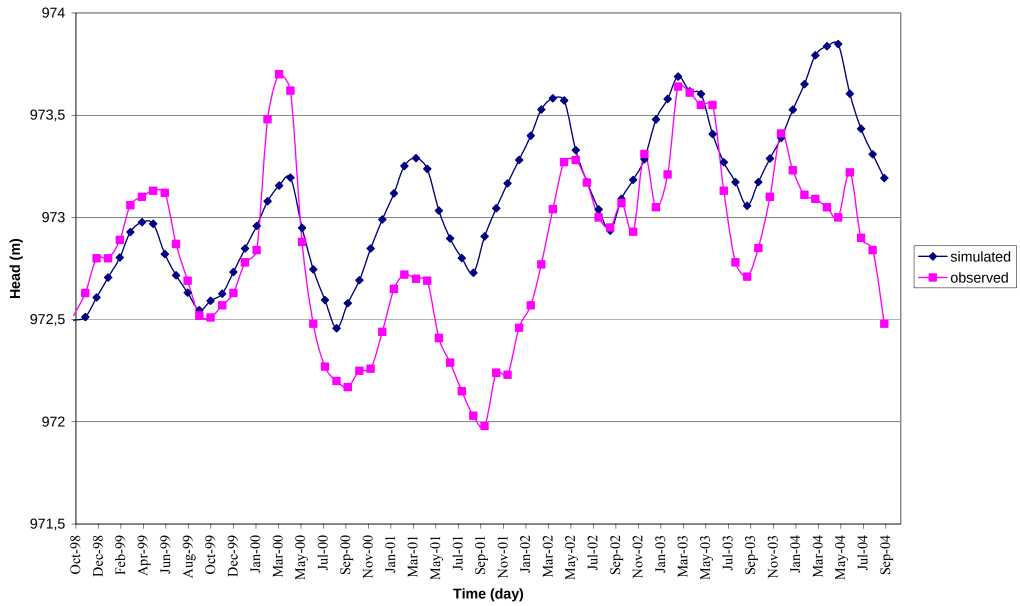

Figure 5.7. Observed and predicted hydrographs for Well no: 14 under transient conditions. (RMSE= 0.44, MAE= 0.35, ME= -0.26)

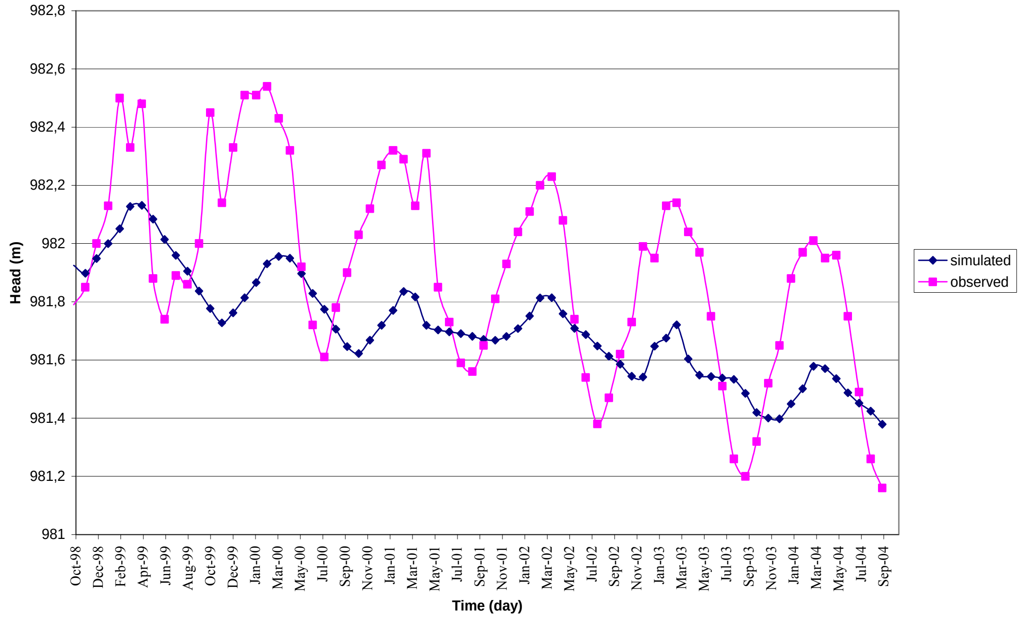

Figure 5.8. Observed and predicted hydrographs for Well no: 18 under transient conditions. (RMSE= 0.34, MAE= 0.28, ME= 0.20)

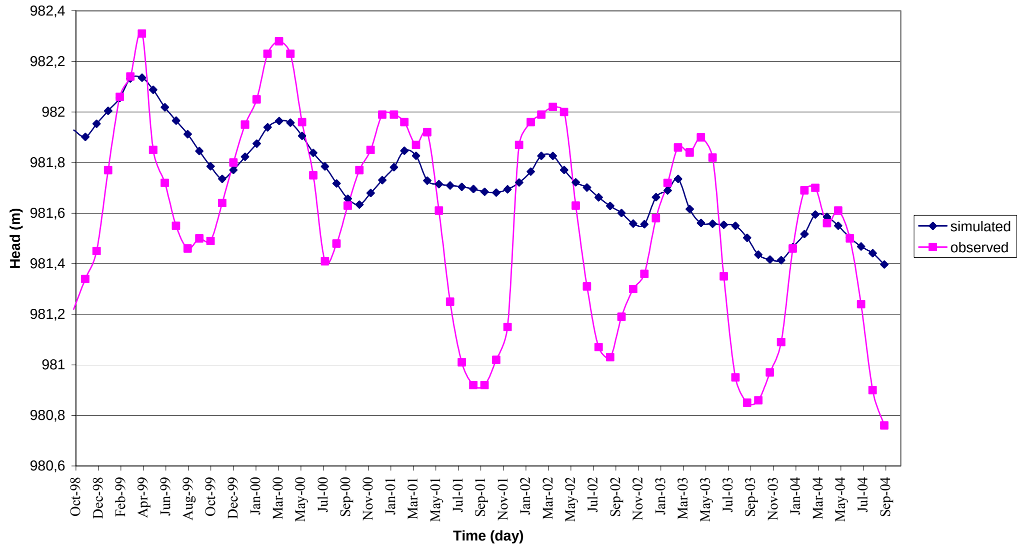

Figure 5.9. Observed and predicted hydrographs for Well no: 19 under transient conditions. (RMSE= 0.36, MAE= 0.29, ME= -0.15)

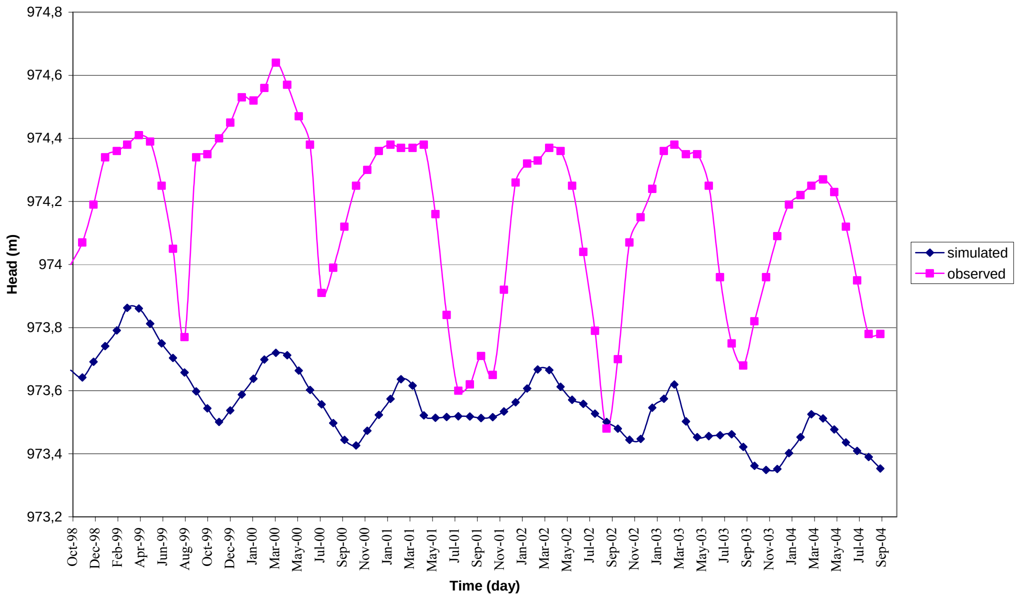

Figure 5.10. Observed and predicted hydrographs for Well no: 20 under transient conditions. (RMSE= 0.65, MAE= 0.60, ME= 0.60)

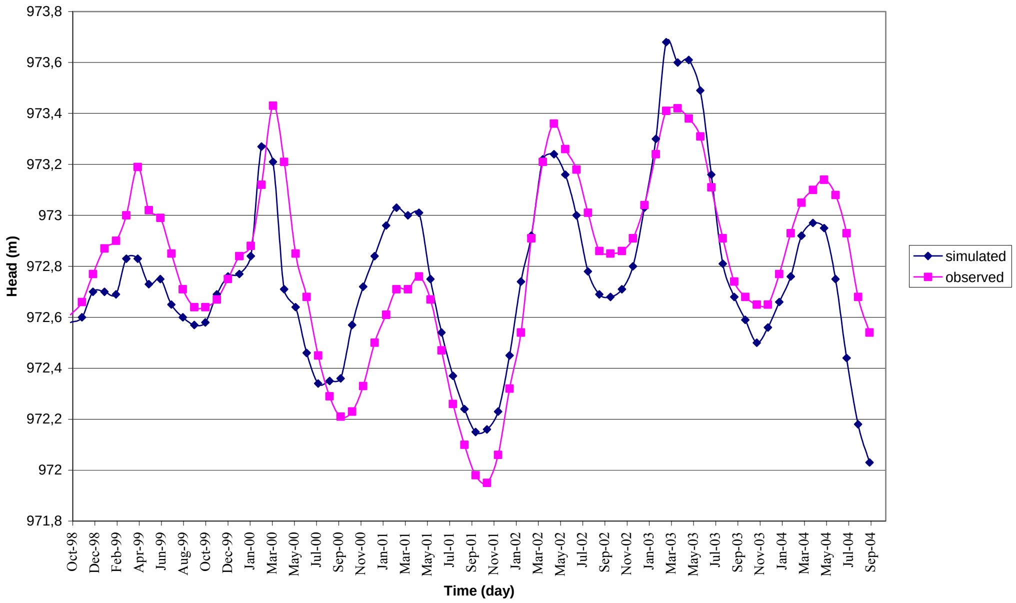

Figure 5.11. Observed and predicted hydrographs for Lake Mogan under transient conditions. (RMSE= 0.21, MAE= 0.18, ME= 0.04)

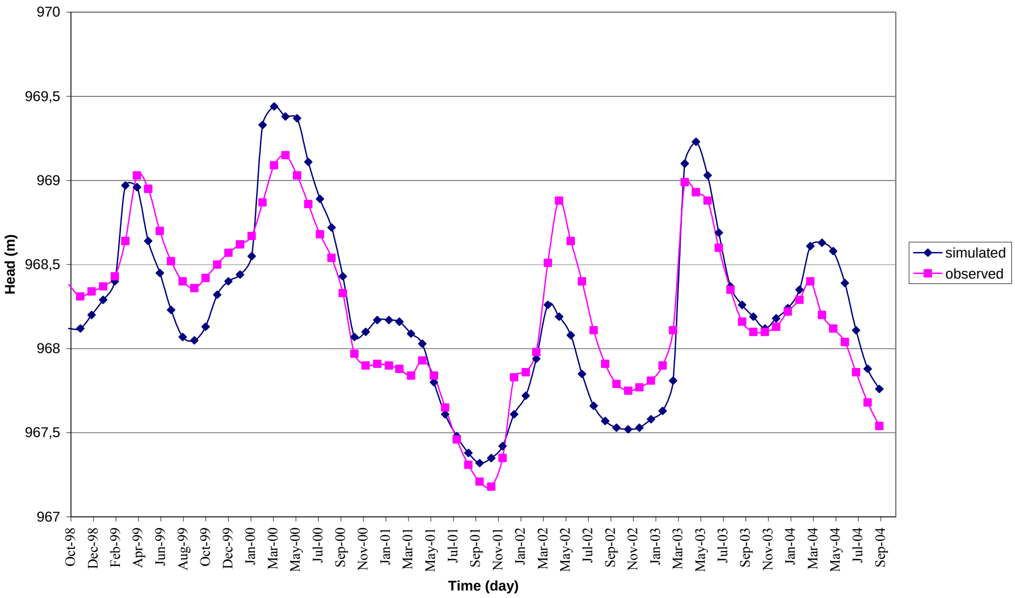

Figure 5.12. Observed and predicted hydrographs for Lake Eymir under transient conditions. (RMSE= 0.26, MAE= 0.22, ME= 0.01)

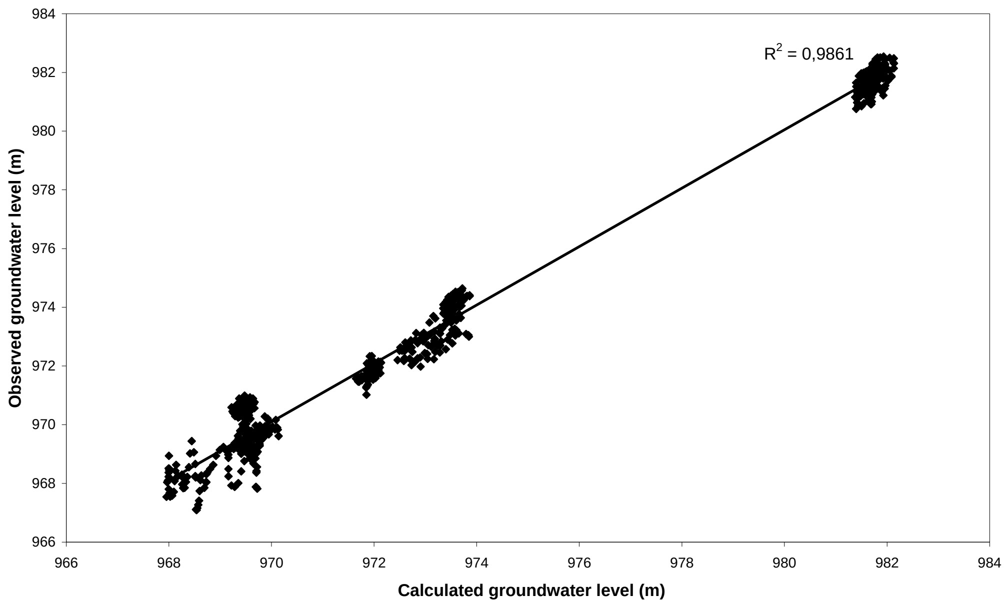

Figure 5.13. Calculated versus observed groundwater level elevations for the monitoring wells for October 1998- September 2004 under transient conditions.

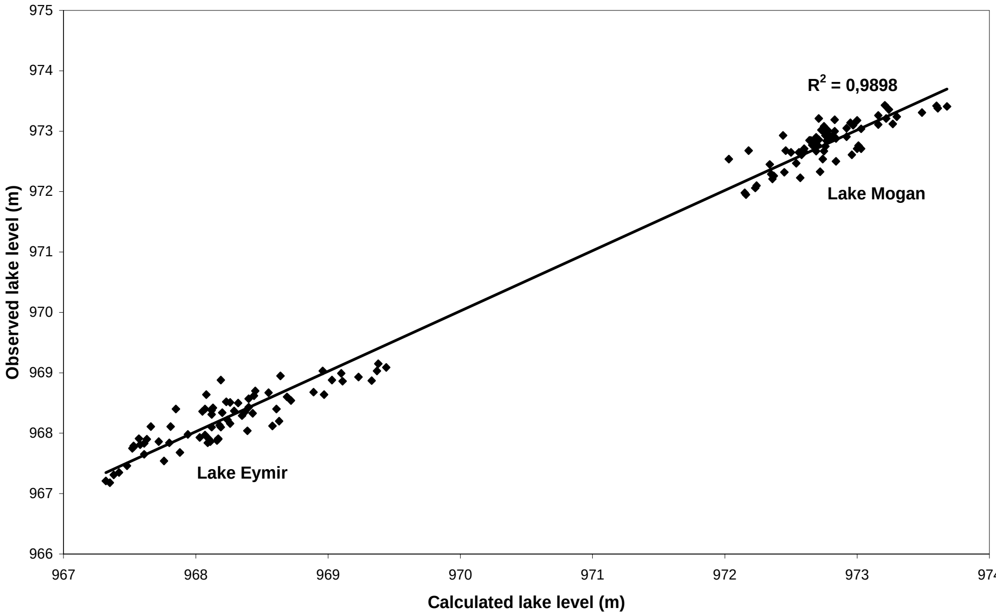

Figure 5.14. Calculated versus observed lake level elevations for Mogan and Eymir lakes for October 1998- September 2004 under transient conditions.

5.3 Groundwater Budget of the Study Area

The groundwater budget for the model is useful in evaluating whether the calibrated model adequately represents the hydrologic system of the study area. During the process of transient calibration a continuous check was maintained on the groundwater budget of the system. The groundwater budget obtained from calibration of the model under transient conditions between October 1998 and September 2004 is given in Table 5.2. In this period, average total discharge was 88 hm^3/year. Most of the discharge has taken place through evapotranspiration losses. The average total discharge was 26 hm^3/year greater than the average total recharge in the area. In this case, it can be concluded that there was an average of 26 hm^3/year decrease in the groundwater reserves of the aquifer. It is noted that most of the recharge to the aquifer was through areal precipitation. The values given in Table 5.2 represent average values for six years and they have changed each year.

Table 5.2. Groundwater budget obtained from calibration under transient conditions for the study area (October 1998- September 2004).

RECHARGE (hm^3/year)		**DISCHARGE (hm^3/year)**	
Precipitation	60.33	Evapotranspiration	85.50
Lake seepage	0.68	Pumpage	1.81
Head dependent boundary	0.70	Lake seepage	0.73
		Head dependent boundary	0.29
Total	61.71	Total	88.33
AVERAGE RESERVE CHANGE= 26.62 (hm^3/year)			

Groundwater recharge, discharge and change in reserves for each year in the period between October 1998 and September 2004 are given in Table 5.3. In this table, negative values of change in reserves shows periods when discharge is greater than recharge. Yearly changes in groundwater reserves are shown in Figure 5.15. It is noted from this figure and Table 5.3 that the decline in groundwater reserves was smaller than the average value for water years 2001 and 2002. This is attributed to the smaller amount of evapotranspiration losses in these years.

Table 5.3. Yearly groundwater budget and reserve changes obtained from calibration of the model under transient conditions for the study area (October 1998- September 2004).

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve* Change (hm^3/year)
	Precipitation	Lake seepage	Head dependent boundary	Total	Evapotranspiration	Pumpage	Lake seepage	Head dependent boundary	Total	
1999	73.70	0.65	0.80	75.15	109.00	1.81	0.48	0.48	111.77	-36.62
2000	76.80	0.78	0.76	78.34	112.20	1.81	0.70	0.30	115.01	-36.67
2001	60.40	0.49	0.72	61.61	68.10	1.81	0.83	0.27	71.01	-9.40
2002	46.40	0.81	0.67	47.88	61.90	1.81	0.58	0.24	64.53	-16.65
2003	44.80	1.02	0.65	46.47	74.10	1.81	0.84	0.22	76.97	-30.50
2004	59.90	0.35	0.62	60.87	87.70	1.81	0.94	0.21	90.66	-29.79
Average	60.33	0.68	0.70	61.72	85.50	1.81	0.73	0.29	88.33	-26.61

.

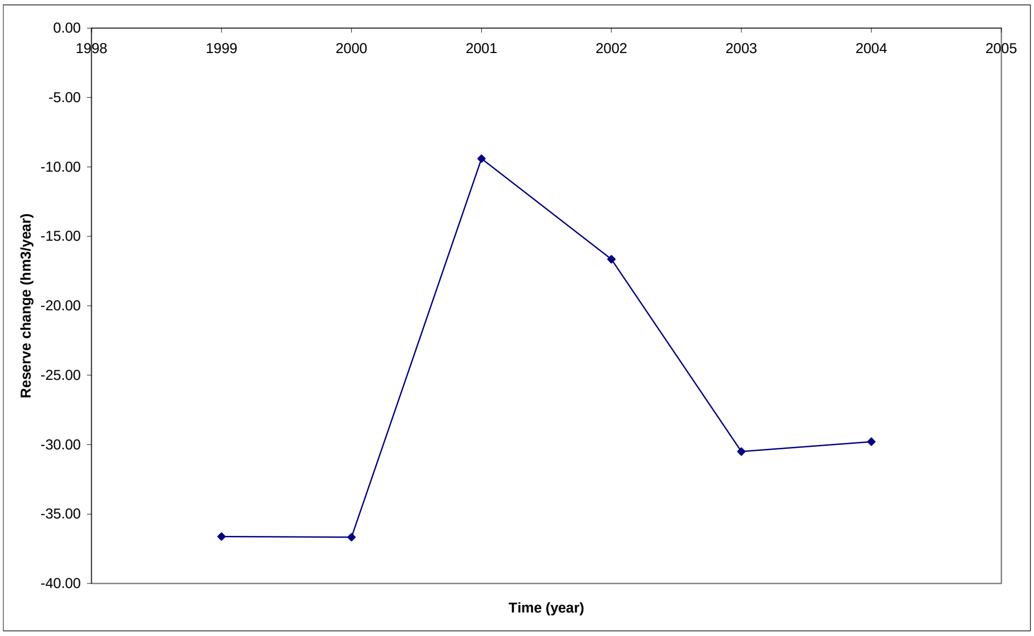

Figure 5.15. Calculated yearly changes in groundwater reserves between October 1998 and September 2004 under transient conditions.

5.4 Hydrologic Budget of the Lakes

During the transient calibration, the hydrologic budgets of the lakes were also continuously checked with the volumetric budget of the aquifer to examine the lake and aquifer interaction. The hydrologic budgets for Lakes Mogan and Eymir obtained from calibration of the model under transient conditions between October 1998 and September 2004 are given in Tables 5.4 and 5.5, respectively.

Table 5.4. Yearly Lake Mogans's budget and volume changes obtained from calibration of the model under transient conditions for the study area (October 1998- September 2004).

Years	Inflow (hm^3/year)				Outflow (hm^3/year)				Volume Change (hm^3/year)
	Precipitation	Runoff	Groundwater inflow	Total	Evapotrans piration	Withdrawal	Groundwater outflow	Total	
1999	2.79	12.10	0.25	15.14	4.38	8.47	0.38	13.23	1.91
2000	3.66	17.46	0.60	21.72	4.12	16.61	0.55	21.28	0.44
2001	2.45	5.44	0.52	8.41	6.26	0.64	0.49	7.39	1.02
2002	1.75	10.20	0.42	12.37	6.16	1.02	0.70	7.88	4.49
2003	1.81	11.77	0.66	14.24	8.47	3.16	0.72	12.35	1.89
2004	2.52	3.08	0.76	6.36	7.86	0.00	0.28	8.14	-1.78
Average	2.50	10.01	0.54	13.04	6.21	4.98	0.52	11.71	1.33

Table 5.5. Yearly Lake Eymir's budget and volume changes obtained from calibration of the model under transient conditions for the study area (October 1998- September 2004).

Years	Inflow (hm^3/year)				Outflow (hm^3/year)				Volume Change (hm^3/year)
	Precipitation	Runoff	Groundwater inflow	Total	Evapotrans piration	Withdrawal	Groundwater outflow	Total	
1999	0.54	9.24	0.22	10.00	0.85	9.21	0.26	10.32	-0.32
2000	0.71	16.78	0.10	17.59	0.80	15.80	0.22	16.82	0.77
2001	0.47	0.64	0.31	1.42	1.22	1.65	0.01	2.88	-1.46
2002	0.34	2.16	0.15	2.65	1.20	1.11	0.11	2.42	0.23
2003	0.35	3.28	0.17	3.80	1.65	1.06	0.30	3.01	0.79
2004	0.49	0.45	0.18	1.12	1.53	0.03	0.07	1.63	-0.51
Average	0.48	5.43	0.19	6.10	1.21	4.81	0.16	6.18	-0.08

When the pie charts showing the lakes' water budget components are examined (Figures 5.16 through 5.19), groundwater inflows and outflows have the lowest contribution to the overall lakes' budget. Average groundwater inflow and outflow for Lake Mogan accounted for 4 % of the total inflow and outflow for the lake. Groundwater component was also smaller with a value of 3 % in Lake Eymir's average total inflow and outflow. The major components of the inflows to both lakes consisted of the surface runoff, followed by the precipitation. Evapotranspiration and withdrawal accounted for the majority of the losses from the Lake Mogan. However, withdrawal is the major outflow component with 77 % for Lake Eymir, followed by evapotranspiration losses of 20 %.

Simulated lake budgets show that 17.1 L/s of groundwater enters Lake Mogan on the southern, western and eastern sides and 16.5 L/s discharges to groundwater system on the downgradient northern side. Lake Eymir, located downstream of Lake Mogan, is primarily fed by the water released from the Lake Mogan. The groundwater inflow to Lake Eymir is 6.0 L/s whereas the outflow to groundwater system on the northern downgradient side is 5.1 L/s. Most of the groundwater outflow from Lake Mogan is lost by evapotranspiration in the wetland between the lakes. The simulated groundwater inflow and outflow rates to both lakes are in conformity with the results of earlier studies based upon Darcy flux estimates (METU, 1995). The results confirmed the accuracy of the numerical model and verified the conceptual understanding of the hydrogeologic system. The calibrated model is subsequently used to assess the sensitivity of the model parameters by conducting sensitivity analyses.

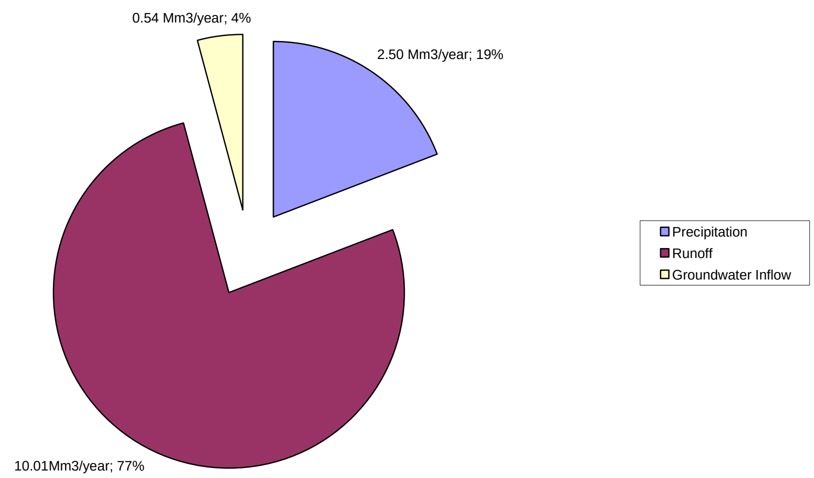

Figure 5.16. Lake Mogan's average inflow rates obtained from transient calibration of the model between October 1998 and September 2004.

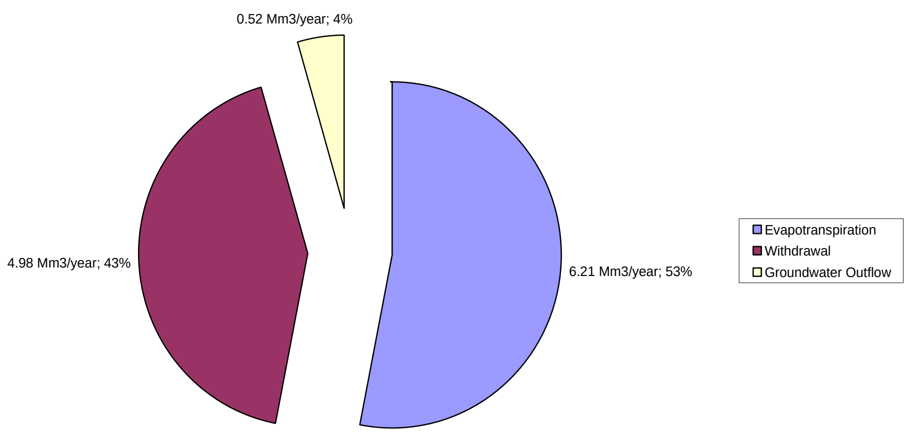

Figure 5.17. Lake Mogan's average outflow rates obtained from transient calibration of the model between October 1998 and September 2004.

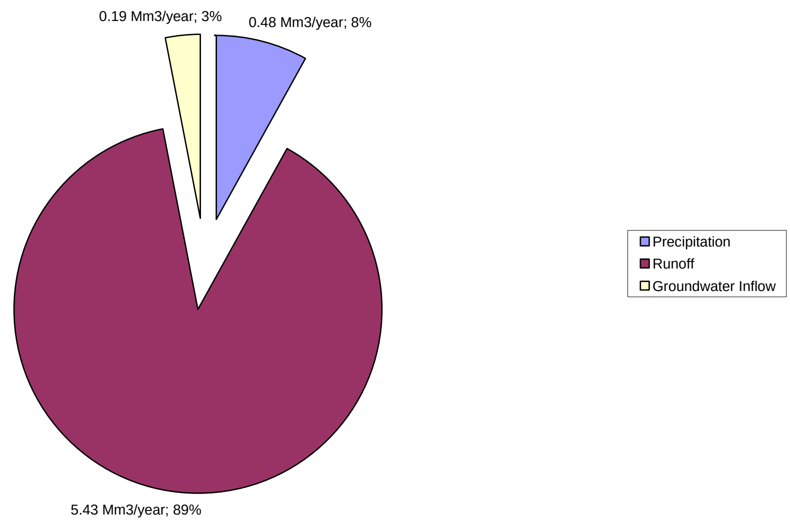

Figure 5.18. Lake Eymir's average inflow rates obtained from transient calibration of the model between October 1998 and September 2004.

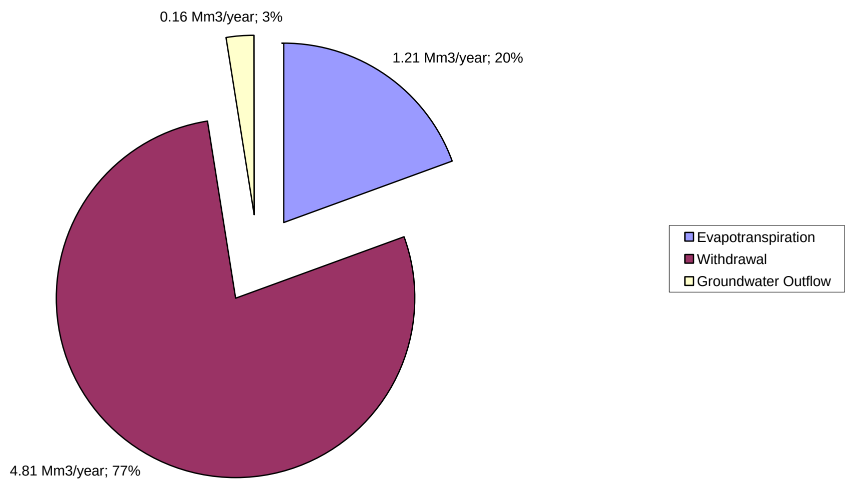

Figure 5.19. Lake Eymir's average outflow rates obtained from transient calibration of the model between October 1998 and September 2004.

5.5 Sensitivity Analyses

A sensitivity analysis was done to determine the sensitivity of the model to changes in input model parameters. Sensitivity analysis can help determine which model parameters have the greatest effect on a model. The results of the analysis can guide future data collection efforts and will reduce modeling errors. The sensitivity simulations were done by changing one input parameter at a time, while keeping the other parameters constant. A limitation of this approach is that the effects of simultaneous changes of multiple input parameters cannot be evaluated. The sensitivity of the model was evaluated by comparing water levels and RMSE, ME and MAE values of the sensitivity simulations with those from the calibrated transient model in the study area.

Model sensitivity was determined for variations in hydraulic conductivity, specific yield and specific storage of the aquifer, areal recharge and evapotranspiration rates, and lakebed hydraulic conductivities for both lakes. The magnitude of these variations was based on a range of reasonable values for each parameter and on the sensitivity observed during the calibration process.

The RMSE, ME and MAE values resulting from the sensitivity analyses are shown in Table 5.6. The values given in bold correspond to the calibrated model results. The largest water level changes resulted from the changes in the hydraulic conductivity and recharge values of the Quaternary alluvium (Zone 1 in Figure 4.14). The responses in Zones 2 to 5 cannot be observed due to the lack of monitoring wells in these parts of the study area. An increase in the hydraulic conductivity of Zone 1 did not affect the RMSE of the lake levels but increased the RMSE values of the groundwater levels. In contrary, a decrease has significantly increased the RMSE of the lake levels. The variation in vertical hydraulic conductivity of the layers did not have an effect on the RMSE of the monitoring wells but it had a slight effect on the lake levels. The increase or decrease in areal recharge rate to Zone 1 while had no effect on lake levels, slightly increased the RMSE of the groundwater levels. The variation in specific yield values did not have a significant effect on the RMSE of the groundwater and lake levels. In contrary, the variations in specific storage values of the layers had affected both systems. The variations in the evapotranspiration rate did not have an effect on the lake levels but had an effect on groundwater levels.

Simulated lake levels were also sensitive to changes in the lakebed hydraulic conductivity values assigned for the lakes. The variations in the lakebed hydraulic conductivities of the both lakes have a significant effect on the lake levels, but no effect on the groundwater levels. Extreme variations in lakebed hydraulic conductivities were also conducted by setting the values to zero and 1 m/d for both lakes. Both values produced a significant effect on the RMSE of the lake levels. While a zero lakebed hydraulic conductivity had no effect on the groundwater levels, a higher value (1 m/d) produced an increase in the RMSE values.

In summary, the results of the sensitivity analysis indicate that the model is sensitive to different parameters as explained above. The lack of monitoring well information in different conductivity zones precluded judging the sensitivity of the model parameters for these zones. Hence, the future data collection network in the system should be extended to these zones.

Table 5.6. Sensitivity analyses results.

Parameter	Value	RMSE for wells	RMSE for lakes	MAE for wells	MAE for lakes	ME for wells	ME for lakes
Hydraulic conductivity Zone 1 (m/d)	5	0.63	0.35	0.56	0.29	0.31	-0.12
	10	0.51	0.37	0.44	0.31	0.21	-0.16
	15	0.47	0.47	0.41	0.4	0.14	-0.27
	20	**0.5**	**0.24**	**0.43**	**0.2**	**0.08**	**0.03**
	25	0.54	0.23	0.47	0.19	0.03	-0.001
	30	0.58	0.26	0.51	0.22	-0.02	-0.068
Hydraulic conductivity Zone 2 (m/d)	1	0.49	0.245	0.43	0.205	0.14	0.007
	5	0.49	0.24	0.43	0.21	0.11	0.01
	10	**0.5**	**0.24**	**0.43**	**0.2**	**0.08**	**0.03**
	15	0.51	0.23	0.44	0.2	0.05	0.004
	20	0.52	0.25	0.45	0.21	0.02	0.053

Table 5.6. (Continued).

Parameter	Value	RMSE for wells	RMSE for lakes	MAE for wells	MAE for lakes	ME for wells	ME for lakes
Hydraulic conductivity Zone 3 (m/d)	1	0.5	0.235	0.43	0.195	0.08	0.03
	2	0.5	0.235	0.43	0.195	0.08	0.03
	5	**0.5**	**0.24**	**0.43**	**0.2**	**0.08**	**0.03**
	10	0.5	0.235	0.43	0.195	0.08	0.02
	15	0.5	0.235	0.43	0.195	0.08	0.002
Hydraulic conductivity Zone 4 (m/d)	0.5	0.5	0.24	0.43	0.2	0.08	0.022
	1	0.5	0.24	0.43	0.2	0.08	0.025
	2	**0.5**	**0.24**	**0.43**	**0.2**	**0.08**	**0.03**
	5	0.5	0.24	0.43	0.2	0.08	0.022
	10	0.5	0.24	0.43	0.2	0.08	0.014

Table 5.6. (Continued).

Parameter	Value	RMSE for wells	RMSE for lakes	MAE for wells	MAE for lakes	ME for wells	ME for lakes
Hydraulic conductivity Zone 5 (m/d)	0.1	0.51	0.24	0.44	0.2	0.05	0.022
	0.5	0.5	0.24	0.43	0.2	0.07	0.011
	1	**0.5**	**0.24**	**0.43**	**0.2**	**0.08**	**0.03**
	2	0.5	0.24	0.43	0.2	0.1	0.024
	5	0.5	0.24	0.43	0.2	0.11	0.011
Ratio of horizontal to vertical hydraulic conductivity	(= K_x/20)	0.5	0.28	0.43	0.235	0.08	0.001
	(= K_x/15)	0.5	0.355	0.44	0.305	0.07	-0.194
	(= K_x/10)	**0.5**	**0.24**	**0.43**	**0.2**	**0.08**	**0.03**
	(= K_x/5)	0.5	0.235	0.43	0.195	0.08	-0.03
	(= K_x/2)	0.5	0.25	0.43	0.21	0.08	0.02

Table 5.6. (Continued).

Parameter	Value	RMSE for wells	RMSE for lakes	MAE for wells	MAE for lakes	ME for wells	ME for lakes
Recharge multiplier Zone 1	0.6	0.54	0.24	0.48	0.2	0.29	0.03
	0.7	0.5	0.24	0.43	0.19	0.18	0.03
	0.8	**0.5**	**0.24**	**0.43**	**0.2**	**0.08**	**0.03**
	0.9	0.53	0.24	0.46	0.2	-0.03	0.02
	1	0.58	0.24	0.5	0.2	-0.13	0.01
Recharge multiplier Zone 2	0.5	0.52	0.24	0.45	0.2	0.11	0.02
	0.6	0.51	0.24	0.44	0.2	0.1	0.02
	0.7	**0.5**	**0.24**	**0.43**	**0.2**	**0.08**	**0.03**
	0.8	0.49	0.24	0.42	0.2	0.06	0.02
	0.9	0.48	0.24	0.41	0.2	0.05	0.02

Table 5.6. (Continued).

Parameter	Value	RMSE for wells	RMSE for lakes	MAE for wells	MAE for lakes	ME for wells	ME for lakes
Recharge multiplier Zone 3	0.4	0.5	0.24	0.43	0.2	0.08	0.02
	0.5	0.5	0.24	0.43	0.2	0.08	0.02
	0.6	**0.5**	**0.24**	**0.43**	**0.2**	**0.08**	**0.03**
	0.7	0.5	0.24	0.43	0.2	0.08	0.02
	0.8	0.5	0.24	0.43	0.2	0.08	0.02
Recharge multiplier Zone 4	0.1	0.5	0.24	0.43	0.2	0.08	0.02
	0.2	0.5	0.24	0.43	0.2	0.08	0.02
	0.3	**0.5**	**0.24**	**0.43**	**0.2**	**0.08**	**0.03**
	0.4	0.5	0.24	0.43	0.2	0.08	0.02
	0.5	0.5	0.24	0.43	0.2	0.08	0.02

Table 5.6. (Continued).

Parameter	Value	RMSE for wells	RMSE for lakes	MAE for wells	MAE for lakes	ME for wells	ME for lakes
Recharge multiplier Zone 5	0.05	0.5	0.23	0.43	0.2	0.09	0.03
	0.01	0.5	0.24	0.43	0.2	0.09	0.02
	0.15	**0.5**	**0.24**	**0.43**	**0.2**	**0.08**	**0.03**
	0.2	0.5	0.24	0.43	0.2	0.08	0.04
	0.25	0.5	0.24	0.43	0.2	0.07	0.04
Specific yield	0.01	0.54	0.23	0.47	0.19	0.06	-0.002
	0.05	0.51	0.23	0.45	0.2	0.08	0.02
	0.1	**0.5**	**0.24**	**0.43**	**0.2**	**0.08**	**0.03**
	0.15	0.49	0.24	0.42	0.21	0.08	0.01
	0.2	0.49	0.24	0.43	0.21	0.08	0.01

Table 5.6. (Continued).

Parameter	Value	RMSE for wells	RMSE for lakes	MAE for wells	MAE for lakes	ME for wells	ME for lakes
Specific storage	$5x10^{-4}$	0.75	0.26	0.64	0.21	-0.08	-0.04
	$5x10^{-3}$	**0.5**	**0.24**	**0.43**	**0.2**	**0.08**	**0.03**
	$1x10^{-3}$	0.67	0.28	0.58	0.22	-0.03	-0.07
	$1x10^{-2}$	0.5	0.24	0.44	0.2	0.08	0.07
	$5x10^{-2}$	0.59	0.4	0.52	0.34	0.03	0.28
Evapotrans piration multiplier	0.3	0.6	0.25	0.51	0.21	-0.21	0.03
	0.35	0.53	0.24	0.45	0.2	-0.06	0.04
	0.4	**0.5**	**0.24**	**0.43**	**0.2**	**0.08**	**0.03**
	0.45	0.51	0.24	0.45	0.2	0.22	0.004
	0.5	0.58	0.24	0.52	0.19	0.36	-0.02

Table 5.6. (Continued).

Parameter	Value	RMSE for wells	RMSE for lakes	MAE for wells	MAE for lakes	ME for wells	ME for lakes
Lakebed hydraulic conductivity for Lake Mogan (m/d)	0.35	0.49	0.51	0.43	0.42	0.09	0.32
	0.3	0.5	0.25	0.43	0.21	0.08	0.03
	0.25	**0.5**	**0.24**	**0.43**	**0.2**	**0.08**	**0.03**
	0.2	0.51	0.65	0.44	0.56	0.07	-0.44
	0.15	0.5	0.46	0.44	0.4	0.07	-0.27
Lakebed hydraulic conductivity for Lake Eymir (m/d)	0.2	0.5	0.28	0.43	0.24	0.03	-0.07
	0.15	0.5	0.26	0.43	0.22	0.08	-0.04
	0.1	**0.5**	**0.24**	**0.43**	**0.2**	**0.08**	**0.03**
	0.05	0.5	0.24	0.43	0.21	0.08	0.001
	0.01	0.5	0.25	0.43	0.22	0.08	-0.02

Table 5.6. (Continued).

Parameter	Value	RMSE for wells	RMSE for lakes	MAE for wells	MAE for lakes	ME for wells	ME for lakes
Lakebed hydraulic conductivity for Lake Mogan (m/d)	0	0.5	0.59	0.43	0.51	0.08	0.47
Lakebed hydraulic conductivity for Lake Eymir (m/d)	0						
Lakebed hydraulic conductivity for Lake Mogan (m/d)	1	0.55	2.9	0.47	2.45	0.03	-2.14
Lakebed hydraulic conductivity for Lake Eymir (m/d)	1						

CHAPTER 6

ALTERNATIVE GROUNDWATER MANAGEMENT SCENARIOS

6.1 Introduction

At the end of transient model studies, having very good agreement between calculated and observed water levels has shown that calibration of the model was successful. These results confirmed accuracy of physical parameters in representing field conditions. Having these parameters with successful calibration also confirms the accuracy of the model in predicting future aquifer and lake responses. Thus, the model is ready for operation as a predictive tool to evaluate the hydraulic response of the aquifer and lake systems to existing or proposed planning and management policies.

In order to aid decision makers in planning and management of the Mogan and Eymir Lakes Basin, alternative scenarios had been developed. In Scenario A, the impact of upstream reservoirs (Dikilitaş and İkizce) existing in the basin was evaluated. In Scenario B, the continuation of existing average recharge and discharge conditions were taken into consideration for future predictions. Finally, Scenario C is developed to evaluate the impact of extended drought conditions on the groundwater and lake systems. A planning period of 16 years, beginning from October 2004 and ending in September 2020, was selected for Scenarios B and C. The Scenarios B and C started from the point where the transient calibrated model ended. The model boundaries and the finite difference grid remained unchanged for all of the scenarios. The trade-off curve between the amount of water released from the reservoirs and the average lake level for Mogan in Scenario A and the hydrographs showing the calculated elevation changes in the groundwater and lake systems for Scenarios B and C were prepared for comparison purposes.

6.2 Scenario A: Impact of Upstream Reservoirs

İkizce and Dikilitaş reservoirs were constructed on creeks feeding Lake Mogan and they have been used for irrigation purposes since 1977 and 1988, respectively. Dikilitaş reservoir is the larger of the two with an active storage capacity of 9.10×10^6 m^3. İkizce reservoir has an active storage capacity of 1.10×10^6 m^3. Dikilitaş and İkizce reservoirs irrigate 2400 ha and 400 ha of land, respectively. Studies conducted by METU (1995) claimed that these reservoirs, especially Dikilitaş, constructed on Çölova Creek have a significant impact on the amount of inflow to Lake Mogan. Although no quantitative evaluation has been made by METU (1995), they recommended that this effect should be taken into account in the operation plan of the reservoirs. Thus, it would be of utmost importance to quantify this effect and to develop a trade-off curve between the amount of water released from the reservoirs and the Lake Mogan's stage. The calibrated model was used to study these effects and quantify the impacts.

Because no data for the period prior to the construction of the reservoirs were available, the effects of the reservoirs were quantified by using the data from the calibration period of 1998-2004. Unfortunately, the available stream-flow data is of very short duration to develop stochastic monthly runoff series. Consequently, a simple approach is used herein to develop runoff series for the condition "without reservoirs". The measured runoff series for Çölova Creek were multiplied by the ratio of the contributing runoff areas for the conditions "with" and "without reservoirs". The contributing runoff areas were determined as 549.2 km^2 and 304 km^2, giving a ratio of 1.80. In addition, both reservoirs were removed from the flow model.

The calibrated model parameters were used without any change. The model was rerun with the new runoff series generated for Çölova Creek, yielding a new inflow series for Lake Mogan for the condition "without reservoirs". The outflow series from Lake Mogan is assumed to be unchanged. The resulting changes in the lake level and groundwater elevations were observed for the period 1998-2004. The simulated stage elevations for Lake Mogan for the conditions "with" and "without reservoirs" are shown in Figure 6.1. The examination of this figure shows that the average stage for Lake Mogan has increased from 972.76 m to 974.64 m for the condition "without reservoirs". Because the outflow series from Lake Mogan was unchanged there were no changes in the stage of the Lake Eymir. The results of the simulation also demonstrated that the groundwater levels were not affected. Thus, the results of this simulation showed that if the upstream reservoirs existing in the basin were not constructed, the stage in Lake Mogan may have increased on the average by 1.88 m. Furthermore, if the outflow series were also increased from Lake Mogan, the stages in Lake Eymir would also be increased significantly.

In order to enhance decision makers' ability to decide on the amount of water that should be released from these reservoirs, a series of simulations were conducted to generate a trade-off curve between the amount of water released and the average stage in Lake Mogan. Five simulations were done by releasing 100000 m^3/month, 200000 m^3/month, 300000 m^3/month, 400000 m^3/month and 500000 m^3/month from the reservoirs in the months June through September and calculating the corresponding average elevations of Lake Mogan to construct a trade-off curve for the decision makers (Figure 6.2). The trade-off curve shows that the relation between the amount of water released from the reservoirs and the average stage in Lake Mogan is almost linear. The stage increases from the calibrated average value of 972.76 m (no release) to 973.5 m for a monthly release of 500000 m^3. Here, a trade-off between the amount of water to be used for irrigation and sustainable lake stages exist. These two objectives are generally non-commensurable and conflicting. Hence, a decision has to be made between them. This is however a prerogative of decision makers. They may select an optimum point on the curve that best represents their choice between these two conflicting objectives.

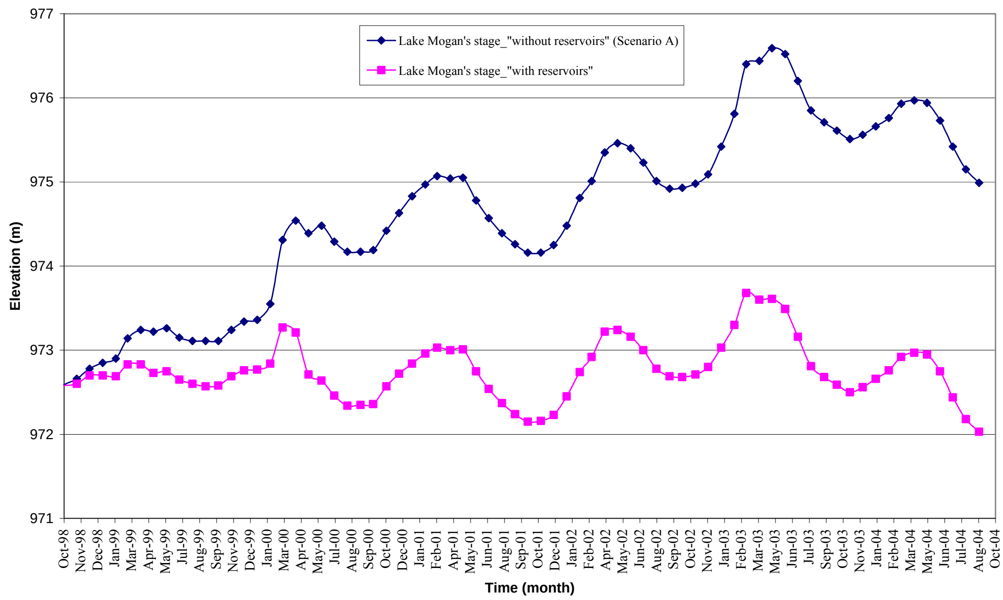

Figure 6.1. Predicted stages in Lake Mogan for conditions "with" and "without reservoirs" (Scenario A).

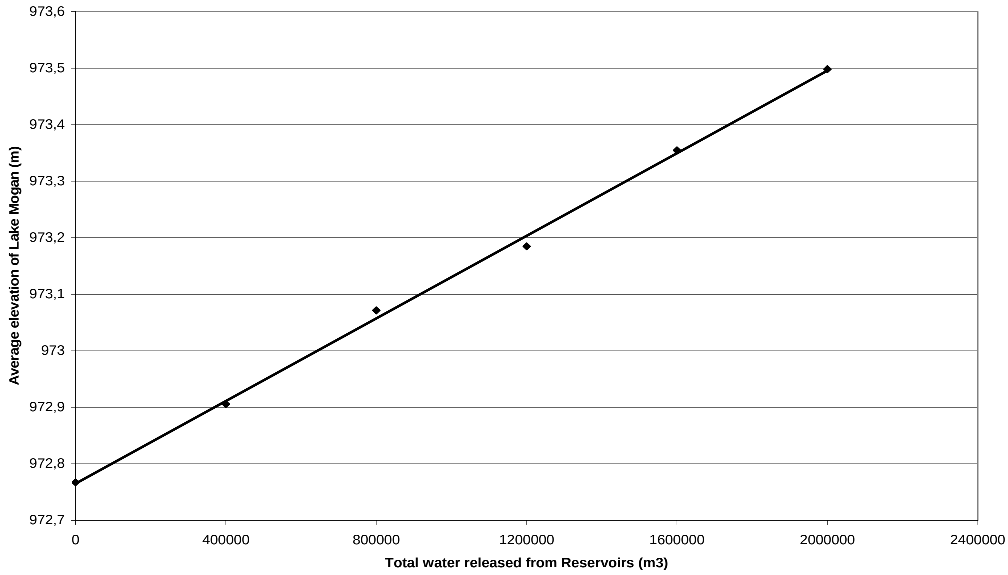

Figure 6.2. Trade-off curve between the average stage of Lake Mogan and the amount of water released from the reservoirs.

6.3 Scenario B: Continuation of Existing Average Conditions

This scenario assumes that the average conditions observed for 1998-2004 continue throughout the basin for a planning period of 16 years to predict the long-term responses of the groundwater and lakes system. The monthly average values of measured inflows and outflows for both lakes calculated from the calibration period of October 1998- September 2004 were used consecutively for the planning period beginning from October 2004 and ending in September 2020. In Scenario B, together with constant yearly pumpage rates, other calibrated model parameters were used with no change.

Predicted water level hydrographs in the planning period for the groundwater system and the lakes obtained from this simulation are shown in Figures 6.3 through 6.13. For comparison purposes, the results of the Scenario B are given with the results of Scenario C as will be explained later. As it can be seen from these graphs, if the average conditions continue for 16 years, there would be declines in groundwater elevations especially in the monitoring wells located upstream from Lake Mogan (nos. 18, 19 and 20) and downstream from Lake Eymir (no. 3). The predicted maximum decline at the end of the planning period is about 2.75 m. It appears that it would take more than 16 years to reach a pseudo steady-state conditions. In effect, this could also be noticed by the observed slight rise (about 0.8 m) in water levels between the two lakes (Monitoring wells nos. 4, 5, and 9). The rate of rise in water levels in these wells however decreases with time. The water levels in these wells have increased in response to transient recharge from Lake Mogan. The predicted response of Lake Mogan to average conditions is a slight decrease through years 2004-2016, then a steady- state condition in the elevations to the end of the planning period (2020). The maximum predicted decrease in Lake Mogan's level at the end of the planning period was 0.5 m. In the case of Lake Eymir, however, water levels decline continuously throughout the planning period. The water levels at Lake Eymir would decline about 1.2 m at the end of the planning period from the levels at 2004. The greater amount of decline observed in water levels of Lake Eymir is due to its low storage capacity compared to Lake Mogan.

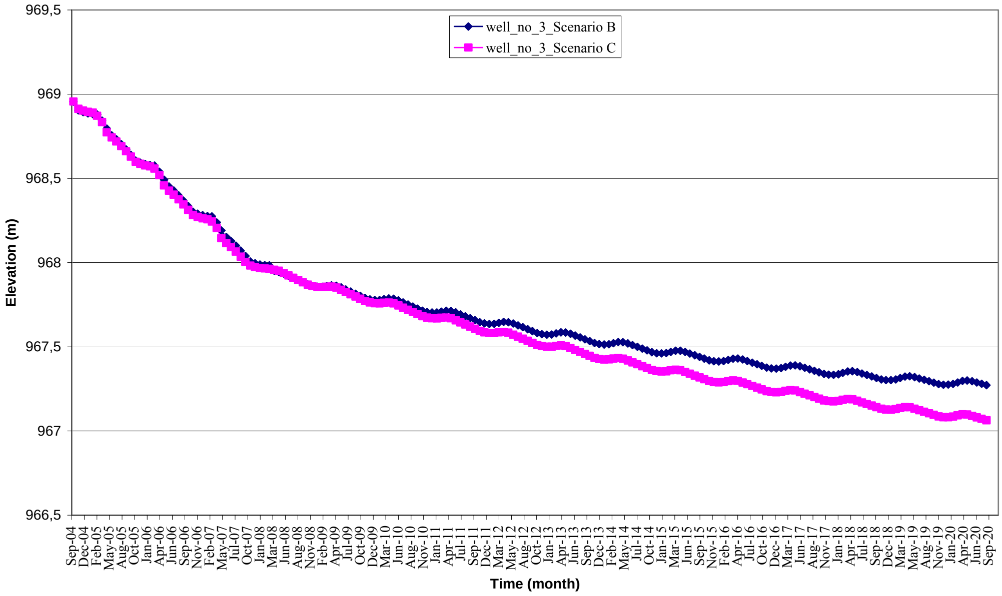

Figure 6.3. Predicted groundwater elevations for Scenarios B & C in Well no: 3.

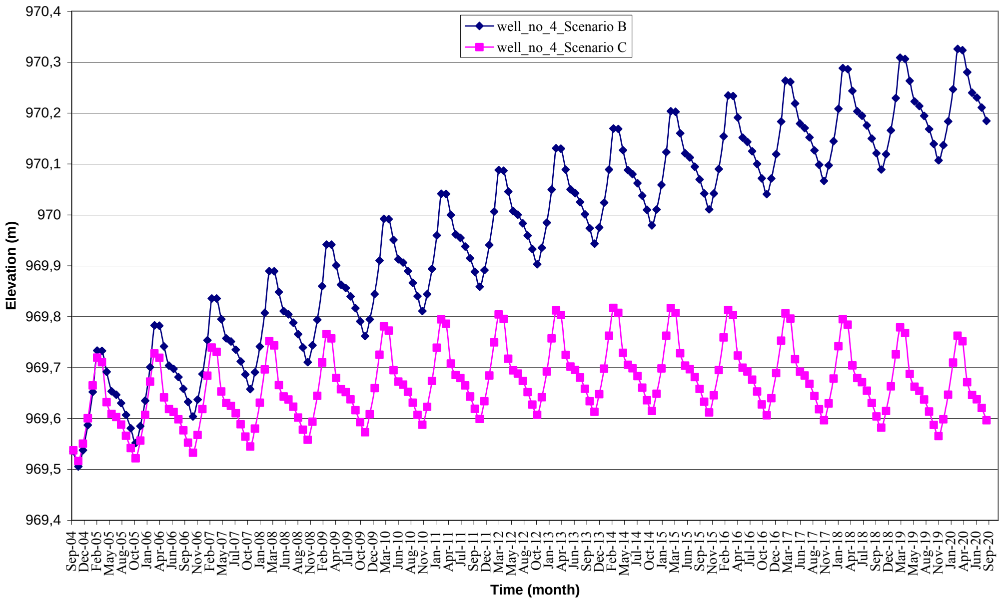

Figure 6.4. Predicted groundwater elevations for Scenarios B & C in Well no: 4.

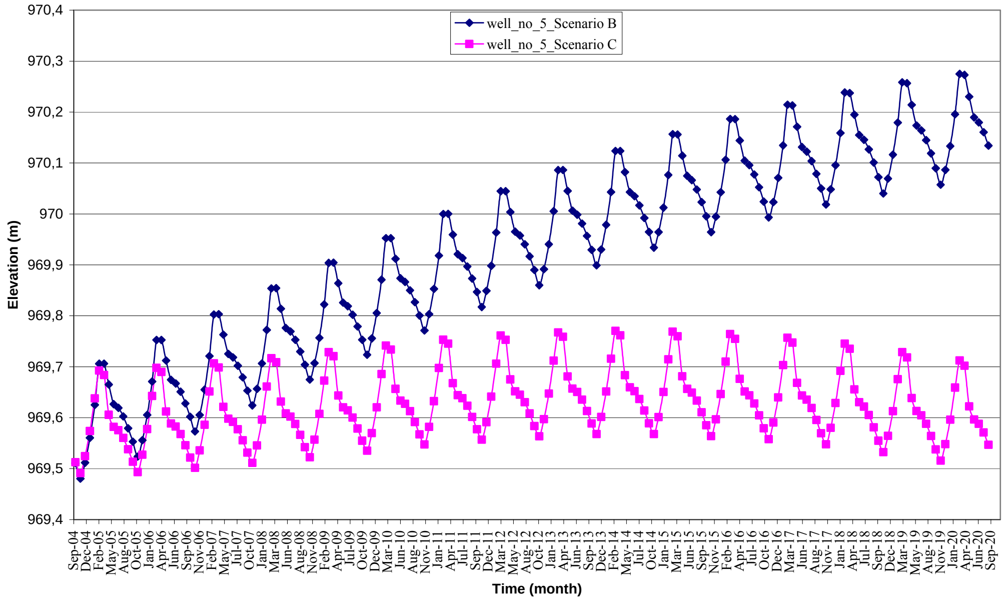

Figure 6.5. Predicted groundwater elevations for Scenarios B & C in Well no: 5.

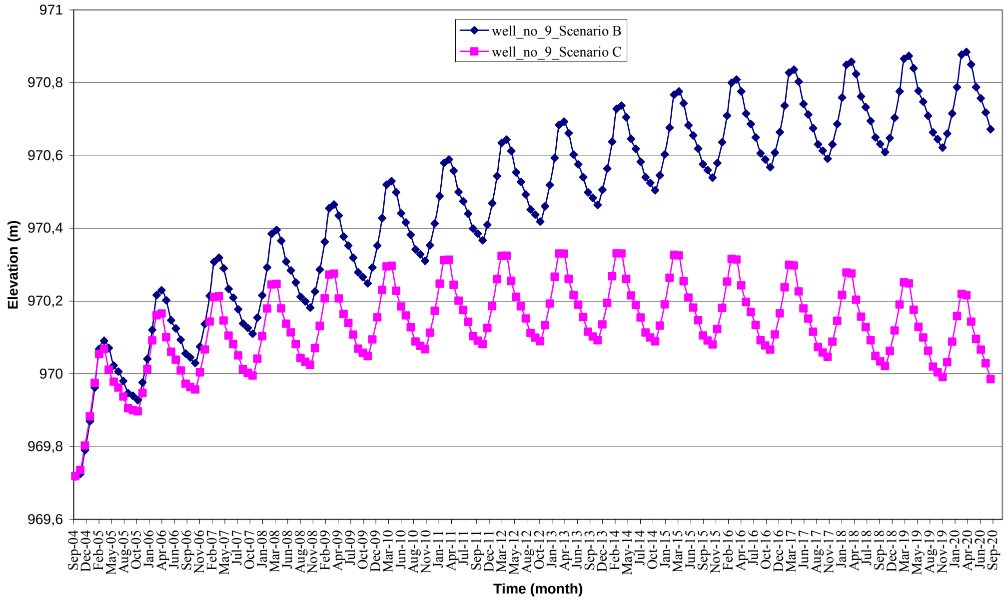

Figure 6.6. Predicted groundwater elevations for Scenarios B & C in Well no: 9.

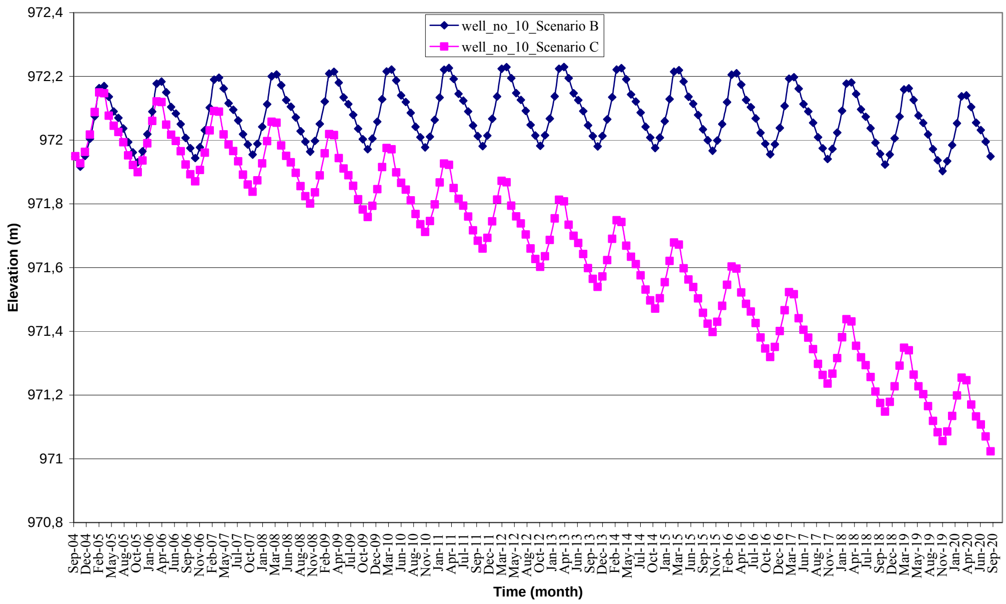

Figure 6.7. Predicted groundwater elevations for Scenarios B & C in Well no: 10.

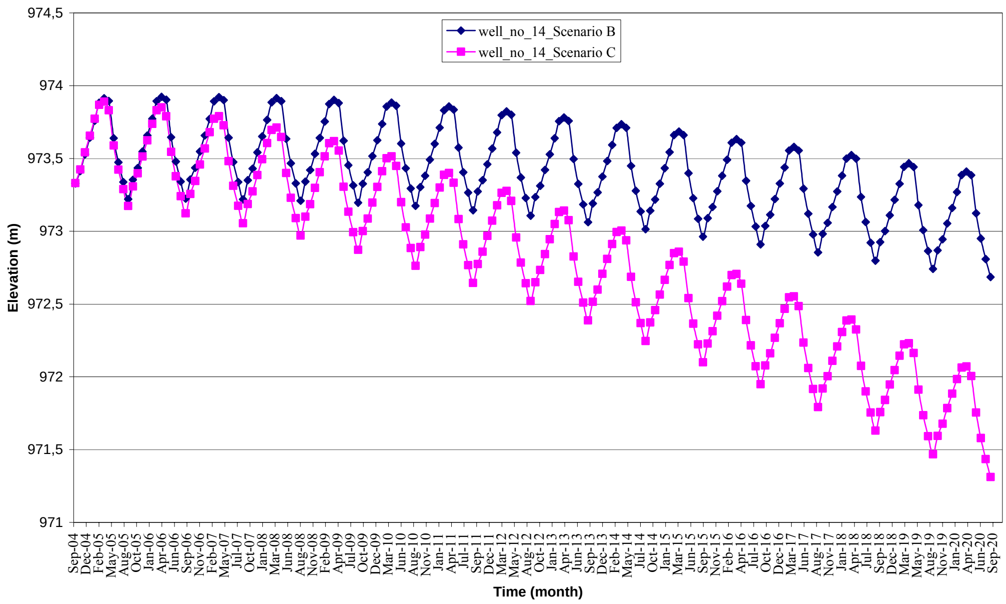

Figure 6.8. Predicted groundwater elevations for Scenarios B & C in Well no: 14.

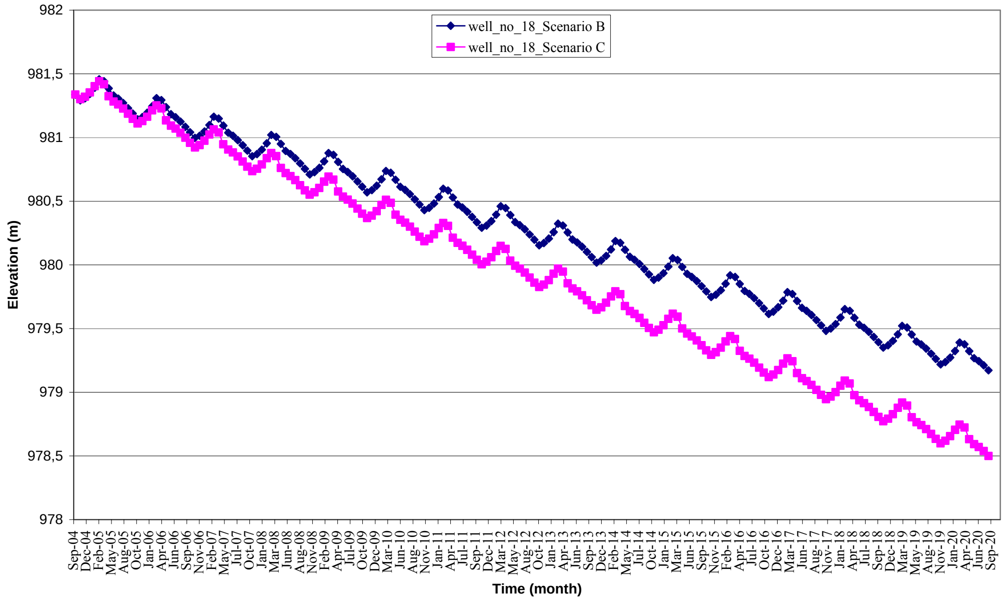

Figure 6.9. Predicted groundwater elevations for Scenarios B & C in Well no: 18.

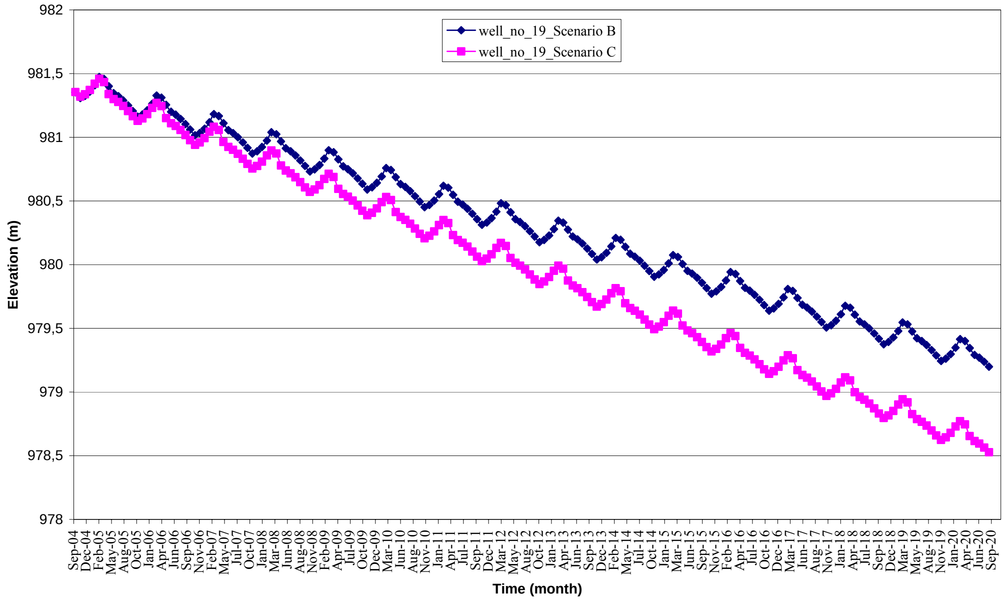

Figure 6.10. Predicted groundwater elevations for Scenarios B & C in Well no: 19.

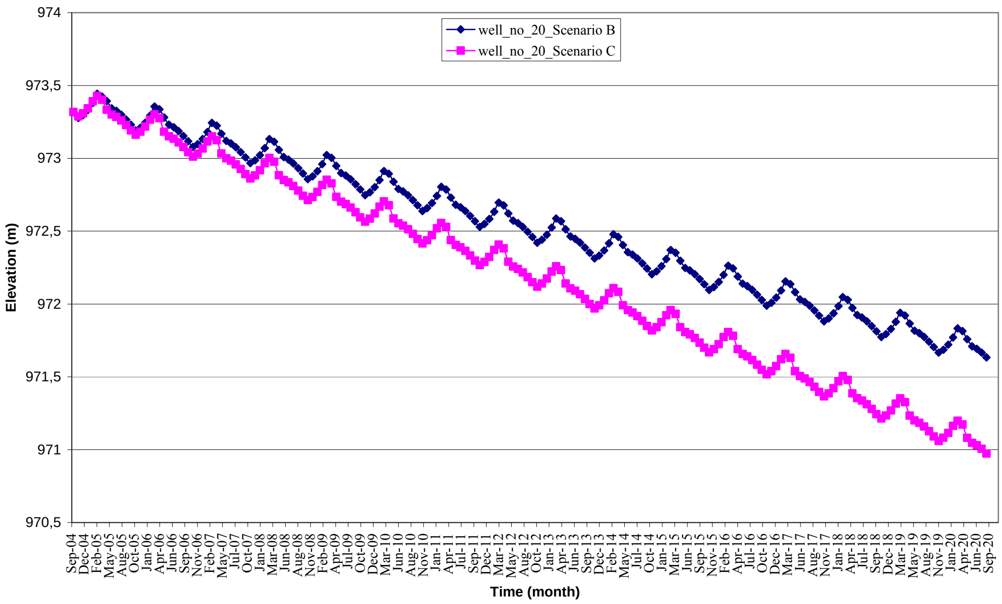

Figure 6.11. Predicted groundwater elevations for Scenarios B & C in Well no: 20.

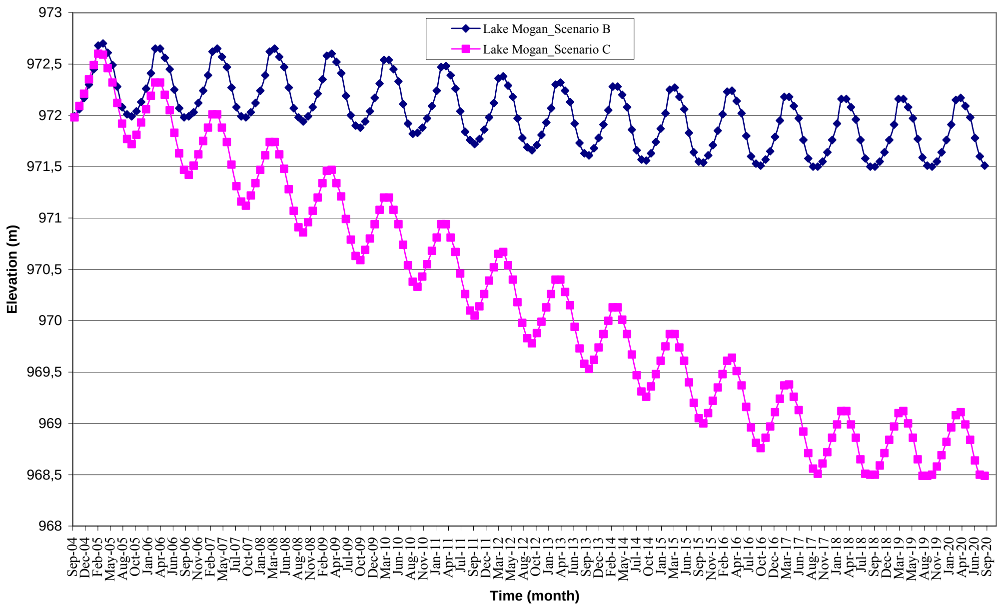

Figure 6.12. Lake Mogan's stage variation during Scenarios B & C.

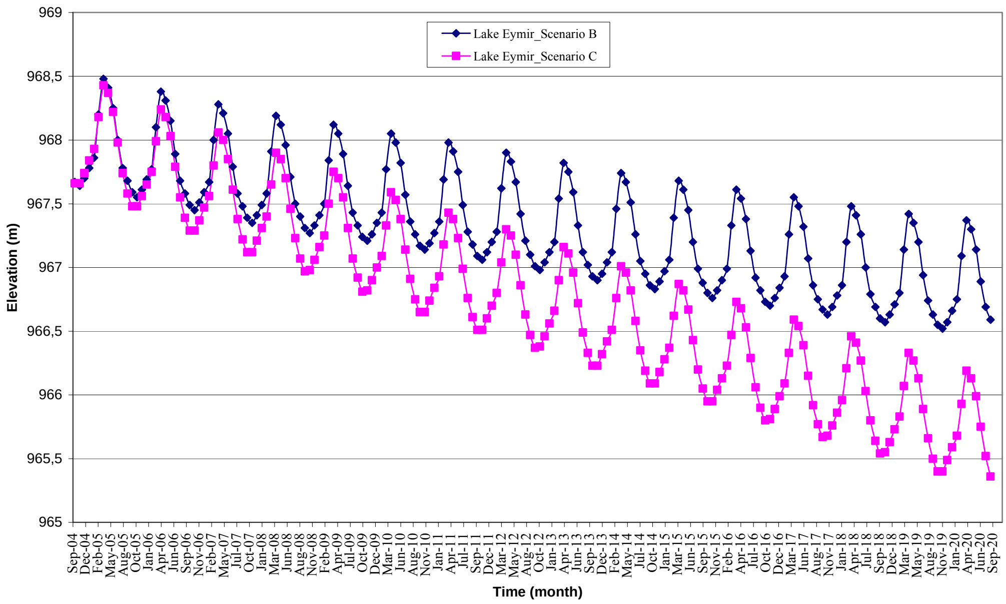

Figure 6.13. Lake Eymir's stage variation during Scenarios B & C.

6.4 Scenario C: Impact of Extended Drought Conditions

The global warming and subsequent drought conditions are becoming important environmental concern by many countries in the world. The City of Ankara has been experiencing a serious drought in 2007. These prompted the author to test a scenario (Scenario C) whereby the calibrated model was used to assess the effects of extended drought conditions on the groundwater regime and the lakes during the planning period beginning from October 2004 and ending in September 2020. This simulation examined the effects of a decrease in the monthly precipitation by 5 % and an increase in the mean monthly temperature by 1°C. Temperature and evaporation relation of the Ankara Meteorological Station was utilized to obtain new evaporation series for the model because this station has a long-term data which yielded a correlation coefficient 0.88. Then, the temporal distribution of recharge for the Quaternary alluvium was determined by conducting a hydrologic simulation for water years 2004 through 2020 using the reduced monthly precipitation and calculated evaporation rates. New runoff series were generated for the runoff entries of the lakes by multiplying the calculated monthly runoff coefficients with reduced monthly rainfall rates. The monthly withdrawal rates of the lakes were also decreased by 5 %. The reduced withdrawal rate from Lake Mogan was added as inflow to Lake Eymir. Together with constant yearly pumpage rates, other calibrated model parameters were remained the same.

Groundwater and lake elevations obtained from the model run were also presented in Figures 6.3 through 6.13 together with Scenario B as mentioned earlier. The results have shown even if the pumpage conditions were remained the same during the 16 years of the planning period with extended drought conditions, there would be greater declines in the groundwater and lake levels as compared with Scenario B. The predicted declines point outs that Lake Mogan would dry out at September 2018. Afterwards, it will become rewet only in wet seasons (Figure 6.12). Lake Eymir, however, would continuously decline to a stage of 965.36 m till September 2020 (Figure 6.13), leaving about 1.3 m of water column to dry out. Thus, the results of this scenario indicated that very small, but long-term changes to precipitation and temperature have the potential to cause significant declines in groundwater and lake levels.

In this scenario, the pumpage from the groundwater system during the planning period was kept the same as used in the calibration period. Considering the level of development in the area, it is conceivable that the lakes may become dry earlier than what is predicted herein in consequence to increased pumpage.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

A numerical simulation model has been developed for the Lakes Mogan and Eymir Basin in Central Anatolia to study groundwater contributions to lake budgets, to evaluate the impacts of upstream reservoirs on lake levels, and to assess the potential climatic changes on lake and groundwater levels. Available data on physiography, geology, hydrology, and meteorology have been used to develop a conceptual hydrogeological model of the system. Following conceptualization, the three dimensional finite difference groundwater model (MODFLOW) involving a lake package has been developed for the system. The resulting model consisted of nine layers and 13532 active cells in each layer that varied in size from $100m \times 100m$ to $500m \times 500m$.

The model has been calibrated under transient conditions over a period of six years using monthly stress periods. Calibration of the model was performed through trial-and-error changes to regional hydrologic parameters to minimize the differences between simulated and measured hydraulic heads at nine monitoring wells and lake stages at two lakes. Regional parameters included groundwater recharge, hydraulic conductivity, storativity, lake seepage rates, and evapotranspiration losses. Local changes to these parameters have not been conducted to remove subjectivity. The calibrated model simulated hydraulic heads at an average root mean square error of 0.5 m at monitoring wells and the lake stages with an average root mean square error of 0.24 m. A sensitivity analysis was conducted by introducing perturbations to each of the regional parameters to determine the limits within which they may vary.

Simulated lake budgets show that 17.1 L/s of groundwater enters Lake Mogan on the southern, western and eastern sides and 16.5 L/s discharges to groundwater system on the downgradient northern side. Lake Eymir, located downstream of Lake Mogan, is primarily fed by the water released from the Lake Mogan. The groundwater inflow to Lake Eymir is 6.0 L/s whereas the outflow to groundwater system on the northern downgradient side is 5.1 L/s. Most of the groundwater outflow from Lake Mogan is lost by evapotranspiration in the wetland between the lakes. The simulated groundwater inflow and outflow rates to both lakes are in conformity with the results of earlier studies based upon Darcy flux estimates (METU, 1995). The results confirmed the accuracy of the numerical model and verified the conceptual understanding of the hydrogeologic system. The calibrated model is subsequently used to assess the impacts of upstream reservoirs and potential climatic changes on both the groundwater and lake systems.

In order to aid decision makers in planning and management of the Mogan and Eymir Lakes Basin, alternative scenarios had been developed. In Scenario A, the impact of upstream reservoirs (Dikilitaş and İkizce) was evaluated. In Scenario B, the continuation of existing average recharge and discharge conditions were taken into consideration for future predictions. Finally, Scenario C was developed to evaluate the impact of extended drought conditions on the groundwater and lake systems. A planning period of 16 years, beginning from October 2004 and ending in September 2020, was selected for Scenarios B and C.

The following *conclusions* can be made:

- Groundwater inflows and outflows have the lowest contribution to the overall lakes' budget. Average groundwater inflow and outflow for Lake Mogan accounted for 4 % of the total inflow and outflow for the lake. Groundwater component was also smaller with a value of 3 % in Lake Eymir's average total inflow and outflow.

- The major components of the inflows to both lakes consisted of the surface runoff, followed by the precipitation. Evapotranspiration and withdrawal accounted for the majority of the losses from the Lake Mogan. However, withdrawal is the major outflow component with 77 % for Lake Eymir, followed by evapotranspiration losses of 20 %.

- The results of Scenario A in which the impacts of upstream Dikilitaş and İkizce reservoirs are examined show that these reservoirs have a significant effect on lake stages but not on groundwater levels.

- In order to enhance decision makers' ability to decide on the amount of water that should be released from these reservoirs, a series of simulations were conducted to generate a trade-off curve between the amount of water released and the average stage in Lake Mogan. The trade-off curve shows that the relation between the amount of water released from the reservoirs and the average stage in Lake Mogan is almost linear. The stage increases from an average value of 972.76 m (no release) to 973.5 m for a monthly release of 500000 m^3. Here, a trade-off between the amount of water to be used for irrigation and sustainable lake stages exist. These two objectives are generally non-commensurable and conflicting. Hence, a decision has to be made between them. This is however a prerogative of decision makers.

They may select an optimum point on the curve that best represents their choice between these two conflicting objectives.

- The results of Scenario B in which the existing average conditions are assumed to continue for 16 years show that there would be declines in groundwater elevations in areas upstream from Lake Mogan and downstream from Lake Eymir. The results also show that it would take more than 16 years to reach a pseudo steady-state conditions. The predicted response of Lake Mogan to average conditions is a slight decrease through years 2004-2016, then a steady- state condition in the elevations to the end of the planning period (2020). The maximum predicted decrease in Lake Mogan's level at the end of the planning period was 0.5 m. In the case of Lake Eymir, however, water levels decline continuously throughout the planning period. The water levels at Lake Eymir would decline about 1.2 m at the end of the planning period from the levels at 2004. The greater amount of decline observed in water levels of Lake Eymir is due to its low storage capacity compared to Lake Mogan.

- The results of Scenario C in which the effects of extended drought conditions were simulated by decreasing average monthly precipitation by 5 % and increasing average monthly temperature by 1°C show that there would be greater declines in the groundwater and lake levels as compared to the average conditions simulated in Scenario B. The results point out that Lake Mogan would dry out at September 2018. Afterwards, it will become rewet only in wet seasons. Lake Eymir, however, would continuously decline to a stage of 965.36 m till September 2020, leaving about 1.3 m of water column to dry out. Thus, the results of this scenario indicated that very small, but long-term changes to precipitation and temperature have the potential to cause significant declines in groundwater and lake levels.

These results however are bound by the limitations, assumptions and the accuracy of the data used in the model.

The *recommendations* that follow can be categorized into those related to the water management practices and to those related to the future studies to be conducted in the basin:

- Both lakes should be managed in an integrated manner because Lake Eymir is primarily fed by the water released from Lake Mogan.

- Because surface runoff is the main inflow to Lake Mogan, the courses of the streams should be protected from dumping of waste materials and settlement by people.

- Efficient monitoring and data acquisition systems should be implemented to enhance the decisions regarding the management of the basin.

- A river basin authority composed of all the stakeholders should be formulated to make operations decisions for the management of the basin.

- The model developed herein is based upon the available data. The spatial distribution of the monitoring wells was inadequate along the lakes. Some of the previously drilled monitoring wells were damaged and not operational. Except the Quaternary alluvium, there were no monitoring wells in other hydrogeologic units to provide a reliable characterization and calibration of them. Hence, a proper groundwater monitoring network should be designed and implemented.

- The model should be calibrated again as new data become available from the monitoring system developed.

- Although not considered in this study, the water quality is a primary issue for surface and groundwater resources in the basin. The model developed should be extended to simulate the solute transport from point and non-point sources.

- A reservoir operations model should be developed for both lakes in order to make optimum release decisions. The model developed herein could be utilized in this manner.

- A deterministic approach was conducted in this study because the available data was short-term. Because most of the hydrologic inputs and system parameters are random in nature, a stochastic approach would also be needed as long-term data become available.

- Lakes Mogan and Eymir act as storage reservoirs and protect the City of Ankara and the Town of Gölbaşı from floods. Although this aspect is not studied herein, the model developed in this study could be used to assess the flood protection capacity of the both lakes. In this regard, the streamflow routing package developed by Prudic (1989) should be incorporated into the model.

REFERENCES

Anderson, M. P., Munter, J. A., 1981, "Seasonal Reversals of Ground-Water Flow Around Lakes and the Relevance to Stagnation Points and Lake Budgets", Water Resources Research, 17 (4), 1139-1150.

Anderson, M. P., Cheng, X., 1992, "Long and Short Term Transience in a Groundwater/lake System in Wisconsin, USA", Journal of Hydrology, 145, 1-18.

Anderson, M. P., Woessner, W. W., 1992, "Applied Groundwater Modeling: Simulation of Flow and Advective Transport", Academic Press Inc, San Diego, California.

Anderson, M. P., Hunt, R. J., Krohelski J. T., Chung, K., 2002, "Using High Hydraulic Conductivity Nodes to Simulate Seepage Lakes", Ground Water, 40 (2), 117-122.

Argus ONE, 1997, "Argus Open Numerical Environments-A GIS Modeling system, Version 4.0, User's Guide", 484 pages.

Arıgün, Z., 1994, Eymir ve Mogan Göllerinin Beslenme Havzasının Batı Kesiminin Hidrojeoloji İncelemesi, MSc. Thesis, Ankara University.

Canpolat, F., Çamur, M.Z., Yazıcıgil, H., 2001, "Hydrogeochemical Evaluation of Heavy Metal Loadings to Waters and Sediments by Leachate: A Case Study from the Gölbaşı Waste Disposal Site, Ankara, Turkey", International Geology Review, 43 (10), 930-944.

Cheng, X., Anderson, M. P., 1993, "Numerical Simulation of Ground-Water Interaction with Lakes Allowing for Fluctuating Lake Levels", Ground Water, 31 (6), 929-933.

Cheng, X., Anderson, M. P., 1994, "Simulating the Influence of Lake Position on Groundwater Fluxes", Water Resources Research, 30 (7), 2041-2049.

Council, G. W., 1998, "A lake package for MODFLOW", Proceedings of the 3rd International Conference of the International Groundwater Modeling Center, Colorado, USA, 675-682.

Crowe, A. S., 1993, "Application of a Coupled Water-Balance-Salinity Model to Evaluate the Sensitivity of a Lake Dominated by Groundwater to Climatic Variability", Journal of Hydrology, 141, 33-73.

Çamur, Z. M., Yazıcigil, H., Altınbilek, H. D., 1997, "Hydrogeochemical Modeling of Waters in Mogan and Eymir Lakes Special Environmental Protection Area, Ankara, Turkey," Water Environment Research, 69 (6), 1144-1153.

Dogramacı, S., S., 1993, Determination of Geohydrological Characteristics of Pliocene Deposits in Gölbaşı Basin, MSc. Thesis, Hacettepe University.

Domenico A. P., Schwartz W. F., 1998, "Physical and Chemical Hydrogeology", John Wiley & Sons, Inc., New York, 506 pages.

Harbaugh, A. W., and McDonald, M. G., 1996, "User's Documentation for MODFLOW-96, an Update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model", U.S. Geological Survey, Open-File Report, 96-485, USA.

Harbaugh, A. W., Banta, E. R., Hill, M. C., and McDonald, M. G., 2000, "MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model: User Guide to Modularization Concepts and the Ground-Water Flow Process", U.S. Geological Survey, Open-File Report, 00-92, USA.

Hunt, R. J., Krohelski J. T., 1996, "The Application of an Analytic Element Model to Investigate Groundwater-Lake Interactions at Pretty Lake, Wisconsin", Journal of Lakes and Reservoir Management, 12 (4), 487-495.

Hunt, R. J., Anderson, M. P., Kelson, V. A., 1998, "Improving a Complex Finite Difference Ground-Water Flow Model Through the Use of an Analytic Element Screening Model", Ground Water, 36 (6), 1011-1017.

Hunt, R. J., Lin Y., Krohelski J. T., Juckem, P. F., 2000, "Simulation of the Shallow Hydrologic System in the Vicinity of Middle Genesee Lake, Wisconsin, Using Analytic Elements and Parameter Estimation", U.S. Geological Survey Water-Resources Investigations Report, 00-4136, USA.

Kalkan, İ., Şaroğlu, F., Özmutaf, M., Atiker, M., Yıldırım, N., Süzük, H., Tanıl, A., 1992, "Eymir ve Mogan Gölleri'nin (Ankara-Gölbaşı) Korunmasına Yönelik Jeoloji-Hidrojeoloji İncelemesi", Maden Tetkik ve Arama Genel Müdürlüğü, Final Rep., project no. 92/101, 45 pages.

Kim, J., Sultan, M., 2002, “Assessment of the Long-Term Hydrologic Impacts of Lake Nasser and Related Irrigation Projects in Southwestern Egypt”, Journal of Hydrology, 262, 68-83.

Knupp, M. P., 1996, “A Moving Mesh Algorithm for 3-D Regional Groundwater Flow with Water Table and Seepage Face”, Advances in Water Resources, 19-2, 83-95.

Krabbenhoft, D. P., Bowser, J .C. Anderson, M. P., Valley, W. J., 1990a, “Estimating the Groundwater Exchange with Lakes, 1. The Stable Isotope Mass Balance Method”, Water Resources Research, 26 (10), 2445-2453.

Krabbenhoft, D. P., Anderson, M. P., Bowser, J. C., 1990b, “Estimating the Groundwater Exchange with Lakes, 2. Calibration of a Three-Dimensional, Solute Transport Model to a Stable Isotope Plume”, Water Resources Research, 26 (10), 2455-2462.

Küçük, İ., and Angı, E. A., 2005, “Mogan ve Eymir Gölleri Havzasının Hidrometeorolojik Özellikleri”, Elektrik İşleri İdaresi Genel Müdürlüğü, 161 pages.

Lee, T. M., 1996, “Hydrologic Controls on the Groundwater Interactions with an Acidic Lake in Karst Terrain, Lake Barco, Florida”, Water Resources Research, 32 (4), 831-844.

McDonald, M. G., and Harbaugh, A. W., 1984, “A Modular Three-Dimensional Finite-Difference Groundwater Flow Model”, U.S. Geological Survey, Open-File Report, 83-875, USA, 528 pages.

Merritt, M. L., Konikow L. F., 2000, "Documentation of a Computer Program to Simulate Lake-Aquifer Interaction Using the MODFLOW Ground-Water Flow Model and MOC3D Solute-Transport Model", U.S. Geological Survey Water-Resources Investigations Report, 00-4167, 146 pages.

METU, 1995, "Gölbaşı Mogan Eymir Gölleri İçin Su Kaynakları ve Çevre Yönetim Planı Projesi", Orta Doğu Teknik Üniversitesi, Final Rep., project no. 93-03-03-04-01, 680 pages.

MTA, 1997, Geological Map of Ankara- 1/100000, Ankara Sheet, Ankara.

Narayan, A. K., Armstrong, D, 1995, "Simulation of Groundwater Interception at Lake Ranfurly, Victoria, Incorporating Variable Density Flow and Solute Transport", Journal of Hydrology, 165, 161-184.

Ozbilgin, M. M., Dickerman D. C., 1984, "A Modification of the Finite-Difference Model for Simulation of Two-Dimensional Ground-Water Flow to Include Surface-Groundwater Relationships", U.S. Geological Survey Water-Resources Investigations Report, 83-4251, USA, 98 pages.

Özaydın, V., 1997, "Water Balance of Lakes Using Stable Isotope Mass Balance Method", PhD. Thesis, Middle East Technical University.

Pinder, G. F., 1970, "A Digital Model for Aquifer Evaluation: U.S. Geological Survey Techniques of Water-Resources Investigations", Book 7, Chapter C1.

Plummer, L. N., Prestemon, E. C. , Parkhurst, D. L., 1991, "An Interactive Code (NETPATH) for Modeling Net Geochemical Reactions Along a Flow Path", U.S. Geological Survey Water-Resources Investigations Report, 91-4078, USA, 227 pages.

Prickett, T. A., Lonnquist, C. G., 1971, "Selected Digital Computer Techniques for Groundwater Resource Evaluation", Illinois State Water Survey Bulletin 55.

Prudic, D. E., 1989, "Documentation of a Computer Program to Simulate Stream-Aquifer Relations Using the Modular Finite-Difference Groundwater Flow Model", U.S. Geological Survey Open File Report, 88-729, USA, 113 pages.

Smerdon, D. B., Devito, J. K., Mendoza, A. C., 2005, "Interaction of Groundwater and Shallow Lakes on Outwash Sediments in the Sub-Humid Boreal Plains of Canada", Journal of Hydrology, 314, 246-262.

Trescott, P. C., 1975, "Documentation of Finite-Difference Model for Simulation of Three-Dimensional Ground-water Flow", U.S. Geological Survey, Open-File Report, 75-438, USA.

Trescott, P. C., Pinder, G. F., Larson, S. P., 1976, "Finite-Difference Model for Aquifer Simulation in Two Dimensions with Results of Numerical Experiments", U.S. Geological Survey Techniques of Water-Resources Investigations, Book 7, Chapter C1, USA, 116 pages.

Urbano, L. D., Person, M., Hanor, J., 2000 "Groundwater-Lake Interactions in Semi-Arid Environments", Journal of Geochemical Exploration, 69-70, 423-427.

Voss, I. C., 1984, "SUTRA: A Finite Element Simulation Model for Saturated-Unsaturated, Fluid-Density-Dependent Groundwater Flow with Energy Transport or Chemically-Reactive Single-Species Solute Transport", U.S. Geological Survey Water-Resources Investigations Report, 84-4369, USA,409 pages.

Winter, T. C., 1976, "Numerical Simulation Analysis of the Interaction of Lakes and Groundwater", U.S. Geological Survey Professional Paper 1001, USA, 45 pages.

Winter, T. C., 1978, "Numerical Simulation Analysis of Steady-State Three Dimensional Groundwater Flow Near Lakes", Water Resources Research, 14 (2), 245-254.

APPENDIX A

DISCHARGE HYDROGRAPHS OF THE CREEKS FLOWING INTO LAKE MOGAN

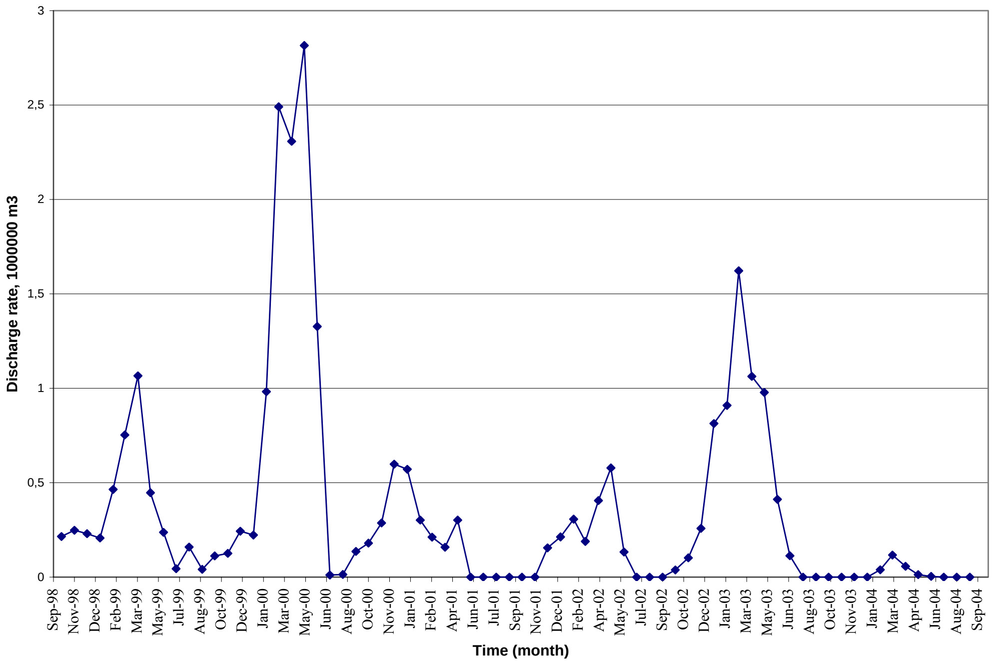

Figure A.1. Discharge rate versus time graph of Çölovası Creek, Yavrucak.

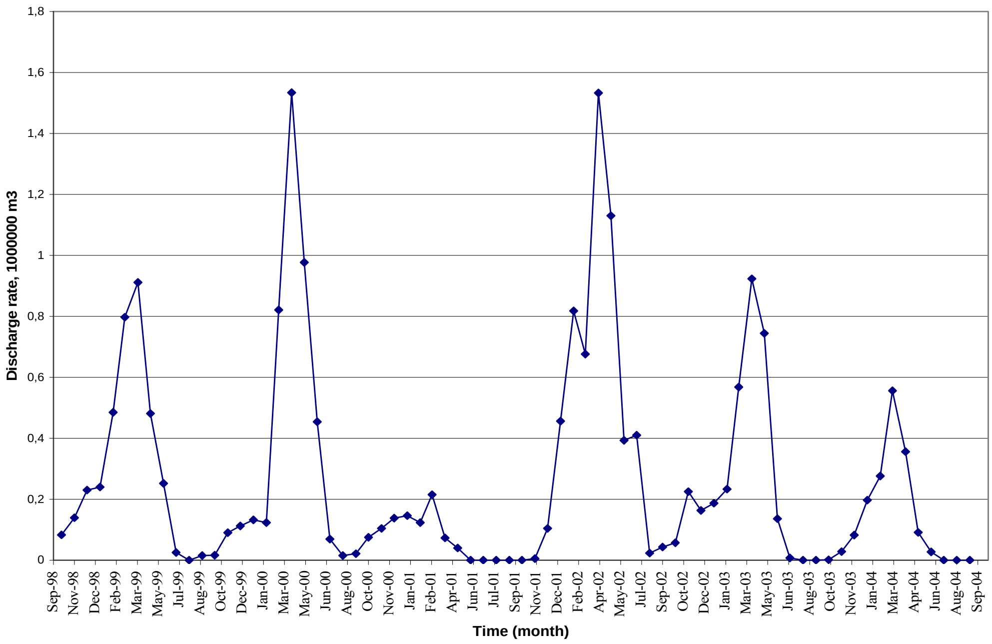

Figure A.2. Discharge rate versus time graph of Yavrucak Creek, Yavrucak.

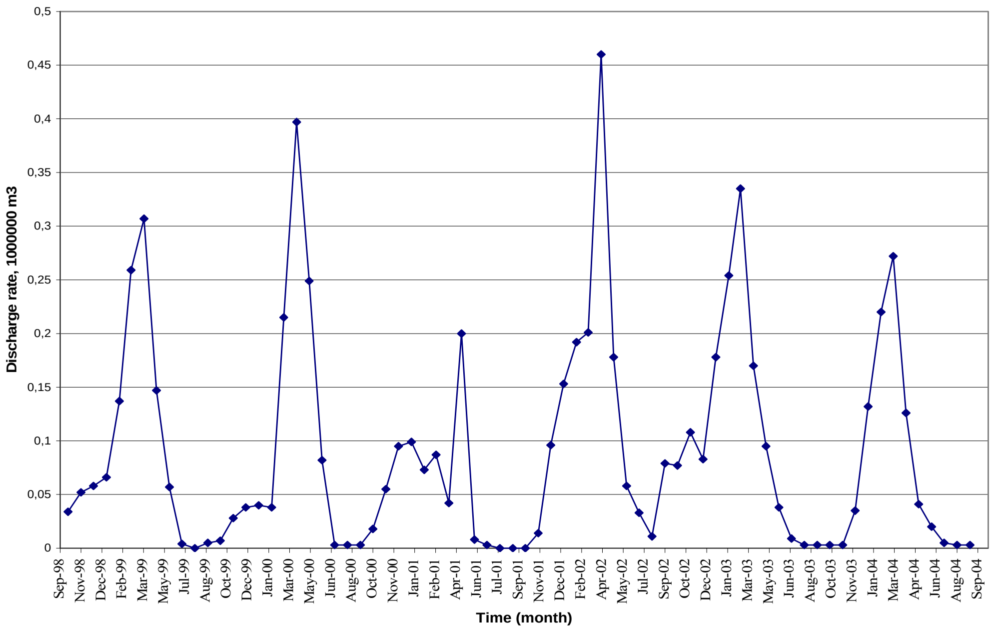

Figure A.3. Discharge rate versus time graph of Sukesen Creek, Gölbaşı.

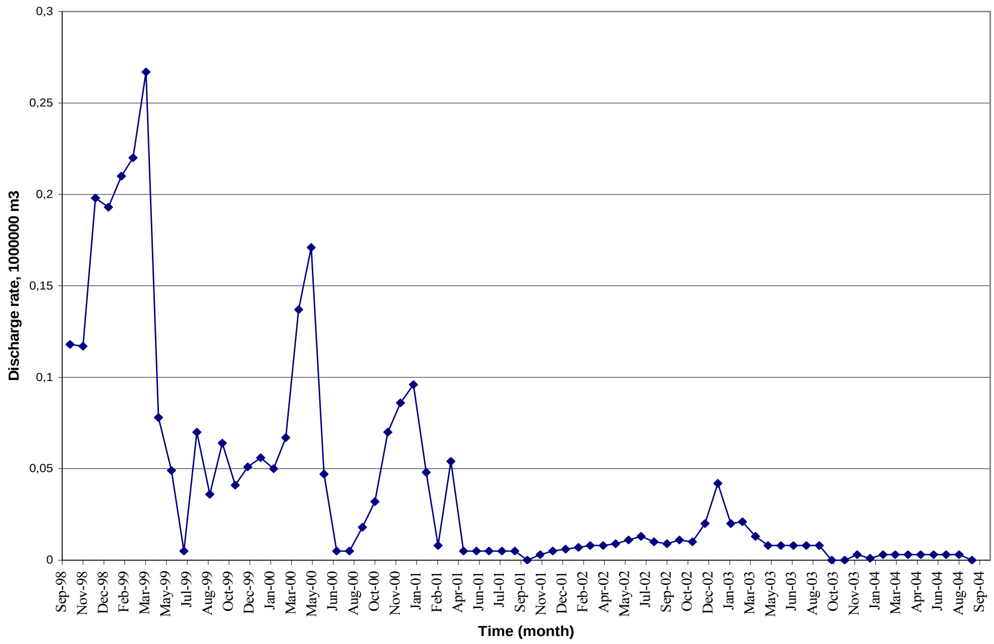

Figure A.4. Discharge rate versus time graph of Başpınar Creek, Oğulbey.

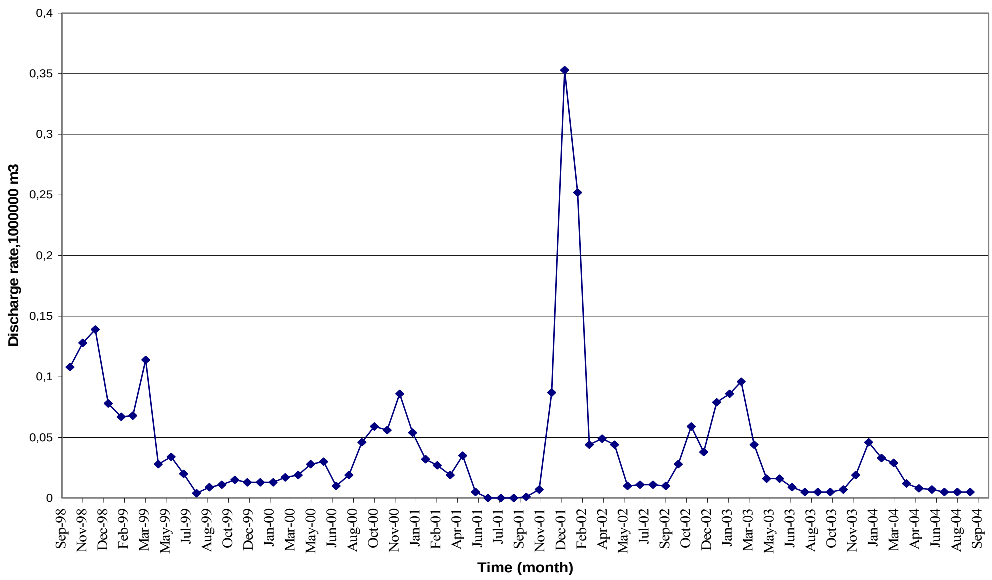

Figure A.5. Discharge rate versus time graph of Gölcük Creek-1.

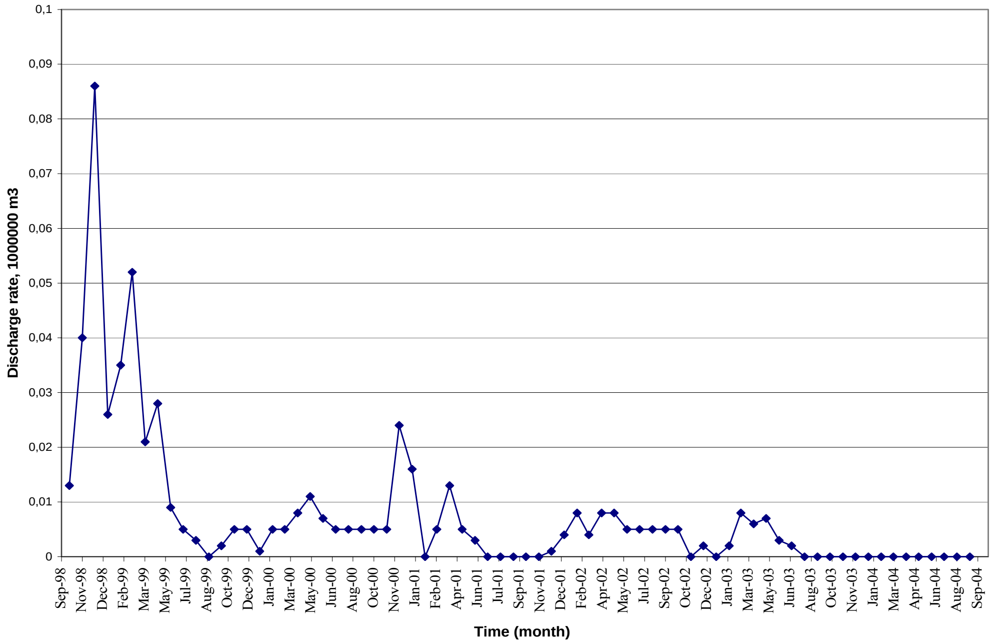

Figure A.6. Discharge rate versus time graph of Çolakpınar Creek.

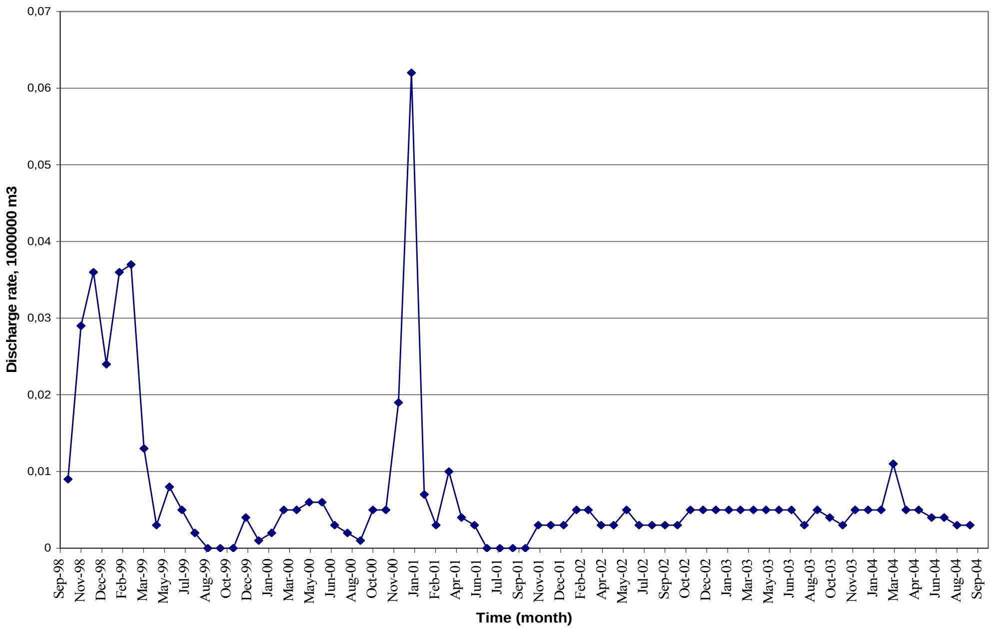

Figure A.7. Discharge rate versus time graph of Tatlım Creek, Hacılar.

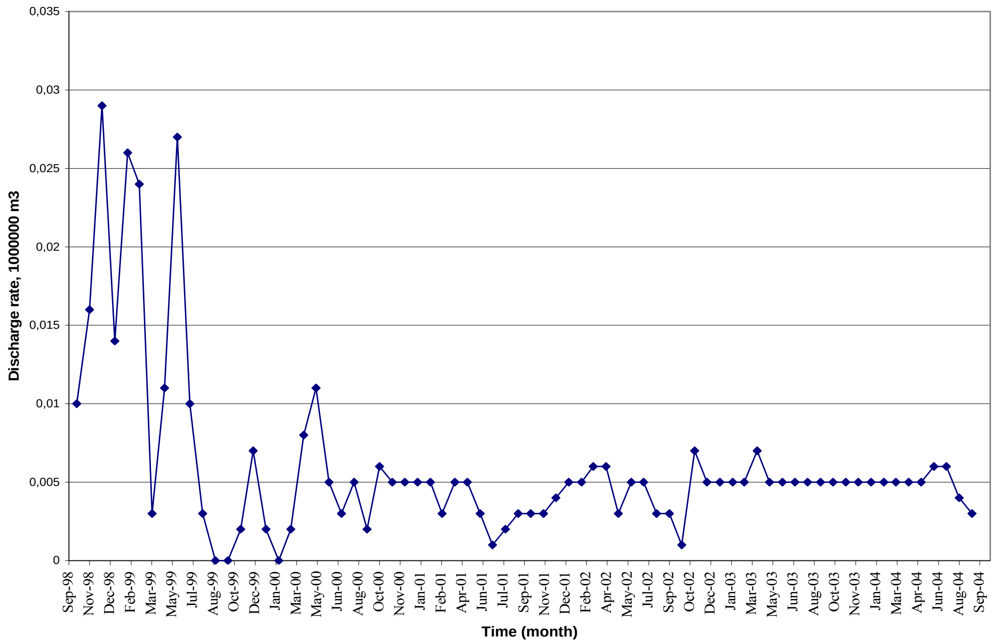

Figure A.8. Discharge rate versus time graph of Kepir Creek.

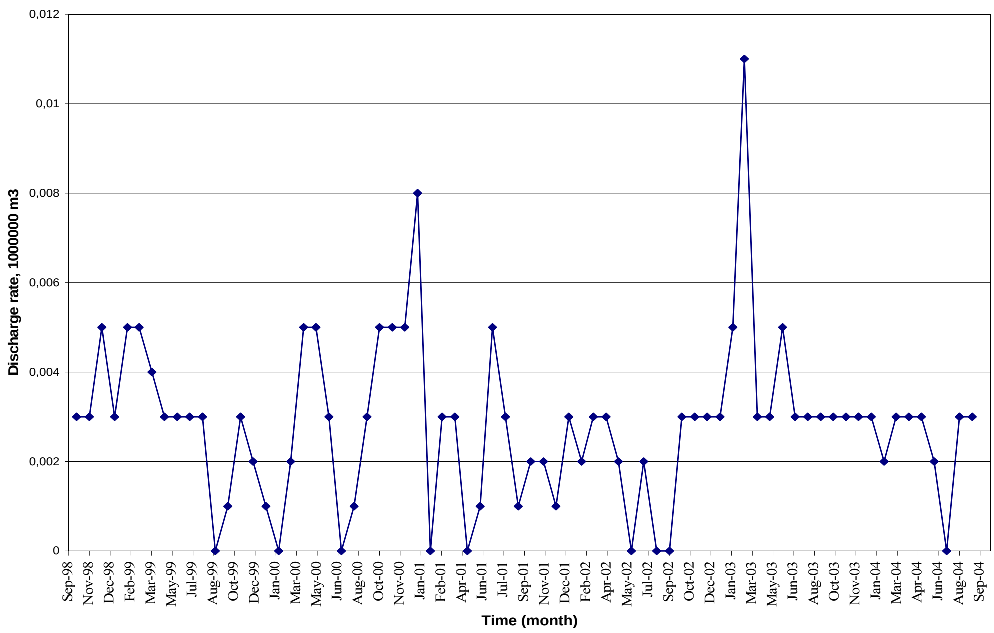

Figure A.9. Discharge rate versus time graph of Kumluk Creek-2.

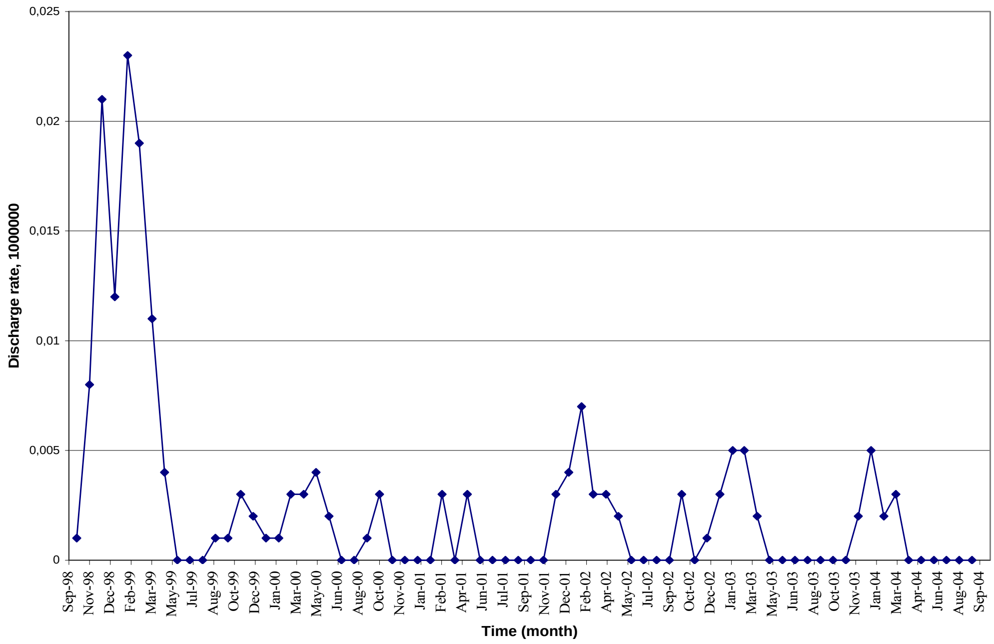

Figure A.10. Discharge rate versus time graph of Yağlıpınar Creek, Yağlıpınar.

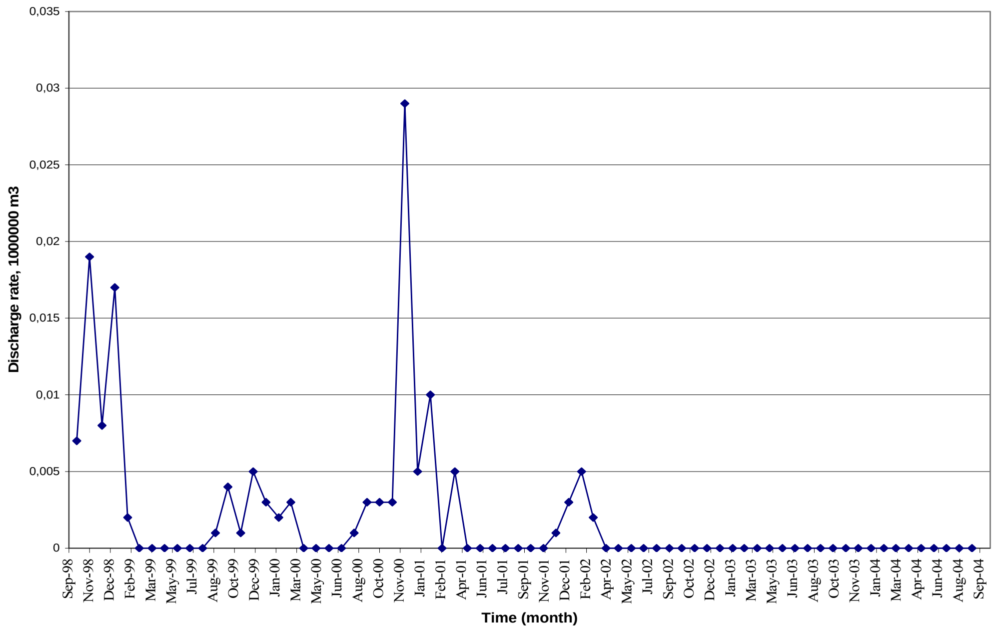

Figure A.11. Discharge rate versus time graph of Kaldırım Creek, Hacılar.

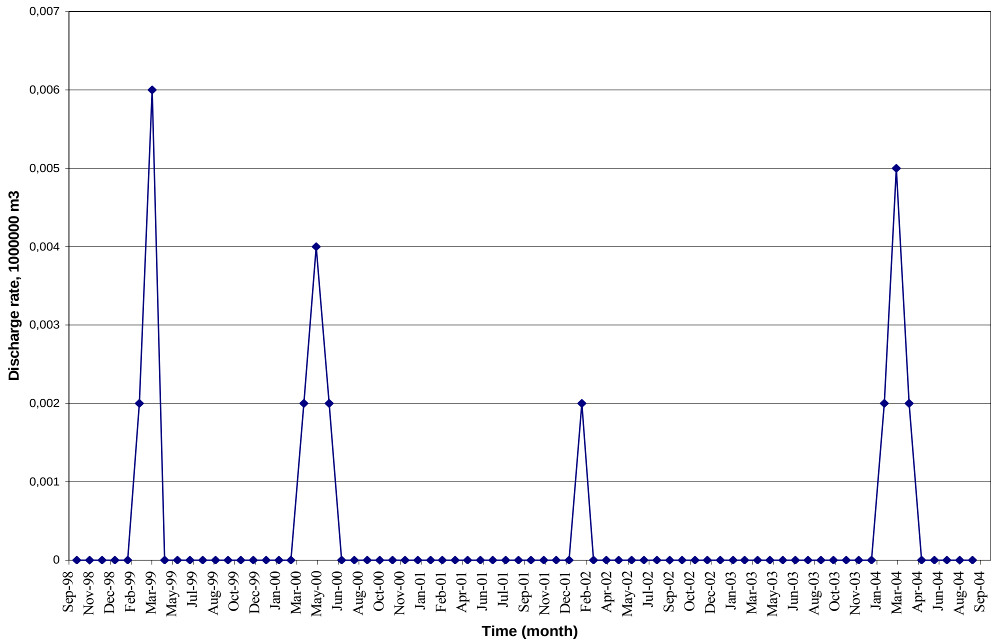

Figure A.12. Discharge rate versus time graph of Kurt Creek.

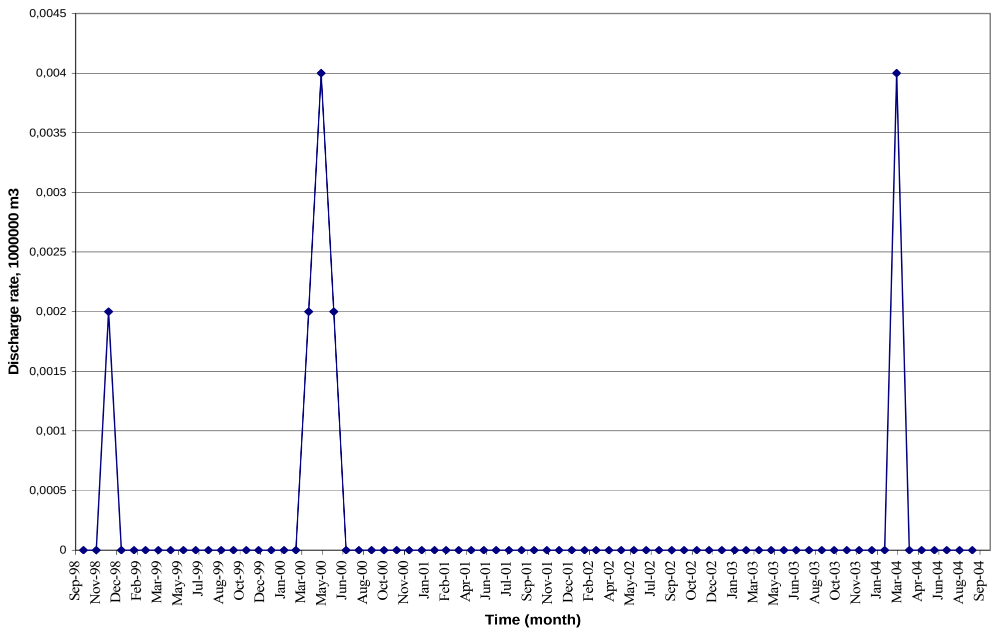

Figure A.13. Discharge rate versus time graph of Bağ Creek.

APPENDIX B

GROUNDWATER ELEVATIONS AND LAKE LEVELS

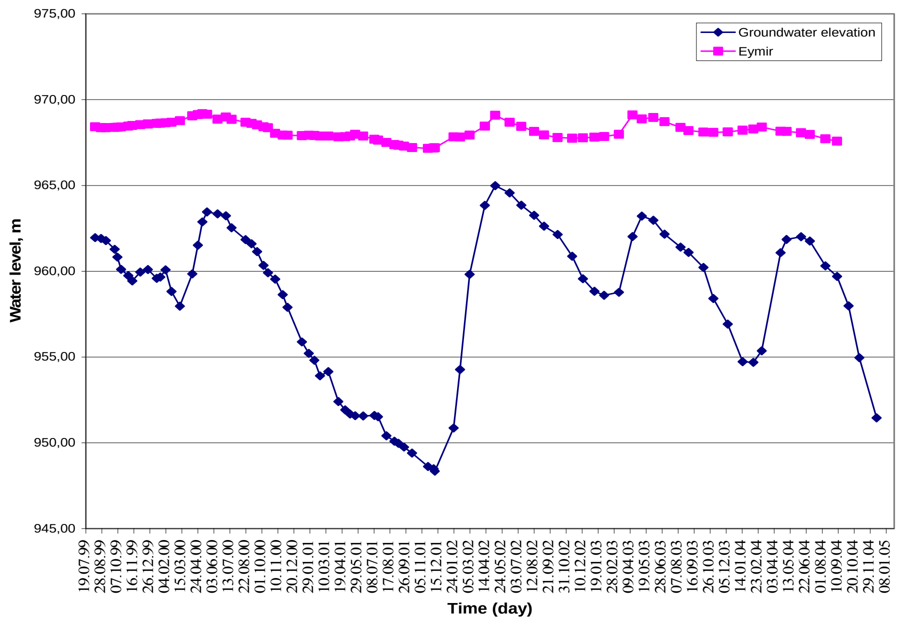

Figure B.1. The relation between groundwater elevation in Well no: 1 and Lake Eymir.

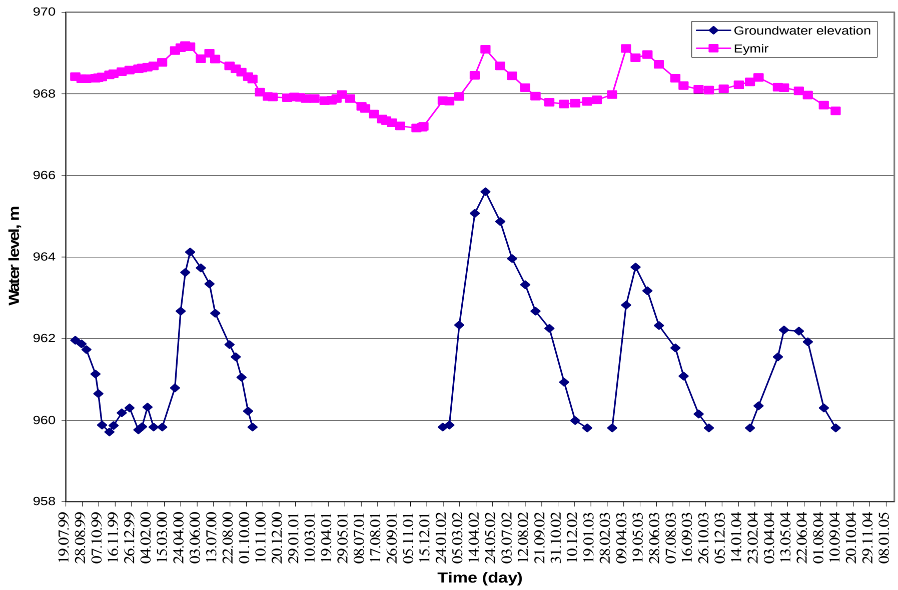

Figure B.2. The relation between groundwater elevation in Well no: 2 and Lake Eymir.

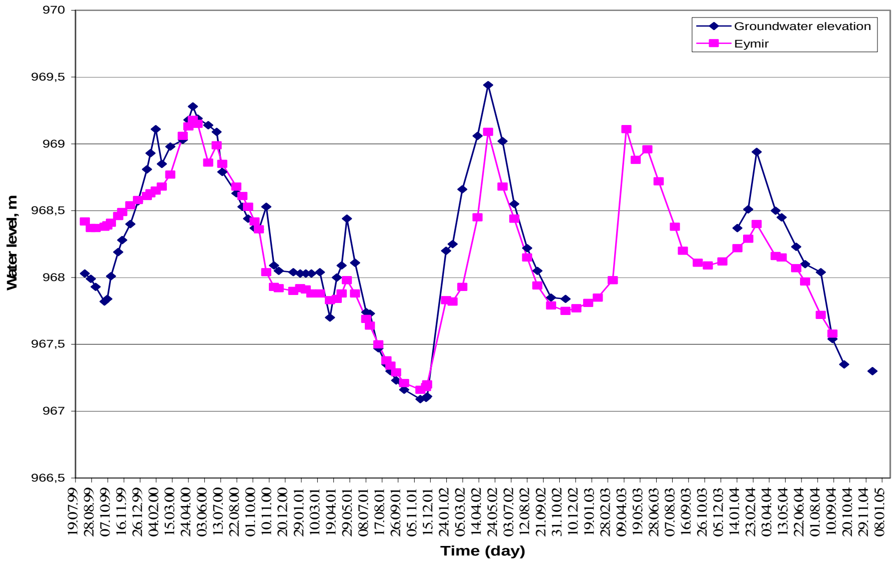

Figure B.3. The relation between groundwater elevation in Well no: 3 and Lake Eymir.

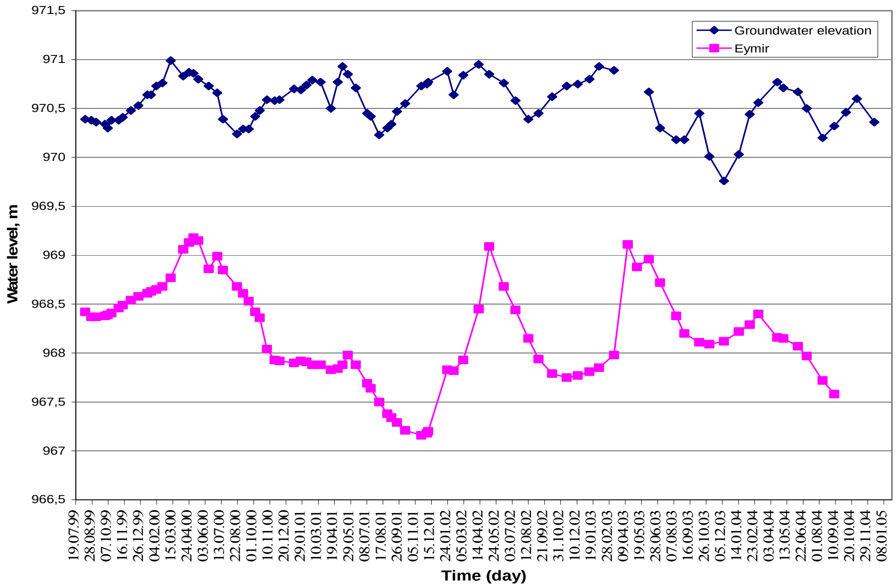

Figure B.4. The relation between groundwater elevation in Well no: 4 and Lake Eymir.

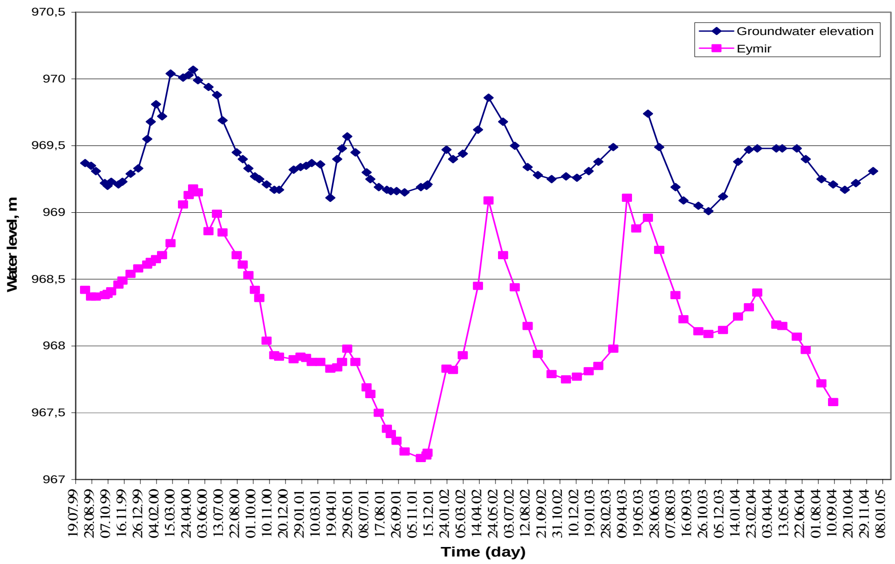

Figure B.5. The relation between groundwater elevation in Well no: 5 and Lake Eymir.

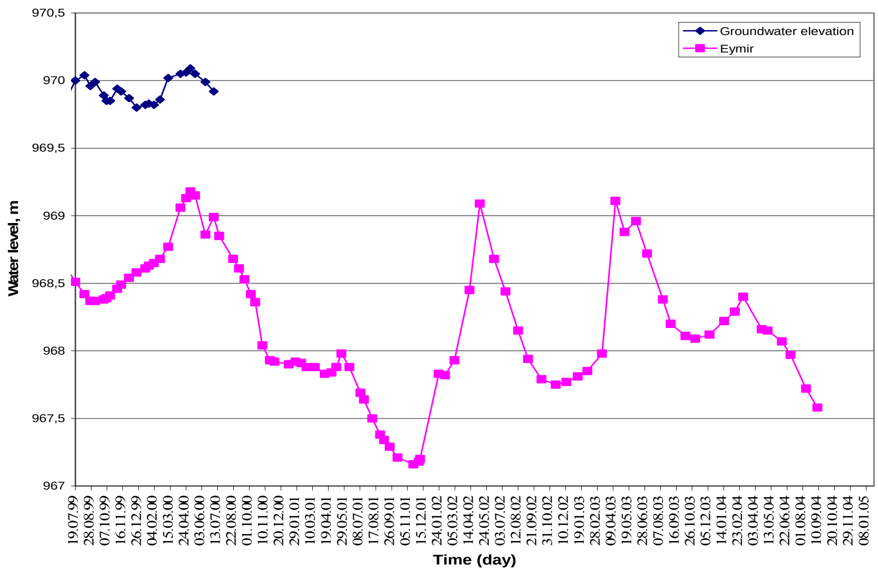

Figure B.6. The relation between groundwater elevation in Well no: 8 and Lake Eymir.

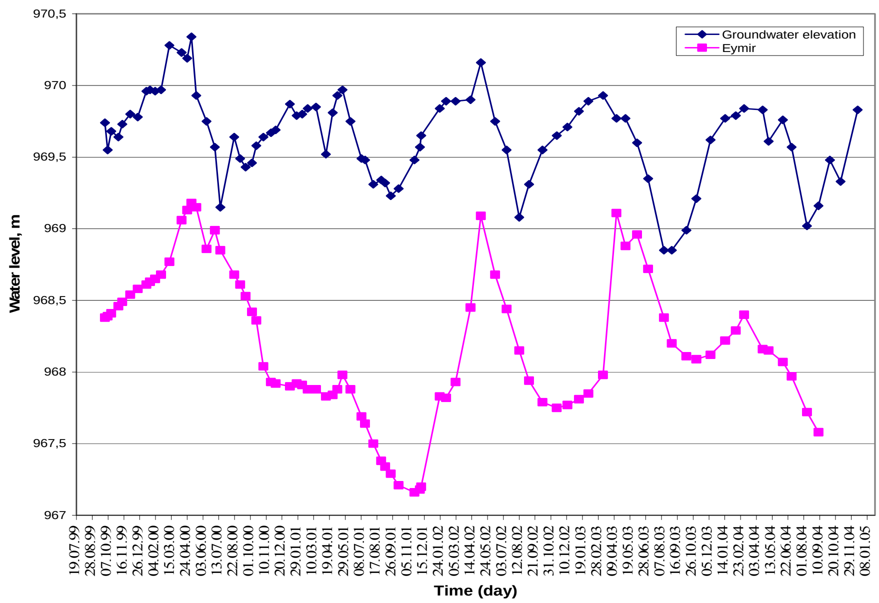

Figure B.7. The relation between groundwater elevation in Well no: 9 and Lake Eymir.

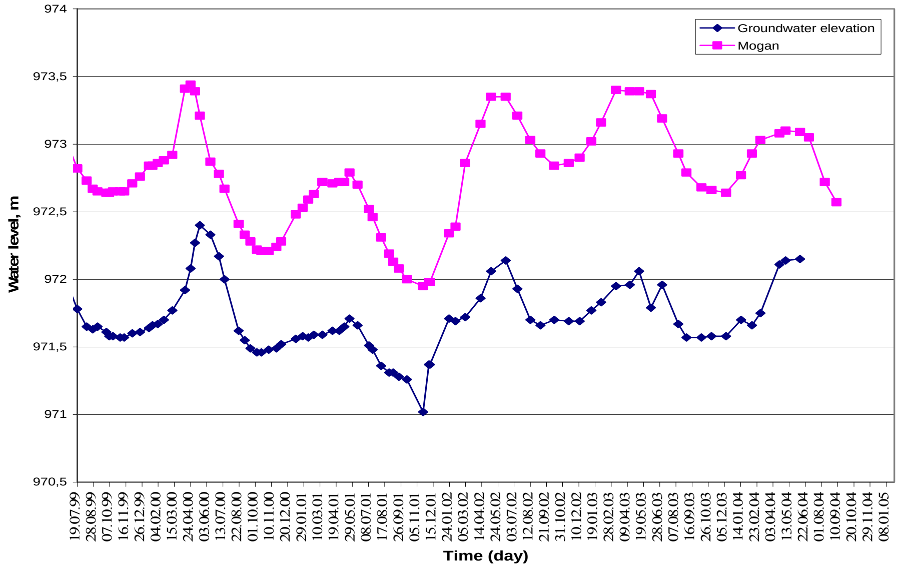

Figure B.8. The relation between groundwater elevation in Well no: 10 and Lake Mogan.

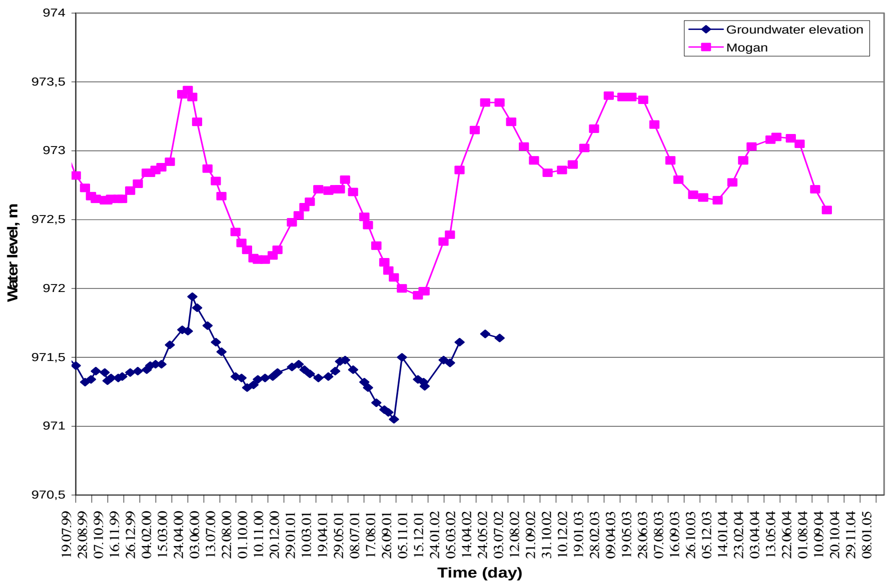

Figure B.9. The relation between groundwater elevation in Well no: 11 and Lake Mogan.

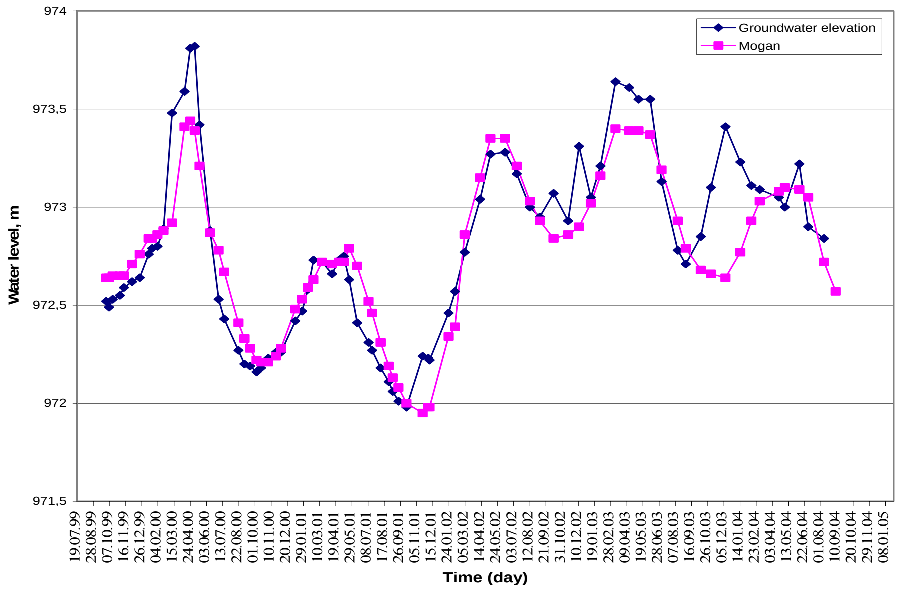

Figure B.10. The relation between groundwater elevation in Well no: 14 and Lake Mogan.

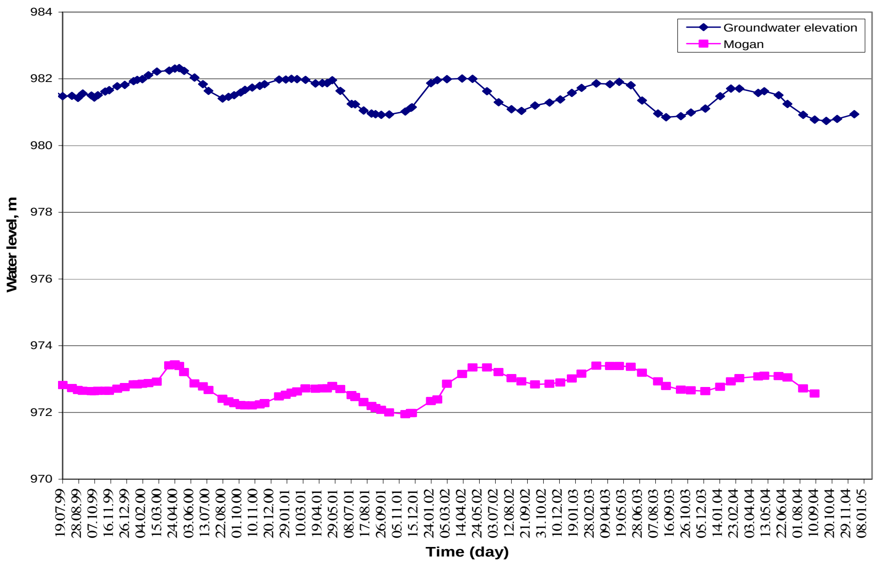

Figure B.11. The relation between groundwater elevation in Well no: 17 and Lake Mogan.

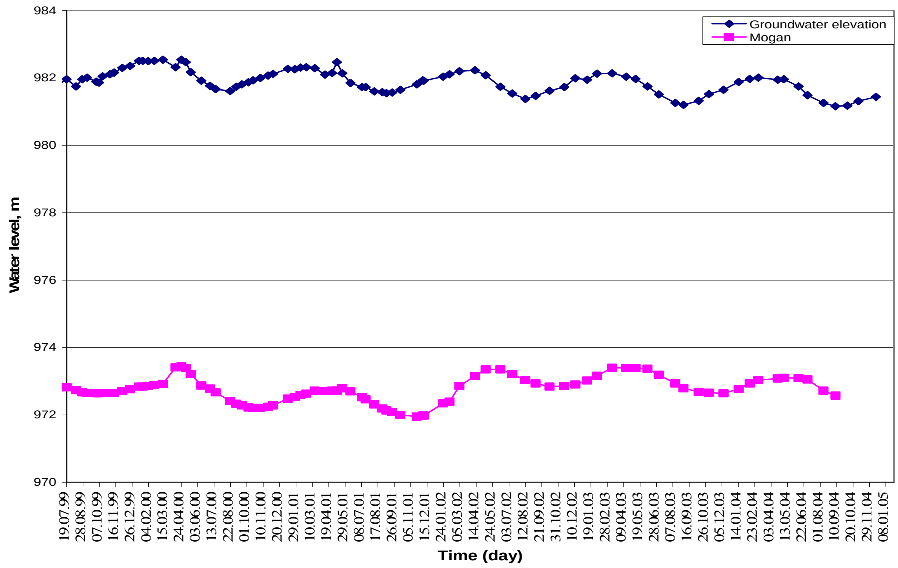

Figure B.12. The relation between groundwater elevation in Well no: 18 and Lake Mogan.

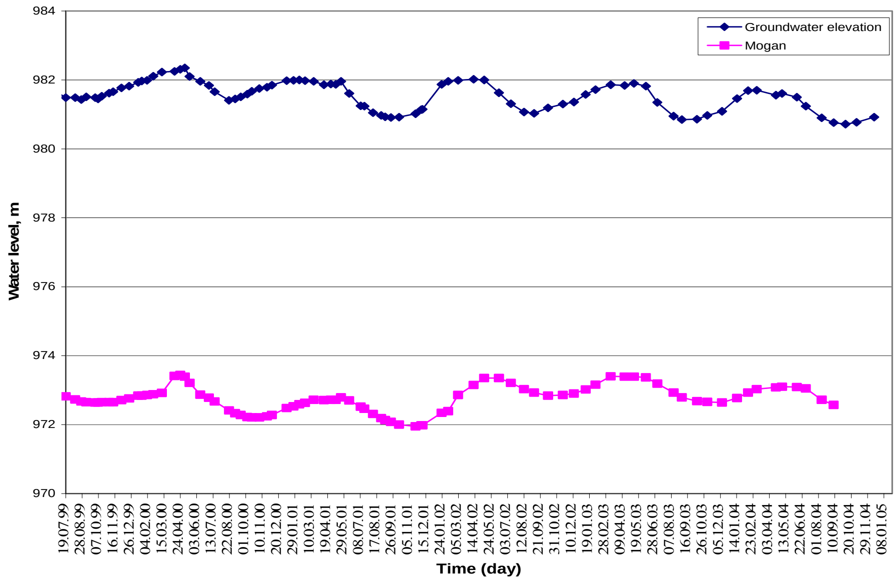

Figure B.13. The relation between groundwater elevation in Well no: 19 and Lake Mogan.

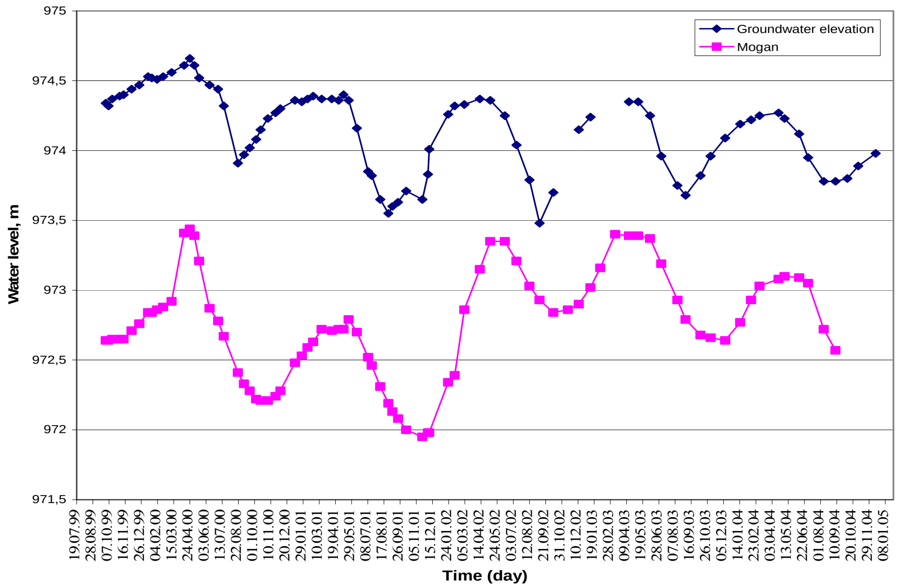

Figure B.14. The relation between groundwater elevation in Well no: 20 and Lake Mogan.

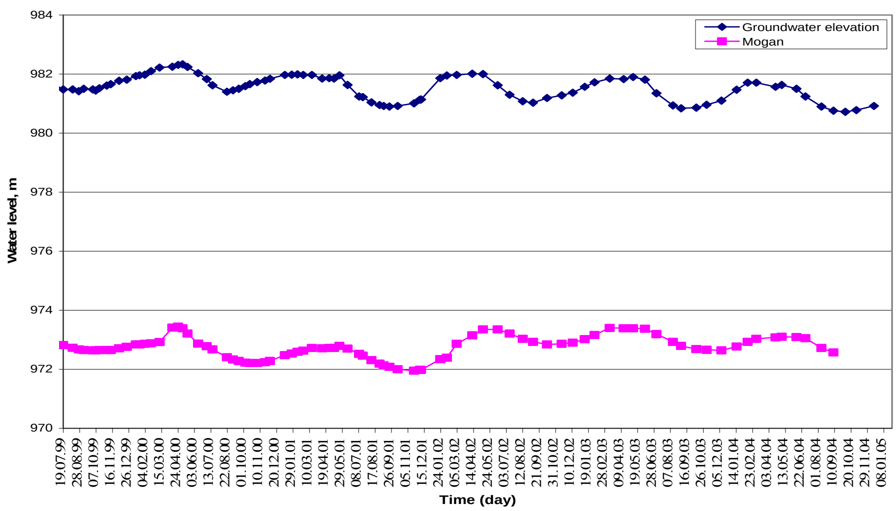

Figure B.15. The relation between groundwater elevation in Well no: 23 and Lake Mogan.

APPENDIX C

GROUNDWATER ELEVATIONS
AND PRECIPITATION HYETOGRAPHS

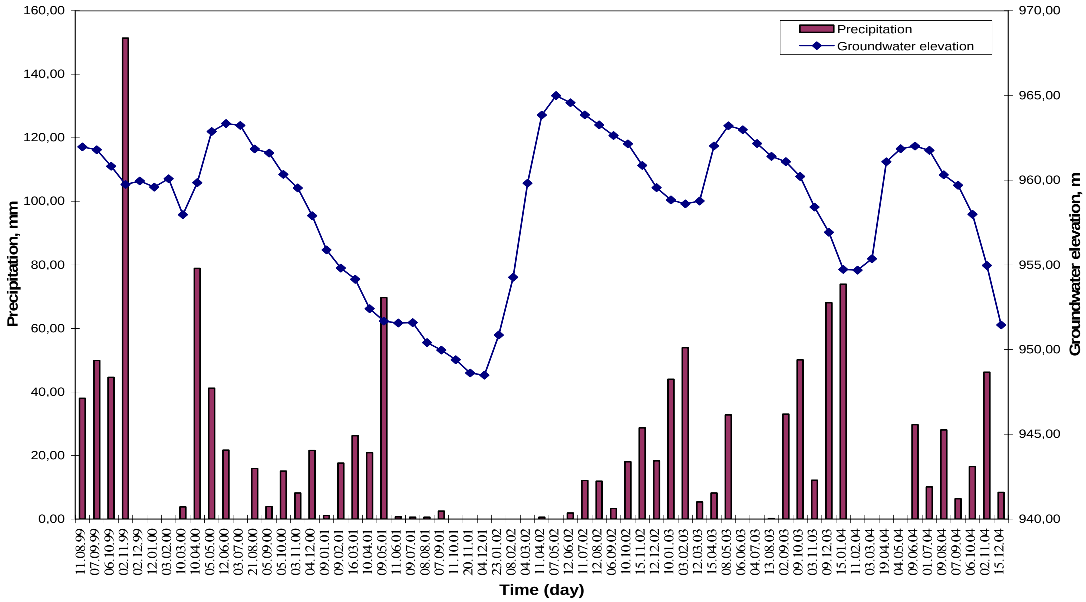

Figure C.1. The relation between precipitation and groundwater elevation in Well no: 1.

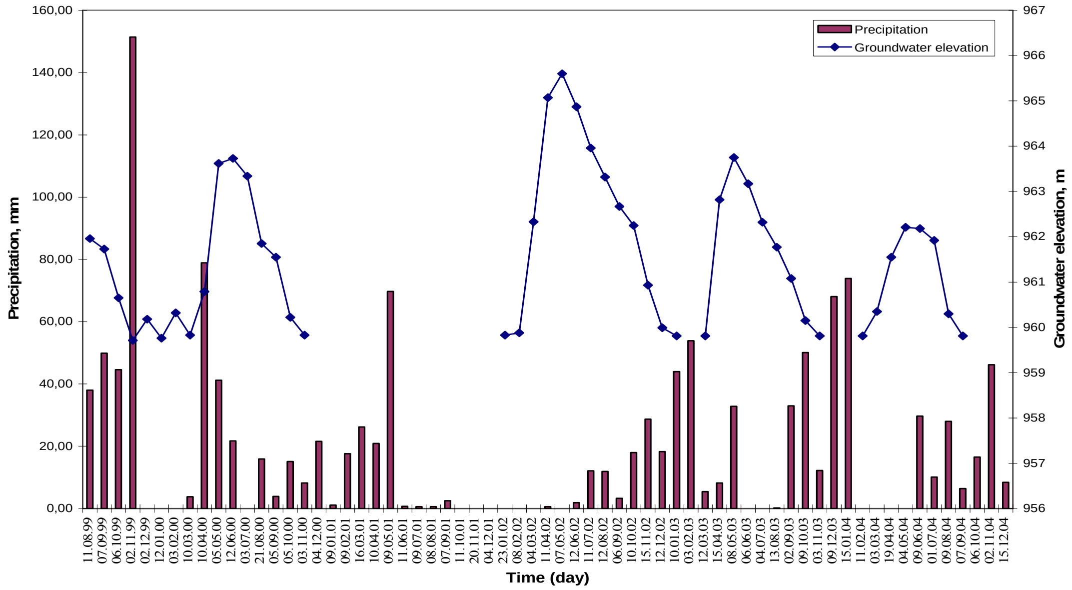

Figure C.2. The relation between precipitation and groundwater elevation in Well no: 2.

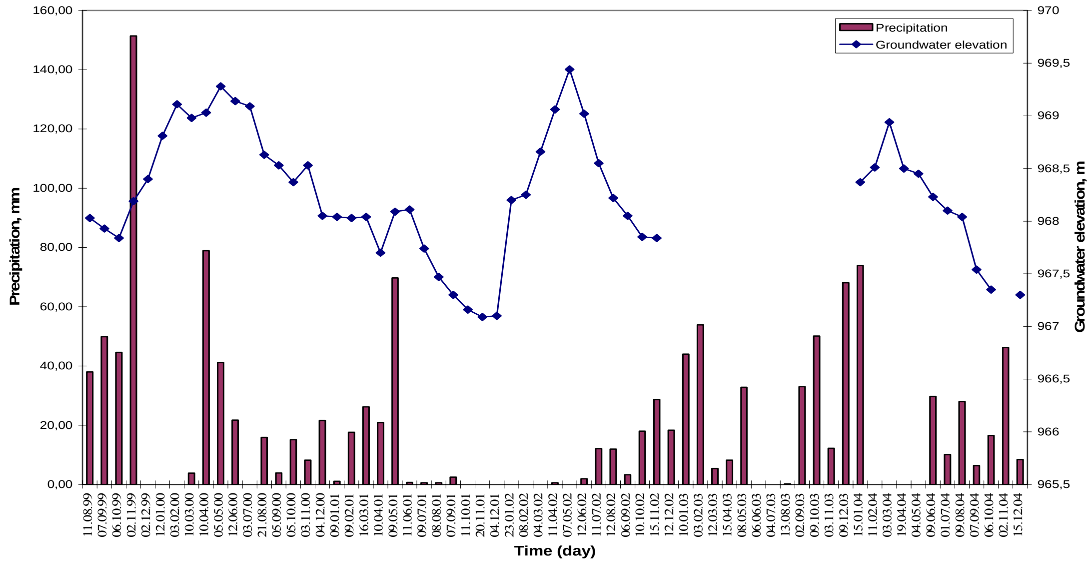

Figure C.3. The relation between precipitation and groundwater elevation in Well no: 3.

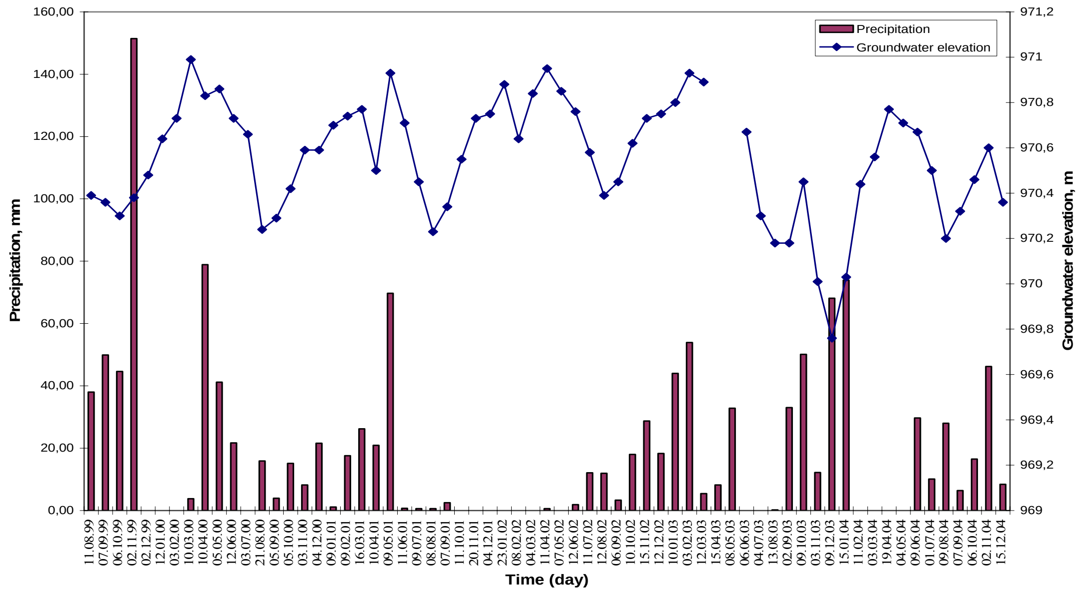

Figure C.4. The relation between precipitation and groundwater elevation in Well no: 4.

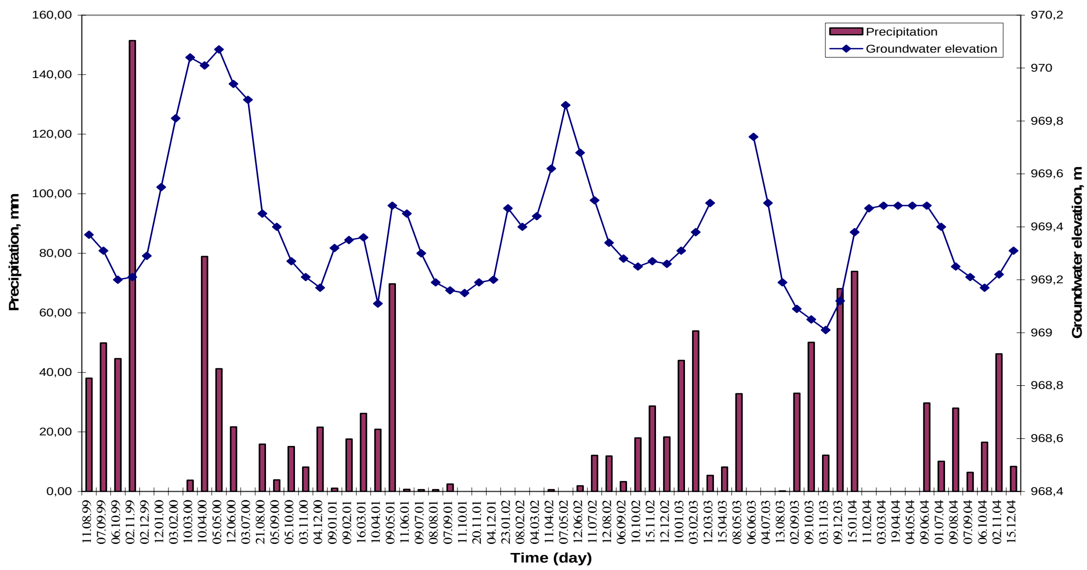

Figure C.5. The relation between precipitation and groundwater elevation in Well no: 5.

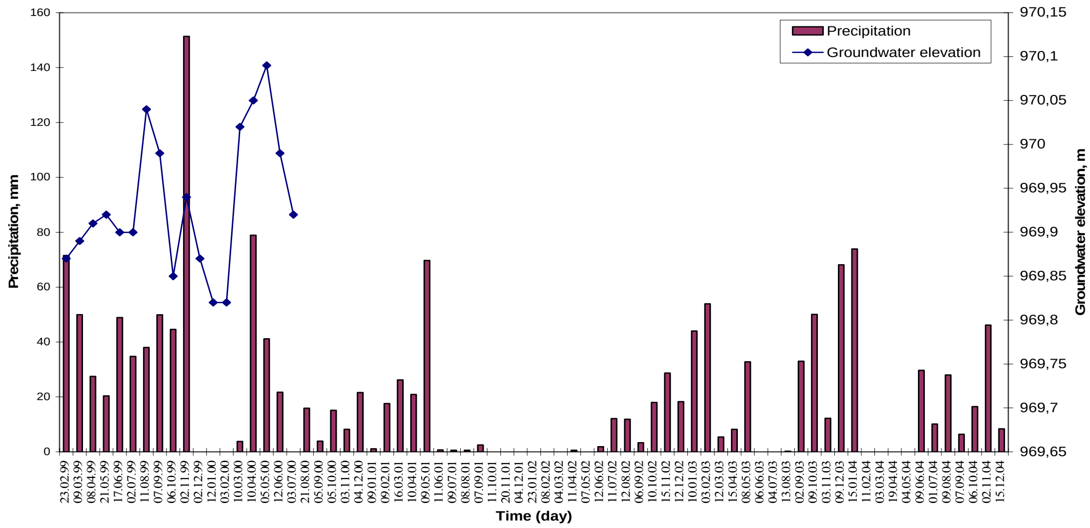

Figure C.6. The relation between precipitation and groundwater elevation in Well no: 8.

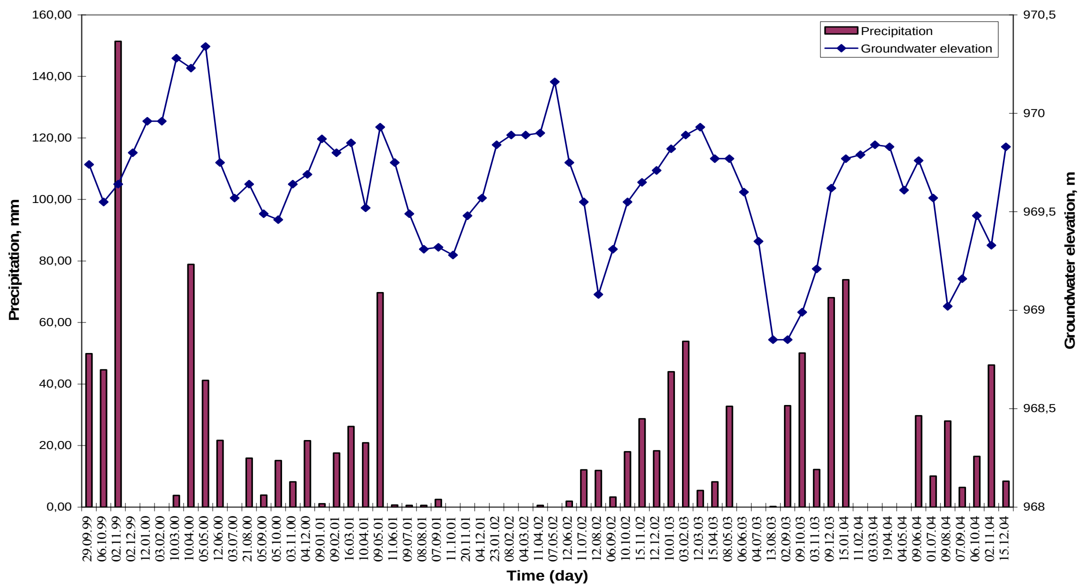

Figure C.7. The relation between precipitation and groundwater elevation in Well no: 9.

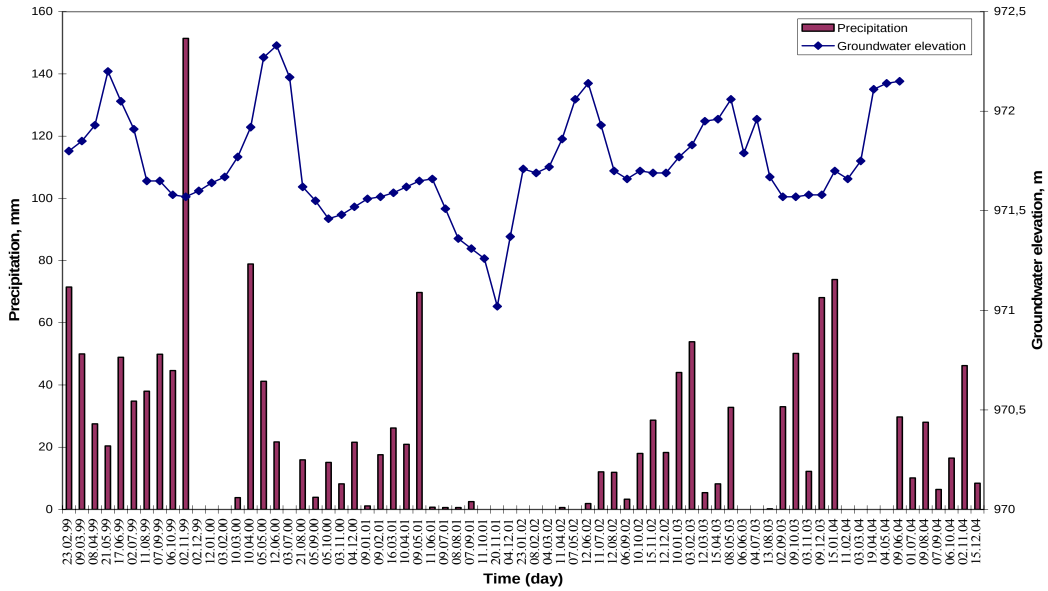

Figure C.8. The relation between precipitation and groundwater elevation in Well no: 10.

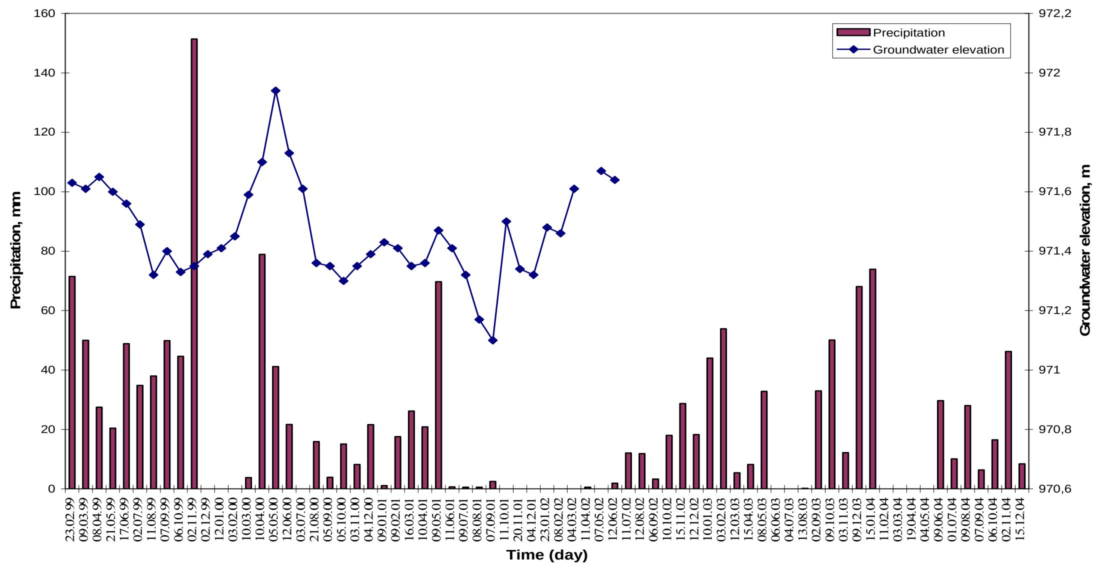

Figure C.9. The relation between precipitation and groundwater elevation in Well no: 11.

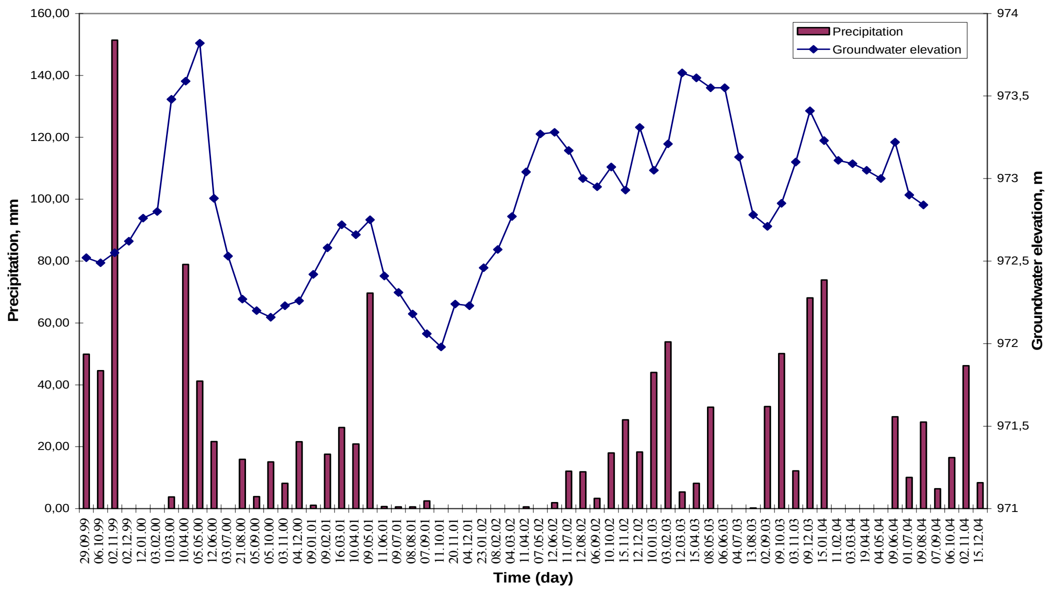

Figure C.10. The relation between precipitation and groundwater elevation in Well no: 14.

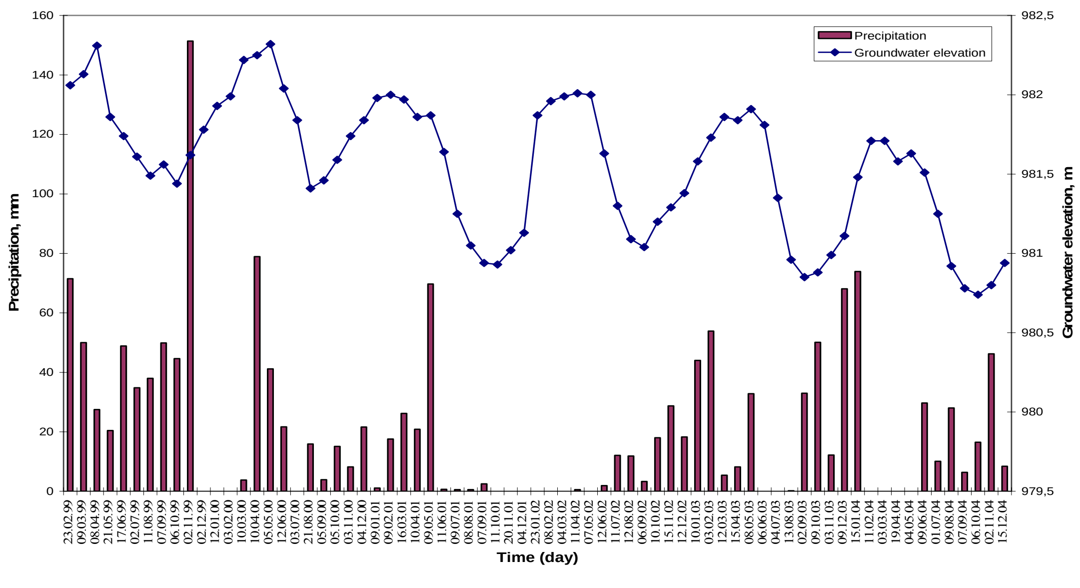

Figure C.11. The relation between precipitation and groundwater elevation in Well no: 17.

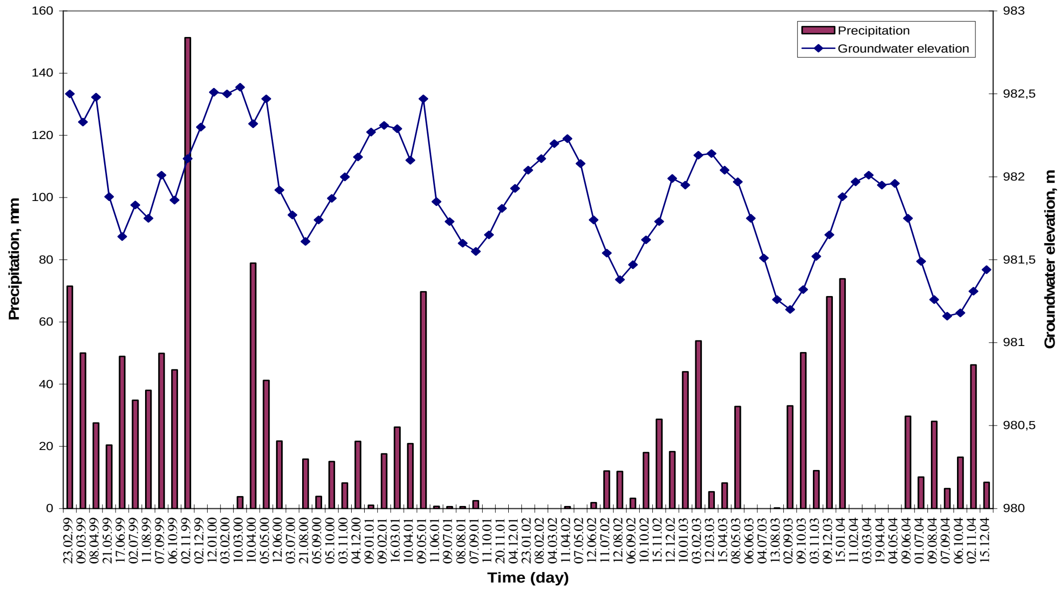

Figure C.12. The relation between precipitation and groundwater elevation in Well no: 18.

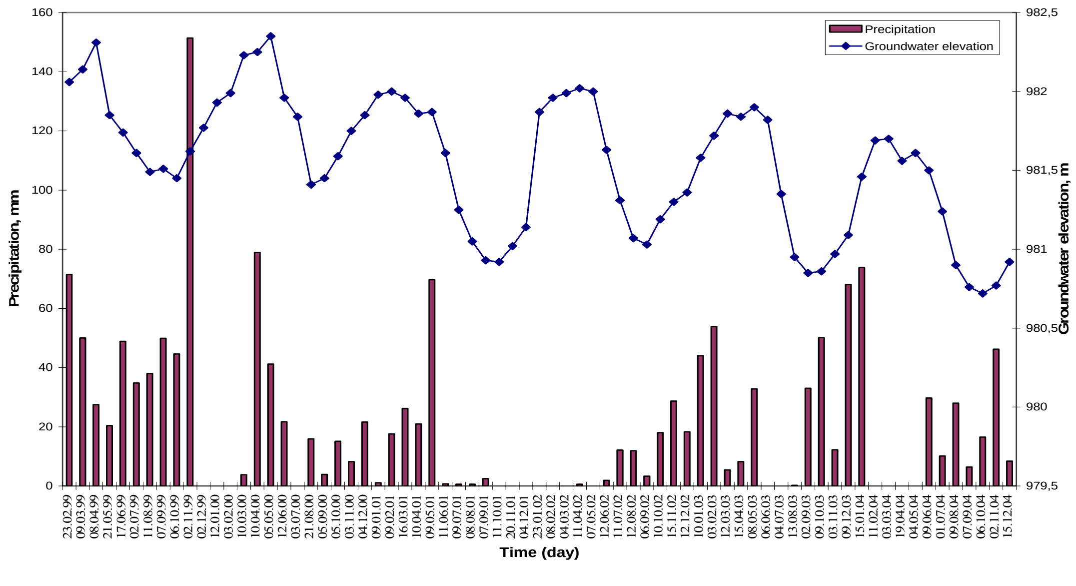

Figure C.13. The relation between precipitation and groundwater elevation in Well no: 19.

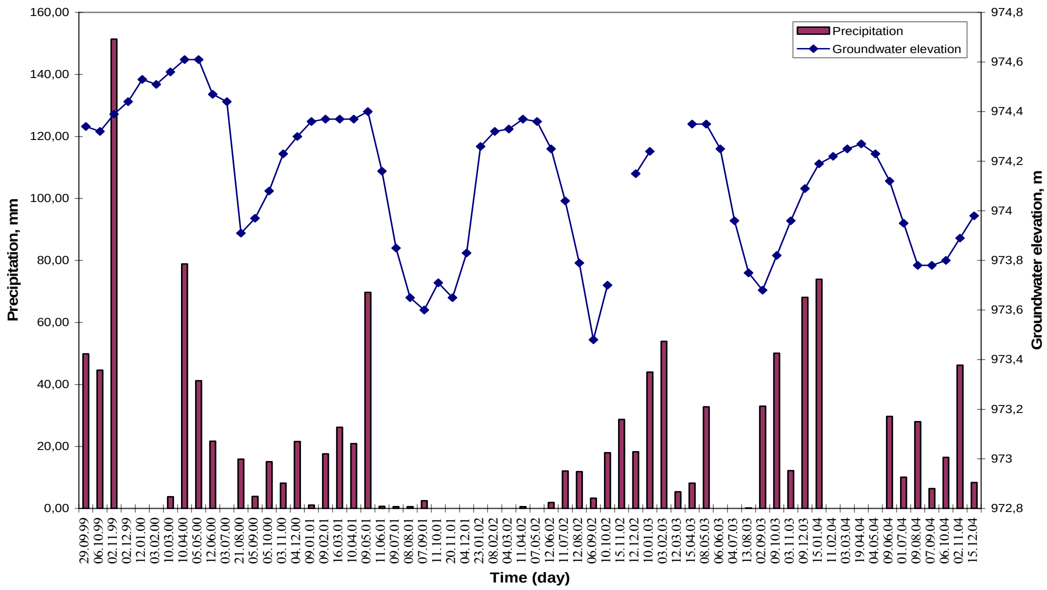

Figure C.14. The relation between precipitation and groundwater elevation in Well no: 20.

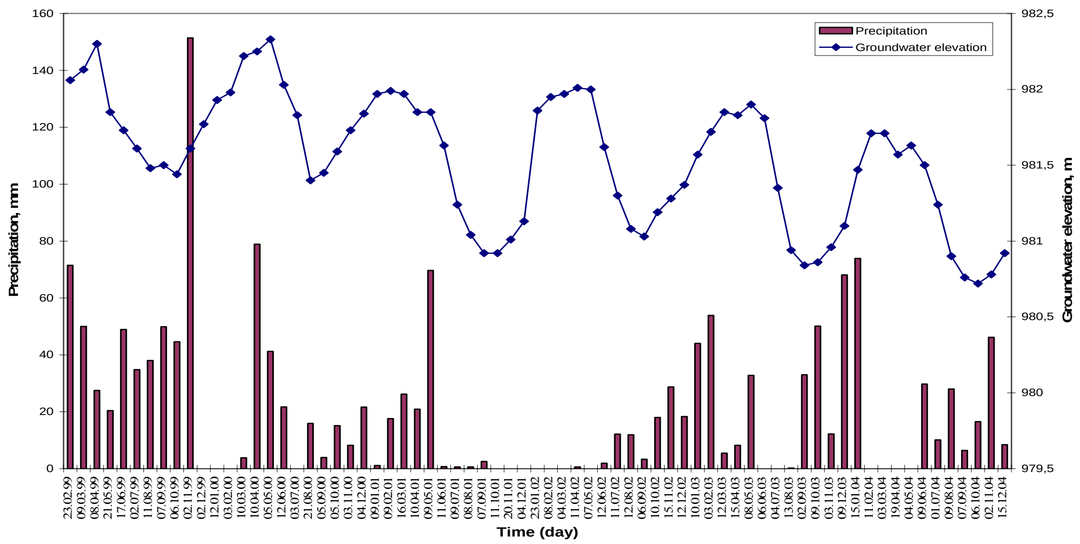

Figure C.15. The relation between precipitation and groundwater elevation in Well no: 23.

CURRICULUM VITAE

PERSONAL INFORMATION

Surname, Name: Yağbasan, Özlem

Nationality: Turkish (TC)

Date and place of Birth: 2 November 1976, Ankara

Marital Status: Single

Phone: +90 312 232 35 88

Fax: +90 312 232 35 26

email: ozlemy@gazi.edu.tr

EDUCATION

Degree	Institution	Year of Graduation
MS	Gazi Uni. Environmental Sciences	2000
BS	Ankara Uni. Geological Engineering	1998
High School	Gazi Anatolian High School, Ankara	1994

WORK EXPERIENCE

Year	Place	Enrollment
1998- Present	Gazi Uni. Environmental Sciences	Research Assistant

FOREIGN LANGUAGES

Fluent English

HOBBIES

Musics, Movies, Sports