INVESTIGATION OF THE SAFE AND SUSTAINABLE YIELDS FOR THE SANDY COMPLEX AQUIFER SYSTEM IN ERGENE RIVER BASIN

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Approval of the Graduate School of Natural and Applied Science.

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ABSTRACT

INVESTIGATION OF THE SAFE AND SUSTAINABLE YIELDS FOR THE SANDY COMPLEX AQUIFER SYSTEM IN ERGENE RIVER BASIN

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This study aims to determine the safe and sustainable development and management of groundwater resources in Ergene River Basin located in northwestern Turkey. A numerical groundwater model was developed for the Sandy Complex aquifer, which is the most productive and the most widespread aquifer in the basin. The finite difference model with 5900 cells was used to represent the steady and unsteady flow in the aquifer. The model was calibrated in two steps: a steady state calibration by using the observed groundwater levels of January 1970, followed by a transient calibration by using the observed groundwater levels for the period of January 1970 and December 2000.

The resulting model was used to develop groundwater pumping scenarios in order to predict the changes in the aquifer system under a set of different pumpage conditions for a planning period of 30 years between January 2001 and December 2030. A total of eight pumping scenarios were developed under transient flow conditions for the planning period and the results were evaluated to determine the safe and sustainable yields of the aquifer. The results, presented in the form of a trade-off curve, demonstrate that the continuation of the present pumping rates exceeds both the safe and the sustainable yields of the aquifer system.

Keywords: Ergene River Basin, calibration, groundwater management, safe yield, sustainable yield

ÖZ

ERGENE HAVZASI KUMLU KOMPLEKS AKİFER SİSTEMİNİN EMNİYETLİ VE SÜRDÜRÜLEBİLİR VERİMLERİNİN ARAŞTIRILMASI

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Temmuz 2004, 155 sayfa

Bu çalışmanın amacı Türkiye'nin kuzeybatısındaki Ergene havzası yeraltısuyu kaynaklarının emniyetli ve sürdürülebilir geliştirilmesini ve işletilmesini sağlamaktır. Havzadaki en yaygın ve üretime en uygun akifer olan Kumlu Kompleks akiferin sayısal yeraltısuyu modeli oluşturulmuştur. Yaklaşık 5900 hücreden oluşan Sonlu Farklar Akım Modeli akiferdeki kararlı ve kararsız akımı benzeştirmesi için kullanılmıştır. Model kalibrasyonu 1970 yılının Ocak ayında saha koşullarında gözlenen su seviyeleri ile yapılan kararlı akım koşullarında kalibrasyon ve bunu izleyen Ocak 1970-Aralık 2000 döneminde gözlenen su seviyeleri ile yapılan kararsız akım koşullarında kalibrasyon olmak üzere iki aşamada gerçekleştirilmiştir.

Ortaya çıkan model Ocak 2001 ve Aralık 2030 yılları arasını kapsayacak şekilde 30 yıllık bir planlama dönemi göz önüne alınarak akifer sisteminin çeşitli pompaj koşulları altındaki tepkisini belirlemek ve alternatif yeraltısuyu yönetim senaryoları kurulması için kullanılmıştır. Planlama dönemi için toplam sekiz yönetim senaryosu kararsız akım koşulları altında kurulmuş ve sonuçlar akiferin emniyetli ve sürdürülebilir verimlerinin belirlenmesinde kullanılmıştır. Değiş-tokuş eğrisi şeklinde sunulmuş olan sonuçlar, günümüzdeki pompaj koşullarının akiferin emniyetli ve sürdürülebilir verimlerinin üstünde olduğunu göstermiştir.

Anahtar Kelimeler: Ergene Havzası, kalibrasyon, yeraltısuyu yönetimi, emniyetli verim, sürdürülebilir verim

TO MY FAMILY….

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CHAPTER 1

INTRODUCTION

1.1 Purpose and Scope

In recent decades the value of groundwater has increased, as it is an important source of fresh water throughout the world. More than 2 billion people worldwide depend on groundwater for their daily supply (Kemper, 2003). A large amount of the world's agriculture, irrigation and large numbers of industries depend on groundwater. In areas where there are no surface water supplies or the surface water is contaminated by industrial facilities groundwater is almost always overexploited although the groundwater resources are renewable. Therefore the investigation of groundwater development under safe and sustainable yield concepts with their hydrologic implications is becoming an increasingly important issue all over the world as aquifers are being depleted when they are pumped above these limits.

Not surprisingly, persistent groundwater level declines and decrease in base-flow of the streams are also observed in northwestern Turkey. The Sandy Complex aquifer in Ergene River basin located in north-western Turkey has experienced rapid declines in groundwater levels during the past two decades.

This study was undertaken to determine the safe and sustainable yields and the limits of utilization for the Sandy Complex aquifer system by developing a groundwater flow model. The model was calibrated by finding a set of parameters, boundary conditions and stresses that produce simulated heads and fluxes matching field-measured values. The calibrated model was subsequently utilized to determine the response of the aquifer system under a set of pumping scenarios for a planning period of 30 years. Model results were presented in the form of trade-off curves to decision-makers ability to select an optimum development strategy to sustain the aquifer.

1.2 Location and Extent of the Study Area

Ergene River basin is located within the Thracian basin in northwestern Turkey stretching up to the borders with Greece and Bulgaria. It lies between $40^0$45’-$42^0$10’ north latitudes and $26^0$15’-$28^0$15’ east longitudes (Figure 1.1). The basin is situated within the provincial boundaries of the cities of Edirne, Kırklareli and Tekirdağ. Catchment area of Ergene River Basin is 11325 km^2. The basin is surrounded by Istranca Mountain range in the north and Korudağ and Ganos Mountains in the south.

1.3 Previous Studies in Ergene River Basin

In Turkey, General Directorate of the State Hydraulic Works (DSİ) is the agency responsible for investigation, management and conservation of groundwater resources.

The geological survey of the Ergene River basin by DSİ concerning water resources began in 1958. Since then studies conducted by Erguvanlı (1958), Kuran (1959), Alkan (1967) and Çongar (1967) formed the basis for initial data collection in the basin.

Italconsult conducted a study between 1968-1970 named as “Ergene Basin Groundwater Development Project”. The purpose of the project, which the DSİ commissioned Italconsult to perform under the terms of a Contract, was to evaluate the groundwater resources in the Ergene River Basin. A master plan was designed to determine convenient zones for irrigation by groundwater. Groundwater recharge and discharge calculations were made and a groundwater budget was evaluated in this project. Agriculture and irrigation were also examined in this study. A resistance-capacitance type electric

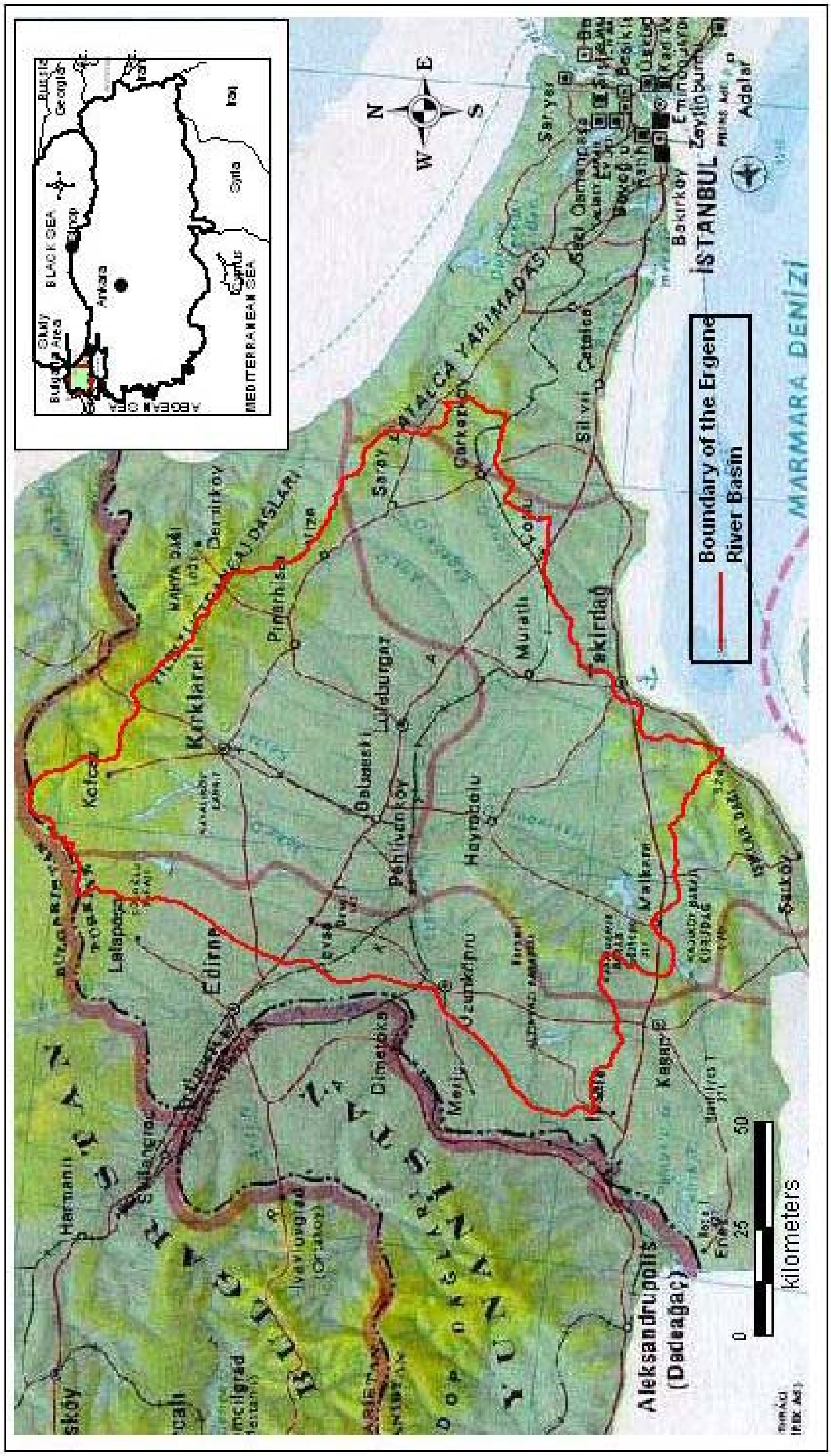

Figure 1.1. Location map of the Ergene River Basin

analog model was constructed and operated to predict the hydrogeological conditions. The analog model constructed used the finite difference approximation with its 2 km X 2 km sized square mesh. The model was used to test five scenarios for groundwater exploration for the 1970-1990 period. While developing these scenarios two main policies for groundwater abstraction were considered as continuation of the year 1970 pumping conditions and the annual recharge equals the annual pumpage rates. For all scenarios groundwater level and groundwater level change maps were given.

After the study of Italconsult, no detailed study has been carried out regarding the groundwater resources of the Ergene River Basin. DSİ revised the study of Italconsult and a new report was prepared named as “Ergene Havzası Hidrojeoloji Raporu” in 2001. In this study brief information concerning the geology, hydrogeology and groundwater quality was given. Also groundwater recharge and discharge calculations were made and a groundwater budget was evaluated.

CHAPTER 2

DESCRIPTION OF THE STUDY AREA

2.1 Physiography

Ergene Basin is a part of the Thracian Basin together with Meriç Basin. Through the northeast part of the Thracian Basin, Istranca mountain ranges trends along southeast northwest direction with a maximum elevation of about 1300 m. Ganos Mountains, having an elevation of about 700 m, borders the basin along the southern part. The central part consists of a large spoon shaped basin draining southwestwards where there are hills and ridges rising to heights not exceeding 100-200 m. The relief map given in Figure 2.1 shows the drainage pattern and morphological characteristics of the basin. Ergene Basin, having a total catchment area of about 11325 km^2, is dissected by streams and their tributaries thus producing a rugged topography. There is a low strait separating the Ergene Basin and the lower parts of the Meriç Basin towards west.

Ergene River emerges from the Istranca Mountains and follows a 281 km long path through the center of the plain and finally discharges to Meriç River. It is one of the most important branches of the Meriç River and it has got many tributaries in the Ergene Basin.

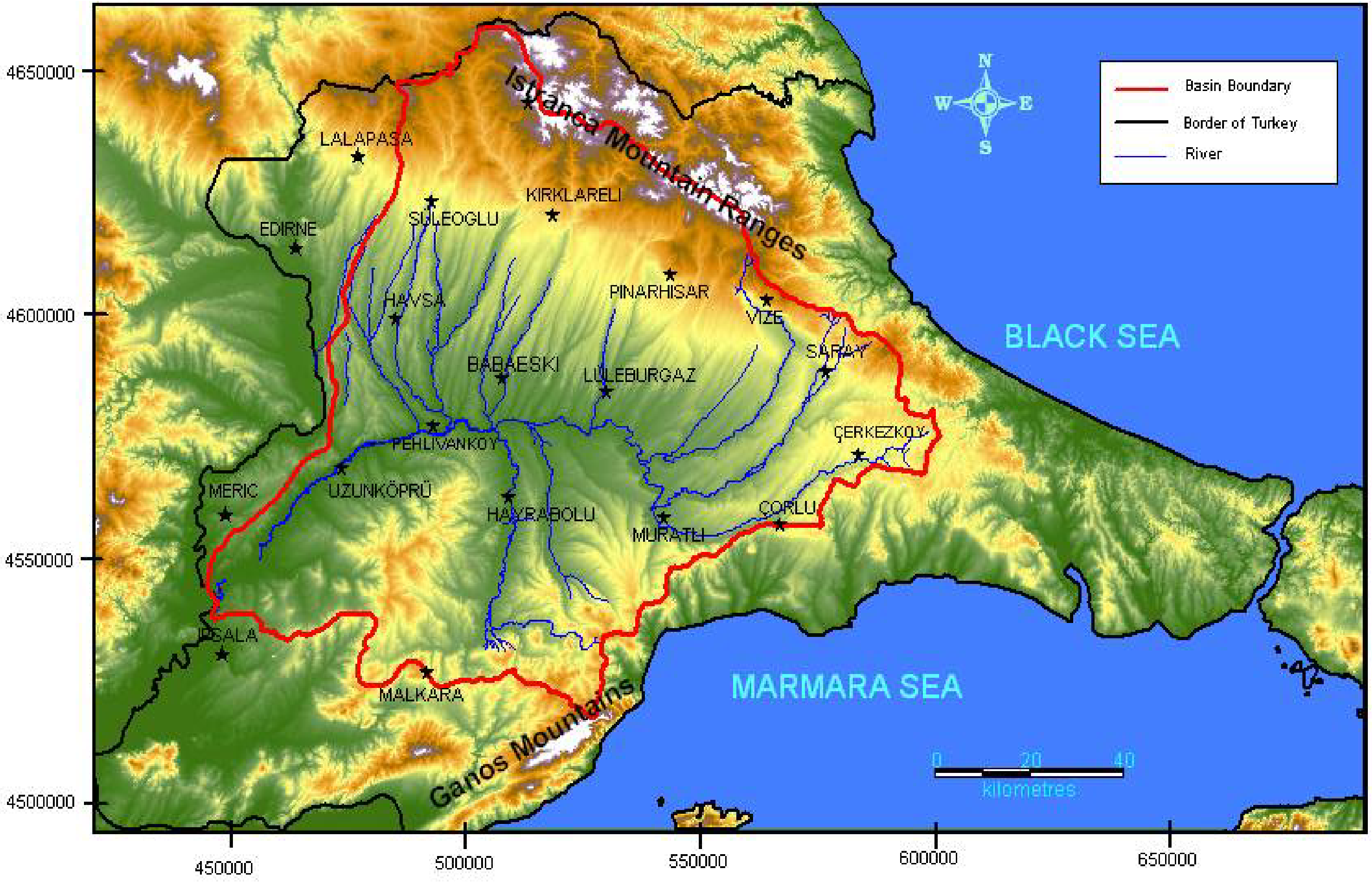

Figure 2.1. Relief map of the Ergene River Basin.

2.2 Climate

Ergene River Basin has a continental- type climate in inland regions. The average annual temperature is around 13.5 °C with monthly averages changing between 2.2 to 7 °C in winter, whereas with an average of about 23 °C in summer. Meteorological records are available from the stations in Beyazköy, Ayvacık, Doğanköy, Marmaracık and Kurtdere operated by DSİ and in Alpullu, Babaeski, Banarlı, Çerkezköy, Çorlu, Dambaslar, Dereköy, Edirne, Hasköy, Havsa, Hayrabolu, Kırcasalih, Kırklareli, Lüleburgaz, Malkara, Muratlı, Pehlivanköy, Pınarhisar, Saray, Sarımsaklı, Süloğlu, Tekirdağ, Uzunköprü and Vize operated by DMİ (State Meteorological Works). Continuous records are available from most of these stations for the period of 1964-2000.

Measurement of daily precipitation is made at all of the meteorological stations. Other than measurement of precipitation, temperature, evaporation, relative humidity, wind and radiation is also measured at some of these stations. According to long term measurements, the minimum average annual precipitation is measured as 508.1 mm in Beyazköy meteorological station, and the maximum annual precipitation is measured as 700.9 mm in Ayvacık meteorological station. The arithmetic average obtained by using the annual precipitation values obtained from various stations located in the basin is 591.3 mm (Table 2.1). Figure 2.2, 2.3 and 2.4 shows the cumulative deviation from average annual precipitation graph, based on the data obtained from Edirne, Çorlu and Lüleburgaz meteorological stations respectively for the record period of 1929-2002. The distributions of dry and wet periods are well observed from these graphs: for Edirne and Lüleburgaz stations 1939-44, 1951-69 and 1994-99 are indicated by wet periods whereas 1944-51 and 1971-94 are indicated by dry periods. For Çorlu station 1942-50, 1956-61 and 1983-93 are indicated by dry periods, 1950-56, 1961-82 and 1993-2001 are indicated by wet periods.

Table 2.1. The mean monthly and annual precipitation measured in the meteorological stations found in the Ergene River Basin (mm).

Name of the Station	Years of Record	MONTH												Annual Precipitation
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Alpullu	1942-1987	74.3	54.3	52.7	46.3	50.4	48.0	31.1	18.4	25.3	50.8	83.5	75.0	607.8
Ayvacık	1969-2000	65.5	55.5	57.2	56.8	47.8	45.2	36.7	26.4	31.6	87.7	94.2	92.0	700.9
Babaeski	1939-1983	64.6	52.8	49.8	44.3	49.6	46.5	33.0	20.7	31.3	49.0	74.3	81.6	590.7
Banarlı	1965-1989	76.1	53.7	57.9	51.6	43.5	43.4	20.4	18.8	22.8	49.4	83.8	80.5	598.0
Beyazköy	1965-2000	52.5	41.5	43.6	44.1	46.6	38.1	21.8	14.2	27.9	47.4	65.9	68.1	508.1
Çerkezköy	1964-1997	69.0	48.1	45.7	44.6	47.0	49.2	26.2	21.3	27.7	52.9	77.6	76.8	539.5
Çorlu	1937-2002	64.2	50.3	48.4	42.8	44.6	37.3	22.3	20.1	32.4	49.6	74.3	82.7	563.9
Dambaşlar	1965-1999	66.7	50.7	55.9	48.0	46.0	47.1	31.9	19.1	29.4	62.8	76.7	82.3	587.0
Doğanköy	1967-2000	63.0	57.7	59.1	51.6	39.7	42.0	18.9	18.6	31.3	64.7	78.1	83.6	608.7
Edirne	1929-2002	57.6	48.4	48.7	49.0	50.1	46.2	30.6	24.5	33.9	53.9	72.8	72.6	588.3
Hasköy	1965-1987	62.9	49.9	47.9	45.1	51.4	38.8	27.2	20.9	34.9	50.0	60.8	66.9	556.1
Havsa	1964-1987	68.3	52.4	56.8	50.2	46.4	42.6	22.7	17.1	37.5	49.9	64.0	78.9	572.2
Hayrabolu	1929-1989	72.7	57.7	55.5	45.0	42.8	39.7	28.3	12.9	30.0	52.1	74.0	88.0	592.8
Kırcasalih	1965-1978	72.2	68.6	64.5	50.3	48.0	38.2	16.9	14.8	41.5	70.4	72.0	85.1	634.7

Table 2.1. (Continued)

Name of the Station	Years of Record	MONTH												Annual Precipitation
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Kırklareli	1930-2002	59.4	48.0	46.9	43.9	49.9	49.4	27.5	22.8	27.7	49.0	69.5	70.4	564.3
Kurtdere	1969-2000	59.4	51.1	56.2	48.0	41.0	39.7	22.6	13.7	24.8	64.6	75.4	80.0	581.9
Lüleburgaz	1929-2002	67.2	52.4	53.1	44.9	46.1	45.8	27.9	18.9	33.8	55.3	77.1	79.9	593.6
Malkara	1931-2002	81.4	69.0	72.2	48.4	50.6	42.7	24.4	15.8	37.0	56.9	95.0	119.5	668.9
Muratlı	1959-1990	64.4	47.8	55.4	47.5	41.0	48.1	24.4	21.2	27.0	57.9	84.1	91.7	584.1
Pehlivanköy	1938-1984	75.4	62.5	59.5	49.0	44.7	44.5	23.6	21.7	37.1	67.3	83.2	82.7	599.4
Pınarhisar	1930-2002	59.0	52.8	46.8	46.7	51.0	50.8	27.0	20.7	35.9	49.8	73.4	81.9	595.7
Saray	1956-1982	87.5	57.1	60.1	53.7	53.0	35.0	23.0	31.6	42.1	76.5	91.9	93.6	678.5
Sarımsaklı	1938-1990	62.8	51.3	48.8	45.7	48.2	41.2	26.2	19.1	27.6	47.0	75.1	71.2	553.0
Süloğlu	1964-1988	52.3	42.3	39.8	43.3	49.1	43.1	21.6	20.0	28.8	39.2	57.6	58.9	486.3
Tekirdağ	1970-2002	59.4	51.8	56.5	44.5	41.0	36.0	26.7	18.5	34.8	57.9	73.4	73.6	560.2
Uzunköprü	1970-2002	60.5	57.0	72.7	52.4	38.9	43.7	26.3	24.2	33.3	68.5	96.0	89.5	639.9
Vize	1957-2002	82.3	51.3	54.4	46.7	43.1	41.7	28.9	17.2	27.9	60.5	70.4	93.0	611.1
AVERAGE														591.3

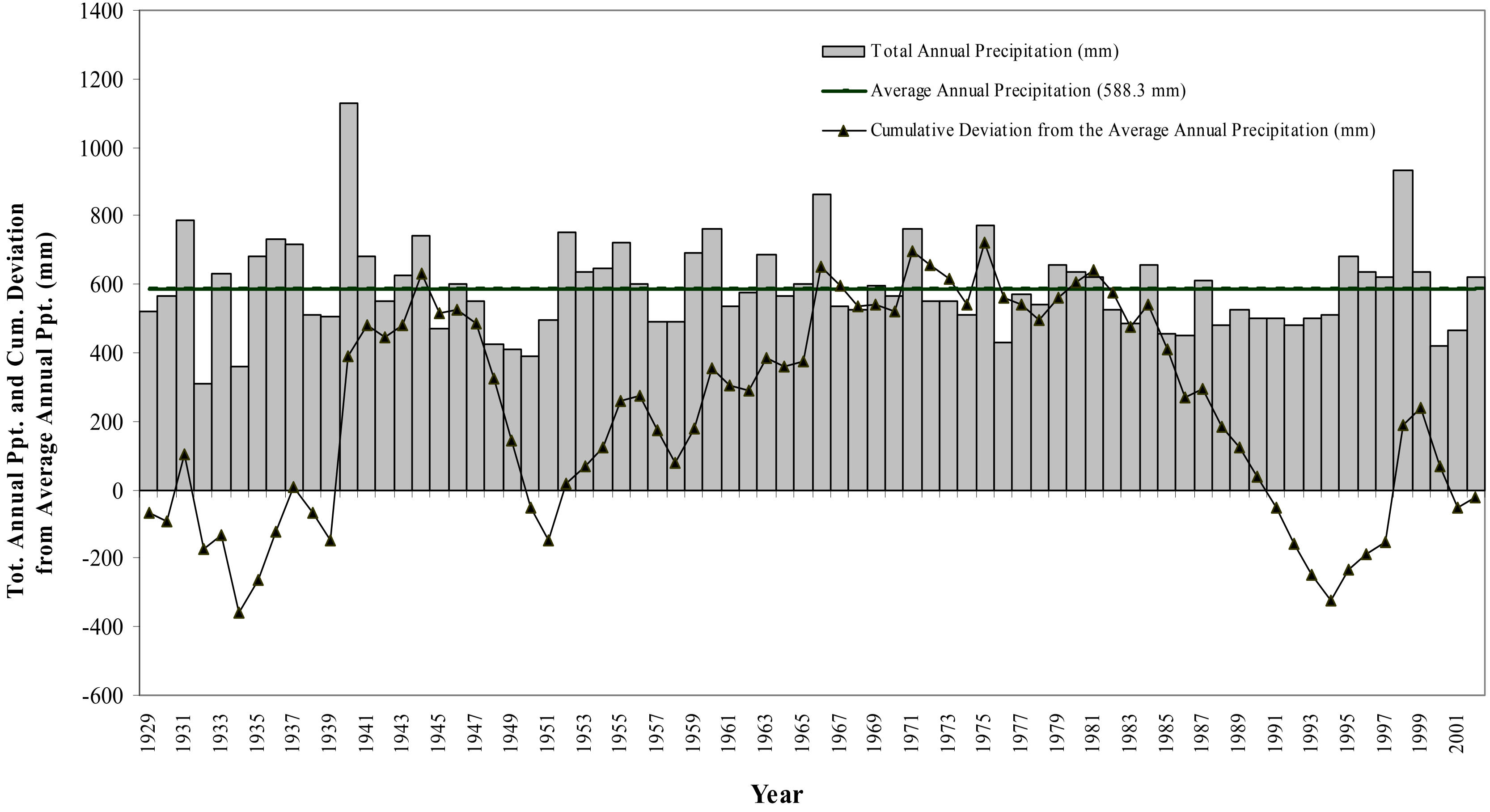

Figure 2.2. Cumulative deviation from the average annual precipitation and distribution of precipitation for Edirne Station.

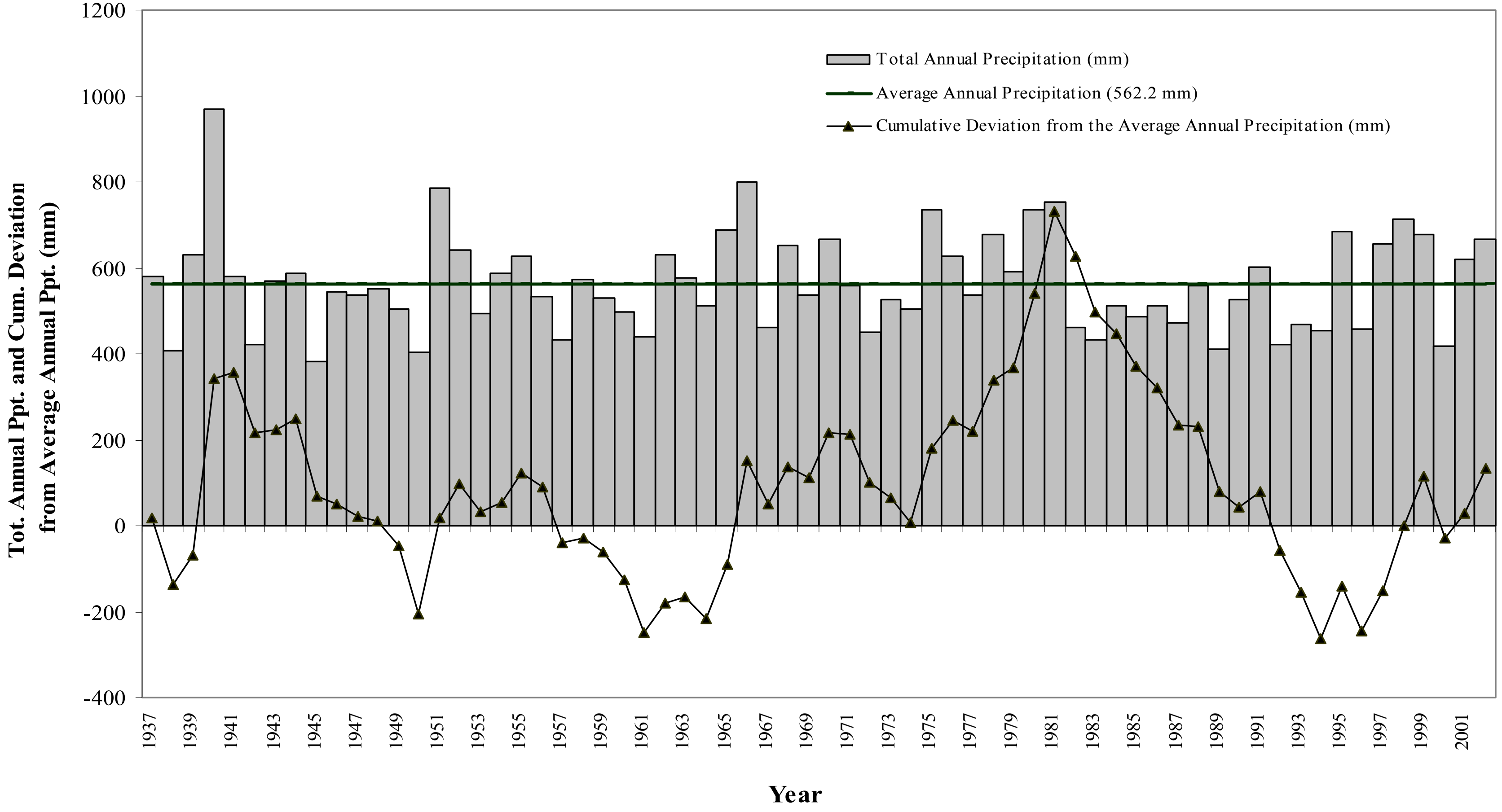

Figure 2.3. Cumulative deviation from the average annual precipitation and distribution of precipitation for Çorlu Station.

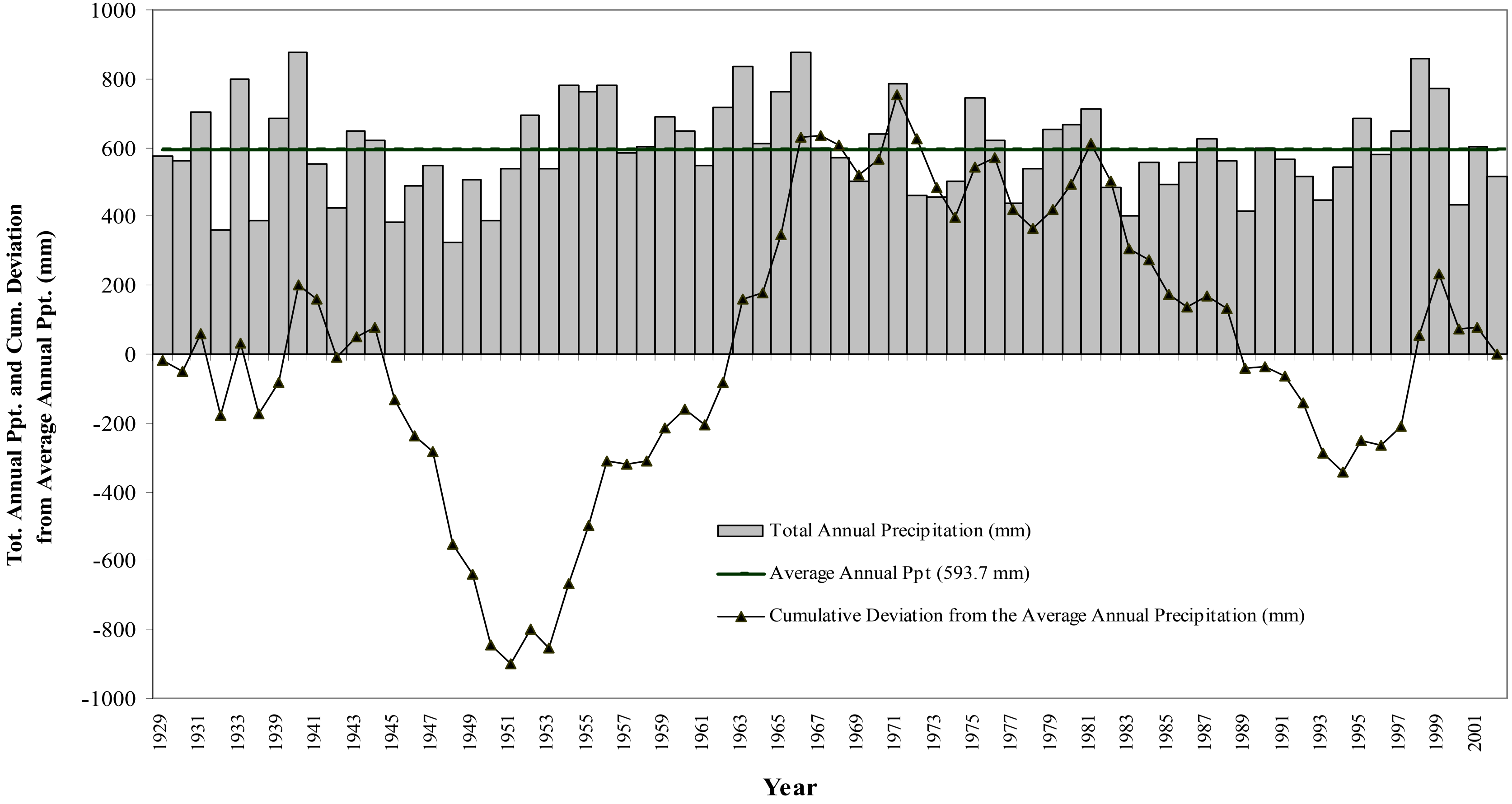

Figure 2.4. Cumulative deviation from the average annual precipitation and distribution of precipitation for Lüleburgaz Station.

Measurement of evaporation is made at Edirne (1962-2002) and Beyazköy (1965-2000) meteorological stations using Class-A pan. According to long-term measurements obtained from these stations annual average evaporation is 935.7 mm for Edirne and 1171.4 mm for Beyazköy.

According to the long term measurements obtained from Edirne, Kırklareli and Lüleburgaz meteorological stations, mean annual relative humidity is determined as 73% (DSİ, 2004).

2.3 Geology

2.3.1 Regional Geology

The basement of Thracian basin named as Istranca Massive, is formed from Paleozoic metamorphic and magmatic rock units. To the north, quartzites alternating with chloritic phyllites and mica schists occur, while to the south marbles and igneous rocks are found.

The basement rocks are overlaid by Tertiary deposits represented by Eocene, Oligocene, Miocene and Pliocene. Deposition of these Tertiary sediments started during the Middle Eocene. Eocene rocks are made up of conglomeratic sandstone followed by a reef limestone complex. These rocks are followed by the Upper Eocene-Lower Oligocene units consisting of a well-bedded alternation of claystones, siltstones and sandstones deposited in shallow waters. Upper Oligocene rocks were laid down in lagoon and bay environments and comprised of calcareous and micaceous claystones. The age of upward-fining sequences of sandstones and claystones of intertidal fluviatile origin are Early to Middle Miocene. The Pliocene terrestrial units consist of sands and clays with occasional pebble beds. Quaternary deposits are mostly laid down during the development of the present drainage system in Ergene Basin therefore found in the main valleys of the basin (Figure 2.5) (Doust and Arıkan, 1974).

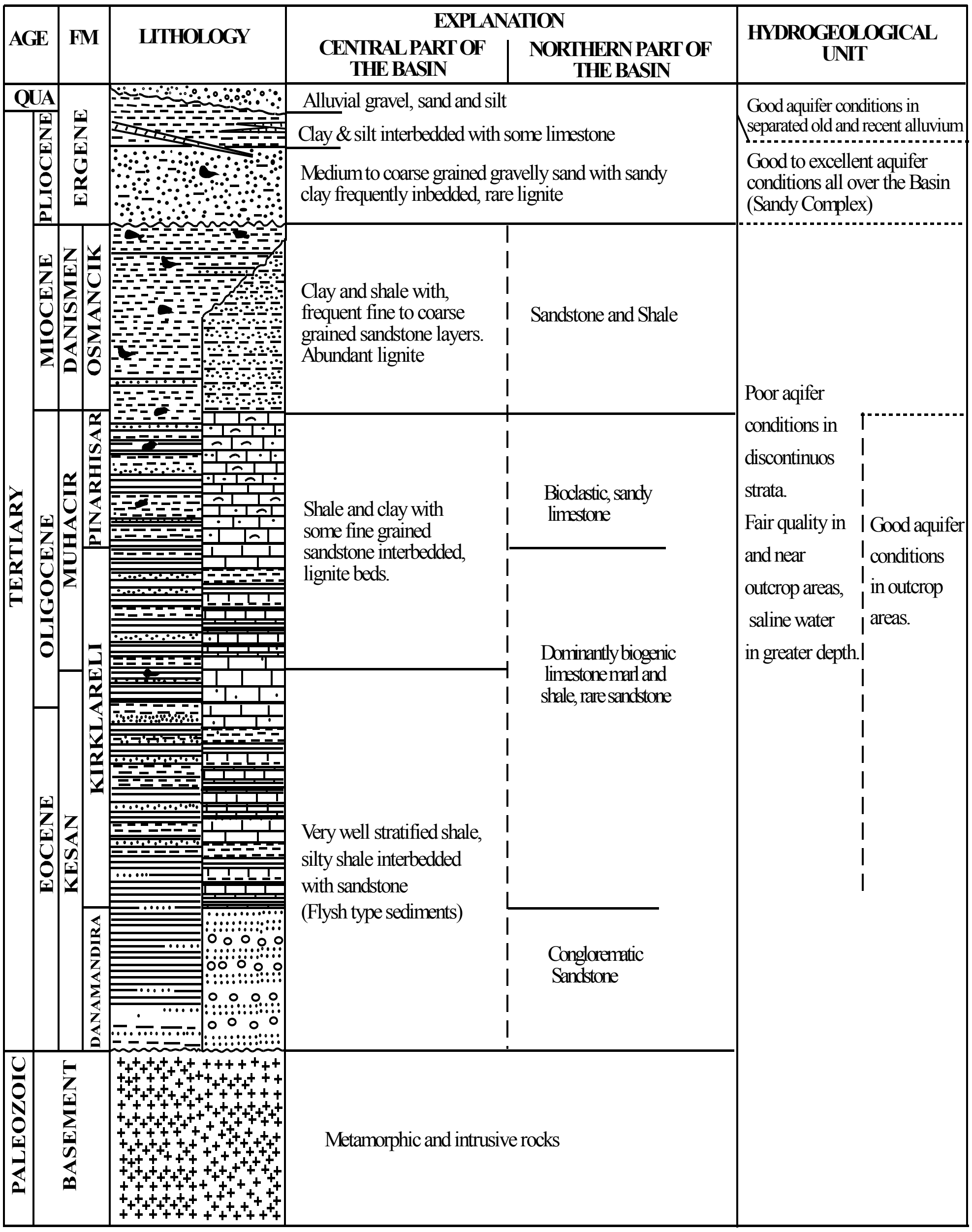

Figure 2.5. Generalized columnar section of the Ergene River Basin (Doust and Arıkan, 1974)

2.3.2 Basin Geology

Ergene River Basin is a part of Thracian basin. It is located in the northwestern portion. There are mainly two geographically restricted rock-stratigraphic sequences for the central and northern part of the basin. The stratigraphic sequences for the central and northern part of the basin are shown in the generalized columnar section given in Figure 2.5.

The central part of the basin succession comprises a sequence of claystones, sandstones and siltstones on the Paleozoic basement. Four major lithological divisions have been recognized: Keşan, Muhacir, Danişmen and Ergene Formations. An alternation of shale-claystones, siltstones and fine-grained poorly sorted sandstones deposited by turbidity currents forms the Eocene to Lower Oligocene Keşan Formation. Claystones with sandstones and siltstones of lagoonal origin form the Upper Oligocene Muhacir Formation. An alternation of claystones and fine to medium-grained sandstones of intertidal and fluviatile origin form the Miocene Danişmen Formation. Clays, marls, sands and conglomerates of lacustrine and fluviatile origin forming the Pliocene to Quarternary Ergene Formation is separated from underlying series by an unconformity (Doust and Arıkan, 1974).

The second succession representing the northern part of the basin begins with the conglomeratic sandstones of Danamandira Formation followed by a reef limestone complex, the Kırklareli Formation. It is overlain by the Pınarhisar Formation, composed mainly of bioclastic, sandy limestone. The Pınarhisar Formation is followed by the sandstones of Osmancık Formation. As in the central part of the basin, the Pliocene to Quaternary Ergene Formation unconformably overlies the rest of the sequence (Doust and Arıkan, 1974). The Pliocene series of Ergene Formation was divided into two subgroups named as Çorlu Formation for the lower part and Babaeski Formation for the upper part by Italconsult (1970).

Pliocene Çorlu Formation has been named as the “Sandy Complex” by the hydrogeologists because this name well reflects its lithostratigraphical characteristics. It outcrops in the western and eastern parts of the basin whereas in the central part it is found beneath the Babaeski Formation. The lower boundary of the formation is clear: it is always marked by an increase in grain size of the sandy strata relative to the underlying formations. The gravelly coarse sands are always in contrast with the Miocene. The upper boundary is also clearly marked by the contact between predominantly medium-coarse sand with clayey-silty sediments. The sand grains are generally subangular to subrounded. Only gravel grains have well-rounded in shape. The depositional environment is deltaic-lacustrine type.

Babaeski Formation represents the upper part of the Pliocene. It is present in outcrops or below the Quaternary cover in the central part of the basin. Babaeski Formation consists of a monotonous sequence of brownish-yellow clay, silty clay finely interbedded with rare thin beds of argillaceous sand and fine gravel. Lacustrine type porous limestone beds can also be seen. The depositional environment of the Babaeski Formation was different from that of the Çorlu Formation, lithostratigraphic characteristics indicating a lacustrine type environment (Italconsult, 1970). In Figure 2.6 a geological map showing the distribution of the units observed in the study area can be seen (Modified from MTA, 2002).

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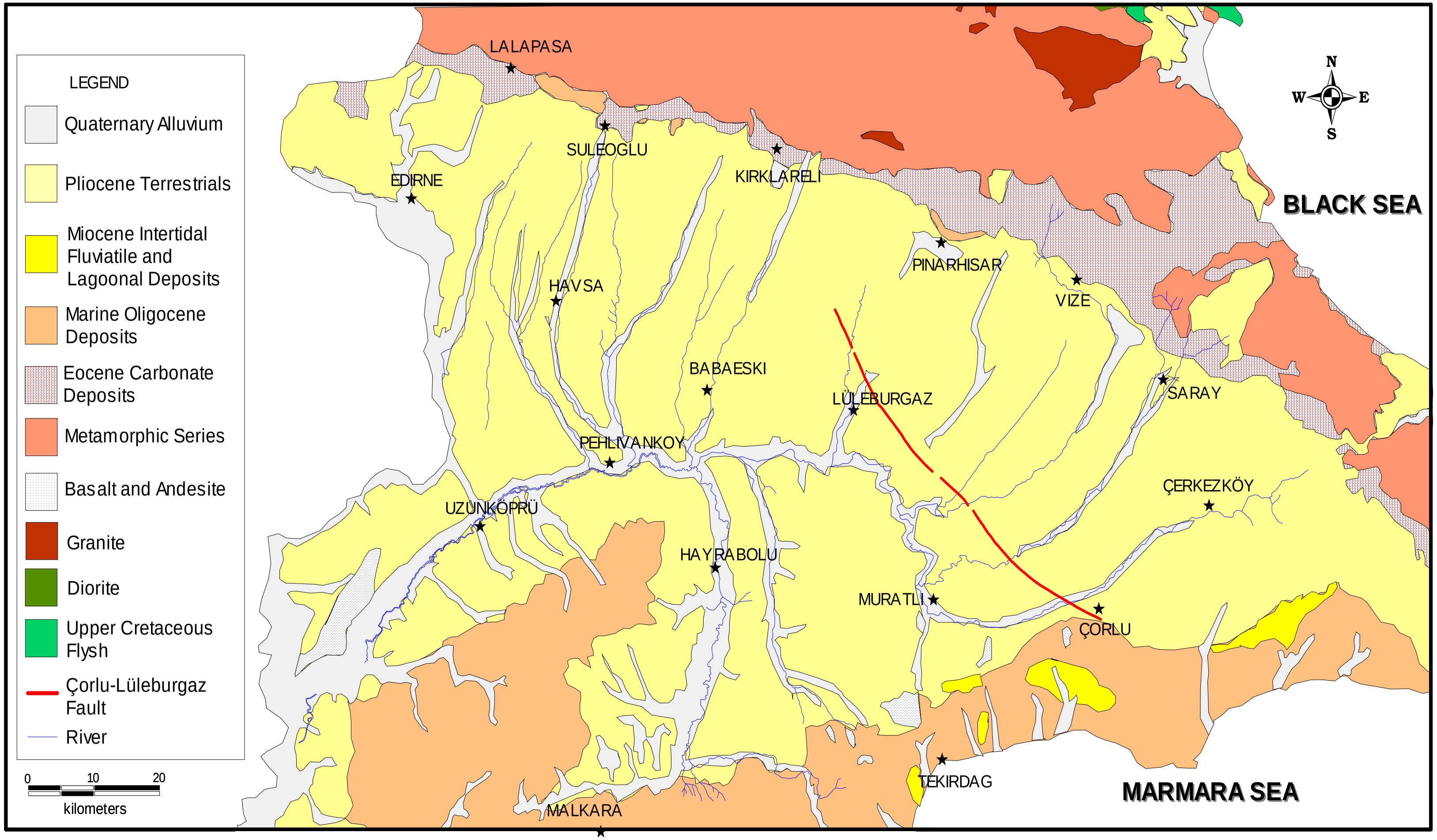

Figure 2.6. Geological Map of the Ergene River Basin (Modified from MTA, 2002).

2.4 Hydrogeology

2.4.1 Water Resources

2.4.1.1 Surface Water Resources

The Ergene River and its tributaries constitute the major component of surface water resources in the Ergene River Basin (Figure 2.7). The most prominent tributaries can be listed as; Lüleburgaz Brook, Ergene Stream, Çorlu Stream, Karıştıran Stream, Şeytan Stream, Pınarbaşı Stream, Süloğlu Stream, Ana Stream, Beşiktepe Stream and Hayrabolu Stream. Several stream gauging stations were established on the main channel and also on tributaries by DSİ and EİEİ (Electrical Survey Administration). According to streamflow measurements obtained from these stations, significant decrease in streamflow is evident in summer period in some of the tributaries. In summer, although Ergene River can not get enough water from its source, the main channel never dries up completely because of the fact that the groundwater used for certain purposes is discharged to the river. According to the measurements of monthly flows starting from 1969 until 1993 at 105-Uzunköprü Station (drainage basin 10194.8 km^2), location of which can be seen in Figure 2.7, the annual average streamflow value is 23.93 m^3/sec (Figure 2.8) (DSİ, 2001).

2.4.1.2 Springs

According to Italconsult (1970), the main springs within the basin are located in the southern part of the Eocene limestone aquifer. These are karstic springs; the ones in Kaynarca Kocakaynak have an average discharge of 200 lt/sec, whereas the ones in Poyralı have around 150 lt/sec. In addition to these, there are Pınarbaşı springs located in the Pliocene limestone aquifer, east of Lüleburgaz, having an average discharge of 400 lt/s. Moreover, there are many springs with discharges ranging between 10-70 lt/sec along a line between Pınarhisar and Vize.

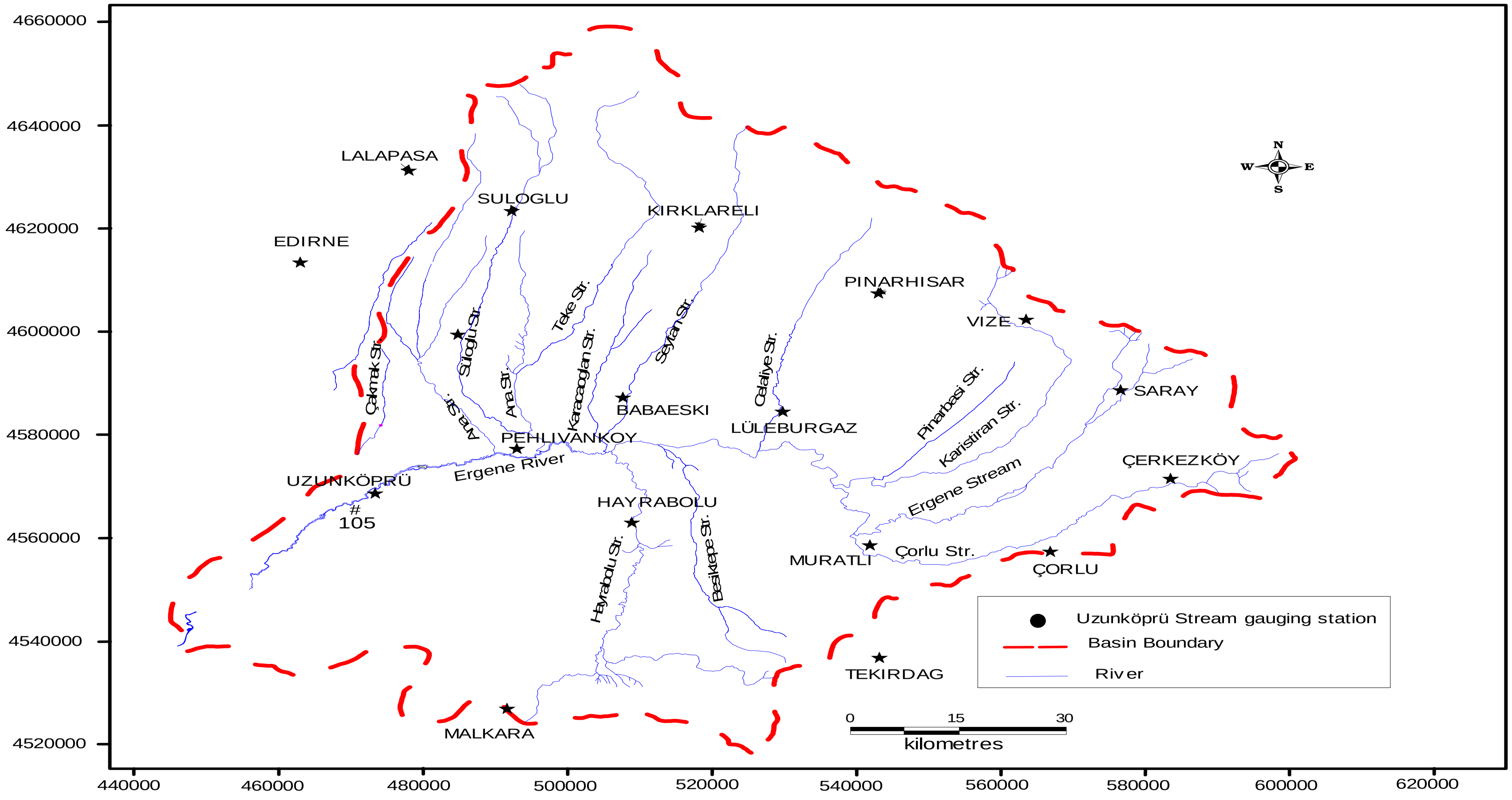

Figure 2.7. Drainage pattern of the Ergene River Basin.

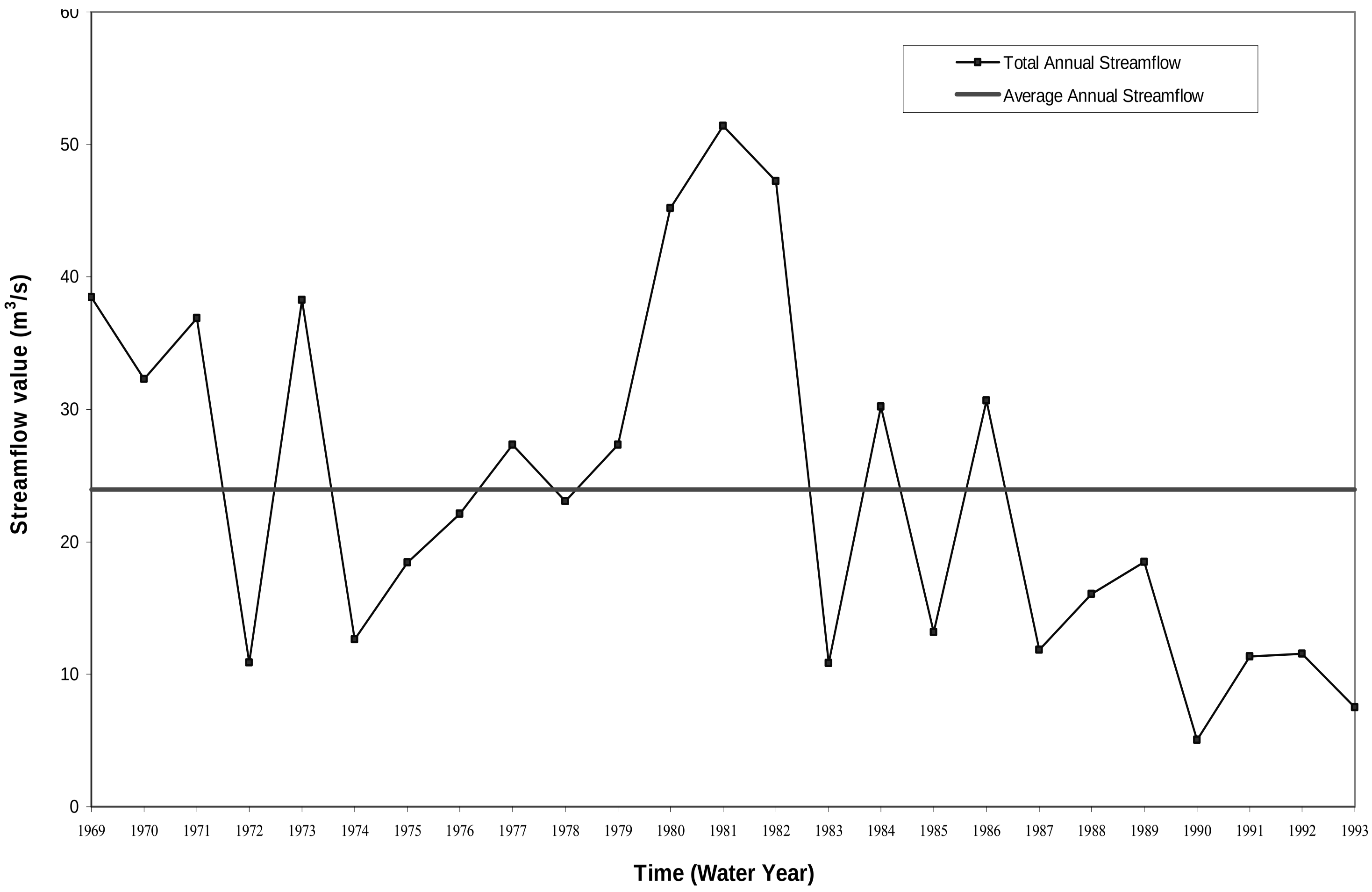

Figure 2.8. The discharge values versus time for 105-Uzunköprü station (DSİ, 2001).

2.4.1.3 Wells

In the Ergene River Basin, there are numerous shallow and deep-water wells opened for domestic and irrigation purposes and for the industrial use. The number of wells opened for Toprak Su cooperatives for irrigation purposes during the period between 1970 and 2003 is 394. Besides, there are more than 5000 wells opened by DSİ, YSE, İller Bankası, Köy Hizmetleri and by individuals. According to Italconsult (1970) in 1969, there were 66 abandoned wells, 49 observation wells, 95 drinking-water supply wells, 1117 production wells for irrigation, 30 unused wells and 45 wells opened for the project carried by them.

More than 1000 wells were drilled by DSİ for exploration, drinking-domestic and irrigation purposes. The usage of the aquifer was initiated around 1958 in the eastern part of the basin by private users in an uncontrolled manner. In the assessment of the historical data, the most important information concerns the evaluation of the amount of water abstracted each year since 1958. It was estimated that there were about 400 private irrigation wells operating from the Pliocene Sandy Complex Formation in 1970 (Italconsult 1970). In 1970's wells for irrigation purposes were drilled and until 2003, 365 wells were drilled for 57 cooperatives. The water allocated to the cooperative wells for irrigation purposes by DSİ is 122.8 hm^3/year.

233 wells were drilled by İller Bankası by the end of 2003 in order to cover the drinking and domestic water needs of municipalities in Ergene River basin, 78 of them were opened in Edirne, 40 in Kırklareli and 115 in Tekirdağ.

Köy Hizmetleri has drilled 176 wells in Edirne, 122 wells in Kırklareli and 86 wells in Tekirdağ in order to cover the drinking and domestic uses of villages.

Starting from the year 1989 number of wells drilled by DSİ and İller Bankası show a rapid increase. This increase can be attributed to the increasing demand for groundwater because of industrial use, dry periods, and decreasing water level elevations.

Numerous wells were opened by individuals, municipalities and private companies for the irrigation, drinking and domestic purposes. The location of some of the wells opened by DSİ, YSE, İller Bankası and Köy Hizmetleri can be seen in Figure 2.9. Most of the wells opened by individuals do not have reliable information, as they can not be recorded by DSİ.

2.4.2. Water Bearing Units and Characterization

2.4.2.1 Hydrogeologic Classification of Units

The Ergene River basin was studied in detail by Italconsult in 1970 by using geological, geophysical and well-log information. The various lithologic units in the basin were classified hydrogeologically based on their water bearing potential. The oldest units in the Ergene basin are the Paleozoic basement crystalline rocks, comprising gneisses, schists, marbles and granodiorites appearing in outcrop over about 1800 km^2 of the area in the Istranca Mountain Range. The crystalline basement is of no practical interest from the hydrogeological aspect, as it does not show aquifer characteristics. On the other hand, Eocene limestone aquifer overlying the metamorphic rocks has secondary porosity and permeability produced by the presence of fractures and solution cavities and as a result they show productive aquifer characteristics. The permeability decreases rapidly with increasing depth and the salinity of the water increases. Thus the lower portion of the aquifer is not exploitable (Italconsult, 1970). As stated before, there are some springs discharging from this aquifer.

In the Oligocene, and especially in the Miocene series, there are frequent occurrences of fine to coarse-grained water bearing clastic rocks, intercalated with clay and shale. These sandy- silty strata can be considered as

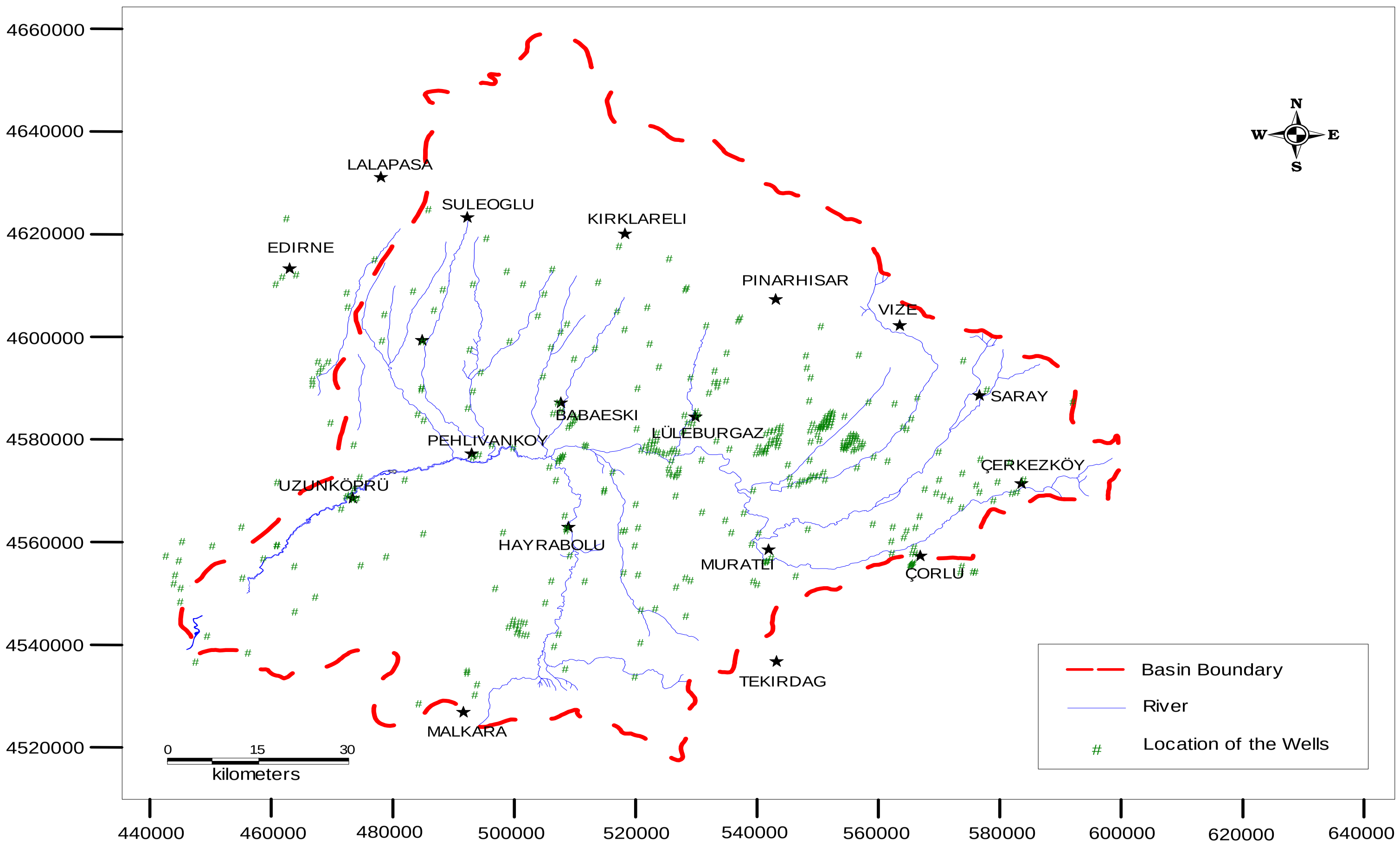

Figure 2.9. Map showing the locations of some of the wells drilled by DSİ, İller Bankası, YSE, and Köy Hizmetleri.

scattered water bearing strata. The water bearing horizons in the Mio-Oligocene series appear to be of very limited importance as far as regional importance as far as regional groundwater development potential is concerned.

The Pliocene Çorlu Formation, or in other words the "Sandy Complex aquifer" is the most productive and the most widespread aquifer in the Ergene river basin. Unconfined conditions prevail in the eastern and western parts, while in the central part of the basin the aquifer is under confined conditions. There is an internal boundary known as the Çorlu- Lüleburgaz fault. It runs SE-NW for about 60 km and interrupts the continuity of the aquifer in the artesian area (Figure 2.10). From certain aspects, the two separated parts of the aquifer may be considered as two distinct hydraulic units. The lower boundary of the formation is clear: it is always marked by an increase in grain size of the sandy strata relative to the underlying formations. The gravelly coarse sands are always in contrast with the Miocene or Oligocene. The upper boundary is also clearly marked by the contact between predominantly medium-coarse sand with clayey-silty sediments. According to the results of the 212 sieve analysis carried out by Italconsult in 1970 the dominant maximum diameter of the grains was 0.3 mm, indicating a considerable homogeneity of the sandy strata throughout the basin. The sand grains are generally subangular to subrounded. Only gravels have a well-rounded shape. The water bearing formation between the lower aquiclude and the upper aquiclude (or aquitard) has a very mixed lithological composition. It consists of alternation of beds which are generally clean sands with good permeability, and more or less silty clayey lens-shaped beds either completely impermeable or have only very low permeability. These beds of extreme variability extent locally and give the impression of a multilayer aquifer system. However, in regional terms the aquifer system can be considered as a single hydraulic unit. The average hydraulic conductivity of the Sandy Complex aquifer is 12.96 m/day (Italconsult, 1970). The maximum total saturated thickness of the aquifer occurs in the central part of the basin with more than 350 m.

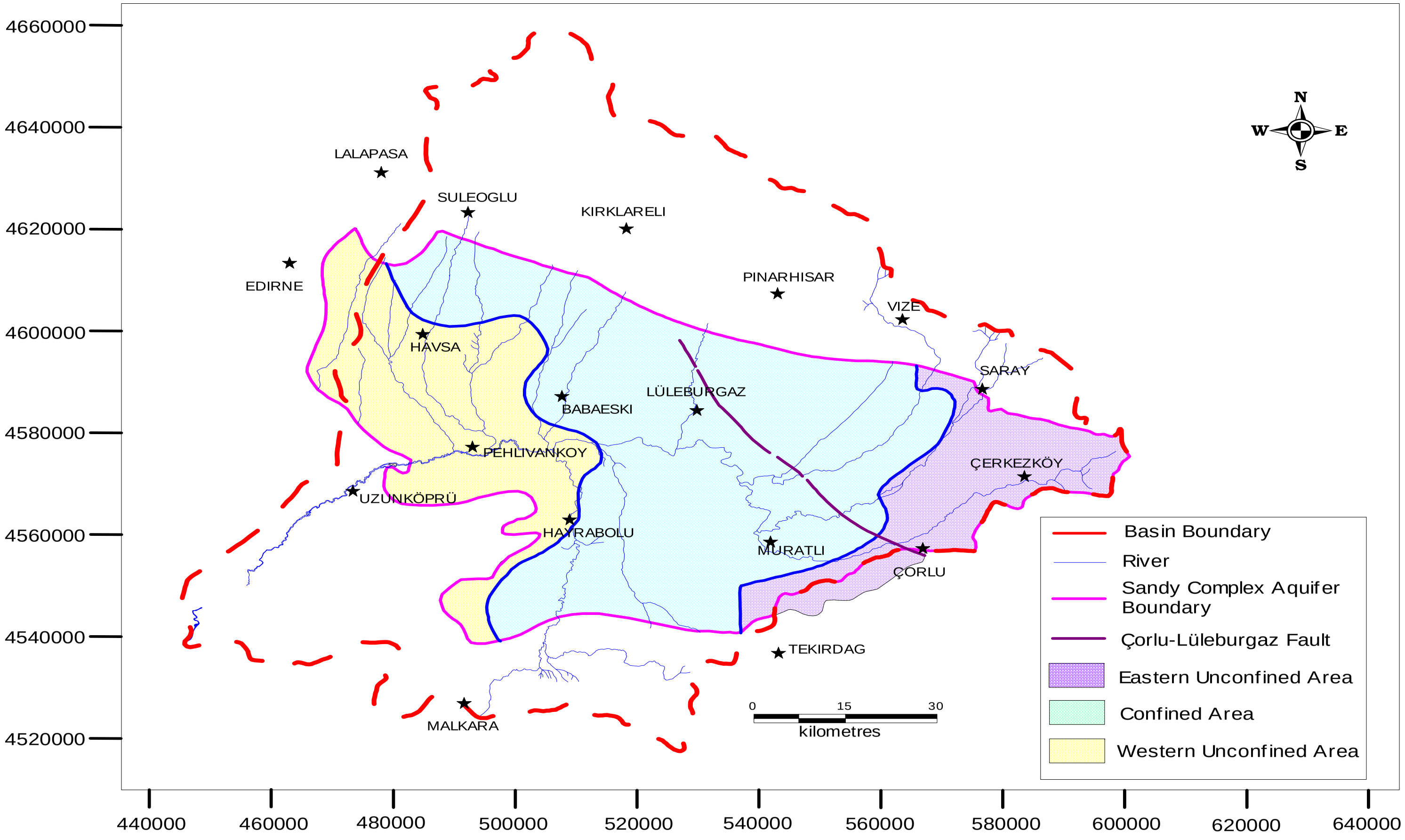

Figure 2.10. Map showing the Sandy Complex Aquifer Boundary, Çorlu- Lüleburgaz fault, eastern and western unconfined and confined areas.

In the valleys of the Ergene and its tributaries alluvial deposits are present. These deposits can be regarded as a separate unconfinedaquifer only when lying on impermeable Pliocene strata (Babaeski Formation). When they lie on the Çorlu Formation, they can be considered as recharging the Sandy Complex aquifer. The aquifer formation consists of fine to coarse grained, gravelly sands with silty intercalations. The thickness of the alluvium ranges between 5-25 m. The average hydraulic conductivity is about 32 m/ day.

2.4.2.2. Areal Extent, Depth and Thickness of Water Bearing Formations

When hydrogeologic classification of units is considered, two important units are observed in regional scale. These units are the Pliocene Sandy Complex and the Eocene limestone Formation. The remaining units don’t have any importance in regional scale because of their impervious character and limited outcrops. The Quaternary alluvium aquifers are polluted by the streams carrying contaminants.

The Eocene limestone aquifer extends in the NW-SE direction on the northern edge of the area for about 140 km. It has an area of 700 to 800 km^2 about 630 km^2 of which is in the limestone outcrop area towards the north and about 70 to 170 km^2 lies at depth at the foot of the outcrop in confined conditions beneath an Oligocene mantle.

The Sandy Complex aquifer encloses about half of the Ergene drainage basin. Unconfined conditions prevail in the eastern and western parts extending about 830 km^2 and 1550 km^2 respectively, while in the central part of the basin the groundwater is confined over an area of 3475 km^2. Sandy Complex aquifer extends for about 5855 km^2.

2.4.2.2.1. Sandy Complex Aquifer Bottom Elevation

The altitude of Sandy Complex aquifer bottom plane is well known from the completely penetrating bores and from the geophysical data obtained by Italconsult (1970); however, sufficient information is missing around Çerkezköy, Banarlı and Bayramlı (Figure 2.11). The available information

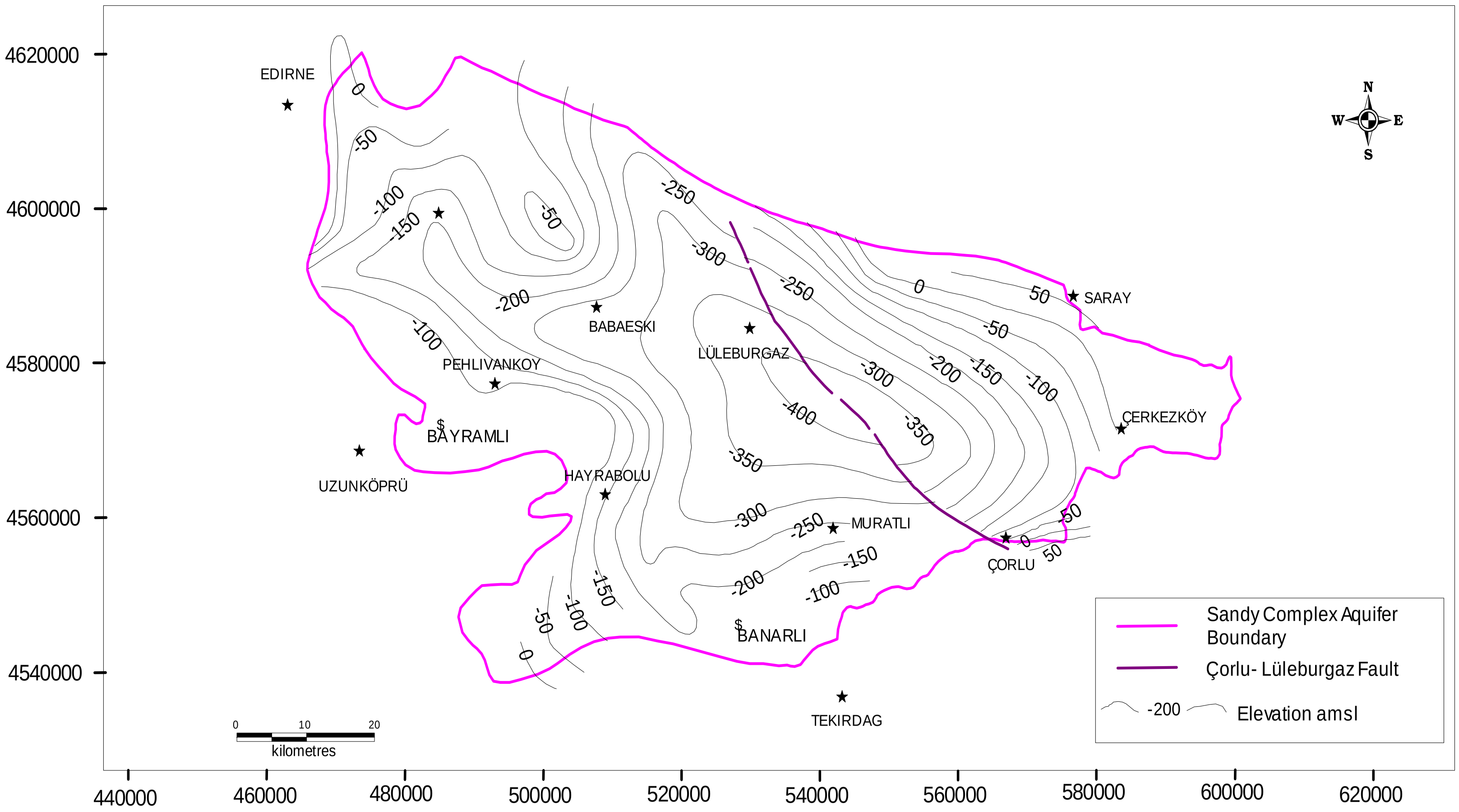

Figure 2.11. Structural contours showing the base of the Sandy Complex Aquifer (Italconsult, 1970)

indicates that the basement surface has a spoon shape. However, the Çorlu-Lüleburgaz fault displaces the base of the aquifer. The eastern part is uplifted by an amount of 50 m with respect to western part. Totally four cross sections, three of which were oriented in N-S and one in NW-SE were prepared (Figure 2.13-2.16). The orientations of the cross sections are shown in Figure 2.12. In the cross section D-D' the regularity of the basement surface of the Sandy Complex aquifer can be seen, with a basement elevation decreasing down to -400 m in the vicinity of the Çorlu- Lüleburgaz fault (Figure 2.16).

2.4.2.2.2 Sandy Complex Aquifer Top Elevation

The structural contour map of the top of the Sandy Complex was prepared by Italconsult (1970) for the central and northwestern parts where confined conditions prevail (Figure 2.17). For the eastern and western parts where unconfined conditions prevail, the top elevation is taken to be equal to the water table elevation.

2.4.2.3. Hydraulic Head Distributions

The hydraulic head distributions are needed in determining the aquifer geometry, together with the aquifer bottom and top elevations. In Ergene River basin groundwater levels were first measured in January 1970 by Italconsult (Italconsult, 1970). There are also three contour maps showing the hydraulic head in May 1994 (Su Yapı Mühendislik ve Müşavirlik A. Ş.), in October 1997 (DSİ) and in 2001 (DSİ) (the month is not stated). Furthermore water level data were also available from 13 observation wells located in various parts of the Sandy Complex aquifer. The locations of the observation wells can be seen in Figure 2.18.

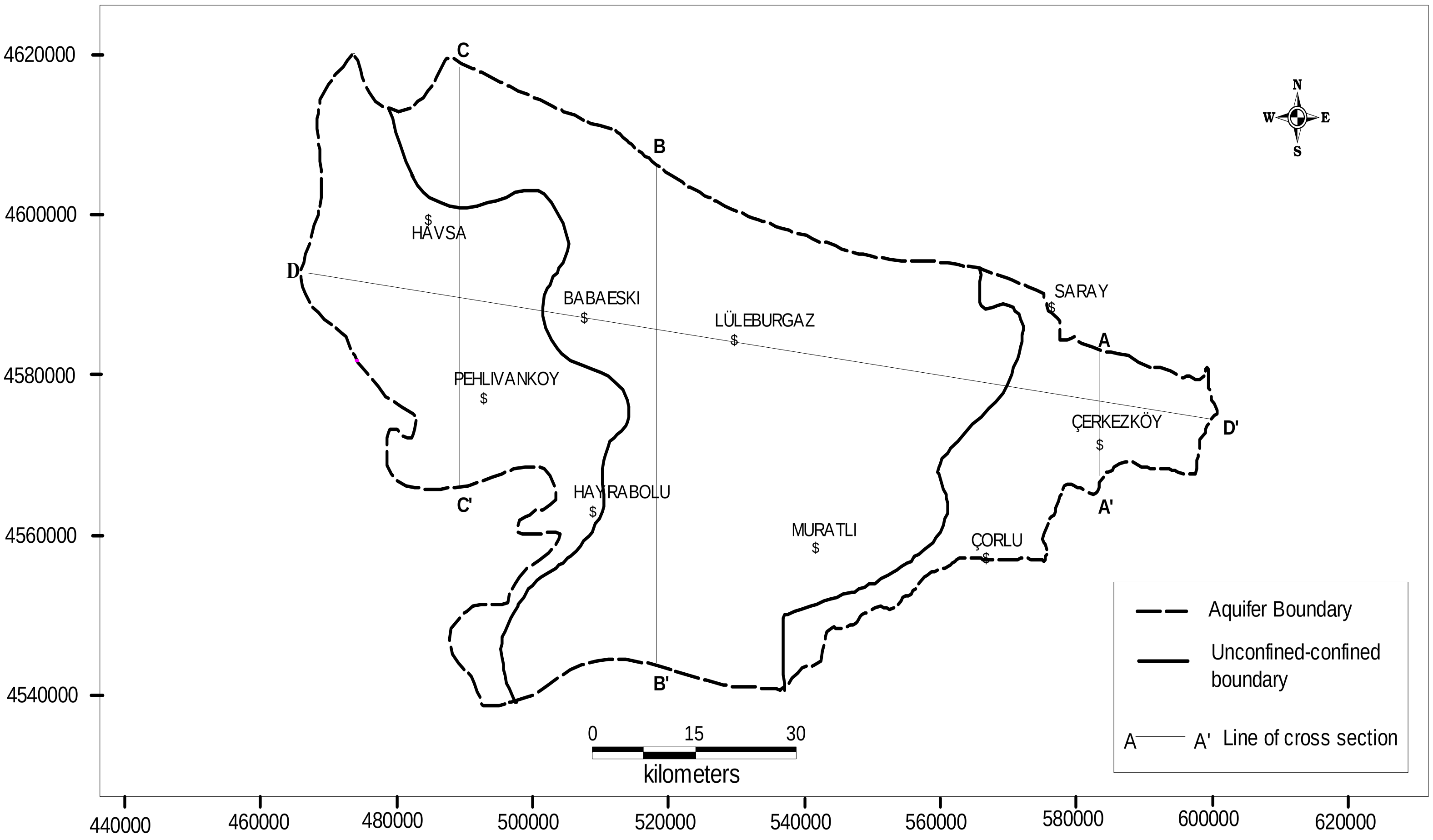

Figure 2.12. Map showing the lines of cross sections.

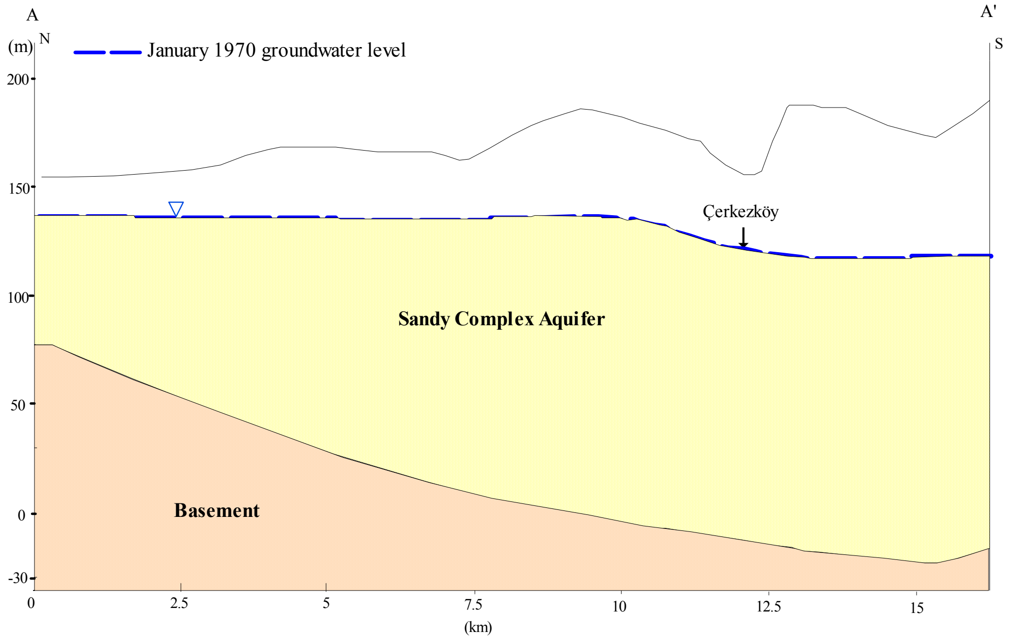

Figure 2.13. Cross section along line A-A’.

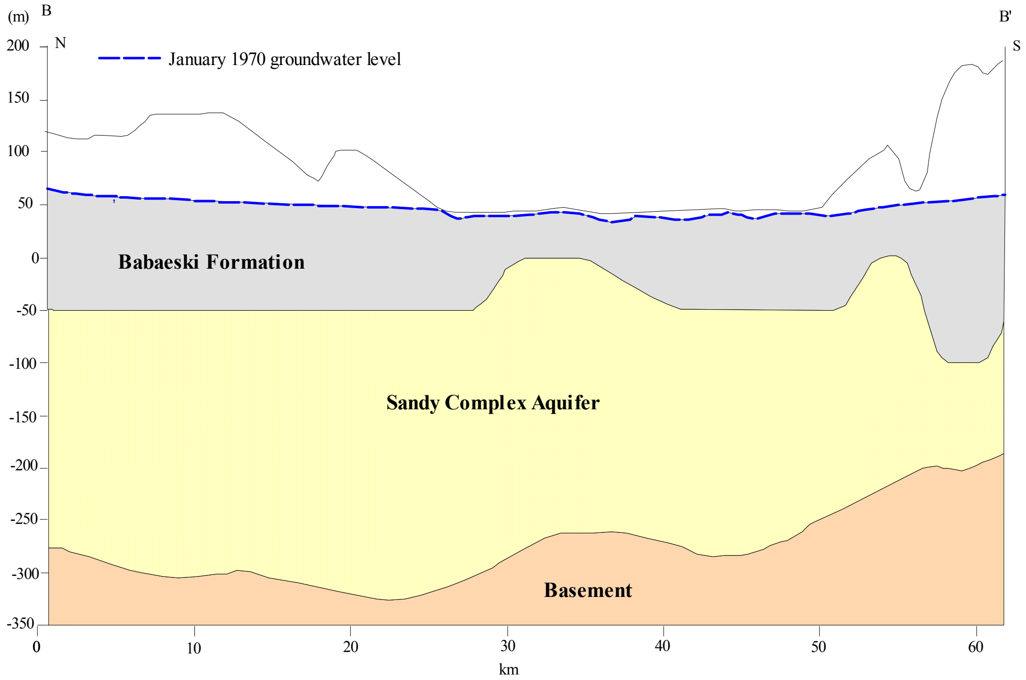

Figure 2.14. Cross section along line B-B’.

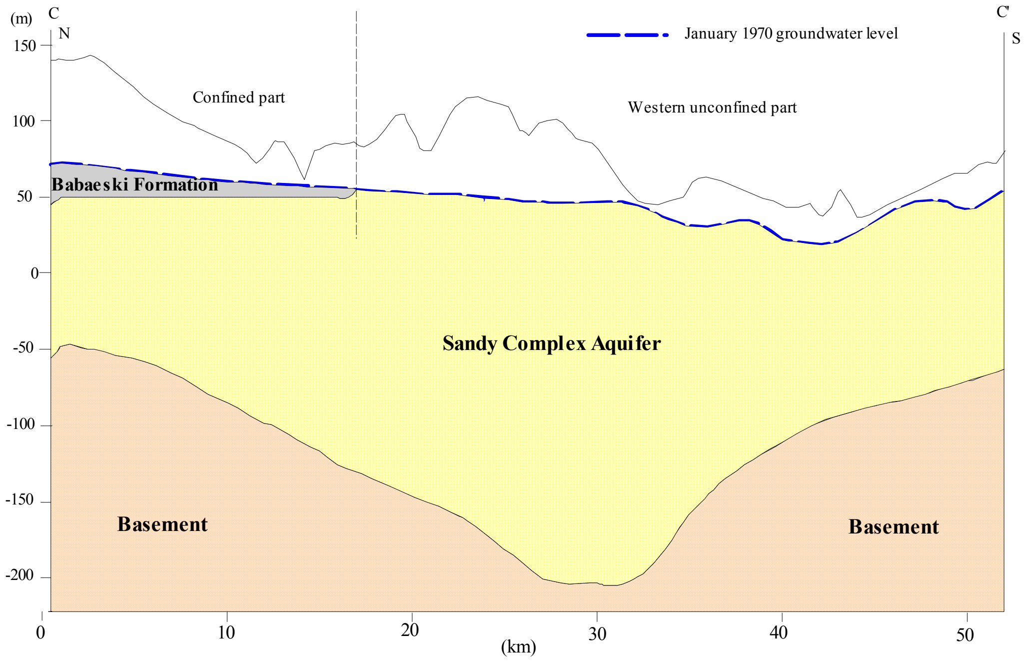

Figure 2.15. Cross section along line C-C’.

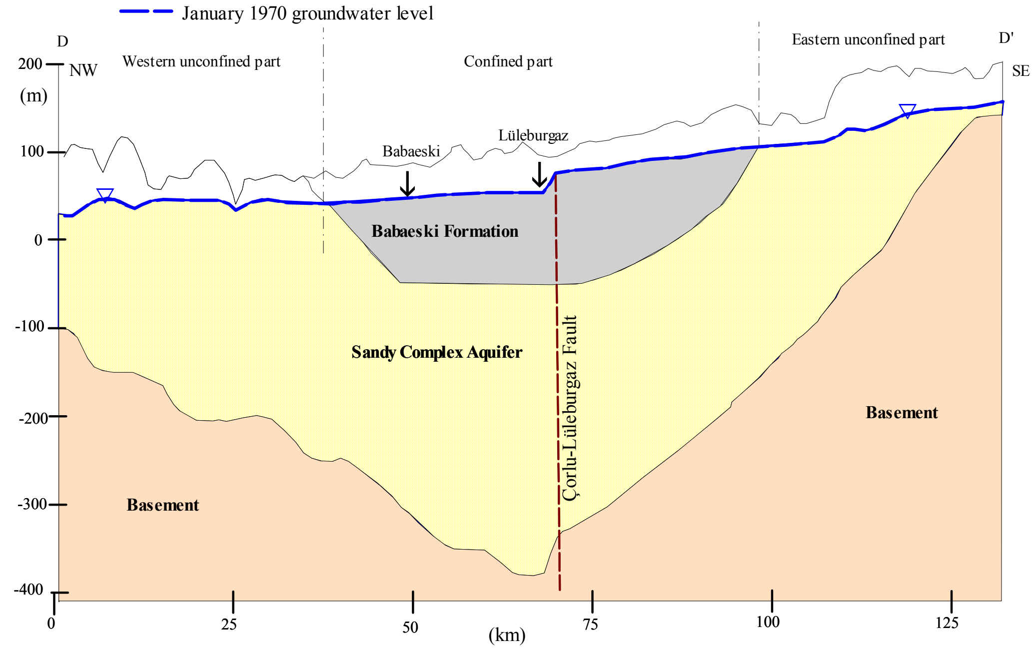

Figure 2.16. Cross section along line D-D’ showing the Çorlu-Lüleburgaz fault, confined and unconfined parts of the Sandy Complex Aquifer.

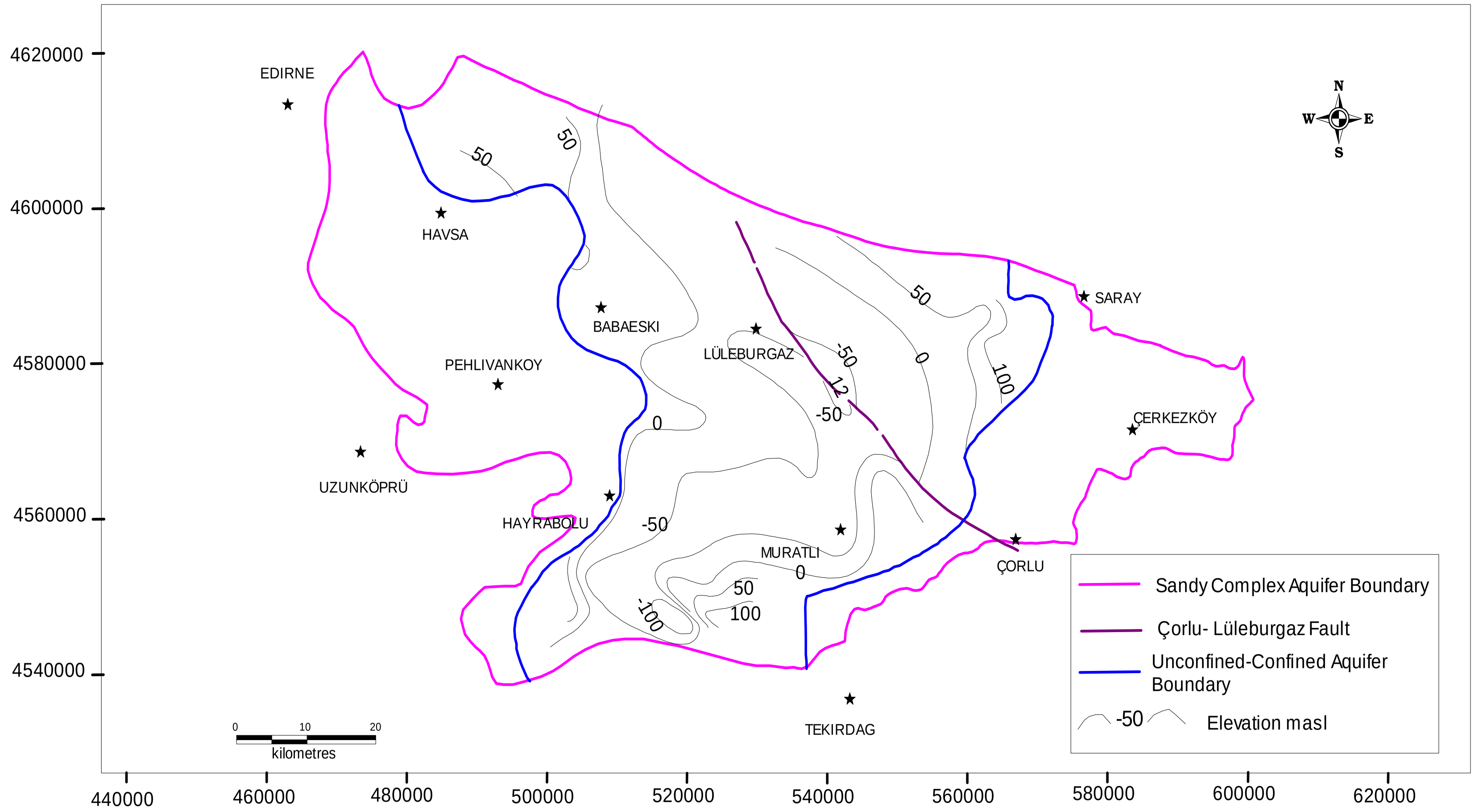

Figure 2.17. Structural contour map for the top of Sandy Complex Aquifer in the confined part (Italconsult, 1970).

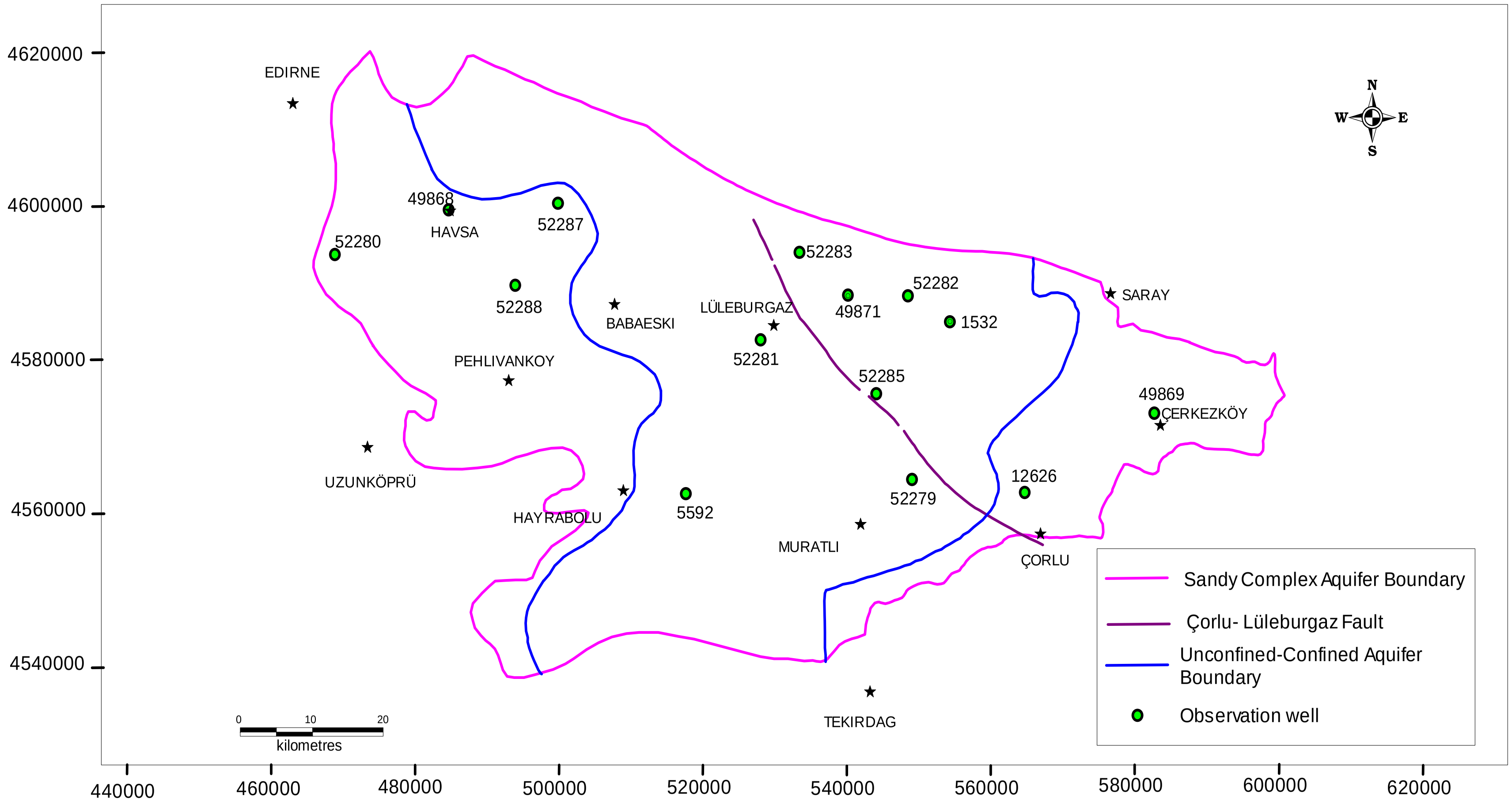

Figure 2.18. Map showing the locations of the observation well in the Ergene River Basin.

2.4.2.3.1 Groundwater Levels in January 1970

Contour map showing the groundwater levels in January 1970 (Italconsult, 1970) is given in Figure 2.19. Unfortunately no groundwater data were available around Çerkezköy, Banarlı and Bayramlı. As seen from the figure, the groundwater discharges towards the Ergene River In general groundwater levels along the plain were rather high when compared to the present conditions.

2.4.2.3.2 Temporal Changes in Water Levels

As stated before, there is no reliable water table contour map available for all over the basin; therefore the temporal changes in groundwater levels were analyzed in the observation wells whose location can be seen in Figure 2.18.

Due to the heavy abstraction of water for irrigation purposes and also for domestic and industrial use, there are changes in the groundwater levels in time (Figure 2.20). In the eastern unconfined part, there is 16 m of drawdown in observation well no. 12626 and 28 m of drawdown in well no. 49869 in 31 years. It can be seen that the groundwater levels don't show any significant decline till 1989, however after 1989 there is an abrupt change especially in well no 49869 most probably due to the abstraction of water for industrial purposes around Çerkezköy. In western unconfined part, in wells no 49868, 52287 and 52288 there are 7 m decline in groundwater levels, which is low when compared to the ones located in eastern unconfined part since there is no pumpage for industrial purposes from this part of the aquifer. Around well no 52280, there are fluctuations of more than 25 m in groundwater levels owing to the pumpage of the water for the irrigation of paddy between the months April

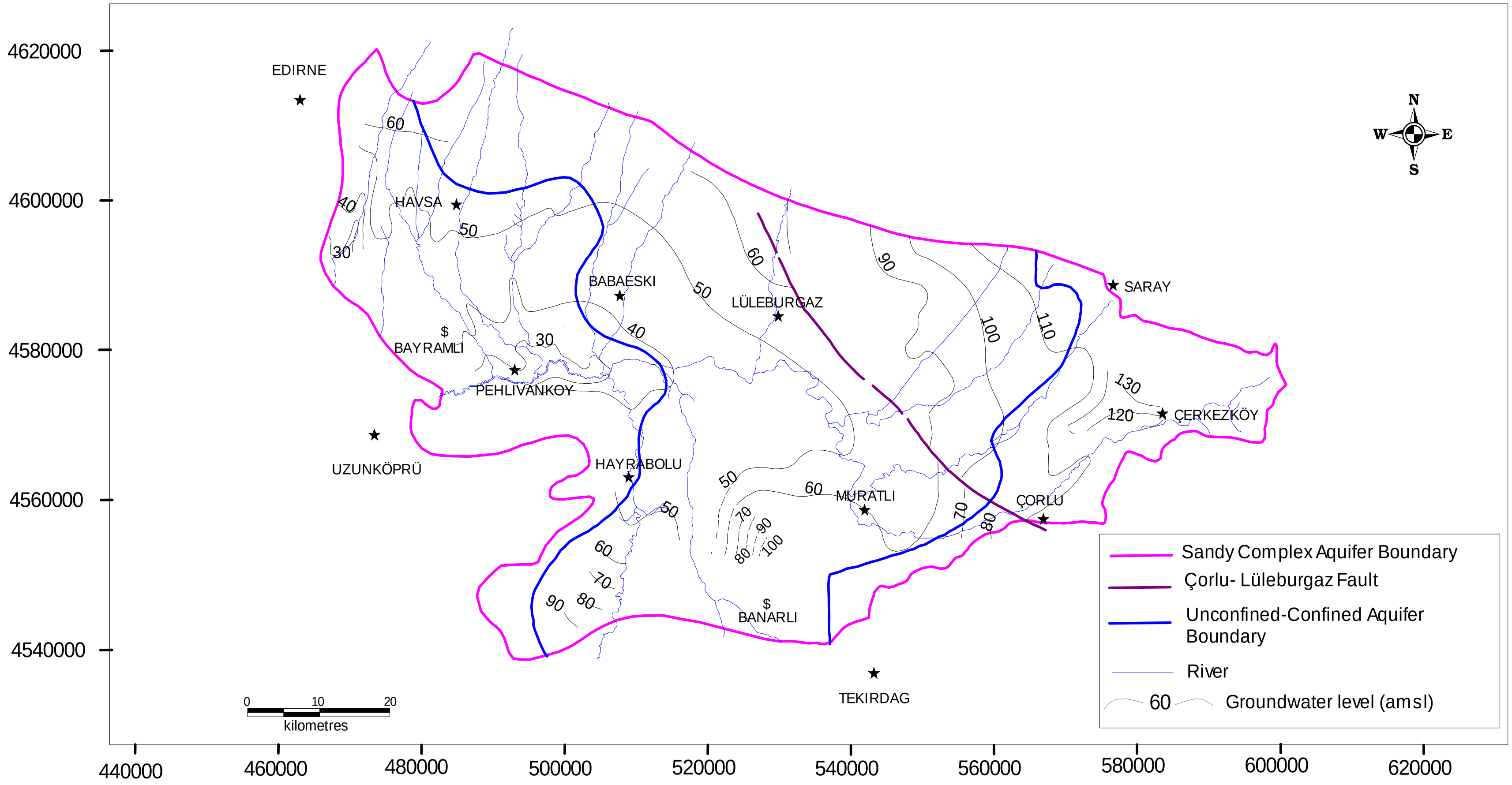

Figure 2.19. Contour map showing the distribution of groundwater levels in January 1970 (Italconsult, 1970).

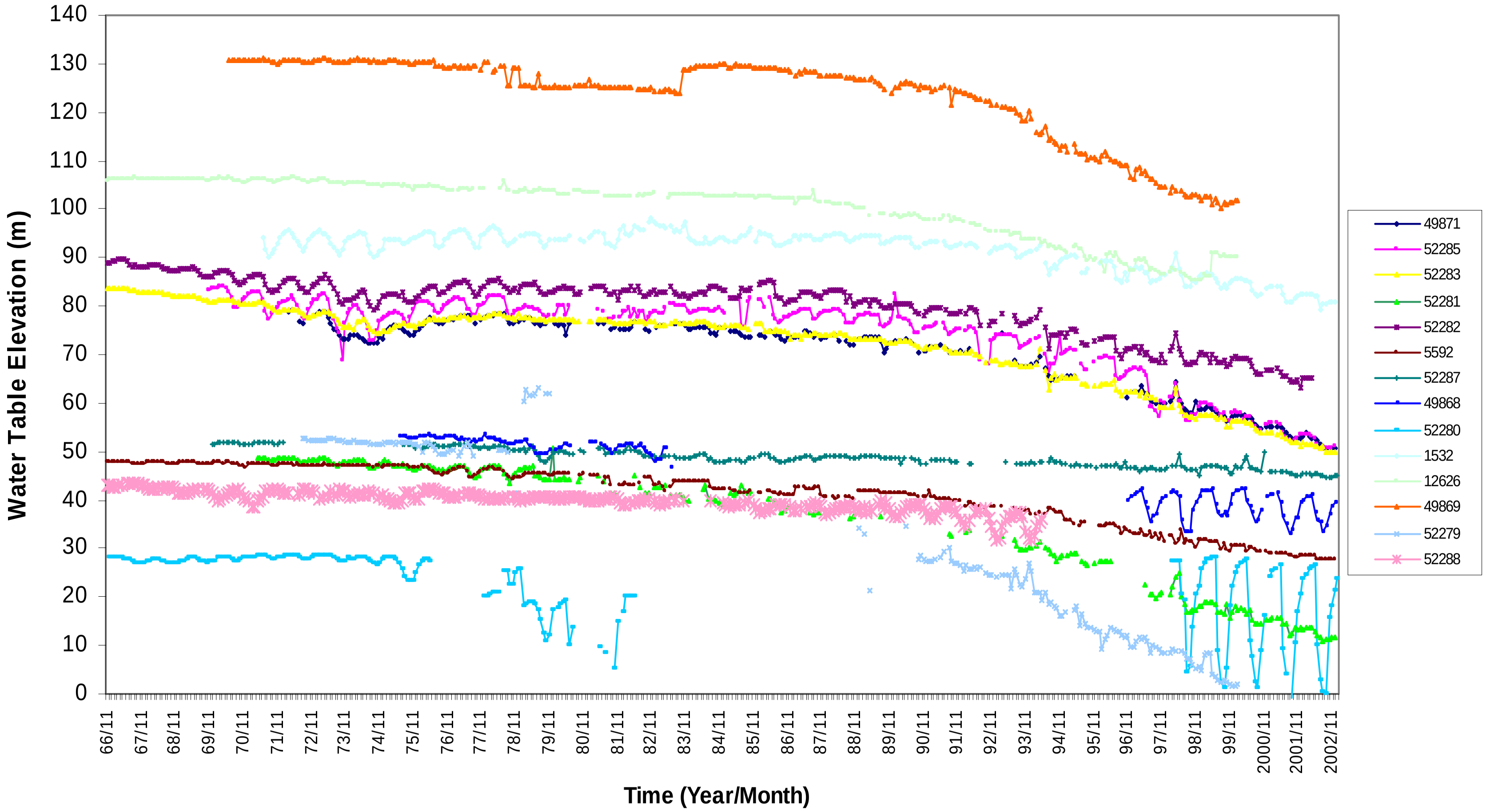

Figure 2.20. Groundwater level hydrographs for observation wells in the basin.

and August. In the confined part, the declines in groundwater are higher than the other two parts. The trends for the drawdowns in wells no 52283, 49871, 52282, 52285 are almost the same. In well no 1532, there is 13 m of drawdown that is less than the drawdowns observed in all other wells located in the confined part. The maximum amount of drawdown is observed in well no 52279 with a value of 50 m. In all wells located near to the Çorlu- Lüleburgaz fault, there are significant declines in groundwater levels owing to the intensive use.

2.4.2.4 Analysis of Saturated Thickness

In order to evaluate the areal distribution of saturated thickness of the aquifer system, aquifer bottom grid was extracted from grids of groundwater levels in January 1970. Corresponding contour map of saturated thickness is given in Figure 2.21. Analysis of saturated thickness yields that the maximum saturated thickness of the Sandy Complex aquifer is observed near the Çorlu-Lüleburgaz fault with a value of more than 350 m in the confined part. In the unconfined parts, around Doyran, Lefeci and Sütlüce the thickness is minimum with a value less than 50 m.

2.4.2.5 Hydraulic Properties of Water Bearing Formations

Determination of the aquifer parameters and the frequency distributions of the specific capacity values are important during aquifer characterization studies. Numerous discharge tests were run to ascertain the hydraulic characteristics of the Sandy Complex aquifer by Italconsult (1970). 199 tests performed between 1959- 1969 have been examined and statistically evaluated. Statistical analysis was applied in frequency distributions of specific capacities, well losses, transmissivities divided by screen length and the relationship of transmissivity and specific capacity (Italconsult, 1970). As a result of these analyses, by using 73 well data, it was seen that specific capacities were not

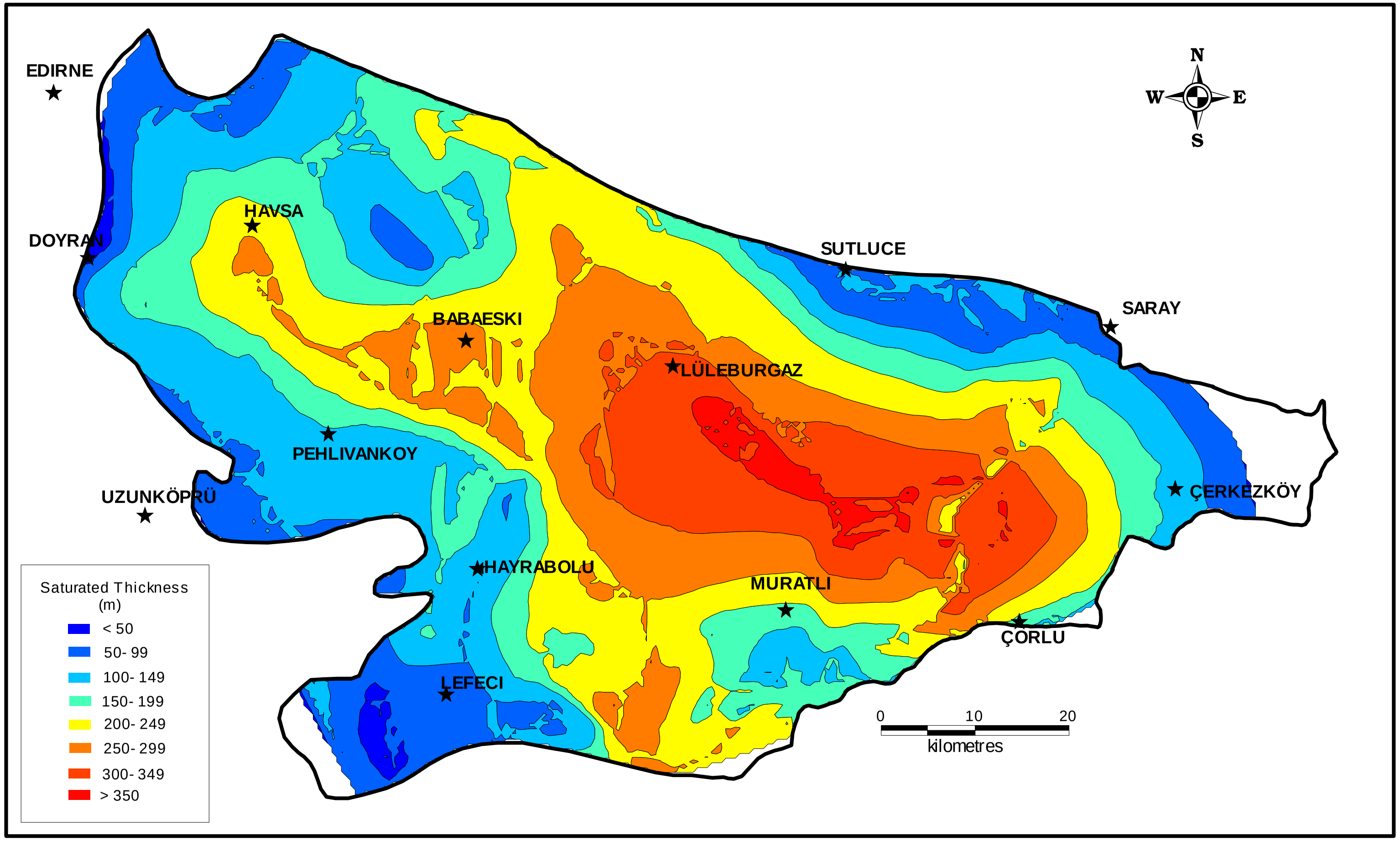

Figure 2.21. Contour map showing the saturated thickness in January 1970.

normally distributed and the sample mean specific capacity was calculated to be 4.91 l/sec/m by Italconsult (1970). The frequency distribution of the well loss coefficient values taken from step drawdown test results show a similar distribution to that of specific capacity and the sample mean was found out to be 2119 sec^2/m^5 by Italconsult (1970). According to Italconsult (1970), the frequency distribution of tranmissivity divided by screen length showed a sharp peak around values from 8.6 to 17.3 m/day indicating the permeability of the aquifer is relatively constant and variations of transmissivity were caused by variations in penetration, well completion and development.

From October 27, 1968 to January 1970, 55 pumping tests were performed on 38 wells by Italconsult (1970). The interpretation of these tests was devised by different methods and the results coincided. According to these results, the range of values for the hydraulic conductivity was relatively narrow and the average value for the hydraulic conductivity was 12.96 m/day. The average storage coefficient in the confined parts was found out to be about 10^{-3} (Italconsult, 1970).

CHAPTER 3

GROUNDWATER FLOW MODEL

3.1 Model Description

A groundwater flow model was designed to represent the Ergene River Basin Sandy Complex aquifer system in order to establish the optimum pumping policy of the basin.

A model is any device that represents an approximation of a field situation like simulating how groundwater flows and by the way helping groundwater managers in understanding and managing the resource and making the informed predictions (Anderson and Woessner, 1992). Mathematical models can be solved either analytically or numerically. The aquifer systems are generally modeled by numerical simulation methods, that is by solving the groundwater flow equations using the finite difference and/or finite element methods. The variables are given by a finite number of algebraic equations defining certain parameters like decision variables (e.g. pumpage) which provide a control on the state variables (e.g. drawdown or hydraulic head), and spatially distributed system parameters that define the conductivity (i.e. transmissivity) and the storativity of the system. These continuous variables are replaced with discrete variables defined at selected points within the system domain (Driscoll, 1986).

Mathematical models consists of boundary conditions, which are the mathematical statements specifying the dependent variable (head) or the derivative of the dependent variable (flux) at the boundaries of the domain (e.g.

Drichlet and/or Neumann), and initial conditions that show the state of the system just before the application of stresses (i.e. discharge), in addition to a governing equation (Wang and Anderson, 1982).

The aquifer system (in fact; the groundwater flow) is represented using partial differential equations, which are solved employing the available mathematical methods. But, these are often too complex to be solved by simple mathematical techniques. To solve these equations, a numerical solution technique such as finite difference, finite element, integrated finite difference, boundary integral equation and analytic elements are commonly employed and by that way the partial differential equations are transformed into a set of algebraic equations. A computer program or code is used to solve a set of algebraic equations iteratively which are generated by approximating the partial differential equations (governing equation, boundary conditions, and initial conditions) that form the mathematical model. As a result special objectives for different planning and management schemes can be achieved.

The finite difference and the finite element methods are the approximating techniques to operate on the mathematical model by changing it into a form that can be solved quickly by a computer. The set of algebraic equations, defining a certain parameter such as the hydraulic head at a finite number of nodal points, produced in this way can be expressed as a matrix equation which is solved by numerical methods. The finite difference method is easy to understand and program as fewer input data is needed to construct a grid which is usually implemented with rectangular cells. The finite element method is implemented with a variety of element types (e.g., triangular elements). The finite element method is better in approximating irregularly shaped boundaries or in solving the problems of heterogeneous or anisotropic medium. Each method has special features which may be desirable for a particular application. In fact, finite difference method has been demonstrated as a special case of the finite element method. For problems having a mesh of regularly spaced nodal points, the finite element method yields the finite difference equation. However, there is a fundamental difference in philosophy: finite difference methods compute a value for the head at the node which also is the average head for the cell that surrounds the node. No assumption is made about the form of the variation of head from one node to the next. Finite element methods, on the other hand, precisely define the variation of head within the element by means of interpolation (basis) functions. Heads are calculated at the nodes for convenience, but defined everywhere by means of basis functions (Anderson and Woessner, 1992). While choosing which method to use, the availability of the software, the complexity of the problem and the familiarity of the modeler with a specific method play an important role.

The simulation within this study is conducted by using MODFLOW (McDonald and Harbaugh, 1984), which uses the implicit finite difference approximation (also called a backward difference formulation).

Mathematical Model

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

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \qquad \text{Eq. 2.1}$$

where

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

h is the hydraulic head (L)

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

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

t is the time (t).

In general, S_s, K_{xx}, K_{yy}, K_{zz} may be functions of space (S_s = S_s (x,y,z) and $K_{xx} = K_{xx}$ (x,y,z), etc.] and W and h may be functions of space and time [h=h(x,y,z,t), $W = W$ (x,y,z,t)] so that equation 2.1 describes groundwater flow under nonequilibrium conditions in a heterogeneous and anisotropic media.

Numerical Model

In order to solve the equation 2.1 aquifer system is discretized into a mesh of points termed nodes, forming rows, columns and layers (Figure 3.1).

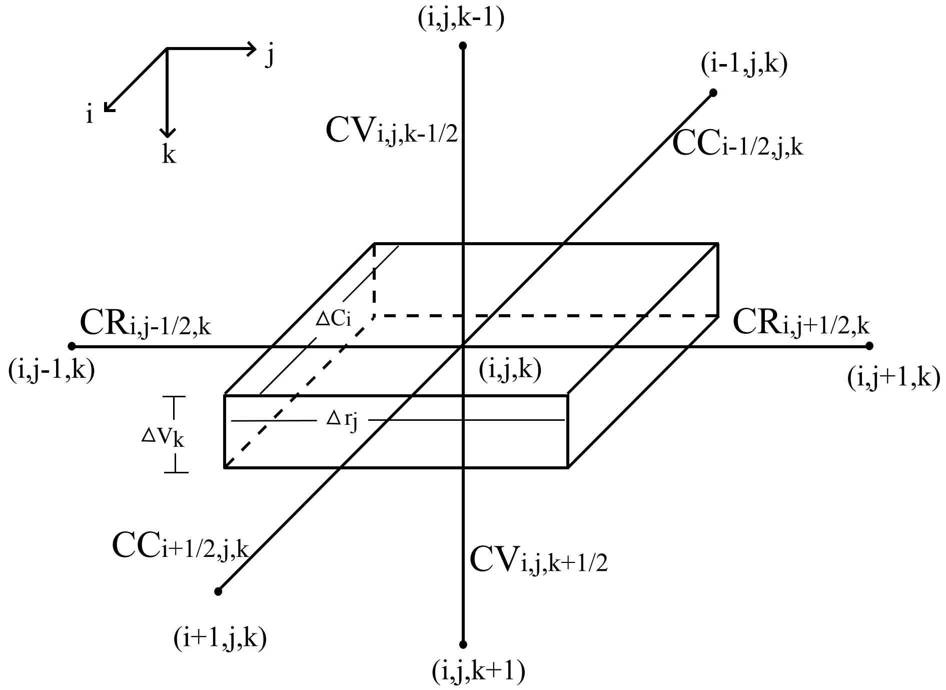

Figure 3.1. Definition of conductance terms between model cells (Yazıcıgil and Rasheeduddin, 1987)

The system described by equation 2.1 is replaced by a finite set of discrete points in space and time, and the partial derivatives are replaced by differences between functional values at nodal points. Eventually, a system of N equations with N unknowns is formulated where the N unknowns are the heads at nodal points. N shows the number of blocks in the porous media. By using block centered finite difference grid equation 2.1 can be rewritten as;

$$\begin{aligned}
&CR_{i,j-1/2,k}\left(h^2_{i,j-1,k}-h^2_{i,j,k}\right)+CR_{i,j+1/2,k}\left(h^2_{i,j+1,k}-h^2_{i,j,k}\right)\\
&+CC_{i-1/2,j,k}\left(h^2_{i-1,j,k}-h^2_{i,j,k}\right)+CC_{i+1/2,j,k}\left(h^2_{i+1,j,k}-h^2_{i,j,k}\right)\\
&+CV_{i,j,k-1/2}\left(h^2_{i,j,k-1}-h^2_{i,j,k}\right)+CV_{i,j,k+1/2}\left(h^2_{i,j,k+1}-h^2_{i,j,k}\right)\\
&+Q_{i,j,k}=SS_{i,j,k}\frac{\left(\Delta r_j \Delta c_i \Delta v_k\right)\left(h^2_{i,j,k}-h^1_{i,j,k}\right)}{t_2-t_1}
\end{aligned}\qquad \text{Eq. 2.2}$$

where the 2 subscript of h shows present time step while the subscript 1 shows the pervious time step and ;

i, index in x dimension,

j, index in y dimension,

k, index in z dimension,

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

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

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

$$CR_{i,j+1/2,k}=2DELC_i\frac{TR_{i,j,k}TR_{i,j+1,k}}{TR_{i,j,k}DELR_{j+1}+TR_{i,j+1,k}DELR_j}$$

$$CR_{i,j-1/2,k}=2DELC_i\frac{TR_{i,j,k}TR_{i,j-1,k}}{TR_{i,j,k}DELR_{j-1}+TR_{i,j-1,k}DELR_j}$$

$$CC_{i+1/2,j,k}=2DELR_j\frac{TC_{i,j,k}TC_{i+1,j,k}}{TC_{i,j,k}DELC_{i+1}+TC_{i+1,j,k}DELC_i}$$

$$CC_{i-1/2,j,k} = 2DELR_j \frac{TC_{i,j,k}TC_{i-1,j,k}}{TC_{i,j,k}DELC_{i-1} + TC_{i-1,j,k}DELC_i}$$

$$CV_{i,j,k+1/2} = KV_{i,j,k+1/2} * DELR_j * DELC_i / DELV_{i,j,k+1/2}$$

$$CV_{i,j,k-1/2} = KV_{i,j,k-1/2} * DELR_j * DELC_i / DELV_{i,j,k-1/2}$$

$DELR_j$	increase in length along j column in x direction (L),
$DELC_i$	increase in length along i column in y direction (L),
$DELV_k$	increase in length along k column in z direction (L),
t	increase in time,
TR	transmissivity in x direction (L^2/T),
TC	transmissivity in y direction (L^2/T),
KV	hydraulic conductivity in z direction (L/T).

Obtained finite difference equation is solved using numerical methods and eventually at the end of solution process at each time step a new array of heads and drawdowns are obtained for the end of the time step.

Model Input

Necessary model inputs are finite difference data like column widths and physical data. Physical data involves;

Starting hydraulic heads
Boundary Conditions
Storativity distribution
Hydraulic Conductivity distribution
Aquifer top-bottom elevation
Recharge-Discharge data
Vertical conductivity.

Model Output

Model outputs are printed or written on user specified files. These outputs are;

1. All input parameters
2. Information on time steps
3. Volumetric Budget
4. Printing or disk output of calculated head and drawdown by layer and time step
5. Cell-by-cell flow terms.

3.2 Finite Difference Grid

The first step in building a numerical model is to create a finite difference grid. In order to do this the aquifer was divided into cells where hydraulic parameters (i.e. hydraulic conductivity and storativity) were assumed to be the same. Although the hydrogeologic parameters of cells are constant, these parameters may vary from cell to cell. For this reason, the rapidly changing parameters are better represented with the smaller cell dimensions. However, small sized cells lead to increasing number of cells so that in order to solve the model more time and memory of the computer are required. Moreover, hydrogeologic parameters may not be available for each cell in the model domain. For this reason, while constructing a finite difference grid the heterogeneity of aquifer, distribution of available data and aquifer boundaries should be considered in a way that all are represented by a minimum number of cells.

The boundary of the aquifer was defined by Italconsult (1970), as shown in Figure 3.2. The area within these boundaries is divided into cells having 1000 m X 1000 m dimensions making up a total of 5903 cells, with 90 rows and 149 columns. The finite difference grid was able to cover all the regions where aquifer is present.

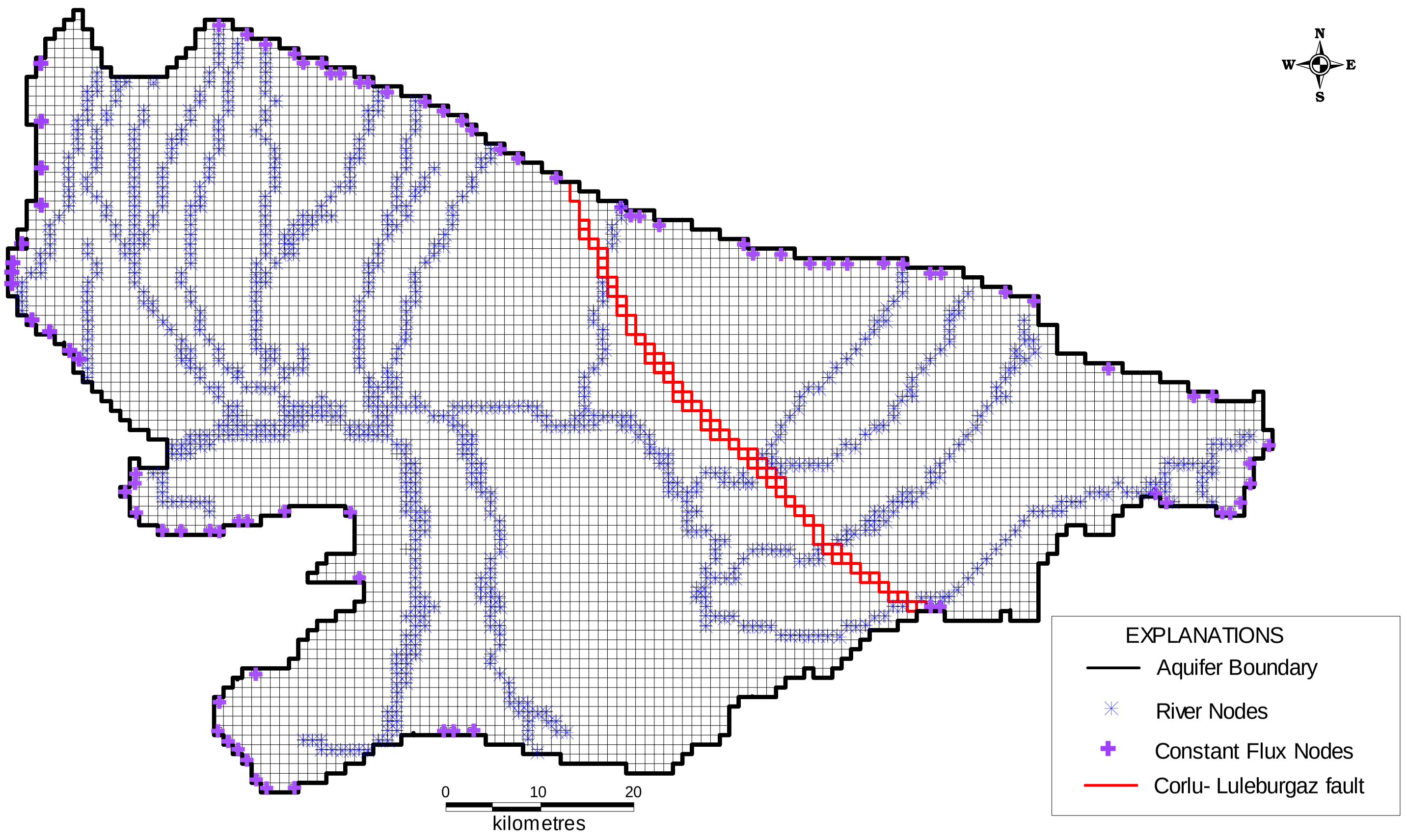

Figure 3.2. Groundwater Flow Model Finite Difference Grid and the boundary conditions.

3.3 Boundary Conditions

In determination of the aquifer boundary both geologic and hydrogeologic structure of the area are considered. Correct selection of boundary conditions is a critical step in model design: the boundaries must be chosen so that the simulated effect is relalistic.

During the calibration studies boundary of the model was overlapped with the geology of the basin and boundary conditions were defined through the boundaries of the model. In the finite difference grid of the Ergene River basin four types of boundary conditions namely constant flux, no flow, river and flow barrier boundary conditions were used (Figure 3.2).

Throughout the aquifer boundary, it was expected that there is an inflow towards the aquifer from the Eocene limestone formation in the northern part. During calibration in the southeastern part around Şalgamlı it was seen that there is again an inflow to the aquifer and in the western part around Doyran there should be an outflow from the aquifer. The magnitude of the flux assigned to these cells was obtained from hydrologic budget studies. For the remaining parts of the boundary it is assumed that there is no flow towards the aquifer or the flow amount is considered to be negligible. The Ergene River and its tributaries were modeled as a river boundary, hydraulic conductances of which were determined during calibration studies. The internal Çorlu-Lüleburgaz fault was modeled as barrier boundary.

CHAPTER 4

CALIBRATION OF THE GROUNDWATER FLOW MODEL

4.1 Introduction

Calibration of a flow model refers to a demonstration that the model is capable of producing field-measured heads and flows, which are the calibration values. Calibration is accomplished by finding a set of parameters, boundary conditions and stresses that produce simulated heads and fluxes matching field-measured values within a preestablished range of error (Anderson and Woessner, 1992). The input parameters such as hydraulic conductivity, storativity, recharge and evapotranspiration, which can not be defined for all the cells of the finite difference grid with available data, were modified in order to match the observed water level elevations with the output from the model. During this calibration process, Root Mean Square Error defined as:

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_c - h_o)_i^2} \qquad \text{Eq. 4.1}$$

checked simultaneously. In this equation n is total number of observation points, h_c is the computed head value and h_o is the observed head value.

Model calibration was performed in two steps: steady state and transient. In the first step, by comparing January 1970 measured water level elevations with the calculated water level elevations together with the hydrologic budget calculated by Italconsult (1970) calibration of the model under steady state conditions was done. January 1970 measured water level elevations are supposed to present steady-state conditions in the system under the assumption that in 1970 there was not excessive pumping i.e. steady state model refers to initial conditions of the transient model. One of the most important purposes in performing a steady state calibration is that: the hydraulic conductivity and the boundary conditions were calibrated without any consideration of storage characteristics. The storage characteristics of the aquifers must be specified only when transient release of water from storage is important (Anderson and Woessner, 1992).

As a second step, the time interval between January 1970 and December 2000 covering up totally 372 months was chosen and discretized into monthly stress periods and the groundwater flow model was calibrated for all the stress periods. While performing the transient calibration, one property of the aquifer that is the storativity is modified together with the location and the discharge amounts of the wells. So as to check the results of the transient calibration time vise variations in the calculated heads at the locations of DSİ observation wells (Figure 2.11) (1532, 49871, 52281, 52287, 12626, 52285, 52282, 49868, 49869, 52283, 5592, 52280, 52279, 52288) were compared with the observed ones.

4.2 Steady State Calibration

The groundwater flow model was calibrated using January 1970 measured water level elevations under steady state conditions (Figure 2.12). In all of the cells in the model domain, the input parameters were defined at the beginning of a steady state calibration.

First of all, a hydraulic conductivity value of 12.96 m/day was assigned as an initial value for all cells as stated in chapter 2. Then during calibration process the values of some cells were modified and the distribution of the hydraulic conductivity values obtained as a result of calibration (Figure 4.1).

Figure 4.1. Areal distribution of hydraulic conductivity (m/day) values obtained by steady state calibration.

Secondly, the contour map of the aquifer top elevation for the confined parts of the aquifer prepared by Italconsult (1970) was transferred to the model cells. For the unconfined parts, the aquifers top elevation was taken to be the water table elevation (Figure 2.10).

Thirdly, the aquifer bottom elevation map which was prepared by Italconsult (1970) was directly transferred to model cells.

Then for the calculation of the recharge values, the model area was subdivided into three parts (Figure 4.2). The eastern and western parts are the areas where the aquifer is unconfined. The aquifer is confined in the central part. For the central confined part, it was assumed that there is no recharge from the precipitation at all, because the overlying Babaeski Formation belonging to Ergene Group acts as an impervious layer, thereby preventing the infiltration. The approximate thickness of this layer is 160 m at the center of the basin. Its thickness exceeds 200 m towards the southern part of the basin.

For the eastern and western unconfined parts, where the aquifer crops out, the effective overall infiltration was about %15 of the precipitation according to Italconsult (1970). A contour map has been prepared by using the annual average precipitation values of the stations as shown in Figure 4.3. Fifteen percent of these precipitation values were assigned as recharge to the cells in the eastern and western unconfined parts.

Information regarding the exact location of the wells and their pumpage rates in Ergene River Basin were lacking. The total discharge from the aquifer was estimated as 26.6 hm^3/year for the year 1969 (Italconsult, 1970). The locations of the wells in the model domain and the discharge amounts for January 1970 were directly taken from the study conducted Italconsult (1970). The locations of cells where pumping has been made are shown in Figure 4.4.

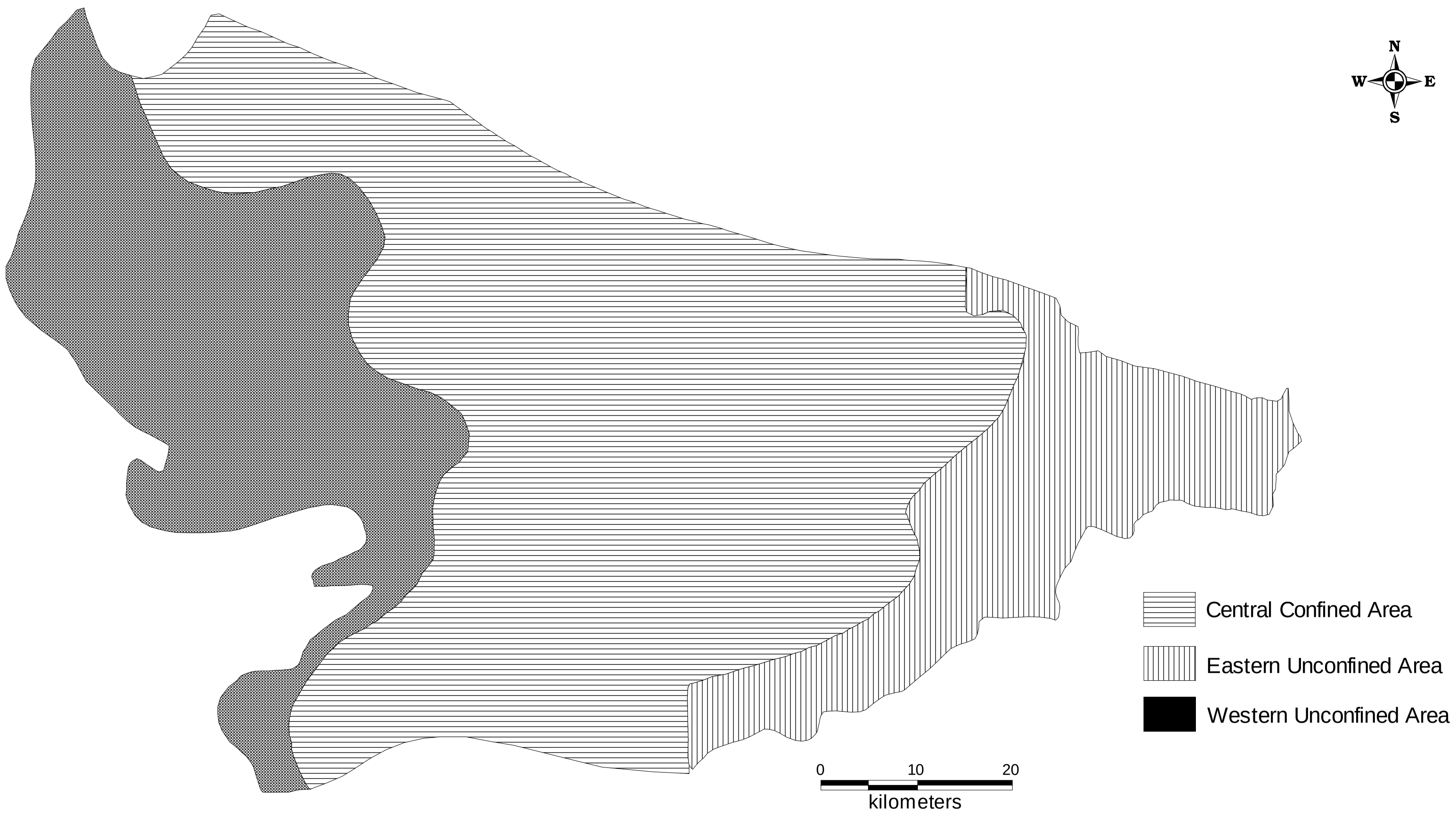

Figure 4.2. Map showing the central confined, western and eastern unconfined areas.

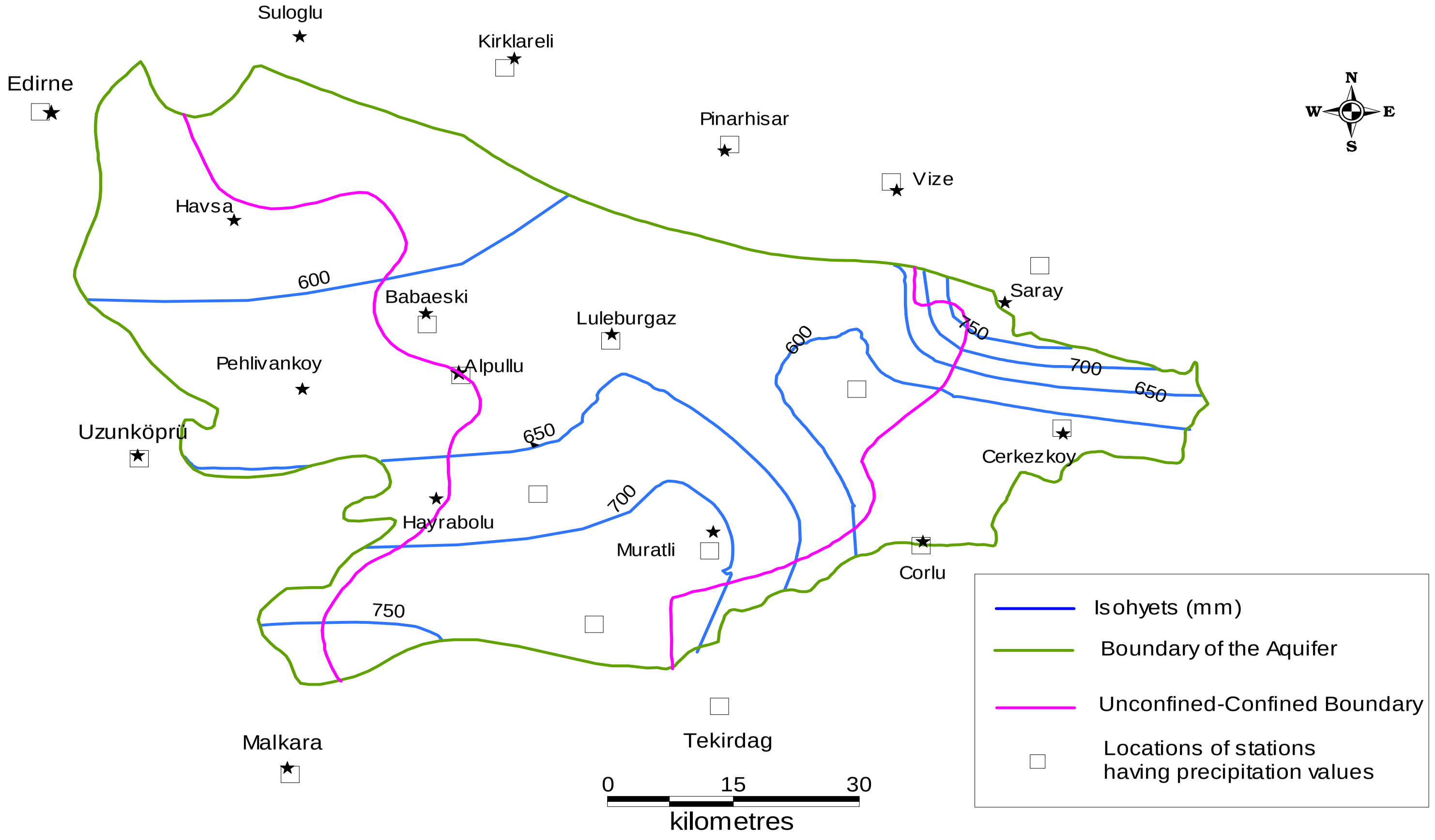

Figure 4.3. The contour map showing the average annual precipitation values for 1969.

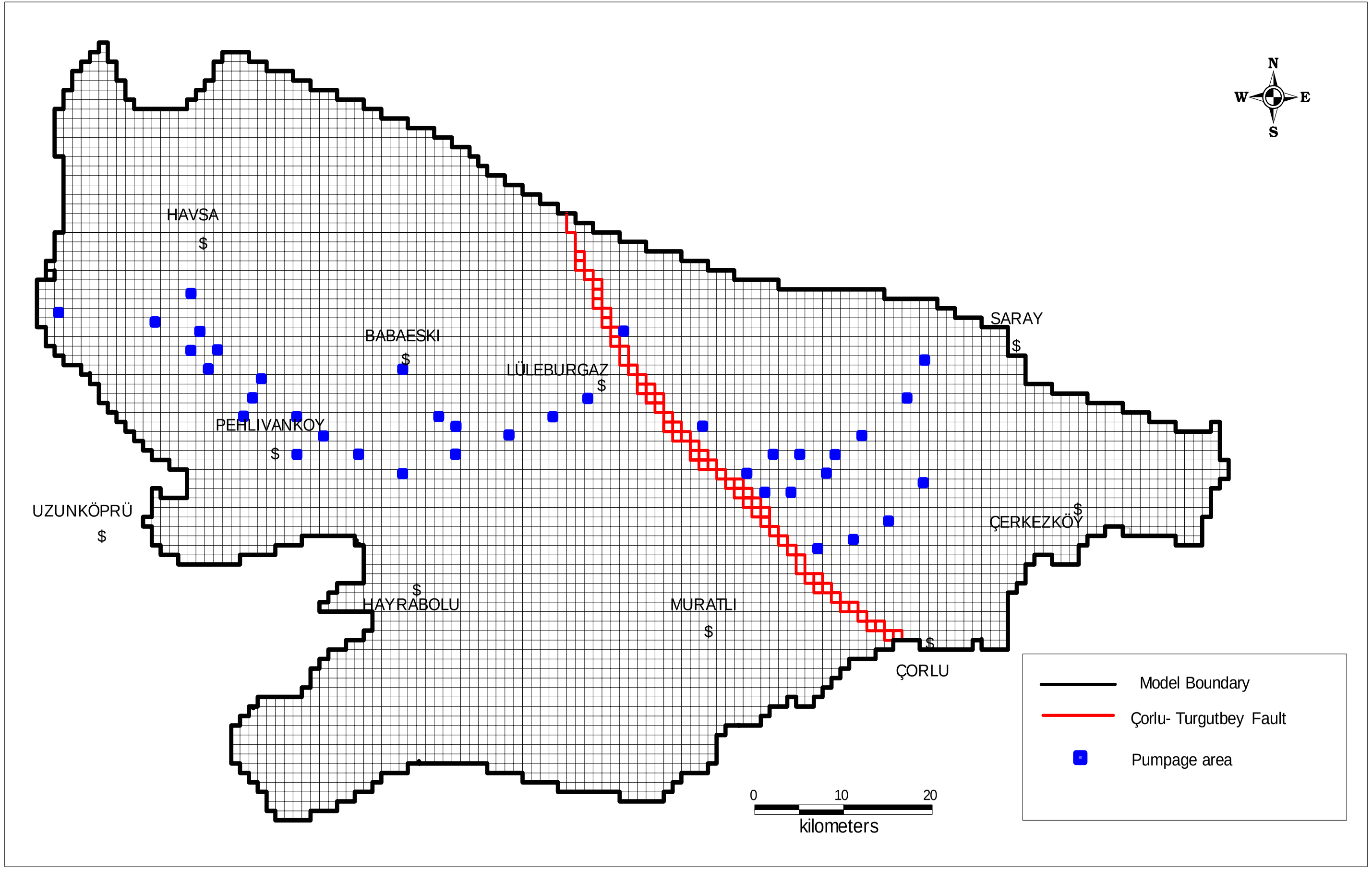

Figure 4.4. Map showing the location of cells where there were pumping in 1969 (Italconsult, 1970).

The evapotranspiration process was also accounted for in the model, although there is no information available about the areal distribution of evapotranspiration in the Ergene River Basin. The maximum evapotranspiration surface was taken as topographic surface, the extinction depth was taken 2 m below ground surface and the evaporation rate was assumed to be $5X10^{-5}$ m/day for all cells in the model domain. During calibration studies, no change has been made in these values.

The Ergene River and its main tributaries were modeled as river boundary. They were digitized from a 1:400000 scale map prepared by Italconsult (1970) and overlapped with the finite difference grid. The river and its tributaries were assigned as river elements in the corresponding model cells. There is no data available about the conductance of the Ergene River and the tributaries. However, as a starting value, to be calibrated with trial and error during calibration, 50 m^2/day was assigned to the river cells.

The effects of Çorlu-Lüleburgaz fault on the groundwater table elevations were explained in Chapter 2. It acts as a barrier boundary indicated by a head loss averaging around 30 m across the fault. It runs about 60 km through the eastern part of the basin. It is digitized and overlapped with the finite difference grid. Cells where the fault corresponds were defined as horizontal flow barrier. The hydraulic characteristic of the barrier was assigned as 0.001 (m/day or 1/day) to be changed during calibration. For an unconfined layer, the hydraulic characteristic (1/day) is equal to the hydraulic conductivity of the barrier divided by the thickness of the barrier. For a confined layer, the hydraulic characteristic (m/day) is equal to the transmissivity (hydraulic conductivity X height) of the barrier divided by the thickness of the barrier.

During the initial stages of the steady state calibration, some cells along the outer boundary of the aquifer have been assigned as constant head, to determine the amount water flux across the boundary. These cells were selected based on the hydraulic heads and geological maps.

Some of the parameters explained were modified several times to reach a calibrated steady state model and after each run, Root Mean Square Error given in equation 4.1 was checked continuously. The calculated head distribution is given in Figure 4.5. The Root Mean Square Error corresponding to this model run was 4.86 m. This error constitutes to 7% of the average head values in the basin. When the calculated versus observed groundwater level elevations for January 1970 (Figure 4.6) is examined, most of the points lies within or close to the line in which the calculated and observed groundwater level elevations are equal to each other. However, some of the values in the vicinity of the Çorlu- Lüleburgaz fault show deviation from the straight line.

During calibration, budget of the groundwater system was continuously checked together with Root Mean Square Error. In Table 4.1 groundwater budget calculated by Italconsult (1970) for Sandy Complex Aquifer is given and in Table 4.2 the groundwater budget obtained from calibration of the model under steady state conditions for January 1970 can be seen. When these results are compared, the difference in recharge from precipitation is attributed to the difference in recharge areas in both studies. The groundwater budget calculated by Italconsult also states that the total recharge to the aquifer is greater than the discharge from the aquifer and discharge is only from the wells and to the river. Evapotranspiration, recharge from Ergene River and subsurface inflow and outflow from the aquifer were not considered by Italconsult. According to the groundwater budget obtained from this modeling study there is a subsurface inflow of 137 hm^3/year, 54 hm^3/year of which coming from the Eocene limestone located in the northern boundary, 73 hm^3/year is coming from the Mio-Oligocene series located in the southwestern part of the boundary. There is not much information related to the groundwater budget of the Mio-Oligocene series therefore the amount of subsurface inflow from them were estimated during calibration studies. Italconsult (1970) estimated the outcrop area of the Eocene limestone aquifer as 630 km^2. By assuming that recharge is about %25 of precipitation to the outcrop areas, an approximate annual recharge from

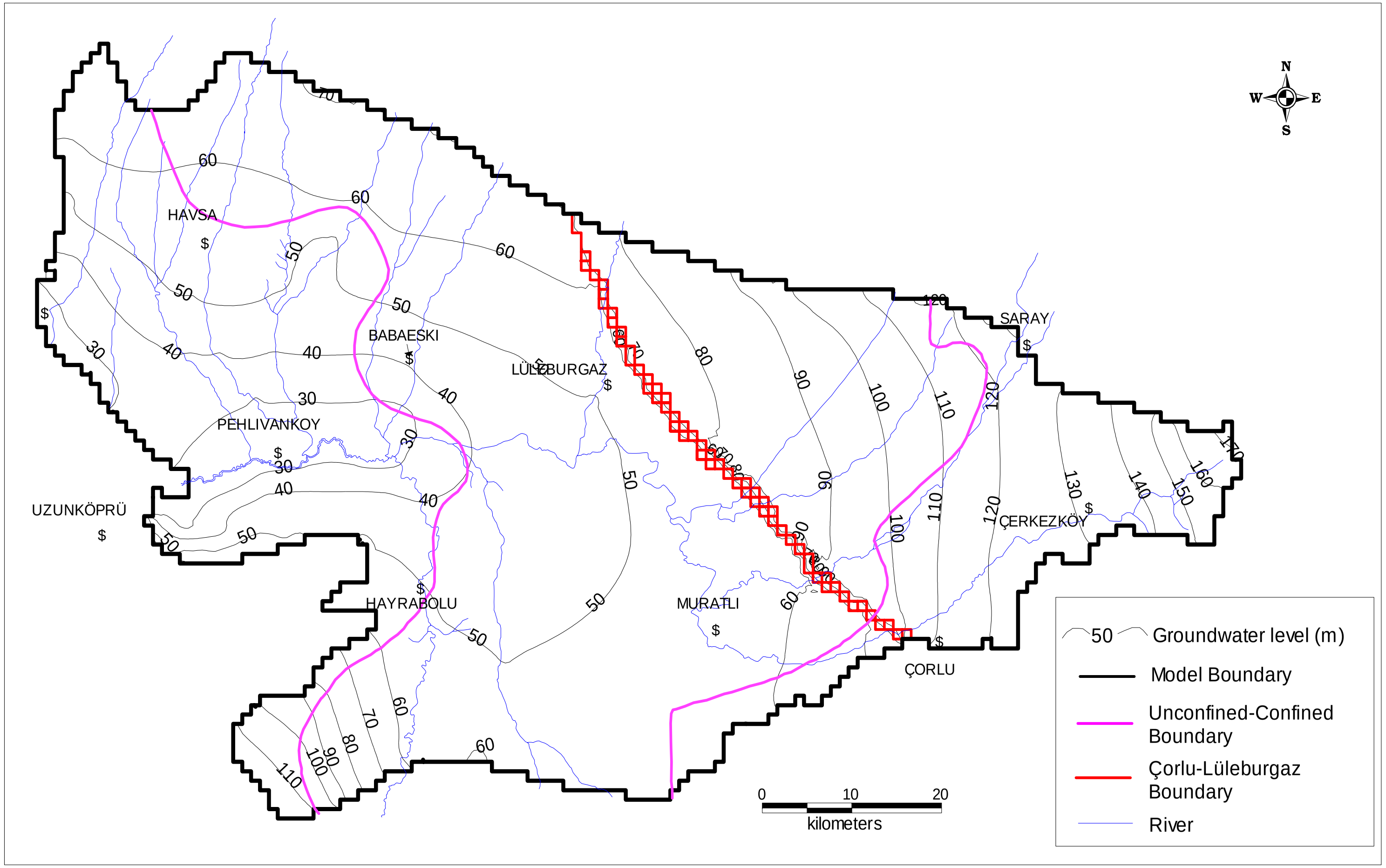

Figure 4.5.Groundwater level elevation map of the Sandy Complex aquifer for January 1970 obtained by steady state calibration.

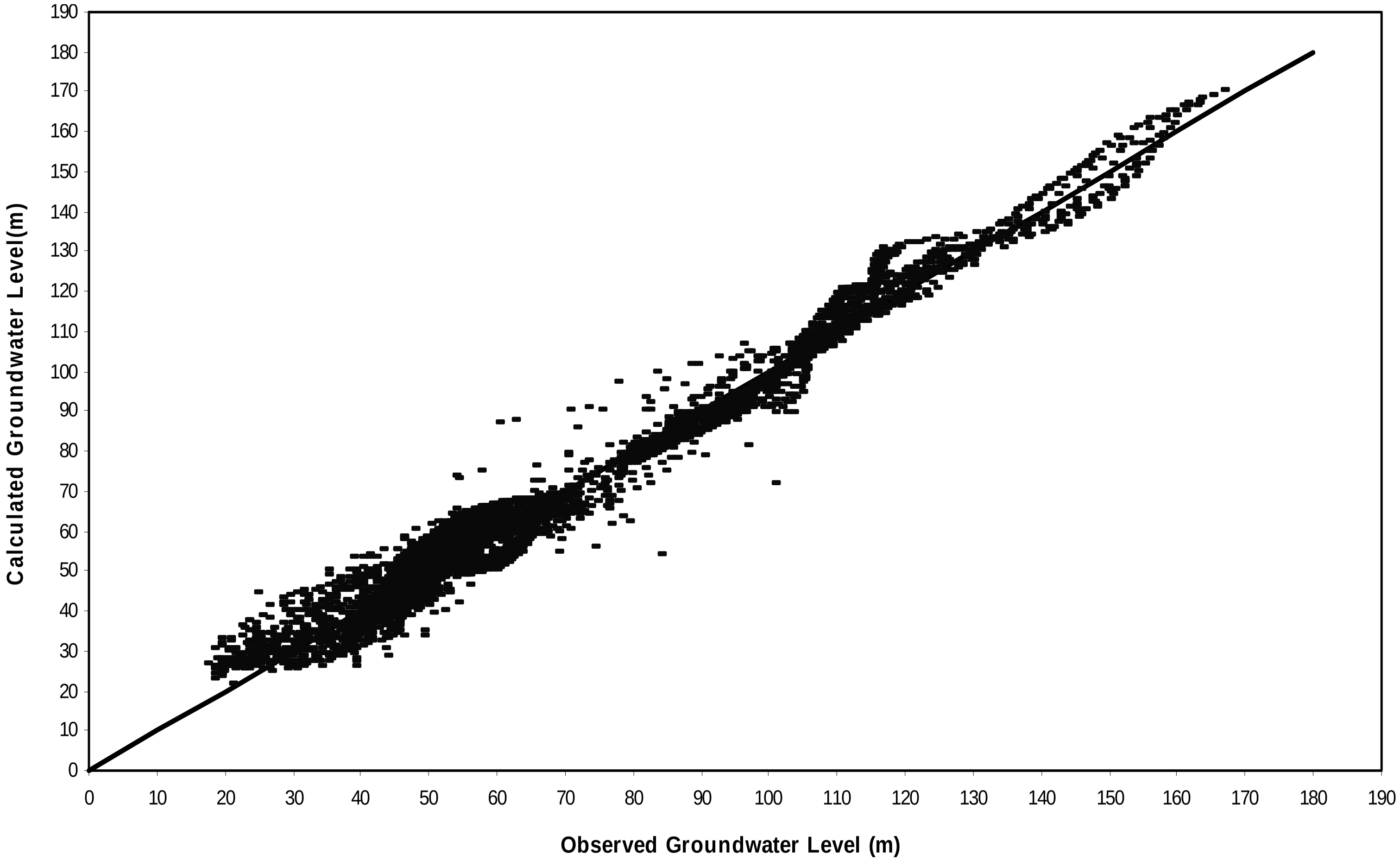

Figure 4.6. Calculated versus observed groundwater level elevations for January 1970 under steady state conditions.

Table 4.1. Groundwater Budget calculated by Italconsult (1969) for Ergene River Basin Sandy Complex Aquifer

RECHARGE (hm^3/year)		DISCHARGE (hm^3/year)	
Precipitation	173.7	Pumpage	26.6
Ergene River	0	Ergene River	119.92
Subsurface Inflow	0	Evapotranspiration	0
		Subsurface Outflow	0
Total	173.7	Total	146.52

Table 4.2. Groundwater Budget obtained from calibration of the model under steady state conditions (January 1970) for Ergene River Basin Sandy Complex Aquifer

RECHARGE (hm^3/year)		DISCHARGE (hm^3/year)	
Precipitation	220.17	Pumpage	23.7
Ergene River	17.04	Ergene River	234.55
Subsurface Inflow	137.45	Evapotranspiration	70.01
		Subsurface Outflow	45.72
Total	374.66	Total	373.98

precipitation to that aquifer would be 110 hm^3/year by taking the average annual precipitation as 700 mm. Therefore, 54 hm^3/year of this precipitation enters to the Sandy Complex aquifer, and the rest is most probably discharged from springs. According to Italconsult (1970), the average total discharge amount from springs was about 2.25 m^3/s that makes up 70 hm^3/year.

In Table 4.1, it can be seen that there is also a significant difference in the values of discharge from the Sandy Complex Aquifer to the Ergene River. There is not any consistency in the baseflow values calculated by Italconsult (1970) and by DSİ (2001). Italconsult (1970) has given the baseflow discharge to the Ergene River as 119 hm^3/year and DSİ as 338 hm^3/year. Therefore as an average, 235 hm^3/year of baseflow were calculated from this modeling study.

4.3 Transient Calibration

The transient simulation begins with steady state initial conditions in January 1970 and ends in December 2000, covering 372 monthly stress periods. The hydraulic conductivity, aquifer top and bottom elevations, evapotranspiration, Ergene River, boundary conditions and horizontal flow barrier values correspond to the ones obtained from the calibrated steady state model. In addition to these values transient recharge and storativity values were assigned to each cell under transient conditions. In performing a transient simulation, it is necessary to specify the parameter of storativity describing the capacity of an aquifer to transfer water to and from storage (Anderson and Woessner, 1992). Distribution of the storativity obtained from the studies of Italconsult (1970) is transferred to the model. In the confined part, 10^{-3} was assigned as a specific storage value. Because there was no reliable data about the spatial distribution of storativity, at the end of the transient calibration, by trial and error the areal distribution of this parameter was achieved (Figure 4.7).

Another parameter changed for the transient model was the recharge values for each stress period. Using Hydrologic Budget Method, recharge to the groundwater from precipitation in the aquifer was calculated starting from year 1970 and ending in year 2000 in a monthly basis. For the confined part no change from the calibrated steady state model was made: that is it was again assumed that there was no recharge from precipitation. For the eastern and western unconfined parts, using precipitation, surface runoff and evapotranspiration values recorded in Beyazköy and Edirne meteorological stations respectively, hydrologic budget studies were conducted and the recharge from precipitation was determined on a monthly basis to be transferred to the model as recharge parameters (Figure 4.8 and Figure 4.9).

Parameters related to the Ergene River and its tributaries were remained unchanged according to the data obtained from the flow gauging stations in the area. There was continuous flow in the river and in all tributaries between years 1970-2000.

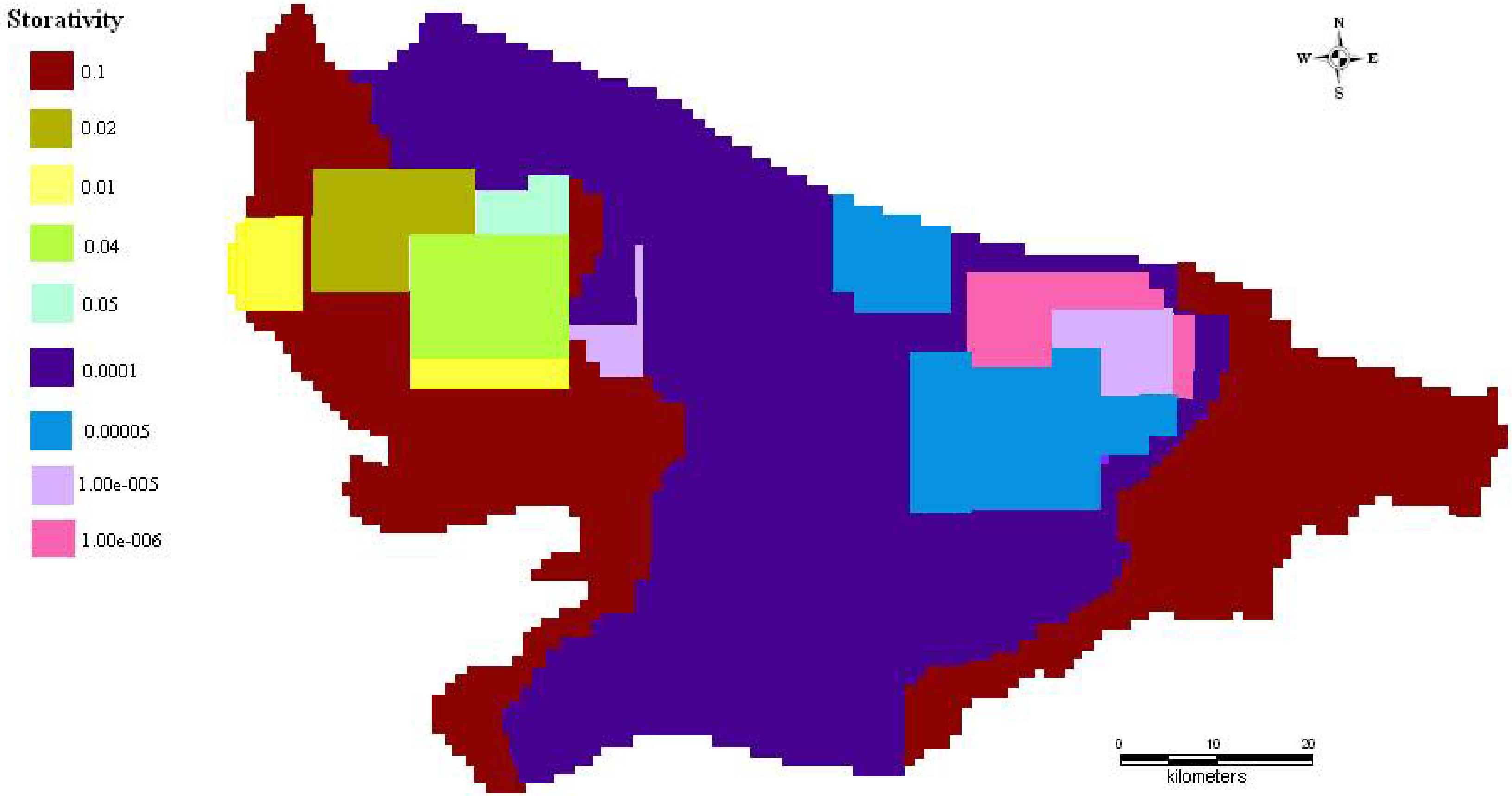

Figure 4.7. Map showing the storativity distribution of the Sandy Complex Aquifer obtained by transient calibration of the model.

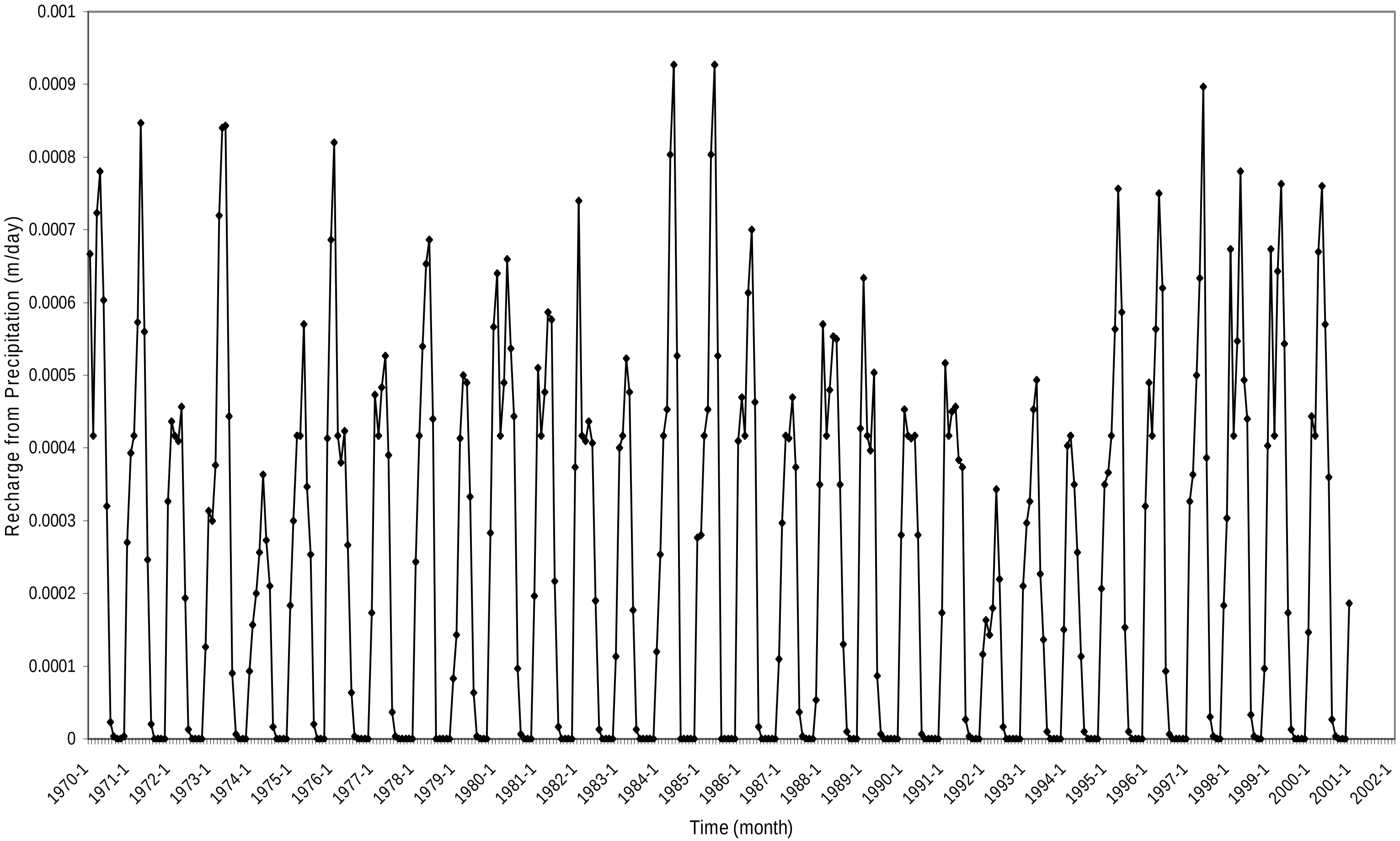

Figure 4.8. Recharge from precipitation for eastern unconfined part between years 1970-2002.

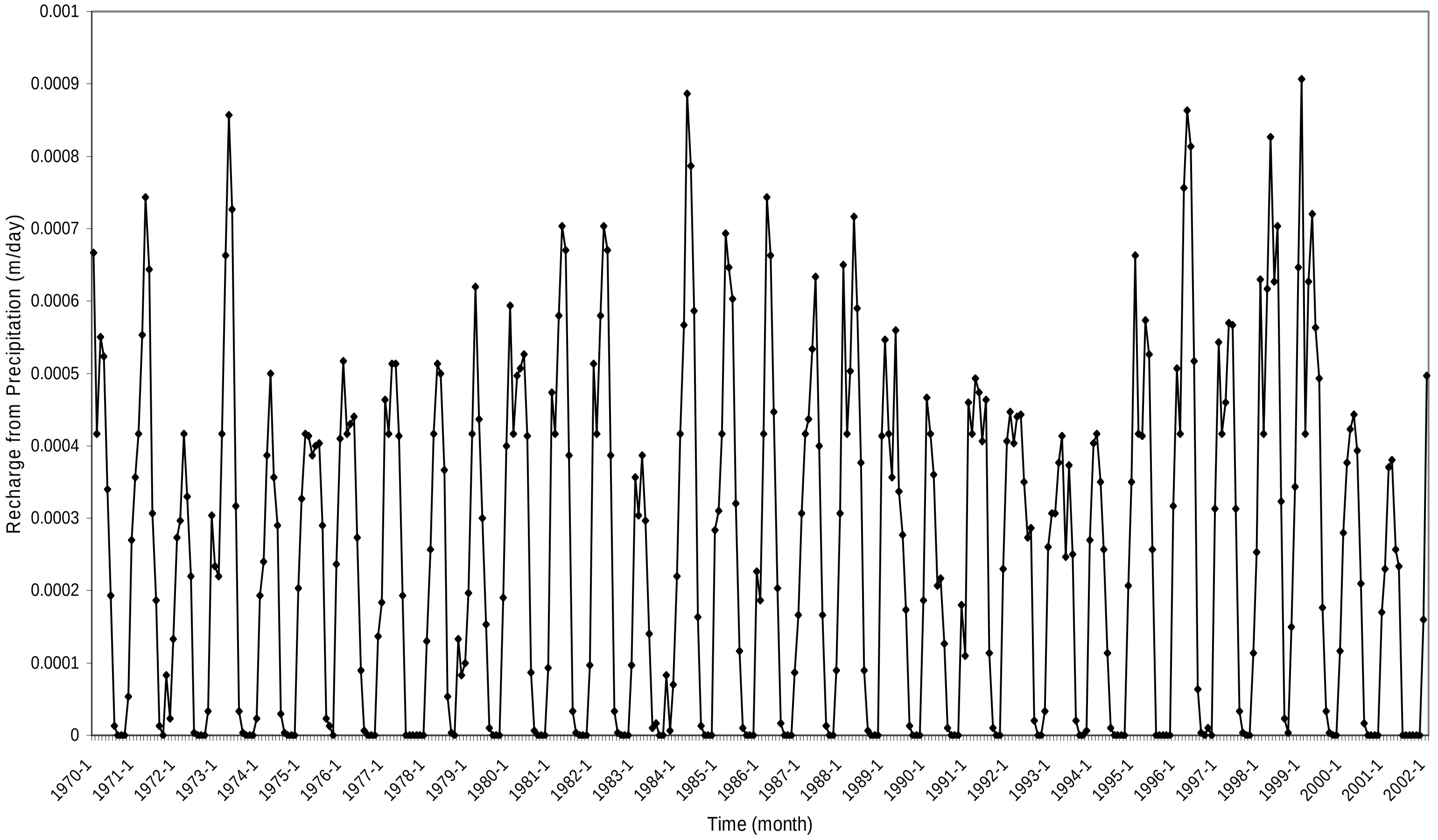

Figure 4.9. Recharge from precipitation for western unconfined part between years 1970-2002.

One of the most difficult input to determine was the monthly groundwater abstraction rates as there were no reliable information about it. In Ergene River Basin, wells were drilled by İller Bankası for domestic and drinking purposes of municipalities, by Köy Hizmetleri for domestic and drinking purposes of villages, by DSİ as cooperative wells and by private companies and individuals. The groundwater is extracted for domestic, drinking, irrigation and industrial uses.

Several information were utilized to determine the monthly discharge rates to be assigned to the cells. The Village Inventory Studies for 1997 published by Devlet İstatistik Enstitüsü was examined to get an idea about the population and the total irrigated area. There were 17 districts within the Sandy Complex Aquifer area as shown in Table 4.3. Unfortunately, no reliable information about the water extracted could have been gathered from this source.

The Municipality Environmental Studies made again by Devlet İstatistik Enstitüsü in 1994, 1995, 1996, 1997, 1998 and 2001 were examined. The results were also unsatisfying because the total amount of water extracted showed a continuous decrease from 1994 to 1998 which was a contradiction to the observed decrease in groundwater level elevations for the same years. The rapid decline in groundwater levels shows an increasing rate of groundwater withdrawal from the basin. Probably, most municipalities just recorded the quantity of water to its subscribers and ignored the loss of water during transfer from source to households. Therefore, the values of the Municipality Environmental studies were not reliable enough to be used in the model.

In Ergene River Basin, groundwater is mostly utilized for irrigation between April and October, generally by cooperative wells of DSİ and by private wells. There were totally 57 cooperatives in the basin in 2003 using groundwater for irrigation (DSİ, 2004). In Table 4.4, names, city in which it is located, allocation of water, assembly dates and irrigation area of these cooperatives are given.

Table 4.3. Total areas of the districts in Sandy Complex Aquifer

District	Total Area of the district within the Aquifer (km^2)	Percentage of the Area
Kırklareli	141.2	2.41
Havsa	517	8.83
Edirne Merkez	251.4	4.29
Süloğlu	29.81	0.51
Uzunköprü	326.4	5.58
Pehlivanköy	89.28	1.53
Babaeski	666.3	11.38
Hayrabolu	877.2	14.98
Tekirdağ	279.1	4.77
Lüleburgaz	937.6	16.02
Pınarhisar	18.4	0.31
Vize	64.51	1.10
Saray	290.2	4.96
Çerkezköy	372.6	6.36
Çorlu	535.9	9.15
Muratlı	370.5	6.33
Malkara	86.55	1.48
Total	5853.95	100

Table 4.4. Information about the cooperatives utilizing groundwater in Ergene River Basin (After DSİ, 2004).

Order No.	Cooperative Name	City Name	Montage Year of Pump	Irrigation Area (ha)	Number of Wells	Allocation (hm^3/year)
1	Merkez- Doyran	Edirne	1971	780	15	7.2
2	Merkez- Karakasım (I-II)	Edirne	1974	700	16	5.8
3	Merkez- Karakasım (III)	Edirne	1996	100	3	0.8
4	Merkez- Tayakadın (I)	Edirne	1986	170	4	1.1
5	Merkez- Tayakadın (II)	Edirne	1993	100	3	0.8
6	Merkez- Tayakadın (III)	Edirne	1999	250	8	1.7
7	Merkez- Tayakadın (IV)	Edirne	2003	300	11	2.6
8	Merkez- Höyüklütatar (I)	Edirne	1990	150	3	0.8
9	Merkez- Höyüklütatar (II)	Edirne	1993	150	3	0.8
10	Merkez- Höyüklütatar (III)	Edirne	1994	350	9	2.4
11	Merkez- Höyüklütatar (IV)	Edirne	1997	300	9	2.0
12	Merkez- Höyüklütatar (V)	Edirne	2003	300	10	2.7
13	Merkez- Elçili	Edirne	1995	200	5	1.5
14	Havsa 7 Grupköy	Edirne	1974	1800	34	15.0
15	Havsa- Necatiye	Edirne	1976	250	5	2.0
16	Havsa- Azatlı	Edirne	1988	130	6	1.1
17	Havsa- Abalar	Edirne	1991	160	5	1.4
18	Havsa- Kabaağaç	Edirne	1994	100	3	0.8
19	Havsa- Naipyusuf	Edirne	1981	200	4	1.5
20	Havsa- Kuzucu (II)	Edirne	1997	150	5	1.1
21	Havsa- Kuzucu (III)	Edirne	2002	150	3	0.5
22	Havsa- Yolageldi	Edirne	1997	115	3	1.0
23	Havsa- Kulubalık (II)	Edirne	2001	400	10	2.6
24	Havsa- Tahal (II)	Edirne	2003	400	11	3.6
25	Havsa- Şerbettar	Edirne	2001	200	6	1.9
26	Uzunköprü- Sazlımalkoç	Edirne	1997	150	4	1.1
27	Uzunköprü- Aslıhan	Edirne	1997	200	6	1.4
28	Uzunköprü- Kırcasalih	Edirne	2001	200	7	2.1
29	Uzunköprü- Ömerbey	Edirne	2003	200	6	1.2
30	Enez- Çavuşköy	Edirne	1981	200	5	2.0
31	Enez- Vakıfköy	Edirne	1979	50	2	0.4
32	Enez- Abdurrahim (I)	Edirne	1979	70	3	0.6
33	Enez- Abdurrahim (II)	Edirne	2002	160	6	1.5
34	Enez- Yenice (I-II)	Edirne	1979	290	7	2.4
35	Enez- Küçükevren	Edirne	1980	250	5	2.0

Table 4.4. (Continued)

36	Enez- Gülçavuş	Edirne	1980	120	4	1.1
37	Enez- Büyükevren	Edirne	1986	250	6	2.4
38	Enez- Sultaniçe	Edirne	1999	100	3	0.6
39	Enez- Çeribaşı	Edirne	2002	100	3	0.8
1	Babaeski- Sofuhalil	Kırklareli	1998	160	4	1.3
2	Babaeski- Ağayeri	Kırklareli	2001	100	4	0.8
3	Lüleburgaz- Evrensekiz	Kırklareli	1970	1000	10	6.4
4	Lüleburgaz- Turgutbey	Kırklareli	1973	210	4	1.8
5	Lüleburgaz- Düğüncübaşı	Kırklareli	1981	160	4	1.2
6	Lüleburgaz- Eskitaşlı (I)	Kırklareli	1991	160	4	1.2
7	Lüleburgaz- K. Karıştıran	Kırklareli	1993	150	4	1.0
8	Lüleburgaz- Ahmetbey	Kırklareli	1993	120	3	1.0
9	Lüleburgaz- Akçaköy	Kırklareli	1994	160	4	1.2
10	Pehlivanköy- Merkez	Kırklareli	1976	440	9	4.2
11	Pehlivanköy- Kumköy	Kırklareli	1976	340	7	4.7
12	Pehlivanköy- Hıdırca	Kırklareli	1977	560	13	3.4
1	Çorlu- İğneler	Tekirdağ	1974	180	3	1.4
2	Çorlu- Pınarbaşı	Tekirdağ	1989	300	7	1.9
3	Çorlu- Velimeşe	Tekirdağ	1996	150	5	2.9
4	Saray- Sofular	Tekirdağ	1980	200	5	1.3
5	Hayrabolu- Şalgamlı	Tekirdağ	1974	360	9	3.5
6	Muratlı- İnanlı	Tekirdağ	1989	220	5	1.3

As stated before, there are numerous private wells all around the basin that are not registered in DSİ records. The registered wells most probably do not obey the limits of groundwater use allocated to them. Accordingly, it was decided that groundwater extraction for irrigation could be found using the crop irrigation water requirements. In a study conducted by Nippon in 1996 in Küçük Menderes River Basin, the average monthly unit requirements were calculated for variety of plants in the basin. These values are presented in Table 4.5 which shows that the irrigation water requirement is 560.4 mm. Due to the

Table 4.5. Irrigation water requirements used for Ergene River Basin (The study of Nippon in Küçük Menderes River Basin, 1996)

Water Requirement (mm)	MONTHS												Annual
	1	2	3	4	5	6	7	8	9	10	11	12	
	0.2	0.5	5.6	22.1	63.1	108.0	130.4	137.7	71.8	18.1	2.5	0.4	560.4

geographic and crop similarities between the two basins, the same irrigation water requirements given in Table 4.5 was used to calculate the yearly total groundwater usage amounts for irrigation by multiplying the irrigated areas with the crop use coefficients.

A number of simulations under transient conditions were done after all the input parameters were transferred to the model. Calibration process continued till reliable results; i.e. sufficient matches between the calculated and observed water level elevations with respect to time at DSİ observation wells (52282, 52281, 12626, 52285, 49868, 49869, and 5592) were obtained (Figure 4.10, 4.11, 4.12, 4.13, 4.14, 4.15, and 4.16). When these figures are examined, in well no. 49868 (Havsa-Merkez) the monthly fluctuations observed in the groundwater levels could not be simulated. These fluctuations maximum of which is about 10 m are because of the excessive pumpage during irrigation season (April- August). There is an error associated with the steady state simulation; the calculated heads are about 2 m higher than the observed ones in well no. 52282 and 49868 (Figure 4.10, 4.14). A part from this error, the same trend of decrease in groundwater levels for both the calculated and observed groundwater levels can be seen in well no. 52282. In well no. 52285, the fluctuations in calculated groundwater levels are higher than the ones in observed levels. The comparison between observed and calculated groundwater levels at observation points no. 49869, 12626, 52281 and 5592 showed good agreement.

Initial groundwater level elevations of January 1970 was substracted from December 2000 (Figure 4.17) groundwater elevations and a water level change map was constructed (Figure 4.18). When these figures are examined, it can be seen that there was a significant decline in groundwater levels due to the heavy abstraction of the water, with an increasing rate especially after 1989 as shown in the water level hydrographs. The maximum decline in groundwater levels, which is about 40 m, is around Muratlı, located in the vicinity of the

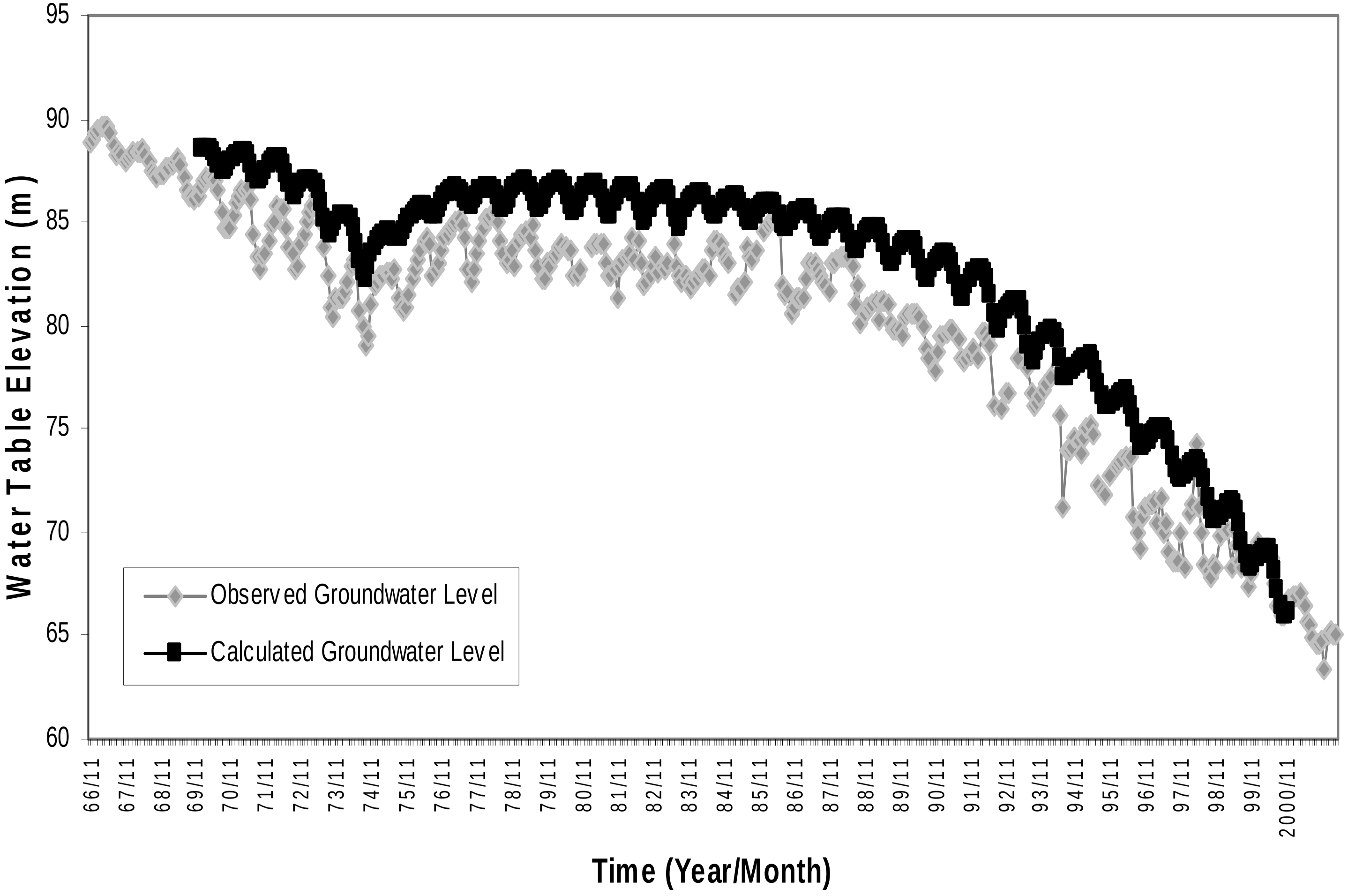

Figure 4.10. Observed and predicted hydrographs for well no. 52282 (Ahmetbey) under transient conditions.

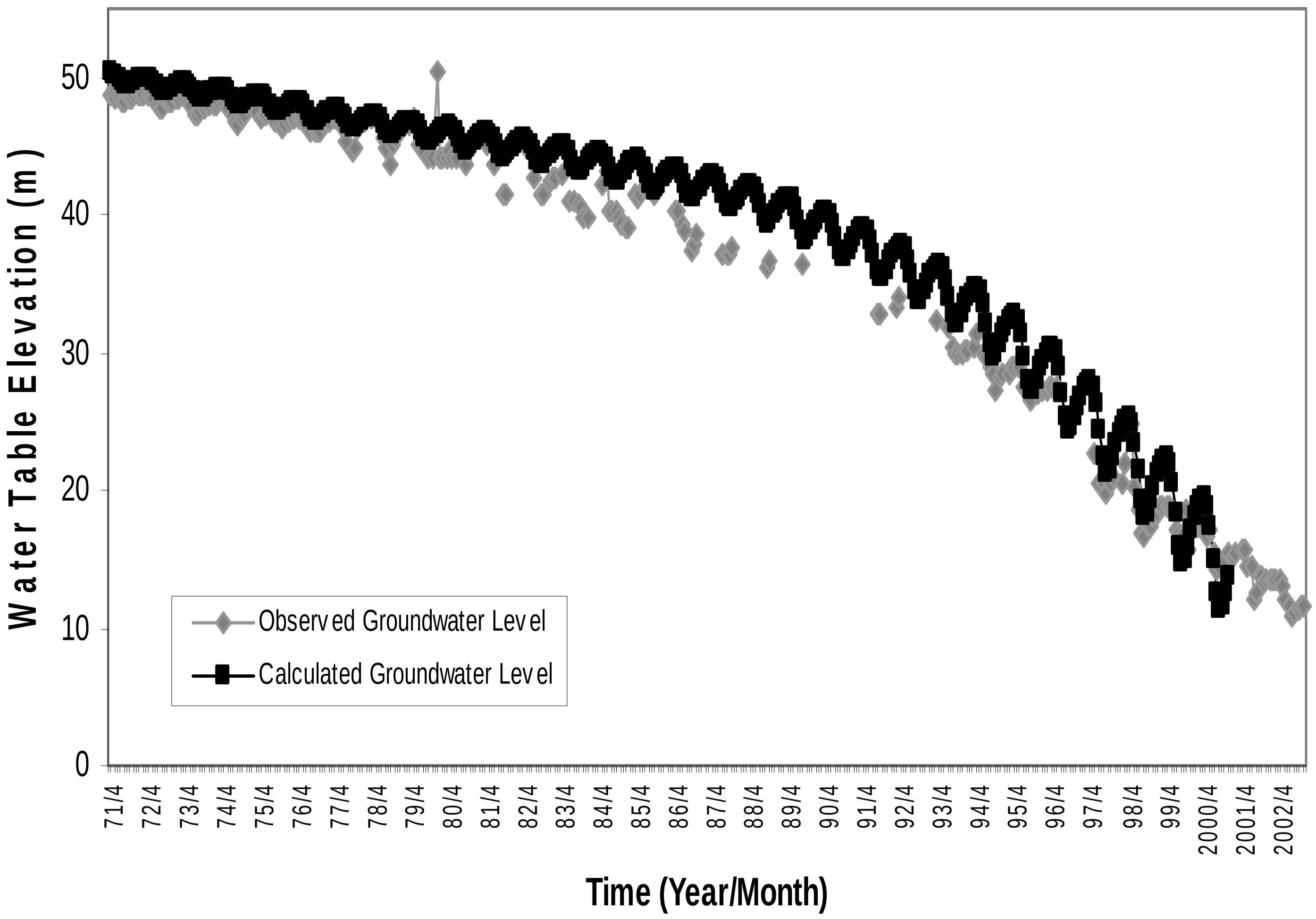

Figure 4.11. Observed and predicted hydrographs for well no. 52281 (Salhane) under transient conditions.

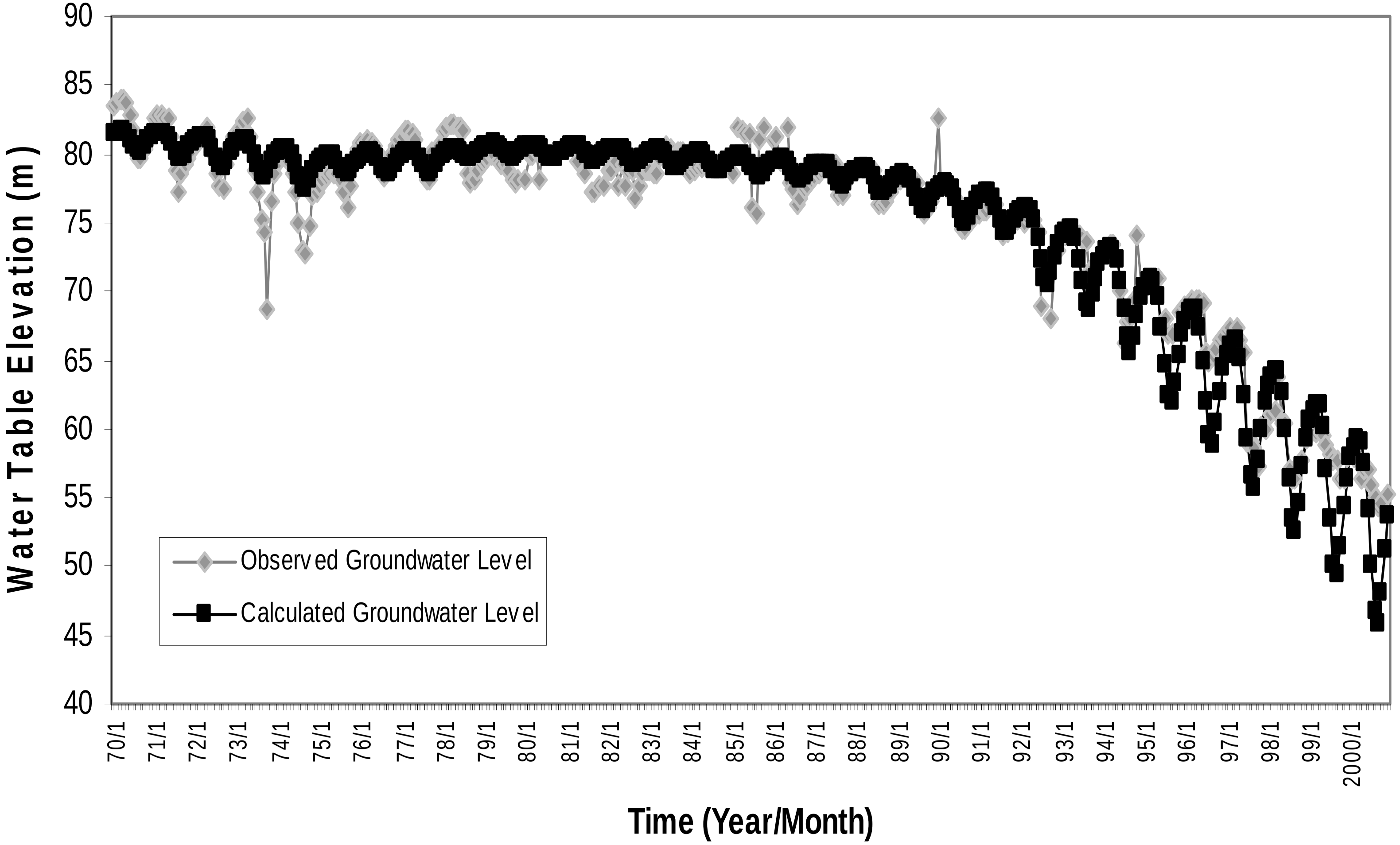

Figure 4.12. Observed and predicted hydrographs for well no. 12626 (Marmaracık) under transient conditions.

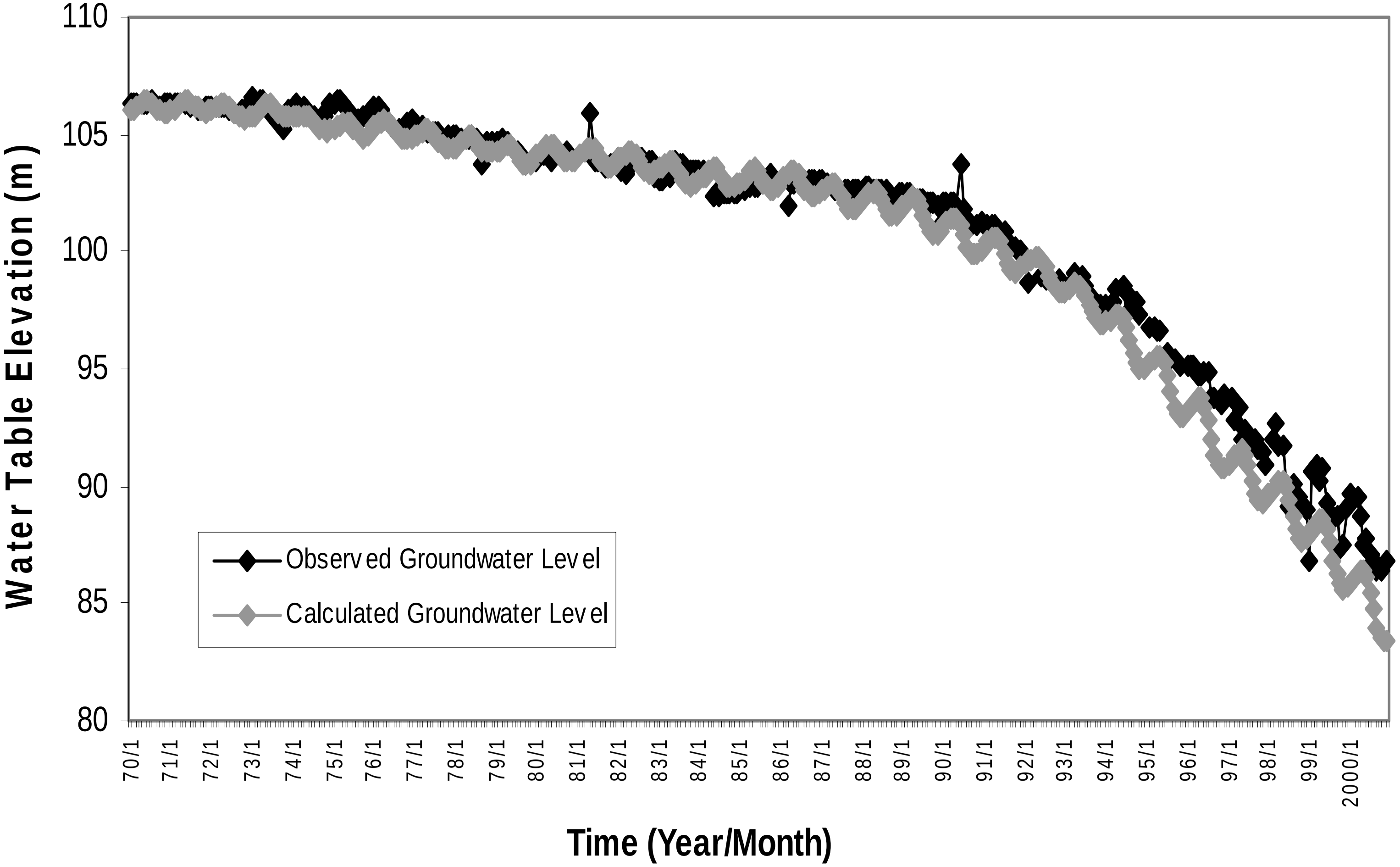

Figure 4.13. Observed and predicted hydrographs for well no. 52285 (K. Karıştıran) under transient conditions.

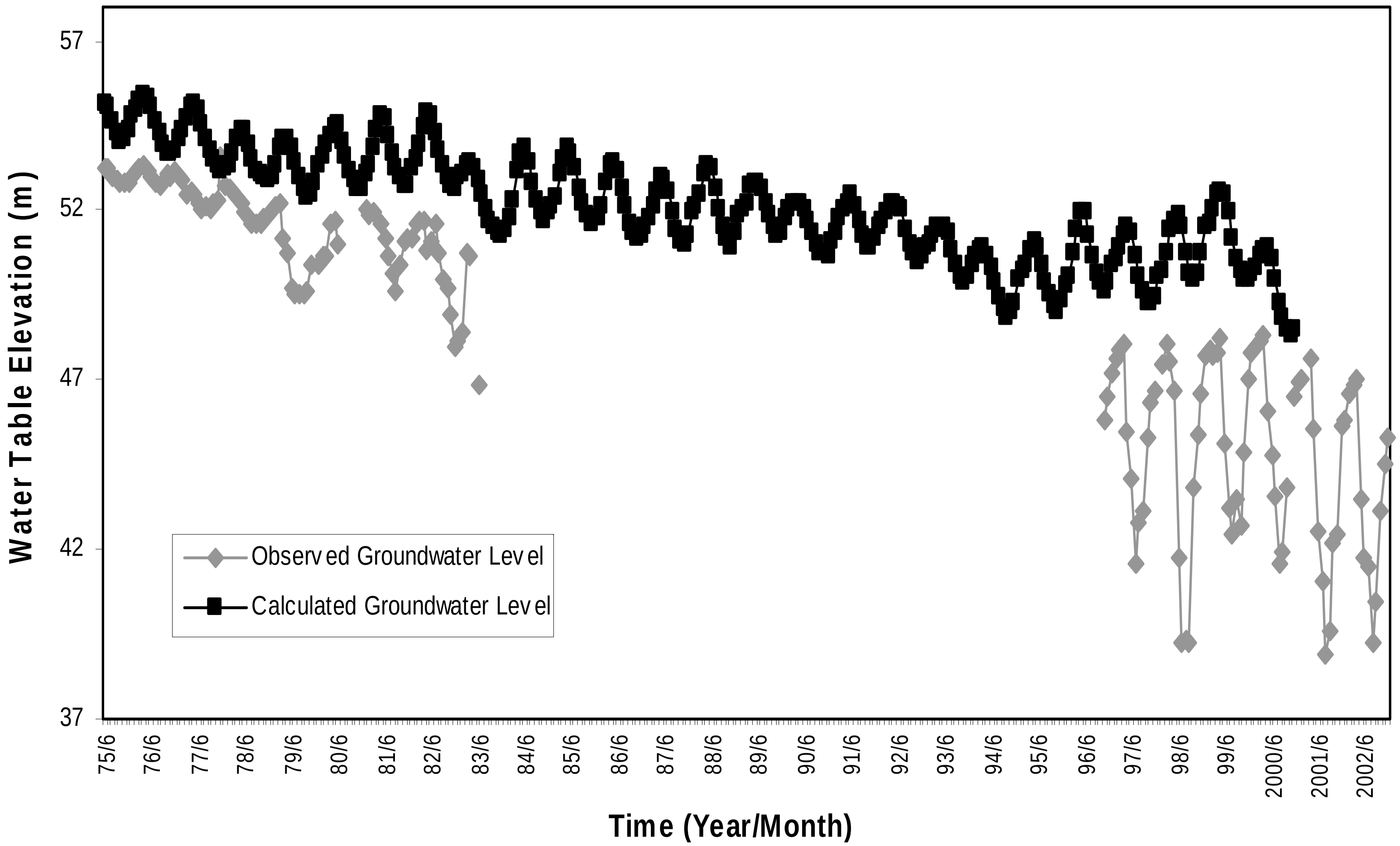

Figure 4.14. Observed and predicted hydrographs for well no. 49868 (Havsa-Merkez) under transient conditions.

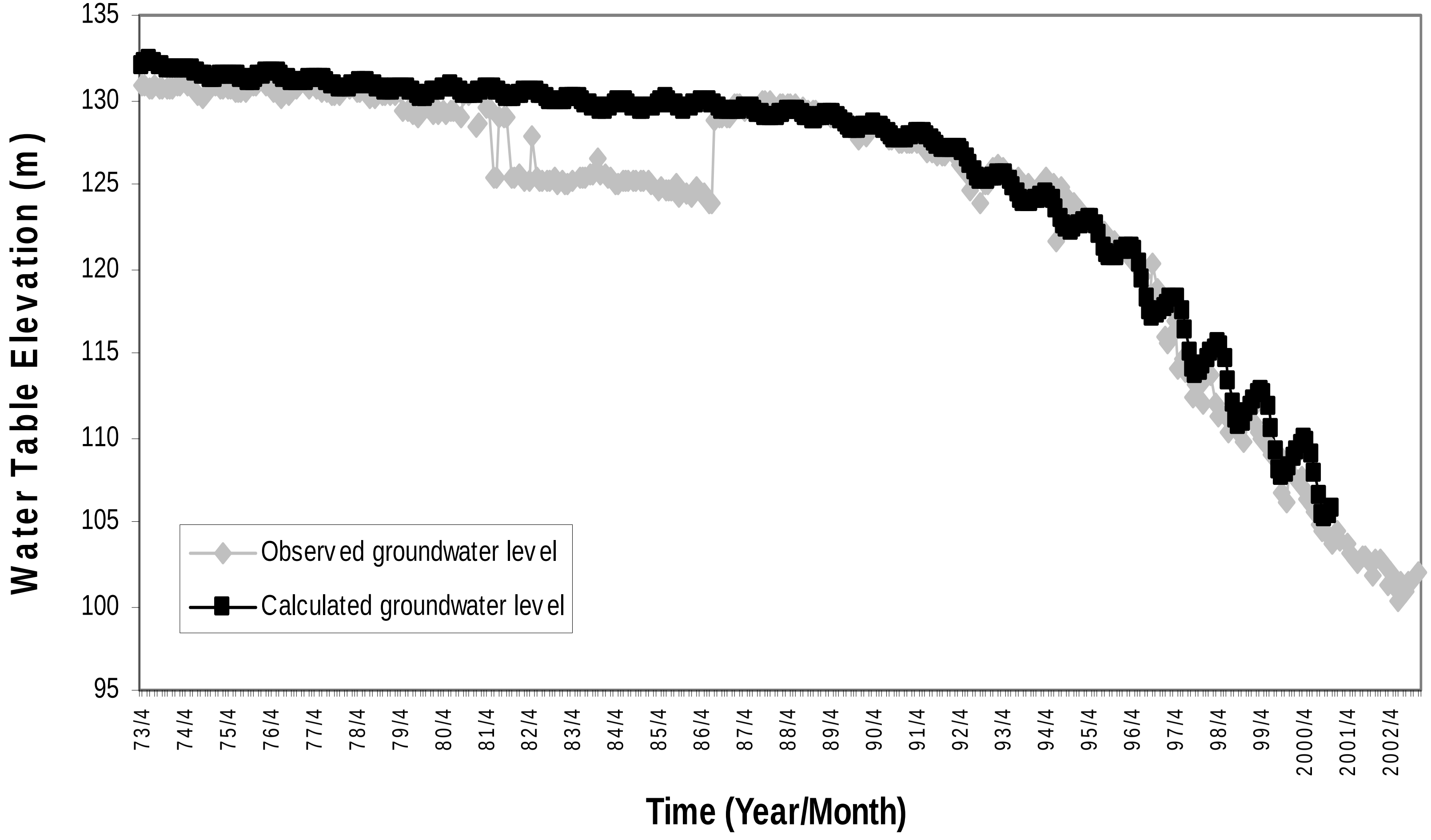

Figure 4.15. Observed and predicted hydrographs for well no. 49869 (Çerkezköy) under transient conditions.

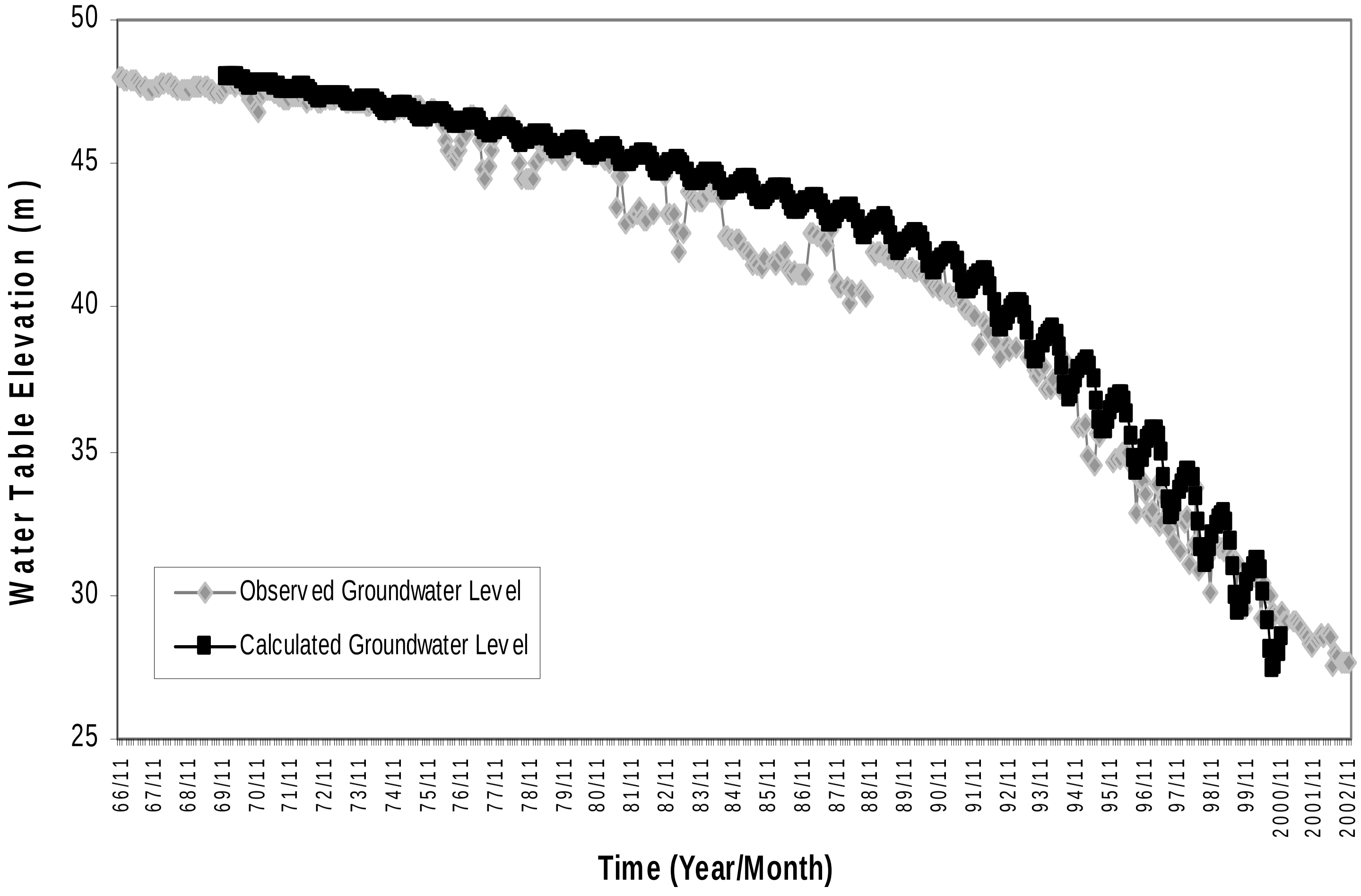

Figure 4.16. Observed and predicted hydrographs for well no. 5592 (Dambaşlar) under transient conditions.

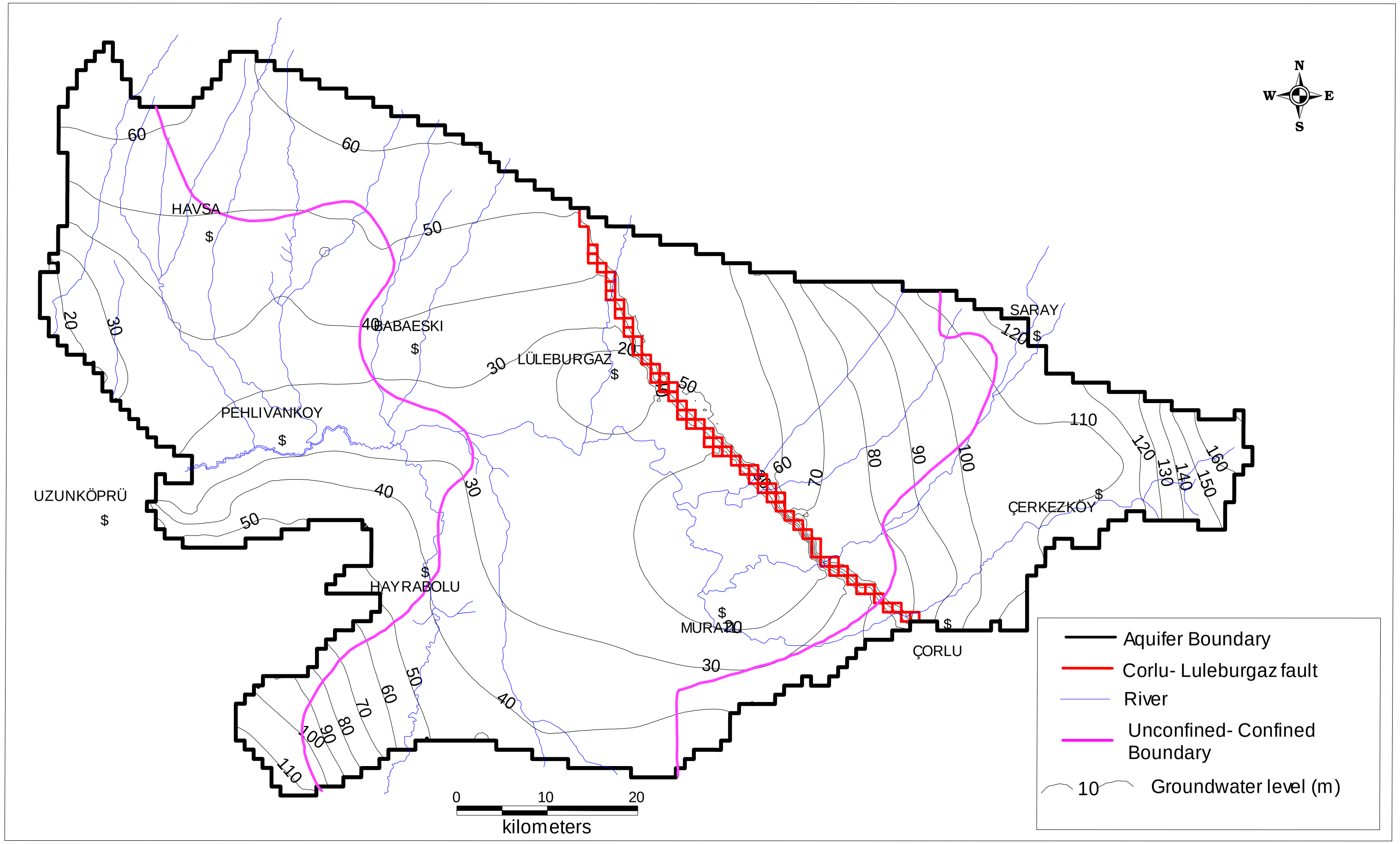

Figure 4.17. Predicted groundwater level elevation map for December 2000 under transient conditions.

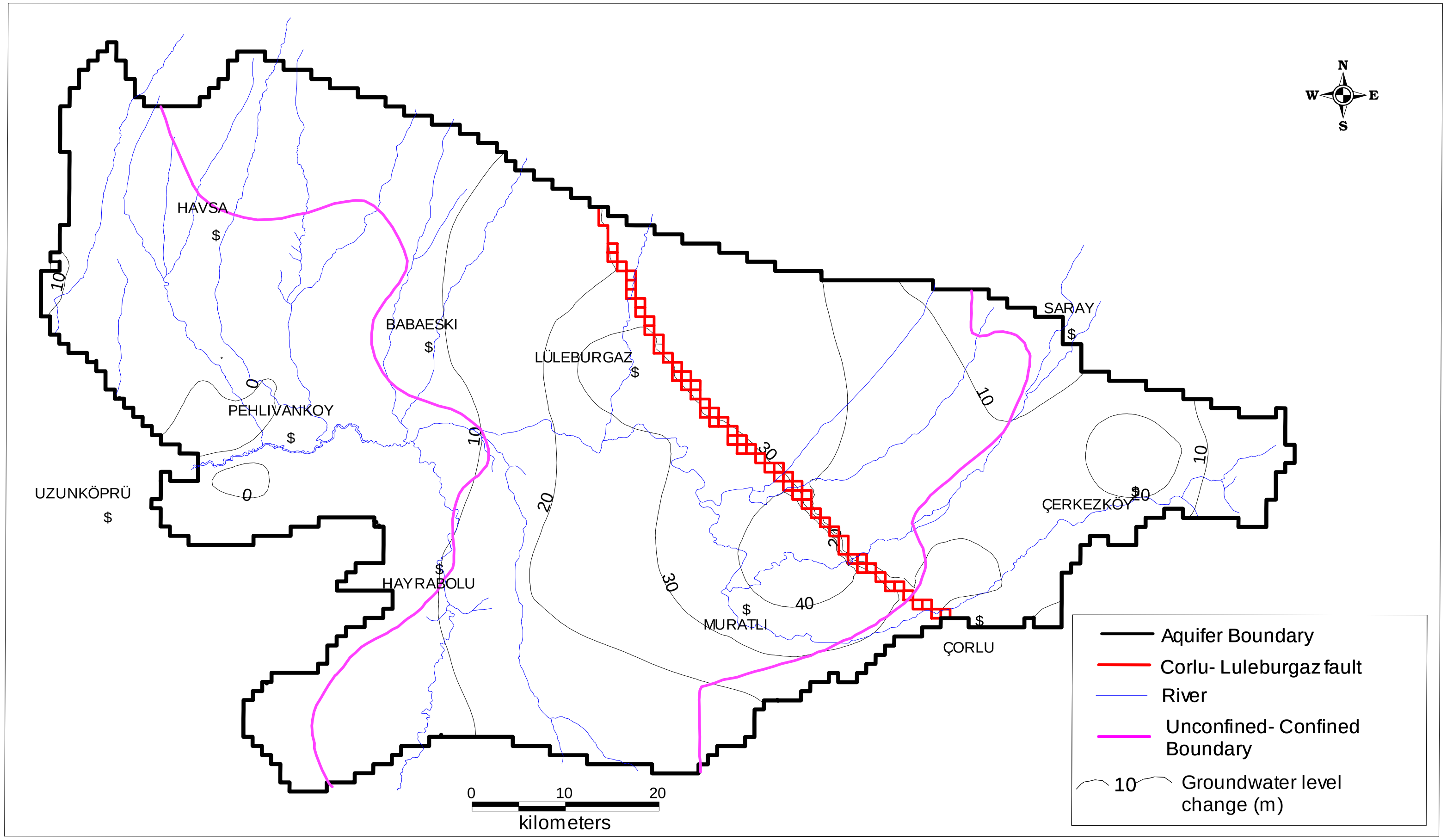

Figure 4.18. Predicted groundwater level change map for the period between January 1970 and December 2000 under transient conditions.

Çorlu-Lüleburgaz fault in the confined part. As it was stated before, the confined part receives no recharge from precipitation therefore the maximum amounts of drawdowns are observed in this part. In western unconfined part, there is not much decrease in groundwater levels at the end of 31 years of transient simulation. In eastern unconfined part, the maximum amount of drawdown is 20 m, near Çerkezköy most probably owing to the pumpage of water for industrial purposes.

Until 1980s industrial development in Ergene River Basin, relying on groundwater, showed an extraordinary increase as a result of the decentralization of the industry located in İstanbul. The amount of water extracted from the Çerkezköy Organized Industrial region Section I in 2003 is available from the field study as a reliable information because it is forbidden to open wells and pump water without the permission of the regions chairman (Table 4.6). Therefore, the amount is continuously recorded by meters. Section II comprises the factories newly included in the organized region so the exact amount of water pumped could not yet be recorded. The water wells opened for industrial purposes are pumped without any interruption throughout the year. When three cities, Tekirdağ, Kırklareli and Edirne are compared, the most developed one is Tekirdağ (Table 4.7) most probably because it is closer to İstanbul then the other two (personal communication with Çerkezköy Organize Sanayi District director). There are two organized industrial regions: Çerkezköy and Çorlu. The development history of industrialization is important as it is directly related to the change in groundwater levels. As a result of the increasing abstraction rates during 31 years of simulation period, water levels were continuously declined.

The average values of recharge discharge and the reserve change between January 1970 and December 2000 are given in Table 4.8. According to the groundwater budget obtained from the transient calibration, the average recharge was 371 hm^3/year, average discharge was 473 hm^3/year and the reserve change was 102 hm^3/year. In Table 4.9 the recharge, discharge, and

Table 4.6. The amount of water used by Çerkezköy Organized Industrial Region in 2003.

Months	Amount of Water Used by Çerkezköy Organized Industrial Region in 2003 (hm^3/year)	
	Section I	Section II
January	1.03	-
February	0.82	-
March	1.08	-
April	1.24	-
May	1.21	-
June	1.17	1.11
July	1.31	0.97
August	1.13	1.00
September	1.24	1.08
October	1.15	0.89
November	0.94	0.77
December	0.99	1.04
Total	13.31	6.86

Table 4.7. Sectoral Development of the industry in Thracian Basin

City Name	Textile	Milk Industry	Flour Industry	Alcohol	Leather
Edirne	12	12	19		
Kırklareli	46	9	16	1	
Tekirdağ	284	13	40	24	110
Total	342	34	75	25	110

Table 4.8. Groundwater budget obtained from calibration of the model under transient conditions for Ergene River Basin Sandy Complex Aquifer (January 1970- December 2000)

RECHARGE	(hm^3/year)	DISCHARGE	(hm^3/year)
Precipitation	213.06	Pumpage	170.58
Ergene River	19.13	Ergene River	190.11
Subsurface Inflow	139.24	Evapotranspiration	66.03
		Subsurface Outflow	46.38
Total	371.43	Total	473.1
AVERAGE RESERVE CHANGE= 101.66 (hm^3/year)			

Table 4.9. Yearly groundwater budget and reserve changes obtained from calibration of the model under transient conditions for the Ergene River Basin Sandy Complex Aquifer (January 1970- December 2000)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve* Change (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
1970	139.2	236.15	16.37	391.69	31.73	70.16	46.38	232.61	380.88	-10.81
1971	139.17	245.00	16.36	400.53	41.22	70.14	46.38	233.97	391.71	-8.83
1972	139.55	157.59	16.50	313.64	47.69	70.07	46.38	223.84	387.98	74.34
1973	139.17	243.66	16.47	399.30	58.45	69.78	46.38	226.58	401.19	1.89
1974	139.17	143.50	16.69	299.36	67.48	69.41	46.38	215.90	399.17	99.81
1975	139.18	239.10	16.86	395.14	64.63	69.19	46.38	215.20	395.40	0.27
1976	139.17	139.55	17.04	295.76	65.51	69.32	46.38	214.70	395.91	100.15
1977	139.17	174.10	17.18	330.45	69.06	68.96	46.38	210.20	394.60	64.15
1978	139.17	192.90	17.41	349.48	74.21	68.68	46.38	203.50	392.77	43.29
1979	139.20	194.10	17.73	351.03	79.32	68.48	46.38	201.20	395.38	44.35
1980	139.20	233.60	17.86	390.66	84.62	68.62	46.38	205.40	405.02	14.36
1981	139.20	235.00	17.95	392.15	89.52	68.33	46.38	204.70	408.93	16.78

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 4.9. Continued

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve* Change (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
1982	139.10	225.60	18.06	382.76	97.72	68.21	46.38	204.40	416.71	33.95
1983	139.50	130.50	18.50	288.50	107.72	67.79	46.38	191.30	413.19	124.69
1984	139.50	273.80	18.71	432.01	113.12	67.77	46.38	195.20	422.47	-9.54
1985	139.20	250.40	18.87	408.47	120.42	67.40	46.38	195.40	429.60	21.13
1986	139.20	205.00	19.26	363.46	127.42	67.40	46.38	191.60	432.80	69.34
1987	139.20	213.00	19.41	371.61	133.02	66.90	46.38	188.30	434.60	62.99
1988	139.60	262.90	19.52	422.02	148.02	66.80	46.38	190.90	452.10	30.08
1989	139.10	190.40	19.68	349.18	155.92	66.30	46.38	185.20	453.80	104.62
1990	139.20	150.40	20.05	309.65	169.92	65.70	46.38	174.60	456.60	146.95
1991	139.20	229.10	20.18	388.48	185.32	65.20	46.38	173.00	469.90	81.42
1992	139.50	169.40	20.49	329.39	226.92	64.70	46.38	170.70	508.70	179.31
1993	139.20	171.00	20.97	331.17	239.52	63.70	46.38	162.60	512.20	181.03

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 4.9. Continued

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve* Change (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
1994	139.20	149.40	21.47	310.07	272.42	62.80	46.38	154.70	536.30	226.23
1995	139.20	226.10	21.75	387.05	310.02	61.80	46.38	154.70	572.90	185.85
1996	139.20	271.90	21.84	432.94	357.62	61.20	46.38	158.50	623.70	190.76
1997	139.20	242.50	22.15	403.85	391.82	59.80	46.38	153.20	651.20	247.35
1998	139.20	343.20	22.37	504.77	424.52	58.70	46.38	156.60	686.20	181.43
1999	139.20	272.40	22.33	433.93	456.82	57.70	46.38	160.10	721.00	287.07
2000	139.20	193.70	23.06	355.96	476.22	56.00	46.38	144.50	723.10	367.14
Average	139.24	213.06	19.13	371.43	170.58	66.03	46.38	190.11	473.10	101.66

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

change in reserves for each year in the period between January 1970 and December 2000 are shown. The positive values of change in reserves show the periods when discharge is greater than recharge. Yearly changes in groundwater reserves are displayed in Figure 4.19, which shows that the declines in groundwater reserves were below the average until 1989. However, the reserve changes after 1993 were almost the twice (180- 200 hm^3/year) the average value. Furthermore, discharges to Ergene River and evaporation losses were decreased with increasing pumpage (Table 4.9) through time. The water lost by evaporation was decreased from 70 hm^3/year in 1970 to 56 hm^3/year in 2000 and the water discharged to Ergene River was decreased from 233hm^3/year in 1970 to 145 hm^3/year in 2000, while pumpage increased from 32 hm^3/year in 1970 to 476 hm^3/year in 2000.

4.4 Groundwater- Surface Water Interaction

The interaction between surface water and groundwater is a part of the hydrological cycle. There are two main aspects of this process, firstly the flow of groundwater to support river flow and secondly the flow from rivers to groundwater. The storage, flow and quality characteristics of surface water and groundwater being in relation are often different. Therefore, the interaction is important in water resource development since advantage may be taken of the differing characteristics to increase yields or improve the quality of water supplies. Changes in one part of the hydrological cycle may induce beneficial or detrimental changes in another part of the cycle (Wright, 1980).

In Ergene River Basin the groundwater flow model has been used to determine the relationship between groundwater and surface water. Recharge and discharge values for each year for the period between January 1970 and December 2000 were obtained with the help of the model (Table 4.8). According to Figure 4.20, the Ergene River and its tributaries are generally gaining in character and therefore the quality of river water may have been impacted by the quality of the groundwater.

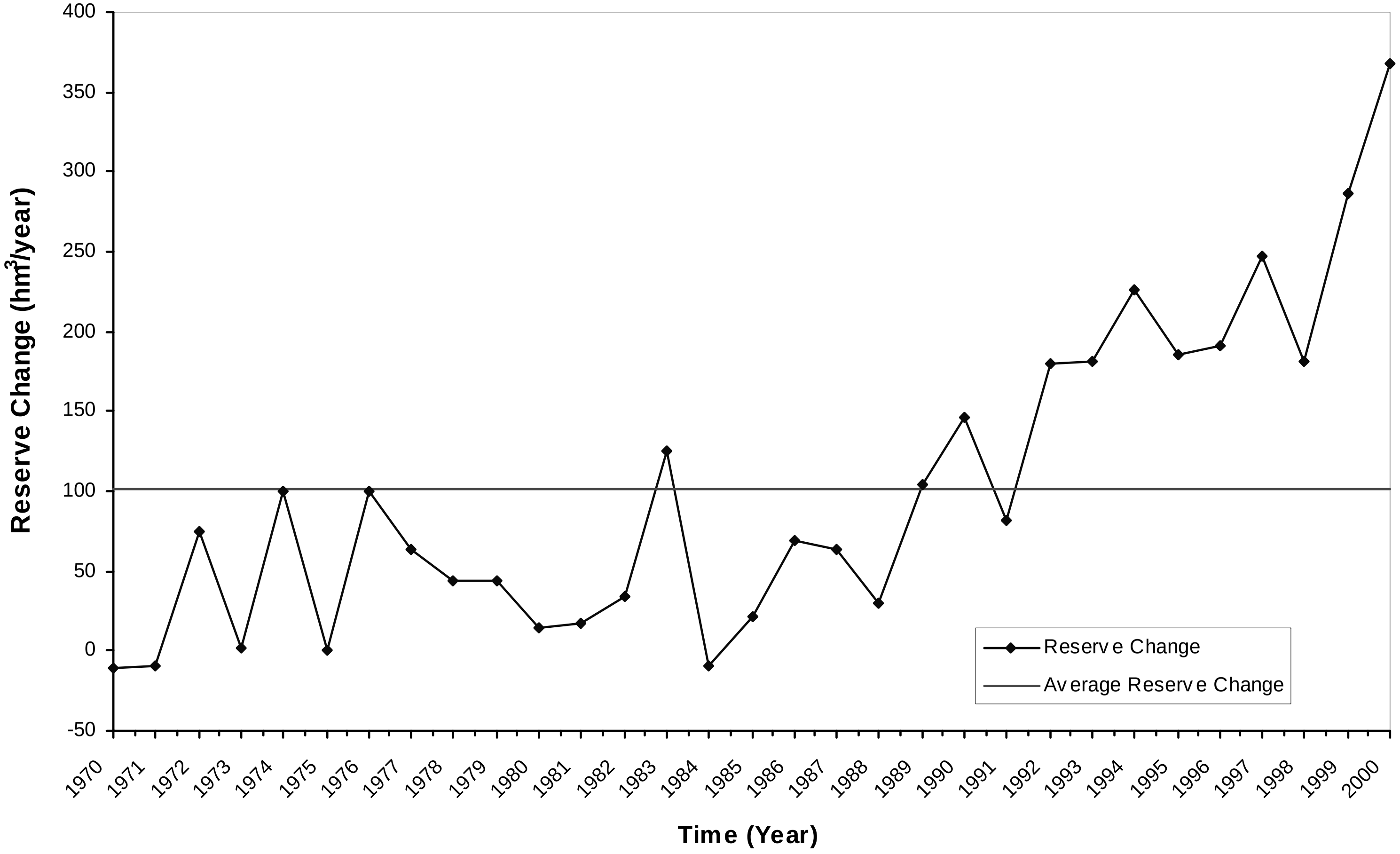

Figure 4.19. Calculated yearly reserve changes in groundwater reserves between years 1970- 2000 under transient conditions.

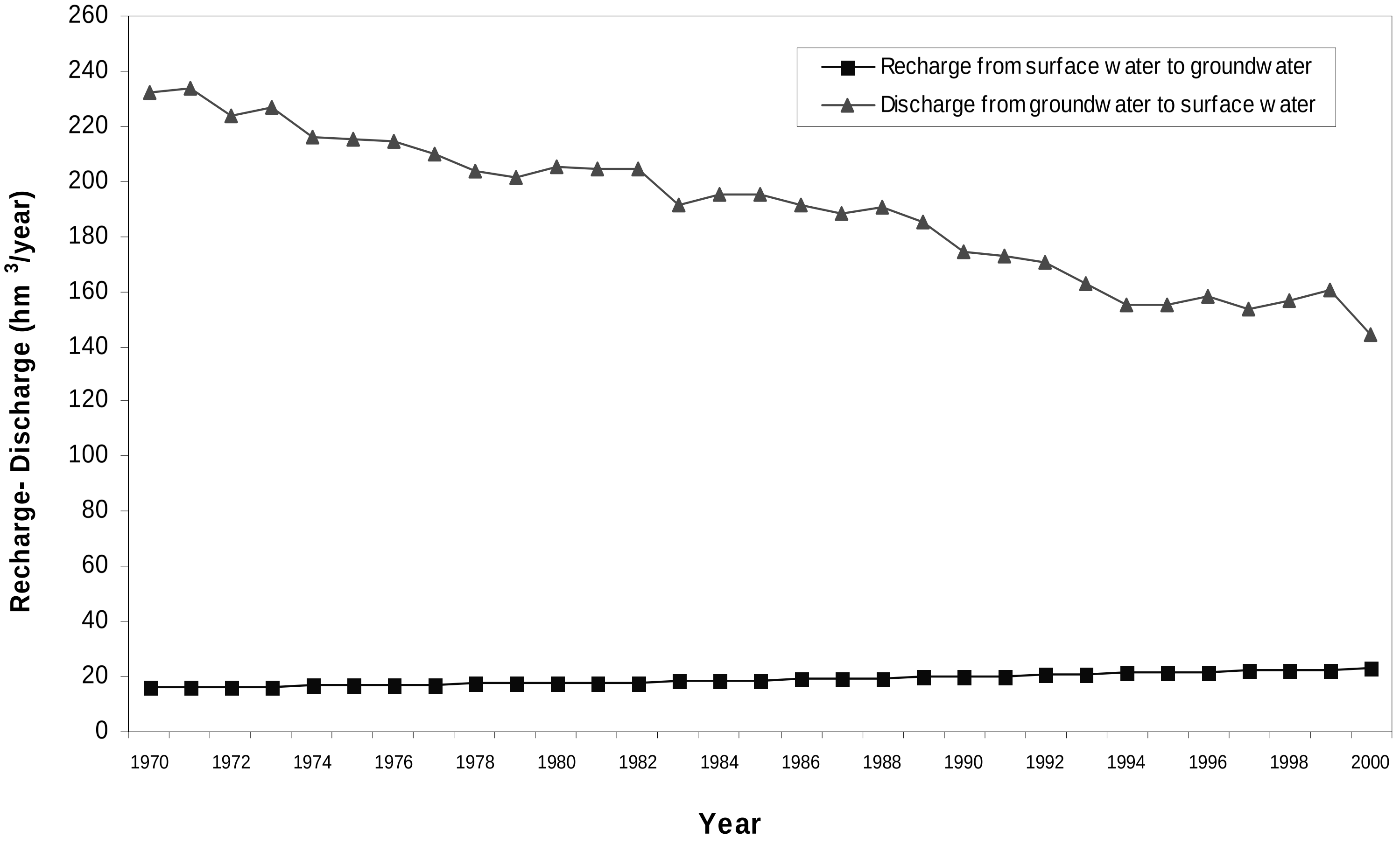

Figure 4.20. Calculated discharges from groundwater to surface water and from surface water to groundwater during 31 years of period between 1970-2000.

In 1970 discharge from groundwater to surface water was 232 hm^3/year and recharge from surface water to groundwater was 16 hm^3/year. With increasing pumping rates the dynamic equilibrium conditions between the two systems were disturbed, producing a decrease in base flow in the amount of 88 hm^3/year and an increase in recharge from surface water to groundwater in the amount of 7 hm^3/year over a period of 31 years.

In Ergene River Basin, the surface water is contaminated as most of the wastewater is discharged to the river. Ergene River acts as a collector by carrying pollutants from Çorlu all the way through Meriç River (Candeğer, 1998). This contamination does not affect the groundwater to some extent as the river gains water from the groundwater. Although it may take several years but if the Ergene River turns into a losing position, the quality of the groundwater system may be impacted seriously. For this reason, the interaction between the groundwater and surface water should continuously be examined.

CHAPTER 5

ALTERNATIVE GROUNDWATER PUMPING SCENARIOS

5.1 Introduction

The calibration of the model was achieved under steady state and transient conditions when the calculated and observed groundwater levels showed good agreement. By that way, with the successfully calibrated model the aquifer parameters representing the field conditions were estimated so as to predict the aquifers responses to any disturbance under the possible management strategies.

In order to help planning and management of the Ergene River Basin, alternative groundwater pumping scenarios have been developed. A planning period of 30 years, beginning from January 2001 and ending in December 2030, was selected for all scenarios. All the scenarios start from the point where the transient calibrated model ends. Under transient conditions, totally eight different scenarios have been worked out for 30 years in order to determine the sustainable yield of the basin. The model boundaries and the finite difference grid remained unchanged for all of the alternatives.

For each scenario, three sets of information were produced for easy comparison of the results. Groundwater level change maps were generated for each alternative by subtracting the groundwater level elevations of December 2030 from January 2001 groundwater level elevations. These maps rely on the recharge and discharge conditions therefore there can possibly be positive or negative values showing a decrease or an increase in the groundwater level elevations. By examining these maps, any change in the groundwater levels can be seen at the end of a scenario; however, the time vise changes of the water levels can not be obtained by this set. Therefore, a second set of information has been gathered showing the water level changes with time at 6 observation wells (DSİ no. 52281, 5592, 52282, 52279, 52285 and 49869). The last set of information for each scenario is the groundwater budget and change in reserves for each year in a planning period of 30 years. For each case, a graph showing the calculated yearly changes in groundwater reserves was prepared.

5.2 Scenario A

In this first scenario, it was assumed that the conditions of year 2000 were assumed to continue for 30 years without any modification of the pumpage rates. Therefore the yearly pumpage rate assigned to the model was approximately 475 hm^3/year. The recharge from the precipitation was taken to be the arithmetic average of the past 31 years (i.e., 213 hm^3/year) for all of the stress periods. The calibrated model parameters were used without any change. Calculated groundwater level elevation and water level change maps at the end of planning period are given in Figures 5.1 and 5.2. As it can be seen from these maps, if the conditions in year 2000 continue for 30 years, there would be important declines in groundwater level elevations at the end of planning period. Excessive drawdowns have been noted around Çerkezköy, Muratlı and K. Karıştıran (Figure 5.2). As a result of the decreases in the water table elevations due to excessive pumping, some areas went dry near Çerkezkoy and Doyran (Figure 5.1). The areas began to go dry by September 2006 around Çerkezköy and by December 2025 around Doyran.

Predicted water level hydrographs in the planning period obtained from simulation are shown in Figures 5.3-5.8. As it can be seen from these figures, the water level elevations continuously decrease for the whole area. It should be noted that the water level elevations would be below sea level around Dambaşlar, Lüleburgaz and Muratlı at the end of year 2030.

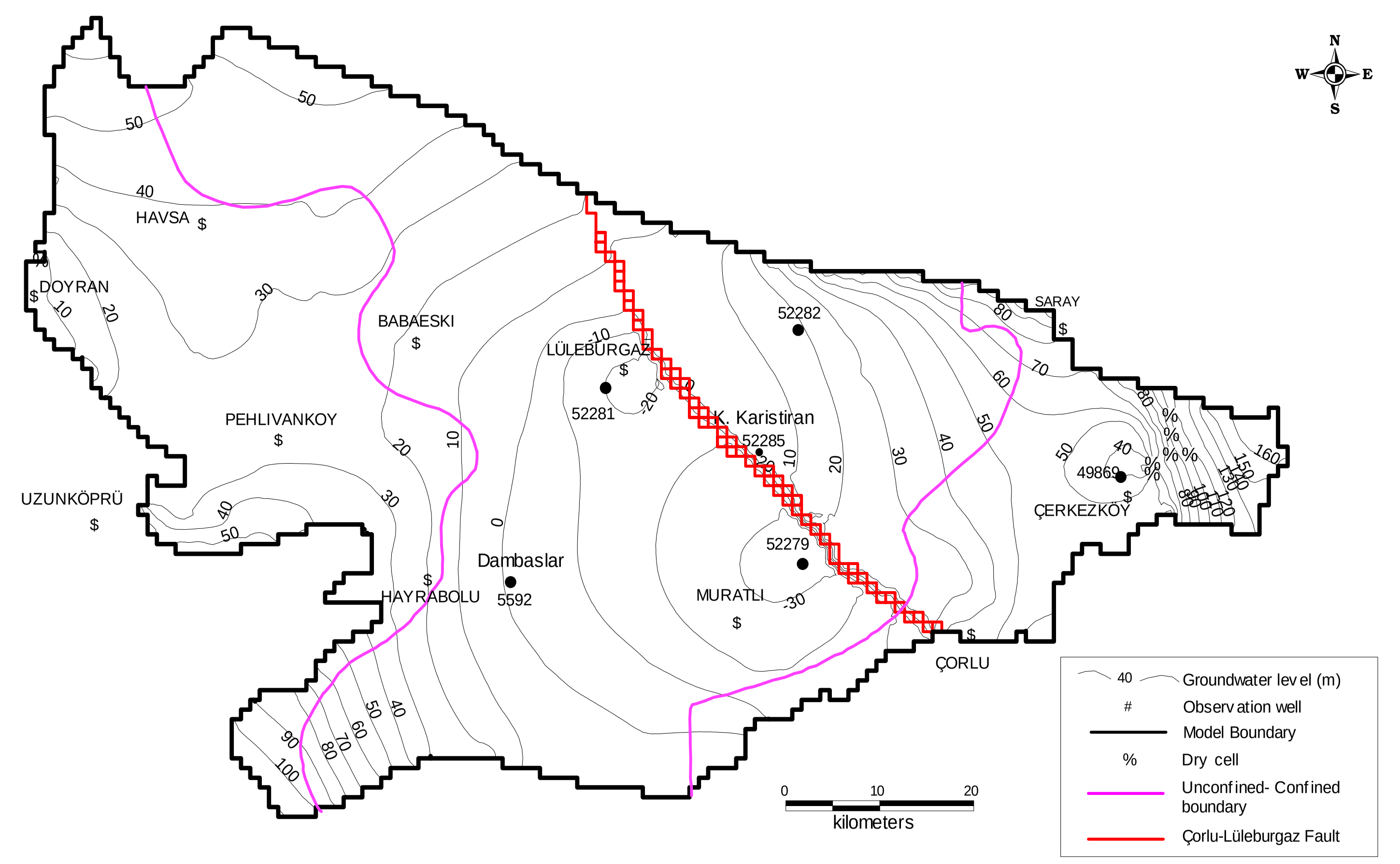

Figure 5.1. Predicted groundwater level elevation map at the end of the planning period for Scenario A (December 2030).

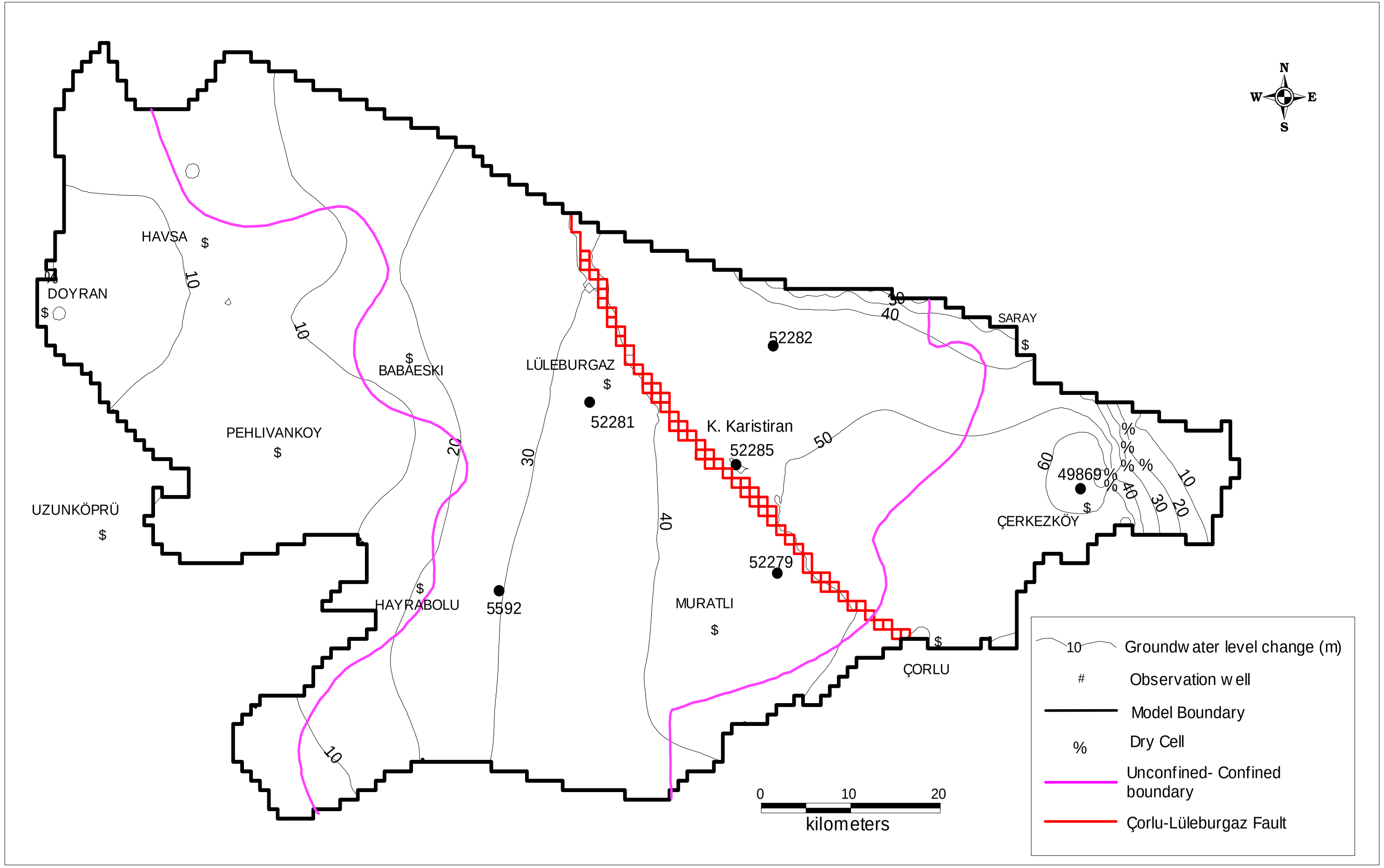

Figure 5.2. Predicted groundwater level change map at the end of the planning period for Scenario A (December 2030).

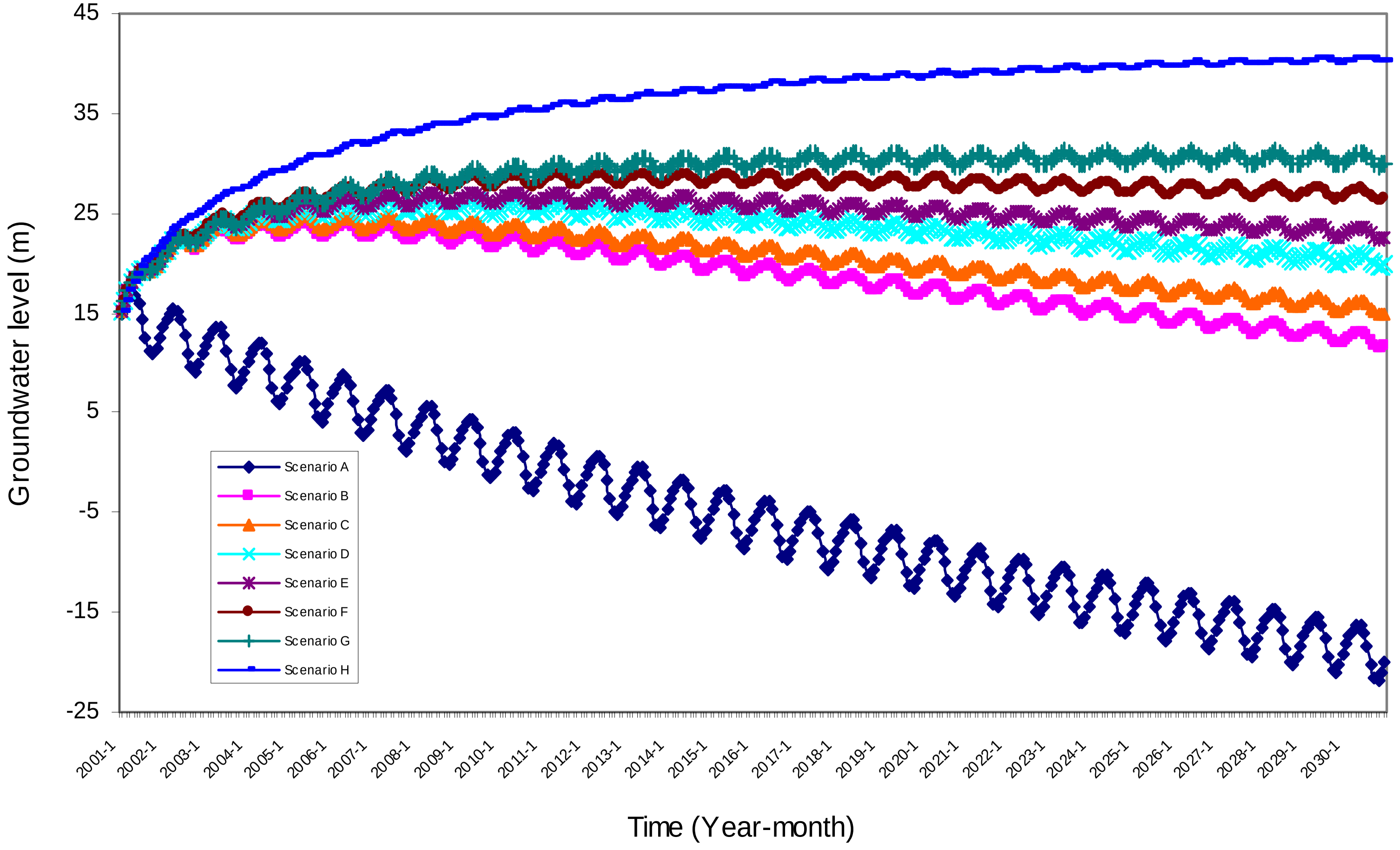

Figure 5.3. Predicted hydrographs obtained from different scenarios for well no. 52281 (Ağayeri) during the planning period.

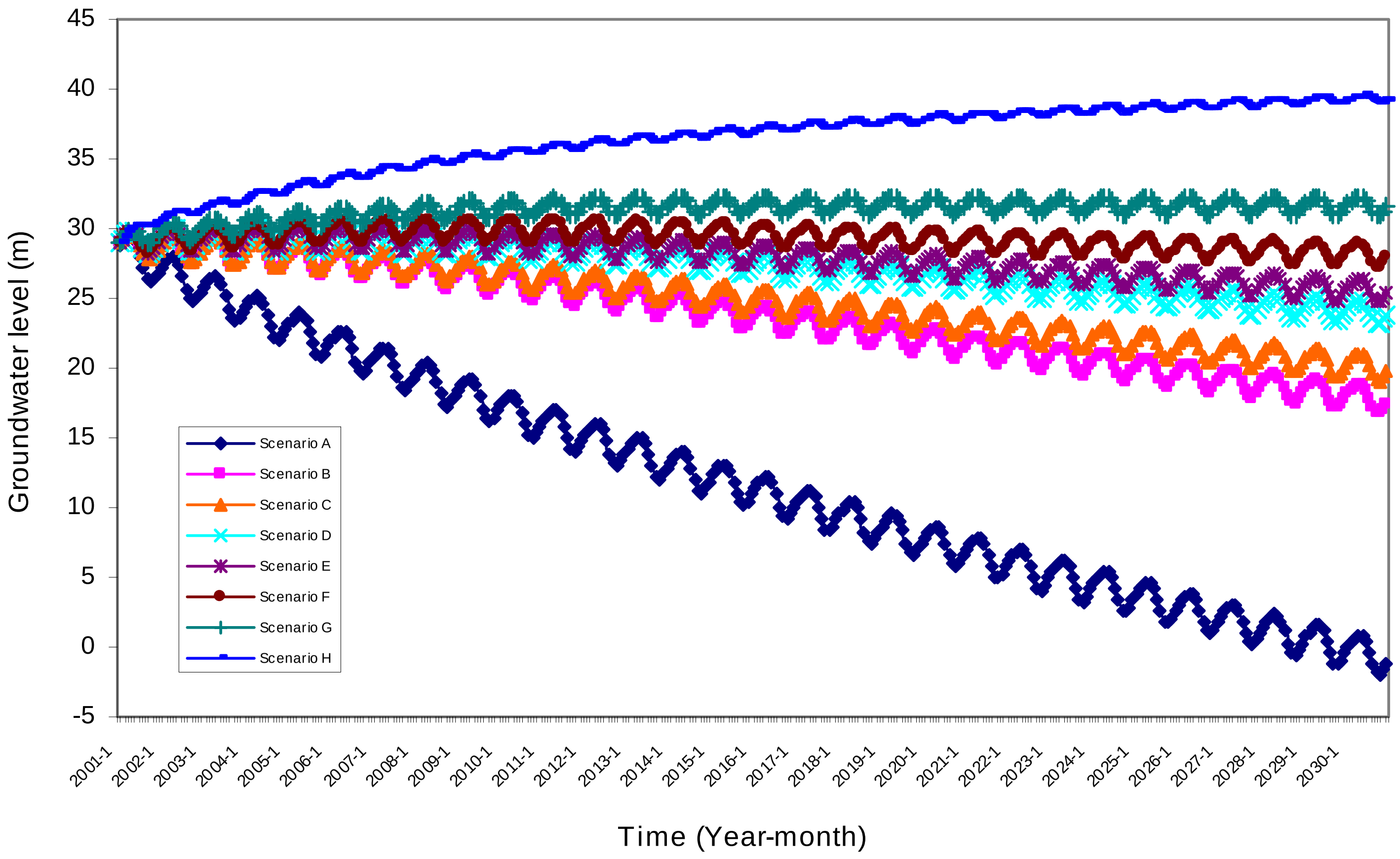

Figure 5.4. Predicted hydrographs obtained from different scenarios for well no. 5592 (Dambaşlar) during the planning period.

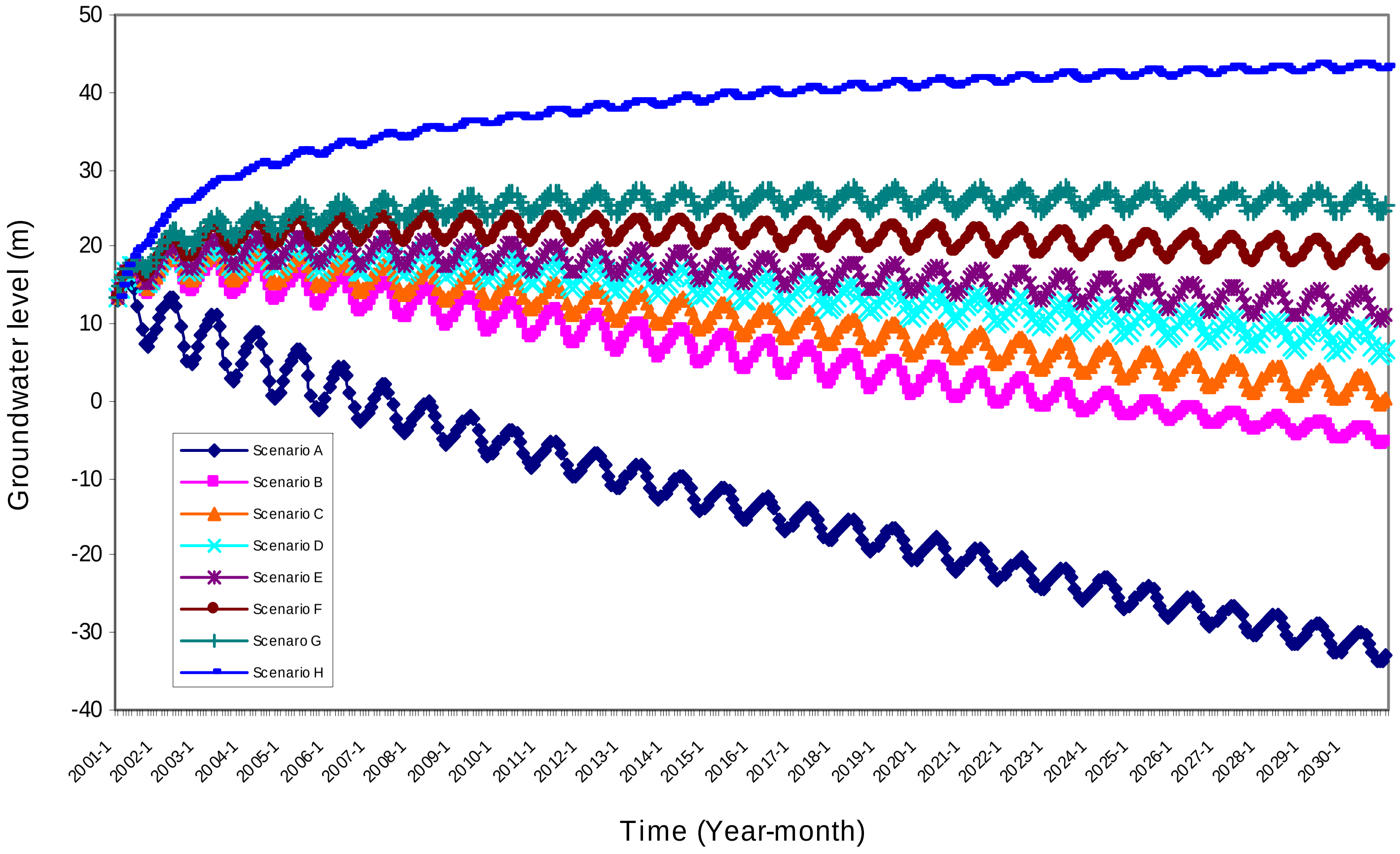

Figure 5.5. Predicted hydrographs obtained from different scenarios for well no. 52279 (Y. Sevindikli) during the planning period.

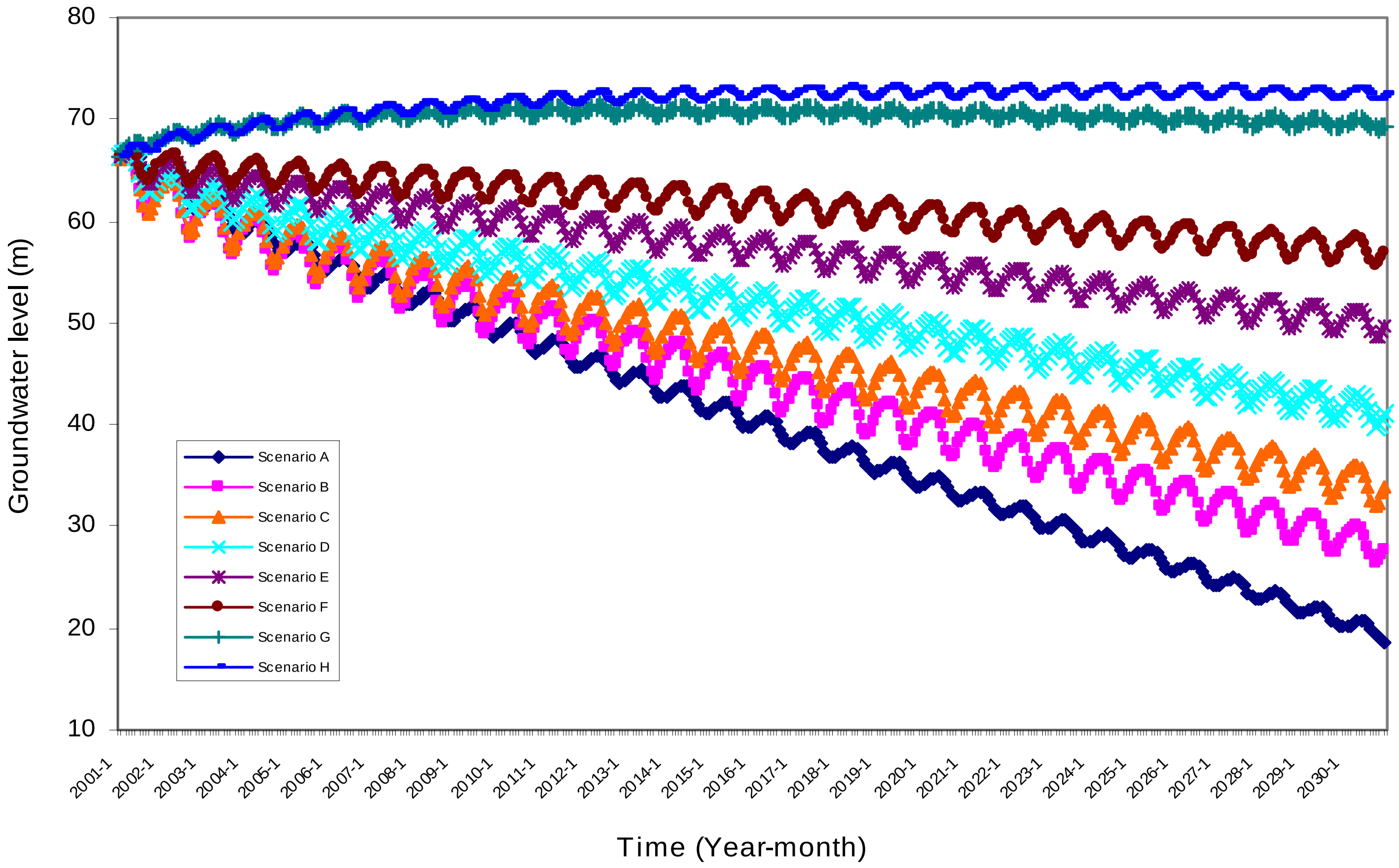

Figure 5.6. Predicted hydrographs obtained from different scenarios for well no. 52282 (Ahmetbey) during the planning period.

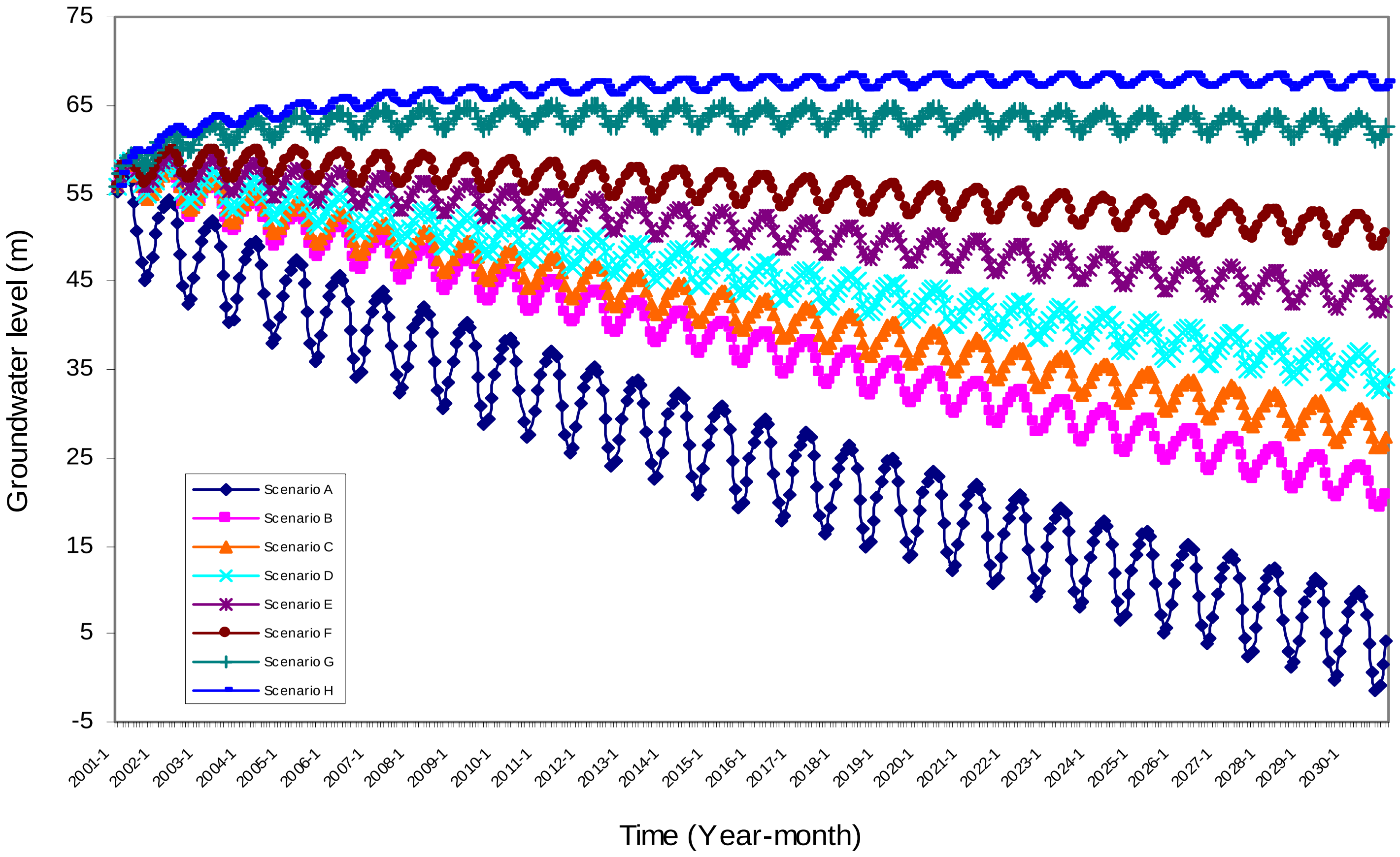

Figure 5.7. Predicted hydrographs obtained from different scenarios for well no. 52285 (K. Karıştıran) during the planning period.

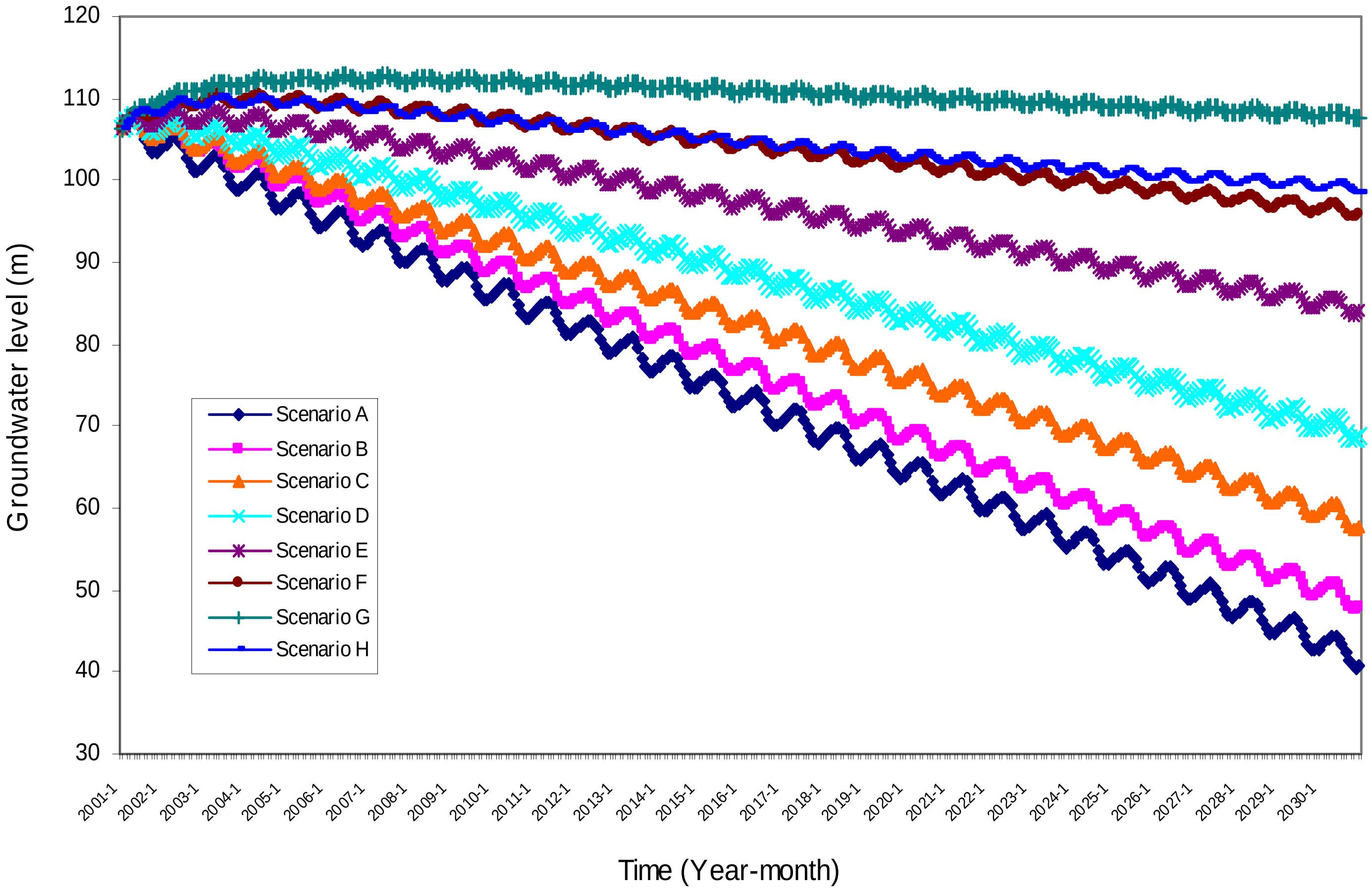

Figure 5.8. Predicted hydrographs obtained from different scenarios for well no. 49869 (Çerkezköy) during the planning period.

The yearly groundwater budget and reserve changes obtained from Scenario A during planning period are given in Table 5.1. As it can be seen from this table, if the conditions of year 2000 continues for 30 years the average decline in the groundwater reserves will be 273 hm^3/year (Figure 5.9). Although pumpage rates assigned to the model didn't change for the planning period, the total amount of water pumped have decreased from 477 hm^3/year to 465 hm^3/year in the calculated budget due to the reason that the cells which became dry weren't considered in the flow calculations.

To conclude, if the pumpage conditions remained the same as the conditions of year 2000 during a planning period of 30 years there would be significant declines in groundwater levels and reserves in the Ergene River Basin. It is estimated that the average basin-wide decline in groundwater levels at the end of the planning period would be 28.3 m.

5.3 Scenario B

In Scenario A, it was verified that a planning period of 30 years with a pumpage rate of 475 hm^3/year would cause important declines in groundwater levels. Therefore, Scenario B was considered for the management of the Sandy Complex aquifer. In this scenario the yearly annual pumpage was taken to be equal to the annual average recharge, which was estimated to be 371 hm^3/year during the 31 years of transient calibration period between January 1970 and December 2000 (Table 4.8). To develop this scenario, the annual pumpage rates were decreased from 475 hm^3/year to 371 hm^3/year and all the remaining parameters remained the same as in Scenario A.

The predicted groundwater level elevation map and groundwater level change map at the end of the planning period obtained from scenario B are given in Figures 5.10 and 5.11 respectively. According to these figures, there was again about 70 m of decline in groundwater levels around Çerkezköy as in Scenario A but the decline in groundwater levels around Muratlı and

Table 5.1. Yearly groundwater budget and reserve changes obtained from Scenario A during the planning period (January 2001- December 2030)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2001	143.33	213.61	23.12	380.06	477.55	54.37	45.52	136.89	714.33	334.27
2002	143.32	213.60	23.33	380.25	478.22	52.88	45.52	130.97	707.59	327.34
2003	143.72	214.53	23.70	381.95	478.59	51.58	45.52	125.62	701.31	319.36
2004	143.33	213.61	24.00	380.93	478.19	50.09	45.52	121.04	694.84	313.90
2005	143.32	213.65	24.26	381.23	478.19	48.79	45.52	117.31	689.81	308.57
2006	143.33	213.60	24.47	381.40	477.58	47.64	45.52	115.14	685.88	304.48
2007	143.75	214.40	24.79	382.94	476.48	46.58	45.52	112.59	681.17	298.23
2008	143.30	213.50	24.94	381.74	475.98	45.34	45.52	109.60	676.44	294.70
2009	143.30	213.50	25.10	381.90	475.98	44.27	45.52	107.10	672.87	290.97
2010	143.30	213.60	25.25	382.15	476.08	43.25	45.52	104.70	669.55	287.40
2011	143.30	214.40	25.43	383.13	476.38	42.39	45.52	102.80	667.09	283.96

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 5.1. (Continued)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2012	143.30	213.50	25.51	382.31	475.68	41.35	45.52	100.30	662.85	280.54
2013	143.30	213.40	25.69	382.39	473.78	40.46	45.52	98.50	658.26	275.87
2014	143.30	213.50	25.79	382.59	473.78	39.61	45.52	96.60	655.51	272.92
2015	143.30	214.30	25.92	383.52	473.78	38.91	45.52	95.20	653.41	269.89
2016	143.30	213.30	25.93	382.53	470.18	38.01	45.52	93.20	646.91	264.38
2017	143.70	213.20	26.07	382.97	473.18	37.36	45.52	91.80	647.86	264.89
2018	143.30	212.20	26.19	381.69	470.08	36.52	45.52	90.10	642.22	260.53
2019	143.30	214.20	26.18	383.68	470.68	35.91	45.52	89.00	641.11	257.43
2020	143.30	213.20	26.24	382.74	470.28	35.13	45.52	87.30	638.23	255.49
2021	143.30	213.30	26.30	382.90	470.48	34.46	45.52	86.00	636.46	253.56
2022	143.30	213.20	26.42	382.92	469.48	33.80	45.52	84.80	633.60	250.68

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 5.1. (Continued)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2023	143.30	214.20	26.40	383.90	471.48	33.26	45.52	83.70	633.96	250.06
2024	143.30	213.30	26.46	383.06	469.48	32.58	45.52	82.40	629.98	246.92
2025	143.30	213.10	26.51	382.91	468.48	31.90	45.52	81.20	627.10	244.19
2026	143.30	213.10	26.66	383.06	467.48	31.30	45.52	80.10	624.40	241.34
2027	143.30	214.00	26.76	384.06	467.48	30.80	45.52	79.20	623.00	238.94
2028	143.30	213.10	26.81	383.21	466.48	30.20	45.52	78.10	620.30	237.09
2029	143.30	213.00	26.85	383.15	467.48	29.60	45.52	77.00	619.60	236.45
2030	143.40	213.00	26.86	383.26	465.48	29.10	45.52	76.10	616.20	232.94
Average	143.35	213.54	25.60	382.48	472.81	39.58	45.52	97.81	655.73	273.24

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

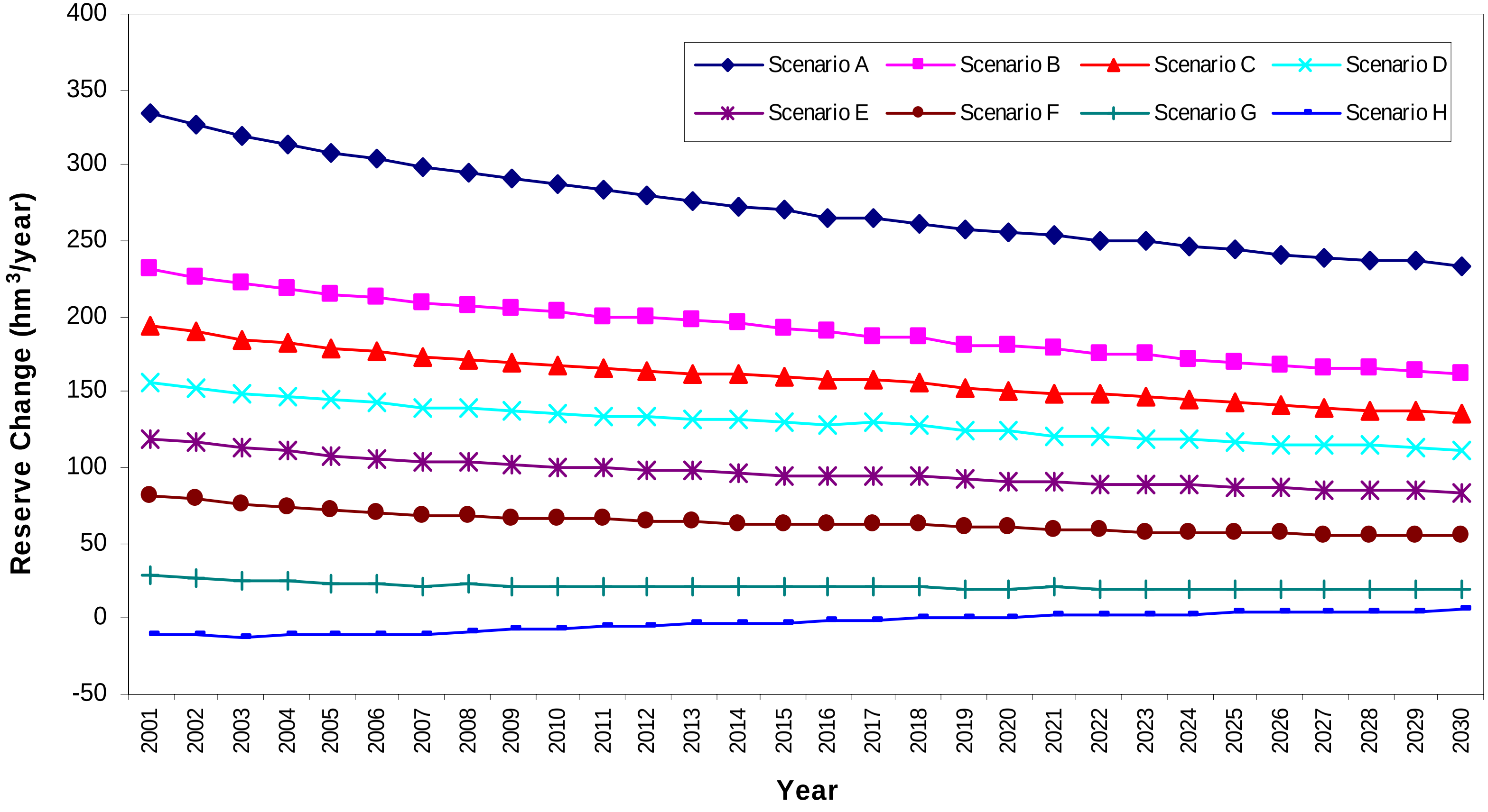

Figure 5.9. Yearly reserve changes calculated from Scenario A-H during the planning period.

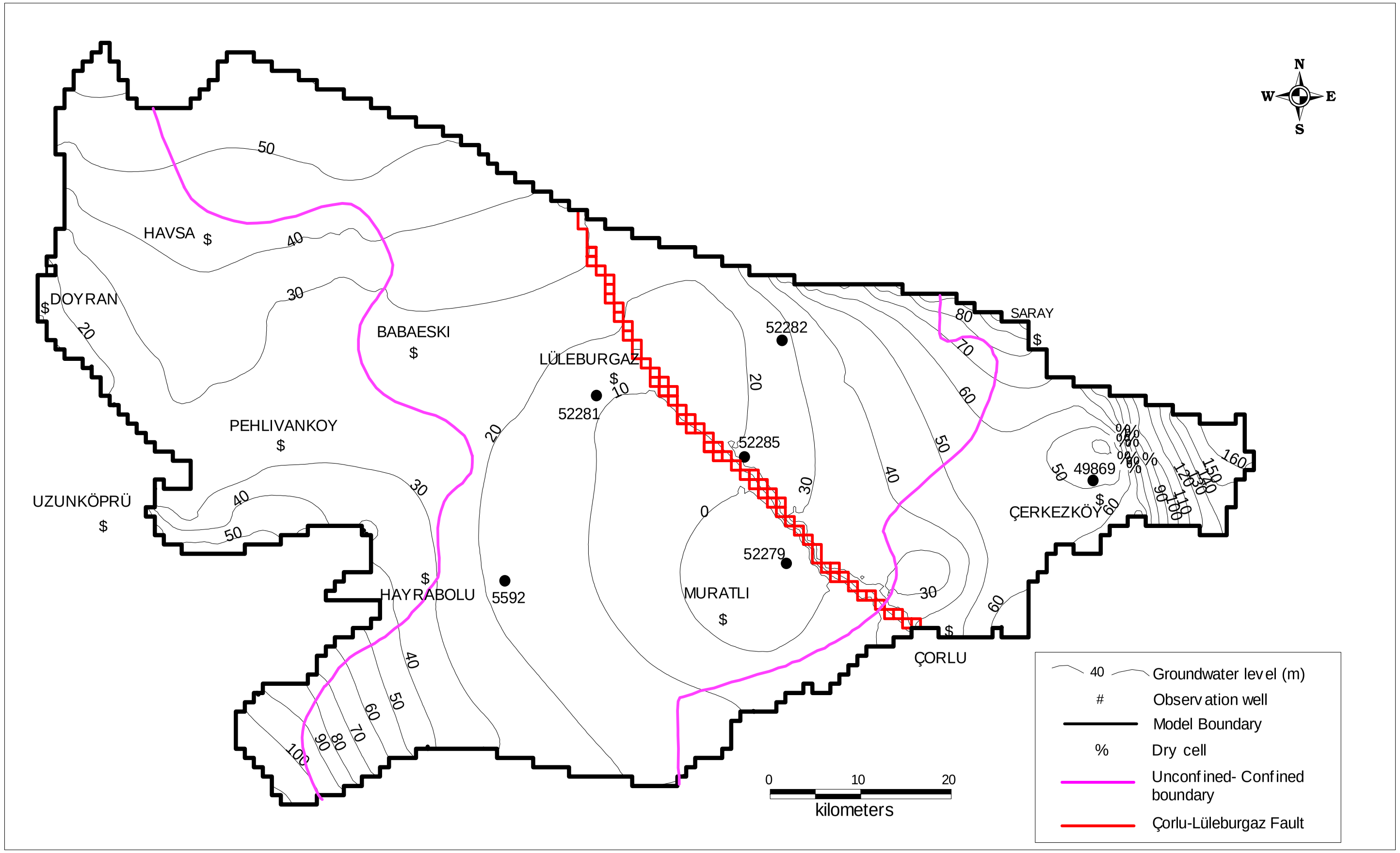

Figure 5.10. Predicted groundwater level elevation map at the end of the planning period for Scenario B (December 2030).

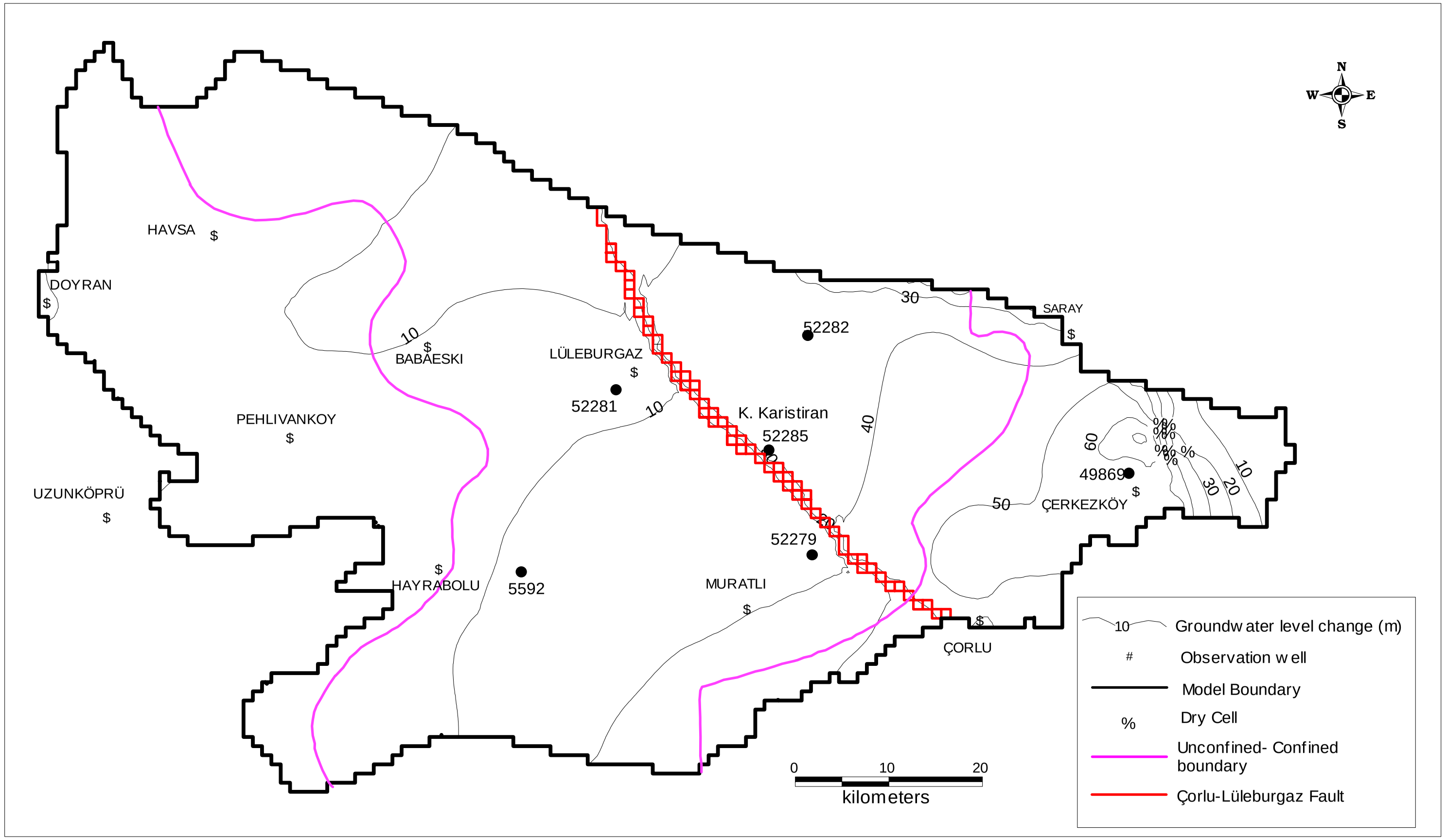

Figure 5.11. Predicted groundwater level change map at the end of the planning period for Scenario B (December 2030).

Lüleburgaz were about 30 m higher. Some dry cells around Çerkezköy occured, but this time no cells became dry around Doyran.

The reduction of the pumpage to the average annual recharge values produced an average areal increase of about 10 m in groundwater levels as compared to Scenario A. The magnitude of the rise in groundwater levels was not uniform all over the basin. The rises in groundwater levels especially in the western and eastern unconfined parts were lower as compared to the area around Çorlu- Lüleburgaz fault located in the confined part. These differences can also be seen from the groundwater level hydrographs (Figure 5.3-5.8). These figures also show that the reduction in pumpage rates to the average annual recharge values did not produce a steady-state condition in groundwater levels at the observation wells at the end of the planning period.

Yearly groundwater budget and reserve changes obtained from scenario B is given in Table 5.2. This table shows that the average recharge to the aquifer is 381 hm^3/year and the total average discharge from the aquifer is 572.8 hm^3/year resulting in an average reserve change of 191 hm^3/year (Figure 5.9) under specified conditions of Scenario B during the planning period. When the changes in groundwater reserves obtained from Scenario A and B are compared it can be seen that the change in Scenario B is 30% less than the former one. Therefore, newly adopted pumping rates of Scenario B are obviously better in the management of the Sandy Complex aquifer than Scenario A. However, even pumping at an average annual recharge produced a basin wide decline of 18.1 m in groundwater levels and an average yearly decline of 191 hm^3/year in groundwater reserves.

5.4 Scenario C

In this third scenario, the pumpage conditions were modified in a way that the total annual pumpage equals to 90% of the total annual average recharge, which was 371 hm^3/year. This means that for this scenario the

Table 5.2. Yearly groundwater budget and reserve changes obtained from Scenario B during the planning period (January 2001-December 2030)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2001	143.33	213.61	22.65	379.59	371.48	54.74	45.52	138.28	610.02	230.43
2002	143.32	213.60	22.72	379.64	371.98	54.09	45.52	134.56	606.15	226.51
2003	143.72	214.53	22.95	381.20	372.38	53.58	45.52	131.44	602.92	221.72
2004	143.33	213.61	23.06	380.00	371.98	52.76	45.52	128.12	598.38	218.38
2005	143.32	213.65	23.23	380.20	371.98	52.11	45.52	125.61	595.22	215.02
2006	143.33	213.60	23.43	380.36	371.98	51.45	45.52	123.51	592.46	212.10
2007	143.75	214.50	23.69	381.94	372.38	50.94	45.52	122.09	590.93	208.99
2008	143.30	213.60	23.81	380.71	371.98	50.16	45.52	120.09	587.75	207.04
2009	143.30	213.60	23.93	380.83	371.98	49.51	45.52	118.70	585.71	204.88
2010	143.30	213.60	24.05	380.95	371.98	48.87	45.52	117.20	583.57	202.62
2011	143.30	214.50	24.21	382.01	371.98	48.38	45.52	116.30	582.18	200.17

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 5.2. (Continued)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2012	143.30	213.60	24.23	381.13	372.28	47.61	45.52	114.80	580.21	199.08
2013	143.30	213.60	24.33	381.23	371.98	46.99	45.52	113.60	578.09	196.86
2014	143.30	213.60	24.43	381.33	371.98	46.37	45.52	112.50	576.37	195.04
2015	143.30	214.40	24.58	382.28	371.88	45.89	45.52	111.80	575.09	192.81
2016	143.30	213.40	24.57	381.27	370.98	45.13	45.52	110.50	572.13	190.86
2017	143.70	213.30	24.71	381.71	367.38	44.65	45.52	109.80	567.35	185.64
2018	143.30	212.10	24.70	380.10	368.68	44.28	45.52	108.50	566.98	186.88
2019	143.30	214.20	24.84	382.34	366.78	43.47	45.52	107.90	563.67	181.33
2020	143.30	213.20	24.83	381.33	366.18	42.76	45.52	106.80	149.56	-231.77
2021	143.30	213.30	24.91	381.51	366.18	42.22	45.52	105.90	148.12	-233.39
2022	143.30	213.10	24.99	381.39	364.98	41.60	45.52	105.10	146.70	-234.69

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 5.2. (Continued)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2023	143.30	214.00	25.12	382.42	365.18	41.20	45.52	104.60	145.80	-236.62
2024	143.30	213.00	25.11	381.41	363.48	40.50	45.52	103.60	144.10	-237.31
2025	143.30	212.90	25.16	381.36	362.68	40.00	45.52	102.70	142.70	-238.66
2026	143.30	212.90	25.23	381.43	361.48	39.50	45.52	102.10	141.60	-239.83
2027	143.30	213.70	25.36	382.36	361.48	39.00	45.52	101.60	140.60	-241.76
2028	143.30	212.70	25.34	381.34	361.48	38.50	45.52	100.60	139.10	-242.24
2029	143.30	212.80	25.40	381.50	361.48	38.00	45.52	99.90	137.90	-243.60
2030	143.40	212.70	25.48	381.58	360.48	37.40	45.52	99.30	136.70	-244.88
Average	143.35	213.50	24.37	381.22	368.30	45.72	45.52	113.25	422.94	41.72

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

average annual pumpage rate was decreased to 333 hm^3/year while the remaining parameters were kept the same as they were in Scenario A. The predicted groundwater level elevations and groundwater level change map for Scenario C at the end of the planning period are given in Figure 5.12 and 5.13, respectively. It is obvious from Figure 5.9 that the declines in groundwater levels especially around Çorlu- Turgutbey fault are less when compared to Scenario A and B. Figure 5.12 shows that all the water level elevations are above sea level meaning about 30 m of increase in the vicinity of the fault around Muratlı and Lüleburgaz.

Predicted groundwater level hydrographs at the observation wells obtained from this scenario show that the groundwater elevations continue to decline as none can reach to steady state conditions at the end of the planning period (Figure 5.3-5.8).

The yearly groundwater budget and reserve changes obtained from Scenario C during the planning period can be seen in Table 5.3. As it is expected the decrease in pumpage rates caused the total discharge from the aquifer to decrease to 541 hm^3/year. Accordingly, the change in the groundwater reserves was 160 hm^3/year, which is %41 and %16 less than the ones obtained from Scenario A and B, respectively.

5.5 Scenario D

After getting the results of the previous scenarios a new case is considered by decreasing the annual pumping rates to be equal to 80% of the annual average recharge during 30 years of the planning period. The annual average recharge was 371 hm^3/year; therefore, the annual average pumpage was assigned to be 297 hm^3/year while all other parameters remained the same as they were in Scenario A.

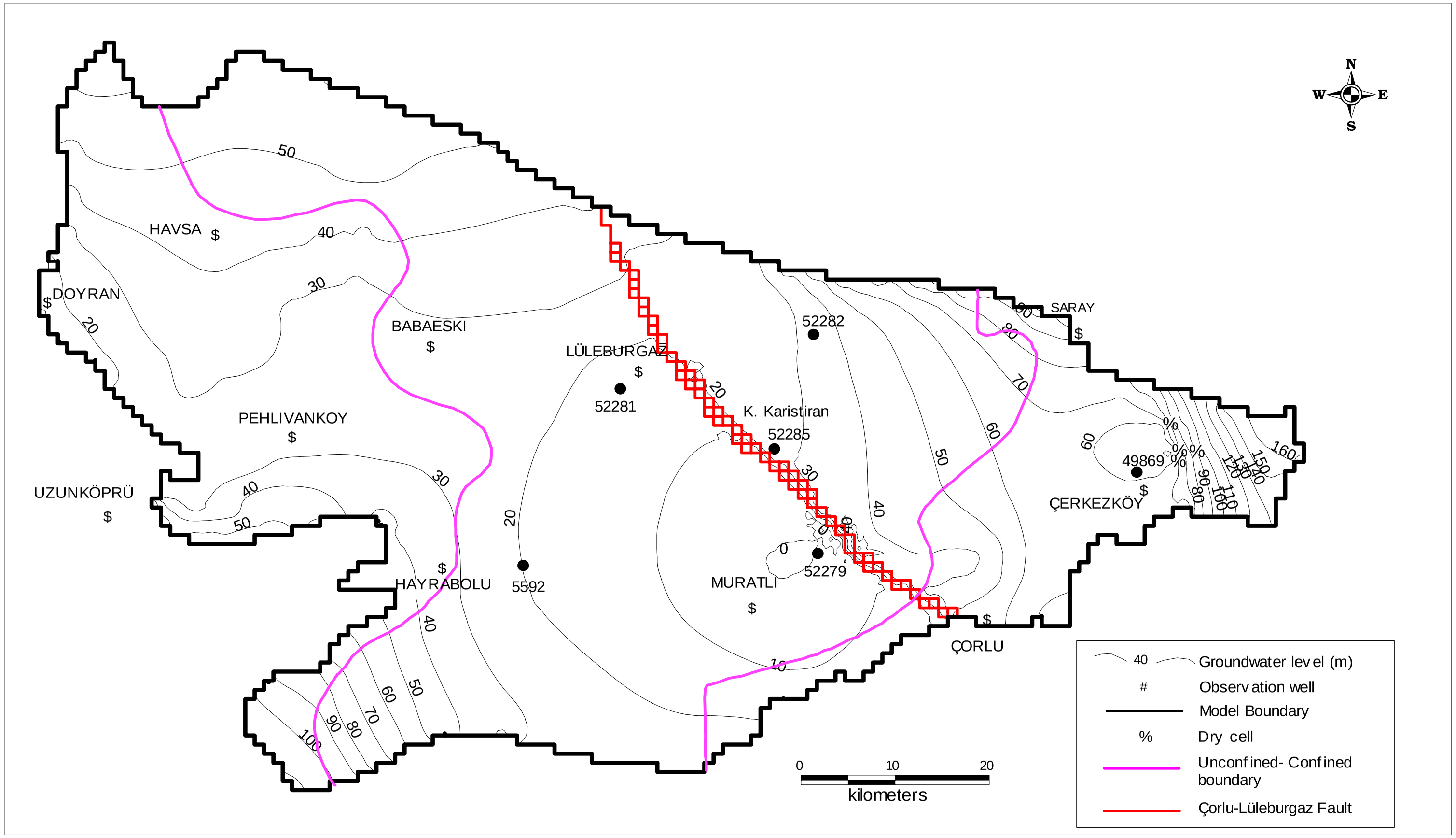

Figure 5.12. Predicted groundwater level elevation map at the end of the planning period for Scenario C (December 2030).

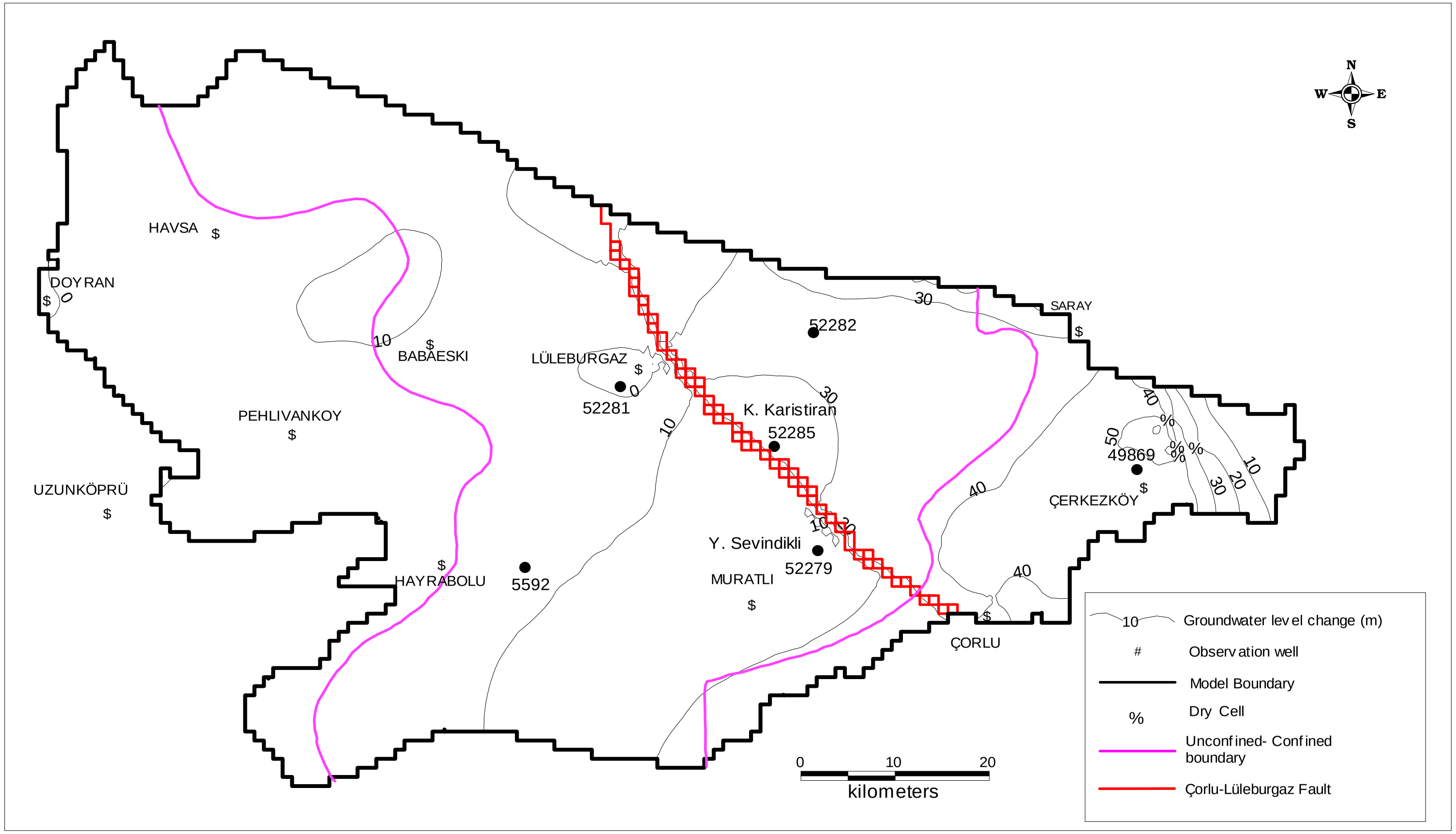

Figure 5.13. Predicted groundwater level change map at the end of the planning period for Scenario C (December 2030).

Table 5.3. Yearly groundwater budget and reserve changes obtained from Scenario C during the planning period (January 2001-December 2030)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2001	143.33	213.61	22.65	379.59	334.22	54.8	45.52	138.25	572.79	193.2
2002	143.32	213.60	22.72	379.64	334.66	54.3	45.52	134.69	569.17	189.53
2003	143.72	214.53	22.94	381.19	335.06	53.92	45.52	131.74	566.24	185.05
2004	143.33	213.61	23.04	379.98	334.58	53.23	45.52	128.61	561.94	181.96
2005	143.32	213.65	23.20	380.17	334.68	52.71	45.52	126.27	559.18	179.01
2006	143.33	213.60	23.38	380.31	334.68	52.18	45.52	124.3	556.68	176.37
2007	143.75	214.50	23.62	381.87	335.08	51.79	45.52	123	555.39	173.52
2008	143.30	213.60	23.73	380.63	334.58	51.13	45.52	121.2	552.43	171.8
2009	143.30	213.60	23.84	380.74	334.68	50.6	45.52	119.8	550.6	169.86
2010	143.30	213.60	23.94	380.84	334.68	50.07	45.52	118.5	548.77	167.93
2011	143.30	214.50	24.10	381.90	334.98	49.7	45.52	117.8	548	166.1

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 5.3. (Continued)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2012	143.30	213.60	24.12	381.02	334.68	49.04	45.52	116.3	545.54	164.52
2013	143.30	213.60	24.21	381.11	334.68	48.52	45.52	115.2	543.92	162.81
2014	143.30	213.60	24.28	381.18	334.68	48.02	45.52	114.3	542.52	161.34
2015	143.30	214.60	24.41	382.31	334.98	47.65	45.52	113.7	541.85	159.54
2016	143.30	213.60	24.43	381.33	334.68	47.01	45.52	112.5	539.71	158.38
2017	143.70	213.60	24.57	381.87	336.78	46.64	45.52	111.9	540.84	158.97
2018	143.30	212.40	24.57	380.27	333.98	46.02	45.52	110.7	536.22	155.95
2019	143.30	214.50	24.69	382.49	332.88	45.65	45.52	110.3	534.35	151.86
2020	143.30	213.50	24.69	381.49	332.48	45.04	45.52	109.2	532.24	150.75
2021	143.30	213.50	24.74	381.54	332.58	44.58	45.52	108.4	531.08	149.54
2022	143.30	213.50	24.80	381.60	332.58	44.1	45.52	107.7	529.9	148.3

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 5.3. (Continued)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2023	143.30	214.40	24.93	382.63	332.88	43.7	45.52	107.4	529.5	146.87
2024	143.30	213.50	24.92	381.72	332.18	43.2	45.52	106.3	527.2	145.48
2025	143.30	213.50	24.98	381.78	331.18	42.6	45.52	105.7	525	143.22
2026	143.30	214.30	25.02	382.62	330.28	42.3	45.52	105.1	523.2	140.58
2027	143.30	214.30	25.15	382.75	330.58	41.9	45.52	104.7	522.7	139.95
2028	143.30	213.30	25.12	381.72	329.48	41.3	45.52	103.8	520.1	138.38
2029	143.30	213.30	25.16	381.76	329.48	40.9	45.52	103.2	519.1	137.34
2030	143.40	213.30	25.21	381.91	328.48	40.4	45.52	102.6	517	135.09
Average	143.35	213.74	24.24	381.33	333.38	47.43	45.52	115.11	541.44	160.11

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

The groundwater level elevation and groundwater level change maps at the end of the planning period are given in Figures 5.14 and 5.15, respectively. With decreased pumpage rates the groundwater levels obtained from this scenario are obviously higher than the previous scenarios. The average areal drawdown at the end of the planning period is estimated to be 11.8 m. The maximum drawdown of about 40 m was observed around Çerkezköy, which was 60 m in Scenario A. In general, the groundwater levels of the eastern unconfined area and the confined area are about 20 m higher than the ones obtained from Scenario A. The increase in the groundwater levels can also be seen from groundwater level hydrographs (Figures 5.3-5.8).

The yearly groundwater budget and reserve changes calculated for Scenario D are given in Table 5.4. It can be seen from this table that the average recharge to the aquifer is 381 hm^3/year and the total average discharge from the aquifer is 511 hm^3/year, giving an average decline in groundwater reserves of 130 hm^3/year (Figure 5.9). Consequently, the decline in groundwater reserve is %52 less than the one obtained from Scenario A.

5.6 Scenario E

So as to see the effects of much more decreased pumpage rates a new scenario was developed by decreasing the annual pumping rates to 70% of the annual average recharge. As stated before the annual average recharge to the aquifer was 371 hm^3/year, therefore, the yearly pumpage rates were assigned as 260 hm^3/year while the remaining parameters were the same as they were in Scenario A.

Groundwater level elevation and groundwater level change maps obtained as a result of Scenario D by December 2030 are shown in Figure 5.16 and 5.17, respectively. As it can be seen from these figures, groundwater level elevations around Lüleburgaz begin to increase as compared to December 2000 groundwater elevations. In general, the drawdowns obtained from Scenario E

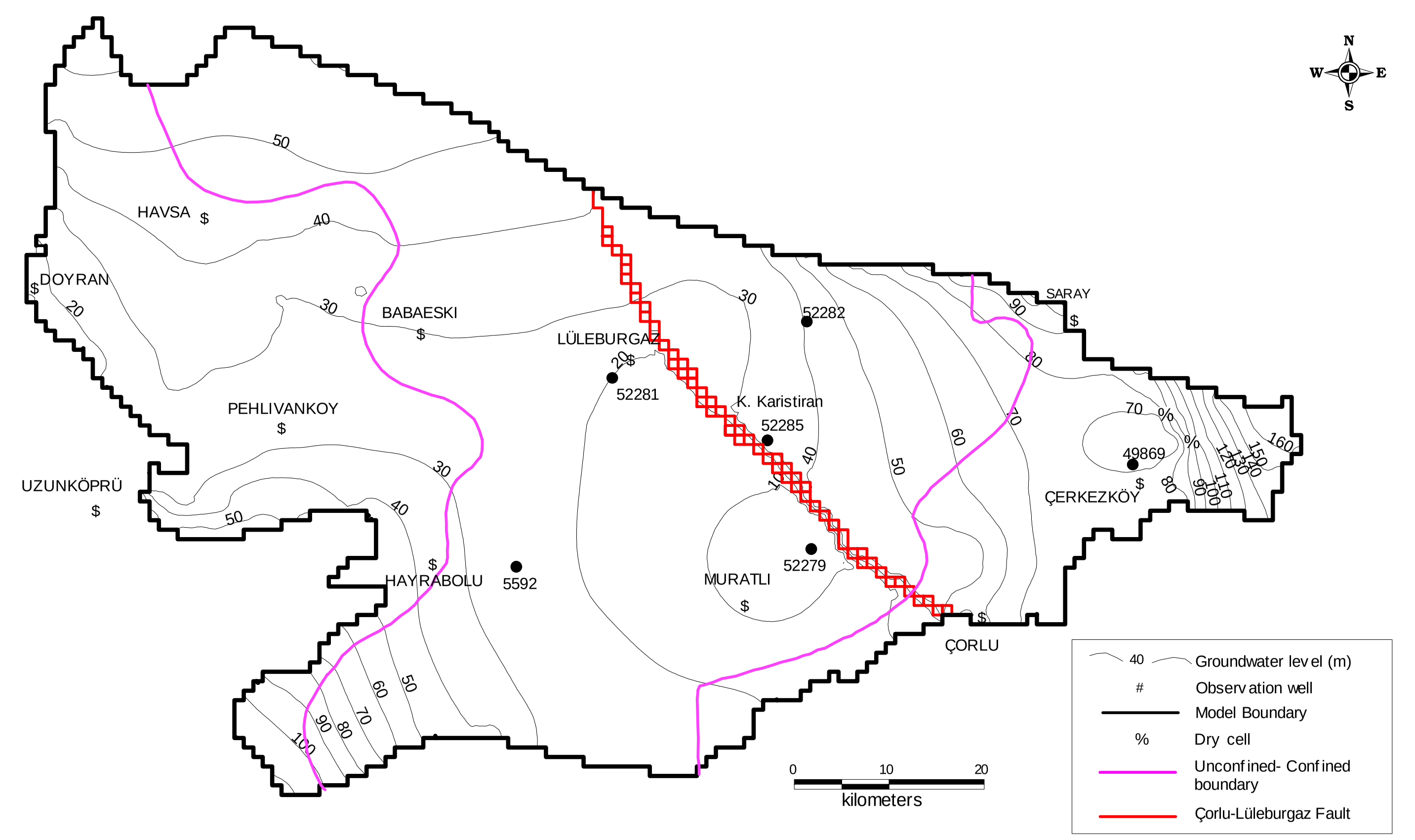

Figure 5.14. Predicted groundwater level elevation map at the end of the planning period for Scenario D (December 2030).

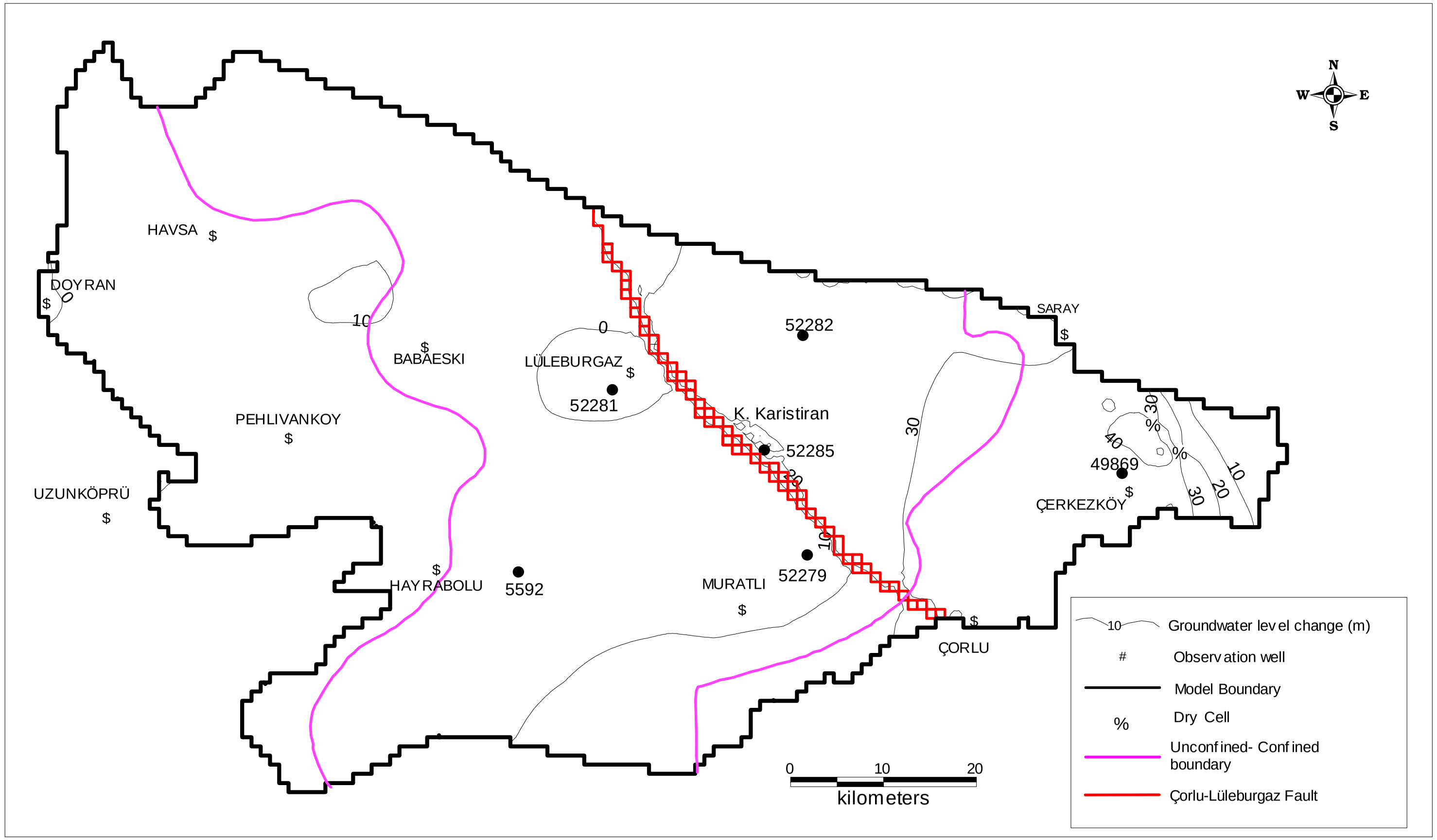

Figure 5.15. Predicted groundwater level change map at the end of the planning period for Scenario D (December 2030).

Table 5.4. Yearly groundwater budget and reserve changes obtained from Scenario D during the planning period (January 2001-December 2030)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2001	143.33	213.61	22.96	379.90	297.22	54.91	45.52	138.38	536.03	156.13
2002	143.32	213.60	23.02	379.94	297.61	54.61	45.52	135.18	532.92	152.98
2003	143.72	214.53	23.21	381.46	297.91	54.43	45.52	132.74	530.60	149.14
2004	143.33	213.61	23.30	380.24	297.68	53.92	45.52	130.07	527.19	146.95
2005	143.32	213.65	23.45	380.42	297.58	53.56	45.52	128.18	524.84	144.42
2006	143.33	213.60	23.59	380.52	297.58	53.18	45.52	126.62	522.90	142.38
2007	143.75	214.50	23.79	382.04	297.98	52.95	45.52	125.67	522.12	140.08
2008	143.30	213.60	23.85	380.75	297.58	52.42	45.52	124.16	519.68	138.93
2009	143.30	213.60	23.94	380.84	297.68	52.02	45.52	123.10	518.32	137.48
2010	143.30	213.60	24.03	380.93	297.58	51.63	45.52	122.10	516.83	135.90
2011	143.30	214.50	24.16	381.96	297.98	51.39	45.52	121.60	516.49	134.53

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 5.4. (Continued)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2012	143.30	213.60	24.17	381.07	297.58	50.85	45.52	120.40	514.35	133.28
2013	143.30	213.60	24.22	381.12	297.58	50.45	45.52	119.60	513.15	132.03
2014	143.30	213.60	24.29	381.19	297.68	50.07	45.52	118.90	512.17	130.98
2015	143.30	214.60	24.40	382.30	297.88	49.81	45.52	118.40	511.61	129.31
2016	143.30	213.60	24.39	381.29	297.68	49.28	45.52	117.40	509.88	128.59
2017	143.70	213.60	24.52	381.82	299.48	49.03	45.52	117.10	511.13	129.31
2018	143.30	212.40	24.50	380.20	297.48	48.51	45.52	116.00	507.51	127.31
2019	143.30	214.50	24.61	382.41	297.98	48.25	45.52	115.80	507.55	125.14
2020	143.30	213.50	24.59	381.39	297.38	47.73	45.52	114.80	505.43	124.04
2021	143.30	213.50	24.64	381.44	295.58	47.40	45.52	114.20	502.70	121.26
2022	143.30	213.50	24.68	381.48	295.48	47.00	45.52	113.60	501.60	120.12

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 5.4. (Continued)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2023	143.30	214.40	24.81	382.51	295.88	46.70	45.52	113.50	501.60	119.09
2024	143.30	213.50	24.78	381.58	295.48	46.30	45.52	112.50	499.80	118.22
2025	143.30	213.50	25.83	382.63	295.58	45.90	45.52	112.00	499.00	116.37
2026	143.30	214.30	24.88	382.48	295.48	45.50	45.52	111.50	498.00	115.52
2027	143.30	214.30	24.99	382.59	295.88	45.30	45.52	111.30	498.00	115.41
2028	143.30	213.30	24.98	381.58	295.48	44.80	45.52	110.40	496.20	114.62
2029	143.30	213.30	25.03	381.63	294.38	44.40	45.52	110.00	494.30	112.67
2030	143.40	213.30	25.08	381.78	294.08	44.10	45.52	109.50	493.20	111.42
Average	143.35	213.74	24.29	381.38	296.95	49.55	45.52	119.49	511.50	130.12

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

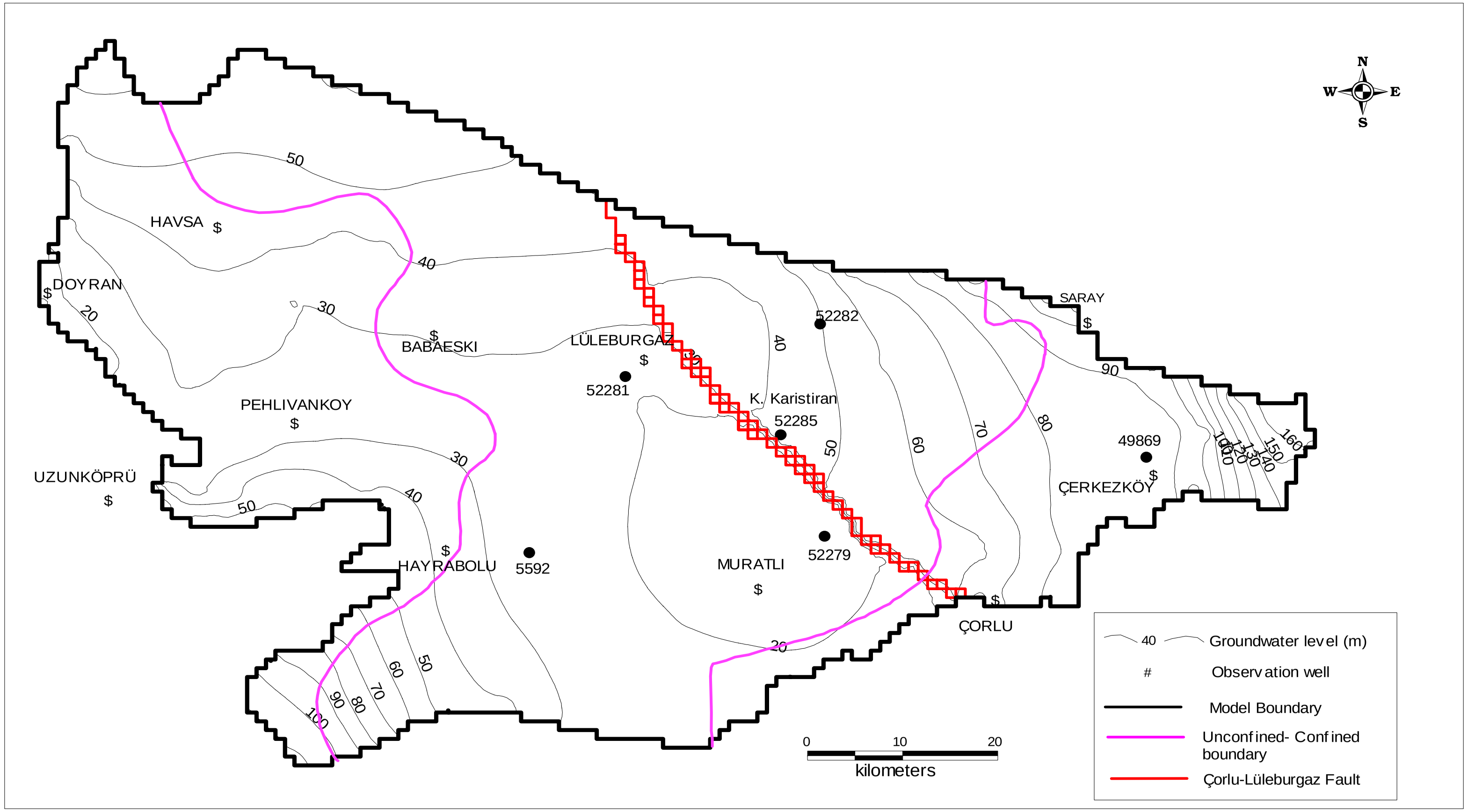

Figure 5.16. Predicted groundwater level elevation map at the end of the planning period for Scenario E (December 2030).

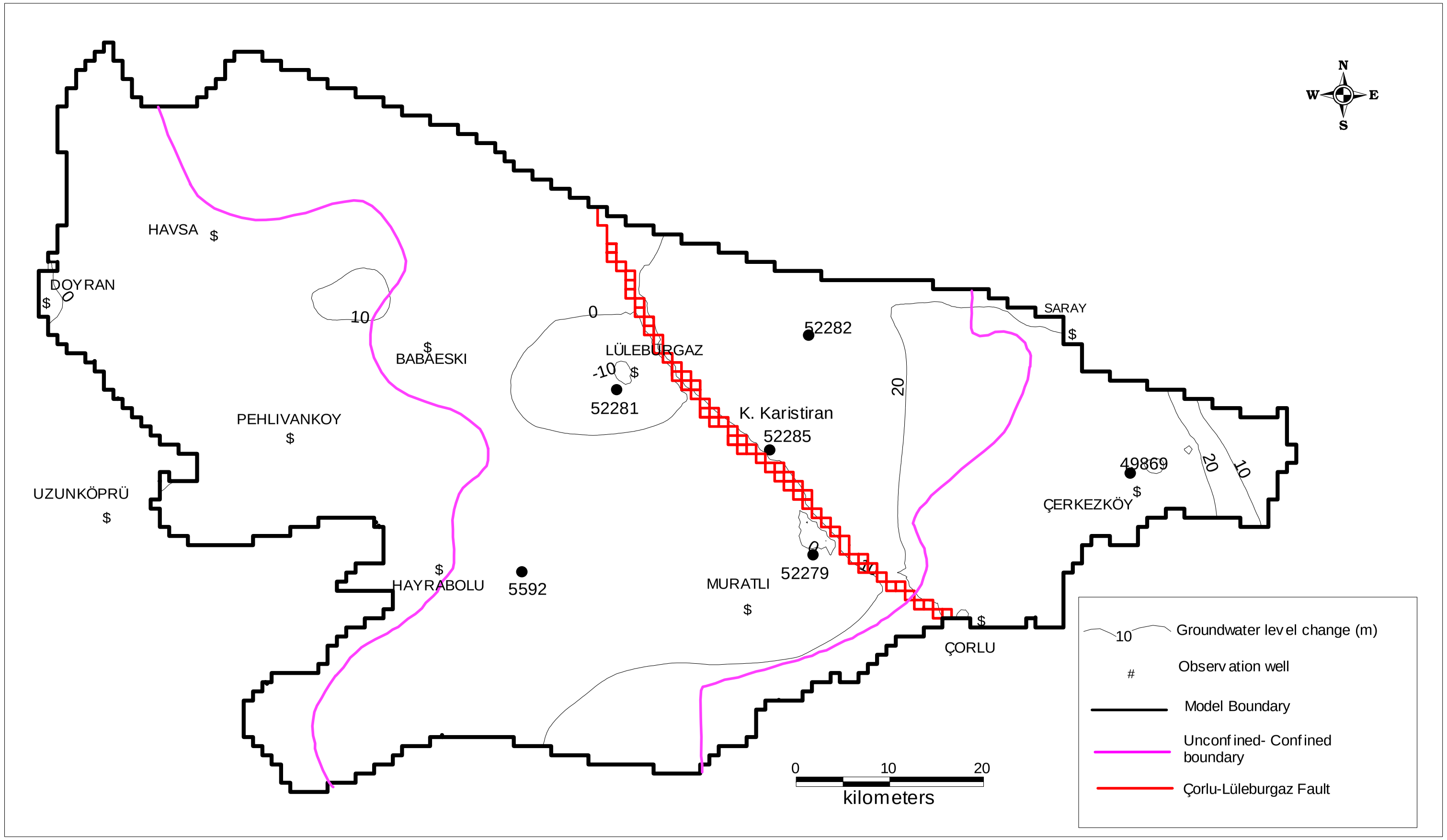

Figure 5.17. Predicted groundwater level change map at the end of the planning period for Scenario E (December 2030).

are about 10 m lower in western unconfined part, 30 m lower around confined and eastern unconfined parts. The average areal decline in groundwater levels was estimated as 8.5 m (Figures 5.3-5.8).

As it can be seen from the annual groundwater budget and the reserve changes (Table 5.5) calculated for Scenario E, the groundwater potential of the basin has been improved under this scenario. An average of 381 hm^3/year recharge and 478 hm^3/year discharge were calculated, leading to 97 hm^3/year decline in groundwater reserves (Figure 5.9). The average reserve change obtained from Scenario E is %65 less than the one obtained from Scenario A.

5.7 Scenario F

In this alternative, it was assumed that the total annual pumpage equals to 60% of the total annual average recharge (371 hm^3/year). For this case yearly pumping rates were introduced to the model as a value of 223 hm^3/year while other parameters remained the same as in the previous scenarios.

Calculated groundwater level elevation and water level change maps at the end of the planning period are given in Figures 5.18 and 5.19, respectively. The average areal decline in groundwater levels was calculated to be 5 m. The decrease in groundwater levels around Çerkezköy was about 10 m showing a significant improvement from Scenario A, which was around 60 m at the end of the planning period.

The yearly groundwater budget and reserve changes obtained from Scenario F during planning period are given in Table 5.6. As it can be seen from this table, the average annual change in the groundwater reserves is 64 hm^3/year (Figure 5.9). This value gives 77 % improvement in the decline of the reserve from that of scenario A (i.e., continuation of the present conditions).

Table 5.5. Yearly groundwater budget and reserve changes obtained from Scenario E during the planning period (January 2001-December 2030)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2001	143.33	213.61	22.96	379.9	260.22	54.98	45.52	138.38	499.1	119.2
2002	143.32	213.6	23.02	379.94	260.57	54.83	45.52	135.2	496.12	116.18
2003	143.72	214.53	23.21	381.46	260.87	54.8	45.52	132.77	493.96	112.5
2004	143.33	213.61	23.295	380.24	260.56	54.42	45.52	130.15	490.65	110.415
2005	143.32	213.64	23.44	380.4	260.58	54.21	45.52	128.32	488.63	108.23
2006	143.33	213.6	23.57	380.5	260.58	53.93	45.52	126.8	486.83	106.33
2007	143.75	214.5	23.76	382.01	260.88	53.82	45.52	125.91	486.13	104.12
2008	143.3	213.6	23.83	380.73	260.48	53.39	45.52	124.47	483.86	103.13
2009	143.3	213.6	23.93	380.83	260.58	53.12	45.52	123.5	482.72	101.89
2010	143.3	213.6	24.01	380.91	260.58	52.84	45.52	122.6	481.54	100.63
2011	143.3	214.5	24.14	381.94	260.88	52.7	45.52	122.2	481.3	99.36

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 5.5. (Continued)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2012	143.3	213.6	24.13	381.03	260.58	52.27	45.52	121.1	479.47	98.44
2013	143.3	213.6	24.19	381.09	260.58	51.99	45.52	120.4	478.49	97.4
2014	143.3	213.6	24.23	381.13	260.58	51.7	45.52	119.7	477.5	96.37
2015	143.3	214.6	24.34	382.24	260.88	51.55	45.52	119.4	477.35	95.11
2016	143.3	213.6	24.32	381.22	260.58	51.13	45.52	118.5	475.73	94.51
2017	143.7	213.6	24.45	381.75	262.18	50.98	45.52	118.3	476.98	95.23
2018	143.3	212.4	24.42	380.12	260.48	50.55	45.52	117.3	473.85	93.73
2019	143.3	214.5	24.53	382.33	260.88	50.42	45.52	117.2	474.02	91.69
2020	143.3	213.5	24.51	381.31	260.48	50	45.52	116.3	472.3	90.99
2021	143.3	213.5	24.55	381.35	260.58	49.7	45.52	115.8	471.6	90.25
2022	143.3	213.5	25.02	381.82	260.58	49.4	45.52	115.3	470.8	88.98

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 5.5. (Continued)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2023	143.3	214.5	24.67	382.47	260.88	49.3	45.52	115.2	470.9	88.43
2024	143.3	213.5	24.61	381.41	260.48	48.9	45.52	114.4	469.3	87.89
2025	143.3	213.5	24.68	381.48	260.58	48.6	45.52	114	468.7	87.22
2026	143.3	213.6	24.71	381.61	260.58	48.4	45.52	113.4	467.9	86.29
2027	143.3	214.5	24.82	382.62	260.88	48.2	45.52	113.5	468.1	85.48
2028	143.3	213.6	24.8	381.7	260.58	47.8	45.52	112.6	466.5	84.8
2029	143.3	213.6	24.83	381.73	260.58	47.5	45.52	112.3	465.9	84.17
2030	143.4	213.7	24.88	381.98	260.58	47.3	45.52	111.8	465.2	83.22
Average	143.35	213.76	24.20	381.31	260.68	51.29	45.52	120.56	478.05	96.74

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

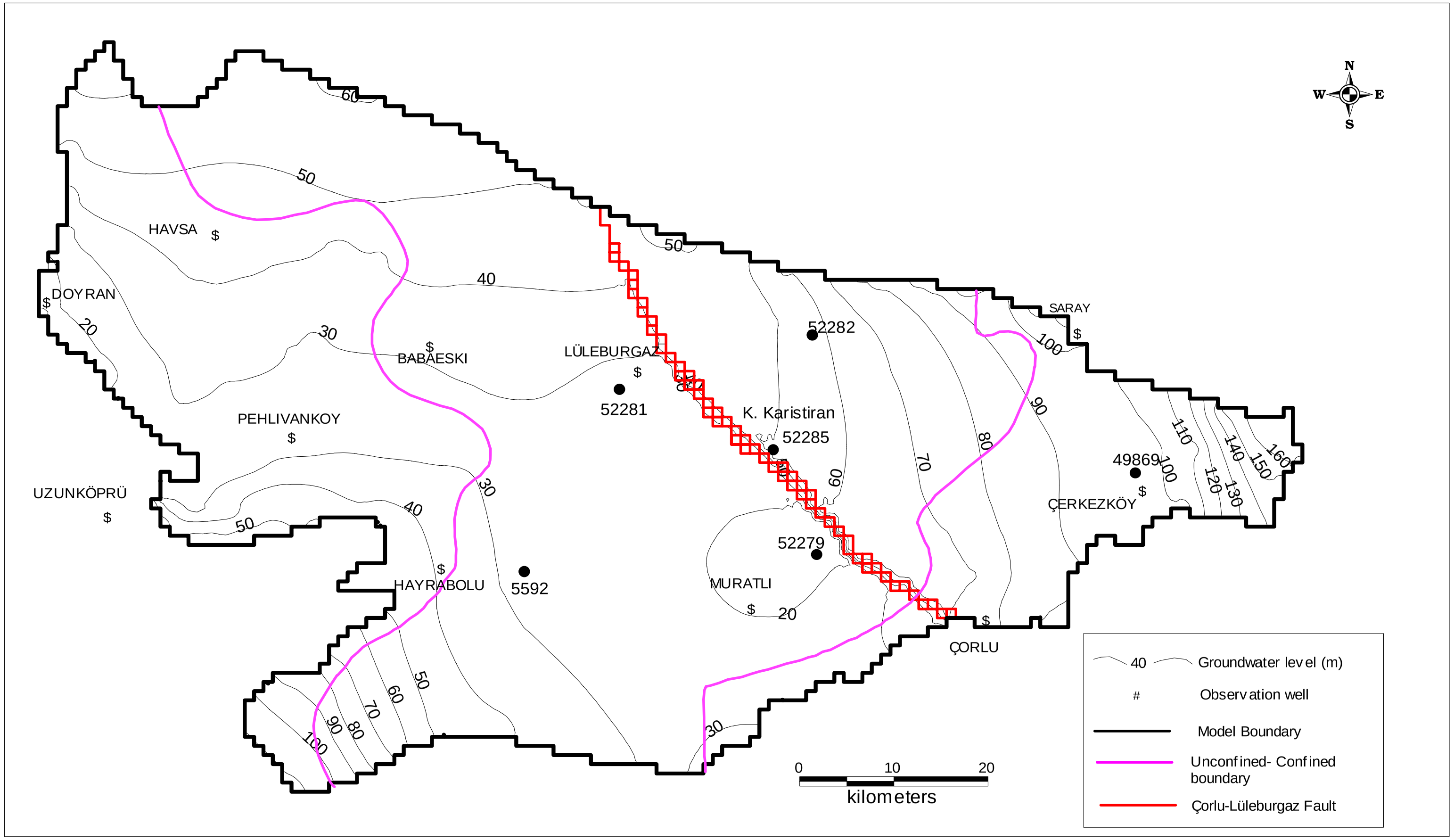

Figure 5.18. Predicted groundwater level elevation map at the end of the planning period for Scenario F (December 2030).

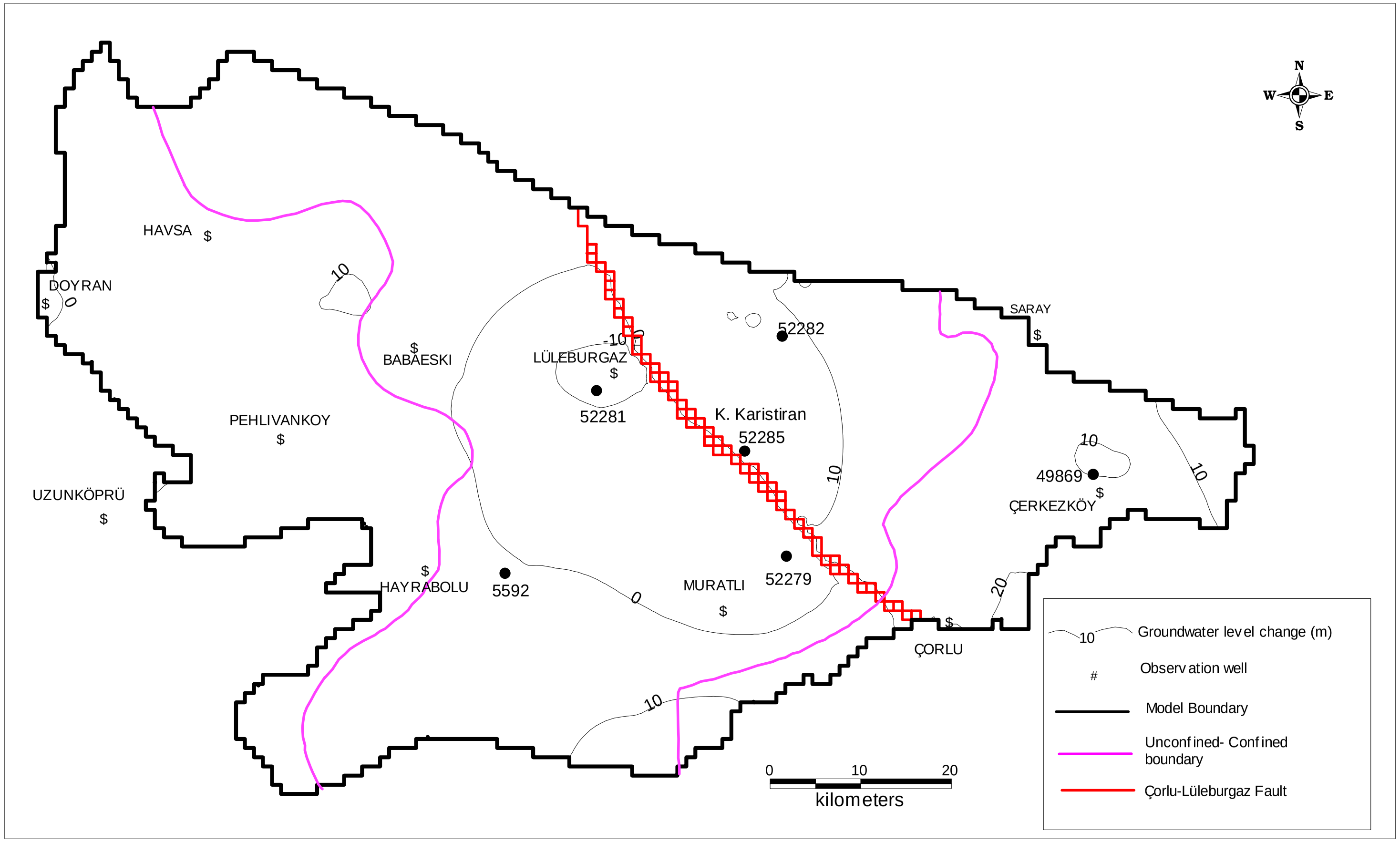

Figure 5.19. Predicted groundwater level change map at the end of the planning period for Scenario F (December 2030).

Table 5.6. Yearly groundwater budget and reserve changes obtained from Scenario F during the planning period (January 2001- December 2030)

Years	Recharge (hm3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2001	143.33	213.61	22.96	379.90	222.86	55.06	45.52	138.43	461.87	81.97
2002	143.32	213.60	23.01	379.93	223.15	55.10	45.52	135.38	459.15	79.22
2003	143.72	214.53	23.19	381.44	223.44	55.22	45.52	133.12	457.30	75.86
2004	143.33	213.61	23.26	380.20	223.17	55.01	45.52	130.66	454.36	74.16
2005	143.32	213.64	23.40	380.36	223.18	54.92	45.52	129.04	452.66	72.30
2006	143.33	213.60	23.52	380.45	223.08	54.81	45.52	127.72	451.13	70.68
2007	143.75	214.50	23.69	381.94	223.48	54.84	45.52	127.01	450.85	68.91
2008	143.30	213.60	23.73	380.63	223.18	54.54	45.52	125.74	448.98	68.35
2009	143.30	213.60	23.82	380.72	223.08	54.40	45.52	124.90	447.90	67.18
2010	143.30	213.60	23.89	380.79	223.18	54.24	45.52	124.30	447.24	66.45
2011	143.30	214.50	24.02	381.82	223.48	54.23	45.52	124.00	447.23	65.41

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 5.6. (Continued)

Years	Recharge (hm3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2012	143.30	213.60	24.01	380.91	223.08	53.91	45.52	123.10	445.61	64.70
2013	143.30	213.60	24.06	380.96	223.18	53.75	45.52	122.60	445.05	64.09
2014	143.30	213.60	24.10	381.00	223.18	53.57	45.52	122.00	444.27	63.27
2015	143.30	214.60	24.21	382.11	223.48	53.55	45.52	122.00	444.55	62.44
2016	143.30	213.60	24.18	381.08	223.08	53.22	45.52	121.20	443.02	61.94
2017	143.70	213.60	24.28	381.58	224.58	53.19	45.52	121.10	444.39	62.81
2018	143.30	212.40	24.25	379.95	223.08	52.87	45.52	120.40	441.87	61.92
2019	143.30	214.50	24.34	382.14	223.48	52.87	45.52	120.30	442.17	60.03
2020	143.30	213.50	24.31	381.11	223.08	52.50	45.52	119.70	440.80	59.69
2021	143.30	213.50	24.33	381.13	223.18	52.30	45.52	119.30	440.30	59.17
2022	143.30	213.50	24.35	381.15	223.08	52.20	45.52	118.90	439.70	58.55

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 5.6. (Continued)

Years	Recharge (hm3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2023	143.30	214.50	24.45	382.25	223.48	52.10	45.52	118.90	440.00	57.75
2024	143.30	213.50	24.40	381.20	223.18	51.80	45.52	118.30	438.80	57.60
2025	143.30	213.50	24.42	381.22	223.08	51.70	45.52	118.00	438.30	57.08
2026	143.30	213.60	24.46	381.36	223.18	51.50	45.52	117.60	437.80	56.44
2027	143.30	214.50	24.54	382.34	223.48	51.40	45.52	117.70	438.10	55.76
2028	143.30	213.60	24.50	381.40	223.08	51.20	45.52	117.00	436.80	55.40
2029	143.30	213.60	24.53	381.43	223.18	50.90	45.52	116.80	436.40	54.97
2030	143.40	213.70	24.56	381.66	223.18	50.80	45.52	116.40	435.90	54.24
Average	143.35	213.76	24.03	381.14	223.25	53.26	45.52	123.05	445.08	63.94

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

5.8 Scenario G

To have a greater number of alternatives in order to choose the best one among them, Scenario G is constructed by assuming that the total annual pumpage being equal to 45% of the total annual average recharge (371 hm^3/year). The yearly pumpage rates were assigned to the model as 167 hm^3/year while the remaining parameters kept the same as in Scenario A.

Groundwater level elevation and groundwater level change maps obtained as a result of Scenario G by December 2030 are shown in Figure 5.20 and 5.21, respectively. As it can be seen from these figures, groundwater level elevations around Lüleburgaz and Muratlı increase as compared to December 2000 groundwater elevations. The overall average areal decline in groundwater levels was estimated to be 0.2 m from that of year 2000 levels thus this scenario does not produce significant changes in groundwater levels from year 2000 conditions. This can also be seen from the hydrographs of all of the observation wells (Figures 5.3-5.8). Groundwater levels have reached to steady-state conditions at the end of the planning period.

The yearly groundwater budget and reserve changes obtained from Scenario G during the planning period is given in Table 5.7. This scenario produced an average of 22 hm^3/year water losses from the aquifer during the planning horizon leading to an improvement of %92 when compared to Scenario A (Figure 5.9).

5.8 Scenario H

As a last scenario, Scenario H is constructed to determine the optimum pumpage rates in the basin by assuming that this time the total annual pumpage is equal to 35% of the total annual average recharge (371 hm^3/year). The yearly pumpage rates were assigned to the model as 128 hm^3/year while the remaining parameters remained the same as in Scenario A.

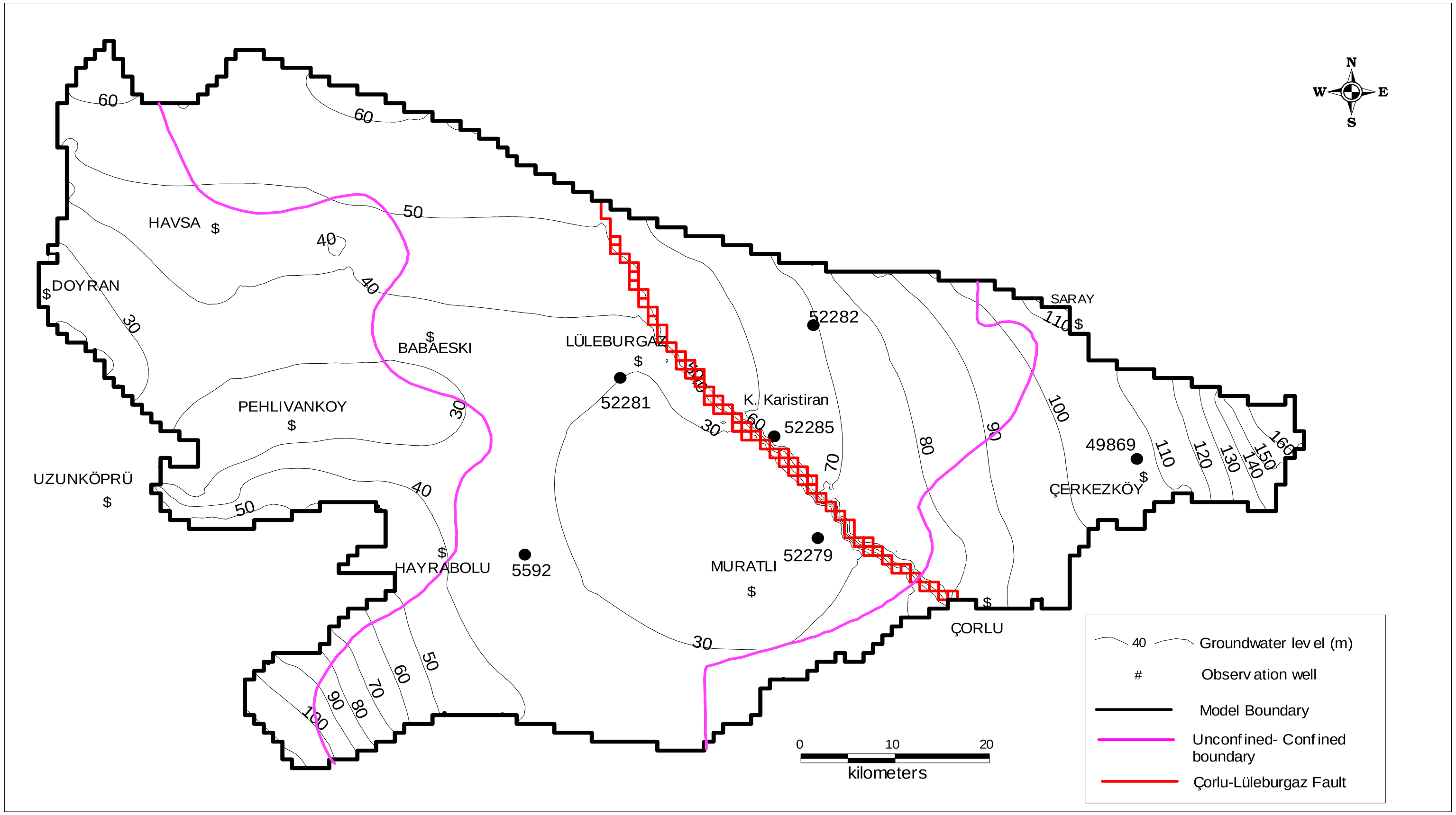

Figure 5.20. Predicted groundwater level elevation map at the end of the planning period for Scenario G (December 2030).

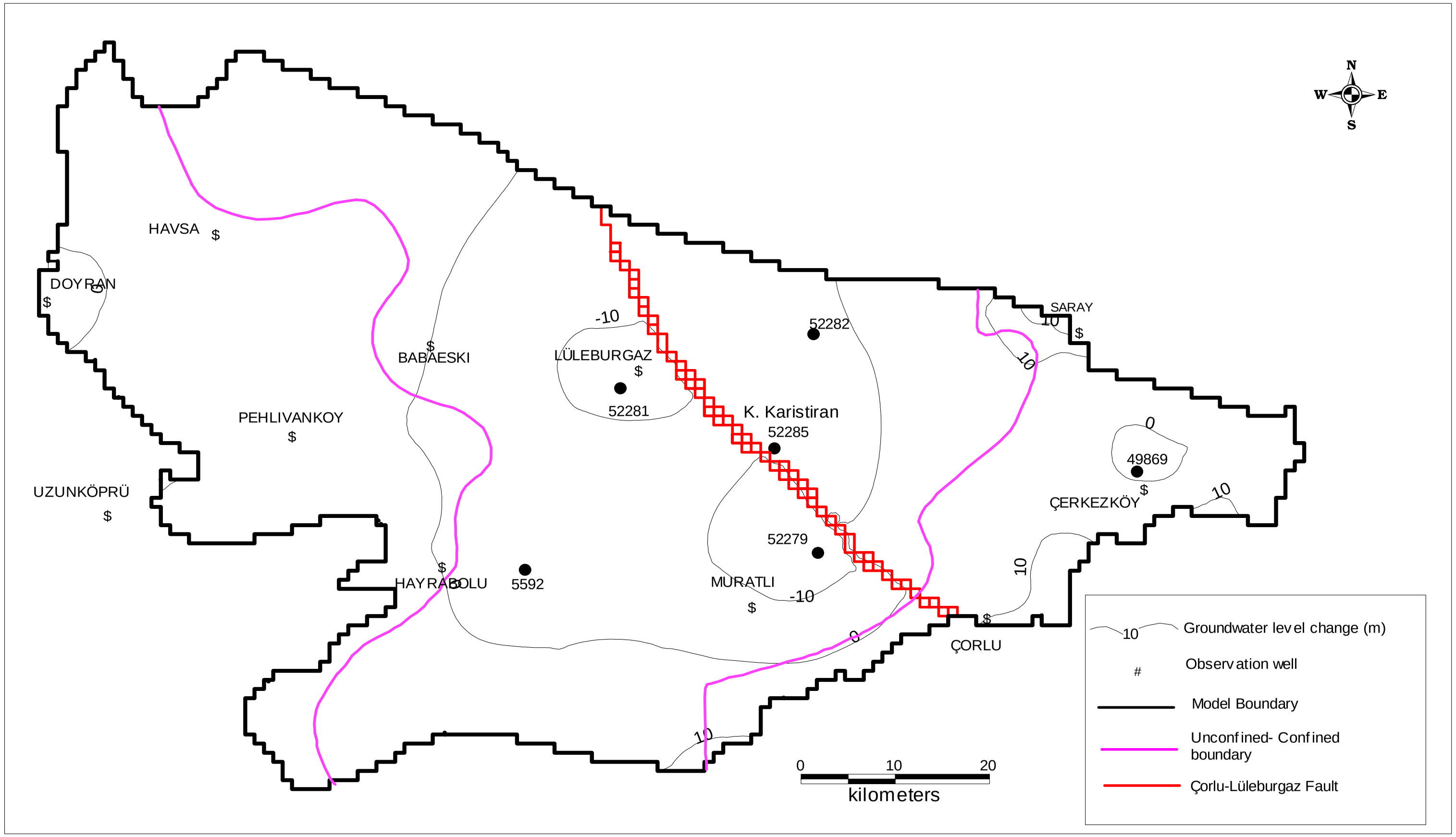

Figure 5.21. Predicted groundwater level change map at the end of the planning period for Scenario G (December 2030).

Table 5.7. Yearly groundwater budget and reserve changes obtained from Scenario G during the planning period (January 2001- December 2030)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2001	143.33	213.61	22.87	379.81	167.62	55.22	45.52	139.46	407.82	28.01
2002	143.32	213.60	22.81	379.73	167.83	55.59	45.52	138.05	406.99	27.26
2003	143.72	214.53	22.93	381.18	168.08	55.98	45.52	136.83	406.41	25.23
2004	143.33	213.61	22.93	379.87	167.84	56.00	45.52	135.19	404.55	24.68
2005	143.32	213.64	22.99	379.95	167.83	56.14	45.52	134.27	403.76	23.81
2006	143.33	213.60	23.05	379.98	167.88	56.23	45.52	133.57	403.20	23.22
2007	143.75	214.50	23.14	381.39	168.08	56.46	45.52	133.45	403.51	22.12
2008	143.30	213.60	23.13	380.03	167.78	56.37	45.52	132.68	402.35	22.32
2009	143.30	213.60	23.17	380.07	167.88	56.39	45.52	132.30	402.09	22.02
2010	143.30	213.60	23.18	380.08	167.78	56.41	45.52	132.10	401.81	21.73
2011	143.30	214.50	23.25	381.05	168.08	56.58	45.52	132.30	402.48	21.43

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 5.7. (Continued)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2012	143.30	213.60	23.21	380.11	167.88	56.42	45.52	131.70	401.52	21.41
2013	143.30	213.60	23.22	380.12	167.88	56.41	45.52	131.50	401.31	21.19
2014	143.30	213.60	23.23	380.13	167.78	56.39	45.52	131.50	401.19	21.06
2015	143.30	214.60	23.30	381.20	168.08	56.53	45.52	131.70	401.83	20.63
2016	143.30	213.60	23.25	380.15	167.88	56.35	45.52	131.20	400.95	20.80
2017	143.70	213.60	23.32	380.62	167.88	56.47	45.52	131.50	401.37	20.75
2018	143.30	212.40	23.25	378.95	167.78	56.26	45.52	130.90	400.46	21.51
2019	143.30	214.50	23.32	381.12	168.08	56.40	45.52	131.40	401.40	20.28
2020	143.30	213.50	23.27	380.07	167.78	56.20	45.52	130.80	400.30	20.23
2021	143.30	213.50	23.26	380.06	167.88	56.20	45.52	130.80	400.40	20.34
2022	143.30	213.50	23.28	380.08	167.88	56.10	45.52	130.70	400.20	20.12

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 5.7. (Continued)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2023	143.30	214.50	23.34	381.14	168.08	56.20	45.52	131.00	400.80	19.66
2024	143.30	213.50	23.28	380.08	167.88	56.10	45.52	130.50	400.00	19.92
2025	143.30	213.50	23.29	380.09	167.78	56.00	45.52	130.50	399.80	19.71
2026	143.30	213.60	23.30	380.20	167.88	55.90	45.52	130.50	399.80	19.60
2027	143.30	214.50	23.37	381.17	168.08	56.10	45.52	130.70	400.40	19.23
2028	143.30	213.60	23.32	380.22	167.88	55.80	45.52	130.20	399.40	19.18
2029	143.30	213.60	23.32	380.22	167.88	55.80	45.52	130.10	399.30	19.08
2030	143.40	213.70	23.33	380.43	167.78	55.80	45.52	130.10	399.20	18.77
Average	143.35	213.76	23.20	380.31	167.89	56.16	45.52	132.25	401.82	21.51

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Groundwater level elevation and groundwater level change maps obtained as a result of Scenario H by December 2030 are shown in Figure 5.22 and 5.23, respectively. As it can be seen from these figures, groundwater level elevations around Lüleburgaz, Dambaşlar, K. Karıştıran and Muratlı have increased as compared to December 2000 groundwater elevations. In fact this scenario produced an average areal rise in groundwater levels in the amount of 3.9 m from that of year 2000 level. As it can be seen from the hydrographs of all of the observation wells (Figures 5.3-5.8) groundwater levels have reached to steady-state conditions at the end of the planning period except for the well located in Çerkezköy. The groundwater elevations around Çerkezköy are higher than the ones obtained from Scenario G. However while constructing this scenario, it was thought that the industrial development relying on groundwater around Çerkezköy would probably need much more amount of water pumped. Therefore to be more realistic, more wells have been added to the model around Çerkezköy and some has been taken out in other parts.

The yearly groundwater budget and reserve changes obtained from Scenario H for the planning horizon is given in Table 5.8. According to this table, the total average discharge from the aquifer is 377 hm^3/year whereas the average recharge is 379 hm^3/year, leading to a rise in groundwater reserves in the amount of -2.68 hm^3/year.

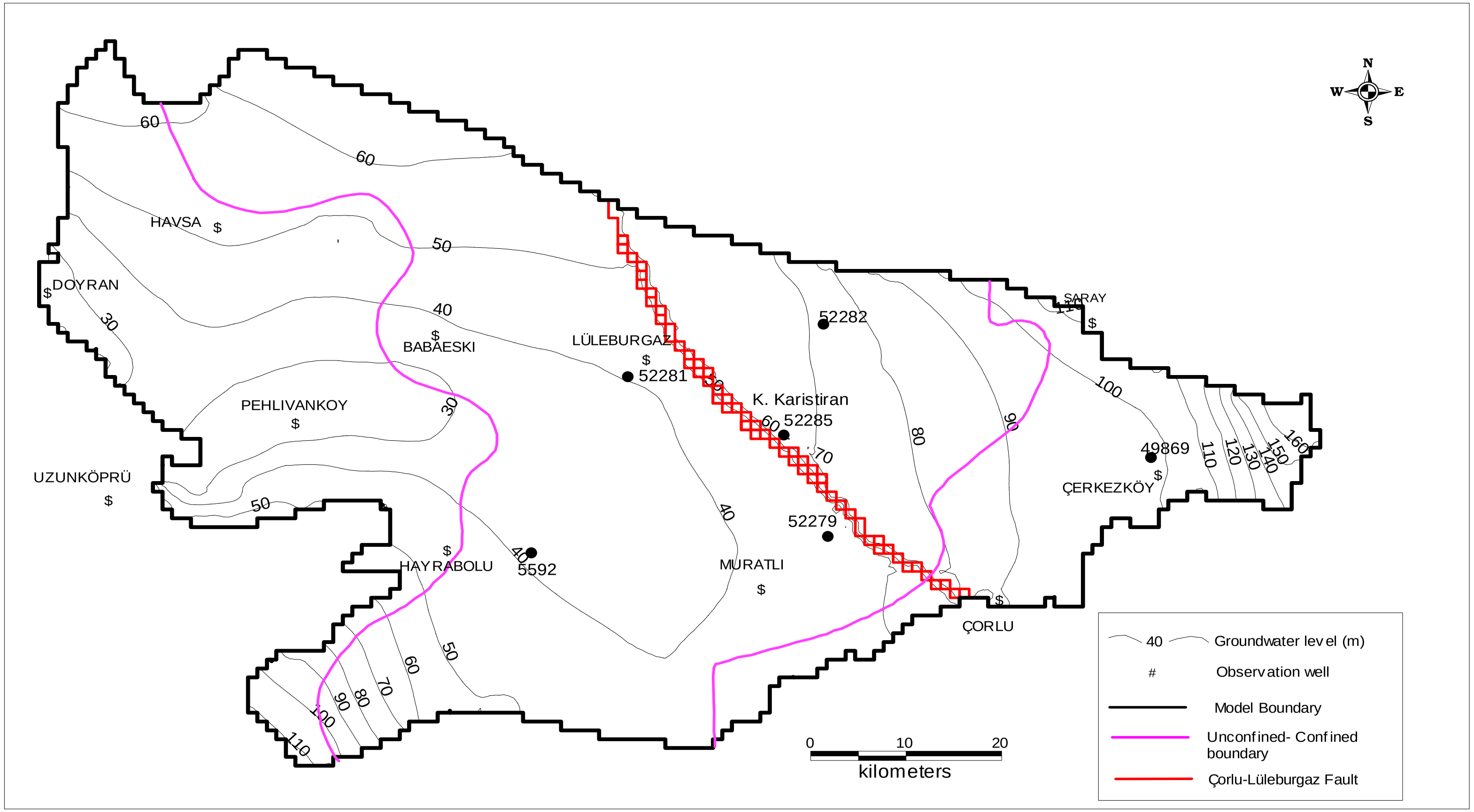

Figure 5.22. Predicted groundwater level elevation map at the end of the planning period for Scenario H (December 2030).

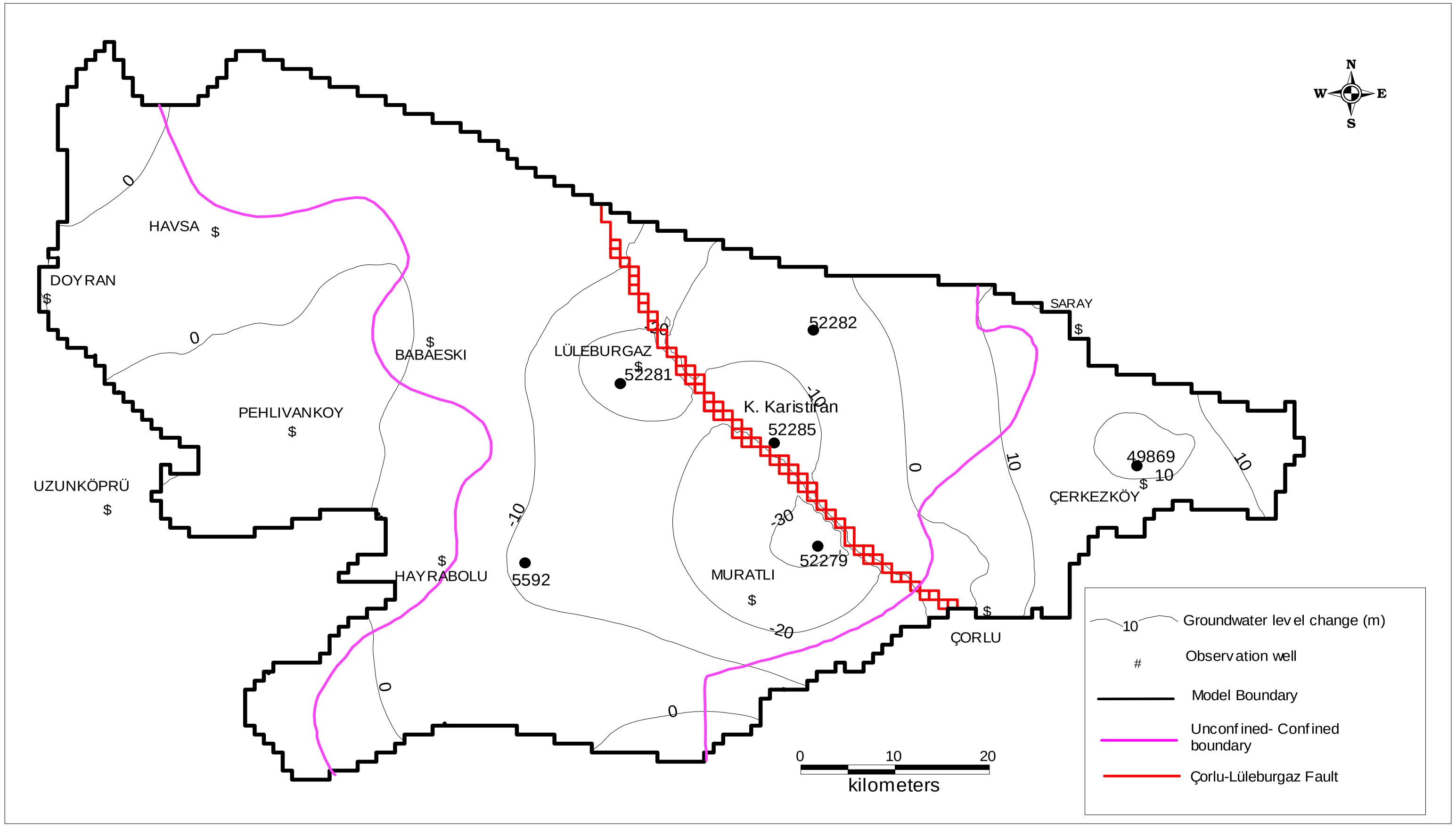

Figure 5.23. Predicted groundwater level change map at the end of the planning period for Scenario H (December 2030).

Table 5.8. Yearly groundwater budget and reserve changes obtained from Scenario H during the planning period (January 2001- December 2030)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2001	143.33	213.61	22.76	379.70	127.61	55.39	45.52	139.87	368.39	-11.31
2002	143.32	213.60	22.52	379.44	127.78	56.10	45.52	139.30	368.70	-10.74
2003	143.72	214.53	22.54	380.79	127.99	56.81	45.52	138.87	369.19	-11.60
2004	143.33	213.61	22.46	379.40	127.77	57.13	45.52	138.08	368.50	-10.90
2005	143.32	213.64	22.47	379.43	127.78	57.53	45.52	138.05	368.88	-10.55
2006	143.33	213.60	22.50	379.43	127.78	57.87	45.52	138.26	369.43	-10.00
2007	143.75	214.50	22.39	380.64	127.99	58.34	45.52	139.05	370.90	-9.74
2008	143.30	213.60	22.32	379.22	127.77	58.45	45.52	139.12	370.86	-8.36
2009	143.30	213.60	22.26	379.16	127.77	58.69	45.52	139.67	371.65	-7.51
2010	143.30	213.60	22.25	379.15	127.78	58.90	45.52	140.28	372.48	-6.67
2011	143.30	214.50	22.13	379.93	127.99	59.25	45.52	141.35	374.11	-5.82

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 5.8. (Continued)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2012	143.30	213.60	22.08	378.98	127.77	59.26	45.52	141.60	374.15	-4.83
2013	143.30	213.60	22.04	378.94	127.77	59.42	45.52	142.24	374.95	-3.99
2014	143.30	213.60	22.07	378.97	127.77	59.56	45.52	142.89	375.74	-3.23
2015	143.30	214.60	22.00	379.90	127.99	59.85	45.52	143.97	377.33	-2.57
2016	143.30	213.60	22.04	378.94	127.78	59.81	45.52	144.19	377.30	-1.64
2017	143.70	213.60	22.07	379.37	128.64	60.07	45.52	144.32	378.55	-0.82
2018	143.30	212.40	22.00	377.70	127.73	60.00	45.52	145.30	378.55	0.85
2019	143.30	214.50	22.04	379.84	127.99	60.25	45.52	146.31	380.07	0.23
2020	143.30	213.50	21.97	378.77	127.74	60.17	45.52	146.43	379.86	1.09
2021	143.30	213.50	22.01	378.81	127.77	60.24	45.52	146.92	380.45	1.64
2022	143.30	213.50	21.55	378.35	127.78	60.31	45.52	147.41	381.02	2.67

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

Table 5.8. (Continued)

Years	Recharge (hm^3/year)				Discharge (hm^3/year)					Reserve Change* (hm^3/year)
	Subsurface Inflow	Precipitation	Ergene River	Total	Pumpage	Evapotranspiration	Subsurface Outflow	Ergene River	Total	
2023	143.30	214.50	21.92	379.72	127.99	60.53	45.52	148.30	382.34	2.62
2024	143.30	213.50	21.91	378.71	127.77	60.42	45.52	148.31	382.02	3.31
2025	143.30	213.50	21.96	378.76	127.77	60.47	45.52	148.72	382.48	3.72
2026	143.30	213.60	21.89	378.79	127.77	60.52	45.52	149.10	382.91	4.12
2027	143.30	214.50	21.88	379.68	127.99	60.73	45.52	149.92	384.16	4.48
2028	143.30	213.60	21.86	378.76	127.77	60.06	45.52	149.85	383.20	4.44
2029	143.30	213.60	21.91	378.81	127.77	60.63	45.52	150.17	384.09	5.28
2030	143.40	213.70	21.81	378.91	127.77	60.66	45.52	150.48	384.43	5.52
Average	143.35	213.76	22.12	379.23	127.84	59.25	45.52	143.94	376.56	-2.68

Note: * Positive values indicate a decline in groundwater reserves while the negative values indicate a rise.

The results of the alternative scenarios are summarized in Table 5.9. These results are also presented in the form of a trade-off curve to determine the optimum pumpage policy for the Ergene River Basin (Figure 5.24). In this curve the "average groundwater level change" as the first y axis, "average groundwater reserve change" as the second y axis and "the average annual pumpage" as the x axis obtained from all scenarios can be seen. The average groundwater level change was calculated by dividing the sum of the groundwater level changes between January 2001 and December 2030 for each cell to the total number of the cells within the model domain. According to the trade-off curve, an increase in annual pumpage increases the average declines in groundwater levels and reserves and vice versa. It can be seen from the figure that there is a rapid decrease in reserve change and the groundwater level change from Scenario A to Scenario B, although the rest of the scenarios lies on almost the same line in other words the slope doesn't change. And if there is a significant decrease in annual pumpage (Scenario H), a rise both in groundwater levels and reserves would take place.

Safe yield is a term used to express the amount of groundwater pumped from an aquifer without exceeding the amount that is naturally recharged through precipitation, surface water and subsurface inflow. This concept ignores the other components of discharge from the system like base flow to the streams besides pumpage. Therefore, the safe yield for Sandy Complex aquifer would be 371 hm^3/year that is the value used in Scenario B. Even with an annual pumpage rate being equal to the annual recharge, the decrease in groundwater levels is 18.1 m, producing a decline of 191.58 hm^3/year in groundwater reserves. Thus pumping the aquifer at the safe yield value would not be safe. Therefore, another yield concept that is called the "sustainable yield" allowing adequate provision of water to sustain streams, springs, wetlands, and groundwater dependent ecosystem (Sophocleous, 1997) should be considered.

Table 5.9. Average groundwater pumpage policy and resulting average changes in groundwater reserves, groundwater levels, and base flows during the planning period (January 2001- December 2030)

Scenario	Average pumpage (hm^3/year$^-$)	Average change in groundwater reserves (hm^3/year$^-$)[a]	Average change in groundwater levels (m)[b]	Average base-flow to streams (hm^3/year$^-$)
A	472.8	273.2	28.3	97.8
B	368.3	191.6	18.1	113.3
C	333.4	160.1	15.1	115.1
D	297.0	130.1	11.8	119.5
E	260.7	96.7	8.5	120.6
F	222.9	63.9	5.0	123.1
G	167.9	21.5	0.2	132.3
H	127.8	-2.7	-3.9	143.9

[a] Positive values indicate a decline in groundwater reserves while negative values indicate a rise

[b] Positive values indicate a decline in groundwater levels while negative values indicate a rise

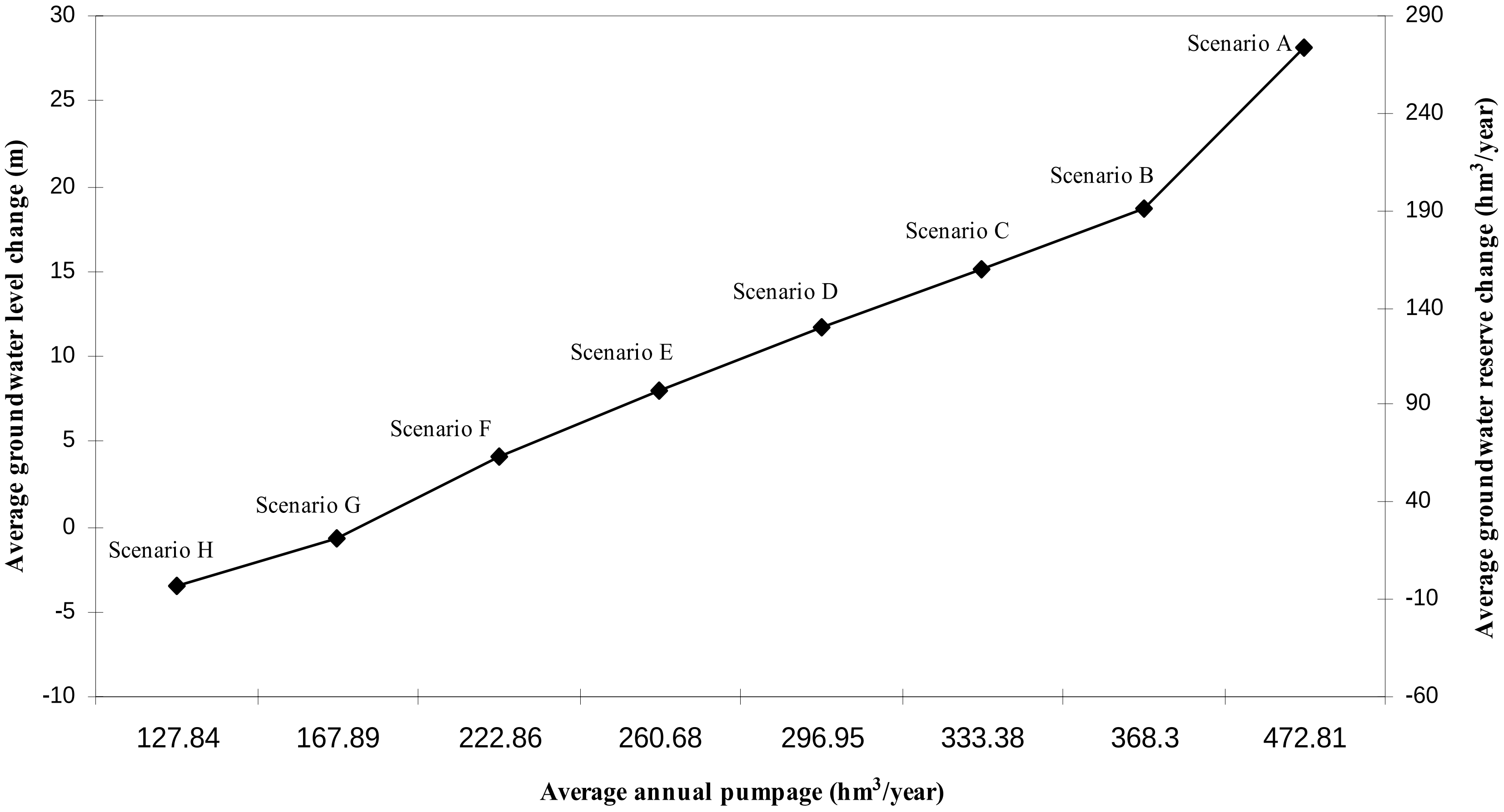

Figure 5.24. Trade-off curve for Scenarios A-H.

To better understand why safe yield is not sustainable yield, a review of hydrologic principles is required. Under natural conditions, prior to development of wells, aquifers are in a state of approximate dynamic equilibrium: over hundreds of years, recharge equals discharge. Discharge from wells upsets this equilibrium by producing a loss of water from aquifer storage. A new state of dynamic equilibrium is reached only by an increase in recharge (induced recharge), a decrease in natural discharge, or a combination of the two. Initially, groundwater pumped from the aquifer comes from storage, but ultimately it comes from induced recharge. The timing of this transition, which takes a long time by human standards, is a key factor in developing sustainable water-use policies. However, it is exceedingly difficult to distinguish between natural recharge and induced recharge to ascertain possible sustainable yield (Sophocleous, 1997).

In order to determine the sustainable yield of the Sandy Complex aquifer by considering the base flow into streams, Scenario G or H should be used. In Scenario G, the annual pumpage is 168 hm^3/year with almost no changes in groundwater levels from year 2000 conditions and a decline of 21.5 hm^3/year in groundwater reserves that is insignificant when compared to Scenario A. The base flow to the streams under Scenario G is 19 hm^3/year greater than the value calculated under the safe-yield concept in Scenario B. In Scenario H, the annual pumpage is 128 hm^3/year with a rise of 3.9 m in groundwater levels as compared to the year 2000 conditions and a rise of 2.68 hm^3/year in groundwater reserves. The base flow to the streams is 30.69 hm^3/year greater than the value calculated under the safe yield concept (Scenario B). However, this increase in base-flow is obtained with a marginal rise in groundwater levels and reserves. Thus, it appears that the annual pumpage rate used in Scenario G would be the sustainable yield of the system. But the current pumping rate which is 475 hm^3/year (Scenario A) is significantly greater than both the sustainable yield (168 hm^3/year) and safe yield (371 hm^3/year) of the system. Therefore, an appropriate suite of management policies and plans should be adopted.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

In this study a groundwater flow model was developed and utilized to determine the safe and sustainable yields for the Ergene River Basin Sandy Complex aquifer. Various data concerning the b topography, geology, meteorology and hydrogeology of the basin have been collected and evaluated to characterize the aquifer system. Subsequently, a finite difference grid was created. Aquifer was divided into 5903 cells where hydraulic parameters were assumed to be same. The finite difference grid was able to cover all the regions where the aquifer is present.

The input parameters such as hydraulic conductivity, storativity, recharge and evapotranspiration can not be defined for all the cells of the finite difference grid with available data therefore they were modified in order to match the observed water level elevations with the output from the model, i.e. the model was calibrated. Model calibration was performed in two steps that are: under steady state and transient conditions. In the first step, January 1970 measured water level elevations were compared with the calculated water level elevations. In the second step of the calibration groundwater flow model was calibrated between January 1970-December 2000 with monthly stress periods under transient conditions. Results of the transient calibration were checked with the predicted and observed water level hydrographs at DSİ observation wells (52281, 5592, 52282, 52279, 52285 and 49869).

Alternative groundwater pumping scenarios were developed to determine the safe and sustainable yields for the Ergene River Basin Sandy

Complex aquifer. Groundwater flow model developed for the aquifer was used to predict the response of the aquifer to different pumpage conditions and the results obtained were evaluated.

A total of eight pumping scenarios were developed under transient flow conditions for a planning period of 30 years starting from 2001 until 2030. All of these scenarios (A-G) were developed to determine the limits of utilization for the Sandy Complex aquifer.

In Scenario A, the predicted changes in groundwater levels and reserves were determined by assuming that the present recharge and pumpage conditions do not change during the 30 years of planning horizon. The pumpage rate assigned to the model was the same through the planning period.

According to the results obtained from Scenario A the change in groundwater reserves would be 273 hm^3/year and the groundwater levels would decline at an areal average value of 28 m at the end of the planning period in comparison to December 2000 levels (Table 5.9). Accordingly, even if the pumpage conditions were remained the same during the 30 years of planning period in the Ergene River basin, there would be significant declines in groundwater levels. Moreover, as the results have shown significant decline in groundwater levels under the present conditions, it is a matter of fact that increasing rates of abstraction in future will lead to even greater loss of water from the aquifer storage.

To determine an optimum pumpage policy Scenarios B, C, D, E, F, G and H were developed in which the annual pumping rates were decreased to be equal to 100, 90, 80, 70, 60, 45 and 35% of the annual recharge values (371 hm^3/year), respectively. All the other parameter values were remained the same as in Scenario A.

Alternative groundwater pumping scenarios explained above were developed to determine the safe yield and the limits of utilization for the

Ergene River Basin Sandy Complex aquifer. As it can be seen from the results of groundwater pumping scenarios, the present annual groundwater pumpage rate (475 hm^3/year) is about 307 hm^3/year and 104 hm^3/year greater than the sustainable yield (168 hm^3/year) and traditionally defined safe yield (371 hm^3/year), respectively. Therefore, if the present annual pumping rates continue without any increase during the planning period, it would cause an average decline of 273 hm^3/year in groundwater reserves and 28 m of decline in groundwater levels at the end of the planning horizon. Accordingly, the groundwater pumping costs would increase, the current wells in excessively dewatered areas have to be replaced with deeper new wells, and the base flow to streams would decrease year by year. Therefore, an appropriate suite of management policies and plans should be adopted.

While adopting management policies and plans controls on new development, water metering on all new wells, annual water use reporting, water conservation measures and efficient irrigation schemes should be adopted. The irrigation cooperatives should be encouraged instead of private irrigation so by that way uncontrolled drilling can be prevented. The public should also be involved by improving their perception of the problems related to groundwater.

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