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Investigation of Safe and Sustainable Yields for the Sandy Complex Aquifer System in the Ergene River Basin, Thrace Region, Turkey

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Abstract: This study aims to determine the safe and sustainable yields for the Sandy Complex aquifer system in Ergene River basin in northwestern Turkey. A numerical ground-water flow model was developed for the Sandy Complex aquifer, which is the most productive and the most widespread aquifer in the basin. The finite difference ground-water model was used to simulate steady and unsteady flow in the aquifer. The model was calibrated in two steps: a steady-state calibration, by using the observed ground-water levels of January 1970; then a transient calibration, by using the observed ground-water levels for the period of January 1970 and December 2000.

The resulting model was used to develop ground-water 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 both the safe and the sustainable yield values are exceeded if pumping continues at the present rate. An appropriate suite of management policies and plans are provided that will promote the sustainable development of the aquifer system.

Key Words: Ergene River basin, calibration, ground-water management, safe yield, sustainable yield

Ergene Havzası Kumlu Kompleks Akifer Sisteminin Emniyetli ve Sürdürülebilir Verimlerinin Araştırılması, Trakya Bölgesi, Türkiye

Özet: Bu çalışmanın amacı Türkiye'nin kuzeybatısındaki Ergene havzası Kumlu Kompleks akifer sisteminin emniyetli ve sürdürülebilir verimlerinin belirlenmesidir. Havzadaki en yaygın ve en verimli akifer olan Kumlu Kompleks akiferin sayısal yeraltısuyu modeli oluşturulmuştur. Sonlu farklar yeraltısuyu 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. Akifer sisteminin sürdürelebilir gelişmesini teşvik edecek bir dizi uygun yönetim politikaları ve planları önerilmiştir.

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

Introduction

In recent decades the value of ground water has increased, as it is an important source of fresh water throughout the world. More than 2 billion people worldwide depend on ground water for their daily supplies (Kemper 2004). A large portion of the world’s agriculture and industry also depend on ground water. In areas where there are no surface-water supplies or the surface water is contaminated by industrial facilities, ground water is almost everywhere overexploited with serious and harmful consequences, such as decline of water levels, increase in pumping costs, decrease in base-flow to streams and wetlands with consequent loss of ecosystems, and eventual depletion of the aquifers. This has happened in several places in the world, including western Turkey, the High Plains of the United States, and the North China Plain, among others. Not surprisingly, persistent ground-water level declines and decrease in the base flow of streams have also been observed in western Turkey within the last two decades. Şakıyan & Yazıcıgil (2004), in their study of the Küçük Menderes River basin aquifer system, have shown that it is impossible to meet the growing need for irrigation water in the basin from ground-water resources that are already overexploited. The undesirable consequences that will be created by heavy pumpage of ground-water resources were demonstrated in that study and the construction of planned surface-water reservoirs and the implemention of efficient water-management plans were suggested as a solution (Şakıyan & Yazıcıgil 2004).

Management of ground-water resources and allocation of ground-water-use rights in Turkey are based to a large extent on the concept of safe yield, commonly used by Turkish hydrogeologists and government institutions (Yazıcıgil & Ekmekçi 2003). Safe yield is a term used to express the annual amount of ground water pumped from an aquifer without exceeding the annual amount that is naturally recharged through precipitation, surface water and subsurface inflow. Because the concept of safe yield ignores the other components of discharge from the system, such as evapotranspiration or base flow to streams and wetlands, ground-water management policies based upon this parameter yield some unintended consequences, such as drying up of streams, springs and wetlands with the loss of ecosystems or contamination of ground water by polluted streams. Thus, as it has been shown by Sophocleous (1997), Bredehoeft (1997) and Şakıyan & Yazıcıgil (2004), pumping an aquifer at the safe-yield value would not necessarily be safe. Therefore, management of ground-water resources in a basin under ideal conditions would require the use of the concept of sustainable yield which allows adequate provision of water to sustain streams, springs, wetlands, and ground-water dependent ecosystems (Sophocleous 2000). This concept has been developed since the 1980s and can be defined as the quantity of ground water that can be pumped in the long term by considering the future generations and all components of the hydrologic system, not only ground water but surface waters as well (Sophocleous 1998). Hence, it is of utmost importance to identify the level of ground-water development in an aquifer and to compare it to the safe and sustainable yield values considering all hydrologic changes that might occur in the surface and subsurface environments (i.e., changes in base-flow conditions, decline in ground-water reserves and water levels, etc.).

The Sandy Complex aquifer in the Ergene River basin of northwestern Turkey has experienced rapid declines in ground-water levels over the past two decades. The present study was undertaken to determine the safe and sustainable yields and the limits of utilization for the Sandy Complex aquifer system in order to ensure the continued availability of its ground-water resources for future generations. To determine the safe and sustainable yields of the Sandy Complex aquifer, a ground-water flow model was developed after characterization of the system. The model was calibrated by finding a set of parameters, boundary conditions and stresses that produce simulated heads and fluxes that match 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 a trade-off curve to enhance decision-makers’ ability to select an optimum development strategy, and to observe the consequences of further development of the Sandy Complex aquifer.

Physiography, Climate and Geological Setting

The Ergene River basin is part of the Thrace Basin, one of the largest Tertiary sedimentary basins located in northwestern Turkey (Figure 1). The catchment area of the Ergene River basin is 11325 km^2. The Ergene River

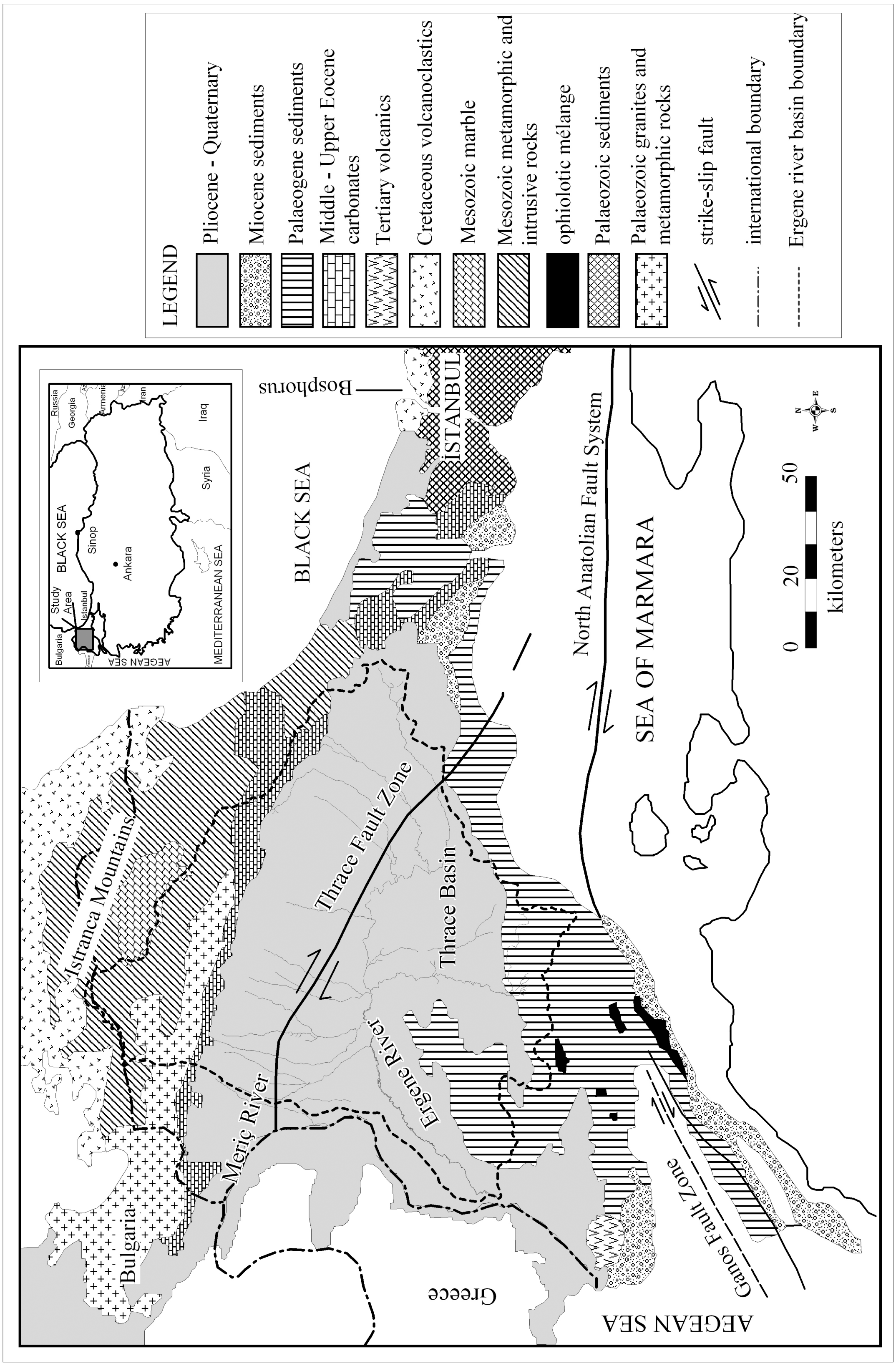

Figure 1. Geological map of the Ergene River basin (modified and simplified from Turgut & Eseller 2000).

and its tributaries constitute the only surface-water system of the study area. The Ergene River emerges from the Istranca Mountains and follows a 281-km-long path through the centre of the plain and finally discharges into the Meriç River, of which it is one of the most important tributaries. The study area has a continental-type climate with a mean annual precipitation of 590 mm (DSİ 2001).

Turkish Thrace can be subdivided into two parts, namely the Istranca Massif – which is characterised by units belonging to pre-Tertiary time – and the Thrace Basin, which is a Tertiary sedimentary basin which developed upon metamorphic and crystalline units of the Istranca Massif during the Middle Eocene (Ekmekçi 2005 and references therein). The Istranca Massif consists of a late-Variscan crystalline basement of granites and felsic gneisses unconformably overlain by a Lower Mesozoic transgressive continental to shallow-marine metasedimentary sequence (Okay *et al.* 2001). The Thrace Basin, on the other hand, consists of Tertiary deposits represented by Eocene, Oligocene, Miocene and Pliocene materials (Doust & Arıkan 1974; Keskin 1974; Perinçek 1987; Turgut *et al.* 1991; Görür & Okay 1996; Sakınç *et al.* 1999; Turgut & Eseller 2000).

Infill of the Thrace Basin was dominated by a shallowing-upward, dominantly clastic succession of Middle Eocene to Oligocene age. Medial Eocene to Early Oligocene sedimentation within the basin was characterized locally by tuffaceous turbidites, whereas continental to shallow-marine clastics and carbonates with subordinate volcaniclastic materials were laid down both along the basin margins and on bathymetric highs projecting into the basin interior (Figure 2) (Doust & Arıkan 1974; Keskin 1974; Turgut *et al.* 1991; Perinçek 1991; Görür & Okay 1996). Post-Early-Oliogocene sedimentation was marine to terrestrial and represented by coal-bearing clastics and carbonates with some tuffaceous material (Doust & Arıkan 1974; Turgut *et al.* 1991; Görür & Okay 1996).

The sedimentary succession in the central part of the basin, deposited unconformably on the metamorphic and crystalline rocks of the Istranca Massif in the north and ophiolitic mélange in the south, begins with turbidites of Middle Eocene to Lower Oligocene age (the Keşan formation: Doust & Arıkan 1974; Görür & Okay 1996) (Figure 2). The turbidites comprise more than 4000-m-thick interbedded sandstones and shales with subordinate pelagic carbonates and conglomeratic intervals. The sandstones are mostly fine-grained and poorly sorted arenites to wackes with abundant angular to subrounded grains of metamorphic and magmatic rocks, quartz, feldspars, micas and various minerals of volcanic and metamorphic origin (Doust & Arıkan 1974; Görür & Okay 1996). The interbedded shales consist of grey to black calcareous siltstones and claystones, rich in mica and carbonaceous material. Upward in the section, the turbidites contain pyroclastic material and are followed by 450- to 1000-m-thick Upper Oligocene shales, which are calcareous and micaceous with well-developed lamination and common shallow-water fossils, with rippled sandstones and argillaceous limestones (the Muhacir formation: Doust & Arıkan 1974; Görür & Okay 1996). These marginal marine sediments are overlain by the uppermost Oligocene non-marine strata of fining-upward, fine- to medium-grained and poorly sorted sandstones and calcareous shales with conglomeratic and tuffaceous interlayers (the Danişmen formation). Unconformably above them, fluvio-lacustrine deposits of the Late Miocene to Quaternary age are present (Ergene formation). These deposits consist mainly of loose to poorly cemented pebbles, sands, shales, marls and chalky limestones. Their thickness changes from 500 to 1700 m (Doust & Arıkan 1974; Görür & Okay 1996). The Pliocene series of the Ergene formation has been divided into two subgroups, namely the Çorlu formation for the lower part and the Babaeski formation for the upper part (Italconsult 1970). The Pliocene Çorlu formation has been referred to as the 'Sandy Complex' by hydrogeologists because this name well reflects its lithostratigraphic characteristics; it crops out 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 units. 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 particles are well-rounded. The depositional environment is of the deltaic-lacustrine type (Italconsult 1970).

The Babaeski formation represents the upper part of the Pliocene. It exists either as outcrops or below the Quaternary cover in the central part of the basin. The

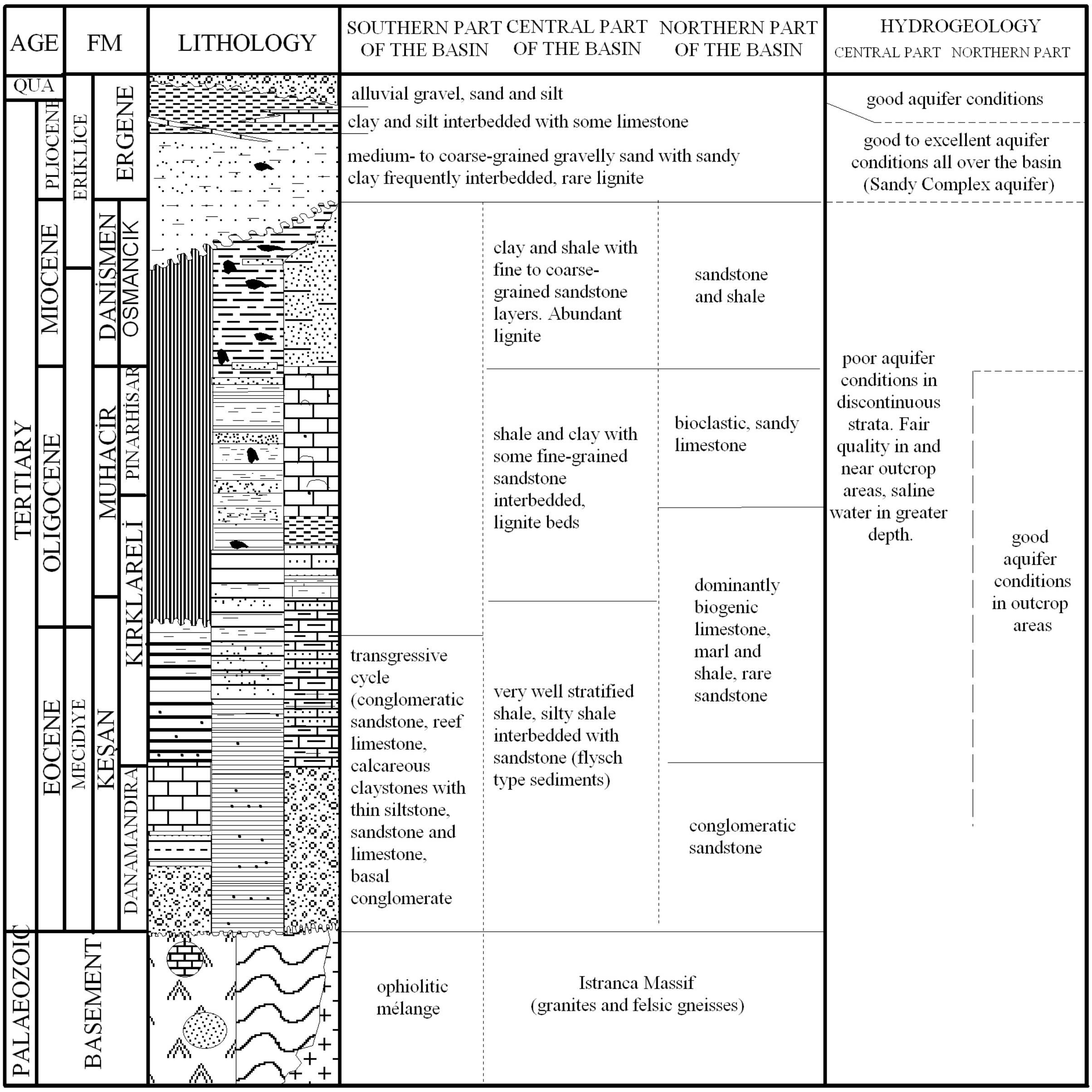

Figure 2. Generalized columnar section of the Ergene River basin (modified from Doust & Arıkan 1974; Görür & Okay 1996).

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 limestone beds also occur. The depositional environment of the Babaeski formation was different from that of the Çorlu formation, lithostratigraphic characteristics indicate a lacustrine-type environment (Italconsult 1970). A geological map showing the distribution of the units observed in the study area is given in Figure 1.

In the southern part of the basin, the succession begins with Middle Eocene coarse conglomerates, sandstones and shales overlain by coralgal reef limestones (the Mecidiye group, comprising the Ballıkdere, Dolucatepe, Müfrete and Tavrı formations: Doust & Arıkan 1974). Towards the top, the reef limestones pass into coal-bearing marginal-marine to continental-clastic deposits of Late Oligocene age. The succession continues upward across an angular unconformity with Upper Miocene to Pliocene terrigeneous to shallow-marine rocks (Eriklice formation: Doust & Arıkan 1974).

In the northern part of the basin, the marginal sequence (the Saray group, comprising the Danamandıra, Kırklareli, Pınarhisar and Osmancık formations: Doust & Arıkan 1974; Görür & Okay 1996) displays similar stratigraphic and lithological characteristics with abundant carbonate facies, although deposition of the sediments here seems to have begun later in the Eocene (Figure 2; Doust & Arıkan 1974; Görür & Okay 1996).

In the Thrace Basin, two principal fault zones namely, the Thrace Fault Zone (TFZ) (Perinçek 1987, 1991) and the Ganos fault zone (GFZ) (Yaltırak 1996), were active during the Neogene. The TFZ is situated to the north and first began to develop around Kırklareli during the Middle–Late Miocene and later migrated to the south, there creating two other fault zones. The GFZ is an older structure than the TFZ; it has been present since the Eocene (Tapırdamaz & Yaltırak 1997).

Hydrogeological Setting

The initial hydrogeological characterization of the Ergene River basin was begun in 1970 by Italconsult using geological, geophysical and well-log information. The various lithological units in the basin were classified hydrogeologically on the basis of their water-bearing potential (Figure 2). The Pliocene Çorlu formation or, in other words, the "Sandy Complex aquifer", is the most productive and most widespread aquifer in the Ergene River basin. It is a regional aquifer tapped by several thousand wells, mainly used for irrigation. This unit extends over an area of 5855 km– and crops out in the western and eastern parts of the basin, whereas in the central part it is confined by the Babaeski formation (Figure 3). The base is regular with a spoon shape, decreasing down to -400 m in the vicinity of the Çorlu-Lüleburgaz fault, running SE–NW for about 60 km, interrupting the continuity of the aquifer in the confined area (Italconsult 1970) (Figure 4). The Çorlu-Lüleburgaz fault is a part of the Thrace Fault Zone. A structural contour map of the top of the Sandy Complex aquifer was prepared by Italconsult (1970) for the central and northwestern parts of the basin where confined conditions prevail (Figure 5). The maximum total saturated thickness of the aquifer occurs in the central part of the basin with more than 350 m. A contour map showing the ground-water levels in January 1970 is given in Figure 6. Ground-water levels vary from 130 m around Çerkezköy in the east to about 30 m around Pehlivanköy in the west. As seen in the figure, the ground-water discharges towards the Ergene River. The Çorlu-Lüleburgaz fault affects ground-water levels in the central part of the basin where ground-water elevations on eastern side of the fault are about 30 m higher than the ones on the western side. The rapid drop in ground-water levels across the fault indicates character as a barrier. Based on pumping tests, the average hydraulic conductivity of the aquifer was estimated at 13 m/day, and the average storage coefficient in the confined part was found out to be on the order of 10^{-3} (Italconsult 1970).

Temporal Changes in Water Levels

Analyses of temporal changes in ground-water levels provided information about the response of the aquifer to abstractions. Temporal changes in water level in the observation wells, whose locations are given in Figure 3, are plotted in Figure 7. Due to the heavy abstraction of water for irrigation as well as domestic and industrial uses, there have been declines in ground-water level over time (Figure 7). In the eastern unconfined part, especially around the Çerkezköy industrial district where ground water is continuously pumped for industrial purposes, there was 28 m of drawdown between the years 1970 and 2000. It should be noted that the ground-water levels showed no significant decline until 1989; however after 1989, there has been an abrupt decrease in water levels in some wells, most probably due to the abstraction of water for industrial purposes around Çerkezköy. For the western unconfined part, there was about a 7-m decline in ground-water levels between years 1970 and 2000, 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. In the confined part, declines in ground water are higher than in the unconfined parts, with a maximum of 50 m due to its low storativity as well as significant withdrawal of water for irrigation use.

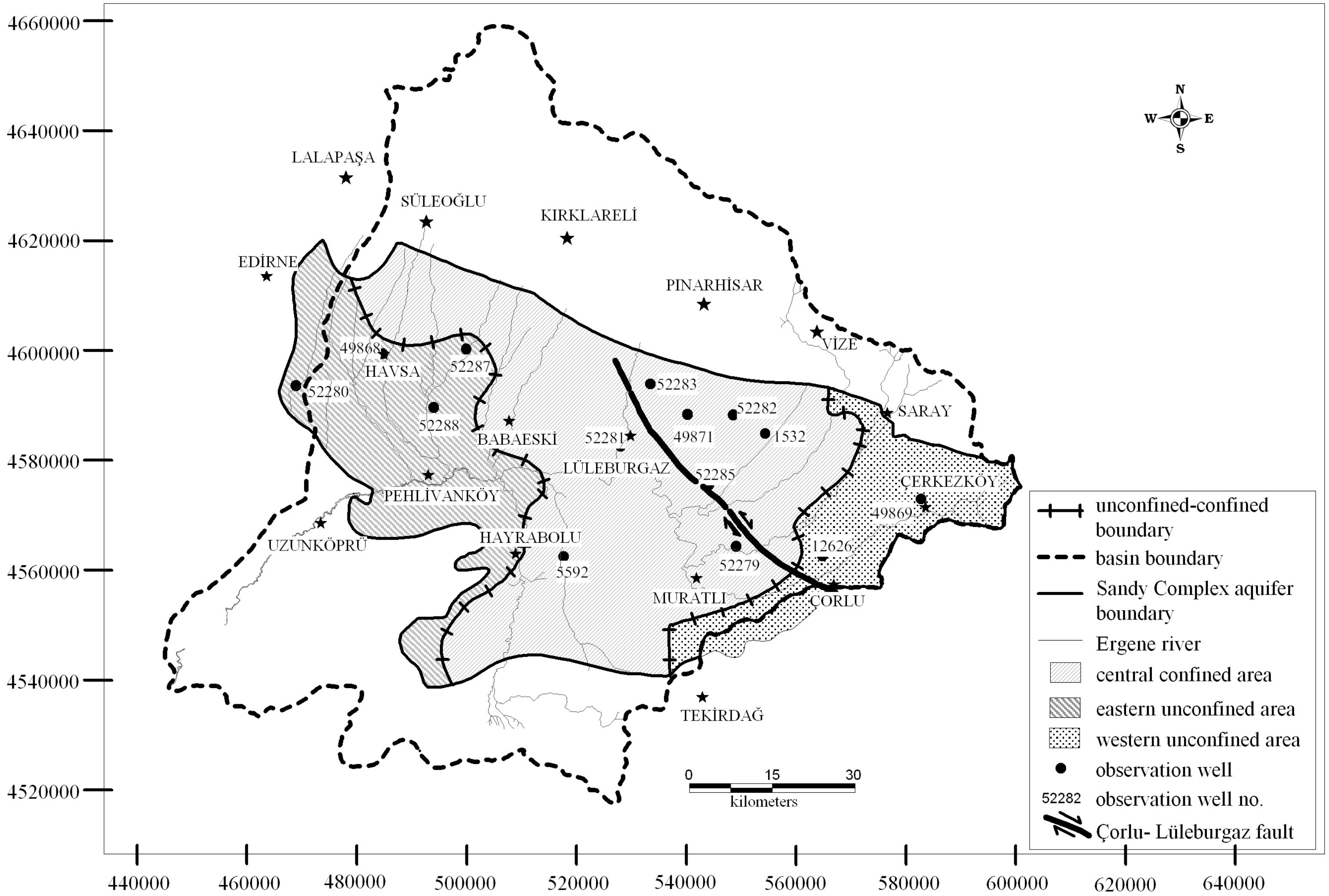

Figure 3. Map showing the Sandy Complex aquifer boundary, the Çorlu-Lüleburgaz fault, the locations of the observation wells, eastern and western unconfined areas, and the central confined area.

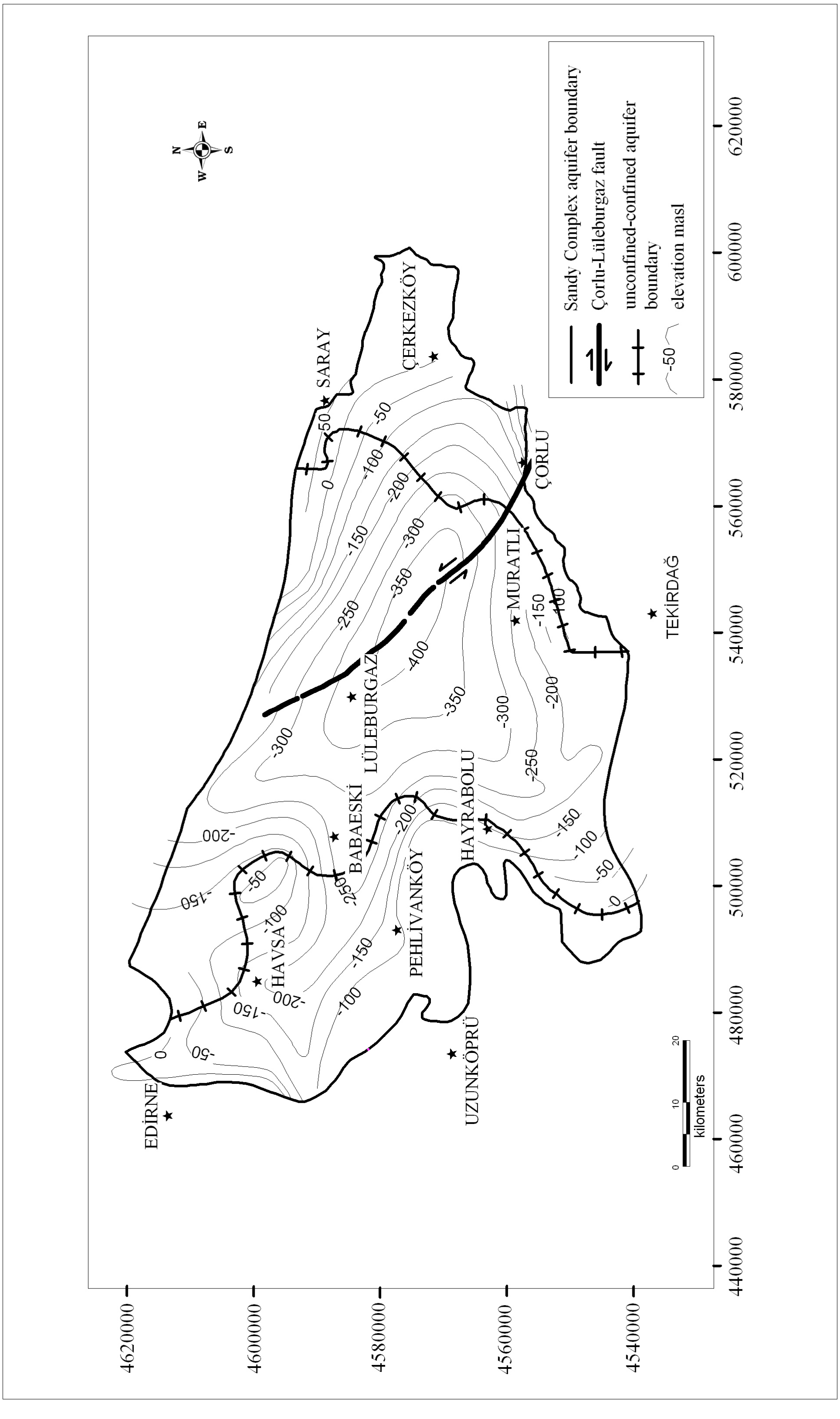

Figure 4. Structural contours showing the base of the Sandy Complex aquifer (Italconsult 1970).

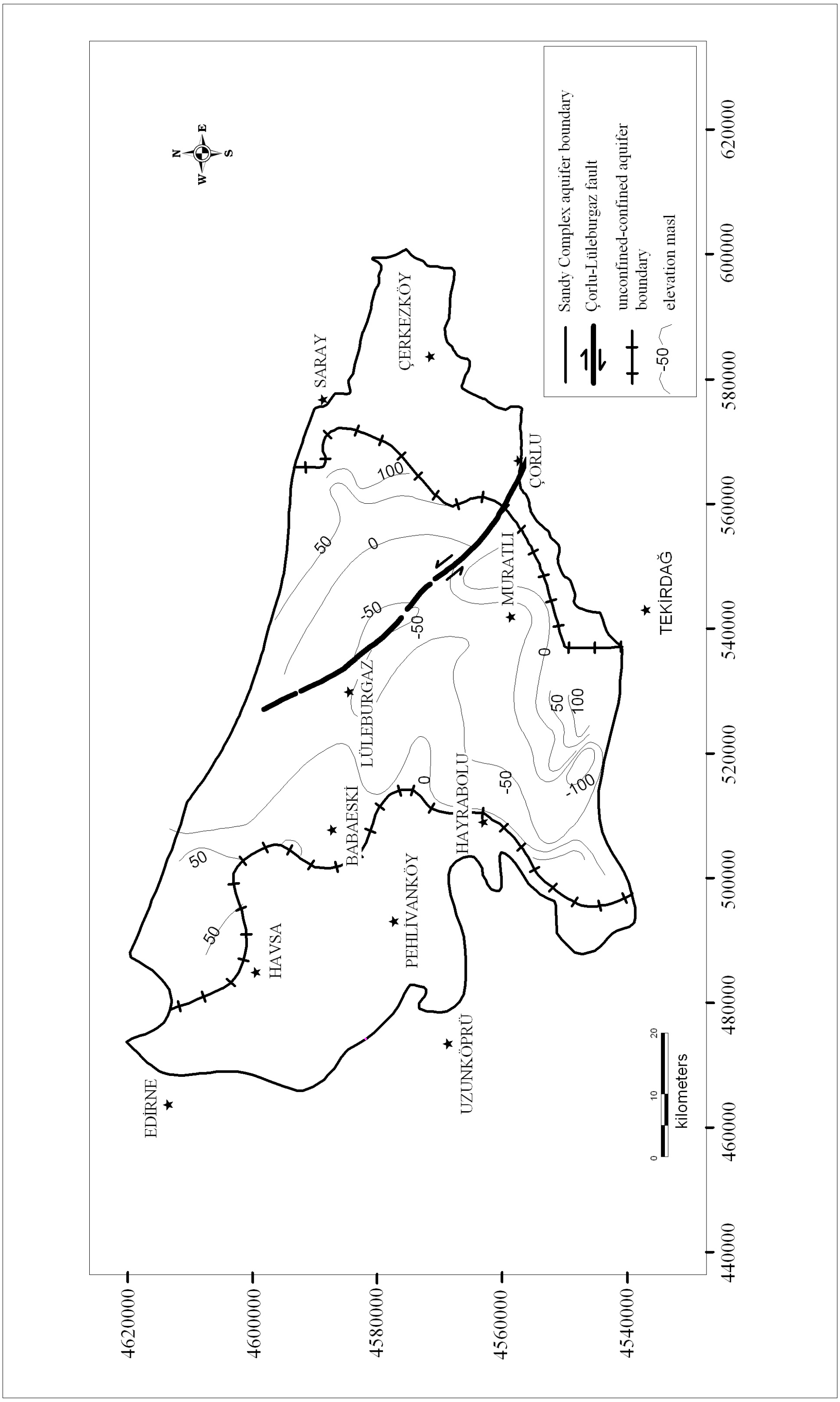

Figure 5. Structural contour map for the top of Sandy Complex aquifer in the confined part (Italconsult 1970).

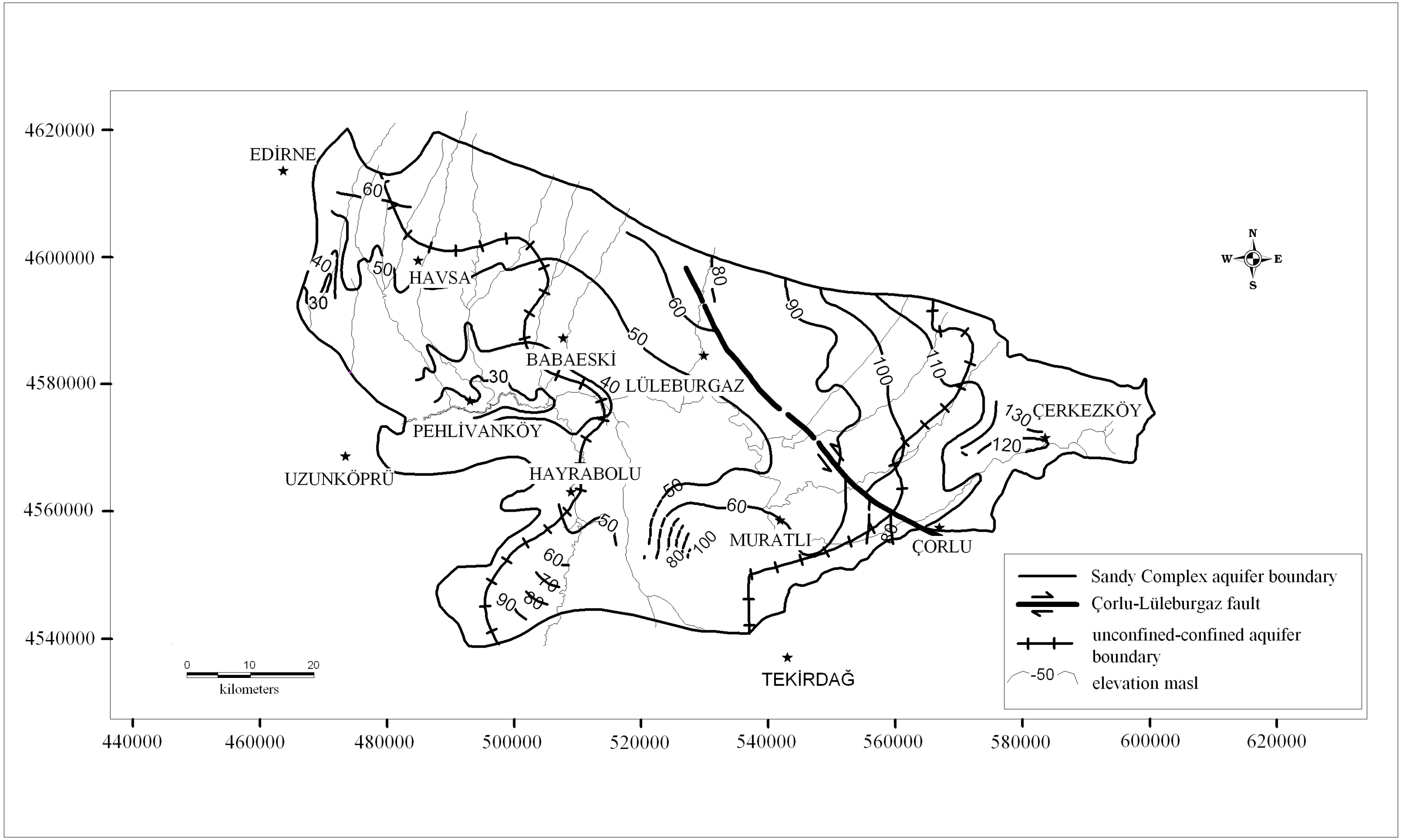

Figure 6. Contour map showing the distribution of ground-water levels in January 1970 (Italconsult 1970).

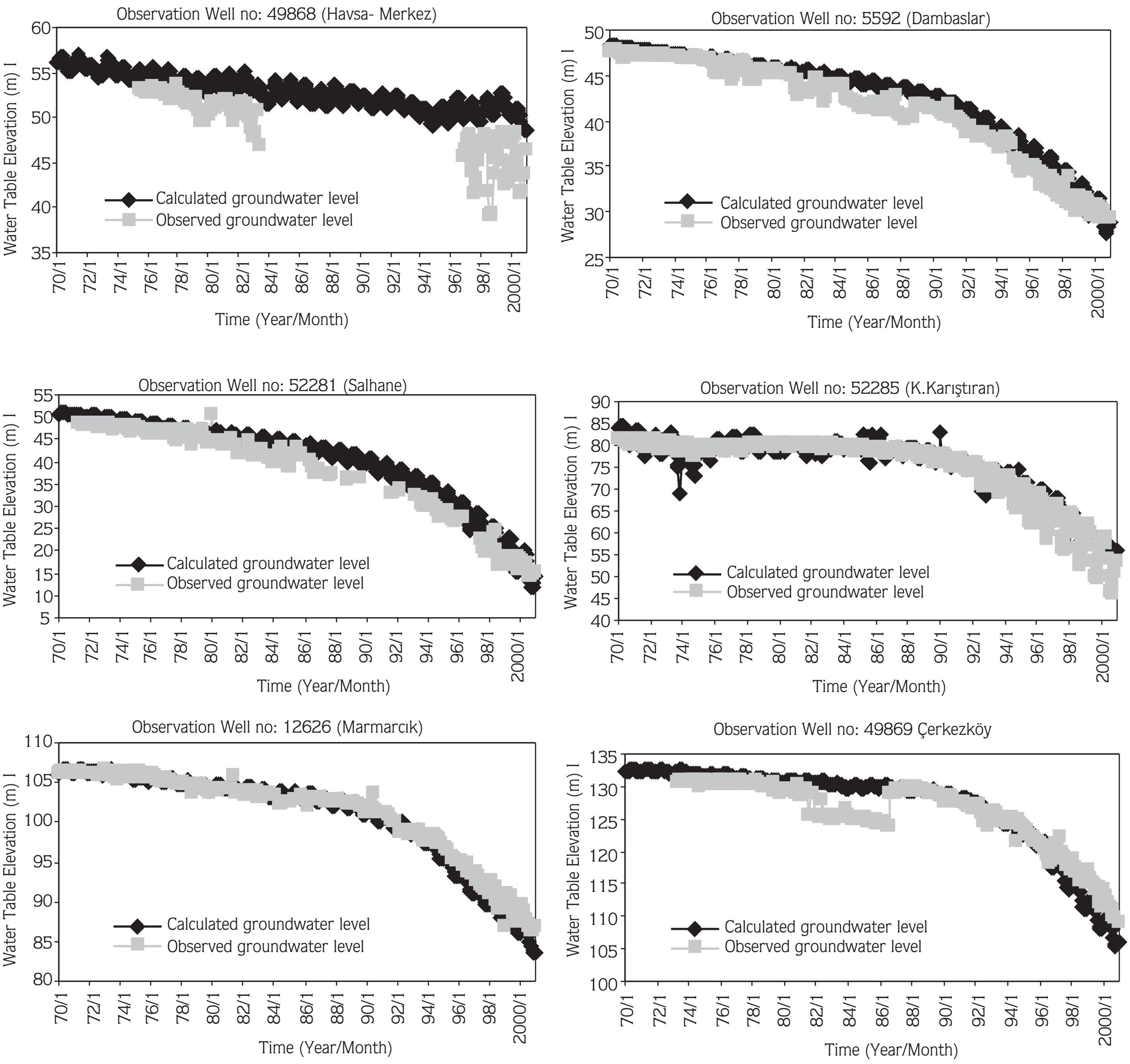

Figure 7. Ground-water level hydrographs for observation wells no. 49868, 5592, 52281, 52285, 12626, and 49869.

Ground-water Model and Boundary Conditions

A ground-water flow model was designed to represent the Ergene River basin Sandy Complex aquifer system in order to determine the safe and sustainable yields of the system and to establish an optimum pumping policy. The simulation within this study was conducted using MODFLOW (McDonald & Harbaugh 1984). The finite-difference grid and the boundary conditions of the aquifer are shown in Figure 8. The aquifer area is divided into cells of 1000 m X 1000 m, making a total of 5903 cells. During the calibration phase, the boundary of the model was overlapped with the geology of the basin, and boundary conditions were defined. In the finite-difference grid for the Ergene River basin, four types of boundary conditions – namely, constant flux, no flow, river and flow barrier boundary conditions – were used

(Figure 8). The Ergene River and its tributaries were modelled as a river boundary, hydraulic conductances of which were determined during calibration studies. The internal Çorlu-Lüleburgaz fault was modelled as a barrier boundary.

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 of water flux across the boundary. These cells were selected on the basis of hydraulic heads and the geological map. 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 (Figure 8). According to the ground-water budget obtained from this modelling study, there is a subsurface inflow of 137 hm^3/year, 54 hm^3/year of which is coming from the Eocene limestone located at the northern boundary, 73 hm^3/year is coming from the Mio–Oligocene series located at the southwestern part of the boundary. There is little information related to the ground-water budget of the Mio–Oligocene series; therefore the amount of subsurface inflow from this series was estimated during calibration studies. The outcrop area of the Eocene limestone aquifer is 630 km^2. Ground-water recharge rate, estimated using hydrologic budget simulations with 33 years of data from the Edirne Meteorological station, gave an average value of about 25% of the average annual precipitation. Thus, annual recharge from 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 the Sandy Complex aquifer, and the rest is most probably discharged from springs. According to Italconsult (1970), the average total discharge from springs is about 2.25 m^3/s, or 70 hm^3/year. This justifies the amount of subsurface inflow assigned to the northern boundary.

Calibration of the Ground-water Model

Model calibration was performed in two steps: steady state and transient. Steady-state calibration was accomplished by comparing January 1970 measured water-level elevations with the simulated water-level

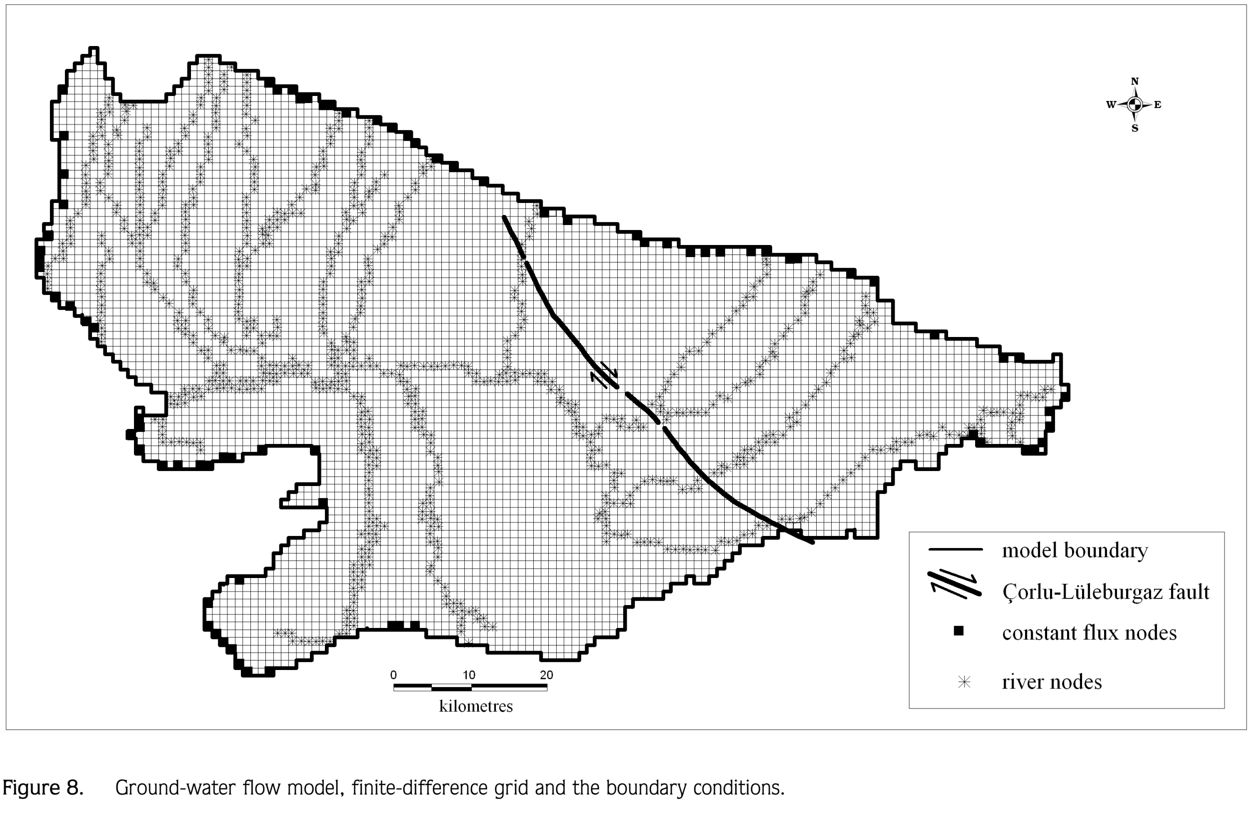

Figure 8. Ground-water flow model, finite-difference grid and the boundary conditions.

elevations. During the steady-state calibration, hydraulic conductivity distribution and the boundary conditions were modified until a root mean square error of 4.86 m was obtained between measured and simulated water levels. When the simulated versus observed ground-water level elevations for January 1970 of the calibrated model (Figure 9) is examined, most of the points lie within or close to the line in which the simulated and observed ground-water-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. January 1970 measured water-level elevations are supposed to represent the steady-state conditions of the system with the assumption that in 1970 there was no excessive pumping.

The transient simulation begins with initial conditions obtained from steady state run for January 1970 and ends in December 2000, covering 372 monthly stress periods. The hydraulic conductivity distributions and the boundary conditions correspond to ones obtained from the calibrated steady-state model. In addition to these values, transient recharge – which was calculated on a monthly basis by conducting hydrologic simulations for the period 1970 to 2000 – and storativity values were assigned to each cell under transient conditions. Transient calibration was conducted at monthly time intervals for the period 1970–2000 by comparing the temporal variations in simulated heads with those of observed water levels at 13 locations (see Figure 3 for locations). One of the most difficult inputs to determine was the monthly ground-water abstraction rates as there were no reliable information. Several types of information, such as irrigated areas, crop-water-use coefficients, and municipality water withdrawal rates, were utilized to determine the monthly discharge rates to be assigned to the model cells (Ökten 2004). A number of simulations under transient conditions were done after input parameters were transferred to the model. The calibration process continued until reliable results, that is, sufficient matches between the simulated and observed water-level elevations with respect to time at DSİ observation wells (49868, 5592, 52281, 52285, 12626 and 49869), were obtained (Figure 7). When this figure is examined, in well no. 49868 (Havsa-Merkez), monthly fluctuations observed in the ground-water levels could not be simulated. The maximum fluctuation was about 10 m due to excessive pumpage during the irrigation season (April-August). In well no. 52285, fluctuations in calculated ground-water levels are higher than the ones in observed levels. The comparison between observed and

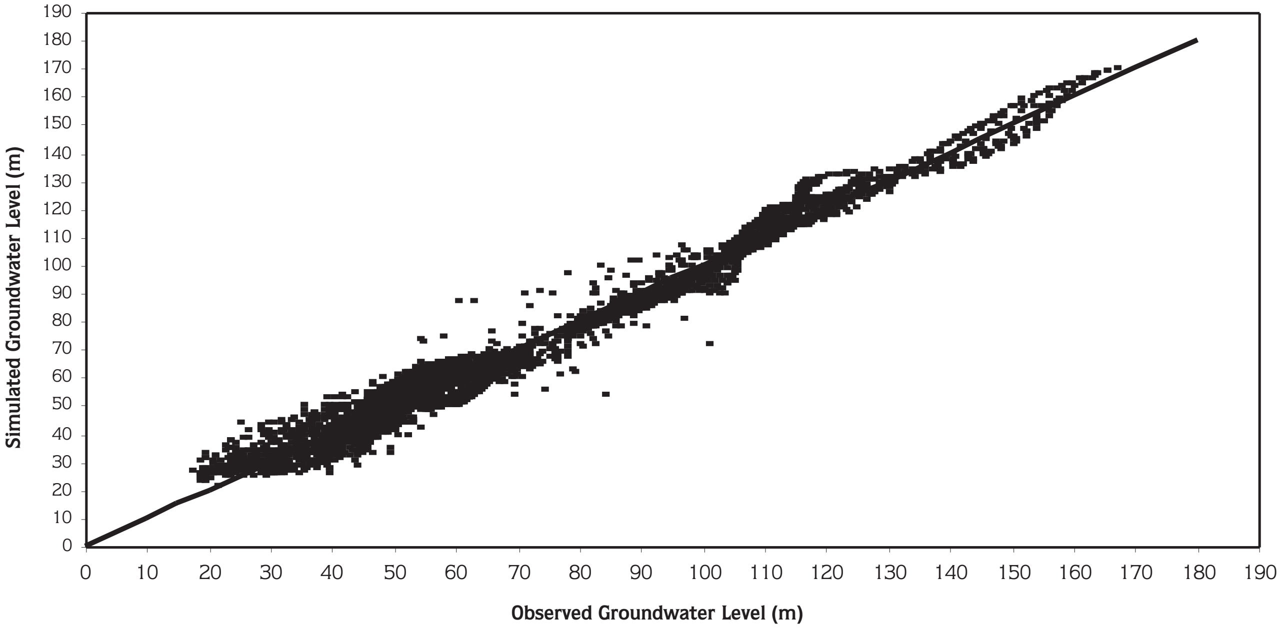

Figure 9. Simulated versus observed ground-water level elevations for January 1970 under steady-state conditions.

simulated ground-water levels at observation points no. 49869, 12626, 52281 and 5592 showed good agreement.

The average recharge, discharge and change in ground-water reserves during 31 years of transient simulation period are given in Table 1. According to this table, the average recharge was 371 hm^3/year, the average discharge was 473 hm^3/year, and the reserve change was 102 hm^3/year. Yearly changes in ground-water reserves are displayed in Figure 10, which shows that the declines in ground-water reserves were below the average until 1989. However, the reserve changes after 1993 were almost twice (180–200 hm^3/year) the average value. Furthermore, discharges to the Ergene River and evaporation losses decreased with increasing pumpage through time. The water lost by evaporation decreased from 70 hm^3/year in 1970 to 56 hm^3/year in 2000, and the water discharged to the Ergene River (i.e., base flow) decreased from 233 hm^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.

Alternative Ground-water Pumping Scenarios

In order to help planning and management of the Ergene River basin aquifer, alternative ground-water pumping scenarios have been developed. A planning period of 30 years, beginning in 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, a total of eight different scenarios have been worked out for 30 years to determine the safe and sustainable yields of the Sandy Complex aquifer. The important results obtained from the pumping scenarios are summarized in Table 2.

In Scenario A, probable changes in ground-water levels and reserves were determined by assuming that the recharge and pumpage conditions for the year 2000 do not change during the 30 years of the planning period. If pumping from the aquifer system continues at an average rate of 472.8 hm^3/year during the planning period, the annual average decline in ground-water reserves would be 273.2 hm^3/year and at the end of planning period the ground-water levels, in comparison to December 2000 levels, would decline at an areal average value of 28 m (Table 2). Accordingly, even if pumpage conditions remained the same during the 30 years of the planning period in the Ergene River basin, there would be significant declines in ground-water levels. Moreover, as the results have shown significant decline in ground-water levels under present conditions, it is a matter of fact that increasing rates of abstraction in the 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 in order 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 remained the same as in Scenario A. The results of these scenarios are presented in the form of a trade-off curve relating “average ground-water-level change”, “average annual pumpage” and “average ground-water-reserve change” to each other, as shown in Figure 11. The trade-off curve quantitatively illustrates

Table 1. Ground-water budget obtained from calibration of the model under transient conditions for the Ergene River basin, Sandy Complex aquifer (January 1970 – December 2000).

Recharge (hm^3/year)		Discharge (hm^3/year)	
Precipitation	213.06	Pumpage	170.58
Seepage from Ergene River	19.13	Base flow to 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)

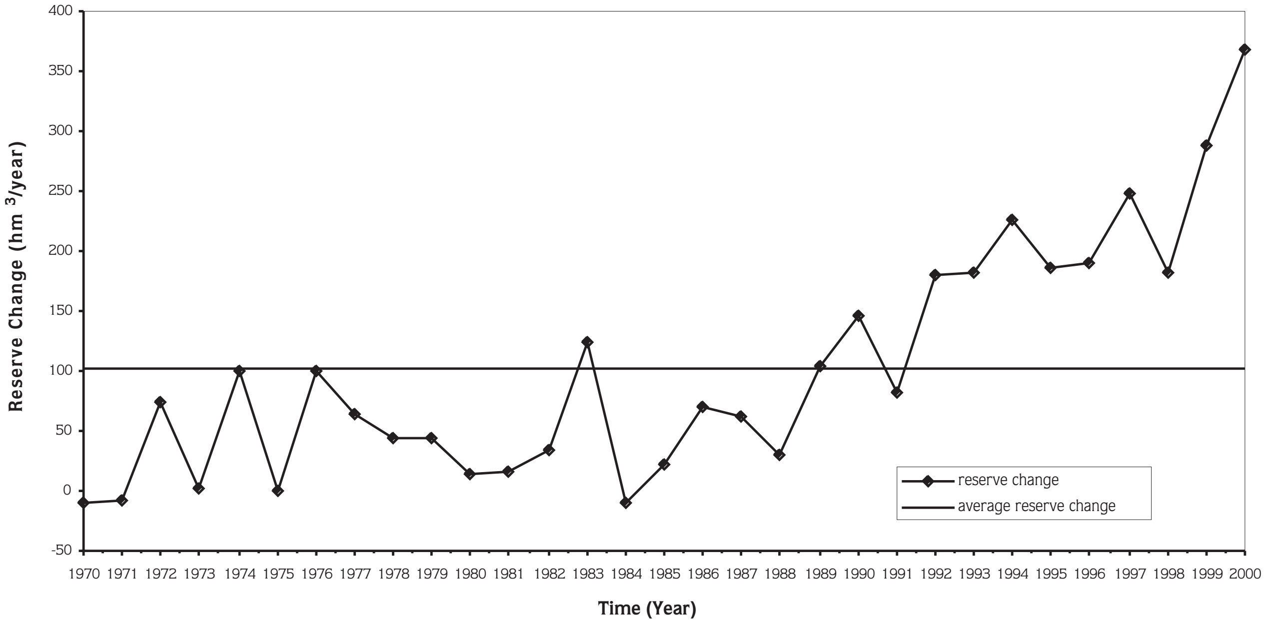

Figure 10. Simulated yearly reserve changes in ground-water reserves between years 1970-2000 under transient conditions.

Table 2. Average ground-water pumpage policy and resulting average changes in ground-water reserves, ground-water levels, and base flows during the planning period (January 2001– December 2030).

Scenario	Average pumpage (hm^3/year)	Average change in ground-water reserves (hm^3/year)[a]	Average change in ground-water 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 ground-water reserves while negative values indicate a rise.
[b] Positive values indicate a decline in ground-water levels while negative values indicate a rise.

that as annual pumpage decreases, the declines in ground-water levels and reserves decrease as well. In cases where annual pumpage decreases significantly (such as in Scenario H), a rise both in ground-water levels and reserves would take place.

According to the traditional definition of safe yield (pumpage=total recharge), the safe yield of the Sandy Complex aquifer is equal to 371 hm^3/year, the value used in Scenario B. However, these pumpage rates would decrease ground-water levels by 18 m at the end of the planning period and produce a decline of 191.6 hm^3/year in ground-water reserves. In Turkey, safe yield is – in most cases – taken as 70% to 80% of the annual recharge, which would correspond to the outcomes

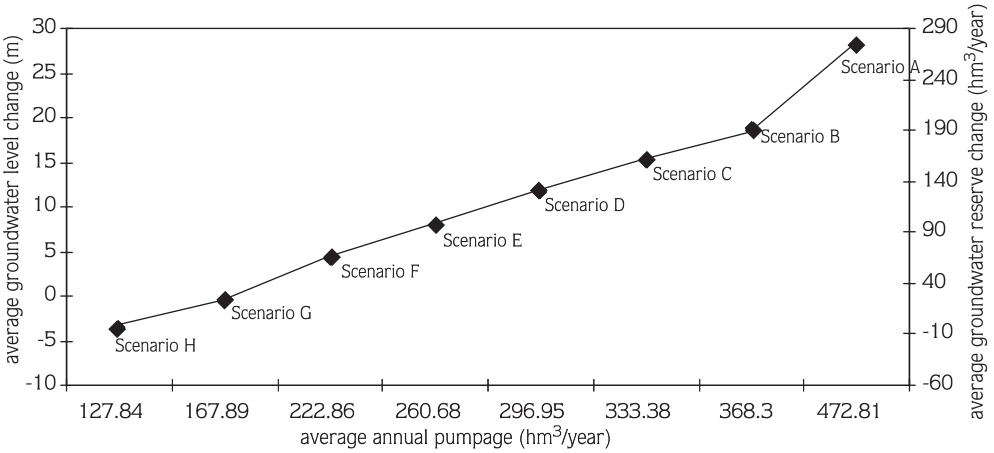

Figure 11. Trade-off curve for Scenarios A-H.

generated under Scenarios E and D, respectively. The results show that even if the safe yield is considered as 70% of the annual recharge (i.e., Scenario E), there would be a decline of 97 hm^3/year in ground-water reserves, producing an areal average decline of 8.5 m in ground-water levels at the end of the planning period (Table 2). Thus, if the aquifer is pumped at the traditionally defined safe-yield value, or even at a reduced fraction of it, there would be significant declines in ground-water levels and reserves in the long run. This outcome confirms the results of earlier studies by Sophocleous (1997), Bredehoeft (1997), and Şakıyan & Yazıcıgil (2004), in that the development of ground-water resources at safe-yield levels is *not* safe in the long term. Therefore, the management of water resources in the basin would require the use of sustainable yield rather than safe yield. Furthermore, the safe-yield concept ignores the other components of discharge from the system, such as base flow to streams and evapotranspiration losses. Besides pumpage, sustainable yield, however, allows an adequate provision of water to sustain streams, springs, wetlands, and ground-water dependent ecosystems. In order to determine the sustainable yield of the aquifer by considering base flow into streams, either the pumping rates of Scenario G or H should be used. In Scenario G, the annual pumpage is 168 hm^3/year, with almost no changes in ground-water levels from the current conditions and a decline of 21.5 hm^3/year in reserves that is insignificant when compared to Scenario A. The base flow under Scenario G is 19 hm^3/year greater than the value calculated under the safe-yield concept in Scenario B. In contrast, the annual pumpage in Scenario H is 128 hm^3/year, with a rise of 3.9 m in ground-water levels as compared to the year 2000 conditions and a rise of 2.7 hm^3/year in ground-water reserves. In addition, the base flow is 31 hm^3/year greater than the value calculated using the safe-yield concept in Scenario B. However, this increase in base flow is obtained with a marginal rise in ground-water 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 rates (Scenario A) are significantly greater than both the sustainable and safe yields of the system. Therefore, it is of utmost importance to develop efficient water-management policies and plans to prevent the eventual depletion of the aquifer system.

Conclusion

Alternative ground-water pumping scenarios explained above were developed to determine the safe and sustainable yields and the limits of utilization for the Ergene River basin Sandy Complex aquifer. As can be seen from the results of the ground-water pumping scenarios, the present annual ground-water 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, even 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 ground-water reserves and 28 m of decline in ground-water levels at the end of the planning horizon. Accordingly, the ground-water pumping costs would increase, the current wells in excessively dewatered areas would 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.

During the course of adopting management policies and plans, controls on new development, water metering on all wells, annual water-use reporting, water-conservation measures, artificial recharge structures and efficient irrigation schemes should be considered. Irrigation cooperatives should be encouraged instead of private irrigation so that uncontrolled drilling might be prevented. The public should also be involved by improving their perception of the problems related to ground water.

It should be noted that the simulated pumpage policies and their simulated outcomes are based upon average and deterministic system inputs (i.e., recharge from precipitation) and system parameters (i.e., hydraulic conductivity) that are subject to uncertainties due to their random nature. These uncertainties can be accounted for by using either of the two approaches: (1) deterministic simulation with sensitivity analyses; and (2) stochastic simulations. However, neither of these approaches are considered herein. Consequently, generated policies and outcomes should be accepted as guiding policies and average expected outcomes, respectively.

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References

BREDEHOEFT, J.D. 1997. Safe yield and the water budget myth. *Ground Water* **35**, 929.

DOUST, H. & ARIKAN, Y. 1974. The geology of the Thrace Basin. *Proceedings of the 2nd Petroleum Congress of Turkey*, 119–131.

DSİ 2001. *Ergene Havzası Hidrojeoloji Raporu* [Hydrogelogy of Ergene Basin]. Devlet Su İşleri Genel Müdürlüğü, Jeoteknik Hizmetler ve Yeraltısuları Dairesi Başkanlığı, Edirne [ubpublished, in Turkish].

EKMEKÇİ, M. 2005. Karst in Turkish Thrace: compatibilty between geological history and karst type. *Turkish Journal of Earth Sciences* **14**, 73–90.

GÖRÜR, N. & OKAY, A.İ. 1996. A fore-arc origin for the Thrace Basin, NW Turkey. *Geologische Rundschau* **85**, 622–668.

ITALCONSULT 1970. *Ergene River Basin Groundwater Development Project*. Master Plan Report: Volume 1: General Report, Volume 2: Outline of Hydrology and Meteorology, Volume 3: Geohydrology and Groundwater Resources, Rome.

KEMPER, K.E. 2004. Groundwater from development to management. *Hydrogeology Journal* **12**, 3–5.

KESKİN, C. 1974. The stratigraphy of the northern Ergene Basin. *Proceedings of the 2nd Petroleum Congress of Turkey*, 137–153 [in Turkish with English abstract].

MCDONALD, M.G. & HARBAUGH, A.W. 1984. *A Modular Three-Dimensional Finite-Difference Groundwater Flow Model,* U.S. Geological Survey Open-File Report, 83-875, USA.

OKAY, A.İ., SATIR, M., TÜYSÜZ, O., AKYÜZ, S. & CHEN, F. 2001. The tectonics of the Strandja Massif: late-Variscan and mid-Mesozoic deformation and metamorphism in the northern Aegean. *International Journal of Earth Sciences* **90**, 217–233

ÖKTEN, Ş. 2004. *Investigation of the Safe and Sustainable Yields for the Sandy Complex Aquifer System in Ergene River Basin*. MSc Thesis, Middle East Technical University, Ankara, Turkey [unpublished].

PERİNÇEK, D. 1987. Seismic characteristics of wrench fault zone in Thrace Basin. *Proceedings of the 7th Biannual Petroleum Congress of Turkey,* 11–21 [in Turkish with English abstract].

PERİNÇEK, D. 1991. Possible strand of the North Anatolian Fault in the Thrace Basin, Turkey – an interpretation. *Turkish Association of Petroleum Geologists Bulletin* **75**, 241–257.

SAKINÇ, M., YALTIRAK, C. & OKTAY F.Y. 1999. Paleogeographical evolution of the Thrace Neogene Basin and the Tethys-Paratethys relations at northwestern Turkey (Thrace) *Palaeogeography, Palaeoclimatology, Palaeoecology* **153**, 17–40.

SOPHOCLEOUS, M. 1997. Managing water resources systems: Why safe yield is not sustainable. *Ground Water* 35, 561.

SOPHOCLEOUS, M. 1998. *Perspectives on Sustainable Development of Water Resources in Kansas*. Kansas Geological Survey Bulletin 239, Lawrence, Kansas, USA.

SOPHOCLEOUS, M. 2000. From safe yield to sustainable development of water resources: the Kansas experience. *Journal of Hydrology* **235**, 27–43.

ŞAKIYAN, J. & YAZICIGİL, H. 2004. Sustainable development and management of an aquifer system in western Turkey. *Hydrogeology Journal* 12, 66–80.

TAPIRDAMAZ, C. & YALTIRAK C. 1997. Trakya'nın Senozoyik volkaniklerinin paleomanyetik özellikleri ve tektonik konumu [Palaeomganetic characteristics of Cenozoic volcanics in Thrace region and their tectonic significance]. *MTA Bulletin* 119, 27–42 [in Turkish with English abstract].

TURGUT, S. & ESELLER, G. 2000. Sequence stratigraphy, tectonics and depositional history in eastern Thrace Basin, NW Turkey. *Marine and Petroleum Geology* 17, 61–100.

TURGUT, S., TÜRKASLAN, M. & PERİNÇEK, D. 1991. Evolution of the Thrace sedimentary basin and its hydrocarbon prospectivity. *In*: SPENCER, A.M. (Ed), *Generation, Accumulation and Production of Europe's Hydrocarbons*. Special Publication of the European Association of Petroleum Geoscientists 1, 415–437.

YALTIRAK, C. 1996. Tectonic history of Ganos fault system. *Turkish Association of Petroleum Geologists Bulletin* 8, 137–156 [in Turkish with English abstract].

YAZICIGİL, H. & EKMEKÇİ M. 2003. Perspectives on Turkish ground water resources. *Ground Water* 41, 290–291.

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