CONCEPTUAL MODEL DEVELOPMENT FOR GÜZELYURT AQUIFER, NORTH CYPRUS

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

BY

DEBEBE BEYENE FANTA

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
ENVIRONMENTAL ENGINEERING

JULY 2015

Approval of the thesis:

CONCEPTUAL MODEL DEVELOPMENT FOR GUZELYÜRT AQUIFER, NORTH CYPRUS

Submitted by **DEBEBE BEYENE FANTA** in partial fulfillment of the requirements for the degree of **Master of Science in Environmental Engineering Department, Middle East Technical University** by,

Prof. Dr. Gülbin Dural Ünver _______________
Dean, **Graduate School of Natural and Applied Sciences**

Prof. Dr. F. Dilek Sanin _______________
Head of Department, **Environmental Engineering**

Prof. Dr. Kahraman Ünlü _______________
Supervisor, **Environmental Engineering Dept., METU**

Assist. Prof. Dr. Bertuğ Akıntuğ _______________
Co-supervisor, **Civil Engineering Program, METU-NCC**

Examining Committee Members:

Prof. Dr. Filiz B. Dilek _______________
Environmental Engineering Dept., METU

Prof. Dr. Kahraman Ünlü _______________
Environmental Engineering Dept., METU

Assist. Prof. Dr. Bertuğ Akıntuğ _______________
Civil Engineering Program, METU-NCC

Prof. Dr. Mustafa Türker _______________
Geomatics Engineering Dept., Hacettepe University

Assoc. Prof. Dr. Ayşegül Aksoy _______________
Environmental Engineering Dept., METU

Date: 14.07.2015

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 materials and results that are not original to this work.

Name, Last name: Debebe Beyene FANTA

Signature :

ABSTRACT

CONCEPTUAL MODEL DEVELOPMENT FOR GÜZELYURT AQUIFER, NORTH CYPRUS

Fanta, Debebe Beyene

M.S., Department of Environmental Engineering

Supervisor: Prof. Dr. Kahraman Ünlü

Co-Supervisor: Assist. Prof. Dr. Bertuğ Akıntuğ

July 2015, 139 pages

Water resources available in the North Cyprus are suffering from severe drought. In order to overcome this, there is a water diversion project being carried out in the North Cyprus by State Hydraulic Works (DSİ). The project is designed to supply about 75 million m^3 of water annually for drinking and irrigation purpose from southern Turkey to Northern Cyprus via pipeline under Mediterranean Sea.

The costal aquifer of Güzelyurt, which is located in North Cyprus, is currently the main source of potable water in the region. Apart from drinking water supply, the aquifer is also used for agricultural irrigation purpose in the Güzelyurt region that provides significant contribution to the economy of the country through citrus orchards. Recent studies have revealed that the amount of water extracted from the aquifer exceeded its safe yield capacity, thus causing the degradation of water quality in the aquifer due to seawater intrusion. The water diversion project of DSİ is expected to relieve the excessive stress on the Güzelyurt Aquifer and may help the aquifer recover from further deterioration.

The primary objective of this research is to develop a conceptual model for the Güzelyurt aquifer, which is the most useful tool available for groundwater resource management. It provides the general 3-D picture of the aquifer geometry, including recharge, discharge and hydraulic characteristics of the aquifer. In addition, the conceptual model is also used to ease understanding the complex nature of the aquifer system and organize the associated field data so that the system can be analyzed effectively for the purpose of future water resources planning. The conceptual model of the Güzelyurt Aquifer was developed in Geographical Information Systems (GIS) and Groundwater Modeling System (GMS) software environment based on the available geological and hydrological data of the study area. Based on the objectives, the surface and subsurface structural framework: areal and vertical extent of aquifer has been determined and also internal and external boundary conditions of the aquifer have been established. Moreover, aquifer zones affected by excessive water withdrawal and seawater intrusion have been delineated.

Keywords: Güzelyurt Aquifer of North Cyprus, Aquifer Conceptual Model, Geographical Information Systems (GIS), Groundwater Modeling System (GMS).

ÖZ

KUZEY KIBRIS TÜRK CUMHURİYETİ (KKTC) GÜZELYURT AKİFERİ İÇİN KAVRAMSAL MODEL GELİŞTİRİLMESİ

Fanta, Debebe Beyene

Yüksek Lisans, Çevre Mühendisliği Bölümü

Tez Yöneticisi: Prof. Dr. Kahraman Ünlü

Yardımcı Tez Yöneticisi: Yrd. Doç Dr. Bertuğ Akıntuğ

Temmuz 2015, 139 sayfa

Kuzey Kıbrıs'ta mevcut su kaynakları ciddi kuraklık tehdidiyle karşı karşıyadır. Kuraklık tehdidinin ortadan kaldırılmasına yönelik olarak Devlet Su İşleri (DSİ) tarafından Kuzey Kıbrıs Su Temini Projesi uygulama konmuştur. Bu proje Türkiye'nin güneyinden Kuzey Kıbrıs'a Akdeniz'in altından döşenecek bir boru hattıyla yıllık bazda 75 milyon m^3 içme ve suluma suyunun temin edimesi amacıyla tasarlanmıştır.

Kuzey Kıbrıs'ta bulunan ve bir kıyı akiferi olan Güzelyurt Akifer'i bölgenin en önemli su kaynağıdır. Güzelyurt Akiferi içme suyu temini amacıyla birlikte, ülkenin ekonomisine ciddi katkı sağlayan Güzelyurt bölgesindeki narenciye bahçelerinin sulanması amacıyla da kullanılmaktadır. Son dönemlerdeki araştırma çalışmaları akiferden çekilen su miktarının emniyetli verim miktarından fazla olması nedeniyle, akiferin tuzlanmaya maruz kaldığını ve su kalitesinde bozulmalar olduğunu göstermektedir. Kuzey Kıbrıs Su Temini Projesinin Güzelyurt Akiferi üzerindeki aşırı çekim baskısını azaltması ve akiferin daha fazla bozulmaya maruz kalmasını önleyerek iyileşmesine yardımcı olması beklenmektedir.

Bu araştırma çalışmasının ana amacı, yeraltısuyu kaynaklarının yönetiminde kullanılan en önemli araçlardan birisi olan kavramsal modelin Güzelyurt Akiferi için geliştirilmesidir. Kavramsal model akiferin 3-boyutlu geometrik yapısını göstermenin yanı sıra akiferin beslenim boşalım ve hidrolik özelliklerini de tanımlamaktadır. Buna ek olarak, kavramsal model, karmaşık aqifer sisteminin anlaşılmasının kolaytırılmasını ve mevcut saha verilerinin organize edilerek su kaynaklarının planlanmasına yönelik olarak sistemin etkin bir şekilde analiz edimesini sağlamak amacıyla da kullanılmaktadır. Güzeyurt Akiferi'nin kavramsal modeli, çalışma sahasına ait mevcut topoğrafik, jeolojik ve hidrolojik veriler baz alınarak, Coğrafi Bilgi Sistemleri (CBS) ve Yeraltısuyu Modelleme Sistemi (YMS) yazılımları ortamlarında geliştirilmiştir. Çalışmanın amaçları doğrultusunda, akiferin 3-boyutlu hidrojeolojik yapısı, alansal ve kalınlık dağılımı belirlenmiştir; ve bunlara ek olarak iç ve dış sınır koşulları tanımlanmıştır. Ayrıca, akiferin aşırı su çekiminden ve deniz suyu girişiminden olumsuz etkilenen kısımları belirlenmiştir.

Anahtar Kelimeler: Kuzey Kıbrıs Güzelyurt Akiferi, Akifer Kavramsal Modeli, Coğrafi Bilgi Sistemleri (CBS), Yeraltısuyu Modelleme Sistemi (YMS).

To My Parents

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to Prof. Dr. Kahraman Ünlü for the support, motivation and encouragement he provided me throughout the study. He has always been optimistic about my progress and made me believe that I can proceed further.

I would like to express my appreciation to my co-advisor Assist. Prof. Dr. Bertuğ Akıntuğ for his support, advice and the trips he has organized that gave me a clear view of the study area.

I would also like to thank Mustafa Alkaravli, Director of Geology and Mining Department of North Cyprus, Dr. Mehmet Necdet, Mr. İbrahim Çolakoğlu, and Mr. Salih Erşangil for their help and contributions in providing raw data and for their expertise comment on the interpretation of the results.

Finally, I would like to thank my family for their words of encouragement and endless support throughout the study.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

CHAPTER 1

INTRODUCTION

1.1. Background

The amount of water stored in the earth crust is immense. It is evident that the volume of water stored in the rocks of the world land areas may be in the order of 8 billion cubic kilometers, half of which is at depths less than 800 m (Rawls, David, Mullen, & Ward,1996). Most of this ground water is not visible to man, but is buried below the earth surface. However, a small percentage of this underground supply is visible as naturally discharging springs, or as streams and rivers which are sustained by ground water when direct runoff from precipitation ceases.

Despite its various dynamic states, the total volume of water on earth has remained virtually unchanged for the last three billion years. As shown in Figure 1.1, 97.5% of the estimated 1,400 million cubic kilometers of water available on earth is saline and the remaining 2.5% is fresh water. The greater portion of the fresh water (68.7%) is found in the form of ice and permanent snow-cover in the Arctic, Antarctic, and in the mountainous regions, whereas the 29.9% exist as a fresh groundwater. The remaining 0.26% of the planet’s freshwater is the surface-water fraction, which is our traditional source of freshwater found in reservoirs, rivers, and lakes (S.H.Schneider, 1996; Shiklomanov, 1998).

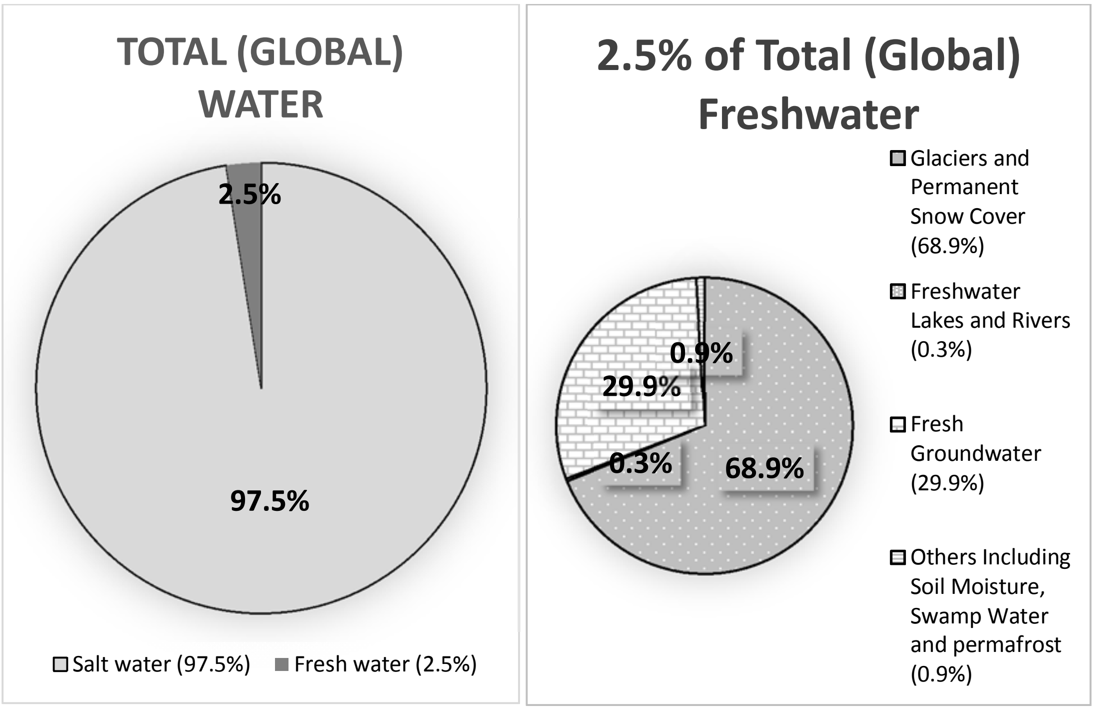

Figure 1.1 The total (Global) water distribution (left) and the sub-distribution of fresh water (right) in our planet (Shiklomanov, 1998).

Groundwater is a critical resource for water supply throughout the world. In addition to rural households and public water supplies that depend on groundwater, farmers also use groundwater for irrigating crops and for their animals. Many commercial businesses and industries also depend on groundwater for their processes and operations. It is a vulnerable resource because it may be degraded or depleted due to many reasons; including, contamination, overexploitation or reduction of groundwater recharge due to climate change, soil compaction and sealing. Depletion of groundwater from water bearing subsurface layers is a serious problem, especially in the arid and semi-arid regions where groundwater is the main source of water for irrigation and other supply affairs.

1.1.1. Overview of Water Resources in the North Cyprus

North Cyprus is an island located in the north eastern Mediterranean region where water is the most precious commodity than any other places (Ergil, 1999). Water resources available around Eastern Mediterranean region, including North Cyprus , are under severe stress due to many factors, such as increase in population growth rates, increased rural-urban migration, the growing tourism industry, uncontrolled irrigation for agricultural use, late adoption of modern irrigation techniques, poor maintenance/efficiency of municipality water supply pipelines, poor water network systems, and increase in the number of industries and recent huge investment in real estate (O. Phillips Agboola et al., 2012). About 92% of domestic and agricultural water supply in North Cyprus comes from groundwater resources (Türker et al., 2012). Groundwater is the main water resources in North Cyprus and all the drinking and municipal water demand is met by groundwater. There are 14 groundwater bearing geologic formations (Aquifers) identified in North Cyprus within eight hydrological regions, each having different water bearing capacity (O. Phillips Agboola et al., 2012). The names and water storage characteristics of these aquifers are given in Table 1.1. Among the 14 aquifers, three of them are the main sources of domestic and irrigation water supply in the region. As shown in Figure 1.2, these aquifers are located in three different basins, namely Güzelyurt Aquifer in Mesarya Plain, Girne Range Aquifer in Girne Limestone Mountains, and Yeşilkoy Aquifer on the inlands of Karpas Peninsula.

Table 1.1 The aquifers and their capacities in Turkish Republic of North Cyprus (Phillips Agboola & Egelioglu, 2012).

Aquifers	**Recharge (10^6 m^3)**	**Sustainable yield (10^6 m^3)**	**Withdrawals (10^6 m^3)**
Güzelyurt	37	37	57
Akdeniz	15	1.5	1.5
Lefke-G. Konagi Y. dalga	15.5	6	6
Yesilirmak	7	1.5	1.5
Girne Mountains	11.5	11.5	11.5
Gazimagusa	2	2	8.5
Beyarmudu	0.5	0.5	0.5
Cayonu-Guvercinlik-Turkmenkoy	2	2	2
Lefkosa-Serdarli	0.5	0.5	0.5
Yesilkoy	1.6	1.6	3
Girne Coast	5	5	5
Yedikonuk-Buyukkonuk	0.3	0.3	0.3
Dipkarpaz	1.5	1.5	1.5
Korucam	1.2	1.2	1.2
Others	2	2	2
Total	**89.1**	**74.1**	**103**

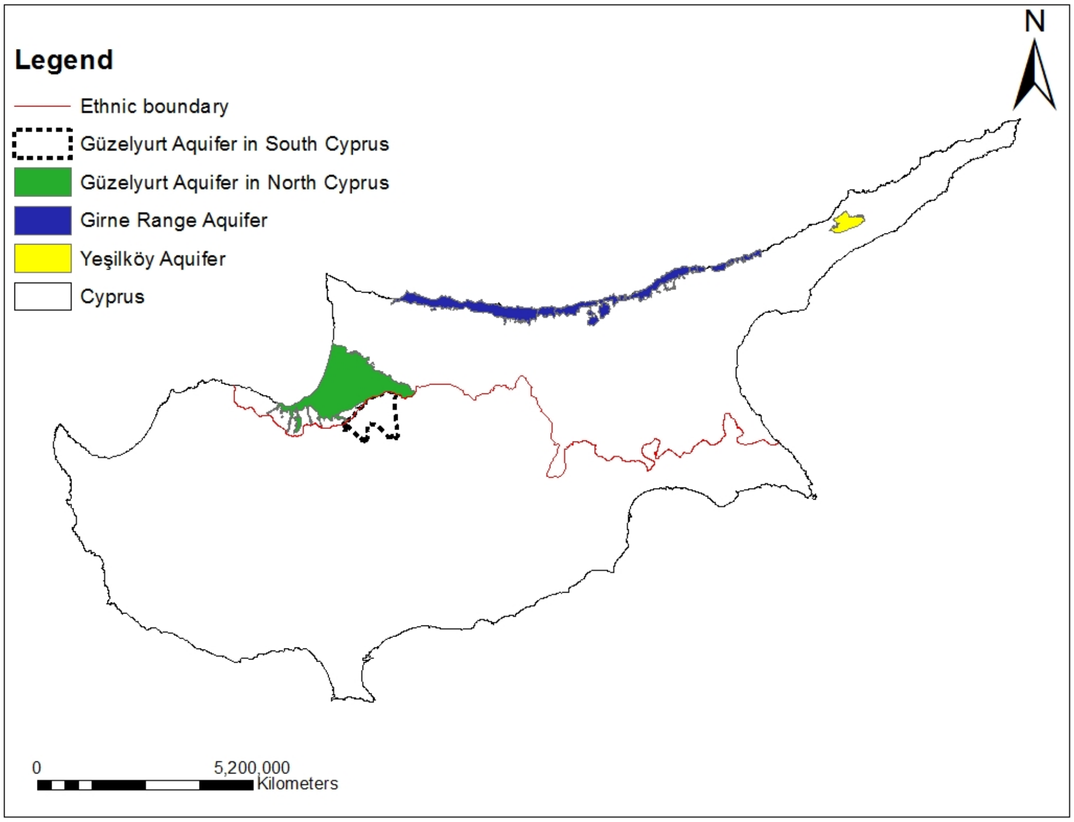

Figure 1.2 The three major aquifers in Cyprus.

Regarding surface water resources, North Cyprus is considered to be very poor because there are no natural lakes or continuously flowing rivers and stream in the country. The surface water potential in North Cyprus totally rely on runoff water collected through ephemeral, seasonal drainage streams of four main precipitation basins, Western Mesarya-Lefke, Eastern Mesarya, Northern shore-Beşparmaklar and Karpaz basins (DSI, 2004). In general, the flow of these drainage streams are primarily precipitation depended and short duration floods in nature, except the ones originating from the Troodos Mountains as a result of snow melt which may cause somewhat longer and regular flows seasonally. A total of 37 ephemeral drainage streams are carrying surface runoff water from the mountains to recharge the fourteen aquifers. Nine of these seasonal drainage streams originate from relatively water-rich Troodos Mountains in the southwestern part of North Cyprus, but flows have been almost totally cut due to construction of dams by the South Cyprus administration. The remaining 28 ephemeral drainage streams are flowing from Beşparmak Mountains in the northern part of the island. All of the 37 drainage streams carry annually a total of about 70 million m^3 of water, out of which about 43 million m^3 is annually carried by eight of the nine streams draining from Troodos Mountains, namely Yeşilırmak Stream, Kamburdere, Maden Stream, Lefke Deresi, Çamlıdere, Çakıldere, Doğancı Stream, and Güzelyurt Stream. The quite large stream, namely Kanlidere is carrying no water due to the blockage of flow by the dams constructed in the upstream of the catchment located in the South Cyprus. The remaining 27 million m^3 of water per year is carried by the 28 streams from Beşparmak Mountains in the north. From the total water carried by the streams, about 38 million m^3 water is assumed to feed the aquifer in the western part of the country while the rest is used for irrigation purpose and some of it flows directly into Mediterranean Sea (O. Phillips Agboola et al., 2012).

In order to conserve water from the seasonal flowing streams for the purpose of increasing groundwater recharge and avoiding the loss of runoff water of streams into the Mediterranean Sea, relatively small-scale dams and ponds are constructed by North Cyprus administration. There are 28 reservoirs, dams and ponds constructed in North Cyprus each with a storage capacity ranging from 2,000 m^3 to 4.5 million m^3 having a total annual storage capacity of about 28.6 million m^3 (DSI, 2004). A list of dams, reservoirs and ponds constructed before and after 1974 are shown in Table 1.2 and also the stream lines together with some of the existing hydraulic structures are shown in Figure 1.3. As seen from the table majority of the dams are used mainly for agricultural purposes, and none of them is used for municipal water supply purposes.

Table 1.2 The list of dams, reservoirs and ponds in North Cyprus constructed before and after 1974. (DSI, 2004)

	Names of Dams	**Years of Construction**	**Capacity (10^3 m^3)**	**Purpose of Use**
Constructed before 1974				
1	*Köprü Kukla Reservoirs*	1900	4,545	Irrigation & GWR*
2	*Akova Dam*	1955	100	Irrigation
3	*Aylika Dam*	1955	455	GWR
4	*Güzelyurt (Omorfo) Dam*	1962	1,879	Irrigation & GWR
5	*Gönyeli Dam*	1962	1,045	Irrigation
6	*Kanliköy Dam*	1963	1,113	Irrigation
7	*Haspolat Pond*	1963	355	Irrigation
8	*Yuvacik (Ovogos)Dam*	1964	845	Irrigation & GWR
9	*Sınırüstü (Syngrasi) Dam*	1967	1,115	Irrigation & GWR
10	*Serhatköy (Mashari) Dam*	1973	2,273	Irrigation & GWR
Constructed after 1974				
1	*Gönendere Pond*	1987	1,100	Irrigation
2	*Geçitköy-Dağdere Pond*	1989	1,800	Irrigation
3	*Karsiyaka Pond*	1989	25	GWR
4	*Tatlısu-Portakallıdere Pond*	1989	156	Irrigation & GWR
5	*Mersinlik-Azganlıdere Pond*	1989	1,020	Irrigation
6	*Ergazi-Sayadere Pond*	1989	400	Irrigation
7	*Eğridere Pond*	1989	1,300	Irrigation
8	*Zeytinlik-Köprüdere Pond*	1990	50	GWR
9	*Arapköy-Uzundere Pond*	1990	340	Irrigation
10	*Arapköy-Ayanidere Pond*	1990	530	Irrigation
11	*Değirmenlik-Çataldere*	1990	317	Irrigation
12	*Serdarlı-Ağıllıdere Pond*	1992	325	Irrigation
13	*Alakati-Çiftlikdere Pond*	1992	775	Irrigation
14	*Hamitköy-Bostanlıkdere*	1992	505	Irrigation
15	*Lefke-Gemikonağı Pond*	1994	4,000	Irrigation & GWR
16	*Yılmazköy-Polatdere Pond*	1994	415	Irrigation
17	*Dağyolu-Üçparmakdere*	1994	310	Irrigation
18	*Akdeniz-Çiftlikdere Pond*	1994	1,500	Irrigation

*GWR is Groundwater Recharge

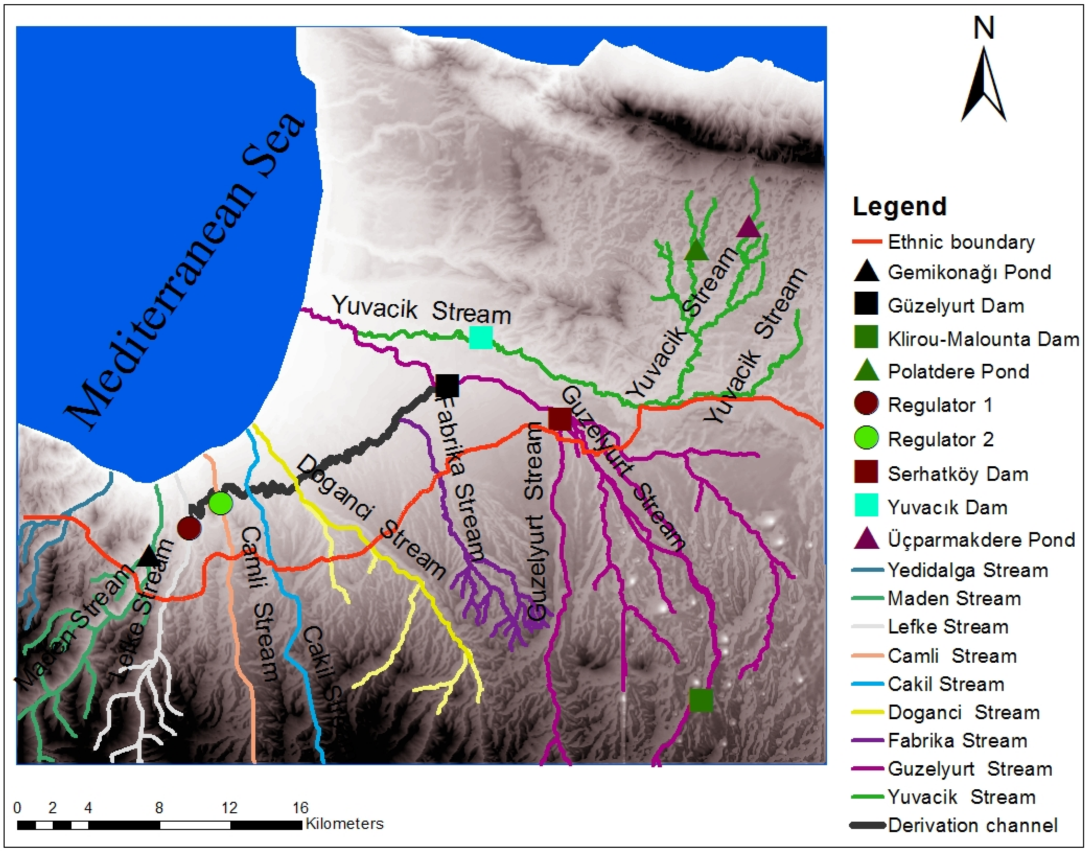

Figure 1.3 Stream lines and some of the hydraulic structures in the study area.

There have been some recent attempts to improve water resources of North Cyprus to overcome the long-lasting water shortage problem and to provide long-term solutions to the problem. Along this line, State Hydraulic Works (DSI) has prepared a report called "North Cyprus Water Master Plan" (DSI, 2004) for North Cyprus. Within the context of this Water Master Plan, construction of a total of 5 new dams is planned to be used mainly for drinking and municipal water supply purposes, in addition to the existing ones listed in Table 1.2. Another and the most recent attempt, as a long term remedy for serious water shortage problem of North Cyprus, has been the implementation of a project called "North Cyprus Water Supply Project" by the Turkish Republic. With this project, a total of 75 million m^3 of water is annually to be transmitted via a unique under-water pipeline from a dam constructed on Dragon Stream in Anamur, Turkey all the way to the Geçitköy Dam located on the cost of Girne in North Cyprus. It is planned that, of the 75 million m^3 of water, 38 million m^3

is to be used for drinking purpose while the remaining 37 million m^3 for irrigation purpose, especially in the Güzelyurt plain, over an expected 50-year time horizon.

1.1.2. The Costal Aquifer of Güzelyurt

The costal aquifer of Güzelyurt is located in the southwestern part of North Cyprus as shown in Figure 1.2. Among the existing and limited amount of water resources, Güzelyurt Aquifer is the largest aquifer and the main source of drinking, municipal and irrigation water resource in the North Cyprus. The aquifer has an estimated water bearing capacity of about 920 million m^3 of water with an annual recharge and discharge of 37 million m^3 and 57 million m^3, respectively, resulting in a deficit of 20 million m^3 (O. Phillips Agboola et al., 2012). Güzelyurt Aquifer is recharged mainly through infiltration of precipitation and drainage streams of runoff water, and partly from surrounding formations. Apart from drinking water supply (8%), the majority of the aquifer (92%) is used for agricultural irrigation purposes in Güzelyurt region, which provides significant contribution to the economy of the country. Almost 80% of the foreign currency of North Cyprus comes from the production of citrus fruit, which requires sustainable water resource. The aquifer has been utilized to satisfy the need for the cultivation of nearly 65 km^2 of citrus fruit orchards. In the past few decades, over 2000 wells have been drilled for mainly irrigation purpose, without taking any precaution of its depletion (Ergil, 2000). Recent studies have revealed that there is significant reduction in the amounts of extractable groundwater over the years as a result of excessive and uncontrolled pumping to satisfy the high water demand. This situation, in turn, created a serious degradation of water quality due to saltwater intrusion near the coastal areas. Excessive water extraction from the aquifer and seawater intrusion are identified as the main problems that the Güzelyurt Aquifer faces. The estimated salt content in the water about 1 km from the shore is around 2,000 ppm NaCl (O. Phillips Agboola et al., 2012).

In order to alleviate the problem and reduce the stress on Güzelyurt Aquifer, there have been projects proposed to import water from Turkey by tankers, water bags, and pipelines. The first project used water bags and carried the first load of water in July 1998 (O. Phillips Agboola et al., 2012). Initially the project was designed to supply 3 million m^3 of water annual by using water bags with carrying capacity of 10,000 m^3. Due to an increased demand of water in the region, the water bags carrying capacity raised to 30,000 m^3 that would enable 7 million m^3 of water to be supplied annually. However, the project terminated due to water loss resulted from the water bags burst when in contact with sharp materials in the Mediterranean Sea. Recently, a project called "North Cyprus Water Supply Project" has been implemented by Turkish Republic as a long-term remedy for serious water shortage problem of North Cyprus. The project is designed to supply about 75 million m^3 of water annually for drinking and irrigation purpose from southern Turkey to North Cyprus via pipeline under Mediterranean Sea (Thomas Seibert, 2014). One of the important contributions of this project is the creation of an opportunity for rehabilitation of the Güzelyurt Aquifer through significant relief of the existing high stress due to excessive water demand, and because of this, reestablishing the deteriorated water budget of the aquifers in the mid-term and long-term.

1.1.3. Groundwater Management

Groundwater is globally a vital resource for water supply, as well as locally for North Cyprus; thus, protection and effective management is essential for the sustainability of groundwater resources. Sustainable groundwater management is utilization of the available groundwater resources without going beyond its water bearing capacity, which can be achieved through appropriate allocation, artificial recharge, and proper monitoring of water resources taking into account of economic, social, and environmental goals.

Management of the costal aquifers is more challenging as they are the most sensitive groundwater resources, for both being in direct contact with the sea, which enhances the seawater intrusion, and the fact that the coastal areas are overpopulated and hence their freshwater resources are always under overexploitation for the satisfaction of anthropogenic needs. The unique aspect of costal aquifer management is that the pumping schemes must be optimized to prevent or at least minimize upcoming or lateral migration of saline groundwater (Post, 2005).

Groundwater management programs should start with the development of conceptual models of aquifers of concern that can be used as the bases for the development of groundwater monitoring plans and groundwater management plans. Such plans ultimately enhanced and developed in details through numerical groundwater model simulations. Suitable management plans can only be achieved by a thorough understanding of the aquifer system at hand. The lack of knowledge about areal and vertical extend of the aquifer material, recharge and discharge characteristics, groundwater flow and storage characteristics, as well as its exposure to contamination due to natural and anthropogenic activities precludes the formation of suitable groundwater management plans (Nastev et al., 2005; Türker et al., 2012). In this regard, conceptual groundwater model is an essential and effective tool for sustainable management of vital groundwater resources.

1.1.4. Conceptual Model as a Tool for Groundwater Management

A conceptual groundwater model (here after referred to as conceptual model) is a 3-D pictorial representation of groundwater system in terms of hydrogeological units, system boundaries including time-varying inputs and outputs, and spatial distributions of material (hydraulic as well as transport) properties of aquifer (Izady et al., 2013; Mercer, 1992). In addition, the conceptual model should identify areas of recharge and discharge from the groundwater system and should aim to identify the degree of interaction between groundwater and surface waters. The description of groundwater system and development of a conceptual model on the basis of aquifers, aquitards, and aquicludes as well as the groundwater flow system within and between these formations is important. The development of conceptual model starts with simple sketches although in its final form it may be detailed through three-dimensional diagrams (Rushton, 2003).

One of the purposes of building conceptual model is to simplify the field problem and organize the associated data so that the system can be analyzed more readily and quantitatively in the later stage by means of numerical models. Groundwater conceptual model is an interpretation or working description of the characteristics and dynamics of physical system, which describe how water enters an aquifer system, flows through the aquifer system and leaves the aquifer system. Therefore, in order to develop an appropriate numerical groundwater model and more quantitative representation of the subsurface hydrology, the formation of an accurate conceptual model is critical.

Recent studies suggest that the hydrogeological conceptual model is a key source of uncertainty in predictions of groundwater flow and transport. According to (Dettinger et al., 1981), there are two types of uncertainty in groundwater systems: intrinsic uncertainty and information uncertainty. Intrinsic uncertainty results from the spatial variability of certain material properties and processes and is reducible uncertainty inherent to the system. Information uncertainty, on the other hand, is the result of noisy or incomplete information about the system and it may also be reduced by further measurement and analysis. Both intrinsic and information uncertainties in groundwater numerical model can be reduced during the stage of conceptual groundwater model development.

Apart from groundwater flow and transport model, groundwater conceptual model is also used for the development of groundwater monitoring system. Groundwater monitoring is the scientifically-designed, continuing measurement and observation of the groundwater quality and quantity (Jousma et al., 2006). The requirement for continuity and sustainability in the monitoring program emphasizes the need to understand thoroughly the hydrogeological and hydrological setting by means of accurate conceptual model apart from the need for long-term planning and commitment of staff and budgets.

European Union (EU) Water Framework Directive, WFD, (Directive 2000/60/EC) which strives for the protection and improvement of the aquatic environment and the contribution to sustainable, balanced, and equitable water use, sets different criteria in order to conserve the available water resources (EU, 2000). The WFD has special emphasis on groundwater through its daughter directive of Groundwater Directive (Directive 2006/118/EC) concerning much about the deterioration of the groundwater through contamination and excessive withdrawal. In order to avoid this, the WFD has required accurate delineation of groundwater bodies in the drinking water aquifers to monitor and improve its quality as well as quantity. Accurate conceptual model development is essential also for proper delineation of groundwater bodies to design monitoring systems compatible with the objectives of the directive. The Groundwater Directive has established the following general quantitative and qualitative objectives for groundwater by obliging the member states (EU, 2006):

- to prevent or limit the input of pollutants into groundwater and to prevent the deterioration of the status of all bodies of groundwater
- to protect, enhance and restore all bodies of groundwater, ensure a balance between abstraction and recharge of groundwater
- to reverse any significant and sustained upward trend in the concentration of any pollutant in order to progressively reduce pollution of groundwater

The above objectives set by the Groundwater Directives would be implemented with development of a reliable conceptual model, which will be used as a basis for monitoring, interpreting and reporting the existing situation of the groundwater, being the most sensitive and the largest freshwater source.

The natural balance between freshwater and saltwater in coastal aquifers is disturbed by excessive groundwater withdrawals and other human activities. Lowering groundwater levels excessively below levels supported by amounts of natural recharge reduces fresh groundwater flow to coastal waters, and ultimately causes saltwater to intrude coastal fresh water aquifers. One example of aquifers currently suffering severely from excessive water withdrawal and seawater intrusion is the coastal Güzelyurt Aquifer in North Cyprus. To overcome the problem, implementing an effective groundwater resource management plan, which will ultimately restore the natural water balance for rising the water table to levels inverting back saltwater intrusion, is inevitable.

1.2. Scope and Objectives of the Study

The primary objective of this research is to develop a conceptual model for the Güzelyurt Aquifer in North Cyprus. Conceptual model is the most useful tool available for the development of groundwater resource monitoring and management plans and implementation of numerical groundwater models. It provides the general 3-D picture of the aquifer geometry, including recharge, discharge and hydraulic characteristics of the aquifer. In addition, the conceptual model is also used to ease understanding the complex nature of the aquifer system and organize the associated field data so that the system can be analyzed effectively.

The specific objectives of this study are

- Description of the hydrogeologic framework of Güzelyurt Aquifer in detail through delineation of the areal and vertical extent of aquifer material, related aquitards, aquicludes, and construction of regional hydrogeologic cross-sections
- Establishing the internal and external boundary conditions of the aquifer

- Determination of the current saturated thickness of Güzelyurt Aquifer and delineation of aquifer zones affected by excessive water withdrawal
- Delineation of local heterogeneities in the 3-D lithological solid diagram of the aquifer
- Delineation of current salt water intrusion zones within the aquifer

This conceptual model can ultimately be used as a basis for the development of a groundwater numerical model to evaluate, for example, the future effects of current pumping rates on drawdowns, the extent of seawater intrusion and impacts of future water resources management plans in the costal aquifer of Güzelyurt.

1.3. Organization of the Thesis

The outline of this thesis is as follows. The first chapter, in general terms, provides information on the availability and use of groundwater resources globally and locally the current status of water resources in North Cyprus putting a special emphasis on Güzelyurt Aquifer; explains the need for development of conceptual models as a useful tool in the development of groundwater monitoring and management plans as well as implementations of numerical groundwater flow and transport models; and finally the objectives of this study. Chapter 2 describes the study area including geographic location, climate, geology, and hydrogeology; presents the available information and data about the Güzelyurt Aquifer; and proposes a general framework for the development of conceptual model for groundwater flow systems. Chapter 3 is about the application of the proposed framework to develop a conceptual model for the Güzelyurt Aquifer including the analysis of available data and information. Chapter 4 presents the result, discussion of the results regarding the description of hydrogeological settings and overall assessment of Güzelyurt Aquifer system and deliver important conclusion of the study. Chapter 5 presents conclusion and future work.

CHAPTER 2

MATERIALS AND METHODS

2.1. Description of the Study Area

2.1.1. Location

Cyprus is the third largest island in the Mediterranean Sea. It lies 65 km from Turkey's southern coast. The island is effectively administered by two distinct communities divided by ethnic boundary as North Cyprus and South Cyprus (Ergil, 2000). The total area of the island is approximately 9,252 km^2, but North Cyprus, which is located on 35^o 10’ N and 33^o 22’ E of Greenwich Meridian, covers a total area of 3,515 km^2 or nearly one third of the whole island and has a population of 285,365 in 2009 (Source: North Cyprus Online, http://www.northcyprusonline.com/). The island is mainly dominated by two mountains: Troodos and Kyrenia with Mesaria central plane located in between as shown in Figure 2.1. Nearly half of the island is covered by Troodos Mountain, which has an altitude of as high as 1,952 m, covers significant part of west and south of the island.

The study area, Güzelyurt aquifer, is located in the southwest region of North Cyprus as shown in Figure 2.2. Güzelyurt Aquifer is situated on latitude 35^o 20’ N and 33^o 15’ E, and it is the largest and most valuable groundwater reservoir in North Cyprus.

2.1.2. Climate Elements

The climate in the island is semi-arid, a typical Mediterranean climate with hot and dry summer, and cool and wet winter. The change in climate over the last 40 years, such as rise in the annual average temperature while a decreasing trend in precipitation has had significant impact on the availability of both surface and groundwater resources, resulting in a severe drought in the region (Ergil, 2000).

Figure 2.1 The map of Cyprus showing Troodos and Kyrenia mountain ranges in red (Wikipedia, 2012).

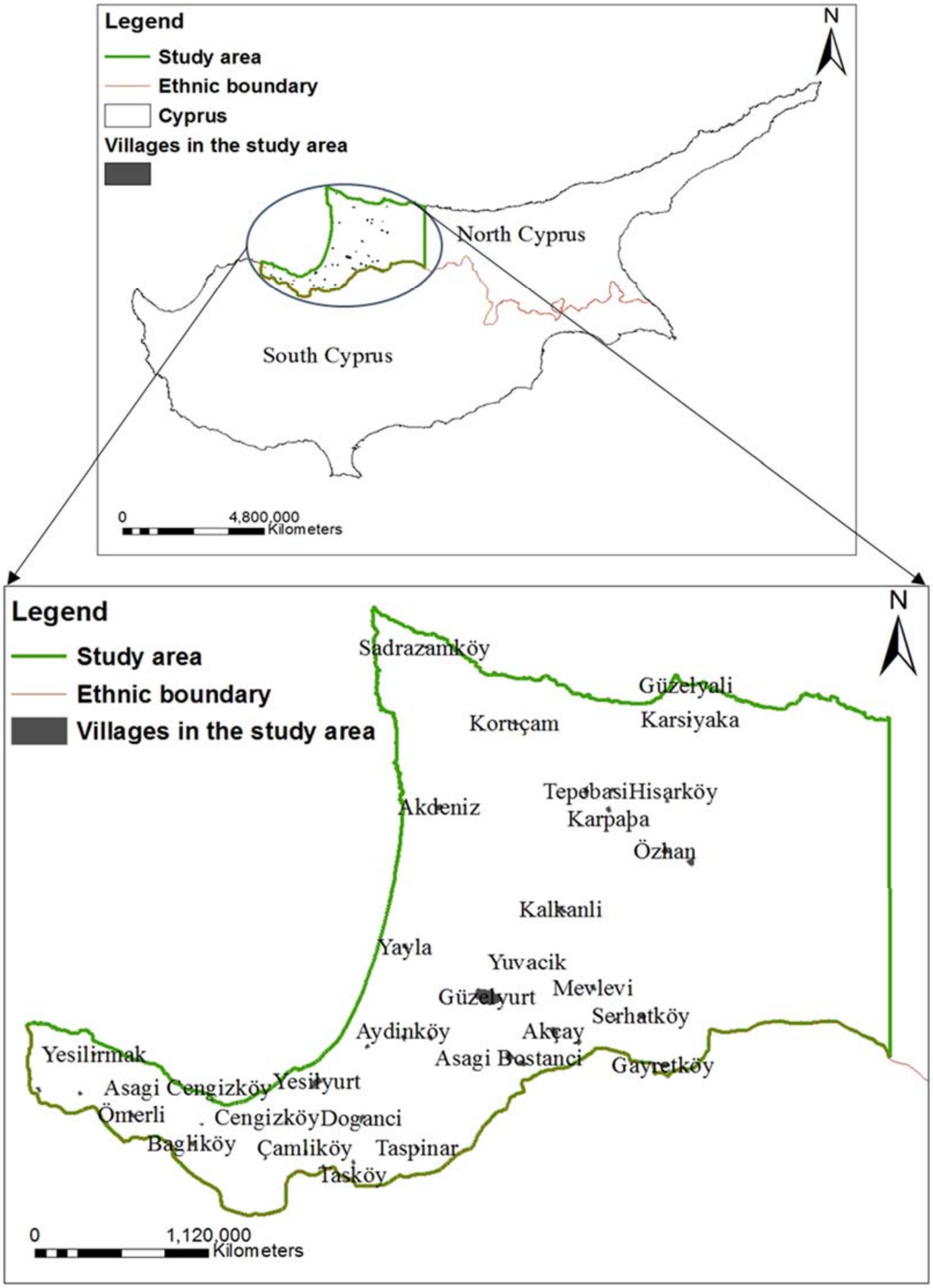

Figure 2.2 The map of Cyprus showing the location of the study area, Güzelyurt Aquifer, in North Cyprus.

2.1.2.1. Temperature

Temperature is one of the important climatic factors affecting especially evaporation and thus groundwater recharge. Based on the temperature data obtained from the North Cyprus Meteorology Department, in the study area January is the coldest month of the year with the average monthly minimum temperature of 7.3 ºC, while August is the hottest month of the year with the average monthly maximum temperature of 29 ºC as shown in Table 2.1 and Figure 2.3. The months between May and November have relatively higher temperatures resulting in a higher evaporation rate and thus less recharge compared to the rest of the months from December to April. The mean highest and lowest annual average temperatures over the years from 1978 to 2011 are 21.5 ºC and 15.9 ºC, respectively. Although the mean annual temperature fluctuates over the period of 1978 through 2011 as shown in Figure 2.4, the overall temperature trend over the last 30 years indicates an increase in temperature with time due possibly to climate change and global warming which enhance the amount of water loss through evaporation and in turn reducing recharge of the Aquifer.

Table 2.1 Distribution of monthly averages of highest and lowest temperature

Month	**Monthly mean temperature (°C)**		**Month**	**Monthly mean temperature (°C)**	
	Lowest	**Highest**		**Lowest**	**Highest**
January	7.3	13.7	July	25.1	28.6
February	7.6	14.7	August	25.0	29.0
March	10.0	15.7	September	21.4	26.1
April	14.6	18.6	October	18.7	28.6
May	17.3	22.6	November	13.0	19.7
June	22.4	26.0	December	9.0	15.2
Mean annual average highest temperature				**21.5**	
Mean annual average lowest temperature				**15.9**	

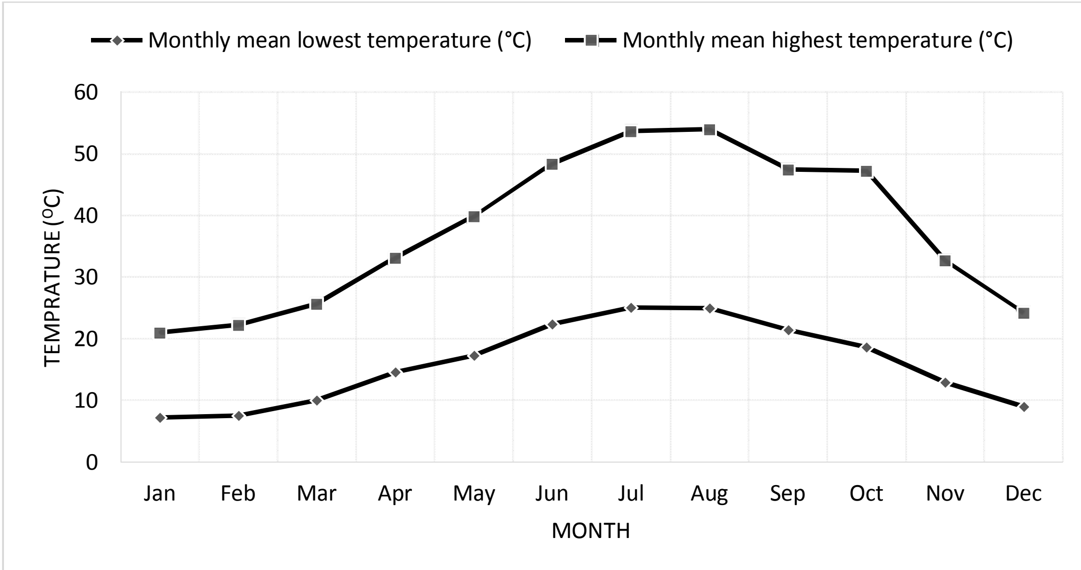

Figure 2.3 The monthly mean highest and lowest temperature in the study area.

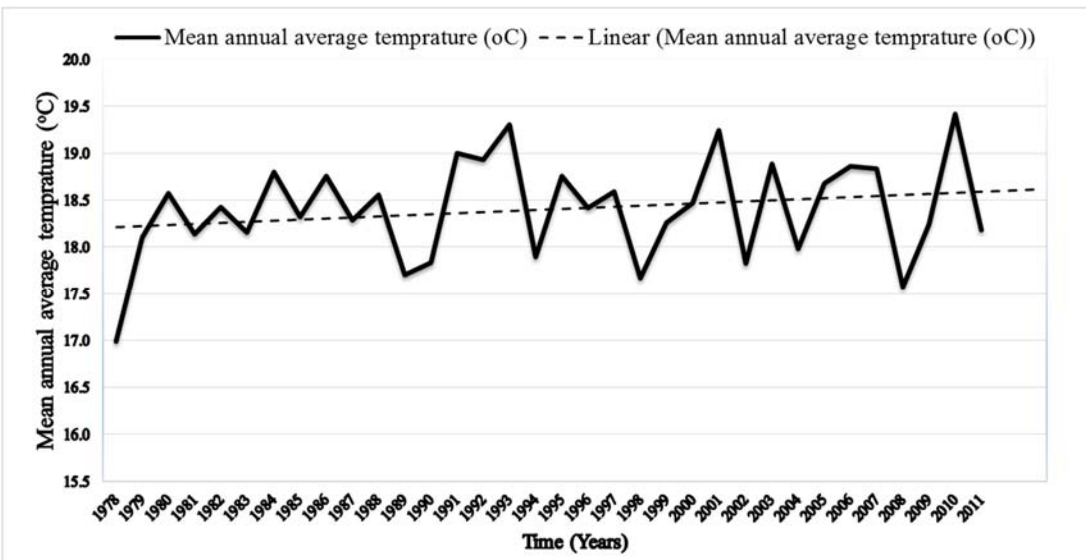

Figure 2.4 Temperature trend from 1978-2011 in the Güzelyurt area from the data obtained from North Cyprus Meteorology Department.

2.1.2.2. Precipitation

Precipitation also has an important effect on groundwater recharge in the study area. Precipitation is considered as the direct source for groundwater recharge and varies both monthly and annually. Using the precipitation data obtained from the North Cyprus Meteorology Department from 1978 to 2011, the distribution of water year cumulative precipitation in Güzelyurt area is shown in Figure 2.5. The average precipitation is calculated from four meteorological stations in the study area, namely Güzelyurt, Gaziveren, Lefke, and Zümrütköy. The annual average rainfall is 285 mm while the minimum and maximum annual precipitation during this period are 173 mm in 1989-1990 water year and 474 mm in 2002-2003 water year, respectively. According to the information obtained from geological field experts in the region and from the groundwater level measurement data of the Güzelyurt area, the period from December to May is considered as wet season whereas from June to November is considered as dry season. Figure 2.5 also shows the curve of cumulative deviation from the water-year mean precipitation. In the figure, the negative values of cumulative deviation from the mean indicate the cumulative water deficit (dry period) while the positive values indicate cumulative water surplus (wet period) relative to the mean precipitation. As can be seen from the figure, the study area has suffered a prolonged water deficit or dry period relative to the mean precipitation until the water year of 2008-2009; there after the cumulative deficit relative to mean was compensated to a limited extent by the precipitation received in the following water years. Thus, it can be inferred that groundwater recharge by precipitation in the study area has been negatively affected.

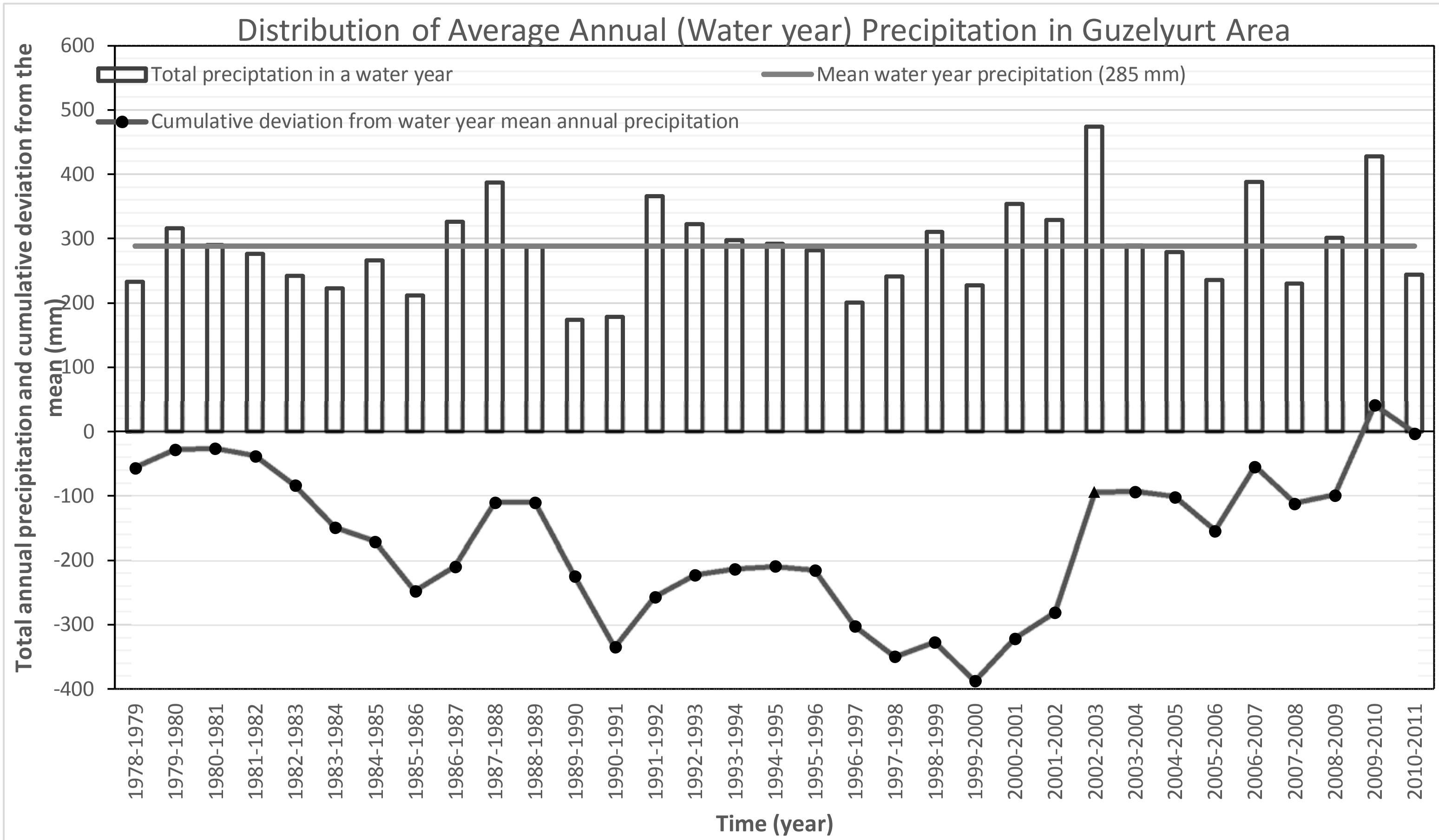

Figure 2.5 Annual precipitation in the study area and the curve of cumulative deviation from the mean precipitation for the period of 1978 to 2011.

2.1.2.3. Evaporation

Evaporation is considered as another predominant climatic factor for groundwater recharge. Based on the data from a field investigation study reported by the General Directorate of Mineral Research and Exploration (MTA, 2002), the average annual evaporation between the years of 1984-1997 is 2017.13 mm while the average precipitation in the same period is 259.36 mm as shown in Table 2.2. There is a huge gap between evaporation and precipitation (net loss of 1757.77 mm) indicates that evaporative water demand is very high in the study area. This high amount of water loss is due to many factors, such as high temperature of the study area, evapotranspiration, less vegetative cover, and low altitude, which is 50-60 meter a.s.l., of the study area. Recent quantitative data about evaporation in the Güzelyurt area is not available. However, due to an increasing trend in annual average temperature in Güzelyurt station (Seyhun, 2013), it can be inferred that there will be an increase in evaporation above 2017.13 mm. Moreover, because of increasing temperature and evaporative demand, and low precipitation, we can conclude that there is very limited recharge in the Güzelyurt Aquifer over the last 30 years because of severe drought in the region.

Table 2.2 Rainfall, Temperature and evaporation data for Güzelyurt coastal plain from 1984-1997 (MTA report 2002)

Time (year)	Rainfall (mm)	Temperature (°C)	Evaporation (mm)
1984	231.64	18.8	-
1985	229.67	18.3	-
1986	251.96	18.8	2306.40
1987	310.81	18.3	1846.00
1988	363.50	18.6	-
1989	76.00	17.7	1958.70
1990	172.10	17.8	2282.30
1991	306.50	19.0	2163.50
1992	345.20	18.9	2071.90
1993	256.20	19.3	2197.70
1994	320.70	17.9	-
1995	213.00	18.8	-
1996	291.50	18.4	2034.20
1997	262.30	18.6	2193.50
Average	**259.36**	**18.8**	**2117.13**

2.1.3. Land Use

In North Cyprus, about 56.7 % of the land is used for agriculture (of about 1870 km^2) while 19.5 % forestry (about 643 km^2), 5.0 % grassing area (163 km^2), 10.7% covered by towns, villages, and reservoirs (386 km^2) and nearly 8.2% is a bare land (269 km^2) with 87 km^2 of irrigable land (O. Phillips Agboola et al., 2012). Gazimağusa, located in the eastern part of North Cyprus, is used to be the main citrus fruit producing area in the late 1960's. However, the desaturation of groundwater in the area due to excessive abstraction forced the farmers to move to Güzelyurt, which has become the leading citrus fruit-producing site in North Cyprus. Like Gazimağusa, depletion of groundwater and seawater intrusion into Güzelyurt Aquifer due to over pumping has greatly reduced both the farming and the land under irrigation, especially in the most productive and deepest part of the aquifer, namely Yayla, Kumköy, Gaziveran etc. (Gökçekuş. H, Tuker. U, Sözen. S, 2002).

2.1.4. Topography

The study area (Güzelyurt plain) is (topographically characterized as) a slightly sloping coastal plain. The central part of the study area, where agriculture is mainly practiced, is almost flat topography. As shown in Figure 2.6, the elevation in the catchment of Güzelyurt Aquifer rises from sea level at the shore (gulf of Güzelyurt) in the west to the maximum of about 1952 m at the southwestern part of the Troodos Mountains. With the exception of relatively high areas of the catchment, the land surface slope is gentle with a slope of about 1 %. Groundwater recharge is directly related to surface drainage pattern, which is the main dendritic distribution of ephemeral drainage streams, or recharge lines where infiltration of rainwater occurs. The drainage lines, that are directed from the higher altitudes towards the flat areas of Güzelyurt plain, shows that the groundwater recharge is mainly coming from the Troodos Mountains in the south east and a little from Beşparmak Mountains in the North of the Güzelyurt catchment.

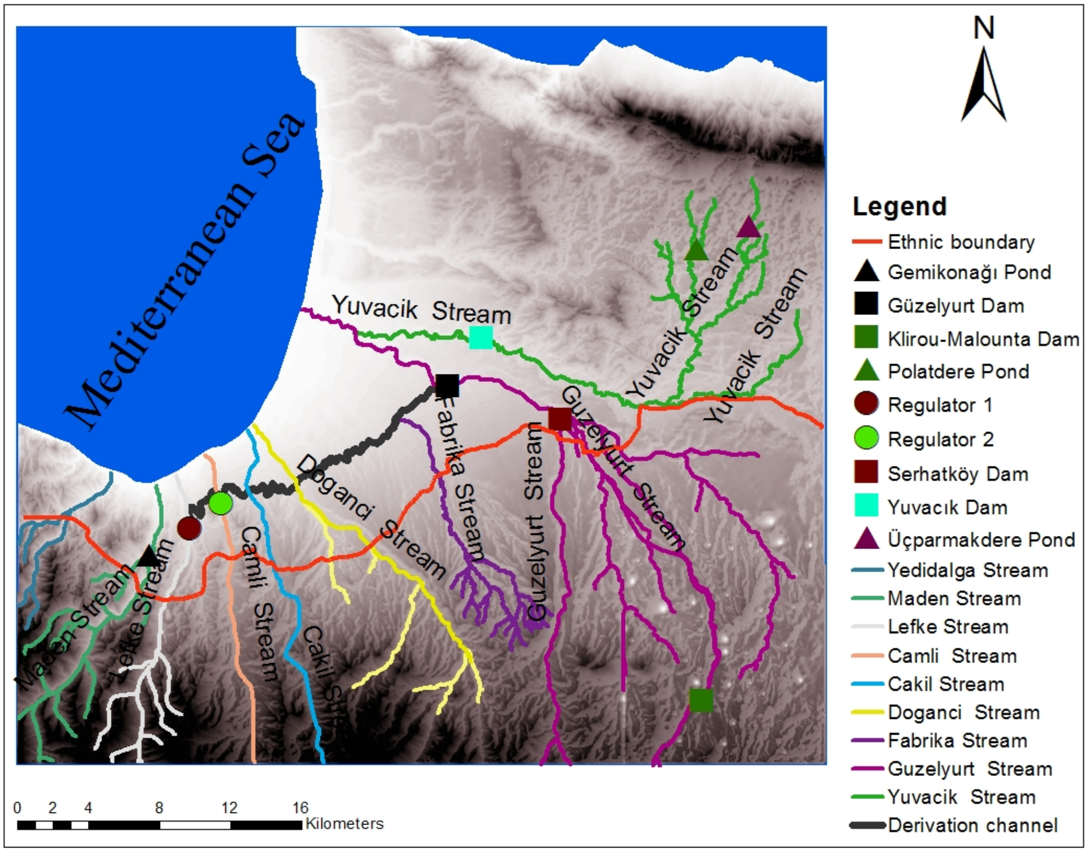

Figure 2.6 Topographic map of the study area showing the surface drainage patterns.

2.1.5. Hydrogeology

Güzelyurt Aquifer is an alluvial unconfined aquifer in direct contact with the sea. It is mainly composed of gravel and sand in the central study area with occasional embedded silt and clay layers and lenses, exhibiting abrupt discontinuities both horizontally and vertically. At higher elevations, alluvial aquifer material has some contacts with calcareous sandstone. The main water bearing formations in the Güzelyurt Aquifer are known as the old alluviums (Qal) and fanglomerates of Bostancı gravel (Qmb). Gürpınar formation composed of calcareous sandstone and calcarnite is in contact with alluvial sand and gravel aquifer in the vicinity of Serhatköy; and it is considered to be a low-water yielding separate aquifer (MTA, 2002; DSİ, 2004).

The thickness of the Güzelyurt Aquifer that rests on an undulating impervious base formed by marl, thick clay, and pillow lava ranges from 45 at the far eastern part to the maximum of 100 at the far western part. The thicker side where the main water supply pumping station located is in a direct contact with the coastline along Güzelyurt bay and is below the mean sea level (Ergil, 2000).

Previous hydrogeological studies in the area indicated that the aquifer is composed of two parts, 10% being confined and 90% being unconfined. However, the confined part, located in the southwest, totally de-saturated in time and became unconfined due to sever drought and continuous withdrawal of groundwater, causing the water table to drop below the confining layer (Ergil, 2000).

2.2. Available Data and Information

Aquifer characterization and conceptualization is an iterative process beginning with an understanding of the groundwater flow system fallowed by data collection and refinement of the understanding. Additional data collection and analysis as well as refinement of the groundwater conceptual model occurs during the entire process of conceptualization as well as during groundwater model development and use (ASTM, 2008).

Creating a conceptual model of the groundwater system involves a review of relevant available data both qualitative and quantitative. The data inventory includes:

- ✓ Collection of data about the topography, hydrology, hydrogeology, and related information of the study area;
- ✓ Collection and review of site specific data which includes the aquifer systems under investigation (lithological and geophysical borehole logs, pumping test reports, etc.), data on the groundwater system (groundwater levels and groundwater quality), groundwater related data of the surface water systems (base flow and spring flow);

- ✓ Collection of data on precipitation, temperature, and evaporation.

All the available data collected should be assembled when developing a conceptual model. In fact, the more the data available, the closer the conceptual model approximates the actual field condition. To this end, all the available data required for the development of groundwater conceptual model of Güzelyurt Aquifer are obtained from the Geology and Mining Department (G&MD) of North Cyprus, which includes borehole lithological descriptions, groundwater level data, groundwater quality data, hydrogeological maps, and topographic maps. These data and information are organized and presented as fallows.

2.2.1. Borehole Lithological Descriptions

The borehole lithological description includes the location of the boreholes and the spatial distribution of geological material in the subsurface. In addition, it gives the top elevation of the borehole and detailed information about the geological material type. The spatial distributions of all available and used lithological boreholes are shown in Figure 2.7. Out of 116 available boreholes, 92 of them were inside the aquifer boundary and only 73 of the 92 boreholes were useful; the rest was unusable because of poor or gross descriptions of lithological materials with extremely large unspecified depth intervals. Also, some boreholes lack material descriptions at some depths in the middle, and some of them had no coordinates. These types of boreholes are excluded from the study.

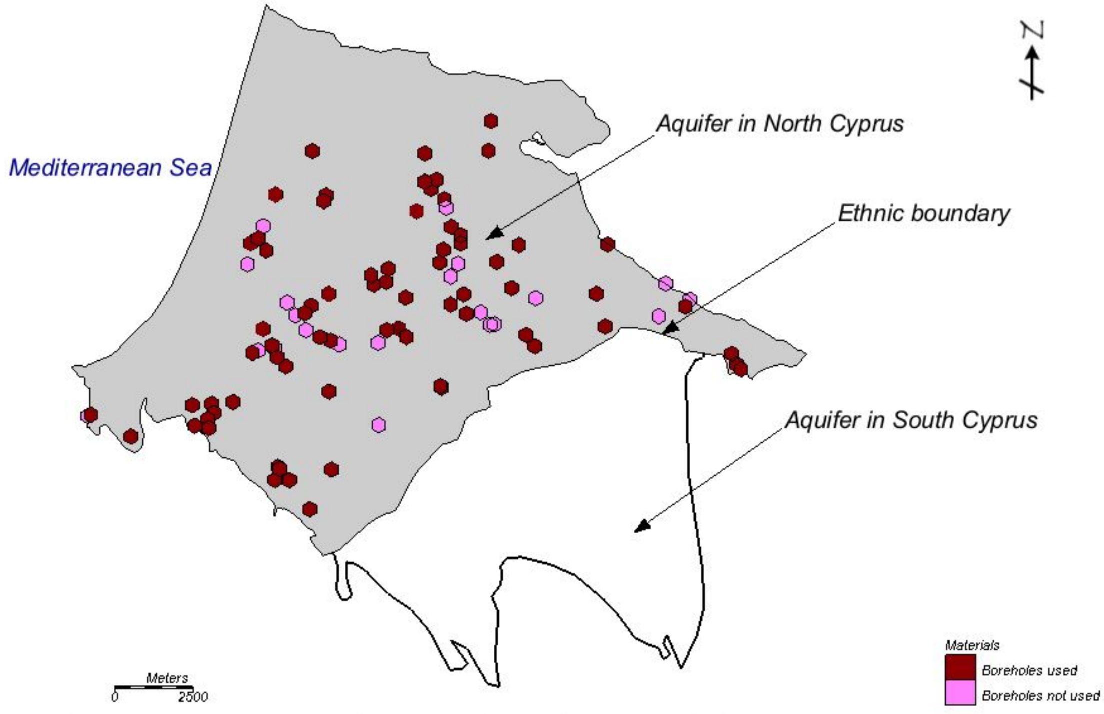

Figure 2.7 The areal distribution of 92 available wells with 73 boreholes used (red) and 19 unused boreholes (pink).

The structure of the available raw borehole data for randomly selected five boreholes is shown in Table 2.3. The information includes the borehole location and serial number to identify the different boreholes; the surface elevation of the borehole (*alt_va*); the depth of the borehole from the surface (*depth_va*); the coordinates, and the lithological description at different intervals (from *lith_top_va* to *lit_end_va*).

With the help of borehole module of the Groundwater Modeling System (GMS) software, the available borehole lithological descriptions, as shown in Table 2.3, have been processed (see Chapter 3, Section 3.1.3 for details) to describe the 3-D representation of the hydrogeologic framework of Güzelyurt Aquifer i.e., delineation of the areal and vertical extent of Güzelyurt Aquifer material, and related aquitards and aquicludes; construction of regional hydrogeologic cross-sections; establishing the aquifer material's top and bottom elevation distributions; delineation of local heterogeneities in the 3-D lithological solid diagram of the aquifer.

Table 2.3 Sample borehole lithological description

site_id	serial_nu_tx	alt_va	depth_va	location_nm	east_utm_va	north_utm_va	district_cd	district_nm	lith_top_va	lith_end_va	lith_desc_tx	lithology_tr_tx
899	5000	49	72	doğancı	492636	3889469	5	Güzelyurt	0	44.19	Gravelly	
899	5000	49	72	doğancı	492636	3889469	5	Güzelyurt	44.19	53.34	Grey marl	
899	5000	49	72	doğancı	492636	3889469	5	Güzelyurt	53.34	71.32	Fine grained	
899	5000	49	72	doğancı	492636	3889469	5	Güzelyurt	71.32	80.77	Grey marl	
643	4541	68	93	doğancı	492451	3889270	5	Güzelyurt	0	6.1		komplomera
643	4541	68	93	doğancı	492451	3889270	5	Güzelyurt	6.1	13.71		kum ve silt
643	4541	68	93	doğancı	492451	3889270	5	Güzelyurt	13.71	19.81		çimentosuz
643	4541	68	93	doğancı	492451	3889270	5	Güzelyurt	19.81	24.38		kum ve silt
643	4541	68	93	doğancı	492451	3889270	5	Güzelyurt	24.38	67.36		çimentosuz
643	4541	68	93	doğancı	492451	3889270	5	Güzelyurt	67.36	93		kil
681	5004	119	73.15	şahinler	507751	3892876	5	Güzelyurt	0	22.86		kumlu siltli
681	5004	119	73.15	şahinler	507751	3892876	5	Güzelyurt	22.86	32		ince taneli
681	5004	119	73.15	şahinler	507751	3892876	5	Güzelyurt	32	54.86		açık gri silt
681	5004	119	73.15	şahinler	507751	3892876	5	Güzelyurt	54.86	73.15		volkanik
674	4999		36.57	lefke	484660	3884233	12	Lefke-	0	1.5	Sandy silt	kumlu silt
674	4999		36.57	lefke	484660	3884233	12	Lefke-	1.5	3.04	Fine sand	ince kum
674	4999		36.57	lefke	484660	3884233	12	Lefke-	3.04	6.09	Sand	kum
674	4999		36.57	lefke	484660	3884233	12	Lefke-	4.57	31.08	Gravel	çakıl
674	4999		36.57	lefke	484660	3884233	12	Lefke-	31.08	36.57	Pillow lavas	volkanit
4789	1769a	64	138	bostancı	498543	3892202	5	Güzelyurt	0	1		güncel
4789	1769a	64	138	bostancı	498543	3892202	5	Güzelyurt	1	83		az çakıllı kumlu
4789	1769a	64	138	bostancı	498543	3892202	5	Güzelyurt	83	100		az kumlu çakıl
4789	1769a	64	138	bostancı	498543	3892202	5	Güzelyurt	100	104		gri renkli silt
4789	1769a	64	138	bostancı	498543	3892202	5	Güzelyurt	104	132		az kumlu siltli
4789	1769a	64	138	bostancı	498543	3892202	5	Güzelyurt	132	138		gri renkli kil

2.2.2. Groundwater Level Data

The distribution of groundwater level elevations, whether it is the water table elevations of an unconfined aquifer or the piezometric surface elevations of a confined aquifer, indicates the hydraulic head distribution in the aquifer. Any phenomenon that produces a change in the groundwater elevation will cause a change in groundwater hydraulic head. The available groundwater level data in the study area includes the well ID and their coordinates, date of groundwater elevation measurements, and the depth of water in the well from the surface of the well. Groundwater level data is available from 2000 to 2013, but there are some missing measurements for some of the wells over the consecutive years. The measurements are made at least twice a year in December to represent the end of the dry season, and in March, April and May to represent the wet season.

The number of wells used for measurements decreased over the years due to lack of timely maintenance services for wells and most importantly due to the dry up of wells as a result of excessive withdrawal of water for irrigation and household consumption. The total number of wells used for measurements is 210; however, only 53 measurement points are continuously monitored from 2010 through 2013. The areal distribution of water level measurement wells are shown in Figure 2.8. Because of significant changes over the years in the location and number of wells used for measurements, only the measurements during the last 5 years are considered in this study; thus, most wells out of the 210 were excluded due to lack of recent water level elevation measurements.

The water level elevation measurement data will be utilized by generating contour maps with the help of Groundwater Modeling System (GMS) and Surfer software to determine the current areal distribution and saturated thickness of the Güzelyurt Aquifer, and to delineate aquifer zones affected by excessive water withdrawal.

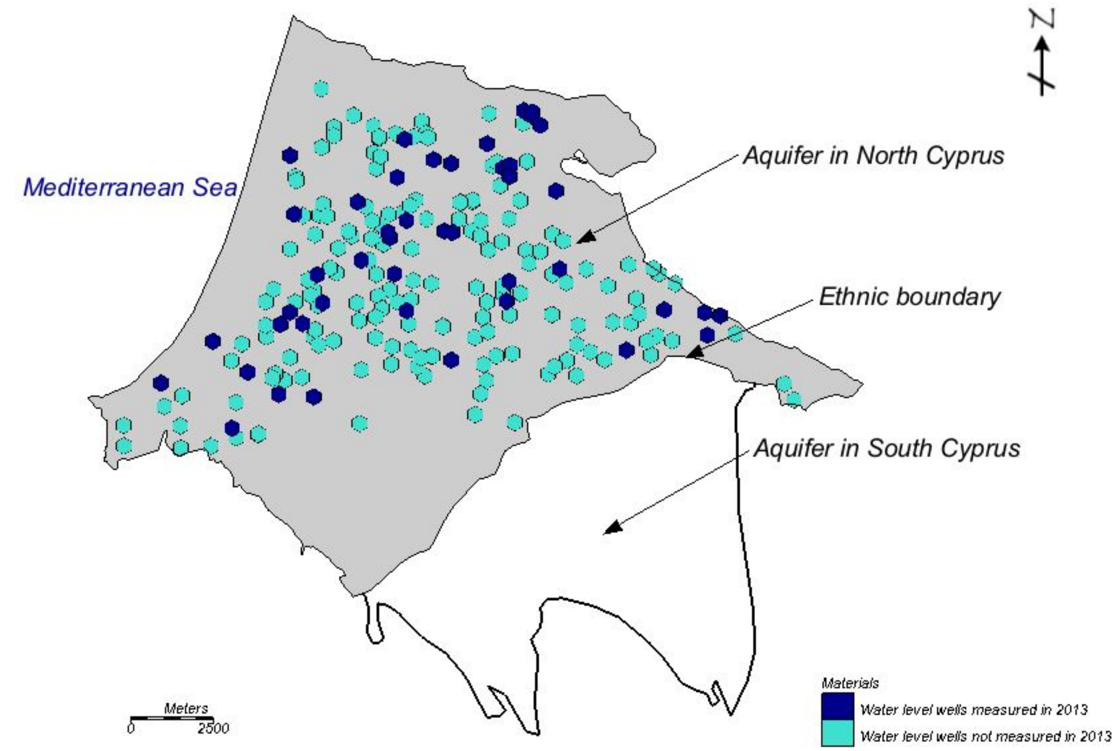

Figure 2.8 The areal distribution of 45water level measurement wells used in 2013 and 210 water level measurement wells not used in 2013 in the study area.

2.2.3. Water Quality Data

Water quality analysis is one of the most important aspects in groundwater studies. The chemical parameters of groundwater play a significant role in classifying and assessing water quality especially in the costal aquifers where there is a higher possibility of seawater intrusion which mainly results from poor groundwater management system in the region (Sadashivaiah, 2008; Sadoon, 2005)

For salt-water intrusion assessment in Güzelyurt Aquifer, Chloride content (Cl) and Electrical Conductivity (EC) measurements are made in groundwater samples collected twice a year in the months of dry and wet seasons during 2010 through 2013. The number of the water quality monitoring wells used for sampling was 193 in 2010, but the number decreased to, 144 wells in 2013 indicating serious reduction in the number of monitored wells in time. One of the reasons for the reduction in the number of monitored wells is malfunctioning of the wells. Figure 2.9 shows the areal distribution of wells used for water quality measurements. Although the water quality measurements were carried out in both dry and wet season, most of the measurement represents the dry season.

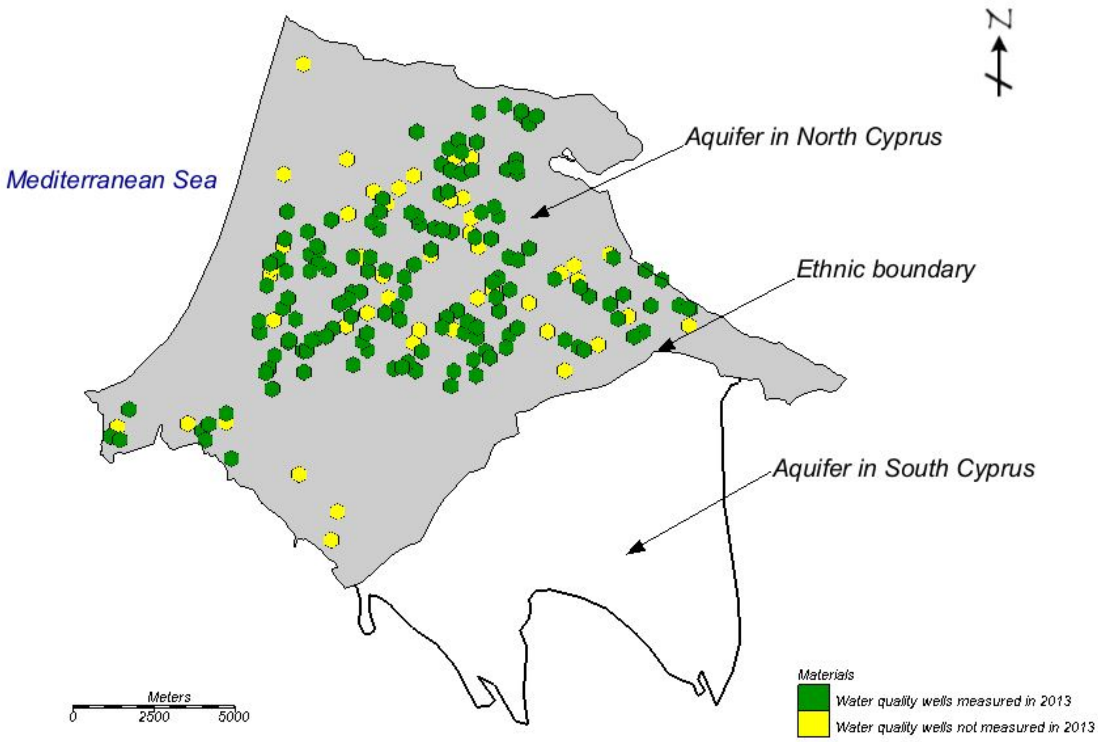

Figure 2.9 The areal distribution of 144 water quality wells measured in 2013 and 193 water quality wells not measurement in 2013 in the study area.

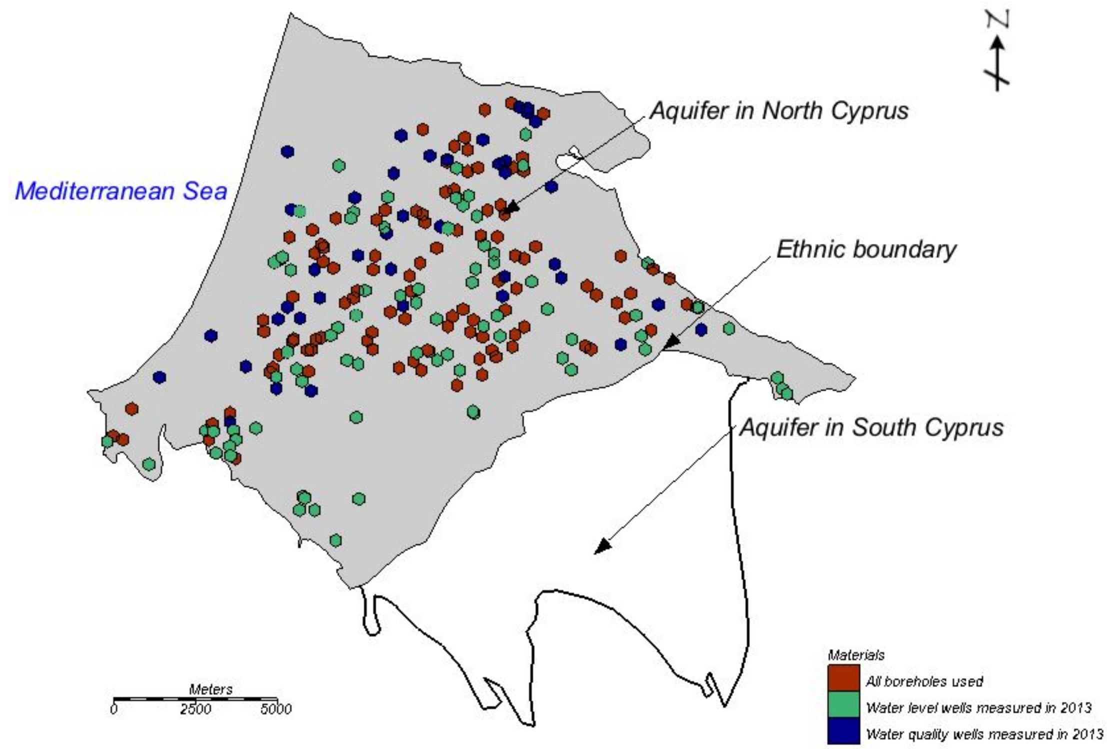

Figure 2.10 The areal distribution of all the available boreholes (73), water level measurement wells used in 2013 (45) and water quality monitoring wells used in 2013 (144) in the study area.

Figure 2.10 shows the areal distribution of all the available boreholes (73), water level measurement wells used in 2013 (45) and water quality monitoring wells used in 2013 (144) in the study area for collection of available field data. It can be seen from the figure that boreholes, which has the lithological description of subsurface material, is not uniformly distributed and is concentrated only in the center of the study area. Although it seems that there are relatively large numbers of field data collection points, such as boreholes, water level and water quality measurement wells, having totally uncommon distribution of data collection points for each set of data limits the utility of available information. For example, none of these water level or water quality monitoring wells has lithological or stratigraphic descriptions.

2.2.4. Hydrogeological Maps

Hydrogeological maps bring basic geological information together with data on the hydraulic and hydro-chemical characteristics of the rocks and their usefulness for groundwater supply (British Geological Survey, 2010). The hydrogeological map of Güzelyurt Aquifer is obtained from two different sources; one of them gives hydrogeological information only about the northern part of Güzelyurt Basin, which is developed by the Geology and Mining Department of North Cyprus as shown in Figure 2.11 and the other one gives information about the entire (i.e., both North Cyprus and South Cyprus sides) Güzelyurt Basin which is generated by the British Geological Survey as shown in Figure 2.12.

The hydrogeological map in Figure 2.11 contains detailed information about the geological formations of the study area. However, it provides information about the two third of the study area. For this reason, the map generated by the British Geological Survey shown in Figure 2.12 is used to complete the hydrogeological data gap. Although the details in the description of hydrogeological units of the site are different in the two maps, there is much coherence between the two sources in terms of identification of the units having aquifer characteristics. These two maps are processed in the ArcGIS environment to combine the two sources and obtain a single hydrogeological map for the entire Güzelyurt basin. This combined map is used to identify and construct the physical formation boundaries of the entire Güzelyurt Aquifer (See Chapter 3, Section 3.1.1 for details).

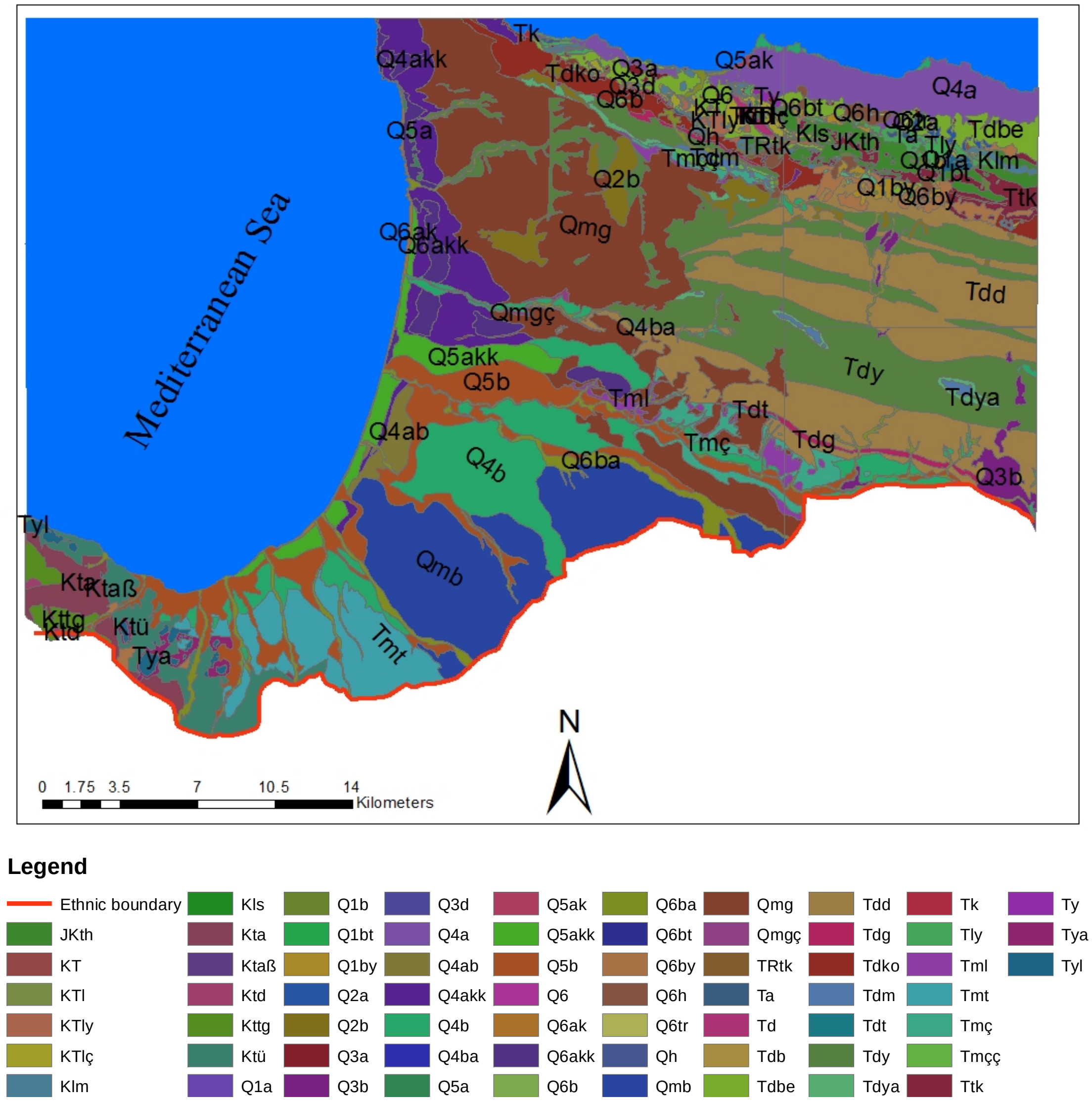

Figure 2.11 Geological map of the study area which is developed by the Geology and Mining Department of North Cyprus (The description of the legend is given in Appendix A, Table A.1).

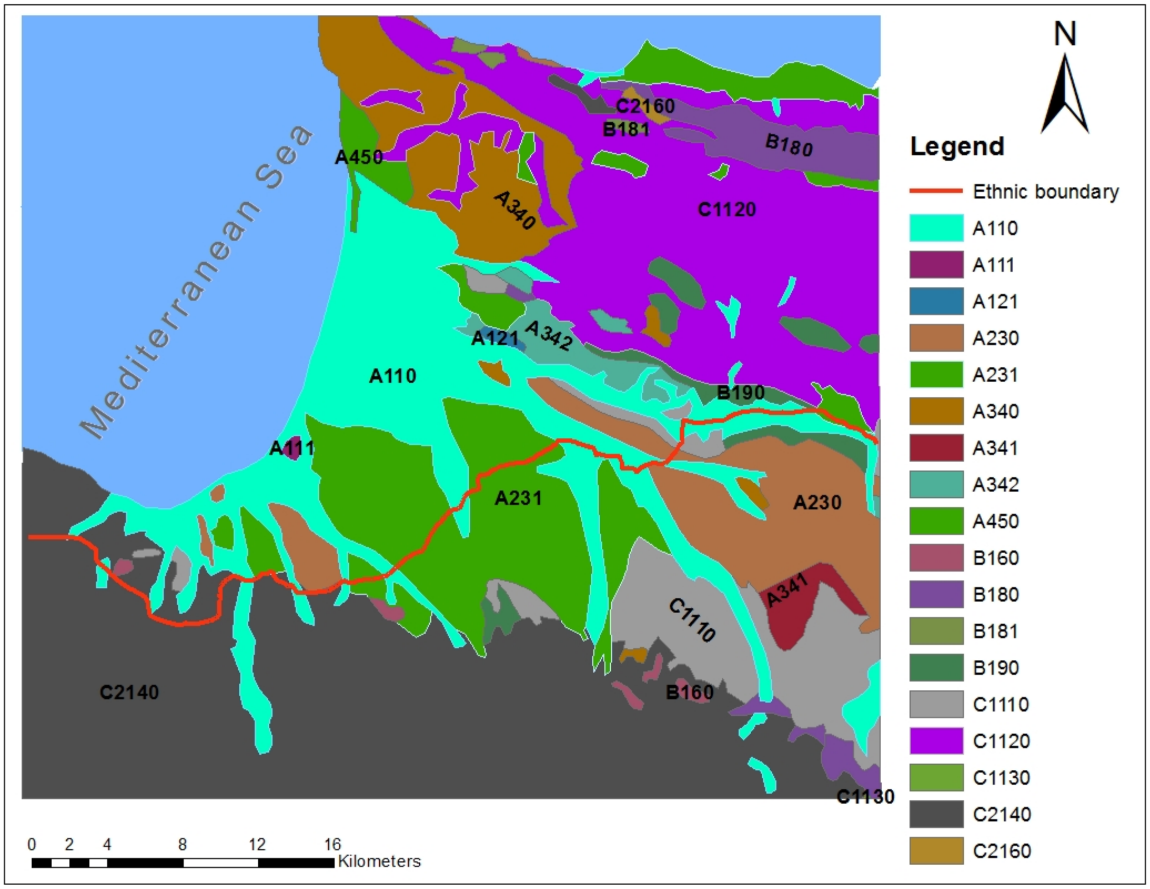

Figure 2.12 Geological map of the study area which is developed by the British Geologic Servey (The discription of the legend is given in Appendix A, Table A.2).

2.2.5. Topographic Map

The topographic map is a basic and essential element for any basin scale hydrological and hydrogeological studies related to the assessment of water resources. Its importance is two folds. First, it is used as a guide for orientation on the surface and the landscape, and secondly, as a source of useful hydrological information i.e., delineation of runoff water surface drainage network, which explains the pattern of groundwater recharge from the surface by precipitation. The available topographic map in the form of land surface elevation contours is shown in Figure 2.13. This topographic map is used to determine the areal surface recharge pattern of Güzelyurt Aquifer (See Chapter 3, Section 3.1.2 for details).

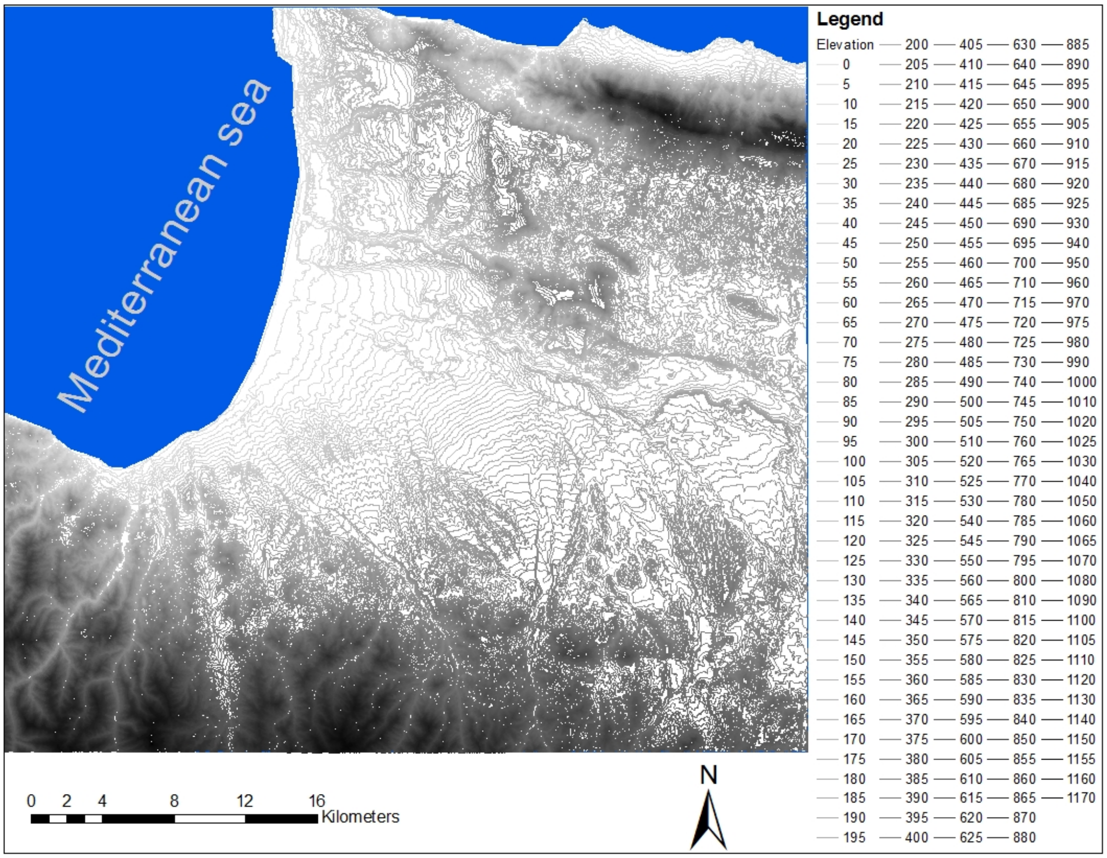

Figure 2.13 The surface elevation contour map of the study area.

2.3. Methodological Approaches for Groundwater Conceptual Model Development

This section describes in details a stepwise general framework of conceptual model development for groundwater systems. First, a literature search on the topic, and then the major steps and relevant minimum data requirements of the developed approach are presented.

2.3.1. Review of Methodological Approaches in Literature

A literature search revealed that most of the studies focusing on groundwater conceptual model development are case specific, such as coastal aquifer, single or multiple aquifer systems, and present no generalized methodological approach. Up to now, within the realms of this literature search, only a few studies have been reported, focusing on proposing a methodological approach to groundwater conceptual model development. In the following, some important findings and conclusions obtained from these studies are summarized.

Geographical location of the aquifer is one of the important factors affecting the conceptual model development. Typical types of aquifers with respect to geographic positon are coastal alluvial aquifers where seawater intrusion is the most common problem. The identification of the aquifers stratigraphic units is important and carried out by analyzing borehole lithological data. In a site specific studies, Barazzuoli et al. (2008) and Kallioras et al. (2006) constructed the 3-D stratigraphic units by using borehole lithological data for the coastal aquifers in Tuscany, Italy and Thrace, Greece, respectively. From the cross-section, they identified the main aquifer layers that are made up of sand and gravel and separated by an aquitards (i.e., clayey deposits with silt or sand in variable proportions). They used water level measurement data to assess the flow regime and to identify whether the aquifer is confined, semi-confined or unconfined. In addition, from the piezometric map, they identified the areas strongly affected by groundwater withdrawal. To assess the seawater intrusion into the coastal aquifers, they have collected and analyzed the water quality data, especially for the chloride content and electrical conductivity, and delineated the seawater-affected zones.

Monitoring network is one of the objectives of developing a conceptual model. A site specific case study by Teresita Betancur V. et al. (2012) on Bajo Cauca aquifer in Antioquiais, Colombia, briefs the development of a conceptual model for groundwater monitoring. The aquifer, being a multilayer aquifer system, consists of an unconfined, and a confined aquifer separated by an aquitard. They collected hydrogeological data and information through the acquisition of data on physiographic, hydrographic (measurement and description of the physical features), climatic, soil and geological characteristics of the region. They converted the topographic map into manageable database i.e., Digital Elevation Model (DEM) and generated there dimensional view of the topography by using GIS software. The use of photo interpretation and image processing together with the review of the relevant literature helped with the characterization of physiography and geology of the study area. Identification and delineation of the hydrogeological units are carried out through the analysis of geologic and stratigraphic information.

Waren et al. (2013) developed a conceptual model for the purpose of conducting a follow up numerical groundwater modelling to predict the effect, magnitude and timing of impacts of groundwater withdrawal from a multi-aquifer system in the North Hill, Montana. First, they focused on the geologic framework of the study area to identify the existing three aquifers, namely bedrock, tertiary and Helena valley aquifers based on the composition of the rock types composing the aquifers. Bedrock aquifer is near the surface and mainly composed of Precambrian siltite and argillite. Tertiary aquifer is predominantly composed of unconsolidated fine-grained materials. Hellen valley aquifer, on the other hand, is composed of unconsolidated materials, mainly sand and gravel; and is considered as the most productive aquifer in the study area. Following the identification of aquifers, available well logs were analyzed to characterize the subsurface condition i.e., the areal extent and thickness of the aquifers. Since it is difficult to analyze all the available well logs, only those drilled to less than 60 m and those with poor lithological description are not used; the remaining well logs are used in Borehole Module of Groundwater Modeling System software (called GMS) in order to develop the 3-D geometry of the aquifer system. The vast array of lithological description, which is given by the drillers, were grouped first into 33 categories and then to five major categories based on the similarities of the material to facilitate the entry into GMS software. Later, groundwater flow system is analyzed mainly focusing on recharge and discharge characteristics of the aquifers. Aquifer properties such as transmissivity, hydraulic conductivity and storage coefficient are identified using aquifer pump test data.

Although these site specific approaches differ in their objectives and type of aquifers being analyzed, they have common data collection and use of Geographic Information System as a tool for characterization and conceptualization of groundwater system. There are two papers reviewed on the methodological approaches. As presented below, one of them is partially site specific (Izady et al., 2013) and the other one is more general approach (ASTM, 2008).

Izady et.al. (2013) proposed a six-step site-specific procedure for the development of a groundwater conceptual model for the Neishaboor Aquifer in Iran. Initially collected and organized all the available data, information and maps. Next, set up controlling observations, such as information and data from piezometer, hydrometric stations, and discharge from withdrawal wells that controls the upcoming steps. The following step includes the determination of the areal extent and vertical thickness of the aquifer that involves aquifer physical boundary, bedrock position and aquifer stratigraphy. Overall, this step has two main outputs, such as aquifer physical boundary delineation as well as defining bedrock and stratigraphy of the aquifer. In step 4, the data on the aquifers hydraulic properties, such as hydraulic conductivity, specific yield etc. are collected and their spatial distributions are estimated. Step 5 deals with the evaluation of surface and groundwater interaction since it is important for identification of the aquifer recharge and discharge characteristics. Any regional flows between the aquifer and its surrounding are determined in this step. Finally, step 6 integrates the results from all previous steps and delivers the final version of the conceptual model.

The most comprehensive methodological approach is outlined by ASTM (2008) by proposing a standard guide for the conceptualization and characterization of groundwater systems, which consists of seven steps. The first step is problem definition and database development. This step basically focuses on defining the objectives, identifying the scale of the groundwater system for characterization, acquisition of topographic, geologic and hydrogeological data from existing sources, and preparation and organization of a new database consistent with the objectives set initially. The second step is the preliminary conceptualization step, which involves mainly the field conceptualization based on the database developed in the previous step. The end-result of this step is the description and visualization of the groundwater system using some cross sectional and plane view illustrations. The following step 3 involves surface characterization of both anthropogenic and natural features, such as agricultural and domestic groundwater use, topography, vegetation, climate in the study area. Step 4 deals with subsurface characterization for which the available soil, geology and geophysical database are used to determine stratigraphic and lithological units. Step 5 is hydrogeological characterization step involving the quantification and evaluation of uncertainties related to hydrostratigraphic units with respect to thickness and hydraulic properties. This step determines the spatial distribution and thickness of the hydrostratigraphic units, as well as their conditions related isotropy/anisotropy, and homogeneity/heterogeneity. Step 6 focuses on groundwater system characterization which deals with the assessment of the type, amount and distribution of groundwater recharge and discharge, identification of initial and boundary conditions, and groundwater budget characterization. Finally, step 7 involves the quantification of the hydrodynamics of the characterized groundwater flow system. Also, it involves a data gap analysis and collection of additional field data on hydrology and hydrogeology to fill the identified data gap. Completion of the seven steps leads to a finalized conceptual groundwater, which is ready to be utilized for follow up studies.

There are different types of tools used for the development of conceptual model. Kolm (1996) used Geographic Information System software (called ArcGIS) for surface and subsurface characterization of the aquifer whereas Waren et al. (2013) used it for only surface characterization. However, for visualization of the subsurface materials, they used Groundwater Modeling System software (called GMS). In recent studies, with the development of computer programs, the use of subsurface visualization tools is becoming common (Cox et al., 2013).

All these approaches summarized so far, except ASTM (2008), are developed considering mostly site and case specific conditions or needs; therefore they do not address the issue in a generalized and comprehensive sense. They all share the same data collection procedures and preliminary conceptualization based on the collected data and organized database. Although, GIS is mainly used as a tool for analyzing spatial information and generating the physical boundaries of the aquifer systems, the use of different 3-D lithological visualization tools, such as Groundwater Modeling System (GMS) to clearly understand the hydrogeological units is only seen in the most recent papers. Therefore, we propose a generalized framework in an integrated manner for the development of conceptual model for groundwater systems, which accounts for the overall objectives, scale and the nature of the modeling problem as well as proper tools available for data processing and minimum data requirements consistent with the intended use and objectives of conceptual model development.

2.3.2. The proposed Framework for Groundwater Conceptual Model Development

The proposed framework for groundwater conceptual model development consists of five steps. The first step (Step 1) defines the problem and states the objectives of conceptual model. The following step 2 involves data collection and database development consistent with the predefined objectives. Step 3, characterizes the hydrogeological framework, by identifying the areal and vertical extent of the aquifer with the help of GIS and 3-D subsurface visualization tools, respectively. The data and information gathered from Step 1 through Step 3 yield *preliminary conceptual model* presenting the aquifer geometry as an intermediate output of the proposed approach. Step 4 targets characterization of groundwater flow system through definition of physical and hydraulic boundaries, description of hydraulic parameter distributions and assessment of water budget with recharge discharge quantifications. With the completion of Step 4, another intermediate output of the process is the improved conceptual model that can serve as the basis for checking its suitability for the predefined objectives and thus data gap analysis for identification of additional data needs. In such cases, Step 2 and 3 can be repeated in a cyclic manner. Finally, Step 5 delivers the final conceptual model that can be used for the intended purpose. Figure 2.14 presents and summarizes the proposed framework as a flow chart. The detail of each step is explained in the following paragraphs.

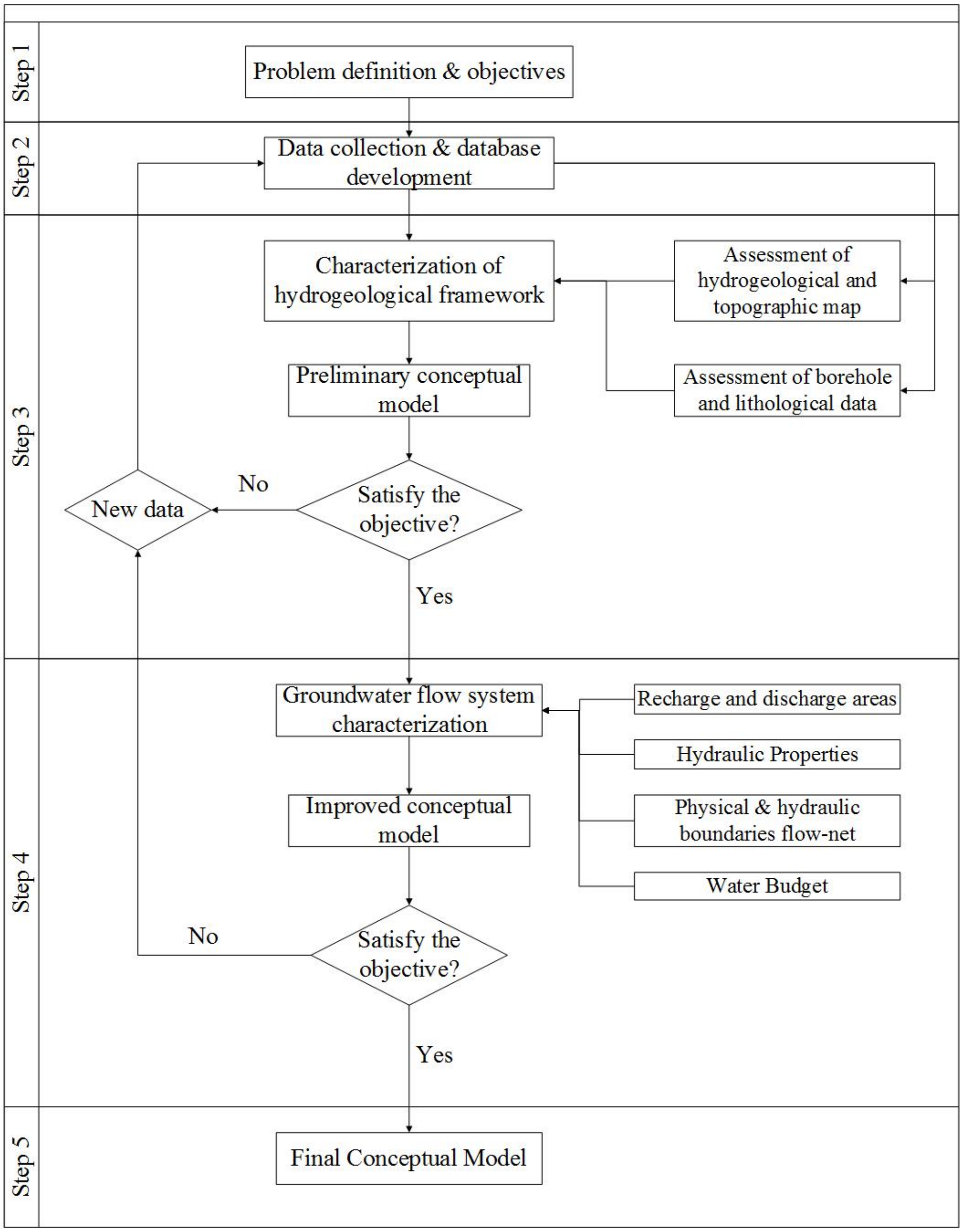

Figure 2.14 The proposed framework for the development of conceptual model.

Step 1: Problem definition and objectives

The intended use of developed groundwater models can be various; such as numerical flow modeling for assessing the impacts of drawdowns due to pumping, numerical contaminant transport modeling for water quality or risk assessment, well network system design for long term groundwater monitoring or remedial system operations, and development of groundwater basin management plans for water allocations and pollution prevention. Regardless of the overall objectives or intended use, following the available data gathering, the first step of groundwater modeling process is the development of a reliable conceptual model that satisfactorily serves for the intended purpose. The required level of details and complexity of conceptual model depends on the objectives of overall groundwater modeling, as well as the scale and nature of the modeling problem; and the details of conceptual model determine the type and extent of data/information required. The level of complexity of conceptual model should be consistent with both the objectives and extent of available data. The scale of groundwater modeling problem, can be regional, sub regional or local (site specific); or the overall objective of modeling can require the analysis of steady state and/or dynamic (transient) behavior of the aquifer system. In conjunction with the modeling objectives, as the scale of the problem gets larger and the dynamic behavior of systems needs to be considered, the size and extent of data requirement as well the level of sophistication of tolls needed for data analysis to build conceptual model generally increase.

Step 2: Data collection and database development

At this stage, both qualitative and quantitative data have to be gathered. The data inventory phase includes:

1. Gathering and analysis of published documents about the climate, topography, hydrology, hydrogeology, and related information of the area investigated;

2. Collection and review of aquifer specific data about the lithology, hydraulic properties, surface water interactions, regional climatic conditions, flow and hydrologic characteristics of aquifer system; such as, lithological and geophysical borehole logs, results of pumping tests, distributions of groundwater levels and groundwater quality, base flow and spring flow, precipitation, evaporation and evapotranspiration measurements.

At this point a check for the reliability of available data with respect to the size and extent, and performing an initial data gap analysis to plan future site investigation needs may be important. In order to fill the data gap, collection of additional data and new information about the groundwater system may also be necessary. The extent of field activities to collect additional data could vary from a rapid reconnaissance survey of the study area, for missing well coordinates, water level measurements, borehole lithology etc. using GPS and relevant field equipment to a more detailed field investigation requiring, for example, exploration drilling and pump tests.

At this step, with the help of different tools used for data analysis, such as GIS, GMS, Microsoft Excel, the database has to be developed for all the available/collected and processed data, specifically for borehole, water level, water quality, recharge-discharge and hydraulic parameter measurements.

Table 2.4 is organized in such a way that the required data types can be related to the objectives, scale and nature of the conceptual model development. The "check" sign indicates that a data type is considered to be a minimum requirement for conceptual model development having the given modeling objective and scale. The required data and information are grouped under seven major data types, which includes topography, geology/hydrogeology, climate, anthropogenic aspects, hydrology, water quality, and groundwater flow system. The modeling objectives are generalized as numerical groundwater flow and contaminant transport modeling, and monitoring well network design. Numerical modeling activities can be undertaken at regional, sub-regional or local scales under steady-state or transient conditions while groundwater monitoring activities can be at main or sub-basin (regional or sub-regional) scale or an individual groundwater body (local) scale. The overall modeling objectives, as well as the scale and nature of the modeling problem determine the type and extent of data/information required. As the scale of the problem gets larger and the dynamic behavior of systems needs to be considered, the size and extent of data requirement to build conceptual model generally increase. For example, as seen from Table 2.4, regardless of the objective, scale and nature of the modeling problem topographic, geological/hydrogeological maps and lithological drilling logs are always considered to be a minimum requirement. At regional or sub-regional scales, the number of map tiles and boreholes needed are much more compared to local scale. A few map tiles and a minimum of three boreholes are sufficient for a local scale problem; however, a few tens of map tiles or boreholes may be necessary for regional scale groundwater studies. Similarly, for steady-state groundwater flow and transport problems average seasonal climatic, hydrologic or water quality data may be sufficient; on the other hand, for transient behavior of groundwater systems long-term weekly or monthly measurements may be necessary, involving construction and maintenance of large databases.

Table 2.4 The minimum data/database requirement in conjuction with the objective, scale and nature of the problem.

Data Type/ Database	Objectives														
	Numerical groundwater flow modeling						Numerical contaminant transport modeling						Well network system design		
	Scale														
	Reg.[a]		Sub-reg.[b]		Local		Reg.		Sub-reg.		Local		Reg.	Sub-reg.	Local
	Nature of the problem														
	SS[c]	Tr[d]	SS	Tr	SS	Tr	SS	Tr	SS	Tr	SS	Tr			
A. Topography															
1. Topographic map	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2. Digital Elevation Model	✓	✓	✓	✓			✓	✓	✓	✓			✓	✓	
3. Surface drainage network map	✓	✓	✓	✓											
B. Geology/Hydrogeology															
1. Geologic/Hydrogeologic map	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2. Geological/Hydrogeologic cross-section															
3. Lithological or drillers log	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
4. Aquifer configuration															
C. Climate															
1. Precipitation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			
2. Temperature															
3. Evapotranspiration															
D. Anthropogenic aspects															
1. Irrigation water use	✓	✓	✓	✓			✓	✓	✓	✓			✓	✓	✓

[a]Reg. = Regional, [b]Sub-reg. = Sub-regional, [c]SS = Steady State, [d]Tr = Transient

Table 2.4 (Continued)

Data Type/ Database	Objectives														
	Numerical groundwater flow modeling						Numerical contaminant transport modeling						Monitoring well network system design		
	Scale														
	Reg.[a]		Sub-reg.[b]		Local		Reg.		Sub-reg.		Local		Reg.	Sub-reg.	Local
	Nature of the problem														
	SS[c]	Tr[d]	SS	Tr	SS	Tr	SS	Tr	SS	Tr	SS	Tran			
2. *Land use map*															
E. Hydrology															
1. *Surface water data*	✓	✓	✓	✓											
2. *Groundwater level data*	✓	✓	✓	✓									✓	✓	✓
3. *Springs and seeps data*	✓	✓	✓	✓									✓	✓	✓
4. **Water Quality**															
1. *Water quality data*							✓	✓	✓	✓	✓	✓	✓	✓	✓
2. *Contaminant source data*							✓	✓	✓	✓	✓	✓			
3. *Contaminant of concern*							✓	✓	✓	✓	✓	✓			
5. Groundwater flow system															
1. *Recharge and discharge data*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			
2. *Pump test data*															
3. *Aquifer hydraulic properties*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			
4. *Flow nets*							✓	✓	✓	✓					

[a]Reg. = Regional, [b]Sub-reg. = Sub-regional, [c]SS = Steady State, [d]Tr = Transient

Step 3: Characterization of hydrogeological framework

Characterization of hydrogeological framework includes the determination of surface and subsurface structural framework: areal and vertical extent of aquifer, aquitard and aquiclude materials. It requires a detailed assessment of hydrogeological and topographic maps for surface characterization, and borehole and lithological data for subsurface characterization.

Surface characterization is delineation of natural features and processes at or near the surface of the earth and it is developed from hydrogeological and topographic maps organized in the database. The features include land use, topography, anthropogenic effects (e.g., consumption of the groundwater for domestic and irrigation purposes), surface water features (rivers, lakes etc.), climate and recharge/discharge areas. Surface characterization is important to understand the interaction of surface and subsurface features and also to create the physical boundaries of the aquifer. Geographic Information System (GIS) is a powerful tool at this step to generate physical boundaries of the aquifer by overlaying hydrogeological maps and Digital Elevation Model (DEM) produced from the topographic map of the basin.

Subsurface characterization is qualitative visualization of 3-D subsurface geologic framework and it is conducted using borehole lithological descriptions and geophysical well logs. The characterization includes subsurface cross-sections, the distributions of aquifer material and aquifer thickness; and delineation of isotropic/anisotropic as well as heterogeneous zones.

Over the last decade, computer software and hardware have been developed in order to enable the 3-D visualization of subsurface structures, such as size and extent of aquifer, aquitard and aquiclude materials. Therefore, at this step, it is important to group the field borehole lithological descriptions into common groups with an ultimate description of aquifer and non-aquifer material to facilitate the entry of the description into the 3-D visualization tools, such as Groundwater Modeling System

(GMS), Groundwater Visualization System (GVS), RockWare (Cox et al., 2013; Waren et al., 2013)

Preliminary conceptual model, which is the output of Step 1 through Step 3, gives the qualitative characterization of the aquifer system, such as the areal extent and vertical thickness, layering characteristics, level of heterogeneity and anisotropy. It helps to collect additional data in order to fill the initial data gap. To acquire additional information in areas where field data are sparse, different GIS and remote sensing tools can be used. In this regard, basic photointerpretation and terrain analysis techniques may be applied to remote sensing data, aerial photography, and topographic map to acquire information regarding the distribution of hydrogeological and groundwater system parameters (Kolm, 1996; Teresita Betancur V., Carlos Alberto Palacio T., 2012).

Step 4: Groundwater flow system characterization

Groundwater flow system characterization is important to know the interaction of groundwater with its environment. Its characterization requires the assessment of recharge and discharge characteristics to understand the water budget (including surface and groundwater interaction), flow-net analysis to delineate the hydraulic boundaries, and distribution of hydraulic properties (i.e., hydraulic conductivity, specific yield etc.).

Assessment of recharge and discharge is the most critical aspect in the development of groundwater conceptual model. In general context, direct and indirect methods are used to determine the amount of water entering the aquifer. Direct methods describe recharge as the mechanism of water percolation from the land surface to the aquifer, while indirect methods are those that use variables such as particle size, porosity and compaction that describe and represent the flow of water through the soil. In semiarid regions, recharge is mainly from streams to aquifers through thick vadose zones. Understanding basic principles of the interaction of surface and groundwater body is important because recharge and discharge of groundwater are mainly dependent on the surface and groundwater interactions.

Groundwater recharge and discharge components of the study area are quantified with the help of groundwater budget. Even if there is an inherent uncertainty associated with the calculation of groundwater budget, it is still useful for determining the relative importance of different processes (Waren et al., 2013). Therefore, the groundwater budget needs to be developed on a regional or large scale, for an entire or geographic region. Ground water budgets or ground water inventories are developed by quantifying all inflows to a system, all outflows from a system, and the storage change of the system over a specified period of time (Hutchison et al., 2008). Natural and anthropogenic factors determine the complexity of the water budget. These factors are climate, hydrography and hydrology, geology, geomorphologic characteristics, hydrogeological characteristics of the surficial soil and subsurface porous media, land cover, land use, presence and operations of artificial surface water reservoirs, surface water and groundwater withdrawals for consumptive use and irrigation, and wastewater management (Kresic, 2009).

Generally, groundwater interacts with all types of surface water, such as streams, lakes, and wetlands, in many different landscapes from the mountains to the oceans. The interaction of ground water with surface water depends on the physiographic and climatic setting of the landscape, such as Mountainous terrain, Riverine terrain, Costal terrain, Glacial and Dune terrain, and Karst terrain. In coastal terrains, the interaction of groundwater and surface water is affected by discharge of groundwater from regional flow systems and from local flow systems associated with scarps and terraces, evapotranspiration, and tidal flooding.

The construction of flow nets is one of the most powerful analytical tools used for the analysis of groundwater flow systems. Groundwater contour maps and flow nets are useful tools to determine the groundwater flow directions, flow rates and flow velocities and ultimately to delineate hydraulic boundaries of the system, to analyze distribution of aquifer transmissivity, and to estimate contaminant path and plume development. Groundwater contour maps and flow nets can be constructed manually, from monitoring well data recorded in the field or using computer programs capable of mapping head contours and drawing streamlines.

The spatial distribution of the aquifer material properties, such as hydraulic conductivity, K and specific yield, S_y and their distribution i.e., isotropy/anisotropy and homogeneity/ heterogeneity are important for groundwater flow system characterization. Determination of hydraulic conductivity is one of the most challenging aspect of hydrological modeling. The aquifer heterogeneity not only affects the groundwater flow but also has the greatest impacts on the movement of contaminant. Special distribution of hydraulic conductivity has been identified as the major cause of uncertainty in the development of conceptual groundwater model (Izady et al., 2013). There are direct and indirect methods to estimate saturated hydraulic conductivity. The direct methods (e.g., pumping test, tracer test, etc.) are based on field measurements of saturated hydraulic conductivity or transmissivity. Apart from hydraulic conductivity, estimation of specific yield is also important. It can be measured directly or indirectly. A long-term aquifer pumping test or a continuous monitoring of the hydraulic head change due to a known recharge are arguably the only reliable methods for determining the value of specific yield, which is one of the key parameter for defining quantities of extractable groundwater (Kresic, 2009).

After delineation of the physical and hydraulic boundaries (i.e., areal and vertical extend) of the aquifer, determination of boundary conditions is also included in Step 4. Upper, lateral and lower boundaries are typical groundwater flow model boundaries. For unconfined aquifers, groundwater level is often considered as the upper boundary. The most difficult ones are often the lateral boundaries. Bedrock is usually considered as the bottom boundary.

The output of Step 4 is an improved conceptual model. At this stage, we have to check the reliability and suitability of the developed conceptual groundwater model for the intended use. If it satisfies the objectives of groundwater conceptual model development set in step 1, then we proceed to step five for delivering the final conceptual model. On the other hand, if it does not meet the objectives, there will be a need to go back and collect additional field data as required on both hydrogeological characterization and groundwater flow system characterization to address the identified data gap.

Step 5: Final conceptual model

This step integrates the results from all the other steps to deliver the final version of the conceptual model. Whenever new hydrogeological and groundwater system data become available, the conceptual model needs to be updated and thus improved further. Collection of new information may makes the original conceptual model invalid (Bredehoeft, 2005); however, it may take several year to get new information and/or scientific evidence to challenge the original conceptual model. The final conceptual model is not only used as a prerequisite for the development of numerical modeling but also used as a key for managerial decision-making.

The proposed methodology can be used as a road map on how to construct a conceptual model for a given case i.e., meeting the different objectives with the minimum data set. The developed methodology has been used for the construction of groundwater conceptual model for Güzelyurt Aquifer, which will be discussed in Chapter 3.

CHAPTER 3

ANALYSIS OF AVAILABLE DATA AND INFORMATION FOR CONCEPTUAL MODEL DEVELOPMENT

This section presents the analyses of all the available data and information. The collected data is processed and analyzed in accordance with the objectives set in Section 1.2 of this thesis, being the development of a conceptual model for the Güzelyurt Aquifer.

Available data and information revealed that the hydrogeology and the hydrology of the study area are relatively complex, as is the case for most subsurface systems. Therefore, use of spatial data analysis tools such as Geographic Information System (GIS) and other tools for 3-D visualization of borehole and topographic data are needed. Available borehole data to be used for geologic/hydrogeologic characterization are sparse at the periphery, but very concentrated towards the center of the study area. The first step in data analysis was the delineation of physical boundaries of Güzelyurt Aquifer in GIS environment using both hydrogeological and topographic maps of the study area.

3.1. Analysis of Hydrogeological Maps Using Geographic Information System (GIS)

The two available hydrogeological maps that are developed by the Geology and Mining Department (G&MD) of North Cyprus and British Geological Survey, respectively, are analyzed independently. The first map is developed only for the part of the Güzelyurt Basin lying in the North Cyprus, whereas the later one is developed for the whole basin; however, due to its undetailed descriptions of the mapping units, just categorizing the geological formations under two general classes as aquifer and non-aquifer material, this map is used to identify the hydrogeological formations having aquifer characteristics which comprise the Güzelyurt Basin lying only in the South Cyprus. This map is also used to crosscheck the continuity of some formations in the Northern Cyprus to avoid uncertainty.

The first step in the analysis of the hydrogeological map of North Cyprus was to classify the identified total 65 different hydrogeological formations lying in the northern part of the study area into common groups based on the degree of water bearing and transmission characteristics of the mapping units. Figure 3.1 shows the original hydrogeological map with 65 mapping units. Unconsolidated aquifer materials such as Gravel and Sand fall into 1st and 2nd groupings, respectively. Consolidated aquifer materials such as Sandstone and Calcarenite are grouped in 3rd grouping. These materials are also aquifer materials but have lower water bearing and transmission capacity compared to unconsolidated aquifer materials. The 4th grouping comprises consolidated non-aquifer materials such as Marl, Limestone and Mudstone whereas the 5th grouping includes consolidated rocks basically forming the base of the aquifer including Pillow lava, Tuff, Trachyandesite & Dacite. The distribution of the first material groups in the study area is shown in Figure 3.2. These five common groups of mapping units are later grouped into three major groups. Because of their high water bearing and transmission capacity, the first and second groupings are merged together into an alluvial material. The cemented materials such as Sandstone and Calcarenite having relatively lower water bearing and transmission characteristic are grouped into consolidated material. Both the fourth and fifth groupings fall into base material because they have no water bearing and transmission capacity. The second regrouped mapping units are shown in Figure 3.3 and the details of grouping with the legends are given in Appendix A, Table A.1. We can see from Figure 3.3 that the Mesaria central plane on the western part of the island located between Troodos and Kyrenia mountains is mainly composed of gravel dominated alluvial material. Sand is concentrated on the coastal part of the Güzelyurt basin. Relatively low permeable consolidated aquifer materials such as sandstone and calcarenite surround the alluvial material from the northern and southern part of the study area. The mountainous areas are mainly composed of consolidated and unconsolidated non-aquifer materials such as mudstone, marl and pillow lava.

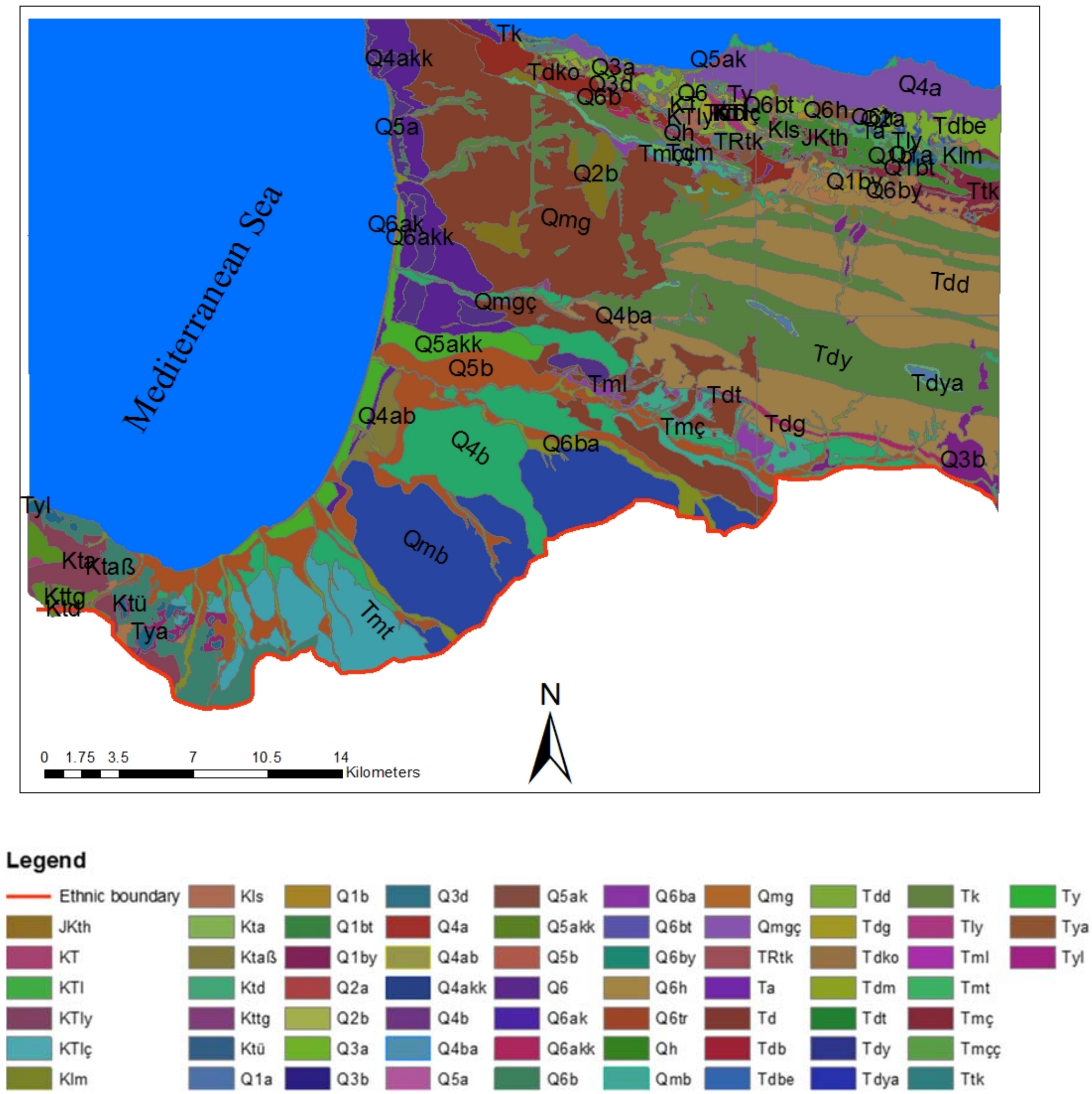

Figure 3.1 Hydrogeological map of Güzelyurt Basin in North Cyprus (The description of the legend is given in Appendix A, Table A.1).

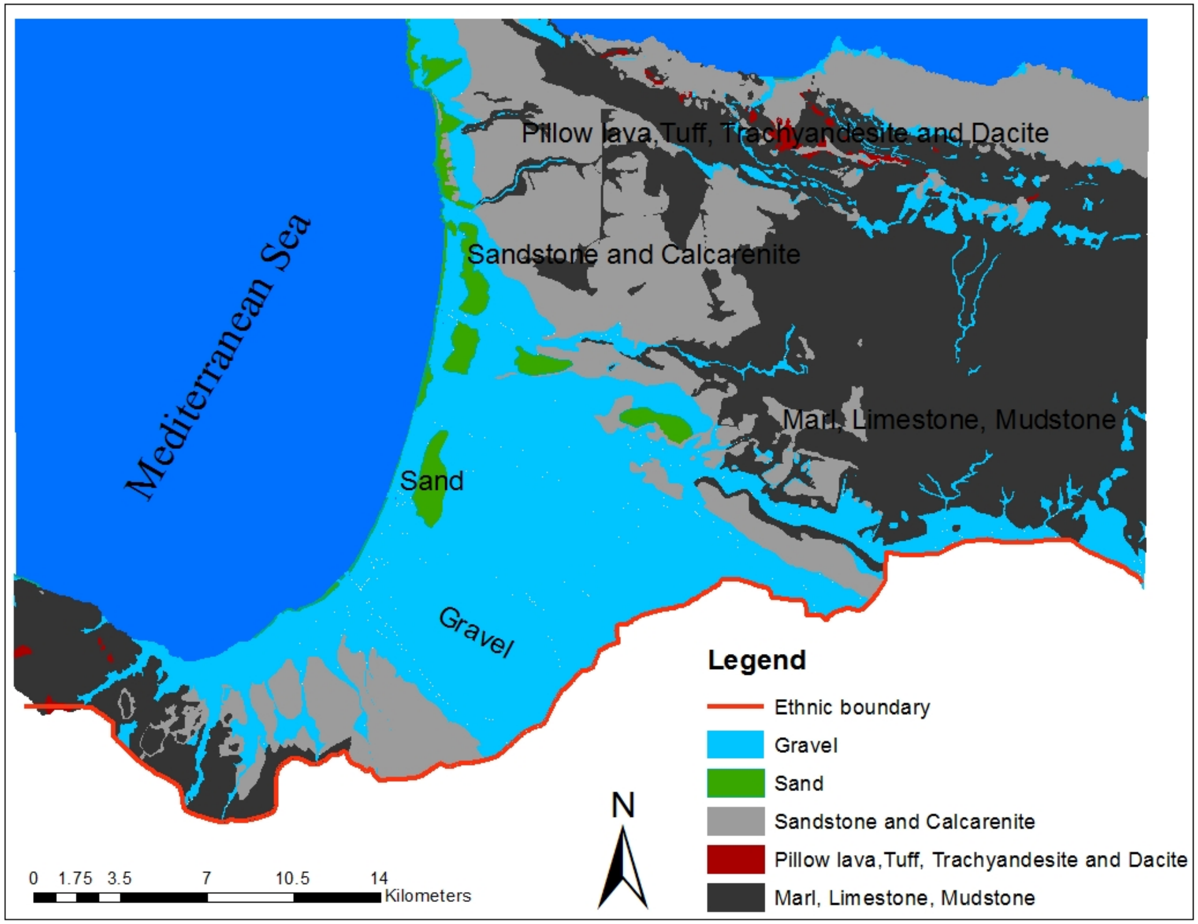

Figure 3.2 The first grouping of mapping units of Güzelyurt Basin in North Cyprus.

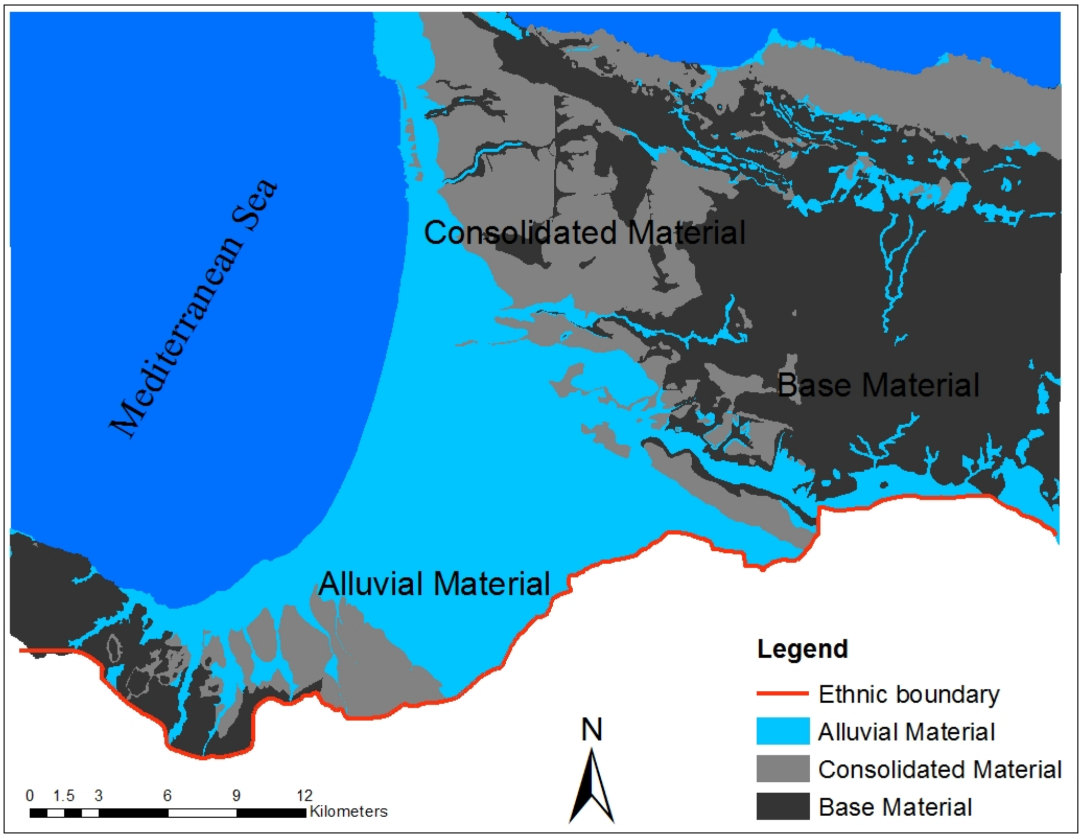

Figure 3.3 The regrouped hydrogeological map of Güzelyurt Basin in North Cyprus.

To determine the physical boundary of Güzelyurt Aquifer that extended beyond the ethnic boundary to the South Cyprus, an analysis similar to the hydrogeological map of North Cyprus was done on the hydrogeological map developed by British Geological Survey. Originally, this map had 18 gross hydrogeological descriptions given in Appendix A, Table A.2**;** and based on the water bearing and transmission characteristics, the mapping units are grouped into three common groups of Alluvial material, Consolidated material and Base material. The original and regrouped hydrogeological formation maps are shown in Figure 3.4 and Figure 3.5, respectively. It can be seen from Figure 3.5 that the Güzelyurt plain is mainly composed of alluvial material such as sand and gravel. Relatively low permeable consolidated aquifer materials mainly surround the alluvial materials. However, Troodos Mountains in the south and Beşparmak Mountains in the north are mainly composed of impermeable materials such as marl, siltstone and pillow lava.

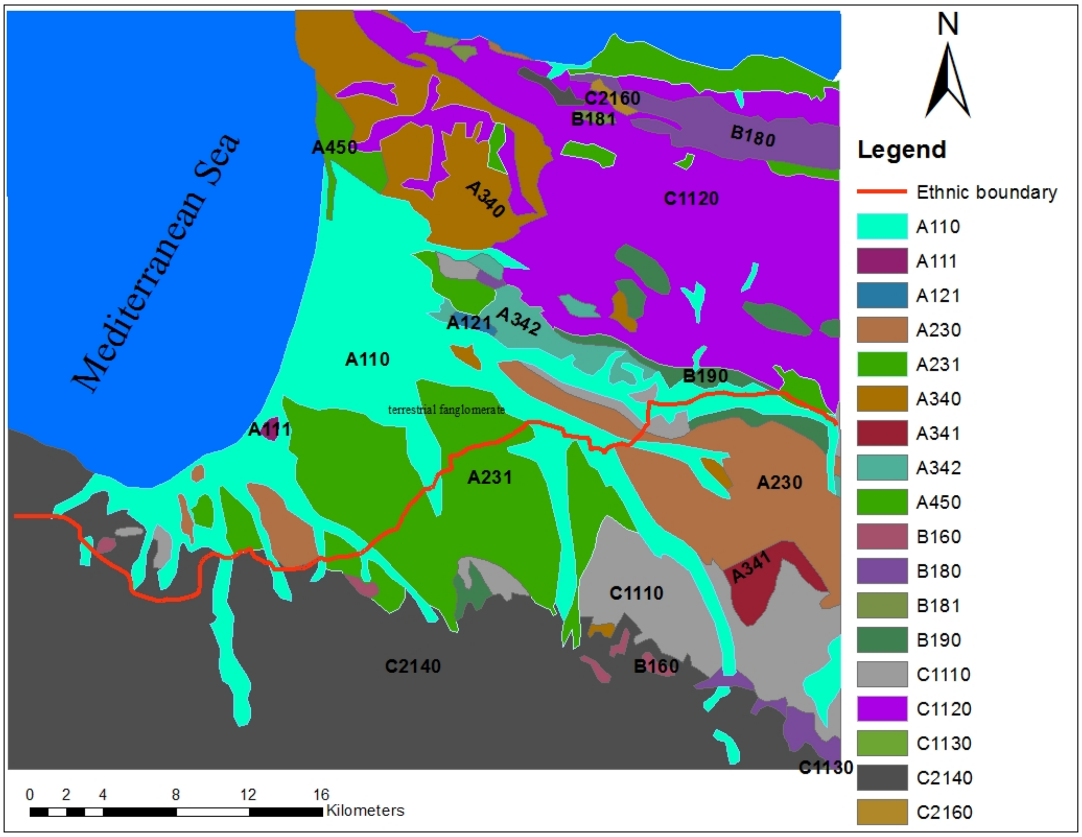

Figure 3.4 Hydrogeological map of Güzelyurt Aquifer developed by the British Geological Survey (see Appendix A, Table A.2 for legand).

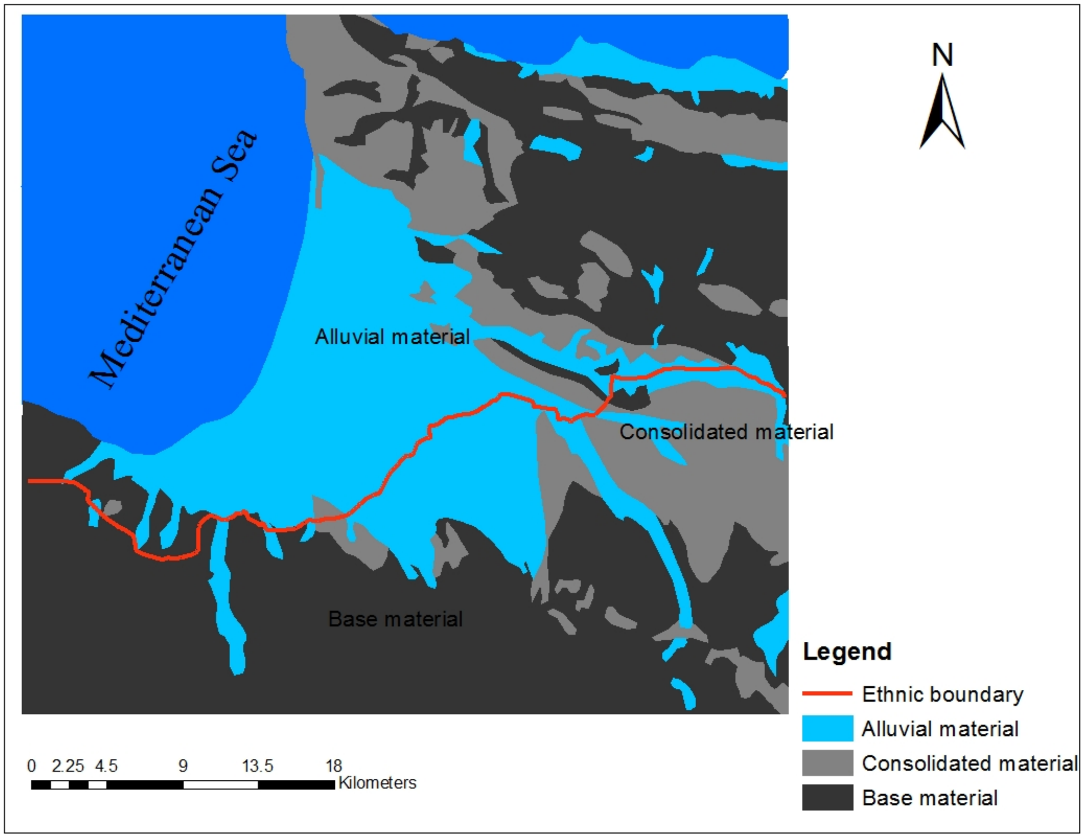

Figure 3.5 The regrouped hydrogeological map of Güzelyurt Aquifer developed by British Geological Survey.

By combining the two regrouped hydrogeological formations in GIS environment, the areal extent and boundaries of material groups have been delineated as shown in Figure 3.6**.** As seen from the figure, water bearing and water transmitting alluvial materials composed mainly of sand and gravel extend from the coast of Mediterranean Sea towards the lower parts of the Troodos Mountains covering a significant area of the Güzelyurt plain. The boundary surrounding these alluvial materials is called the formation boundary of the Güzelyurt Aquifer. Consolidated materials composed of mainly sandstone, fanglomerate, and calcarenite also have a significant amount of recharge capacity; but they are considered as a separate aquifer unit in the Güzelyurt plain due to their different hydraulic properties. The contact zones between alluvial aquifer and the consolidated aquifer materials will be important in terms of identifying the boundary conditions for future numerical modeling studies. The impermeable base material, which is mainly composed of solid rocks such as pillow lavas and marl with very poor water storage and transmission properties, covers the rest of the basin contributing to surface runoff and ultimately recharging the aquifer through mainly alluvial and to some extent through consolidated aquifer materials.

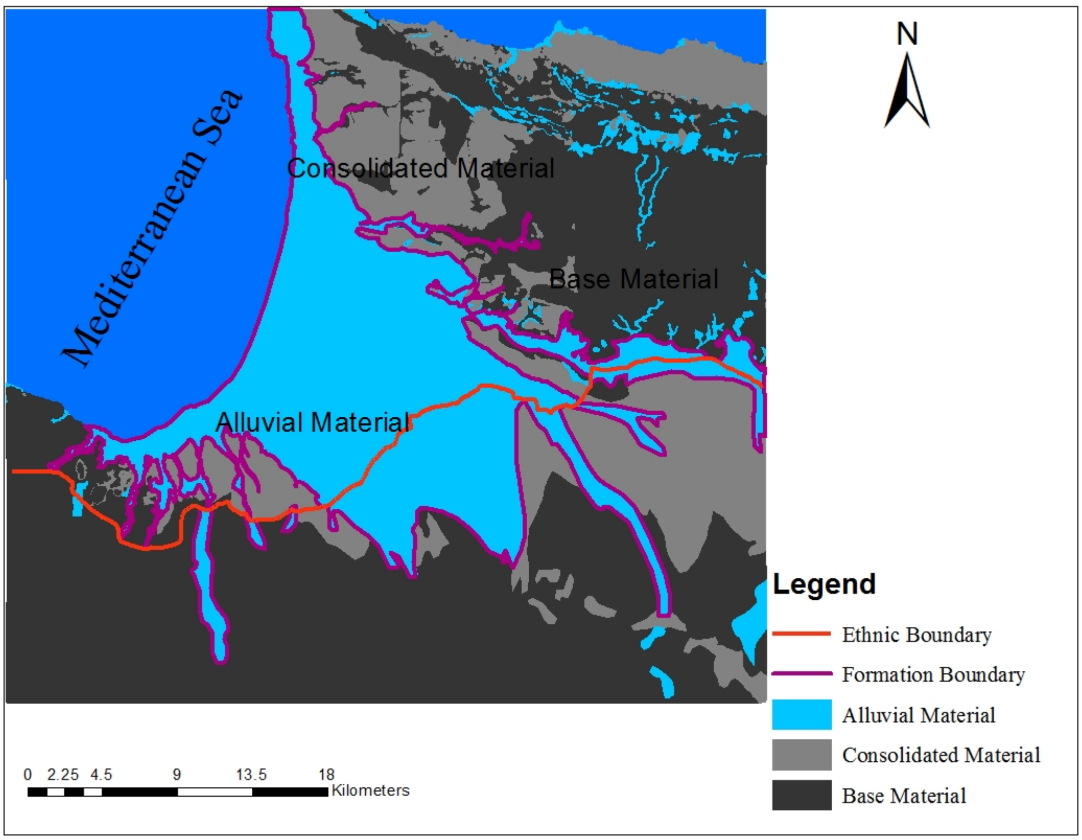

Figure 3.6 Formation boundary of Güzelyurt Aquifer.

3.2. Analysis of Topographic Map

Distribution of Land surface elevations required to create the Digital Elevation Model (DEM) of the project area were extracted from digitally available topographic contour maps consisting of eleven tiles obtained from the Geology and Mining Department

(G&MD) of North Cyprus. Although the Troodos Mountain is as high as 1,952m, due to lack of elevation data of the mountain locate in South Cyprus, we could only attain an elevation of 1,970m. First, the eleven topographic tiles are merged to produce one whole set of topographic contour map of the study area as shown in Figure 3.7. Then as shown in Figure 3.8, the DEM of the study area is created using the spatial analysis tools of ArcMap 10.1 (ESRI, 2012). The interpolation of the elevation data was accomplished using Kriging method, which considers the spatial autocorrelation. The DEM created from the surface contour map is used for the 3-D visualization of the basin and delineate the topographic boundary of the study area in the subsequent analysis. The darker area in the map shows the highest points, especially the Troodos Mountains in the south and Beşparmak Mountains in the northern part of the study area. The Güzelyurt alluvial plain is lower in altitude and gets to zero elevation on the contact point with the sea.

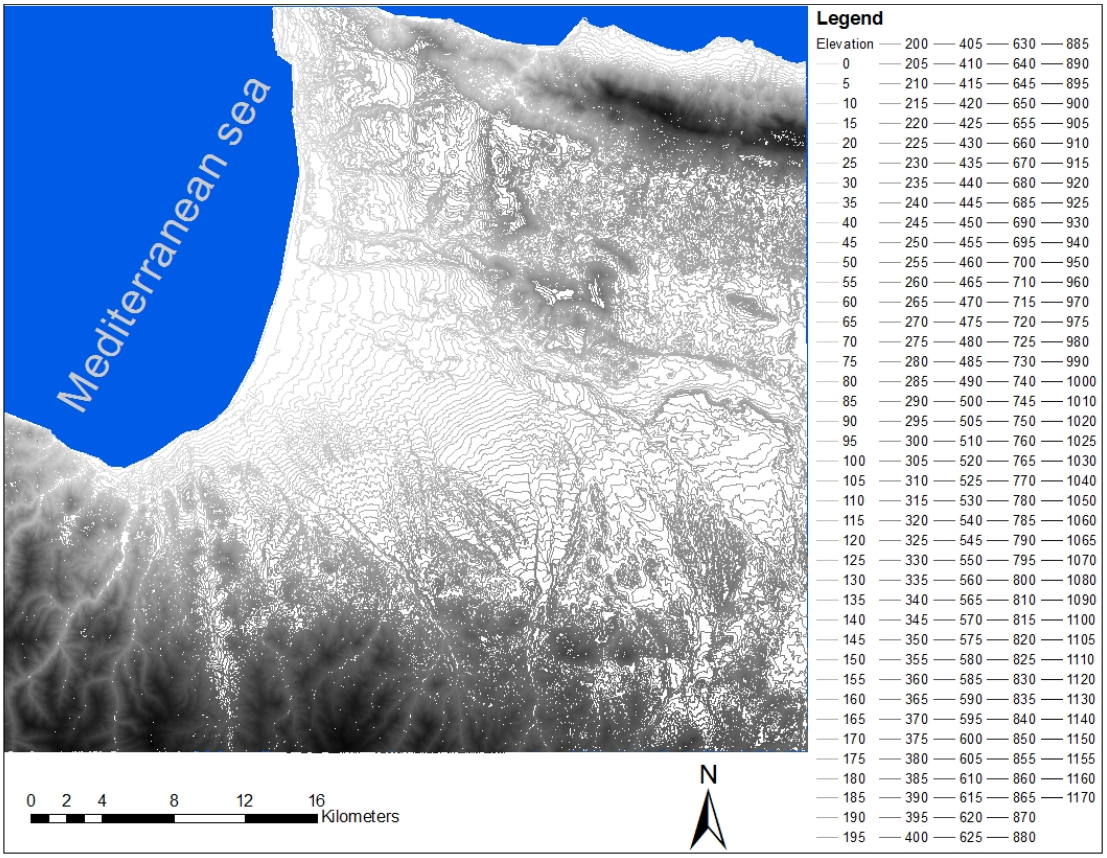

Figure 3.7 Topographic contour map created by merging the eleven tiles of topographic contour maps

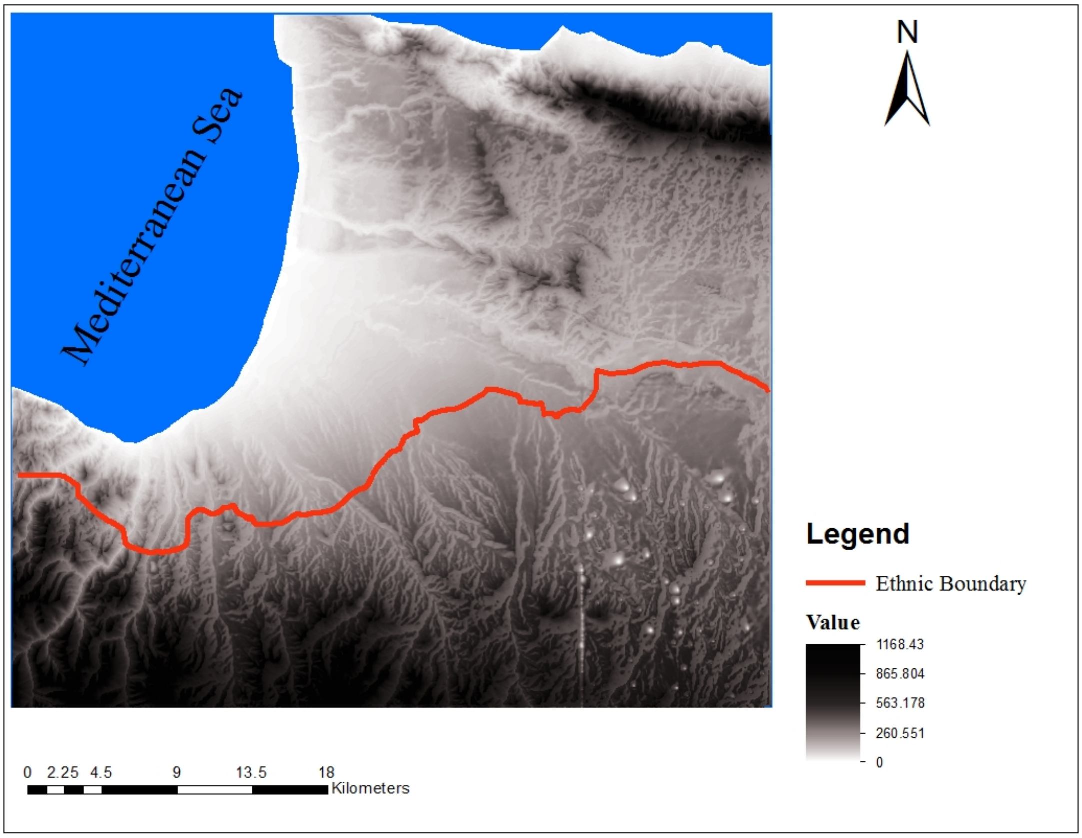

Figure 3.8 Digital elevation model (DEM) created from the topographic contour map of the study area.

Arc Hydro tool, which operates within ArcGIS to support geospatial and temporal data analyses, is used to delineate the watershed characteristics of the study area. There are nine steps to follow in the terrain processing in order to create the watershed of the study area (i.e., fill sink, flow direction, flow accumulation, stream definition, stream segmentation, catchment grid delineation, catchment polygon processing, drainage line processing and adjoint catchment processing). The first step is to fill the sinks or depressions in DEM. If cells with higher elevation surround a cell, the water is trapped in that cell and cannot flow. Therefore, the Fill Sinks function modifies the elevation value to eliminate these problems. Then using the filled DEM as an input, flow direction is calculated. This function computes the flow direction for a given grid. The values in the cells of the flow direction grid indicate the direction of the steepest descent from that cell. By using flow direction as an input flow accumulation is created. Flow accumulation grid that contains the accumulated number of cells upstream of a cell, for each cell in the input grid. Stream definition tool creates the stream grid based on a flow accumulation grid and a user specified threshold. The Stream segmentation tool allows assigning the same unique value to stream cells located within the same stream segment. Segments are defined as either head stream segments (the most upstream branch) or segments located between two segment junctions. All the cells in a particular segment have the same grid code that is specific to that segment. Catchment grid delineation tool creates a grid in which each cell carries a value (grid code) indicating to which catchment the cell belongs. All the raster data developed so far are converted to vector format by using the three functions: Catchment Polygon Processing, Drainage Line Processing and Adjoint Catchment Processing. Adjoint Catchment Processing generated the aggregated upstream catchments from the catchment feature class as shown in Figure 3.9a. Later by merging the catchments flowing to the same pour point, the watershed of Güzelyurt Aquifer is determined as shown in Figure 3.9b. There are two basins developed by overlaying the watershed map on DEM as given in Figure 3.10. Due to the topographic high points dividing the basin making the water flow into two different points, the smaller basin is treated as different basin.

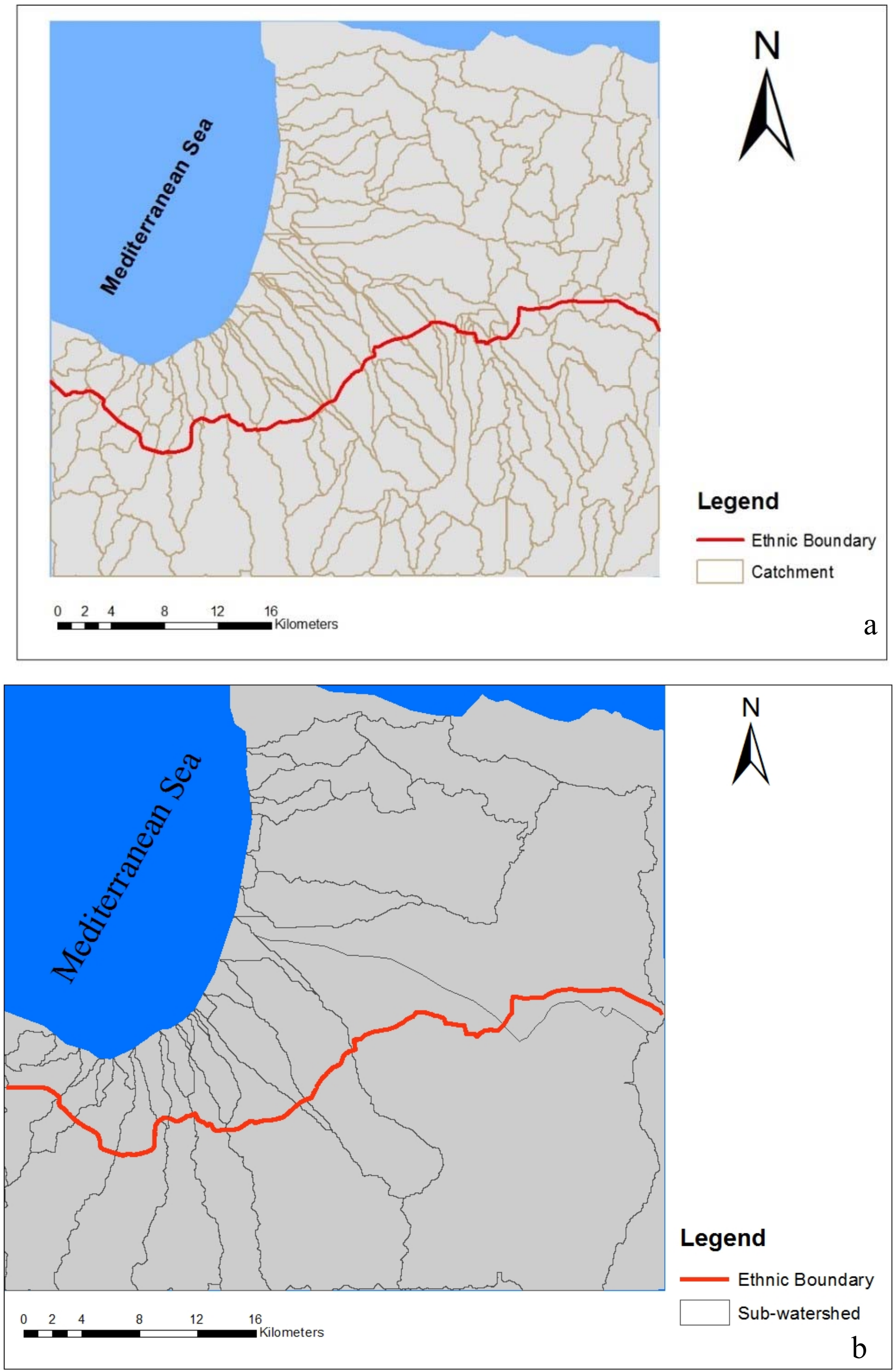

Figure 3.9 The catchments created from DEM (a) and the watershed created using the catchments (b)

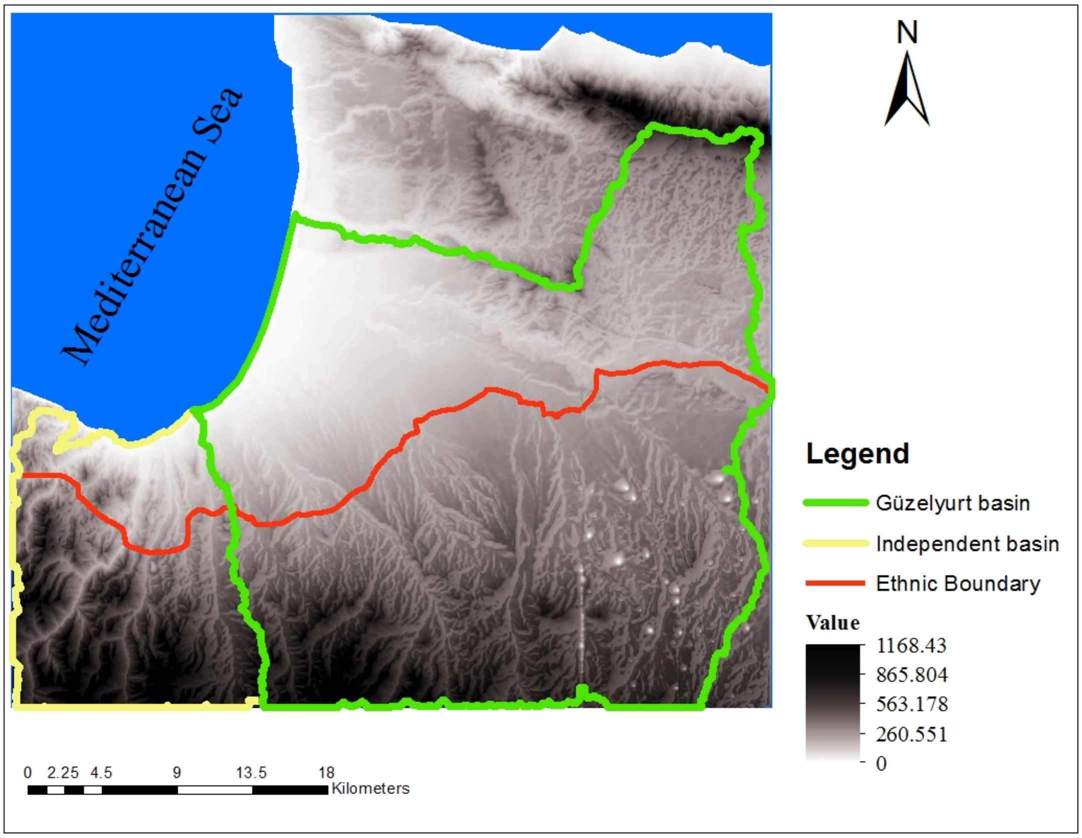

Figure 3.10 The two separate basins identified in the study area.

Finally, the areal extent of the Güzelyurt Aquifer was determined by overlaying the DEM and hydrogeological maps of the study area in the GIS environment. This overlaying produced a base map showing all the physical boundaries (i.e., catchment boundary, formation boundary and aquifer boundary) as given in Figure 3.11. As seen from the figure, at the northwest and at the southwest, aquifer boundaries are delineated by topographic high elevations of the catchment boundaries through the alluvial aquifer material for relatively small distances, while in the rest of the study area, the majority of the aquifer boundaries are coinciding with the formation boundaries of the alluvial aquifer material. Some of the small isolated alluvial formations within the topographic boundary are excluded from the aquifer boundary. However, they will be used in identifying the boundary conditions in future numerical modeling studies.

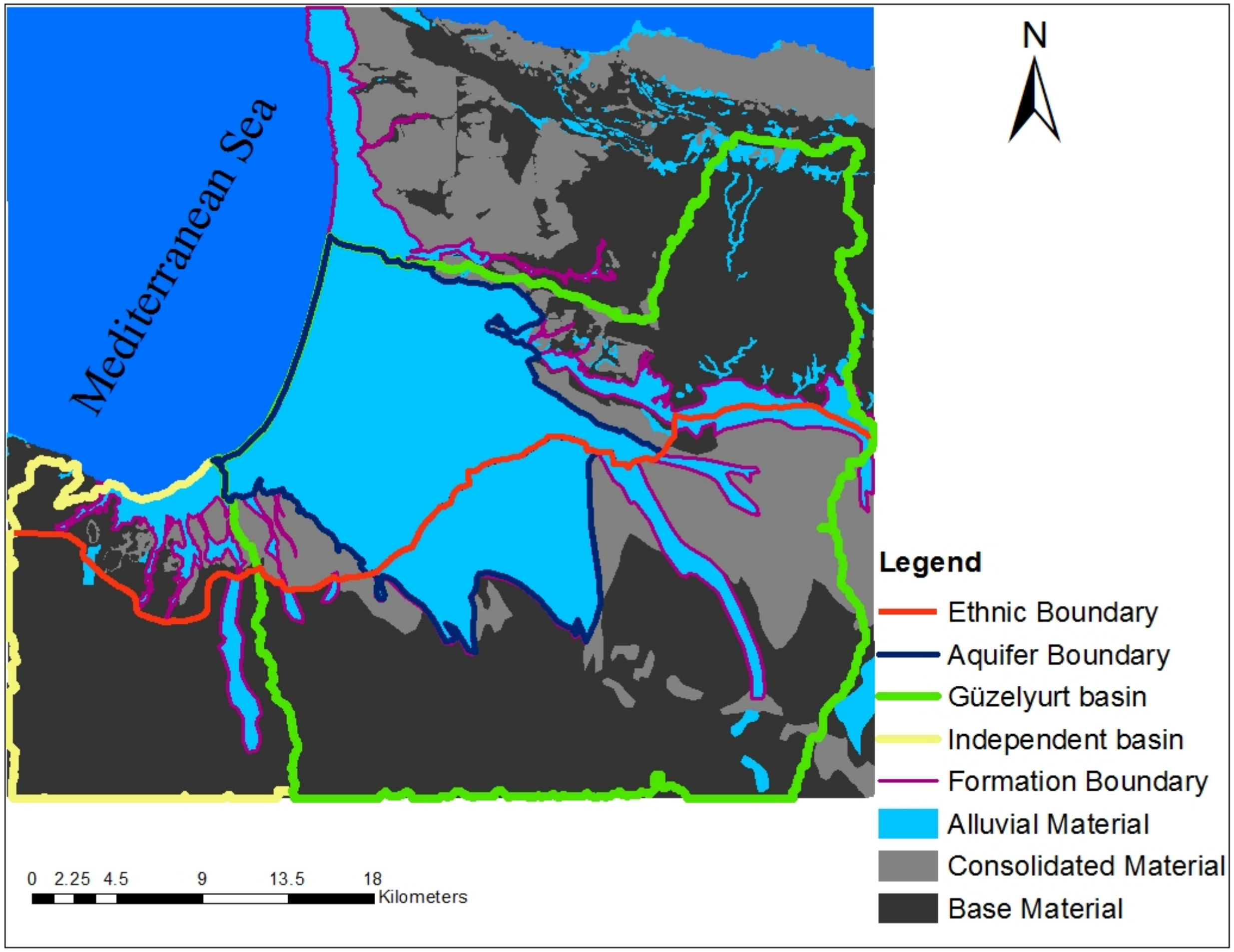

Figure 3.11 Base map showing all the physical boundaries (i.e., catchment boundary, formation boundary and aquifer boundary)

3.3. Analysis of Borehole Data (Well Logs)

The borehole logs are used to analyze the subsurface conditions and the vertical extent of the Güzelyurt Aquifer. There were a total of 116 well logs in the database of Geology and Mining Department (G&MD) of North Cyprus. Out of 116 available boreholes, 92 of them were inside the aquifer boundary and only 73 of the 92 boreholes were useful; the rest was unusable because of poor or gross descriptions of lithological materials with extremely large unspecified depth intervals. For example, some boreholes lack material descriptions either totally or at some depth intervals in the middle; and some of them had no record of surface elevation. Because of such problems, too shallow boreholes with depth less than 20 m are excluded from the database; on the other hand, too deep boreholes with depth greater than 350 m are considered only down to a depth of 200 m. Figure 3.12 shows the vertical distribution of all the selected 73 useful boreholes available in the database.

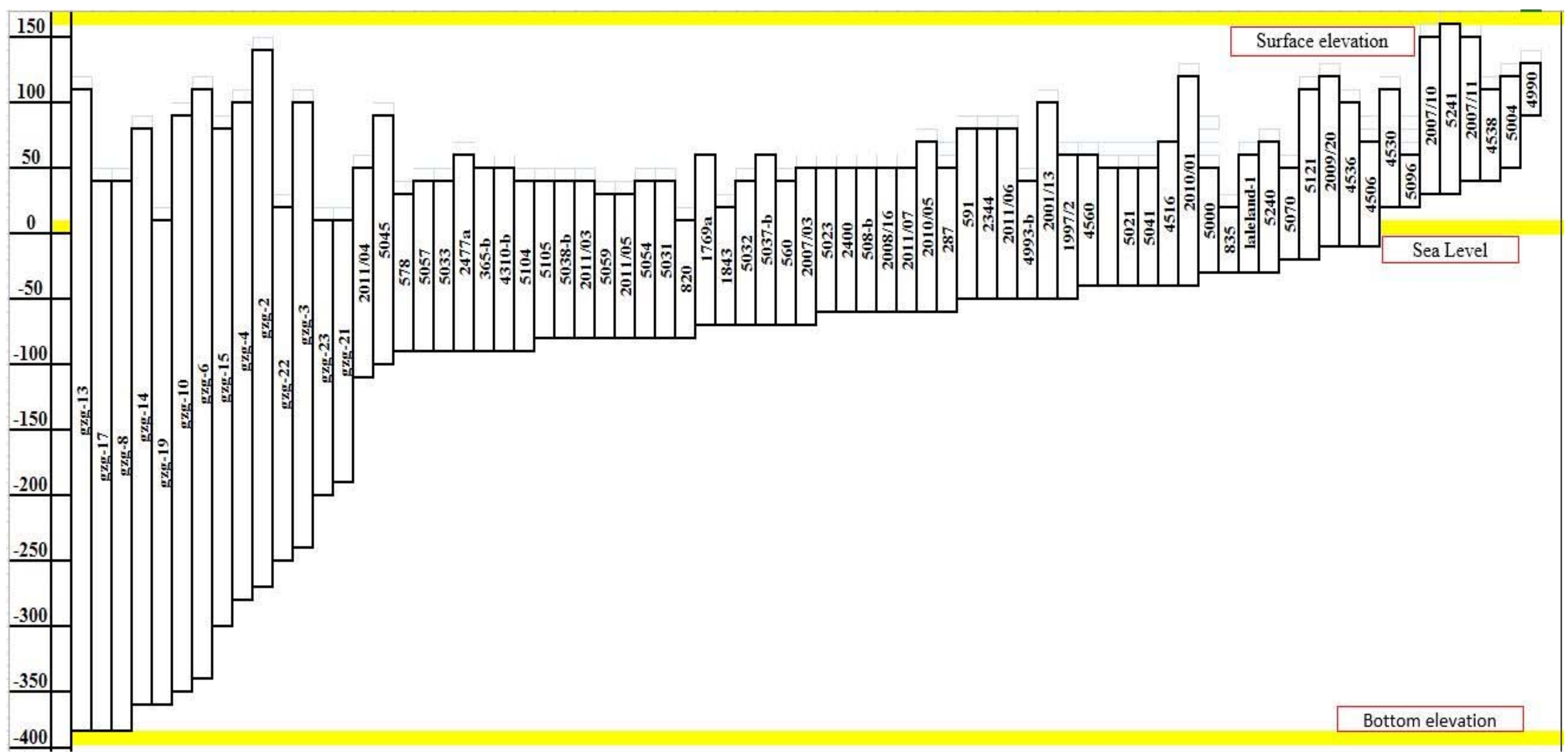

Figure 3.12 Vertical distribution of surface and bottom elevation of the selected 73 boreholes.

More than 90 % of the lithological description was given in Turkish. Therefore, the first step was to carefully translate it into English. Then, the vast array of different lithological descriptive terms (about 624 of them) used by the drillers to describe the materials encountered during drilling activities are regrouped in a hierarchical manner into four broader sub-groups by combining closer lithology. This grouping was necessary to facilitate the entry of lithological information into Groundwater Modeling System (GMS) software for the purpose of processing this information to develop a 3-D visual representation of the aquifer material distribution through determining the thickness; the top and bottom elevations. The first grouping was based on the relative dominance of materials in the lithological description; for example, a description such as *sandy gravel with little silt* was combined into a group of materials called *sandy gravel* since the amount of silt in the composition is insignificant. The first groupings reduced the initial total number of lithological material description from 624 to 122 different group of materials. Using a similar approach, again based on the dominance of materials, (for example, lithological description with *sandy gravel* regrouped into lithological description *gravel*), the 122 materials are regrouped into 2nd grouping material categories with 20 different materials as listed in Table 3.1**.** The 624 lithological descriptions falling into the 20 regrouped materials are listed in Appendix B. Figure 3.13 gives the percentage distribution of the 20 materials in the 2nd grouping. The percentage of materials having water bearing and transmission characteristics such as gravel and sand is the highest in the study area.

Table 3.1 List of 2nd grouping materials

1	Top soil	6	Gravel and Silt	11	Clay	16	Siltstone
2	Alluvium	7	Sand and Silt	12	Sandstone	17	Limestone
3	Gravel	8	Sand and Clay	13	Conglomerate	18	Marl
4	Sand	9	Silt	14	Fanglomerate	19	Mudstone
5	Gravel and Sand	10	Silt and Clay	15	Calcarenite	20	Bedrock

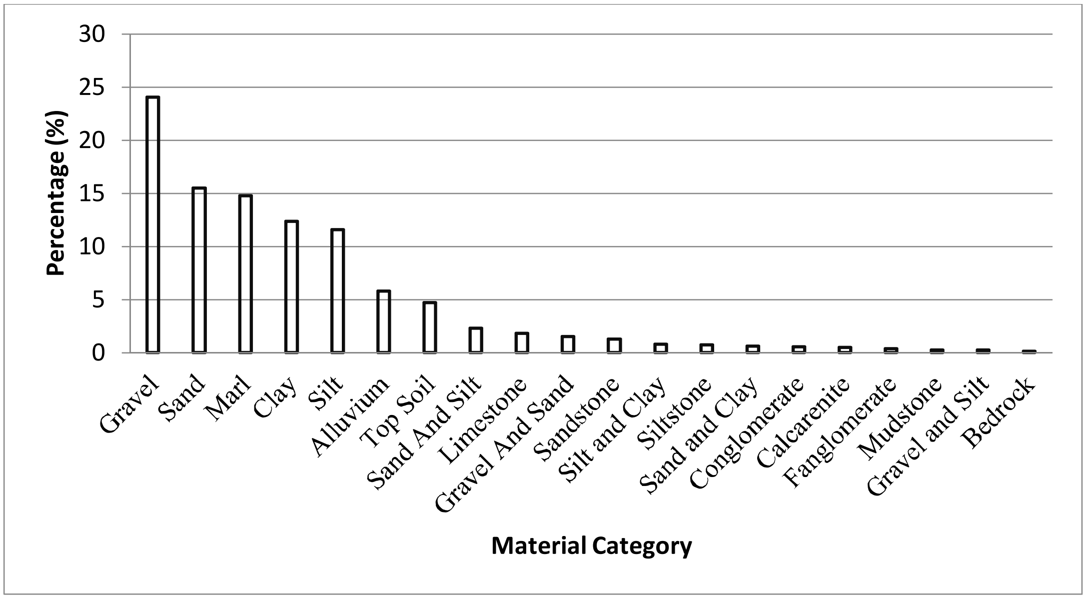

Figure 3.13 Percentage distribution of the 20 materials in 2nd grouping.

The material category names in GMS software are used to identify different materials in the subsurface. The GMS software allows defining hydro-stratigraphic units (HGUs) to group materials further into broader categories that may be used to construct or assign properties for modeling groundwater flow. To further facilitate the entry of borehole descriptions into the GMS software, the 2^{nd} grouping materials are regrouped into 3^{rd} grouping with 6 different material types and finally to 4^{th} grouping which consists of 4 basic hydrostratigraphic units as given in Table 3.2 and Table 3.3, respectively. Unconsolidated materials that can bear and transmit water, such as alluvial material, transition material and top soil from the 3^{rd} grouping are labeled as Primary Aquifer materials while consolidated aquifer materials are considered as Secondary Aquifer materials. Generally, the whole grouping is done using the following steps; for example, a description with sandy gravel with little silt → Sandy gravel → Gravel → Alluvial material → Primary Alluvial aquifer. The distribution of 3^{rd} and 4^{th} grouping materials is shown in Figure 3.14 and Figure 3.15. From the final grouping in Figure 3.14, we can see that an alluvial material, which has high water bearing and transmission characteristics, account for more than 45% of the total composition which is a good indicator of the existence of significant amount of materials with water bearing and transmission characteristics such as gravel and sand in the study area. Aquitard material, mainly composed of silt and clay, covers almost 25% of the area; however, it exists as localized lenses within the aquifer material. There is significant amount of marl dominated base material that underlies the alluvial material. Consolidated aquifer material, which is grouped into secondary aquifer and having relatively low water bearing and transmission characteristics, accounts for about 5% of the total materials found in the study area.

Table 3.2 List of 3rd grouping materials

No	3rd Grouping	2nd grouping
1	Top soil	• top soil
2	Alluvial material	• alluvium, gravel, sand, and gravel and sand
3	Transition material	• sand and silt, gravel and silt, and sand and clay
4	Aquitard material	• silt, clay, and silt and clay
5	Consolidated aquifer material	• limestone, Sandstone, Calcarenite, conglomerate and fanglomerate
6	Consolidated non-aquifer material	• marl, mudstone, siltstone, bedrock and pillow lava

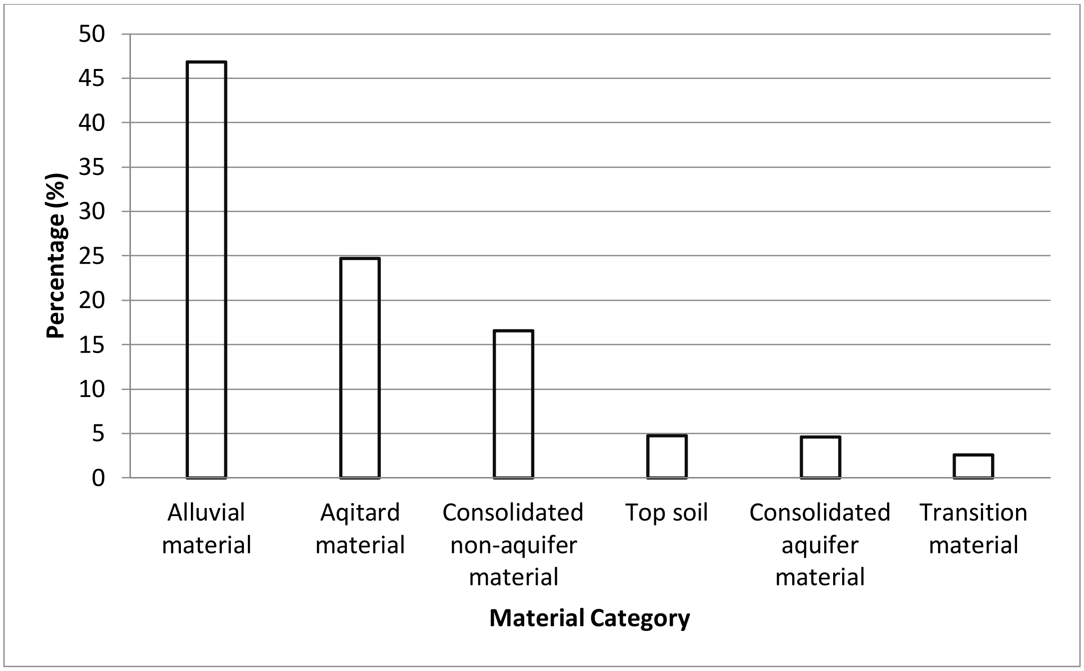

Figure 3.14 The 6 materials distribution in 3rd grouping

Table 3.3 List of 4th grouping materials

No	4th grouping	3rd grouping
1	Primary Alluvial aquifer	• Alluvial material, • Transition material • Top soil
2	Aquitard	• Aquitard material
3	Secondary aquifer	• Consolidated aquifer material
4	Base material	Consolidated non-aquifer material

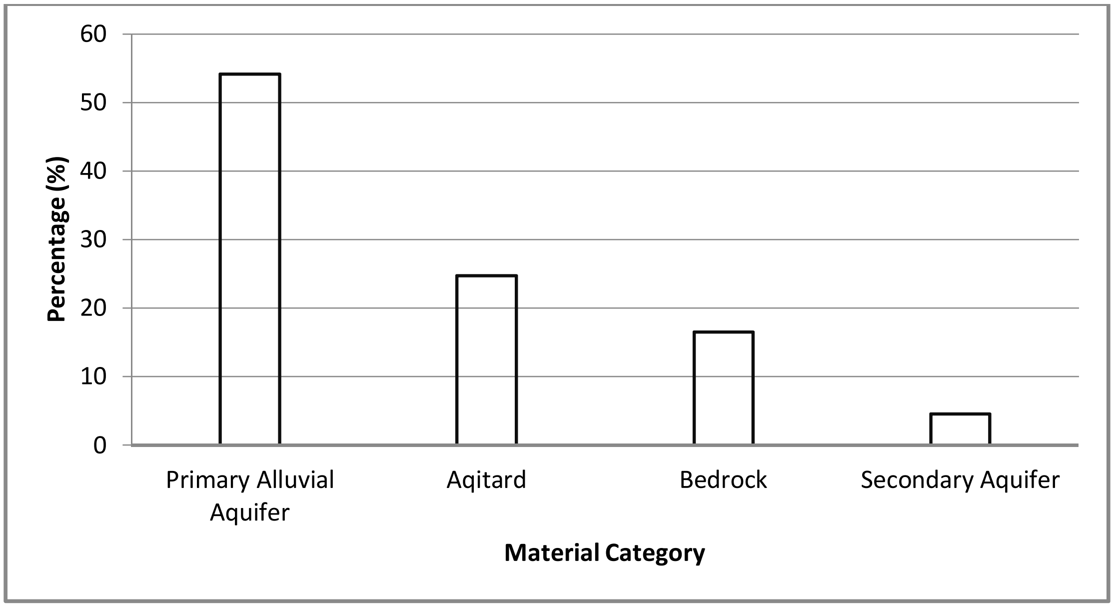

Figure 3.15 The 4 materials distribution in 4th grouping

After cross-checking the locations (x and y coordinates) and elevations of boreholes with geological field experts as part of the analysis, the data from 73 well logs were entered into the Borehole Module of Groundwater Modeling System (GMS) software (Aquaveo, Provo, Ut) to develop 3-D block diagrams and subsurface cross-sections of the Güzelyurt Aquifer. First, the boreholes are entered with their Serial identification number in Section A of Figure 3.16 and the coordinates are recorded in the X and Y boxes. In Section B, the elevations of the boreholes above sea level are entered first and then based on the thickness or depth of subsurface material, the elevation is entered downward in a decreasing manner. Next, the 20 grouped borehole log descriptions in the second grouping are routinely entered into GMS borehole module in soil column ID (Section D), while the regrouped four stratigraphic units in the fourth grouping are typed into HGU ID (Section C) as shown in Figure 3.16. Once all the above steps are carried out, the Horizon Id in Section D is automatically created. The term "horizon" refers to the top of each stratigraphic unit that will be represented in a corresponding Solid diagram. Horizons are numbered consecutively in the order that the strata are deposited (from the bottom up).

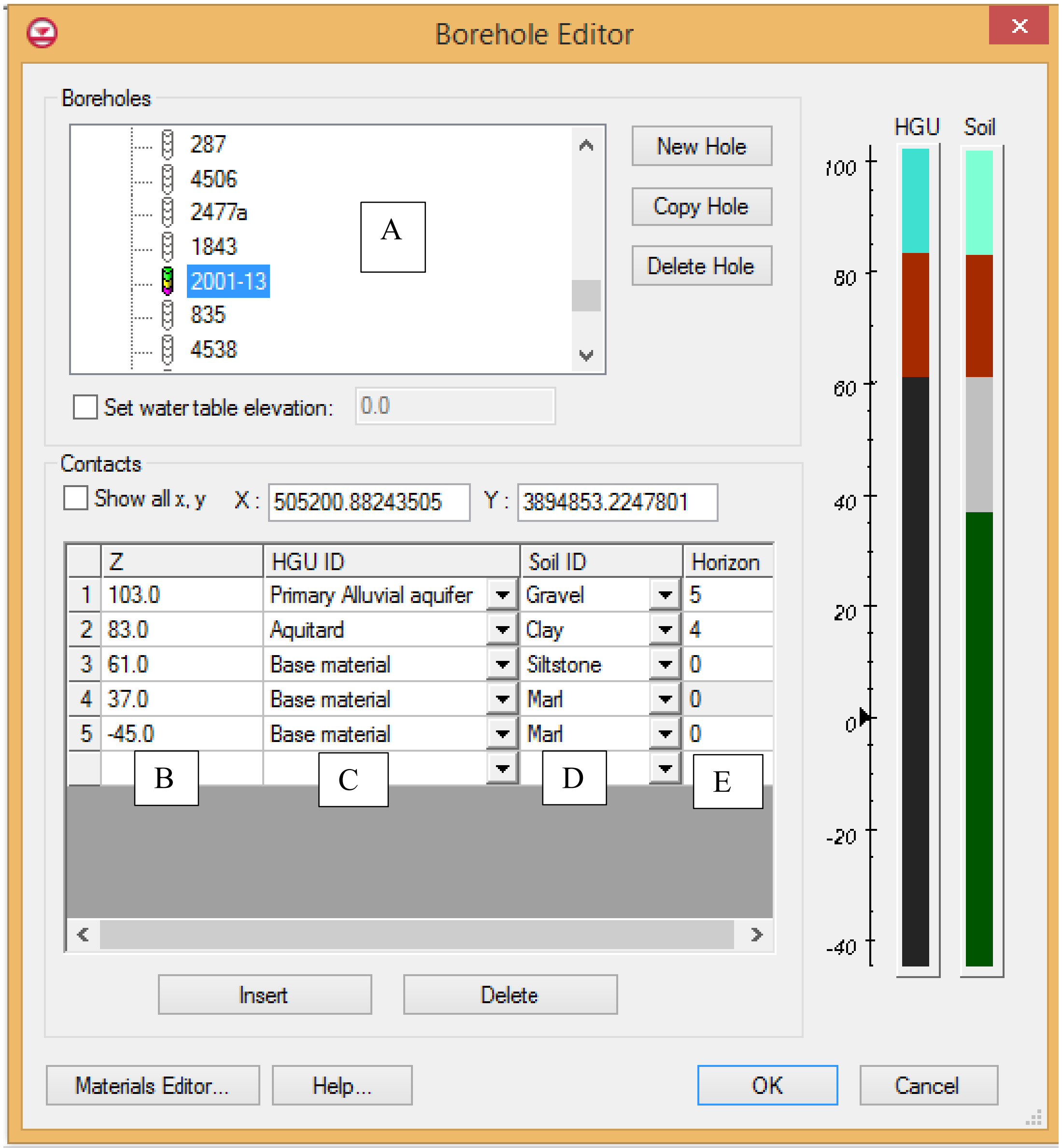

Figure 3.16 Well log data entry and HGU coding.

Having entered the 73 boreholes with their coordinates, the spatial distribution of boreholes can be created. We can see from Figure 3.17 that the spatial distribution of the boreholes is not uniform across the study area; rather it is concentrated in the central part of the study area. Since the boreholes on the coastal side have either shallow or poor lithological description, we installed 10 imaginary boreholes with the help of Geological field experts working in the study area and by interpolating from the boreholes in the surrounding. Figure 3.18 shows the location of the interpolated 10 imaginary boreholes, namely Duplicate-1, Duplicate-2, Duplicate-3, Duplicate-4, Duplicate-5, Duplicate-6, Duplicate-7, Duplicate-8, Duplicate-9, and Duplicate-10. With the exception of Duplicate-9 and Duplicate-10, the surface materials are taken as alluvial material from the hydrogeological map as they are located near the coast. For the rest the two boreholes, it is interpolated from the nearby boreholes.

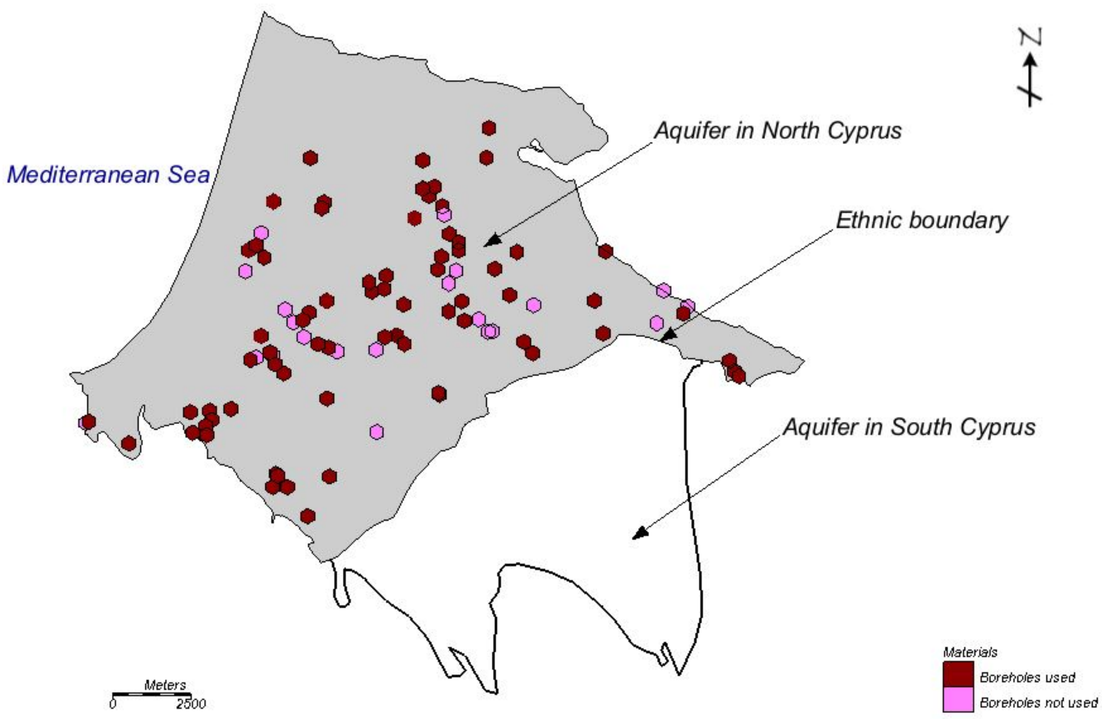

Figure 3.17 The areal distribution of 92 available wells with 73 used boreholes (red) and 19 unused boreholes (pink) generated by using Groundwater Modeling System (GMS).

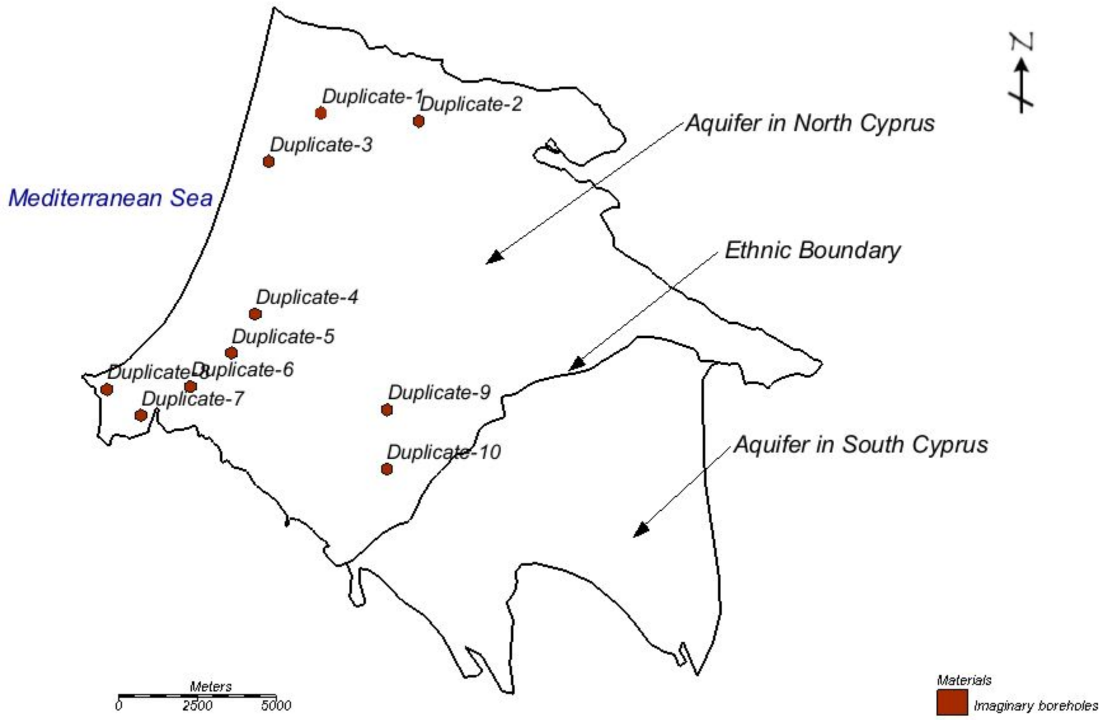

Figure 3.18 The location of newly installed imaginary boreholes.

In order to determine the distribution of aquifer material thickness, seven cross-sectional transacts are defined as shown in Figure 3.19**.** These transacts are drawn along a line with dense or continuous boreholes. In addition, for each transect defined in Figure 3.19, a borehole chart is drawn to scale using Excel for the purpose of visualizing the thickness wise distribution of the boreholes near or on the transact as shown in Appendix C. The charts are also used to interpolate materials of some boreholes, which are not drilled deep enough to reach the base material, from the nearby boreholes on the transact. After careful interpolation of some ambiguous boreholes using the material information from nearby boreholes, the areal distribution of aquifer material thickness is determined.

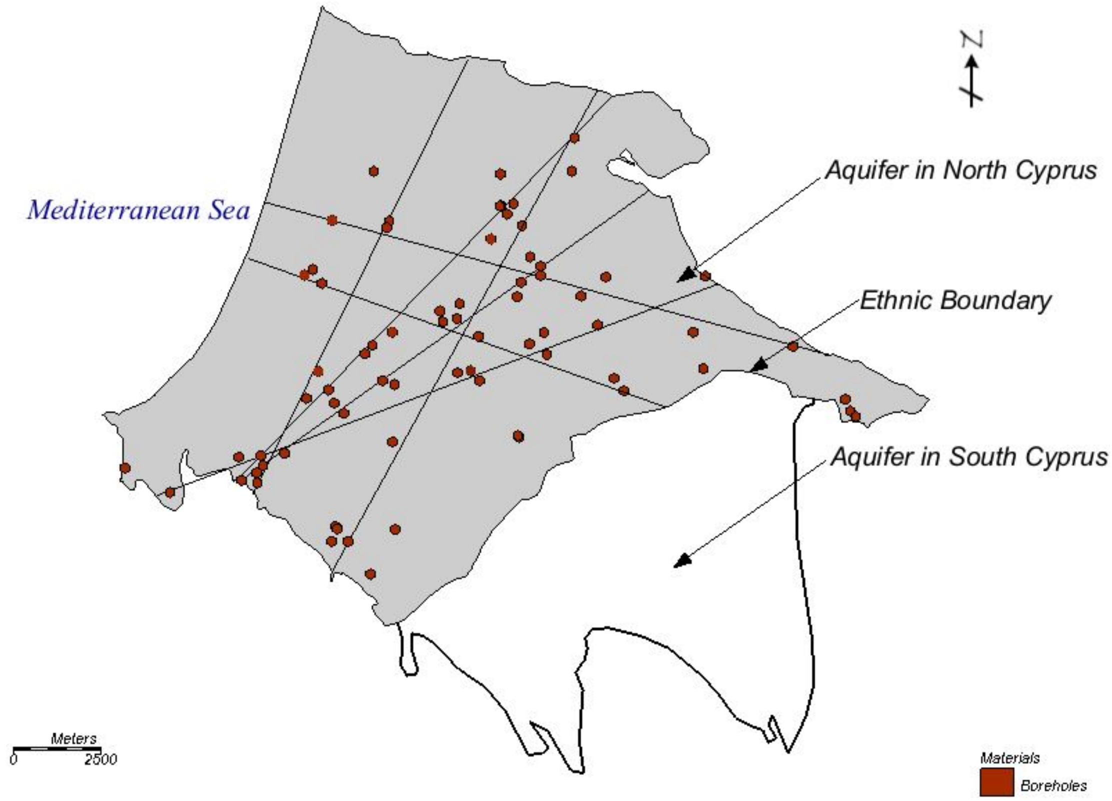

Figure 3.19 The seven transacts and the corresponding boreholes used to determine the areal distribution of aquifer material thickness.

By using the Borehole Module of GMS, a solid block diagram was generated from the detailed borehole data and the TIN surface mesh using the "Horizons" method developed for GMS. A series of cross-sections were cut to visualize the thickness distribution of the aquifer material along the seven transacts as shown in Error! Reference source not found.. Aquitard material mainly composed of silt and clay exists as lenses in the alluvial aquifer material. The continuity of aquitard materials at some specific locations is demonstrated more in detail in **Error! Reference source not found.** through further cross-sections. The coastal area and the northeastern part of the aquifer have a thin, somewhat continuous silt and clay materials. The qualitative thickness and continuity of alluvial aquifer material and the localized discontinuous aquitard lenses can be seen from the figure. However, the quantitative aquifer material thickness is calculated by using an excel sheet and presented as shown in Table 3.4. The alluvial aquifer material thickness is calculated by subtracting the bottom elevation from the top elevation of sand and gravel (Top-Bot1). Deeper alluvial aquifer material (i.e., located below silt and clay lenses) and Aquitard exist in some boreholes. Aquitard thickness = the bottom elevation of alluvial aquifer material – the bottom elevation of aquitard whereas the Deeper alluvial aquifer material = the bottom elevation of aquitard - bottom elevation of deeper alluvial aquifer material. The top elevation of base material can be the bottom elevation of alluvial aquifer material (for boreholes with no aquitard) / the bottom elevation of aquitard (for boreholes with aquitard and without deeper alluvial aquifer material) / the bottom elevation of deeper alluvial aquifer material. Finally, the total aquifer material thickness is calculates as the sum of all material thickneses above the top elevation of base material.

The alluvial material extendes beyond the low conductivitiy material composed mainly of marl, and thick silt and clay layers. It has been excluded from the study, otherwise, alluvial material exists as localized lense within the dens thick silt and clay dominated area, exhibiting perched aquifers lying on base material composed of marl, mudstone, bedrock and pillowlava.

Table 3.4 A sample showing the calculation of Aquifer material thickness and saturated thickness of the Aquifer, where Top: top elevation of Alluvial aquifer material , Bot1: bottom elevation of Alluvial aquifer material, Bot2: bottom elevation of Aquitard , Bot3: top elevation of deeper Alluvial aquifer material, Bot4: top elevation of base material, and Bot5: bottom elevation of base material.

A	K	L	M	N	O	P	Q	R	S	T	U	V	W
								K-L	L-M	M-N	L , M or N-P	R+S+T	Q-O
Borehole ID No.	**Top (m)**	**Bot1 (m)**	**Bot2 (m)**	**Bot3 (m)**	**Bot4 (m)**	**Bot5 (m)**	**Water level elevation (m)**	**Alluvial aquifer material thickness-1 (m)**	**Aquitard thickness (m)**	**Alluvial aquifer material thickness-2 (m)**	**Base material thickness (m)**	**Total aquifer material thickness (m)**	**Saturated thickness (m)**
5070	54	-16			-16	-24	-6	**70**			**8**	**70**	**10**
578	27	1	-30	-35	-35	-80	-21	**26**	**31**	**5**	**45**	**62**	**14**
4541	62	1	-25		-25	-47	15	**61**	**26**		**22**	**87**	**40**
5036	13	-21			-21	-29	-6	**34**			**8**	**34**	**15**
4516	66	21	9	-1	-1	-38	15	**45**	**12**	**10**	**37**	**67**	**16**
2008/16	48	-17			-17	-58	-1	**65**			**41**	**65**	**16**
laleland-1	60	49	32	-12	-12	-29	7	**11**	**17**	**44**	**17**	**72**	**19**
1997/2	59	20	9	6	6	-29	25	**39**	**11**	**3**	**35**	**53**	**19**
2009/20	125	37			37	-12	56	**88**			**49**	**88**	**19**
2010/05	77	7	-33	-37	37	-91	-18	**70**	**40**	**4**	**54**	**114**	**0**
5027	11	-27			-27	-30	-6	**38**			**3**	**38**	**21**
2477a	59	-37			-37	-91	-16	**96**			**54**	**96**	**22**
589	67	20	0	-11	-11	-47	12	**47**	**20**	**11**	**36**	**78**	**23**
5240	66	-11	-27		-27	-47	15	**77**	**16**		**20**	**93**	**42**
5104	36	-33			-33	-85	-6	**69**			**52**	**69**	**27**
2400	42	-37	-49	-62	-62	-63	-34	**79**		**13**	**1**	**92**	**28**
1843	14	-30			-30	-71	-1	**44**			**41**	**44**	**29**
2011/06	82	-1	-19		-19	-49	30	**83**	**18**		**30**	**101**	**49**

3.4. Groundwater Level Data Analysis

In order to determine the saturated thickness of the aquifer and direction of groundwater flow, groundwater level data obtained from the Geology and Mining Department of North Cyprus has been analyzed. The measurements are made at least twice a year in December to represent the end of the dry season, and in March, April or May to represent the end of the wet season. The measurements were given as a depth from the surface; therefore, the first step was to subtract the depth to water from the surface elevation of the well to find the groundwater elevation. The total number of wells used for measurements is 210; however, the average number of water level measurement taken per year is about 65. The coordinates of all the available groundwater level measurement wells were processed using Groundwater Modelling System (GMS) software and their areal distribution is shown in Figure 3.20. The measurements are mainly carried out in the central part of the study area with almost no measurement data points exist near the Güzelyurt District of Taşpınar.

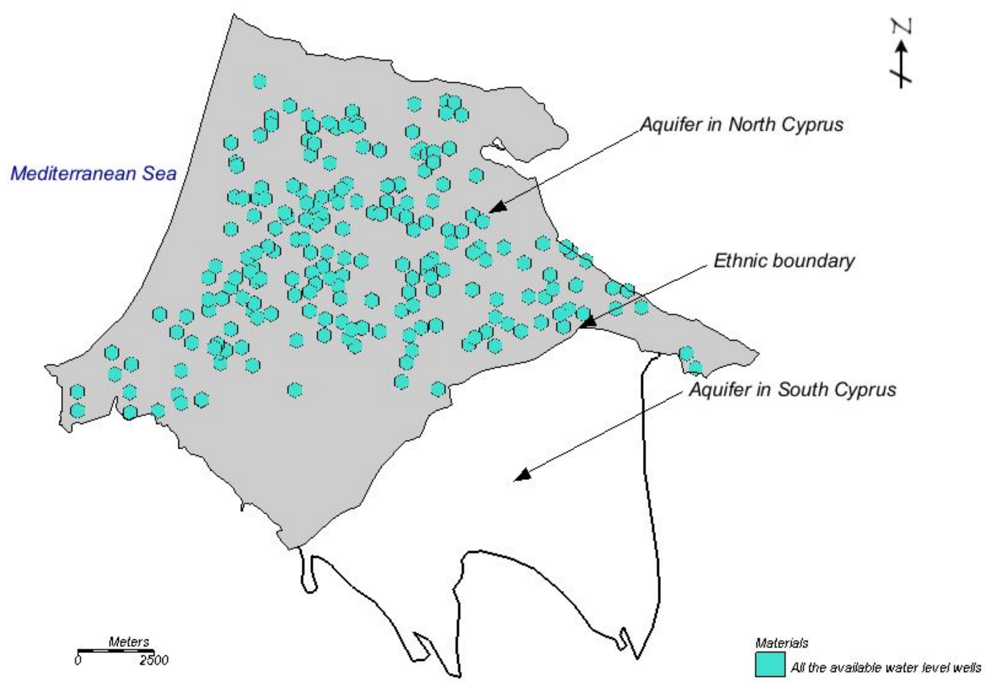

Figure 3.20 The areal distribution of 210 groundwater level measurement wells

The groundwater level measurement data of the last five years have been organized as wet and dry season. However, there were no groundwater level measurement well screen data in the database posing difficulties in identifying whether the water level measurement was carried out from the top or deeper aquifer. Due to this reason, the water level elevation measurement wells are filtered based on the condition that their bottom elevation has to be above the bottom elevation of aquifer material of the nearest borehole. Seasonal contour maps of the filtered water level dataset are formed using ArcMap to show the affected areas due to excessive withdrawal of groundwater. In addition, the distribution of the saturated thickness of the Güzelyurt Aquifer is formed using GMS software. The saturated thickness of the aquifer is quantitatively calculated by subtracting the bottom elevation of aquifer material from groundwater elevation as shown in Table 3.4.

3.5. Water Quality Data Analysis

For salt-water intrusion assessment in Güzelyurt Aquifer, Chloride content (Cl) measurements have been analyzed. To see the annual change in the quality of the groundwater, the water quality data collected in the months of only dry seasons during 2010 through 2013 has been used. The areal distribution of the available water quality wells is shown in Figure 3.21; almost no water quality measurement taken at the periphery of the aquifer in 2013. The encroachment of seawater into the aquifer due to continuous withdrawal of groundwater for municipal and irrigation water supply purpose has been analyzed by the contour maps, formed by using 67 measurement points that are continuously monitored from 2010 through 2013.

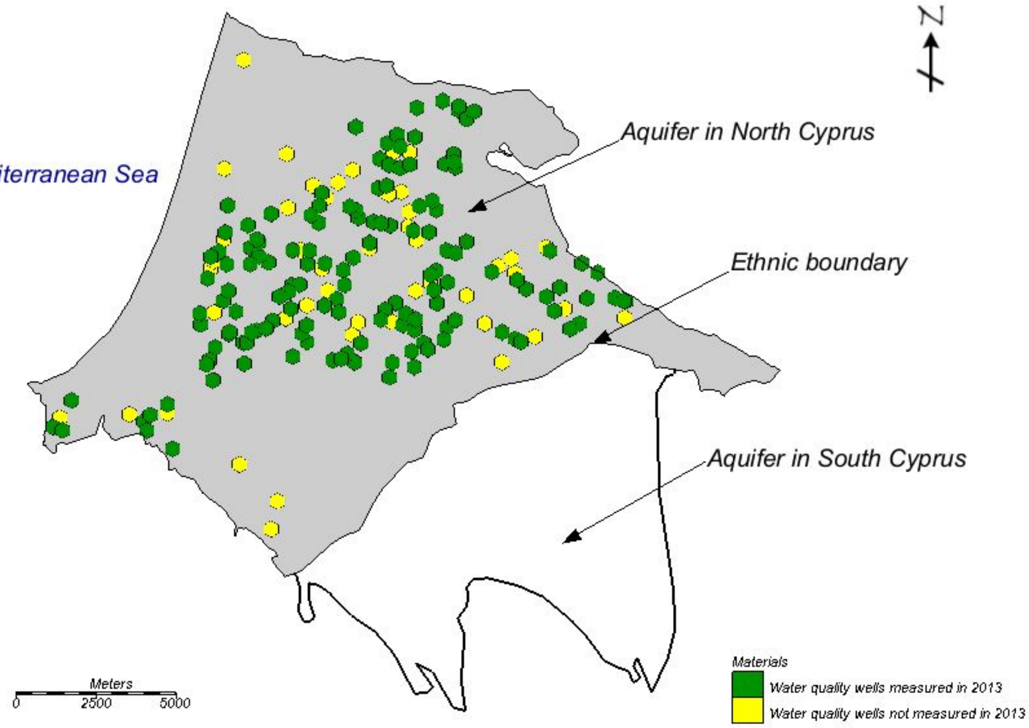

Figure 3.21 The areal distribution of all the available water quality measuremnt wells 144 water quality wells measured in 2013 and 193 water quality wells not measurement in 2013 in the study area.

CHAPTER 4

RESULTS AND DISCUSSION

For development of groundwater conceptual model for Güzelyurt Aquifer, first, all the available data were collected and analyzed as discussed in Chapter 3. Then, using the analyzed data, the proposed method of conceptual model development in Section 2.3 was implemented.

4.1. Description of Hydrogeological Setting

The physical boundaries of the Güzelyurt Aquifer are delineated as shown in Figure 4.1. The 1103 km^2 of catchment area is divided into two by topographic high points in the southwest of the study area. Therefore, there are two independent catchments identified in the study area with water flowing through dendritic networks of ephemeral or seasonal drainage streams originating from Troodos Mountains in the south and Beşparmak Mountains in the north of the study area. Lefke-Güzelyurt derivation canal constricted in the region helps to intercepts the surface runoff flowing directly into the Mediterranean Sea by facilitating groundwater recharge. The surface runoff from the bigger catchment area (880 km^2) is either intercepted by the Lefke-Güzelyurt derivation canal or flows into the Mediterranean Sea. The smaller catchment, which has an area of 223 km^2, is separated by topographic boundary from Güzelyurt Aquifer and treated as a hydrologically independent basin.

There are a number of geological materials within the catchment area of Güzelyurt Aquifer, which can be grouped into alluvial aquifer material, consolidated aquifer material and impermeable base material. Having highest water bearing and transmission capacity, hydrogeological formations composed of sand and gravel are composing the Güzelyurt Aquifer. Consolidated materials, such as sandstone and calcarenite are forming other aquifer formations adjacent to the Güzelyurt Aquifer boundary within the catchment area. Having moderate water bearing and transmission characteristics, consolidated materials exhibit hydraulic interactions with the adjacent Güzelyurt Aquifer. Hydrogeological formations of impermeable base materials mainly exist in higher altitudes, especially towards the Troodos Mountains and Beşparmak Mountains contributing the recharge of Güzelyurt Aquifer through runoff generation.

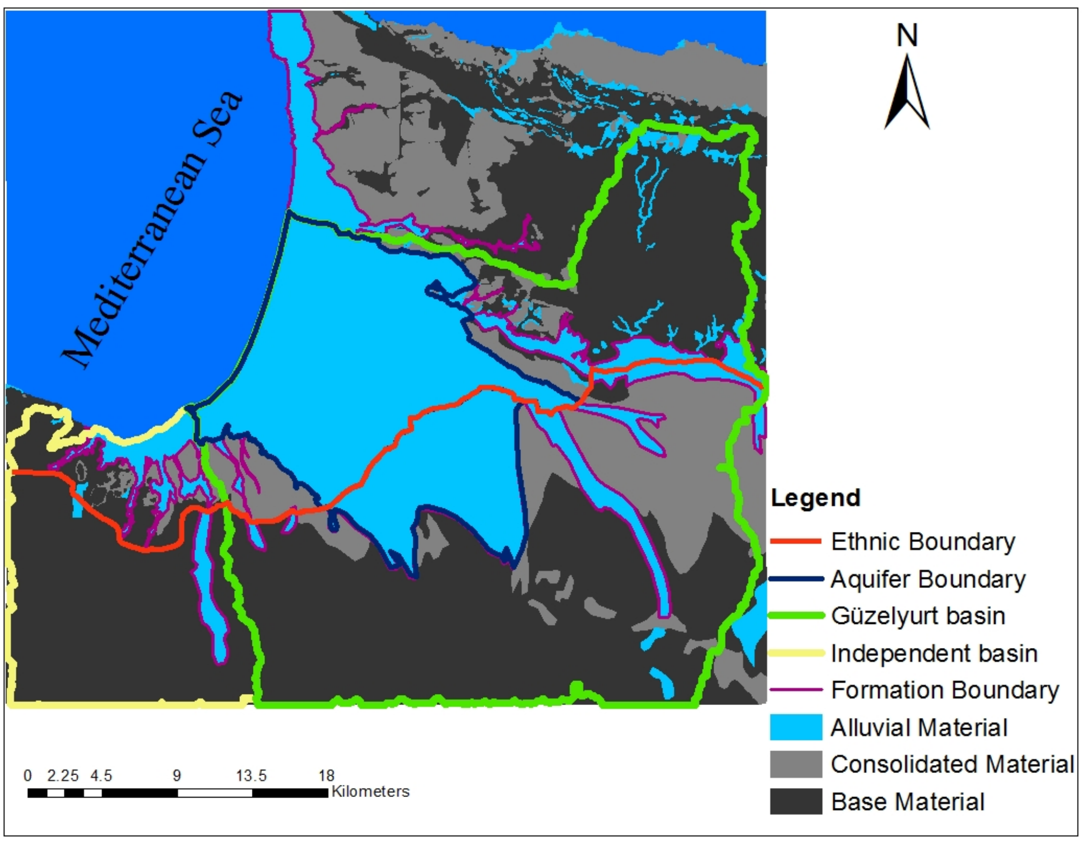

Figure 4.1 Güzelyurt Aquifer's physical boundaries.

The total areal extent of Güzelyurt Aquifer is 253 km^2, of which 180 km^2 lies in the North Cyprus while the rest 73 km^2 lies in the South Cyprus, which is divided by the ethnic boundary. Stratigraphic units of the aquifer are studied only for the part lying in North Cyprus because of lack of borehole data for the aquifer in South Cyprus.

Güzelyurt Aquifer is an unconfined aquifer and in direct contact with the Mediterranean Sea. It is mainly composed of gravel and sand with discontinuous silt and clay lenses, showing abrupt vertical and lateral variation. The aquifer rests on an impervious base formed by gently undulating marl, mudstone, and pillow lava. The alluvial material thickness of Güzelyurt Aquifer exhibits great spatial variation. The average thickness of aquifer material is 87 m; ranging from 21 m around Taşpınar, located at the southeast periphery, to 155 m towards the central part of the study area. As shown in Figure 4.3, the coastal area has fair thickness with uniform distribution of the aquifer material. Out of a total 18.66 km^3 of alluvial aquifer material, 13.87 km^3 (74%) is made up of sand and gravel while silt and clay lenses account for 4.79 km^3 (26%) of aquifer material in the study area as shown by transacts in Figure 4.2. The occurrence of silt and clay lenses within dominant sand and gravel material created heterogeneity in the aquifer. Such zones are called heterogeneous zones of the aquifer with low hydraulic conductivity.

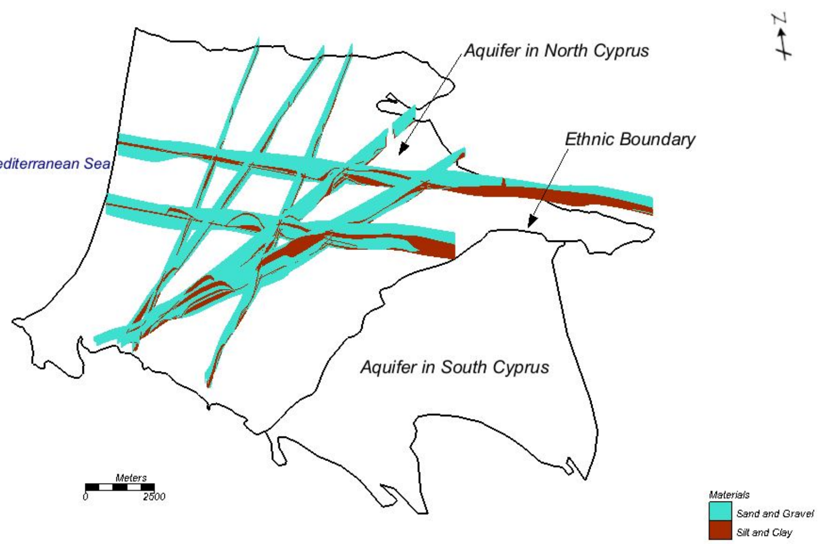

Figure 4.2 The cross-section of subsurface material showing aquifer material thickness in the study area

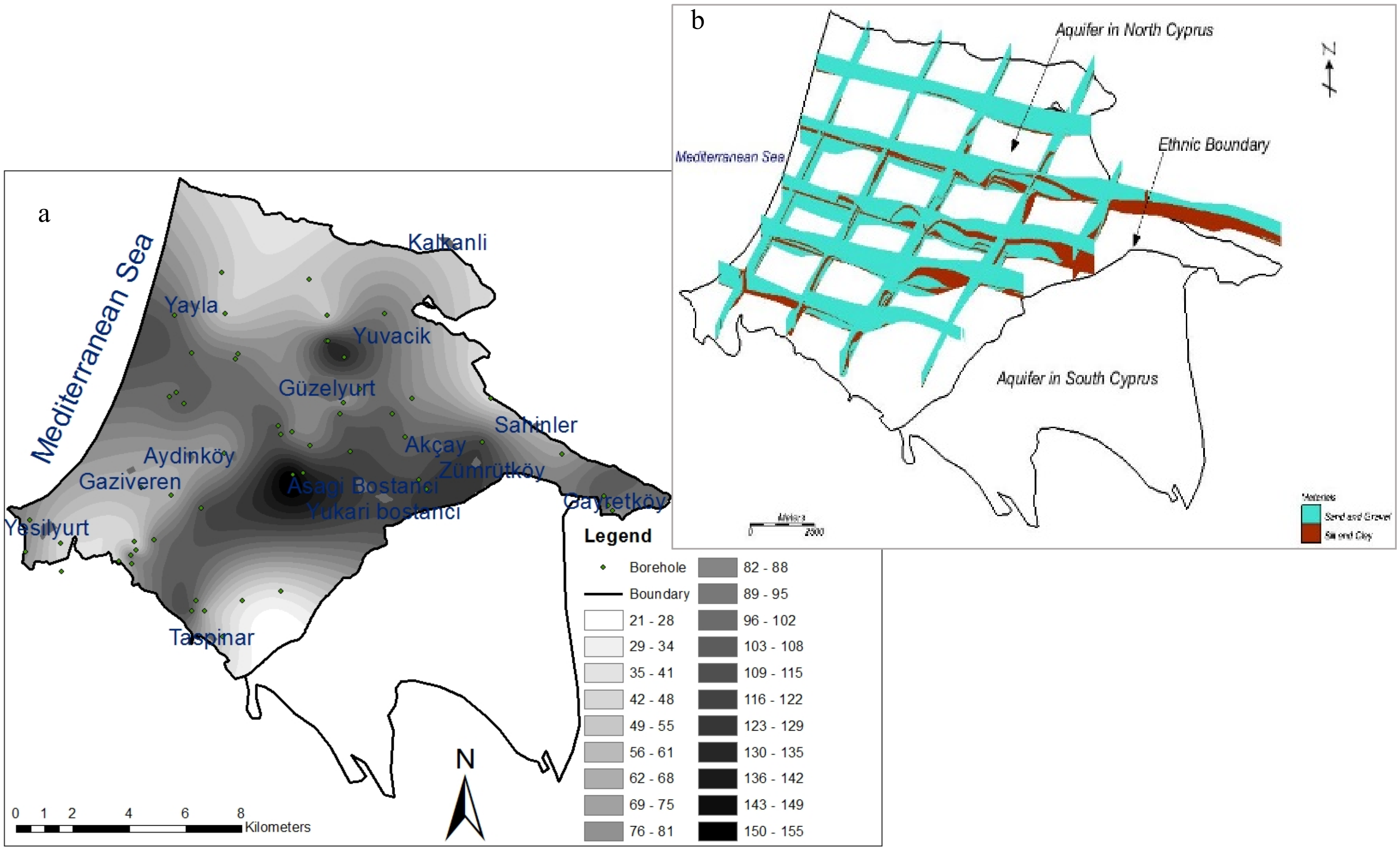

Figure 4.3 The aquifer material thickness distribution (a) and the cross-section of subsurface material showing aquifer material thickness (b) in the study area.

From the contour map generated by using the water level data, presented in Figure 4.4, the areas affected by continuous withdrawal groundwater have been delineated. The zero contour line in the wet season of 2013 passes through the center of Güzelyurt city and it is 8.6 km away from the coast whereas in dry season it passes between the two towns: Aşağı Bostancı and Yukarı Bostancı, which is about 9.8 km away from the coast of Güzelyurt. Out of the total 180 km^2 area of the aquifer, the water level elevation of about 67.5 km^2 area lies below the zero contour line or below mean sea level in the wet season of 2013. This area increased to 85.8 km^2 during the dry season of 2013. The worst affected area with less than (-40 m) below sea level is 5.5 km away from Güzelyurt city during wet season, however, it gets closer to the city in dry season with only 1.5 km away from the city. The three towns: Gaziveren, Aydinköy and Guneskoy are severely affected in both wet and dry season.

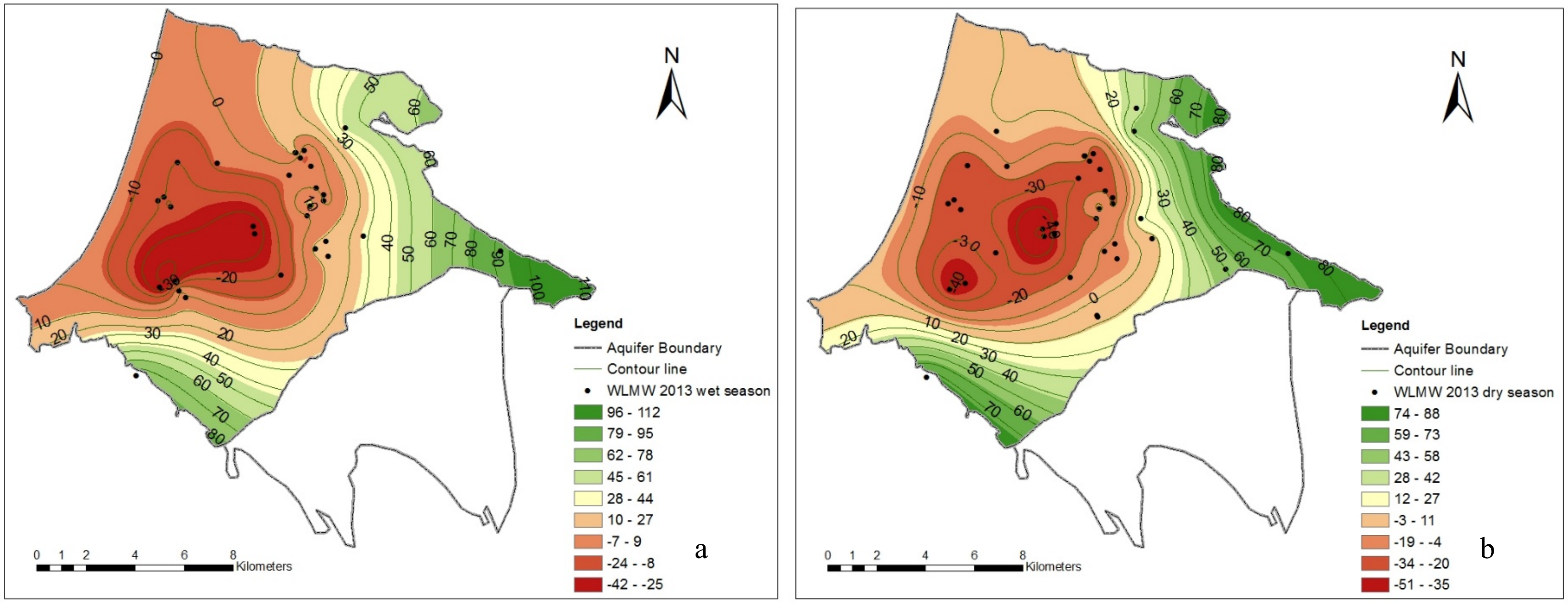

Figure 4.4 Groundwater level elevation contour maps for 2013. (a) for wet season, (b) for dry season.

The continuous withdrawal of groundwater and little amount of recharge, which also occurs only during wet season, have made the aquifer to be desaturated. By using the 2013 wet season groundwater level data, the saturated aquifer volume has been calculated from the solid map formed using GMS software as shown in Figure 4.5. From the total volume of alluvial aquifer material, only 3.73 km^3 (29%) is occupied by water and the percentage goes further down during dry season.

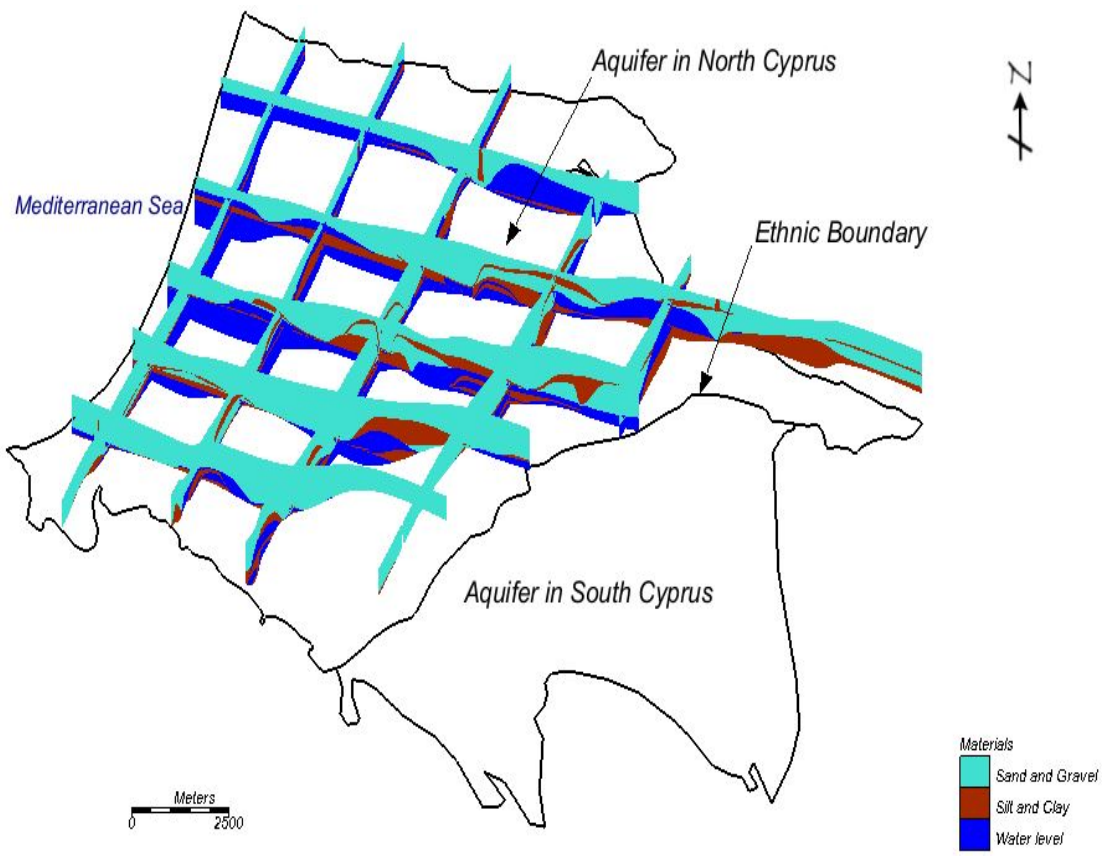

Figure 4.5 Saturated thickness of the aquifer generated using GMS for wet season water level data of 2013.

Seawater intrusion has been analyzed using the chloride data. As shown in Figure 4.6, having displayed a decrease from 2010 to 2011, the chloride content linearly increased from 2011 through 2013. The minimum amount of chloride content in the whole aquifer is 36 mg/L. This value is measured in a monitoring well in 2012 that is about a kilometer away towards east of Güzelyurt city. On the other hand, the maximum amount of chloride content (3018 mg/L in 2010) is measured in the western part of the study area, Kumköy, where there is a continuous withdrawal of groundwater for municipal water supply.

In drinking water, the salty taste produced by chloride depends upon the concentration of the chloride ion. Based on Environmental Protection Authority (EPA), water containing 250 mg/L of chloride may have a detectable salty taste. Therefore, by using the contour maps in Figure 4.7 and Figure 4.8, the areas with chloride content above 250 mg/L have been calculated. From the total aquifer area (180 km^2) about 94 km^2 in 2010, 98 km^2 in 2011, 96 km^2 in 2012 and 95 km^2 in 2013 have above 250 mg/L chloride content. The most affected place is on the west of Güzelyurt city where the pumping station is actively working for municipal water supply of the country. From the precipitation data in hand, we can say that the increase in the seawater contaminated area from 2010 to 2011 is because of the decrease in the average precipitation from 428 mm to 244 mm, respectively. In addition, although the contaminated area decreased from 2012 through 2013, from the water level measurement data, the subsequent increase in the chloride content is the result of continuous withdrawal of groundwater peaking in the groundwater exploited region.

In addition to impact due to the saltwater intrusion, there are also stresses on the aquıfer due to agricultural citrus plantation through pesticide and fertilizer leaching. Leakage from an online septic tank application, under which the unconfined Güzelyurt Aquifer seats, is another source of contamination in the study area.

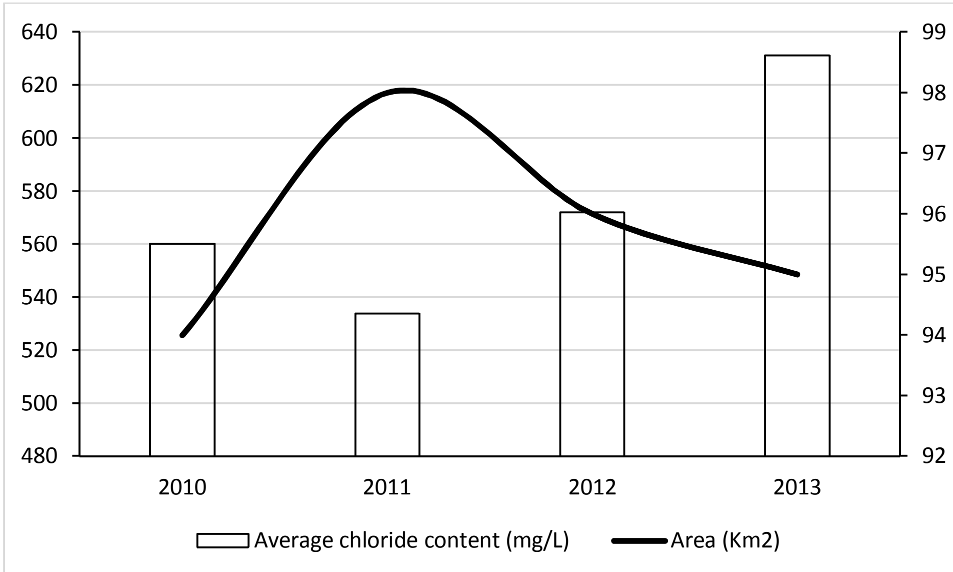

Figure 4.6 Average chloride concentration in mg/L from 2010 through 2013.

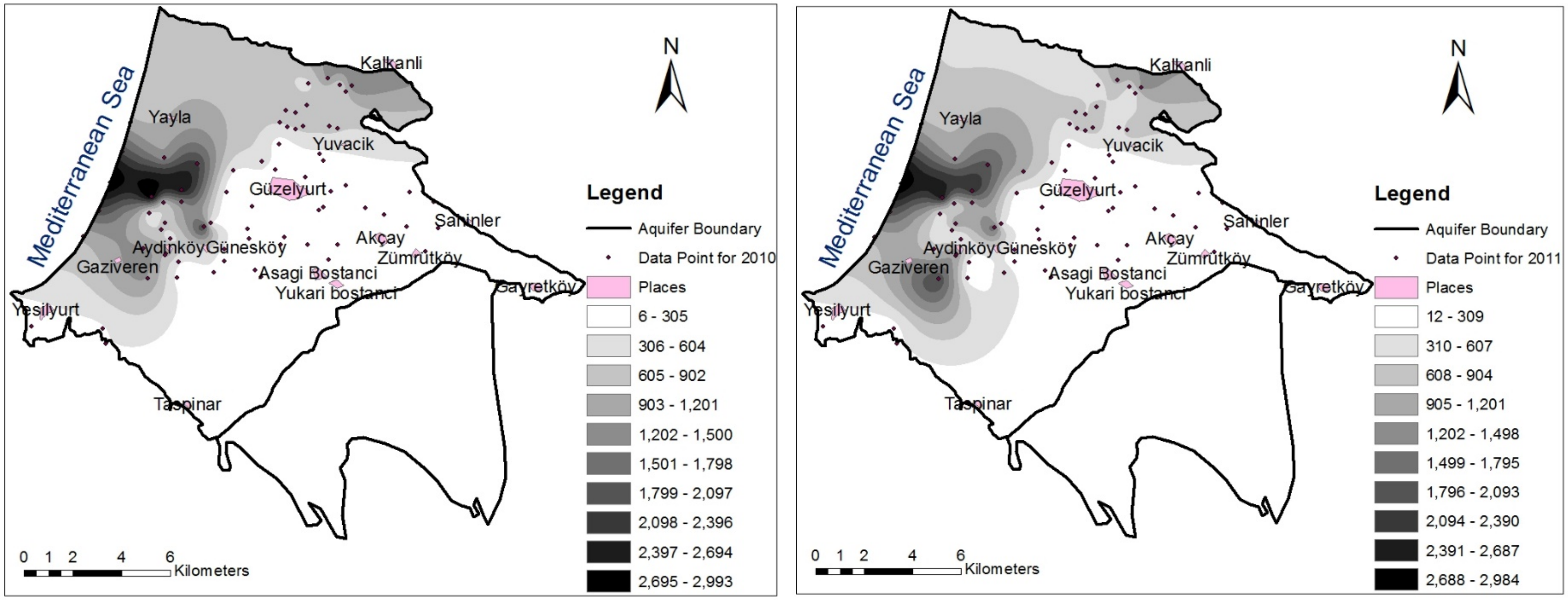

Figure 4.7 A map showing the chloride concentration for 2010 (left) and 2011 (right) in the study area.

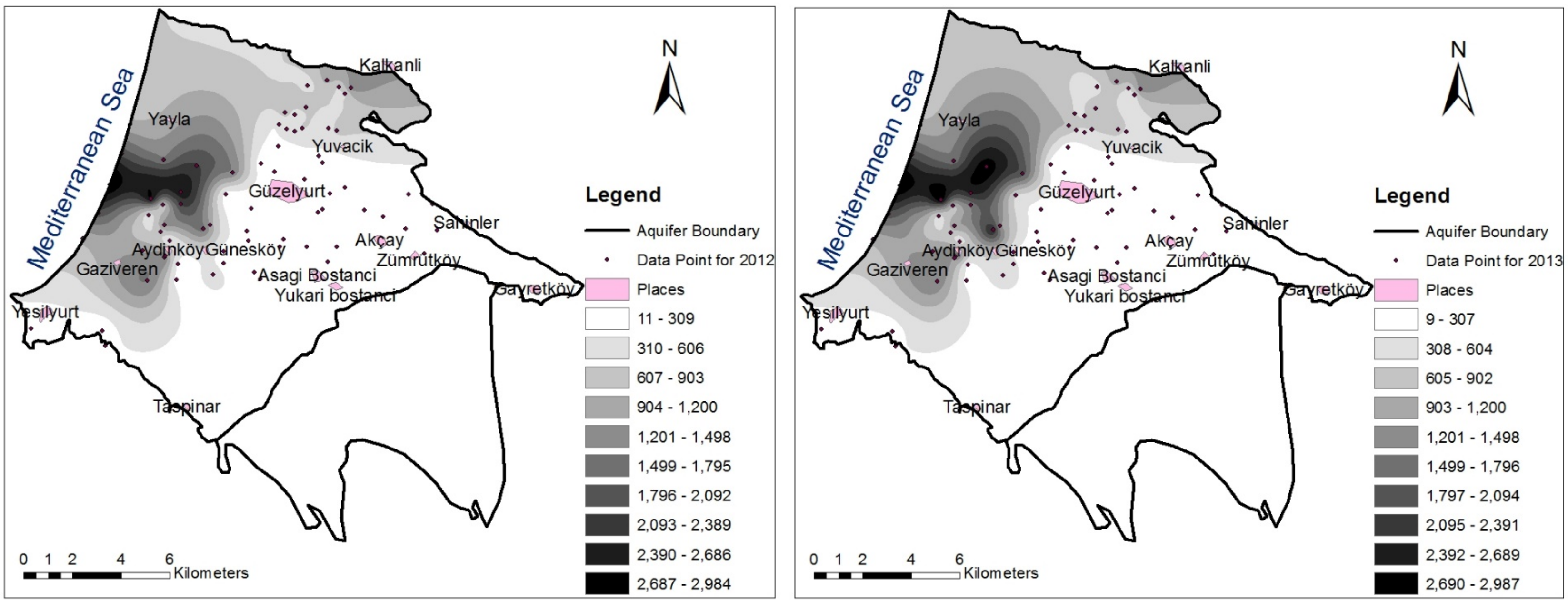

Figure 4.8 A map showing the chloride concentration for 2012 (left) and 2013 (right) in the study area.

The boundaries of Güzelyurt Aquifer within the major catchment area are identified by overlaying the formation boundaries on the topographic boundary. The formation boundary that lies within the topographic boundary is delineated as Güzelyurt Aquifer boundary. As shown in Figure 4.9, Güzelyurt Aquifer as a whole, including the part lying in the South Cyprus, can be conceptualized as a single layer, relatively homogeneous isotropic unconfined aquifer with five well-defined physical and hydraulic boundaries of the flow field:

1. Equipotential boundary along the contact of with Mediterranean Sea. This boundary is about 14 km long along the contact line with the Mediterranean Sea on the western part of the study area.
2. Lateral flow boundary between alluvial (gravel and sand) and consolidated material (sandstone, calcarenite, conglomerate and fanglomerate) aquifers. This boundary extends 26.2 km in the northern and 12.4 km in the southern part of the study area.
3. Impermeable lateral topographic boundary (i.e. groundwater divide) at northwest and southwest near the coastal area. The lengths of these boundaries are 5.1 km at the northwest and 2.8 km at the southwest of the study area.
4. Impermeable bottom boundary composed of base materials, such as marl, mudstone, siltstone, bedrock, pillow lava, and as well as thick silt and clay layers.
5. Water table boundary directly exposed to the surface in an unconfined aquifer. Güzelyurt Aquifer has seasonally fluctuating water table boundary, especially due to the withdrawal of ground water for municipal water supply and irrigation purposes.

Along with the above described boundaries, special attention need to be given to the ethnic boundary separating the north and south parts of the Güzelyurt Aquifer due to the lack of detailed hydrogeological and hydrologic information about the south part of the aquifer. Since the overall recharge contributions through the groundwater flow or recharge to the aquifer from the south is uncertain, ethnic boundary may also be treated a flow boundary for the purpose of numerical modeling purposes.

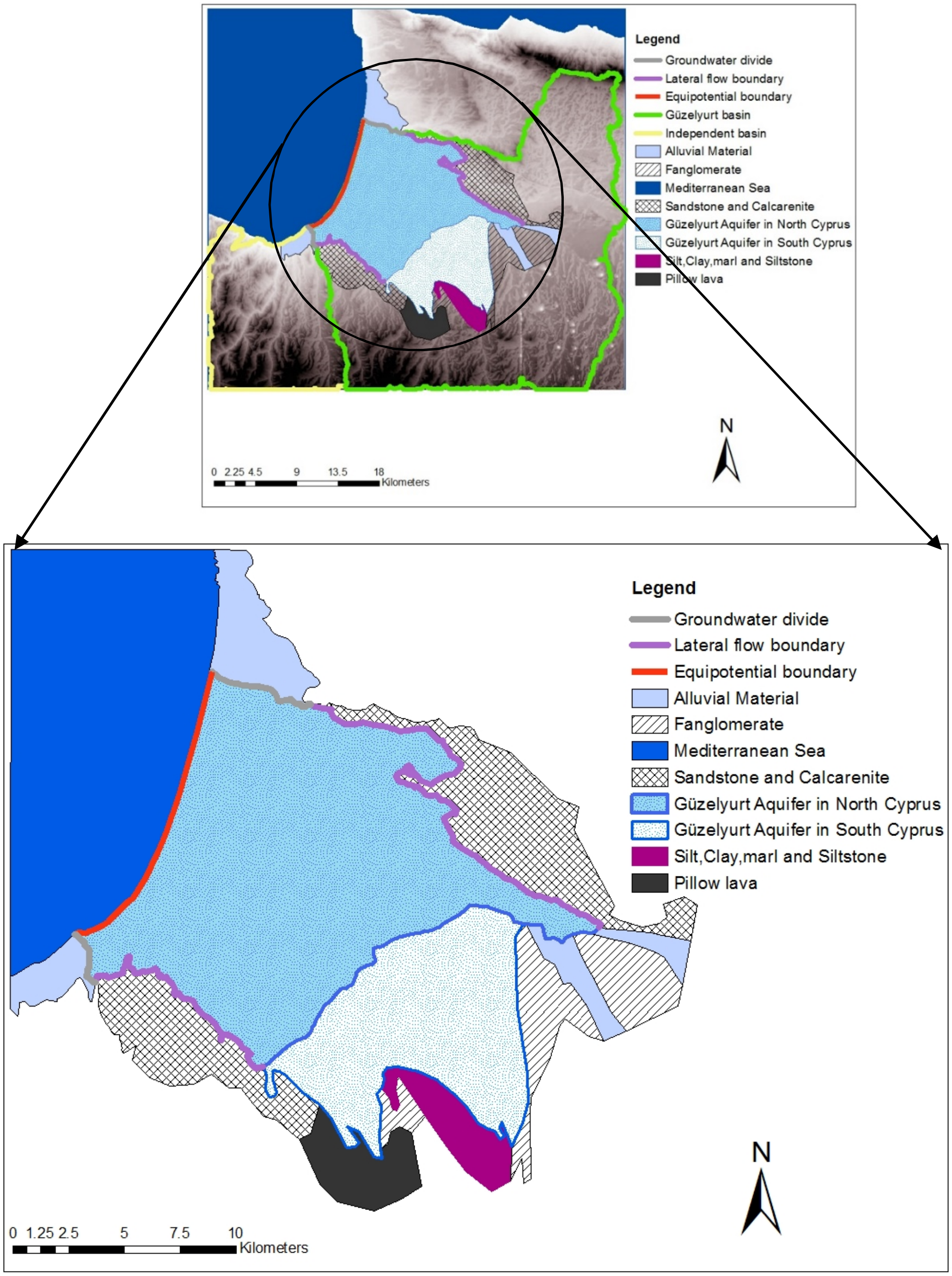

Figure 4.9 Güzelyurt Aquifer physical and hydraulic boundaries

4.2. Assessment of Groundwater Flow System

Groundwater recharge and discharge are important aspects in the analysis of groundwater flow system and water budget. The main sources of groundwater recharge of Güzelyurt Aquifer are the relatively water rich mountains of Troodos and Beşparmak. Recharge of Güzelyurt Aquifer usually occurs in the wet seasons of the year where the surface runoff flowing from the mountains into the Mediterranean Sea through different ephemeral creeks infiltrate into groundwater. In order to enhance groundwater recharge of the Güzelyurt Aquifer by increasing the residence time of the surface runoff, different drainage systems and storage structures, such as dams, reservoirs, ponds, and the Lefke-Güzelyurt derivation canal have been constructed. As shown in Figure 4.10, out of the six streams, three of them (Lefke stream, Çamlı stream and Çakıl stream) flows into the Lefke-Güzelyurt derivation canal through consolidated aquifer material while the rest three (Doğancı stream, Güzelyurt stream and Yuvacik stram) flows directly into alluvial aquifer material. Based on a hydrological study by DSI, it was assumed that 23% of the water in the watershed basin of these six streams is available for runoff and approximately 77% is consumed by evapotranspiration (DSI, 2004). Again out of the 23% of water flowing into the alluvial aquifer material through Doğanci, Güzelyurt and Yuvacik streams, only 25% infiltrates to recharge the groundwater. However, for Lefke, Çamlı and Çakıl steams, approximately 25% of the available 23% of the total precipitation infiltrates into secondary aquifer of consolidated material before reaching the derivation canal. Furthermore, out of the total water in the derivation canal, approximately 25% infiltrates into the aquifer and the rest is consumed by evapotranspiration. The water budget of Güzelyurt Aquifer is shown in Table 4.1.

Table 4.1 Recharge and discharge calculation.

No	Recharge 10^6 m^3/year		Discharge 10^6 m^3/year	
1	Rainfall	12.8	[a]Drinking water wells	9.5
2	Streams	17.4	[a]Irrigation water wells	51.7
3	Güzelyurt derivation canal	4.4		
4	South part	5.2		
	Total	**39.8**	**Total**	**61.2**

[a] Taken from DSI, 2004.

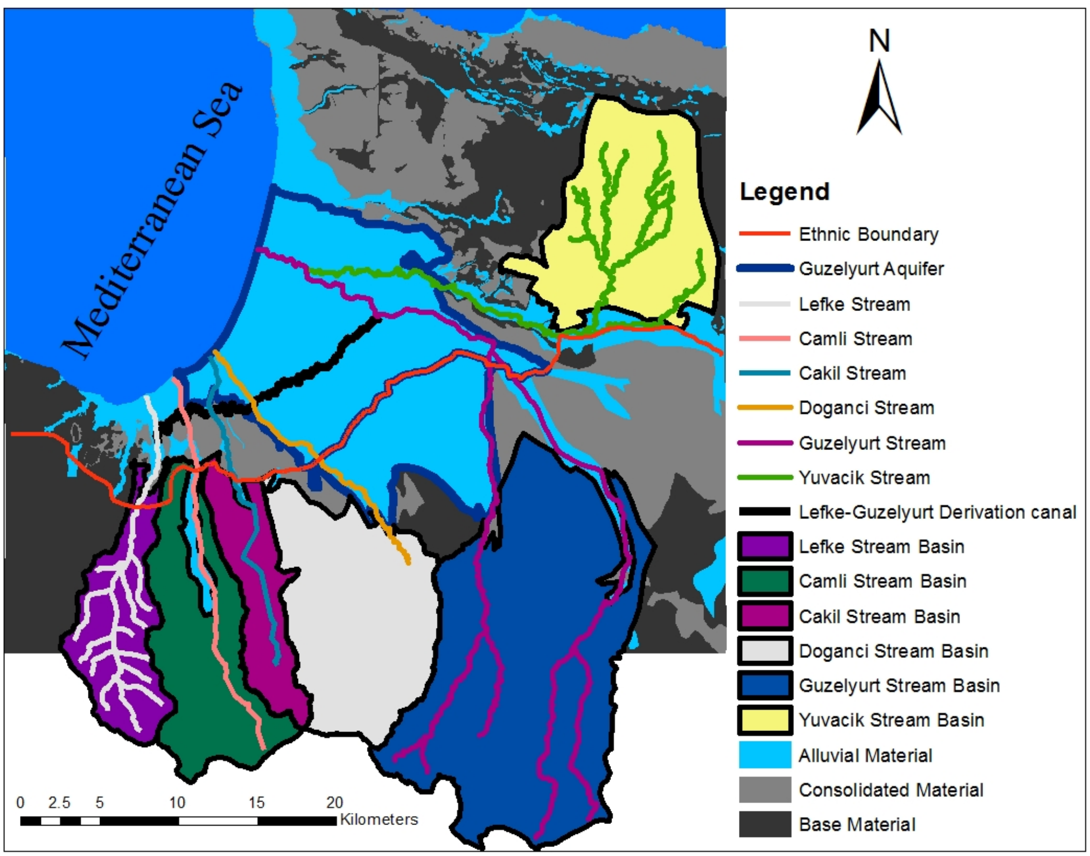

Figure 4.10 The six watershed basins delineated on impermeable formations where precipitation results in a direct runoff.

In addition to the streams and derivation canal, recharge from direct infiltration of precipitation occurs in the entire aquifer boundary where the surface is covered by alluvial materials (gravel and sand) and to some extent by consolidated material (sandstone and calcarenite). Out of the total precipitation, 25% infiltrates to recharge the groundwater and the rest 75% is lost through evapotranspiration (DSI, 2004). The relatively water rich aquifer lying in South Cyprus also has the capacity of recharging the aquifer.

On the other hand, groundwater discharge occurs mainly by the withdrawal of water for irrigation purpose and also withdrawal of water by the Kumköy pumping station installed in the western part of the study area for municipal water supply of the country. There is a deficit of about $21.4*10^6 m^3$/year between annual recharge and discharge, which gives rise for the intrusion of seawater from the Mediterranean Sea into the aquifer.

The groundwater flow system within the Güzelyurt basin can be considered as a regional flow system, with recharge to Güzelyurt Aquifer coming primarily from precipitation on the higher altitudes of Troodos Mountain in the southeast and Beşparmak Mountains in the northern part of the aquifer.

Regarding surface water resources, the study area is considered to be very poor because there are no natural lakes or continuously flowing rivers and stream. The surface water potential totally rely on runoff water collected through ephemeral or seasonal drainage streams of two main watershed basins divided by topography as shown in Figure 4.1.

The continuous withdrawal of groundwater for municipal water supply and irrigation purpose created a cone of depression in the western part of the study area as shown in Figure 4.11, which is created using the wet season groundwater level data of 2013. From contours generated, we can say that groundwater flow during any dry season is directed to this cone of depression. The regional flow being from Troodos Mountains in the south, Beşparmak Mountains in the North, and also seawater from the coastal part of the study area. Although there are some changes in the flow direction during the wet season, majority of the groundwater flow is still directed to the pumping station located at the western part of the study area with small fraction of water flowing into the Mediterranean Sea in the northwest and southwest of the study area.

From the flow net analysis shown in Figure 4.11, the hydraulic gradient is steeper and almost uniform in the eastern part of the Kumköy pumping station. The maximum hydraulic gradient (about 0.0375 m/m) is in the southern part of the pumping station. On the other hand, the area on the western part of the pumping station has smaller gradient (about 0.015 m/m) due to the replenishment of groundwater by the seawater.

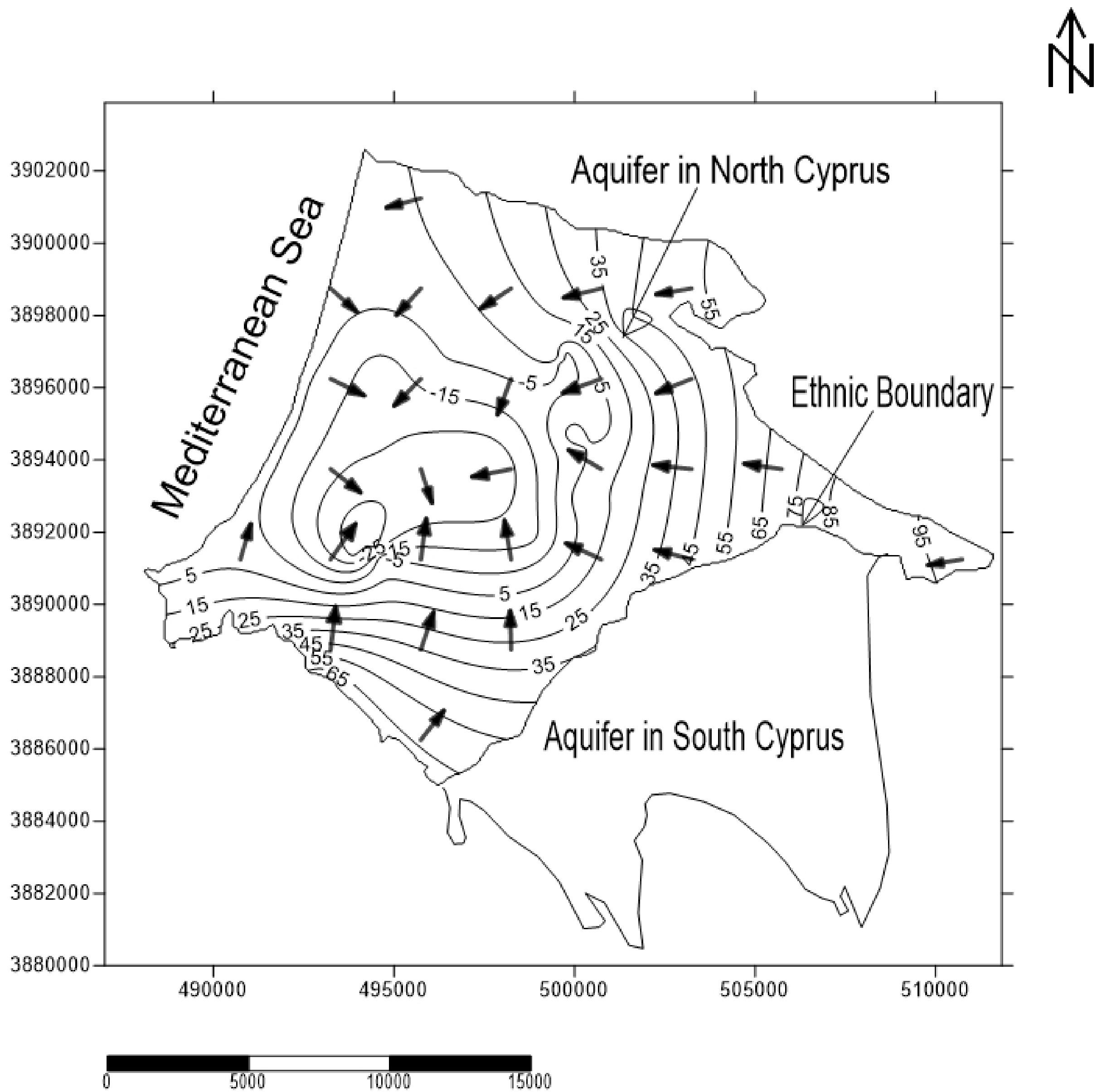

Figure 4.11 A flow net diagram representing groundwater flow in the wet season of 2013 in the study area.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1. Conclusions

The most important findings of conceptual model development for the Güzelyurt Aquifer conducted in this study can be listed as follows:

- Güzelyurt Aquifer can be described as a relatively homogenous (with about 26% of localized silt and clay lenses), isotropic, single layer, unconfined aquifer. The aquifer has variable thickness and rest on an impervious base formed by gently undulating marl, mudstone, and pillow lava. The average vertical thickness of aquifer material is 87 m; ranging from 21 m around Taşpınar, located at the southeast periphery, to 155 m towards the central part of the study area, where the most productive aquifer in terms of aquifer material thickness is located. The northwestern part of the aquifer has moderately uniform distribution of the aquifer material. Localized heterogeneity exists in the aquifer, mainly towards Bostancı, as a result of silt and clay lenses intermingled with gravel and sand.

- There are two hydrologically independent basins identified in the study area that formerly treated as a single basin. The 880 km^2 basin drains runoff water from both Troodos and Beşparmak Mountains into the Güzelyurt Aquifer while the 223 km^2 basin drains into an aquifer that is topographically isolated from the Güzelyurt Aquifer. The areal extent of the aquifer is 253 km^2, of which 180 km^2 lies in the North Cyprus and 73 km^2 lies in the South Cyprus.

- Güzelyurt Aquifer has five well defined physical and hydraulic boundaries. The hydraulic boundaries exist along the contact line of the aquifer with the

Mediterranean Sea (14 km), groundwater divide at the northwest (5.1 km) and southwest (2.8 km) of the aquifer, and water table boundary directly exposed to the surface in an unconfined aquifer. The two physical boundary exists in the aquifer are at the contact line of the aquifer with the secondary aquifer of consolidated materials in the northern and southern part of the aquifer (38.6 km), and impermeable bottom boundary composed of base materials, composed of marl, mudstone, siltstone, bedrock and pillow lava.

- Alluvial deposits in the study area is characterized at the top part by relatively uniform gravel and sand deposits intermingled with sparsely distributed silt and clay lenses found above the low water holdıng and transmission material, composed mainly of marl, and thick silt and clay layers; and at the bottom sparsely distributed gravel and sand lenses within dense and thick silt and clay dominated areas resting on the base material. The top part of the alluvial deposits can be considered as the main aquifer and much more productive than the bottom part that exists as perched aquifer.

- Recharge of Güzelyurt Aquifer mainly occurs through dendritic network of three ephemeral or seasonal streamlines; Güzelyurt stream and Dogancı stream are running from Troodos Mountain in the south whereas Yuvacık stream is running from Beşparmak Mountains in the north. These streams account for 43.7% of the total recharge of the Güzelyurt Aquifer. 11% of the recharge comes from three streams, namely Lefke stream, Çakil stream and Camlı stream that are intercepted by Lefke-Güzelyurt derivation canal to facilitate the recharge by increasing the residence time through alluvial deposit. In addition, direct precipitation has significant amount of recharge (32.2%) through alluvial deposit within the aquifer boundary. Moreover, 13.1% of the recharge comes from the aquifer lying in the South Cyprus. On the other hand, discharge of the Güzelyurt Aquifer is through pumping for water supply (15.5%) and irrigation (84.5%) purpose. Due to high demand of water, the total discharge ($61.2*10^6$ m^3/year) exceeds the total recharge ($39.8*10^6$ m^3/year) leaving the aquifer with a deficit of $21.4*10^6$ m^3/year.

- Kumköy pumping station has already created cones of depression due to its continuous withdrawal of water for municipal water supply system. Apart from the depletion of groundwater in the area, it has resulted in the encroachment of seawater into the aquifer. More than 50% area of the aquifer has chloride concentration that exceed the EPA threshold of 250 mg/L with the maximum concentration in about 500 m distance from the municipal water supply pumping station of Kumköy, which is located on the western part of the study area only 2 km away from the Mediterranean Sea.

- The three towns located near the Kumköy pumping station, namely Gaziveren, Aydinköy and Gunesköy are severely affected in both wet and dry season with the water level (-40m) below mean sea level. Any further extraction of water in the vicinity of the existing pumping station will only exacerbate the seawater intrusion into the aquifer. The average saturated thickness of the aquifer in 2013 is 20.3 m.

5.2. Future Work

For the integration of the conceptual model into the numerical groundwater model, further data/ information need has to be analyzed in order to update the developed conceptual model for detailed future groundwater modelling requirement. To this end, future data need, uncertainty and reliability have been assessed.

5.2.1. Assessment of Data Uncertainty and Reliability of Conceptual Model

In order to develop a reliable groundwater conceptual model, there is a minimum data and information requirement. Conceptual groundwater model requires Topographic map, Digital Elevation Model (DEM), Surface drainage network map, Geologic/Hydrogeologic map, Lithological or drillers log, Precipitation, Irrigation water use, Surface water data, Groundwater level data, Springs and seeps data, Recharge and discharge data, Pump test data, Aquifer hydraulic properties.

Conceptual model is the main source of uncertainty in groundwater modeling. This uncertainty results from insufficient data used to develop hydrogeological conceptual model including geological sample descriptions, water quality information that are used to fully describe hydrology without considerable interpretation from experts (Dettinger et al., 1981; Rojas et al., 2010). In addition, inadequate characterization of recharge discharge conditions, hydraulic parameter distributions may be significant sources of uncertainty. In this regard, the available data for the construction of conceptual model of Güzelyurt Aquifer had problems that can potentially cause uncertainty, such as lack of evenly distributed boreholes and hydrological data of the study area, lack of detailed recharge and discharge characteristics including recent evaporation/evapotranspiration data, and unavailability of any hydrological information of the aquifer lying in South Cyprus.

The help of geological field experts in the area were inevitable to overcome uncertainty problems, especially for the unevenly distributed borehole data. Some boreholes were interpolated for the areas with no or sparse drill logs, based on the surface material types from hydrogeological map and use of closer boreholes for vertical lithological material distribution.

There is uncertainty associated with recharge and discharge characteristics of the aquifer because of limited data regarding aquifer's hydraulic property distribution. In addition, there are uncertainties associated with the lack of hydrogeological and hydraulic property information for the part of aquifer lying in the South Cyprus, which is another source of uncertainty for the conceptual model of the Güzelyurt Aquifer.

5.2.2. Implementation of Conceptual Model

The integration of conceptual model into numerical model is an important step in groundwater modeling which involves the analysis of conceptual model with respect to boundary conditions, hydraulic parameters, and groundwater recharge and discharge characteristics.

5.2.2.1. Hydraulic Parameter and Recharge/Discharge Data Requirement

Hydraulic conductivity and transmissivity of the unconfined Güzelyurt Aquifer have been identified to a limited extent during water master plan studies of DSI (2004) from three wells: MP-29, which is 1 km away from Serhatköy Dam, MP-27 that is 1.5 km away from The Güzelyurt Dam, and MP-28 that is 3 km away from Güzelyurt Dam. From the results shown in Table 5.1, the area near Güzelyurt Dam has the highest conductivity and transmissivity. From the map in Figure 5.1, Güzelyurt Dam is located in the middle of alluvial aquifer; composed of sand and gravel. Although Serhatköy dam is also in alluvial material, the immediate surrounding materials are consolidated aquifer material, resulting in a lower conductivity and transmissivity.

Table 5.1 Hydraulic conductivity and transmissivity ranges near Güzelyurt and Serhatköy Dams (DSI,2004).

Well ID	T (m^2/day)	K (m/day)
MP-29	70-94	0.9-1.3
MP-27	3873-5990	35.8-55.4
MP-28	307-360	4.0-4.7

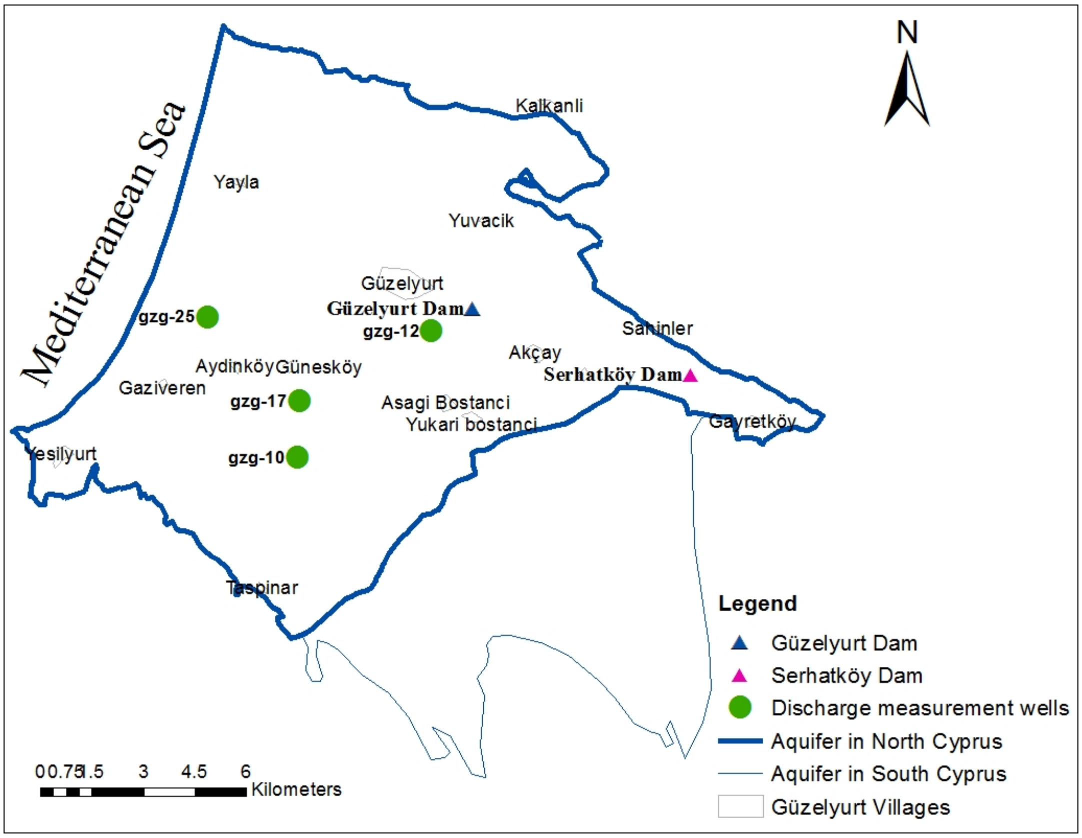

Figure 5.1 The location of discharge measurement wells and the Dam.

The static and dynamic water level has been measured for the wells in Table 5.2. The specific discharge of GZG-25 is the highest making it the best location for withdrawal of groundwater; however, since it is located near the coast of Güzelyurt, seawater intrusion will be the major problem.

Table 5.2 Specific discharges of GZG wells (DSI,2004).

Well ID	Static Water Level (m)	Dynamic Water Level (m)	Discharge (lt/s)	Specific discharge (lt/s/m)
GZG-10	60	180	10.0	0.08
GZG-12	81	95	7.5	0.5
GZG-17	51	93	18.0	0.4
GZG-25	34	39	11.0	2.1

In addition, as shown in Figure 5.2, the results of five pumping tests carried out (four of them are inside the Güzelyurt Aquifer while one of them is outside the boundary) in the study area are available in the Geology and Mining Department. The analysis of these data may also contribute a better description of hydraulic property distribution in the Güzelyurt Aquifer.

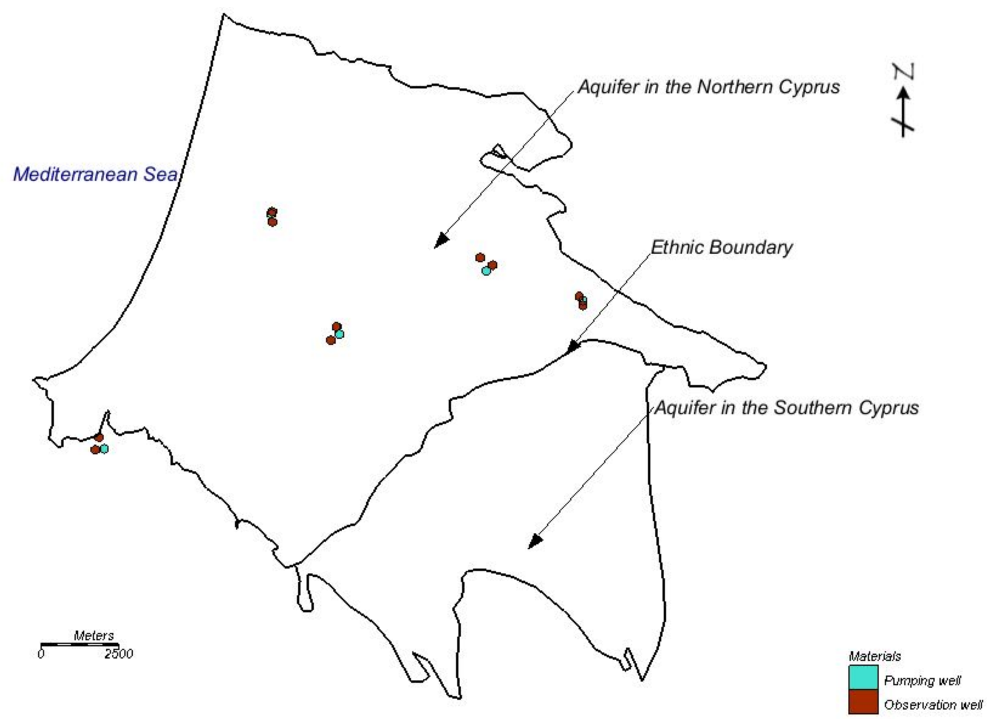

Figure 5.2 The areal distribution of pumping test wells

5.2.2.2. Numerical Model Grid Design and Dimensionality

The areal extent of the Güzelyurt Aquifer (both lying in North Cyprus and South Cyprus) has been delineated. However, the vertical thickness of the aquifer is calculated only for the part lying in North Cyprus. The ethnic boundary dividing North and South Cyprus can be considered as flow boundary to account for the groundwater flow contributed from by the south part of the aquifer. From the analysis of borehole data, Güzelyurt Aquifer is characterized as single relatively homogenous, isotropic alluvial aquifer with limited heterogeneity caused by discontinuous, isolated silt and clay lenses. Thus, it may be sufficient to treat the aquifer as a 2-dimentional flow domain.

Numerical grid design is directly related to dimensionality of the groundwater flow system. The size and distribution of the grid cells is very much related to aquifer thickness and layered heterogeneity conditions as well as, in an heterogeneous case, the size of the mesh is dependent on the size of discontinuous isolated bodies. The Güzelyurt Aquifer needs a discretization using coarser meshes except for the heterogeneous part roughly as shown in Figure 5.3, which may requires finer mesh size.

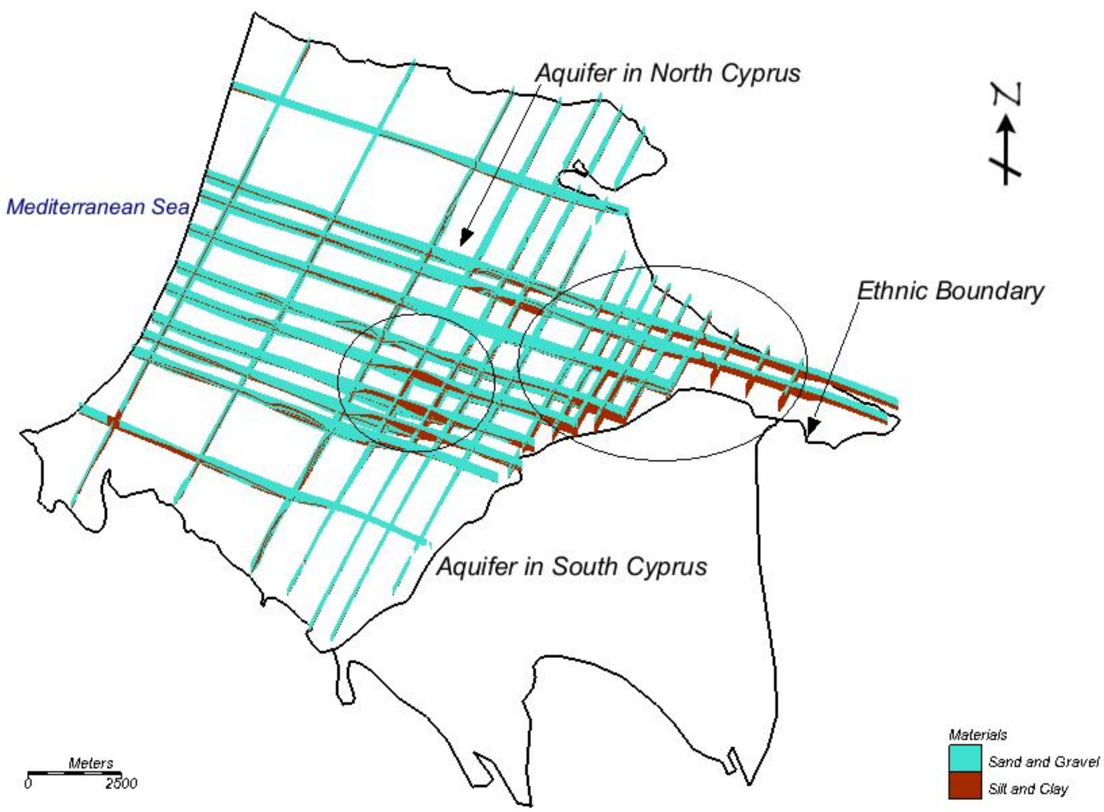

Figure 5.3 Identification of heterogeneous zones in Güzelyurt Aquifer (i.e., indicated by finer grids within the circled zones)

REFERENCES

ASTM. (2008). Standard Guide for Conceptualization and Characterization of Groundwater Systems, *96*(Reapproved 2008), 1–8.

Barazzuoli, P., Nocchi, M., Rigati, R., & Salleolini, M. (2008). A conceptual and numerical model for groundwater management: A case study on a coastal aquifer in southern Tuscany, Italy. *Hydrogeology Journal*, *16*, 1557–1576. http://doi.org/10.1007/s10040-008-0324-z

Bredehoeft, J. (2005). The conceptualization model problem-surprise. *Hydrogeology Journal*, *13*(1), 37–46. http://doi.org/10.1007/s10040-004-0430-5

Cox, M. E., James, A., Hawke, A., & Raiber, M. (2013). Groundwater Visualisation System (GVS): A software framework for integrated display and interrogation of conceptual hydrogeological models, data and time-series animation. *Journal of Hydrology*, *491*, 56–72. http://doi.org/10.1016/j.jhydrol.2013.03.023

Dettinger, D., & Wilson, J. L. (1981). First Order Analysis of Uncertainty in Numerical Part 1 . Mathematical Development, *17*(1), 149–161.

DSI. (2004). Water Master Plan.

Ergil, M. (1999). Estimation of Saltwater Intrusion through a Salt Balance Equation and its Economic Impact with Suggested Rehabilitation Scenarios: A Case Study. *First International Conference on Saltwater Intrusion …*, *150000*.

Ergil, M. (2000). The salination problem of the Güzelyurt aquifer, Cyprus. *Water Research*, *34*(4), 1201–1214.

Flynn, B. R. H., Tasker, G. D., & Survey, U. S. G. (2004). Generalized Estimates from Streamflow Data of Annual and Seasonal Ground- Water-Recharge Rates for Drainage Basins in New Hampshire Scientific Investigations Report 2004-5019 U . S . Department of the Interior.

Gökçekuş. H, Tuker. U, Sözen. S, O. D. (2002). Güzelyurt ilçesinin KKTC açısından önemı, Toprak ve Su.

Gökmenoğlu O, Erduran B, Özgür C, T. Ö. F. (2002). Kuzey Kibris Turk Cumhuriyeti'nin Hidrojeolojisi.

Hutchison, W. R., & Hibbs, B. J. (2008). Ground water budget analysis and cross-formational leakage in an arid basin. *Ground Water*, *46*(3), 384–95. http://doi.org/10.1111/j.1745-6584.2008.00446.x

Izady, a., Davary, K., Alizadeh, a., Ziaei, a. N., Alipoor, a., Joodavi, a., & Brusseau, M. L. (2013). A framework toward developing a groundwater conceptual model. *Arabian Journal of Geosciences*, *7*(9), 3611–3631. http://doi.org/10.1007/s12517-013-0971-9

Jousma, G., Attanayake, P., & Chilton, J. (2006). Guideline on: Groundwater monitoring for general reference purposes. *... Assessment Centre (IGRAC ...*, (March). Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Guideline+on+:+Groundwater+monitoring+for+general+reference+purposes#0

Kallioras, a., Pliakas, F., & Diamantis, I. (2006). Conceptual model of a coastal aquifer system in northern Greece and assessment of saline vulnerability due to seawater intrusion conditions. *Environmental Geology*, *51*(3), 349–361. http://doi.org/10.1007/s00254-006-0331-0

Kresic, N. (2009). Groundwater Resources Sustainability, Management, and Restoration. McGraw-Hill.

Lcry, G. E., & Kolm, K. E. (1996). Conceptualization and characterization of ground-water systems using Geographic Information Systems. *Elsevier Science B.V*, *42*, 111–118.

Mercer, J. W. (1992). Applied groundwater modeling: Simulation to flow and advective transport. *Journal of Contaminant Hydrology*. http://doi.org/10.1016/0169-7722(92)90015-7

Nastev, M., Rivera, a., Lefebvre, R., Martel, R., & Savard, M. (2005). Numerical simulation of groundwater flow in regional rock aquifers, southwestern Quebec, Canada. *Hydrogeology Journal*, *13*(5-6), 835–848. http://doi.org/10.1007/s10040-005-0445-6

New Hampshire Department of Environmental Science (2010). Sodium and Chloride in Drinking Water.

Phillips Agboola, O., & Egelioglu, F. (2012). Water scarcity in North Cyprus and solar desalination research: a review. *Desalination and Water Treatment*, *43*(1-3), 29–42. http://doi.org/10.1080/19443994.2012.672195

Post, V. E. a. (2005). Fresh and saline groundwater interaction in coastal aquifers: Is our technology ready for the problems ahead? *Hydrogeology Journal*, *13*(1), 120–123. http://doi.org/10.1007/s10040-004-0417-2

Rawls, W., David, G., Mullen, J., & Ward, T. (1949). Hydrology Handbook (2nd ed.). New York, NY: ASCE.

Rojas, R., Kahunde, S., Peeters, L., Batelaan, O., Feyen, L., & Dassargues, A. (2010). Application of a multimodel approach to account for conceptual model and scenario uncertainties in groundwater modelling. *Journal of Hydrology*, *394*(3-4), 416–435. http://doi.org/10.1016/j.jhydrol.2010.09.016

Rushton, K. R. (2003). Groundwater Hydrology. Chichester, UK: John Wiley & Sons, Ltd. http://doi.org/10.1002/0470871660

S.H.Schneider. (1996). Encyclopedia of Climate and Weather (Volume 2). Oxford University Press.

Sadashivaiah, C. (2008). Hydrochemical analysis and evaluation of groundwater quality in Tumkur Taluk, Karnataka State, India. *International Journal of …*, *5*(3), 158–164. Retrieved from http://www.mdpi.com/1660-4601/5/3/158/htm

Sadoon, M. N. (2005). Enhancement of Groundwater Resource in Safwan-Zubair Area, South of Iraq Using Artificial Recharge.

Seyhun, R. (2013). Annual and Seasonal Trend Patterns of Climate Change in North Cyprus.

Sheffer, N. a. (2009). Variable Scale Recharge Measurement and Modelling Using the Hydrometeorological DReAM. Hebrew University of Jerusalem.

Shiklomanov, I. A. (1998). World water resources a new appraisal and assessment for the 21st century. Paris: UNESCO.

Teresita Betancur V., Carlos Alberto Palacio T., John Fernando Escobar M. (2012). Conceptual Models in Hydrogeology, Methodology and Results. In G. A. Kazemi (Ed.), *Hydrogeology-A Global Perspective*.

Thomas Seibert. (2014). Turkey resorts to water power with Cyprus pipeline project. Retrieved October 27, 2014, from http://www.al-monitor.com/pulse/tr/originals/2014/03/turkey-cyprus-pipeline-water-power.html#

Türker, U., Alsalabi, B. S., & Rızza, T. (2012). Water table fluctuation analyses and associated empirical approach to predict spatial distribution of water table at Yeşilköy/AgiosAndronikos aquifer. *Environmental Earth Sciences*, *69*(1), 63–75. http://doi.org/10.1007/s12665-012-1934-2

Waren, K. B., Bobst, A. L., Swierc, J. E., Madison, J. D., Water, G., & Program, I. (2013). Hydrogeologic Investigation of the North Hills Study Area Lewis and Clark County , Montana.

Wikipedia. (2012). Geography of Cyprus.

APPENDIX A

THE DESCRIPTION OF MAP LEGENDS

Table A.1. Description of the legend of hydrogeological map of North Cyprus

Mapping Unit IDs	Formation	Lithology	Grouping-5	Grouping-3
JKth	Hilarion limestone	Recrystallized limestone	Marl, Limestone, Mudstone	Base Material
Klm	Mallıdağ formation	Mudstone, Limestone	Marl, Limestone, Mudstone	Base Material
Kls	Selvilitepe breccia	Gravel	Gravel	Alluvial Material
KT	Lower Pillow Lavas	Pillow lava	Pillow lava, Tuff, Trachyandesite and Dacite	Base Material
Kta	Lower Pillow Lavas	Pillow lava	Pillow lava, Tuff, Trachyandesite and Dacite	Base Material
Ktaß	Host andesite and basalt dikes	Andesite and basalt dikes	Pillow lava, Tuff, Trachyandesite and Dacite	Base Material
Ktd	Diabase	Diabase dikes	Pillow lava, Tuff, Trachyandesite and Dacite	Base Material
KTl	Çınarlı volcanic	Pillow lava	Pillow lava, Tuff, Trachyandesite and Dacite	Base Material

Table A.1. (Continued)

KTlç	Çınarlı volcanic	Pillow lava	Pillow lava, Tuff, Trachyandesite and Dacite	Base Material
KTly	Tuff, trachyandesite, dacite	Tuff, trachyandesite, dacite	Pillow lava, Tuff, Trachyandesite and Dacite	Base Material
Kttg	Base group	Pillow lava and diabase dykes	Pillow lava, Tuff, Trachyandesite and Dacite	Base Material
Ktü	Upper pillow lavas	Pillow lava	Pillow lava, Tuff, Trachyandesite and Dacite	Base Material
Q1a	Marine terraces	Calcarenite	Sandstone and Calcarenite	Consolidated Material
Q1b	Terrestrial terraces	Gravel	Gravel	Alluvial Material
Q1bt	Flood deposits	Terra rossa soils, tufa and chalk sequence	Marl, Limestone, Mudstone	Base Material
Q1by	Slope wash	Gravel	Gravel	Alluvial Material
Q2a	Marine terraces	Calcarenite	Sandstone and Calcarenite	Consolidated Material
Q2b	Terrestrial terraces	Limestone	Marl, Limestone, Mudstone	Base Material
Q3a	Marine terraces	Calcarenite	Sandstone and Calcarenite	Consolidated Material
Q3b	Terrestrial terraces	Gravel	Gravel	Alluvial Material
Q3d	Terrestrial terraces	Gravel	Gravel	Alluvial Material
Q4a	Marine terraces	Calcarenite	Sandstone and Calcarenite	Consolidated Material

Table A.1. (Continued)

Q4ab	Terrestrial marine terraces sequential	Coastal sand and gravel	Gravel	Alluvial Material
Q4akk	Terrestrial marine terraces sequential	Coastal sand and gravel	Gravel	Alluvial Material
Q4b	Terrestrial terraces	Gravel	Gravel	Alluvial Material
Q4ba	River Sand & Gravel	Gravel-Sand Sequence	Gravel	Alluvial Material
Q5a	Marine terraces	Calcarenite	Sandstone and Calcarenite	Consolidated Material
Q5ak	Terrestrial marine terraces sequential	Coastal sand and gravel	Gravel	Alluvial Material
Q5akk	Terrestrial marine terraces sequential	Coastal sand and gravel	Gravel	Alluvial Material
Q5b	Terrestrial terraces	Gravel	Gravel	Alluvial Material
Q6	Beylerbey formation	Turbidite sandstone and shale	Sandstone and Calcarenite	Consolidated Material
Q6ak	Sandy sediments	Sand	Sand	Alluvial Material
Q6akk	Coastal dune	Sand	Sand	Alluvial Material
Q6b	Terrestrial terraces	Sandstone, Marl sequence	Marl, Limestone, Mudstone	Base Material

Table A.1. (Continued)

Q6ba	River Sand & Gravel	Gravel-Sand Sequence	Gravel	Alluvial Material
Q6bt	Flood deposits	Terra rossa soils, tufa and chalk sequence	Marl, Limestone, Mudstone	Base Material
Q6by	Slope wash	Gravel	Gravel	Alluvial Material
Q6h	Landslide masses	Turbidite sandstone and shale	Sandstone and Calcarenite	Consolidated Material
Q6tr	Travertine	Turbidite sandstone and shale	Sandstone and Calcarenite	Consolidated Material
Qh	Landslide masses	Turbidite sandstone and shale	Sandstone and Calcarenite	Consolidated Material
Qmb	Bostancı Gravel	Gravel	Gravel	Alluvial Material
Qmg	Gürpınar formation	Gravel, Calcarenite, Sandstone	Sandstone and Calcarenite	Consolidated Material
Qmgç	Gravel member	Gravel	Gravel	Alluvial Material
Ta	Ardahan formation	Sandstone, Siltstone, Gravel, Breccia,	Sandstone and Calcarenite	Consolidated Material
Td	Kaynakköy formation	Dolomitic limestone	Marl, Limestone, Mudstone	Base Material
Tdb	Büyüktepe formation	Gravel	Gravel	Alluvial Material
Tdbe	Beylerbeyi formation	Turbidite sandstone and shale	Sandstone and Calcarenite	Consolidated Material

Table A.1. (Continued)

Tdd	Dağyolu formation	Sandstone, Shale, Marl	Marl, Limestone, Mudstone	Base Material
Tdg	Geçitköy formation	Limestone, Mudstone	Marl, Limestone, Mudstone	Base Material
Tdko	Kozan formation	Sandstone, Marl sequence	Marl, Limestone, Mudstone	Base Material
Tdm	Mermertepe gypsum	Gypsum	Marl, Limestone, Mudstone	Base Material
Tdt	Tirmen formation	Turbidite sandstone and calcarenite	Sandstone and Calcarenite	Consolidated Material
Tdy	Yılmazköy formation	Sandstone, Siltstone, Mudstone	Marl, Limestone, Mudstone	Base Material
Tdya	Yazılıtep formation	Chalk, Clayey limestone, Sandstone and Marl sequence	Marl, Limestone, Mudstone	Base Material
Tk	Kantara formation	Gravelly Sandstone, Gravel	Sandstone and Calcarenite	Consolidated Material
Tly	Yamaçköy formation	Clayey limestone volcanic sequence, Limestone, Chert	Marl, Limestone, Mudstone	Base Material
Tmç	Çamlıbel marl	Gray Marl, Sandstone	Marl, Limestone, Mudstone	Base Material
Tmçç	Gravel member	Gravel	Gravel	Alluvial Material
Tml	Lefkoşa sandstone	Sandstone	Sandstone and Calcarenite	Consolidated Material

Table A.1. (Continued)

Tmt	Taşpınar formation	Sandstone, Marl, Gravel sequence	Sandstone and Calcarenite	Consolidated Material
TRtk	Kaynakköy formation	Dolomitic limestone	Marl, Limestone, Mudstone	Base Material
Ttk	Kaynakköy formation	Dolomitic limestone	Marl, Limestone, Mudstone	Base Material
Ty	Kaynakköy formation	Clayey limestone volcanic sequence, Limestone, Chert	Marl, Limestone, Mudstone	Base Material
Tya	Akiltepe formation	Sandstone, Marl, Chalk	Marl, Limestone, Mudstone	Base Material
Tyl	Lefke limestone	Reef limestone	Marl, Limestone, Mudstone	Base Material

Table A.2 Description of the legend of hydrogeological map of South Cyprus

Mapping Unit Codes	Description	Grouping-3
A110	Unconfined water generally at shallow depth in connection with riverbeds, deltaic gravel-sand deposits and including estuarine deposits.	Alluvial material
A111	Water in alluvial deposits with impermeable to semi-permeable surface	Alluvial material
A121	Dune sand, normally shallow on Kythrea beds	Alluvial material
A230	Unconfined water in marine and terrestrial fanglomerate and terrace formations, locally including calcarenite.	Consolidated material
A231	Very shallow ground water controlled by the configuration of underlying silt, clay or marl, in some formations as above	Alluvial material
A340	Unconfined ground water in Gravel stone, sandy marls and calcarenite (i.e., Nicosia formation), mineralized at depths and along coast by sea water intrusion	Consolidated material
A341	Confined ground water in Gravel stone, sandy marls and calcarenite (i.e., Nicosia formation), mineralized at depths and along coast by sea water intrusion	Consolidated material
A342	Shallow unconfined ground water controlled by the configuration of impervious or semi-pervious strata, in same formations as above	Consolidated material
A450	Unconfined ground water in sandy parts of Middle Miocene (Pakhna formation)	Alluvial material
B160	Unconfined ground water in reef limestone and detrital limestone (Koronia limestone, Terra limestone), saline in coastal areas	Base material
B180	Unconfined ground water in aquifers of secondary importance of mainly massive, highly retentive chalk, occasionally mineralized	Consolidated material

Table A.1. (Continued)

B181	Unconfined ground water in aquifers of secondary importance consisting of cherty, locally marly chalk, sometimes including strata of massive chalk (Chalks of the Lapithos formation of the Kyrenia Range included), occasionally mineralized	Consolidated material
B190	Ground water in highly retentive rocks such as chalk interbedded with marls (Pakhna formation and Lapatza formation)	Consolidated material
C1110	Clay, marl and siltstone (Mainly rocks of the Mesaoria Group locally including marl, silt and clay of the Alluvium)	Base material
C1120	Alternating marl, siltstone, greywacke, clay and shale (Kythrea formation), well water normally highly mineralized	Base material
C1130	Mamonia Complex, including serpentine	Base material
C2140	Volcanic with dominantly submarine pillow lavas, occasional pockets of highly saline water	Base material
C2160	Plutonic rocks, springs common	Base material

APPENDIX B

DISCRIPTION OF LITHOLOGICAL MATERIAL GROUPING

MATERIAL CODES

1. TOP SOIL
2. ALLUVIUM
3. GRAVEL
4. SAND
5. GRAVEL AND SAND
6. GRAVEL AND SILT
7. SAND AND SILT
8. SAND AND CLAY
9. SILT
10. SILT AND CLAY
11. CLAY
12. SANDSTONE
13. CONGLOMERATE
14. FANGLOMERATE
15. CALCARENITE

16 SILTSTONE
17 LIMESTONE
18 MARL
19 MUDSTONE
20 BEDROCK

DRILLER'S DESCRIPTION THAT WERE CATEGORIZED INTO SECOND GROUPING MATERIAL CODE:

1. Top soil

- Fine gravelly alluvium containing very little terra rosa top soil
- gravelly red soil
- red colored top soil
- red soil
- silty sandy soil
- Soil with clay and gravelly alluvium
- Terra Rosa soil
- terra rossa gravel
- top soil
- top soil layer
- vegetative soil
- vegetative soil (terra rossa)
- vegetative soil, gravel

2. Alluvium

- alluvium
- clay, coarse sand and gravel sequence
- clay, sand and gravel
- clay, sand and rare gravel
- clayey alluvium with little fine gravel
- clayey and rare gravelly alluvium
- clay-sand-gravel
- dark gray colored fine sand and silt sequence
- dark gray colored, volcanic origin sand-silt-clay sequence
- dark gray colored, volcanic origin, gravel- sand-silt sequence; dominated by gravelly layers
- dark gray colored, with ample sand, volcanic origin sand-silt-clay sequence
- dark grey colored clay-sand-gravel
- fine gravel, sand and clay

- fine gravelly alluvium with light brown clay
- fine sandy alluvium
- fine sandy alluvium with little silt
- gravel with rare clay and sand
- gravel with sand
- gravel, clay and sand
- gravel, sand and silt
- gravel, sand and clay
- gravelly alluvium
- gravelly sandy alluvium
- gravel-sand-clay
- gravel-sand-clay sequence with volcanic origin
- gravel-sand-clay-silt
- gravel-sand-silt
- gray colored gravell-silt-clay
- light brown colored clayey, silty, little gravelly alluvium
- light silty gravelly alluvium
- loosely binded gravel-silt-clay sequence
- Marl, sand and gravel
- mixture of yellow colored clay, sand and gravel
- sand, gravel and silt layers
- sand, silt and marl
- sandy clay with rare gravel
- sandy clayey fine gravelly alluvium
- sandy gravelly alluvium
- sandy gravelly layers
- silt sand gravel
- silt, sand and gravel
- silt-sand-gravel sequence
- silty fine sandy alluvium
- silty sandy gravelly alluvium

3. <u>Gravel</u>

- brown clayey gravel
- brown colored clayey gravel with little sand
- clayey coarse grained gravel with little sand
- clayey fine gravel with little silt
- clayey gravel
- clayey gravel with little sand
- clayey gravel with little silt
- clayey sandy gravel
- clayey silty fossiliferous gravel
- clayey silty gravel
- clayey yellow sandy gravel
- clayey yellow sandy with little gravel
- coarse and fine grained gravel
- coarse and fine grained sandy gravel
- coarse and fine gravel with very little sand
- coarse and fine mixed gravel with little sand
- coarse grained gravel
- coarse grained gravel with gray clay
- coarse grained gravel with little sand
- coarse gravel
- coarse gravel ;loosely binded volcanic origin layer
- coarse gravel with little sand
- coarse gravel with little silt
- coarse sandy gravel
- coarse-fine gravel
- coarse-fine mixed grained gravel
- dark gray colored gravel with ample sand
- dark gray colored, rounded loose gravel with volcanic origin
- dark gray colored, volcanic origin, rounded, loose attached
- dark gray colored, volcanic origin, rounded, loosely bind
- diabase gravel
- fine (small) gravel
- fine grained gravel
- fine grained gravel with little sand
- fine grained sandy gravel
- fine gravel (clay and silt sequence)
- fine gravel (magmatic origin)
- fine Pillow lava gravels with silt and sand
- fine silty sandy gravel
- gravel

- gravel layer
- gravel without cement
- gravel with clay and sand
- gravel with clay lenses
- gravel with little clay
- gravel with little find sand
- gravel with little marl
- gravel with little sand
- gravel with little sandy silt
- gravel with little silt
- gravel with localized clay lenses
- gravel with rare sand
- gravel with sand
- gravel with volcanic origin
- gravel with volcanic origin
- gravelly marly gravel
- gray gravel
- gray marly gravel
- gray silty diabase gravel
- greenish colored clayey gravel with little sand
- loose layer containing coarse sand sized gravel
- loosely bind layer composed of fine gravel
- macro fossil siltstone and gravel of volcanic origin
- marly coarse sandy fine gravel with macrofossil
- marly gravel
- marly silty gravel
- marly silty sandy gravel
- medium and fine grained gravel with little sand
- medium grained gravel
- medium grained gravel with little sand
- poorly graded and cemented gravel with volcanic origin
- poorly graded gravel with volcanic origin
- rounded and coarse grained volcanic gravel
- rounded and small grained volcanic gravel
- rounded grained macrofossil gravel with volcanic origin
- rounded grained volcanic origin gravel with little clay layers
- sand with little gravel
- sandy clayey gravel
- sandy fine grained gravel
- sandy fine gravel
- sandy fine gravel with greenish colored clay
- sandy fine gravel with light gray clay
- sandy garvel
- sandy gravel with brown clay
- sandy gravel with little clay
- sandy gravel with little silt
- sandy medium grained gravel
- sandy medium grained gravel with little clay
- sandy medium grained gravel with little yellow clay
- sandy silty and clayey gravel
- sandy silty gravel
- sandy silty gravel with volcanic origin
- silty fine gravel
- silty fine gravel with little clay
- silty fine gravel with little sand
- silty fine sandy gravel
- silty gravel
- silty gravel with little clay
- silty light sandy gravelly alluvium
- silty marly gravel
- silty sandy fine gravel with little clay
- silty sandy gravel
- small grained, volcanic origin gravel
- volcanic originated loose rounded grey colored coarse gravel
- well-rounded fine gravel
- yellow clayey coarse grained gravel
- yellow colored clay-volcanic origin gravel
- yellow colored clay-volcanic origin gravel sequences

4. Sand

- brown clayey sand
- brown sand
- clay-coarse sand
- clayey gravelly sand
- clayey sand
- clayey sand with brown gravel
- clayey sand with little gravel
- clayey silty sand
- clayey yellow sand with little gravel
- coarse and fine grained gravelly sand
- coarse grained sand
- coarse gravelly sand with little clay
- coarse gravelly sand with very little clay
- coarse sand
- coarse sand with little greenish colored sand
- coarse sand with localized fine gravel
- dark gray colored gravelly sand
- dark gray colored loosely binded sand
- dark gray colored silty sand
- dark gray colored, loosely binded sand with volcanic origin
- dark grey colored loosely binded sand
- fine grained gravelly sand
- fine grained marly sand
- fine grained sand
- fine grained sand with little gravel
- fine gravelly clayey sand
- fine gravelly clayey silty fine sand
- fine gravelly sand
- fine gravelly sand with little clay
- fine gravelly silty sand with little clay
- fine sand
- fine sand with gravel
- fine sand with little gravel
- fine yellow sand
- fine, medium size gravelly sand
- gravelly clayey sand
- gravelly sand
- gravelly sand with little clay
- gravelly sand: locally more and locally less gravel
- gravelly silty sand
- gray colored fine sand
- gray colored sand with ample gravel
- gray colored silty sand
- gray colored silty sand with little gravel
- gray marly silt sand
- greenish gray sand
- light brown sand
- light colored fine grained sand
- light green colored sand
- marly silty coarse sand
- sand
- sand (alluvium)
- sand with dark gray colored clay bands
- sand with greenish silt
- sand with little clay
- sand with little fine gravel
- sand with little gravel
- sand with little lime stone grains
- sand with silt
- sand with very little gravel
- sand with volcanic origin
- sand, clay and rare gravel
- sandy-gravelly sand
- silt with sand
- silty coarse sand
- silty coarse sand with little fine gravel

5. Gravel and Sand

- coarse sand and gravel with volcanic origin
- coarse sand with volcanic origin and gravel
- dark gray colored gravel-sand
- fine sand and medium gravel
- gravel and sand
- gravel and various sands
- gravel-sand sequence with little gravel
- gravel-sand: top parts gravel, lower parts sand dominated
- volcanic origin coarse sand and gravel

- volcanic originated, locally cemented coarse sand and gravel
-

6. Gravel and Silt

- coarse gravel and silt (alluvium)
- silt and fine gravel (alluvium)
- silt and gravel sequence with localized silt layer

7. Sand and Silt

- coarse sand and silt
- coarse sand and silt(alluvium)
- dark gray colored fine sand and silt sequence
- dark gray colored, fine sand-silt sequence
- fine sand and silt
- gray colored clayey silt and clayey sand
- gray colored localized sand dominated silt-sand sequence
- sand and silt
- sand and silt (alluvium)
- sand silt sequence
- silt and sand sequence (high gravel level) sequence

8. Sand and Clay

- green colored clay and sand

9. Silt

- clayey silt
- clayey silt with little gravel
- clayey silt with macro fossil
- coarse gravelly sandy silt
- coarse gravelly silt
- dark gray colored silt with little gravel
- dark greenish silt
- dark greenish silt with little clay
- dark grey colored gravelly, little sandy silt
- dark grey colored little gravelly silt
- fine grained sandy silt
- fine gravelly clayey silt
- fine gravelly coarse sandy gray silt
- fine gravelly silt with little clay
- gravelly clayey silt
- gravelly marly silt
- gravelly sandy silt
- gravelly sitl with little clay
- gray colored silt
- greenish clayey silt with little fine gravel
- greenish colored clayey silt
- greenish silt
- little fine gravelly silt
- macro fossil clayey silt
- macro fossil clayey silt with little gravel
- marly silt
- medium plasticity marly silt with macro fossil
- sandy silt
- sandy silt with little gravel
- sandy silt with well-rounded gravel
- silt
- silt with clay lenses
- silt with little clay
- silt with little gravel
- silt with little marl
- silt with little sand
- silt with plenty of gravel
- silt with plenty of macro fossil

10. Silt and Clay

- clay and silt
- clay and silt with likely volcanic origin
- gray colored silt-clay
- dark gray colored, plastic, volcanic origin silt -clay
- dark gray colored plastic silt and clay with volcanic origin
- dark gray colored, gravelly silt-clay sequence
- dark gray colored clay-silt sequence
- clay with macro fossil silt
- dark grey colored gravelly clay-silt

sequence

11. Clay

- black clay
- blue clay
- brown clay
- brown clay with little gravel
- brown colored clay with little gravelly sand
- brown colored sandy clay with little gravel
- clay
- clay with fine gravel and rare fine sand
- clay with little gravle
- clay with little sand
- clay with little silt
- clayey sandy round gravel
- coarse gravelly silty clay
- fine clay with little gravel
- fine grained clay
- fine grained gravelly clay
- fine gravelly clay with little silt
- fine gravelly greenish colored clay with little clay
- fine gravelly silty clay
- fine sand silt and clay
- gravelly brown clay
- gravelly clay
- gravelly sandy clay
- gray clay
- gray clay with silt lenses
- gray colored clay
- gray colored clay with little gravel
- green colored silty clay
- greenish clay
- greenish clayey, gray marly organic mudstone
- greenish colored clay
- grey colored clay with fossil
- grey marl with rare gravel
- grey marl with silty clay
- light brown plastic clay
- macrofossil silty clay
- marly clay
- plastic, gray colored clay
- rare sandy clay
- sand with little gravel
- sandy black clay
- sandy clay
- sandy clay containing fine gravel grains
- Sandy clay with fine gravel
- sandy clay with little gravel
- sandy gravelly brown clay
- sandy gray clay with little gravel
- sandy greenish clay with little gravel
- sandy silty clay
- sandy yellow clay
- silty clay
- silty clay with little gravel
- silty clay with macro fossil
- silty gray colored clay with little macro fossils
- silty sandy clay
- yellow clay
- yellow clay with little sand
- yellow colored clay
- yellow colored plastic clay
- yellow colored volcanic origin clay with localized gravel layer
- yellow colored, gravelly clay
- yellow greenish clay with localized gravel
- yellow sandy silty clay with little gravel

12. Sandstone

- fine gravelly sandstone
- sandstone

13. Conglomerate

- conglomerate
- conglomerate with cement
- loosely binded conglomerate with volcanic
- marl-sand-gravel
- marl-sandstone-conglomerate
- originated red gravel-sand
- sandstone conglomerate

14. Fanglomerate

- fanglomerate
- fanglomeratic layer containing volcanic
- originated loosely cemented coarse gravel

15. Calcarenite

- calcarenite
- hard bedded fossiliferous calcarenite limestone and sandstone

16. Siltstone

- beige clayey silty gray siltstone
- clayey siltstone with medium grained gravel
- gray marly siltstone
- grey siltstone
- siltstone
- siltstone
- siltstone with little gravel

17. Limestone

- clay with havara
- gravelly clay with havara
- gravelly clayey havara
- gray colored marly limestone with volcanic rock grains
- limestone
- limestone layered gravel
- limestone with fossils
- limestone with little clay
- limestone with little gravel
- limestone with oxidized volcanic rock grains
- limestone with volcanic rock grains

18. Marl

- beige marl
- chalky, little gravelly gray colored marl
- coarse gravelly greenish gray marl
- coarse sandy gray marl
- dark gray marl
- fine gravelly gray marl with little macro fossil
- fine gravelly greenish gray marl
- fine gravelly greenish marl with little sand
- fine gravelly marl
- fine gravelly marl with rare sand
- fine gravelly silty marl
- fossiliferous dark grey marl with rare silt
- fossiliferous gray marl
- fossiliferous grey-khaki marl with rare silt and fine gravel
- fossiliferous marl with little gravel
- fossiliferous silty gray marl
- gravelly (made up of chalk) grey colored marl
- gravelly gray marl
- gravelly marl
- gravelly silty gray colored marl
- gravelly silty marl
- gravelly yellow colored marl
- gray marl
- gray marl with gravel lenses sequence
- gray marl with greenish clay
- gray marl with little gravel
- gray marl with little sand
- gray marl with little silt
- gray marl with white marl grains
- gray marly volcanic
- greenish clayey gray marl
- greenish dark beige gravelly marl
- greenish dark beige gravelly marl with little sand
- greenish gray marl
- greenish gray marl with little fine gravel
- greenish gray marl with little sand
- greenish gray marl with little silt
- greenish light gray marl with little clay
- greenish marl
- greenish marl with little fine gravel
- greenish marl with little sand (dolomitic)

- greenish marl with localized silt lenses
- greenish marl with silt lenses
- Grey grenish marl with fine gravel containing little chalk
- grey marl
- gypsum with marl
- gypsum with rare marl
- high plasticity, little silty marl
- light brown silty marl
- light colored marl
- light gray marl
- limestone and volcanic origin grained gray marl
- limestone grained gray marl
- localized macro fossil greenish gray marl with little silt
- macro fossil gray marl
- macro fossil silty gray marl
- marl with gravel lenses
- marl with gray silt
- marl with little gravel
- marl with little silt
- marl with little silt and little gravel
- organic mudstone fragments bearing dark grey marl and hematite stains
- recrystallized gypsum with marl
- sandy greenish marl
- sandy greenish marl with little fine gravel
- selenitic gypsum with rare marl
- selenic gypsum, marl and pillow lava fragments
- silty gravelly marl
- silty gray marl
- silty gray marl sequence
- silty gray marl with little gravel
- silty gray marl with macro fossil
- silty gray marl with sand lenses
- Silty khaki-grey marl
- silty marl
- silty sandy marl
- volcanic grained gray marl
- yellow colored marl
- yellow marl
- yellow marl with little gravel

19. <u>Mudstone</u>

- gray mudstone
- organic mudstone with little gray marl and coarse sand
- organic mudstone with gravel and little sand towards bottom

20. <u>Bedrock</u>

- clayey volcanic rock with pillow lava
- pillow lava

APPENDIX C

TRANSACTS

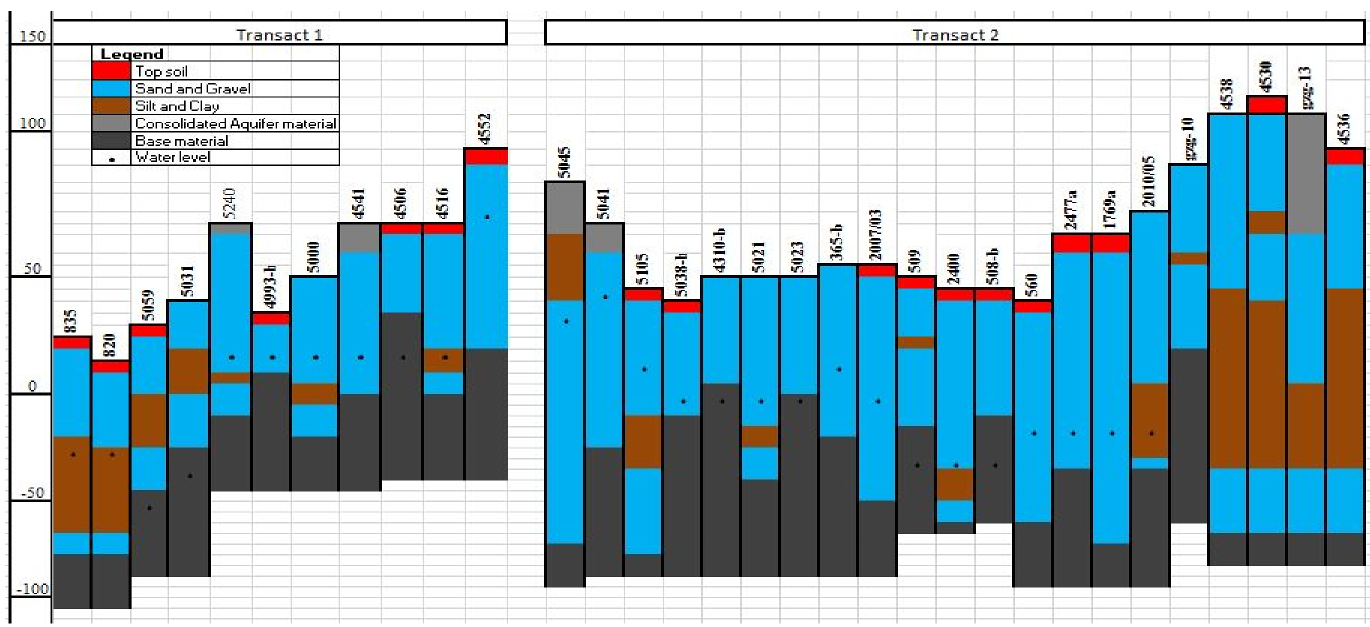

Figure C.1 Boreholes chart of Transact 1 and 2

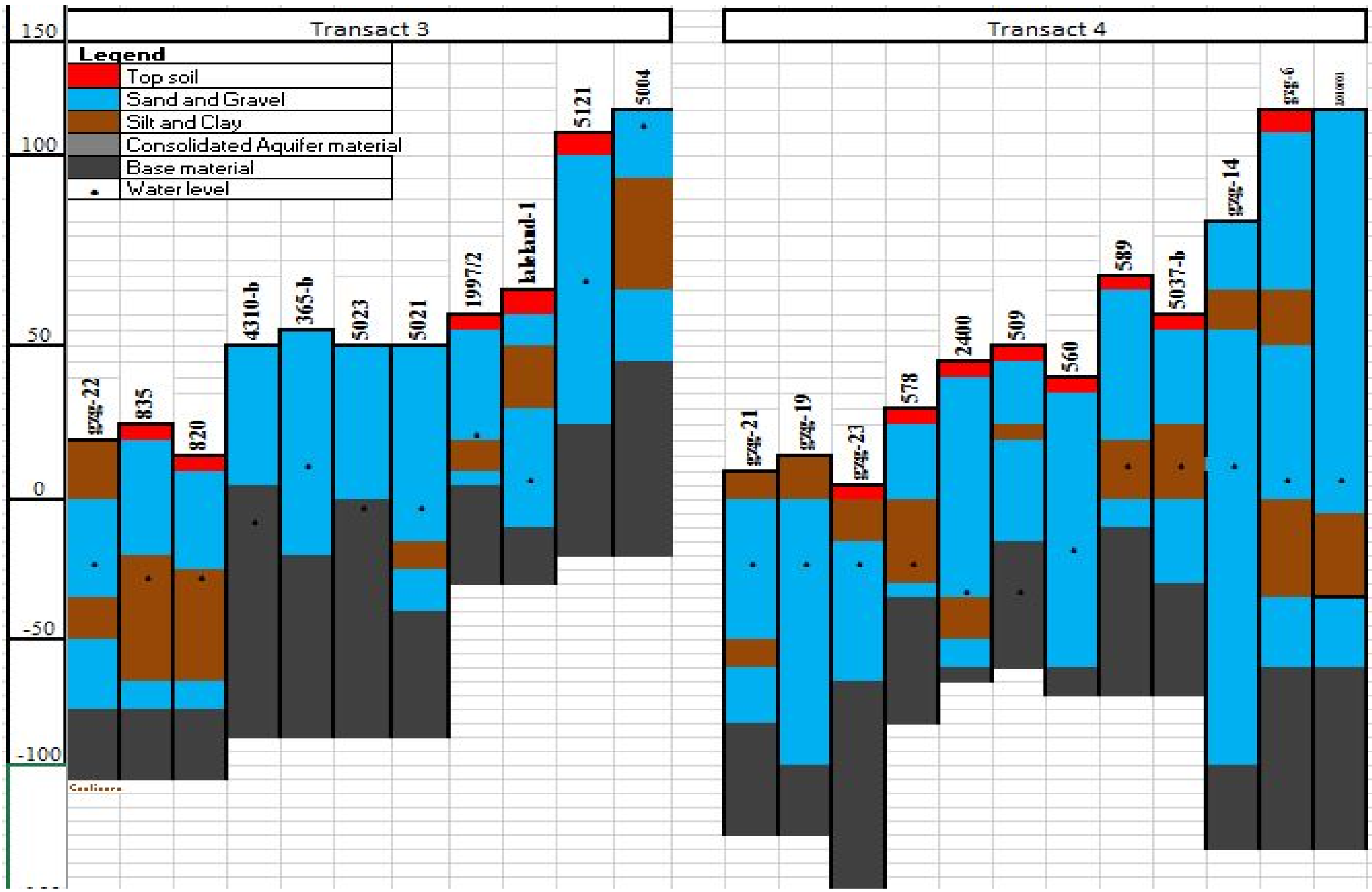

Figure C.2 Boreholes chart of Transact 3 and 4

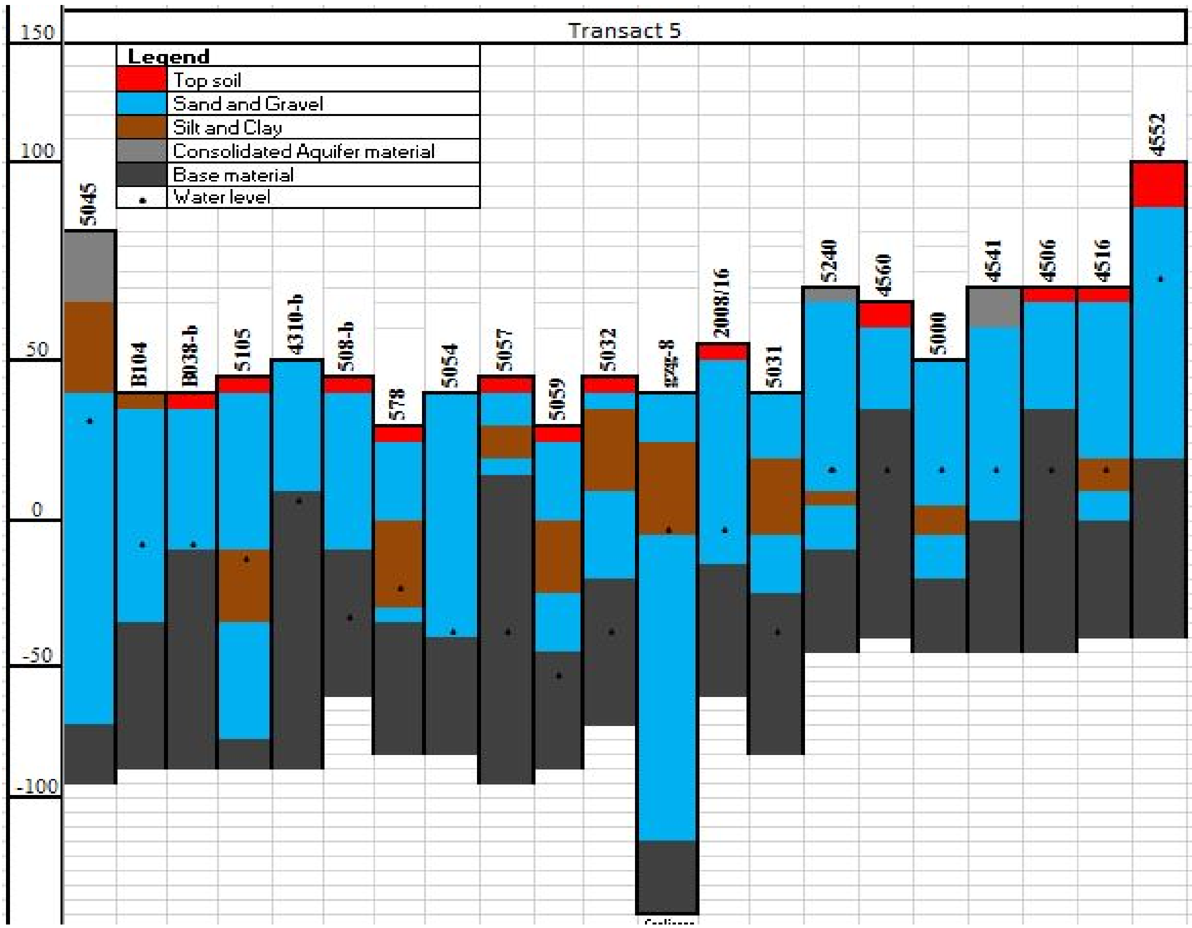

Figure C.3 Boreholes chart of Transact 5

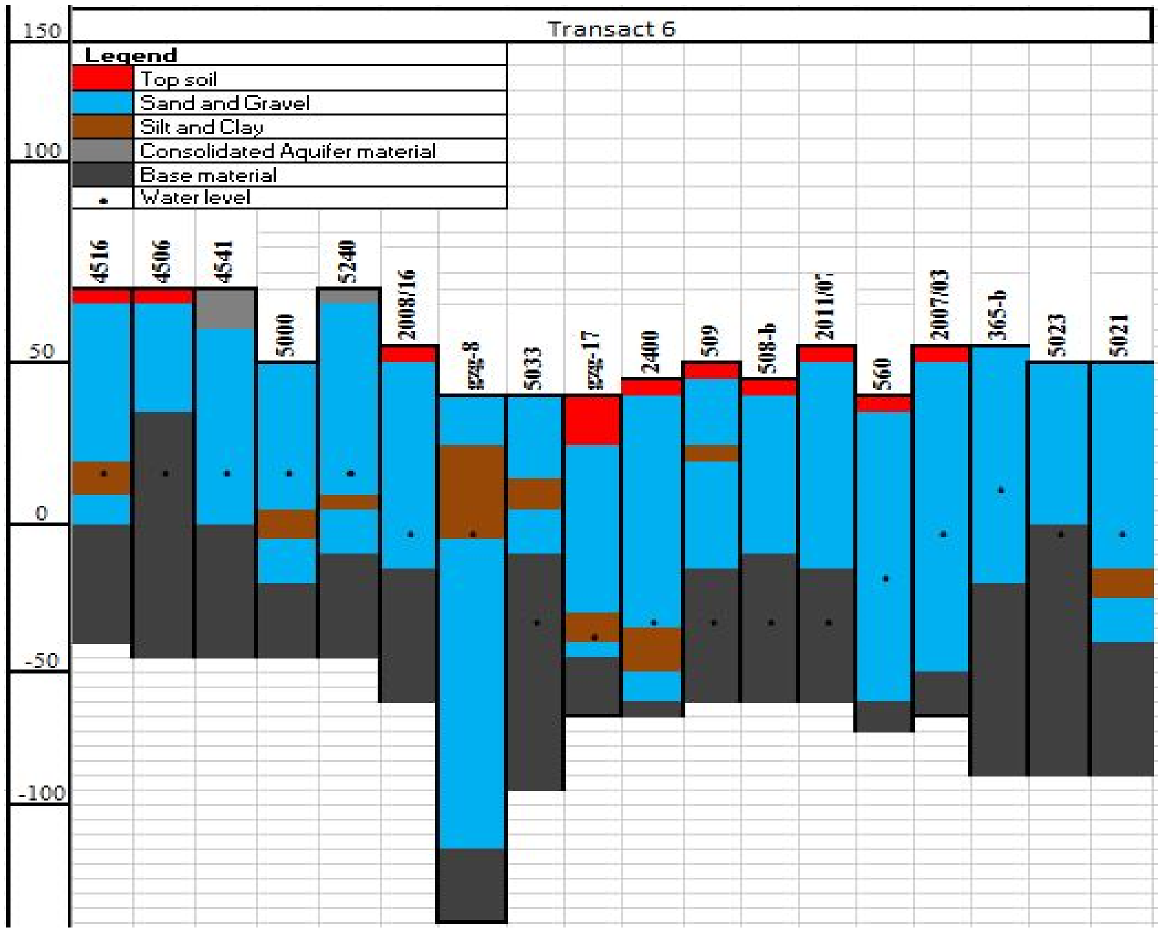

Figure C.4 Boreholes chart of Transact 6

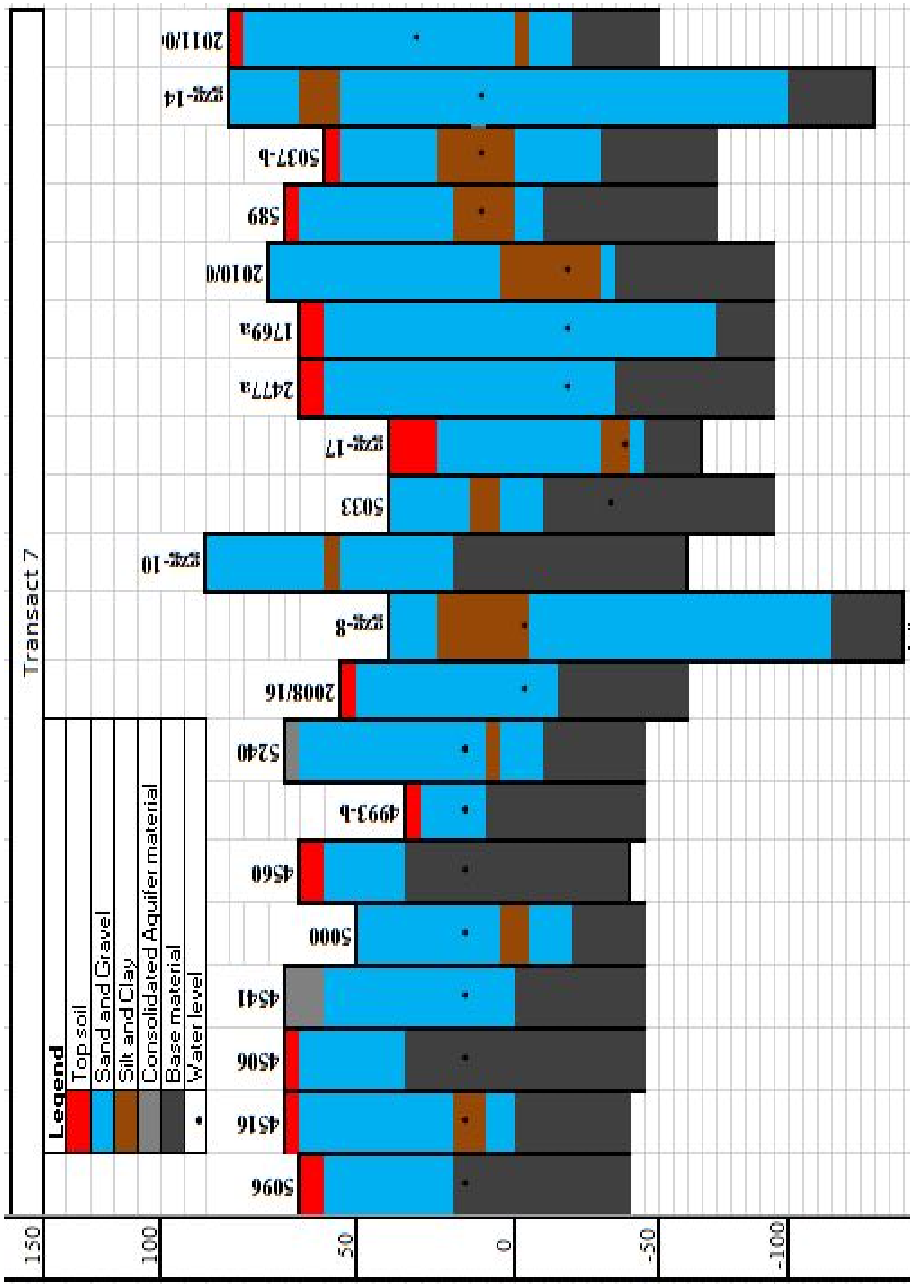

Figure C.5 Boreholes chart of Transact 7