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TECHNICAL ARTICLE

Assessment of Water Supply Impacts for a Mine Site in Western Turkey

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Abstract A nickel mine site located in western Turkey requires approximately 135 L/s of water for 15 years. To assess the potential impacts associated with meeting this water supply requirement, we determined alternative water resources, assessed the potential impacts associated with each resource, and selected the most feasible alternative, given the environmental and technical impacts. Three options were considered: surface water, groundwater, and treated wastewater. A low-flow analysis of Gediz River was conducted for the evaluation of using surface water. For the groundwater alternative, a three-dimensional numerical groundwater flow model of the Turgutlu-Salihli aquifer was established using MODFLOW so that the impacts of withdrawal on groundwater resources could be evaluated. The wastewater option was assessed based on the amount of wastewater generated nearby (in Turgutlu). It was determined that each option is capable of supplying the required water to the mine site. However, storage of the river water in a small dam in wet seasons for use in dry seasons and using treated wastewater would have less impact on existing water users and related ecosystems.

Keywords Gediz River · Groundwater numerical modeling · Mine water supply · Wastewater reuse

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Introduction

Water is an essential component of the mining process, though the amount and source of the water used varies. For example, in a study conducted in semi-arid Botswana, a combination of surface, ground, and waste water, and a variety of harvesting and delivery techniques were used to overcome general water scarcity and periods of drought (Rahm et al. 2006). Various methods can be used to assess the suitability of water resources, but as stated by Shelp et al. (2011), understanding the local water resources is essential.

We assessed the water supply impacts for a planned nickel mine that will be developed near the town of Turgutlu, on the southern slopes of Caldag Mountain, in western Turkey (Fig. 1). Before the start of mining operations, dewatering will be carried out to provide dry conditions in the deeper parts of the mine (Yazicigil 2008). Previous studies conducted during the environmental impact analyses phase by ENCON (2005) determined that 135 L/s of water would be required for 15 years for the mining process. Of that amount, they proposed that 100 L/s would be diverted from the Gediz River, which flows 9 km south of the mine site; the remaining 35 L/s would be pumped from the Salihli-Turgutlu aquifer system. A recent dry spell observed in western Turkey and the subsequent decrease in stream flows and increase on groundwater demands for irrigation purposes produced a need to reevaluate alternative sources and their potential impacts on local water resources. The scope of this study involved determining alternative water resources, assessing the potential impacts associated with each resource, and selecting the most feasible alternative. The three sources evaluated were surface water, groundwater, and the reuse of Turgutlu's domestic wastewater. A low-flow analysis of the Gediz River was conducted to evaluate the use of surface water. A Turgutlu-Salihli aquifer model was developed to evaluate the potential impacts of using groundwater resources. The reuse of treated wastewater from the town of Turgutlu was assessed based on the amount of wastewater generated.

Physiography, Climate, and Geological Setting

The 1,461 km^2 study area is located in the Aegean region and encloses the Turgutlu-Salihli part of the Gediz River Basin (Fig. 1), which is drained by the Gediz River and its tributaries. The study area is surrounded by Golmarmara Lake and ridges with altitudes ranging between 500 and 1,000 m in the north, by Demirkopru Dam and ridges with altitudes ranging between 200 and 400 m in the east, Menderes' metamorphic ridges, with altitudes ranging between 400 and 610 m in the south, and finally by the Karaoglanli district of Manisa and its ridges, with altitudes ranging between 700 and 900 m in the west.

The study area has a mild climate with soft verdant springs, hot and dry summers, sunny autumns, and warm winters marked by occasional showers. The Aegean region has many valleys between the mountains perpendicular to the shores due to graben plains, which permits the marine climate (very similar to Mediterranean climate) to reach inner parts of the region although some of the provinces inland show characteristics of a Continental climate.

Two State Meteorological Organization (DMI) meteorological stations (Turgutlu and Salihli) are located within the study area and four others (Saruhanli, Golmarmara, Akhisar, and Manisa) are located nearby (Fig. 1). Results of meteorological analysis indicate that the average annual temperature of these stations is 16.3°C. The coldest months are January and February, and the hottest month is July. The annual average relative humidity was calculated as 60%. The average annual evaporation is 1,377 mm. Maximum and minimum monthly average evaporations were observed in July and January, respectively. December is the wettest month and August is the driest month. The results of precipitation analysis show that a major wet period existed in the region between 1960 and 1982, which was followed by a long dry period between 1982 and 1996. The long-term annual average precipitation in the basin is 536.4 mm.

Because the study area is located in western Turkey, the main structural elements are normal faults, strike-slip

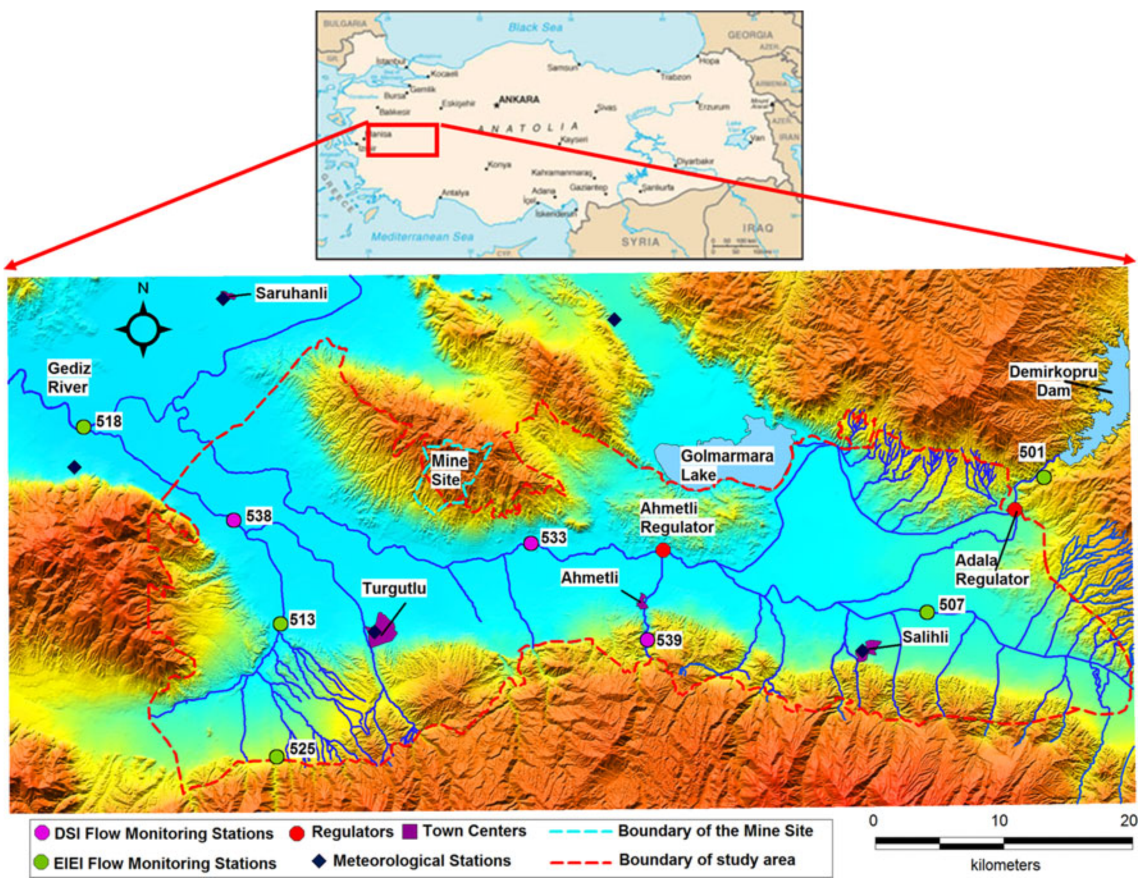

Fig. 1 Location of the study area

faults, reverse faults, overthrust faults and folds which started to develop with the closure of the Izmir-Ankara ocean in the Paleocene, continued with the development of graben in the Neogene; the faults continue to generate low-intensity earthquakes (Yazicigil 2008).

The dominant formations in the study area are Paleozoic, Neogene, and Quaternary units. The basement rock is the Paleozoic Menderes massive metamorphic strata, which consist of gneiss, mica-schist, quartzite, and marble (MTA 1995). The basement rocks crop out along the margins of the basin in the south and the north (Figs. 2, 3). Cakaldogan granite is observed in the southeastern part of the study area with a very limited outcrop. Cakaldogan granite includes plagioclase, quartz, chloritized biotite, partly chloritized hornblende, and a small amount of microcline (MTA, 1995). These series are overlain by Mesozoic aged Izmir-Ankara suture zone rocks with a tectonic contact. Limited and disconnected outcrops of Mesozoic formations are observed, mostly north and west of the study area (Fig. 2). Neogene units cover all of the sequence with an unconformity. They are represented by Miocene and Pliocene strata. Miocene units generally expand through the northern part of the Gediz Plain, generally north of the Manisa, Turgutlu, and Salihli Plains. The southern part of the study area is dominated by Pliocene units (MTA 1995). The upper layer of the study area is made up of Quaternary travertine and sediments carried by the Gediz River and its tributaries (Yazicigil 2008). The alluvium and alluvial fans are made up of rubble, gravel, sand, silt, and clay. Alluvium materials become finer from the hill sides to the Gediz River. In the northern part of the Gediz River in the study area, alluvium spreads over a small area whereas it is widespread in the south. Along the Gediz graben, the boundary between Quaternary and Neogene units is very sharp because of faulting. The Gediz River is closer to the northern boundary than the southern boundary. The southern part of the Gediz River is more mountainous than the northern part, so more sediments are carried by tributaries of Gediz River in the southern part, and the Gediz River has been shifted to the north.

Hydrology and Hydrogeology

The Gediz River is the major water resource within the study area. Nif, Taytan, Gumus, Kursunlu, Tabak, Sart, Ahmetli and Irlamaz are creeks that join the Gediz River (Fig. 1). The Gediz River enters the study area from the south of the Demirkopru Dam (Fig. 1). The Gediz River flows in an E-W direction and leaves the study area at the northwestern boundary. The Demirkopru Dam and its regulators (Fig. 1) are water structures on the Gediz River. There are seven flow monitoring stations located along the studied portion of the River and two located nearby (Fig. 1). Three of the stations are operated by DSI (State Hydraulic Works) while the rest are operated by EIEI (General Directorate of Electrical Power Resources Survey and Development Administration).

Golmarmara Lake is an artificial lake constructed by DSI with 367 hm^3 of storage capacity. It is located in the northern part of the Salihli (Fig. 1). The Demirkopru Dam, with a storage capacity of 1,320 hm^3, is the other surface water reservoir in the study area. It is located in the northeastern part of the study area (Fig. 1).

In the studied part of the Gediz River Basin, there are nearly 3,700 registered wells drilled by DSI, Bank of Provinces, municipalities, and individuals. Records (well logs, coordinates, yield, static-dynamic levels, lithologies

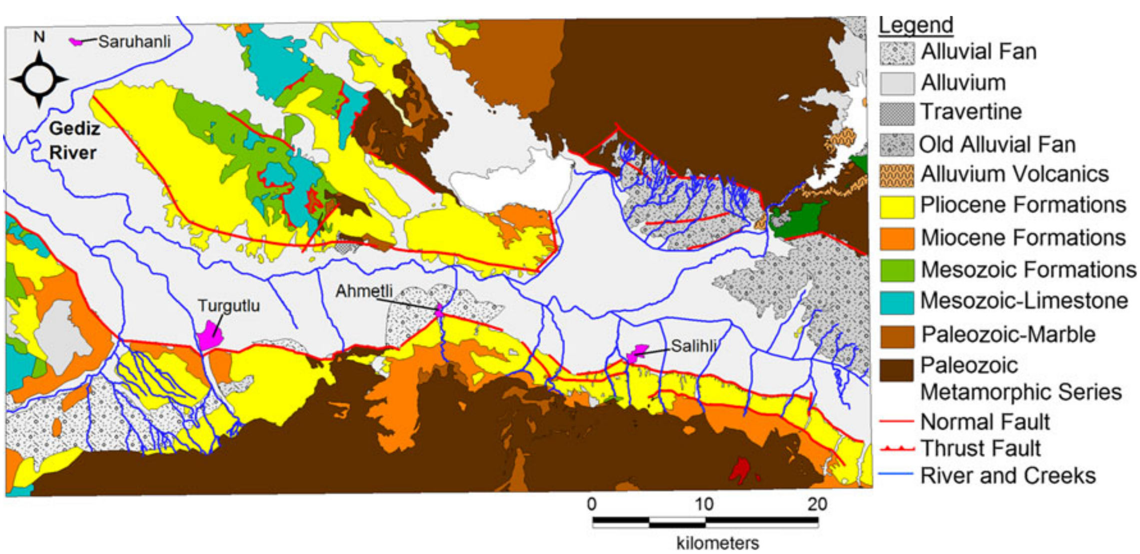

Fig. 2 Geological map of the study area (modified from DSI 1983, MTA 2005)

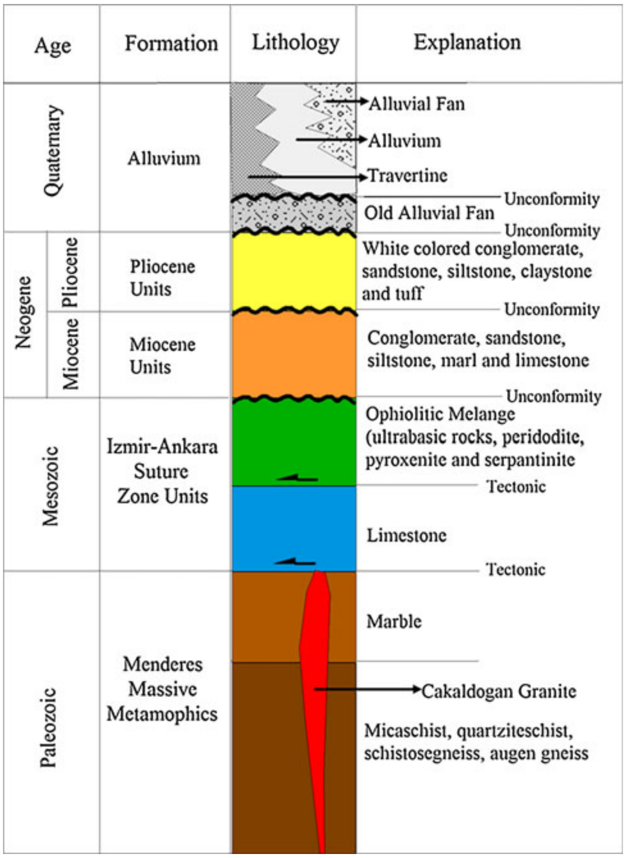

Fig. 3 Generalized columnar section of the study area (modified from MTA 1995)

for every depth, well bottom, screen data, etc.) were obtained from DSI for approximately 3,500 of these wells and analyzed. The density of wells in the study area is approximately 0.42 km^2 per well. Figure 4 shows the distribution of these wells in the study area. The number of wells drilled per year increased significantly after 1991. Most of these wells were drilled for irrigational purposes.

In the Gediz River Basin, the groundwater-bearing units are divided into four hydrogeological units: Paleozoic marble, Mesozoic limestone, Neogene formations, and Quaternary formations. A hydrogeological map of the Gediz River Basin is given in Fig. 4.

Paleozoic metamorphic units generally act as impervious units, with the exception of Paleozoic marble, which sometimes transmits groundwater. However, it is not expected to play an important role in the regional groundwater flow because it has a limited outcrop in the northern part of the study area and does not directly interact with the Salihli-Turgutlu main aquifer system.

Mesozoic limestone is the other groundwater bearing formation. It has small isolated outcrops in the north and west of the study area. Therefore, like the Paleozoic marble, Mesozoic limestone is not expected to play a major role in the regional groundwater flow.

Neogene-aged conglomerates and sandstones form the secondary aquifer in the study area and are colored yellow in Fig. 4. This unit is widespread in the southern and northern parts of the study area, and has a saturated thickness of approximately 400 m. The annual pumpage from the Neogene aquifer system for irrigation and drinking purposes is estimated to exceed 25 hm^3. Although several wells tap this aquifer, the data regarding its hydraulic properties are not available except for one well, which has a well yield of 3.7 L/s and a specific capacity of 0.43 L/s/m. The hydraulic conductivity of the formation is assumed to be half that of the Quaternary deposits, 2 m/day. Due to a lack of detailed information, a regional groundwater elevation map for the Neogene aquifer was not constructed.

Quaternary alluvium and alluvial fan deposits (colored blue in Fig. 4) form the principal aquifer in the study area. The lithology of the alluvium changes from rubble, coarse-grained gravel and sand to clay and silt from uplands toward the Gediz River. The saturated thickness of the Quaternary aquifer ranges between 5 and 305 m. There are numerous wells drilled into the Quaternary aquifer. Yields of the wells range in between 0.30 and 71.35 L/s; the average well yield is 29 L/s. Specific capacity of these wells range between 0.03 and 88.89 L/s/m; the geometric mean of the specific capacity is 3.30 L/s/m. According to pumping test results carried out by DSI, the transmissivity of the unit ranges between 20 and 7,952 m^2/day. Hydraulic conductivity values, determined from the transmissivities, range between 0.14 and 198.80 m/day. The geometric mean of the hydraulic conductivities was calculated as 4.00 m/day. The annual pumpage from the Quaternary aquifer system for irrigation and drinking purposes is estimated to exceed 100 hm^3.

Groundwater elevations in the Quaternary aquifer range from 120 m in the east to 30 m in the west (Fig. 4). In the eastern part of the study area, the Gediz River displays gaining characteristics, but in the western part, it is neither gaining nor losing. From east to west, the hydraulic gradient decreases.

Alternative Water Supply Sources

Three sources of water supply were initially considered individually to meet the required 135 L/s water for 15 years: (1) surface water, (2) groundwater, and (3) treated wastewater.

Surface Water

The first option considered as a source of process water was the Gediz River. ENCON (2005) had proposed that the mine should use a combination of surface water from the

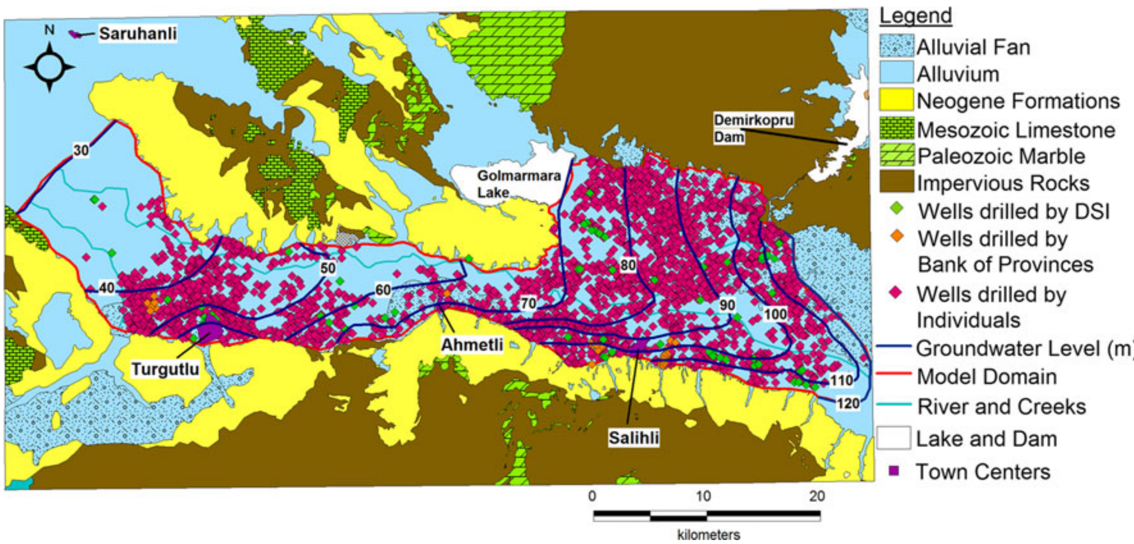

Fig. 4 Hydrogeological map the study area (groundwater levels of 1991)

Gediz River and groundwater from the Quaternary or the Neogene aquifer within the study area. In fact, the surface water extraction structure and the associated pipeline system have been already constructed. However, the recent drought has caused local farmers and governmental officers to raise concerns about using the Gediz River to meet the mine's water supply needs. Hence, it became essential to conduct low flow analyses of the Gediz River to assess the long-term availability of the river water supply. Four types of analyses were carried out: (1) flow frequency histograms and flow duration frequency curve for daily flows, (2) 1-, 7-, 15-, 30-, and 60-day low flow volume frequency curves, (3) low-flow duration frequency curve for a specified discharge value, and (4) longest low-flow duration frequency curve for a specified discharge value. In conducting this analysis, the daily flow data for a period of 13 years at Urganli Station (No. 533) was used because it was closest to the surface water extraction point (Fig. 1). Stream flow data available from the Urganli station (1983–2004) coincides with the dry period observed in the area (1982–1996). Although Station No. 518 has a longer period of data, its data reflects the combined flows derived from a number of tributaries that join the Gediz River downstream of the mine site. Hence, it was not considered in the analyses.

Flow Frequency Histogram and Flow Duration Frequency Curve

Flow frequency values for mean daily flows for a period of 13 years at the Urganli station indicates that the discharge is less than 2 m^3/s about a quarter of the time, between 2 and 5 m^3/s about a quarter of the time, and greater than 5 m^3/s the remaining half of the time.

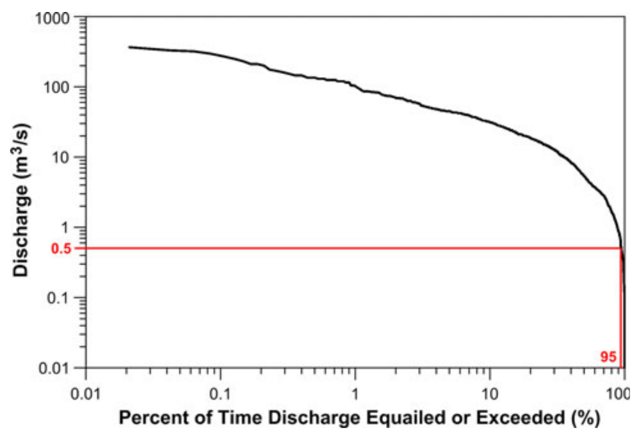

Fig. 5 Daily flow duration frequency curve for the Gediz River at Urganli (No. 533) station

Flow duration frequency curves are one of the most informative means of displaying the complete range of river discharges, from low flows to flood events (Smakhtin 2001). Flow duration curves are cumulative frequency distributions that show the percent of time that a specified discharge is equaled or exceeded during the entire period of record. Flow duration frequency for mean daily flows for a period of 13 years at Urganli station is shown in Fig. 5. The exceedence probability, Q_{95}, is one of the most commonly used indices for indicating extreme low flow conditions, a minimum flow to protect the river, licensing of surface water extractions, and effluent discharge limits assessments (Pyrce 2004). The exceedence probability can be interpreted as the flow discharge that can be expected to be exceeded 95% of the time. Thus, Fig. 5 shows that the Gediz River flow rates at the Urganli station exceeded 0.5 m^3/s 95% of the time.

Low Flow Frequency Curves

Low-flow volume (V) is defined as the minimum volume for a given time interval, *t*, within a specified time unit period (T_u), which in this study was a year of 365 or 366 days. The time intervals selected for the analyses were 1-, 7-, 15-, 30-, and 60-days. Low-flow volumes are expressed as the mean discharge for the time interval, t, or equal to V/t (Salas 1980). The frequency curves of low-flow volumes for the time intervals are shown in Fig. 6. For a specified time interval, the minimum volume of water was determined for each of the 13 years of data, and excedence probabilities were calculated.

Low Flow Duration Frequency Curves

Low-flow duration (D) is defined as the total time for which flows are smaller than a specified discharge (q_o) during a time unit period T_u. If for a given q_o and T_u, there are k times in which the flows fall below q_o with corresponding durations $d_1, d_2,\ldots, d_k$, then the low flow duration is $D = d_1 + d_2 +\cdots+ d_k$ (Salas 1980). The mean daily discharges for the Gediz River at Urganli station were used to find the series of low-flow durations. The specified discharge values (q_o) used in the analyses corresponds to the Q_{95} discharge value (0.5 m^3/s), as discussed above. Based on $T_u = 1$ year and $q_o = 0.5$ m^3/sec, total low flow durations for each year was calculated and exceedence probabilities were determined (Fig. 7).

Longest Low Flow Duration Frequency Curve

Longest low-flow duration (L) is defined as the largest of the low flow durations, i.e. $L = \max (d_1, d_2,\ldots d_k)$ (Salas 1980). Longest low-flow durations corresponding to the specified discharge of $q_o = 0.5$ m^3/sec were determined for each year and exceedence probabilities were calculated.

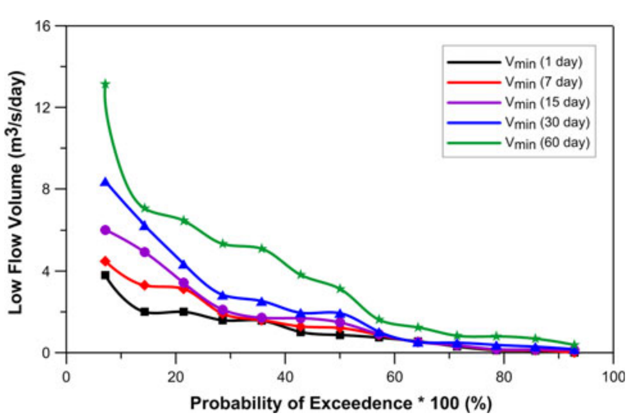

Fig. 6 Low flow frequency curves for the Gediz River at Urganli (No. 533) station

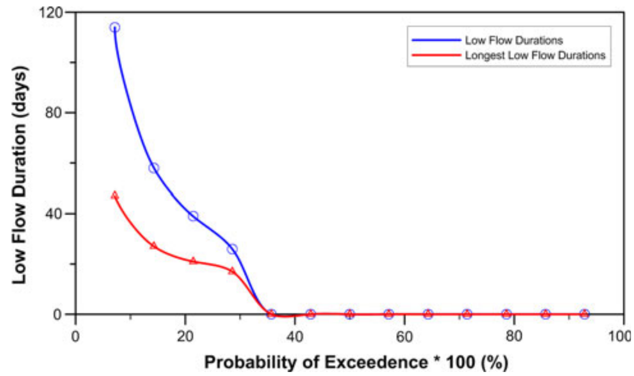

Fig. 7 Low flow duration frequency curves for the Gediz River at Urganli Station (No. 533)

The longest low-flow duration frequency curve for the Gediz River is shown in Fig. 7.

Discussion of the Surface Water Option

Evaluation of the Gediz River flow rates and the low flow analyses conducted indicate that the Gediz River should not be relied upon as the source of process water supply during the dry season (June through September), during which there is a relatively high (about 30%) probability that the flows would be less than the low flow requirements (0.5 m^3/s) for greater than 15 days. This analysis was based on 13 years of data, which did not include the dry spell that was encountered during the last few years. In fact, visual inspection during the short period of the current study showed that the Gediz River was completely dry for more than 60 days during the summer of 2008. Therefore, surface water cannot be the sole source of water required for the mining processes. Moreover, Gediz River water should be treated because it is highly polluted.

Groundwater

To evaluate this alternative, we initially assumed that all of the process water required for the mine would be extracted from the Turgutlu-Salihli aquifer. To that end, a numerical groundwater flow model, MODFLOW (Harbaugh et al. 2000) was established for the Turgutlu-Salihli aquifer system using Visual MODFLOW 2009.1 software, to assess locations for the pumping wells and their potential effects on wells used for domestic, industrial, and irrigation purposes.

Conceptual Model of the Aquifer System

Quaternary and Neogene units were simulated as two separate layers in conceptual modeling, as a result of detailed examination of aquifer properties and evaluation of data. Because of similar hydraulic properties, alluvium and old and young alluvial fans were considered as a single unit. Groundwater elevation and bottom elevation maps of Quaternary units were prepared using data from well logs and results of a geophysical resistivity survey carried out by DSI in (1972). Neogene units consist of Pliocene and Miocene formations. Due to the similarity of hydraulic properties of these formations, they were modeled as a single unit. No bottom elevation map of the Neogene strata was prepared because of the lack of data. However, based on the log of one well drilled by DSI to determine the basement of the aquifer, the thickness of the Neogene units was assumed to be 400 m throughout the whole model domain.

As observed in Fig. 2, although alluvium, alluvial fan, and Neogene deposits are widespread over the southwestern part of the study area along the Nif valley, this part of the study area was simulated within the Neogene aquifer because of a lack of information about groundwater elevations and bottom elevations for these alluvial units. In the rest of the area, Quaternary and Neogene units were characterized separately in the numerical model, the upper layer representing the Quaternary aquifer and the lower representing the Neogene aquifer. Both aquifers are recharged by precipitation where they outcrop and there is a hydraulic connection between them. The upper aquifer is also connected with the Gediz River, as depicted in the water table contour map (Fig. 4). It can be assumed that the conditions observed in 1991 represented pseudo steady-state conditions, before the development of an extensive irrigation network and the rapid increase in number of wells drilled by DSI, the Bank of Provinces, and individuals.

Development of the Groundwater Flow Model

The grid size for most of the model area was set at 75 × 75 m. A coarser grid (100 × 200 m) was used where there was a lack of information, especially near the boundaries between the Neogene and impervious units. The model consisted of two layers, the upper Quaternary aquifer and the lower Neogene aquifer.

Boundary conditions of the layers are given in Fig. 8. As can be seen from the groundwater elevation map (Fig. 4), flow from the northern and southern boundaries to the Quaternary alluvium was considered negligible except for a portion of the southern boundary along the contact between the Quaternary and Neogene units. That part of the boundary was simulated with a general head boundary condition whereas the other parts were assigned as a no-flow boundary. Eastern and northwestern boundaries were simulated by general head boundary conditions to simulate lateral inflows and outflows, since the Gediz River Quaternary aquifer extends beyond these boundaries. The small portion of the northern boundary of the model representing Golmarmara Lake was defined by a constant head boundary consistent with the 70 m average water level elevation at the lake.

For the second layer, the boundary between Golmarmara Lake and the Neogene units was again simulated by a 70 m constant-head boundary condition. General head boundary conditions representing recharge from the southwestern and eastern boundaries and discharge from the northwestern boundary were imposed. The boundary between the Neogene and Paleozoic units (the southern and northern boundaries) were assigned as a no-flow boundary because of the impervious nature of the Paleozoic units (Fig. 8).

The Gediz River and its most important tributaries (Alasehir Creek and Nif Creek) in the study area were simulated with the river package in the model (Fig. 8). In the model, the upper hydrogeological boundary is the groundwater table except near the Gediz River, and Alasehir and Nif Creeks. The lower boundary is the impervious Paleozoic rocks forming the basement rocks in the study area. Boundary conditions for and well locations in both layers are given in Fig. 8. Well Package was used to simulate groundwater extraction.

Hydraulic Parameters, Recharge and Discharge

Due to the regional nature of the model and the lack of spatially distributed data, uniform hydraulic conductivity values were assigned to the individual layers. The hydraulic conductivity value assigned to most of the Quaternary alluvium aquifer was 4 m/day, which represented the geometric mean of the hydraulic conductivities obtained from the pumping tests carried out by DSI. Alluvial fan deposits, being more permeable than alluvium, were assigned a hydraulic conductivity value of 8 m/day (Fig. 9). A hydraulic conductivity of 2 m/day was assigned to most of the Neogene units based on well yields and specific capacities. The alluvial system in the southwestern part of the study area drained by the Nif stream was included in the Neogene aquifer. To account for this, a different hydraulic conductivity value (2.26 m/day) was assigned to that part of the Neogene aquifer (Fig. 9), which was calculated using horizontal flow through the layered system. The vertical hydraulic conductivities for both layers were assumed to be one tenth of the horizontal hydraulic conductivity in that layer.

Recharge from precipitation is the most important source of groundwater recharge. Recharge from precipitation was determined as 89 mm/year, using the water balance approach, with evapotranspiration calculated using

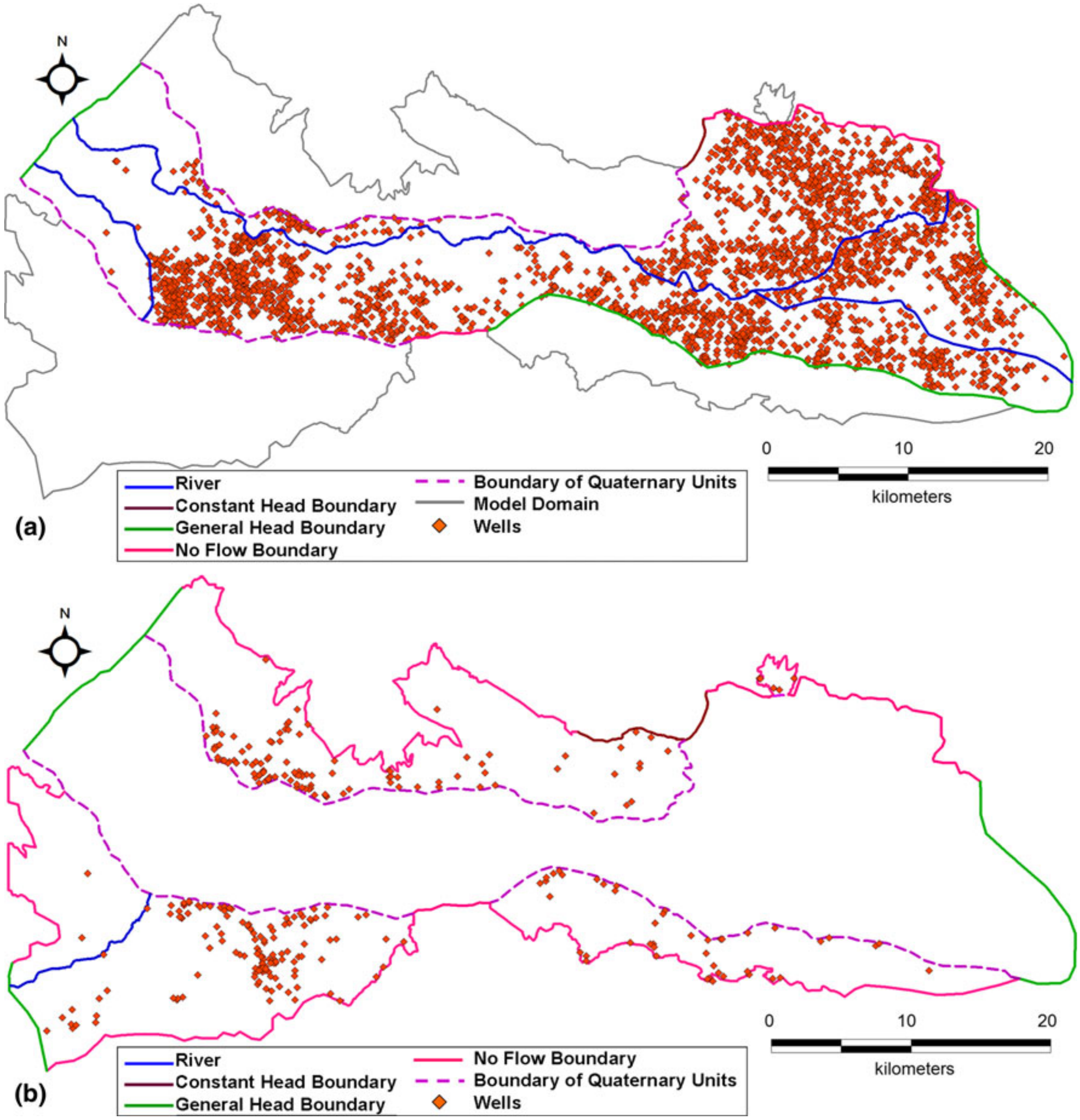

Fig. 8 Boundary conditions of **a** upper and **b** lower layers

the Thornthwaite method (Thornthwaite 1948). Additional recharge is derived from surface flow percolating through old alluvial fan material in the northeastern part of the study area from the upstream mountainous region. The amount of this extra recharge (51 mm/year) was calculated by determining the amount of surface flow that percolate through the old alluvial fan, the area of the mountainous region, and the area of the old alluvial fan (Fig. 9).

The amount of water extracted from the aquifers was calculated to determine total groundwater consumption. Groundwater in the basin is extracted for drinking, domestic and industrial uses, and irrigation. Well locations are shown in Fig. 8. Total groundwater extraction from these wells is summarized in Table 1.

Calibration of the Groundwater Flow Model

The model was calibrated under steady state conditions by assuming that the conditions in 1991 prior to significant development represented a pseudo-steady state in the aquifer system. Because of a lack of significant water level data for the secondary aquifer, calibration was mainly carried out for the upper layer. In the calibration step, the match of observed and calculated groundwater levels and consistency of the conceptual and calculated budget of the system were the primary criteria.

The goodness of the match between observed and calculated water levels was obtained by minimizing the root mean square error (RMS) at the locations of the

Fig. 9 Hydraulic conductivities of the calibrated model for **a** upper and **b** lower layers, and **c** recharge from precipitation calculated by Thornthwaite method, and the area showing where the extra recharge from surface flow is assigned

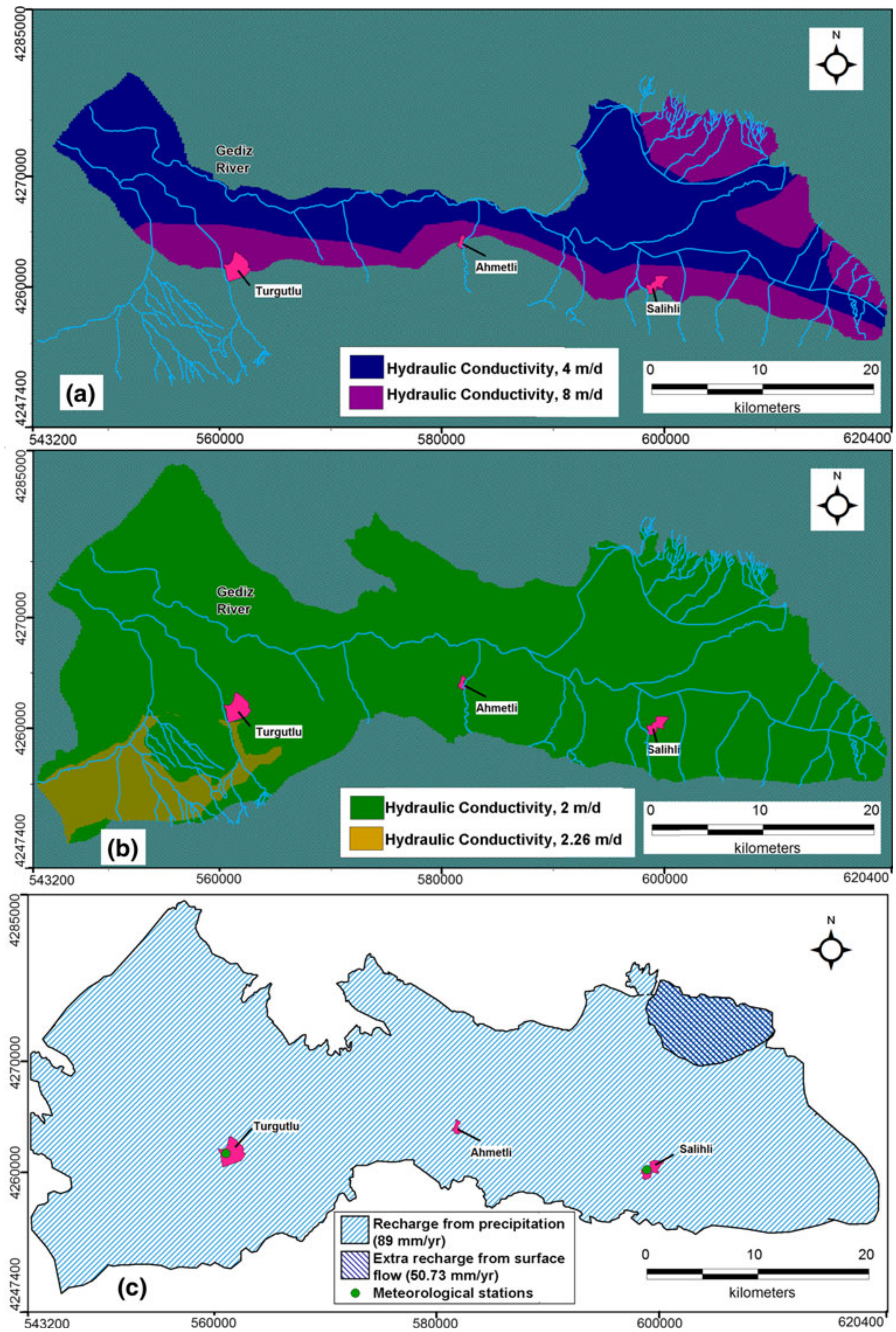

Table 1 Groundwater consumption

	Drinking, domestic and industrial purposes		Irrigational purposes		Total	
	m^3/day	hm^3/year	m^3/day	hm^3/year	m^3/day	hm^3/year
Quaternary units	30,761.0	11.2	264,916.0	96.7	295,677.0	107.9
Neogene units	27,397.3	10.0	42,767.1	15.6	70,137.0	25.6
Total	58,158.3	21.2	307,683.1	112.3	365,841.4	133.5

observation wells. The model was calibrated with an RMS value of 8.44 m and an RMS percentage of 9.87%. These error statistics are acceptable considering the regional nature of the model and the homogeneity of the input parameters used, and so it was concluded that there was a good match between the observed and calculated groundwater levels.

During the calibration step, the budget of the model was also compared with the budget prepared by DSI for the Turgutlu-Salihli aquifer system in 1983. The calculated water budget for the Quaternary aquifer system was comparable with the budget calculated by DSI, considering the areal and the timing differences between the two. The details of model calibration can be found in Agartan (2010).

Groundwater Pumping Scenarios

The calibration results indicate that the model is capable of simulating the pseudo-steady state conditions observed in 1991. New water supply wells have been drilled in the area after 1991 and most likely these wells have produced a transient state in the system since then. Ideally, using 1991 water levels as initial conditions, a transient simulation with discharge and recharge conditions observed since 1991 should have been conducted to derive a hydraulic head distribution as of today. Unfortunately, the lack of water level and storativity data precluded this approach. Hence, assuming that today's conditions also represent a new steady-state, another simulation was conducted accounting for the wells drilled after 1991. This simulation was necessary to provide a basis to analyze the impacts of alternative mine water supply wells on the aquifer system as well as on nearby users. The new steady-state head distributions obtained by the addition of wells drilled after 1991 are shown in Fig. 10 for the Quaternary and the Neogene aquifer systems.

The groundwater budget for today's steady state conditions for both the Quaternary and Neogene aquifers is given in Table 2. When the budgets of the calibrated model (1991) and the today's model are compared, it can be seen that the additional wells have increased recharge from the Neogene to the Quaternary aquifer in the southern boundary due to increased head loss between the two systems. Furthermore, there is a considerable decrease in the amount of water discharged from the Quaternary groundwater system into the Gediz River. For the Neogene aquifer, under-flow from Kemalpasa and recharge from the Gediz River are increased slightly. However, discharge of groundwater into Golmarmara Lake and Gediz River decreased.

After today's steady-state water levels were generated, the next step was to develop pumping scenarios for the 135 L/s of mine site process water, and evaluate the effects this would have on current well yields and the aquifers, using additional steady-state simulations. Two scenarios were set up: in the first scenario (A), it was assumed that all of the water was extracted from the Quaternary aquifer; in the second scenario (B), half of the water was pumped from the Quaternary aquifer and half from the Neogene aquifer.

In scenario A, four wells were hypothetically added where they would have the least impact on existing public and private wells and yet be close to the mine site. Each of the four was assumed to provide one quarter of the 135 L/s. In order to isolate the drawdown effects of the mine water supply wells, the steady-state water levels obtained from today's model (without the mine water supply wells) was assigned as initial head. The model was run under steady state conditions. The location of the scenario wells and the groundwater elevation map of the Quaternary aquifer are given in Fig. 11. Drawdown at the Quaternary aquifer caused by the four mine water supply wells is shown in Fig. 11. The effect of these wells on the Neogene aquifer was not significant.

In scenario B, it was assumed that half of the required water was extracted from the Quaternary aquifer and the remaining was supplied from the Neogene aquifer. To simulate this, two wells were hypothetically drilled into each of the aquifer systems. Discharges at the wells were kept uniform at a value of 33.75 L/s. The well locations were chosen based on the same criteria as in scenario A. The steady-state groundwater head distribution after the addition of the wells is given in Fig. 12. Drawdown maps of both the Quaternary and Neogene aquifers are shown in Figs. 12 and 13, respectively. Drawdown values range between 1 and 7 m.

Discussion of the Groundwater Option

The effects of each groundwater pumping scenario on the aquifer system were evaluated. For scenario A, the pumpage from the four wells created a large cone of depression extending many kilometers from the mine water supply wells (Fig. 11). Consequently, a large number of private wells (i.e. about 500) were affected. The drawdowns created at the private wells ranged between 0.5 and 3 m, and caused drawdowns less than 1 m at Turgutlu's water supply wells (Fig. 11). Impacts to the Neogene aquifer were negligible; therefore, drawdowns in this layer are not displayed.

In scenario B, the resulting cone of depression in the Quaternary aquifer extends nearly 5 km from the mine water supply wells, but is smaller than the one in the Neogene aquifer. Nearly 100 private wells in the Quaternary aquifer were affected (Fig. 12), and the maximum drawdown at these wells was 3 m. In the Neogene aquifer,

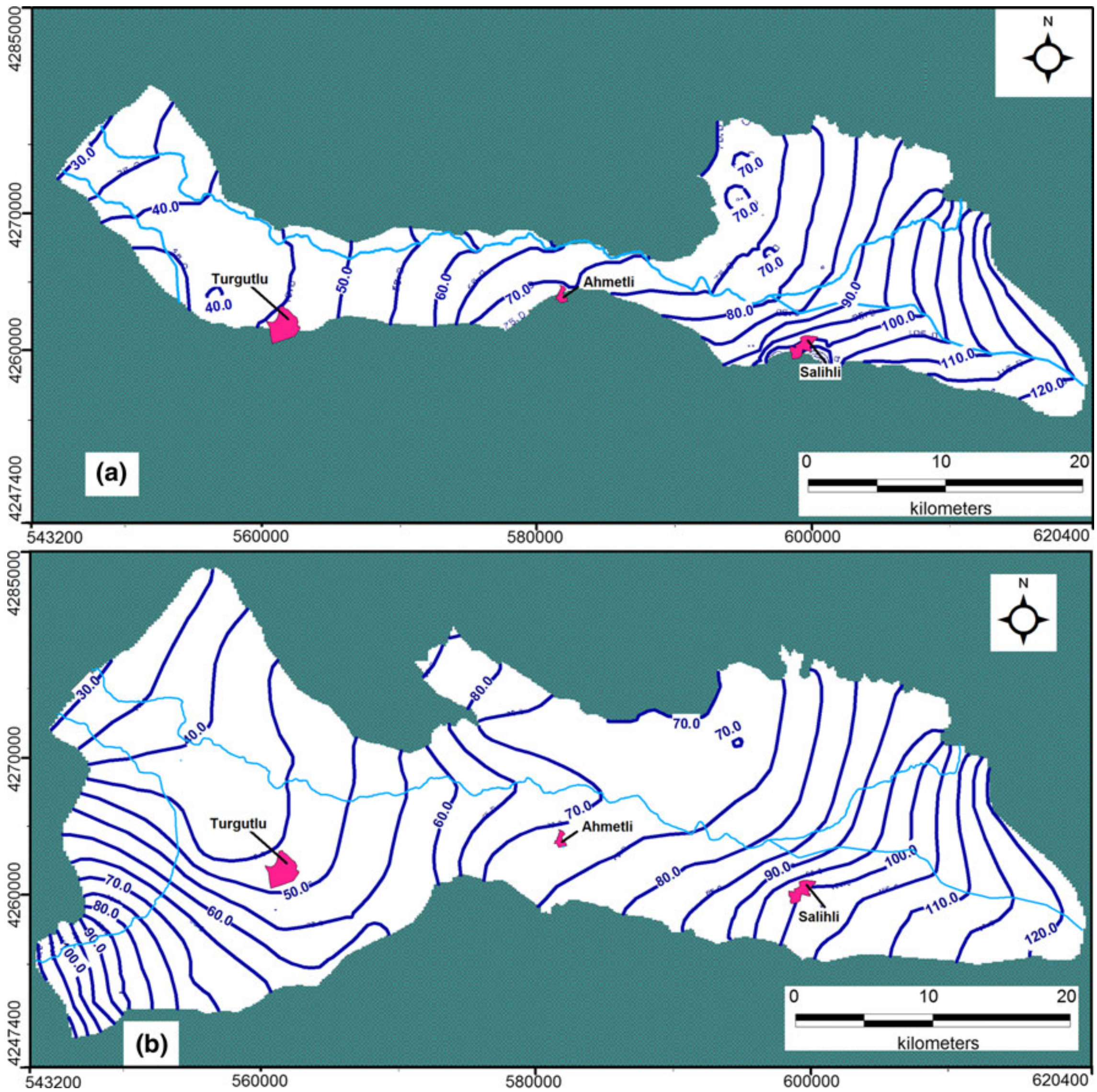

Fig. 10 Groundwater elevation map of the **a** Quaternary and **b** Neogene aquifers after the addition of wells drilled by DSI and Bank of Provinces after 1991 (today's groundwater levels)

approximately 50 private wells were affected by the mine water supply wells and the drawdown at private wells ranged between 1 and 4 m (Fig. 13).

Groundwater is a very vital resource for the people living in and around the study area in meeting their drinking and irrigation water needs due to its good quality. The results of scenarios A and B indicate that, given the large number of wells that would be influenced, the groundwater system should not be the sole water supply source for the mine site.

Reuse of Turgutlu's Wastewater

A third alternative is using treated wastewater. Currently, the town of Turgutlu (population 114,483) does not have a wastewater treatment plant and discharges its waste directly into the Gediz River. This is an important point source of pollution. Therefore, we evaluated the feasibility of using the town's domestic wastewater after treatment. Assuming a 250 L/day/capita water use, of which 80% turns into wastewater (Man-ar 2009), yields 265 L/s. This rate was checked using the total discharge from the ten wells supplying water to Turgutlu. The discharge of these wells totals 332.60 L/s, 80% of which turns into wastewater, giving 266 L/s.

Thus, the amount of available wastewater is approximately 265 L/s, which is almost twice the water requirement of the mine site. After treatment, according to the urban wastewater treatment directive published by the Ministry of Environmental and Forestry (2006), the

Table 2 Groundwater budget of both Quaternary and Neogene aquifers

Recharge (hm^3/year)		Discharge (hm^3/year)	
For Quaternary Aquifer			
Under flow from Salihli	27.75	Outflow from NW boundary	3.43
Recharge from rainfall	65.39	Wells	131.88
Recharge from Gediz River	7.68	Discharge to Gediz River	86.63
Recharge from Neogene to Quaternary in southern boundary	87.23	Discharge to Golmarmara	0.24
Flow from Neogene aquifer to Quaternary aquifer	73.78	From Quaternary aquifer to Neogene aquifer	39.65
Total recharge	261.83	Total discharge	261.84
For Neogene Aquifer			
Under flow from Salihli	7.94	Outflow from NW boundary	8.72
Recharge from rainfall	60.26	Wells	35.44
Recharge from Gediz River	2.17	Discharge to Gediz River	1.43
Under flow from Kemalpasa	12.91	Discharge to Golmarmara	3.39
Flow from Quaternary aquifer to Neogene aquifer	39.65	Flow from Neogene aquifer to Quaternary aquifer	73.78
Total recharge	122.94	Total discharge	122.77

minimum treatment efficiency of wastewater treatment plants should be 70–90% for biochemical oxygen demand (BOD_5), 75% for chemical oxygen demand (COD), and 70–90% for total suspended solids.

From an environmental and hydrogeological perspective, reuse of the treated wastewater appears to be the best alternative because neither surface water nor groundwater will be affected by the water used by the mine site. Furthermore, it will remove an important point source of pollution. However, technical and operational problems may be encountered in implementing this alternative for the 15 years of mine life, such as delays in the construction of the treatment plant, its operational costs, and the process water quality requirements. In any case, this alternative is very appealing and hence, its feasibility should be evaluated carefully.

Evaluation of Alternatives

Three alternative sources to meet the process water requirement of the mine site and their evaluation were explained in the preceding sections. The results indicate that neither surface water nor groundwater should be the sole source for the mine process water. In the environmental impact assessment report prepared for the Caldag Project by ENCON (2005), it was suggested that 100 L/s of the water would be provided from the Gediz River, and the remaining 35 L/s would be pumped from the groundwater system. This scenario was simulated with two different well designs (sub-alternative 1 and 2), which are explained below.

For sub-alternative 1, three wells penetrating the Neogene aquifer were added to the system to obtain 35 L/s of water. Discharges of two wells were set at 14 L/s each, while the other was set at 7 L/s. The resulting cone of depression extended nearly 3 km from the mine water supply wells. Drawdowns at the private wells in the Quaternary aquifer were negligible. However, the maximum drawdown at private wells in the Neogene aquifer was 2 m (Fig. 14). For the second sub-alternative, only one well with a discharge rate of 35 L/s was added to the Quaternary aquifer. The cone of depression extended less than 1 km from the mine water supply well. Maximum drawdown created by the mine water supply well was 2.5 m, but no private wells were affected (Fig. 14). It should be noted that the calculated drawdowns are average values over large cells and do not represent actual well point drawdowns. Although pumpage from the mine water supply wells would not significantly impact the existing wells, the scenarios mentioned in the ENCON (2005) report are not feasible because in dry seasons, 100 L/s water cannot be supplied from the Gediz River due to low flow requirements. As a result, the Gediz River can only be relied on to meet the water requirements of the mine site during wet seasons (October through May).

In dry seasons, the water should either be supplied from groundwater or from Gediz River water captured during the wet season in a storage reservoir with enough capacity to be used as a source of water in the dry season, or a combination of both. Therefore, the scenarios mentioned in the ENCON (2005) report were slightly modified, and sub-alternative 3 was developed. It was assumed that in wet seasons, 100 L/s of the water was supplied from the Gediz River and the remaining 35 L/s was obtained from pumping wells. For dry seasons, all of the required water was supplied from the groundwater system. Four wells, having same discharge rates, were added to

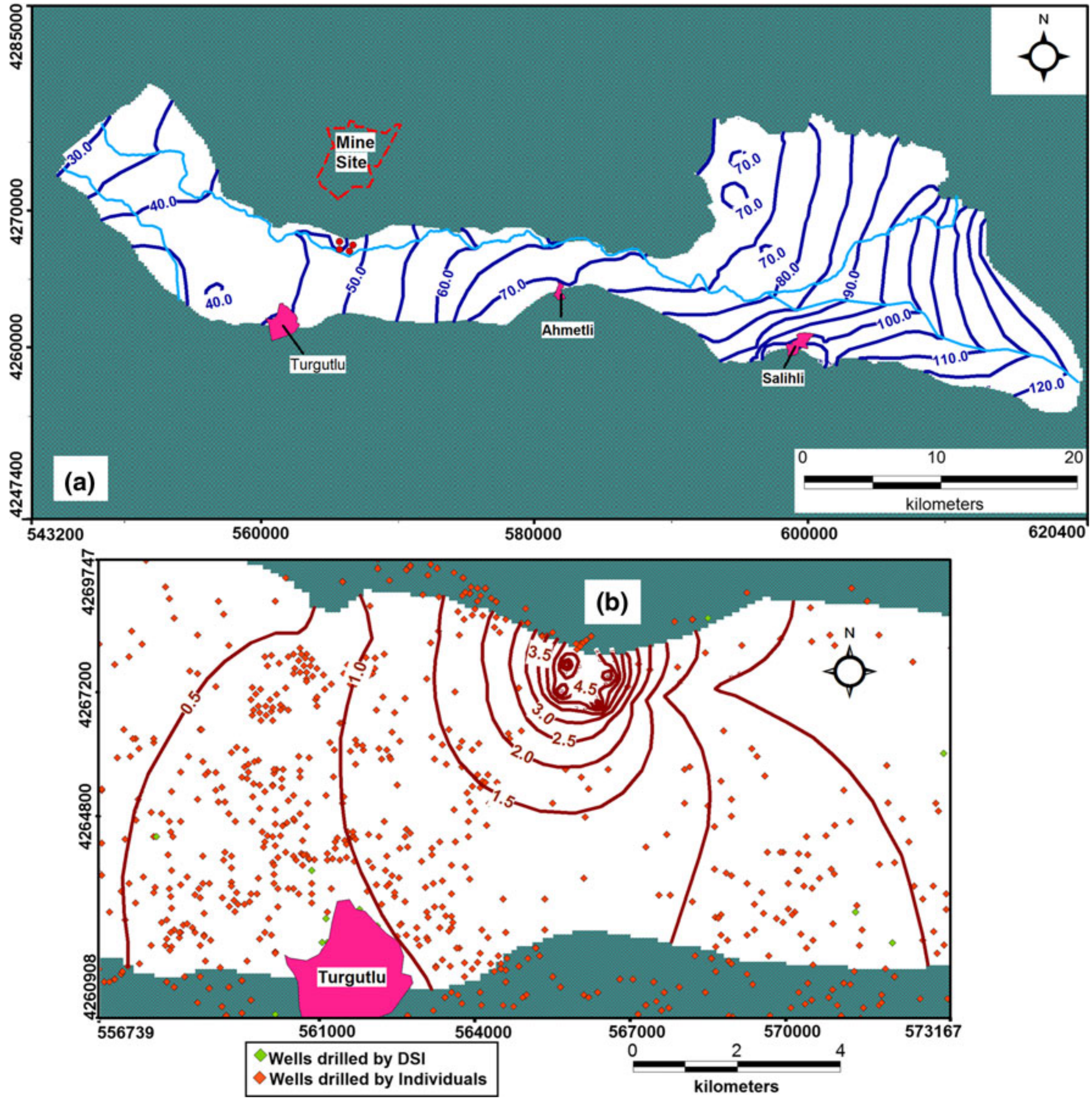

Fig. 11 Location of scenario wells, and **a** groundwater elevation **b** drawdown map of Quaternary aquifer for Scenario A

the system; two of them were in the Quaternary aquifer and the other two were in the Neogene aquifer. The extension of the cone of depression in the Neogene aquifer caused by these four wells was relatively larger than the one in the Quaternary aquifer (Fig. 14). Although the number of private wells in the Quaternary aquifer affected by the mine water supply wells was more than the ones in the Neogene aquifer, maximum drawdown calculated at each layer was no more than 2 m. Therefore, the mine water supply wells do not have significant impacts on the groundwater system and the existing wells. However, the usage of extensive amount of groundwater particularly in the dry seasons is the negative side because many people depend on the groundwater system in this season to meet their irrigation requirements. Hence, to eliminate the pumpage from the groundwater system, the alternative involving the storage of the Gediz River water was developed. This requires that a small dam with a capacity of 1,600,000 m^3 be constructed on the mine site to store the Gediz River water during wet seasons (October through May) and use the stored water later in the dry seasons (June through September). This seems to be the most feasible alternative because the ecosystem of the Gediz River will not be significantly affected and groundwater will not be used. However, the Gediz River water is highly polluted, so it may require treatment before mine use. Alternatives, description of each alternative, the amount of water pumped from surface water and groundwater, and evaluations of each alternative are summarized in Table 3.

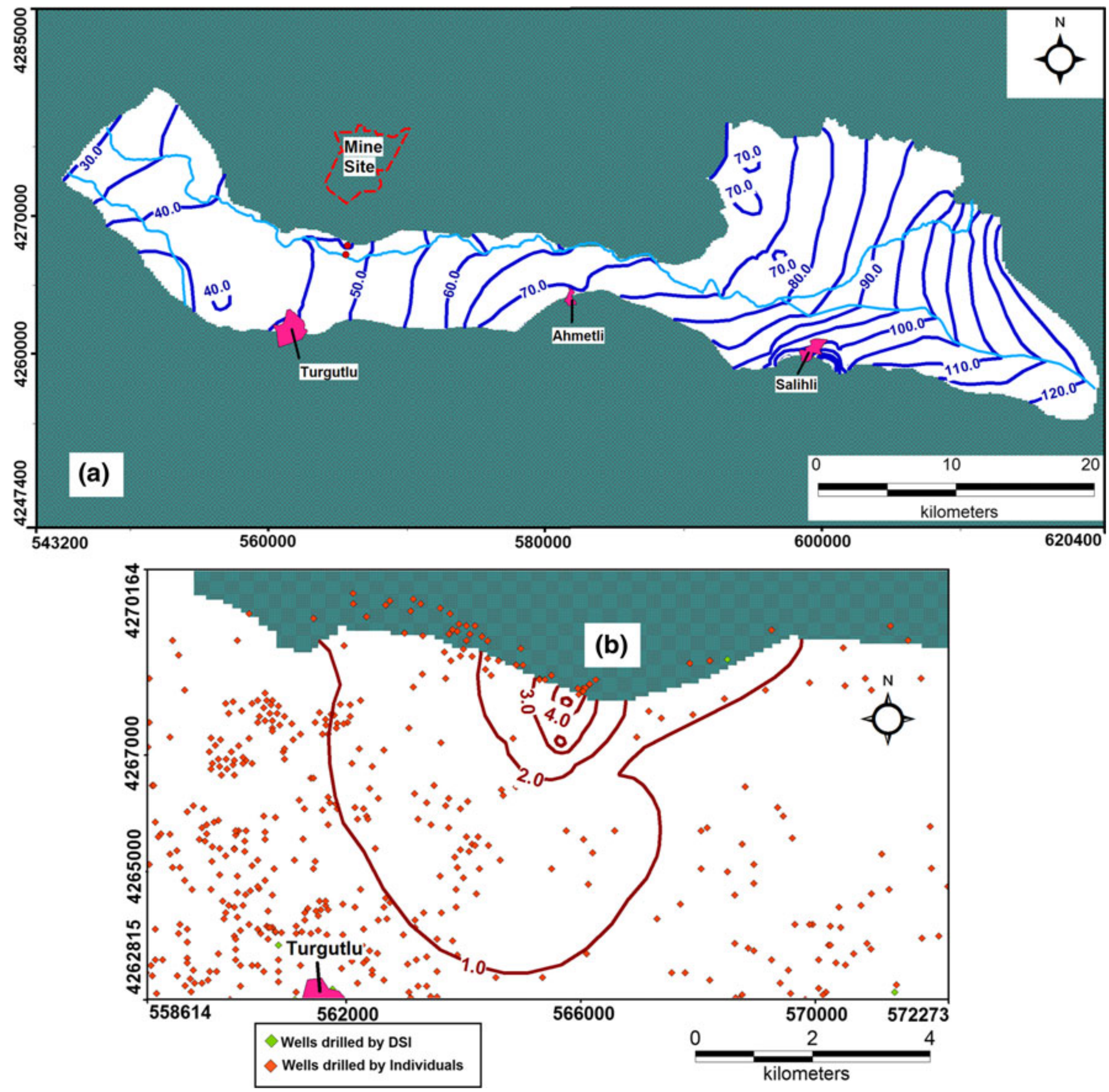

Fig. 12 Location of scenario wells, and **a** groundwater elevation **b** drawdown map of Quaternary aquifer for Scenario B

Summary and Conclusion

The aim of this study was to assess the impacts associated with meeting the water supply requirements for a mine site located in Turgutlu in Western Turkey. The scope of the study involved determining alternative water resources, assessing the impacts associated with each resource, and selecting the most feasible alternative.

To characterize the study area, all available data, including physiography, climate and meteorology, geology, hydrology, and hydrogeology were evaluated. Three alternative water supply sources were initially considered. First, a low-flow analysis was carried out using data from the nearby Urganli (No.533) station on the Gediz River to determine the volumes and duration of low flows. The results show that pumpage of surface water from Gediz River alone cannot meet the water requirement of the mine site, especially during dry seasons.

Second, to evaluate use of groundwater from the Turgutlu-Salihli aquifer, a groundwater flow model was developed, and two groundwater pumping scenarios were simulated. The results of these scenarios showed that pumpage from the groundwater system would affect numerous existing high quality water supply and irrigation wells, decreasing water levels by 1 to 7 m. Therefore, it should not be considered as the sole source of water for the mine site.

Third, it was determined that the quantity of wastewater generated in Turgutlu would, once treated, meet the water requirement of the mine site. Currently, this

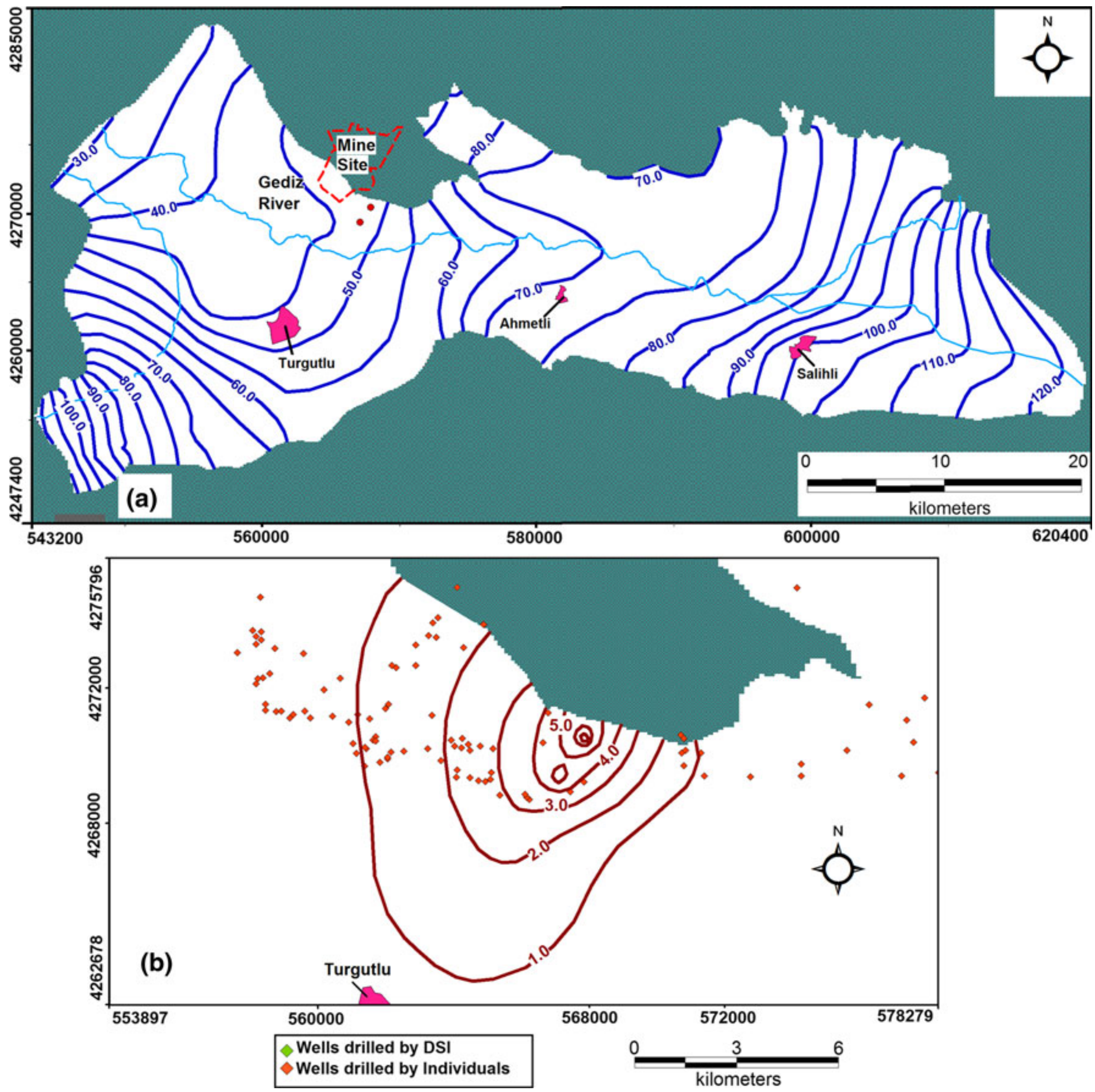

Fig. 13 Location of scenario wells, and **a** groundwater elevation **b** drawdown map of Neogene aquifer for Scenario B

wastewater is discharged, untreated, into the Gediz River. Thus, from an environmental point of view, this would be the best alternative because it would eliminate the current point source contamination and would not affect riparian water rights. However, there are potential operational problems that would have to be carefully considered.

As a result of these determinations, some other options were developed in which surface- and ground-water were used in various proportions. These sub-alternatives were also found not to be feasible because obtaining river water during the dry season would impact the Gediz River ecosystem. Therefore, during dry seasons, the source of water should be a combination of groundwater and Gediz River water stored during wet seasons. Constructing a small dam with enough capacity to store the water required for the mine site in dry seasons seems to be a feasible option because it would not significantly affect either the ecology of the Gediz River or groundwater, but the Gediz River water is highly polluted and may need to be treated.

In conclusion, various water supply options for a mine site near Turgutlu in Western Turkey were evaluated. Results show that each alternative could supply the required water to the mine site. However, constructing a small dam to store Gediz River water during wet seasons and subsequently using the water during dry seasons or constructing a wastewater treatment plant and reusing

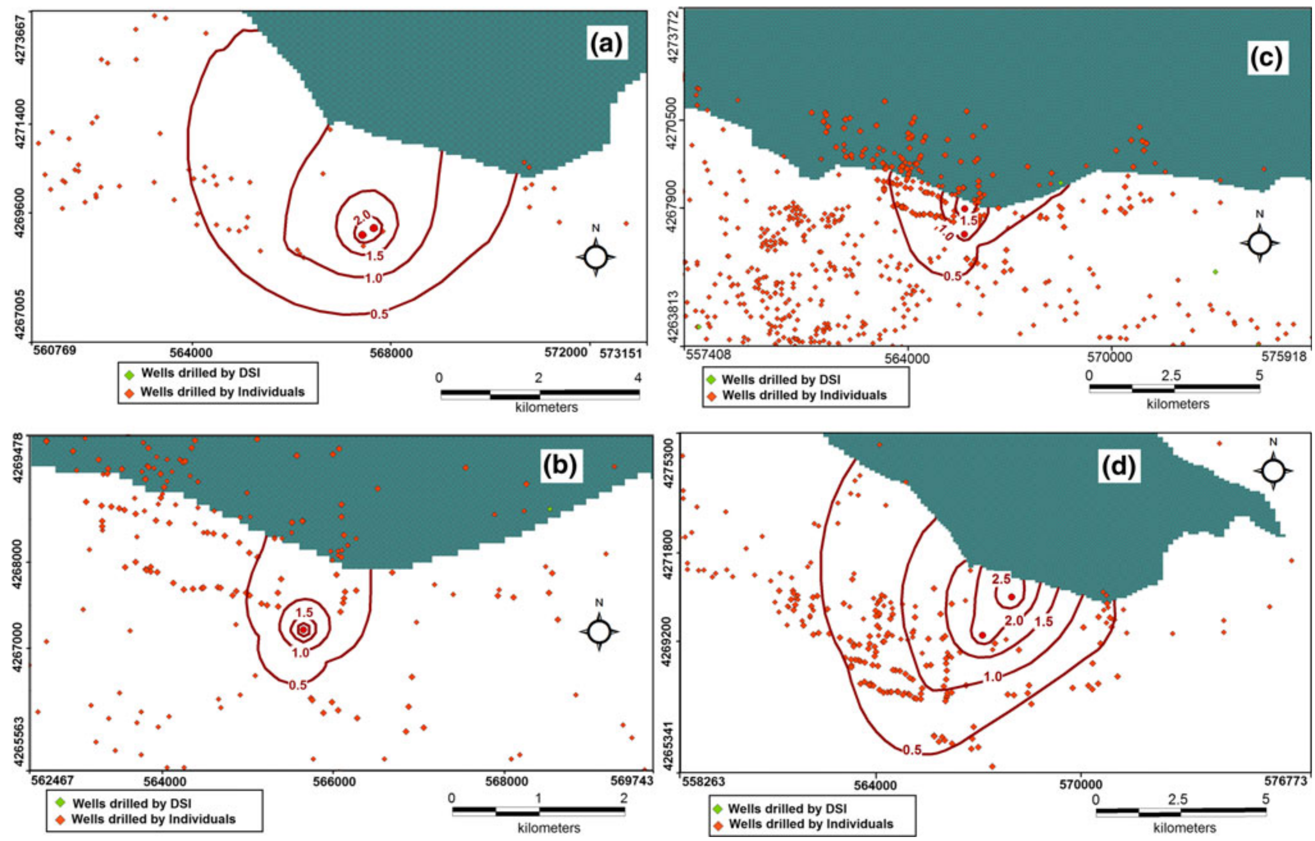

Fig. 14 Drawdown maps at **a** lower layer for sub-alternative 1 **b** upper layer for sub-alternative 2 **c** upper layer for sub-alternative 3 and **d** lower layer for sub-alternative 3

Table 3 Evaluation of all of the alternatives and sub-alternatives

Alternatives	Description	Pumped amount	Discussion
Gediz River water	Pumpage from the Gediz River for all seasons (135 L/s)	4.26 hm^3/year from Gediz River; 0 from groundwater	Negative effects on Gediz River ecology, especially during dry seasons; insufficient water to meet the mine site requirements during dry seasons
Groundwater	All of the water (135 L/s) from Quaternary aquifer	0 from Gediz River; 4.26 hm^3/year from groundwater	Negative effects on existing wells and groundwater system; groundwater quality good enough for drinking and irrigation purposes
	Half of the required water from Quaternary aquifer and half from Neogene aquifer	From Gediz River: 0; from groundwater: 4.26 hm^3/year	
Gediz River & groundwater	Sub-alternative 1&2: 100 L/s of water supplied from the Gediz River and 35 L/s from groundwater (suggested by EİA Report (ENCON 2005)	3.15 hm^3/year from Gediz River; 1.10 hm^3/year from groundwater	Negative effects on ecology of the Gediz River during dry seasons; groundwater quality good enough for drinking and irrigation; treatment required for the Gediz River water
	Sub-alternative 3: 100 L/s of water from Gediz River during wet seasons; all required water from groundwater in dry seasons	2.14 hm^3/year from Gediz River; 2.12 hm^3/year from groundwater	Groundwater quality good enough for drinking and irrigation purposes; treatment required for the Gediz River water
Storage of Gediz River water	Storage of water in small dam in wet seasons to be used in dry seasons (135 L/s)	4.26 hm^3/year from Gediz River; 0 from groundwater	Neither ecology of the Gediz River nor groundwater system affected; treatment required for the Gediz River water
Treated wastewater		4.26 hm^3/year from Turgutlu's wastewater	No effect on the Gediz River and groundwater system; decreased pollution of the Gediz River; potential technical and municipal problems

Turgutlu's wastewater are the alternatives that would least impact existing water users and related ecosystems.

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