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## Effects of the planned ephesus recreational canal on freshwater–seawater interface in the Selçuk sub-basin, İzmir-Turkey

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**Abstract** An artificial water canal opening is planned between the Aegean Sea and the historical Ephesus site for the sake of tourism in the Selçuk sub-basin. In order to predict the effects of the planned canal on freshwater–seawater interface and related contamination in the aquifer, 3-D numerical density dependent flow and solute transport simulations were carried out. The simulations included the pre-pumping and pumping periods without a canal and the prediction period in the presence of the canal. Chloride concentration comparisons of the results obtained from the pre-pumping period and the pumping period indicate that the freshwater-seawater interface in the aquifer has progressed inland due to artificial discharge in the sub-basin. Drawdown during the pumping period is about 15 cm. The planned canal opening

could further lower the groundwater levels in the area and would change the groundwater flow directions in the first 4 years. Then the levels and flow directions will nearly recover. However, the canal opening could cause further seawater intrusion into the aquifer to the extent that groundwater would be unfit to use for irrigation after the seventh year of the canal opening in the irrigation cooperative II wells area and would be unfit to use for drinking purposes after the tenth year in the municipality wells area located at the south of the cooperative II wells. On the other hand, the cooperative I wells would not be effected by the opening of the canal.

**Keywords** Salt-water intrusion · Density-dependent mass transport · Artificial canal · Turkey · İzmir · Selçuk

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### Introduction

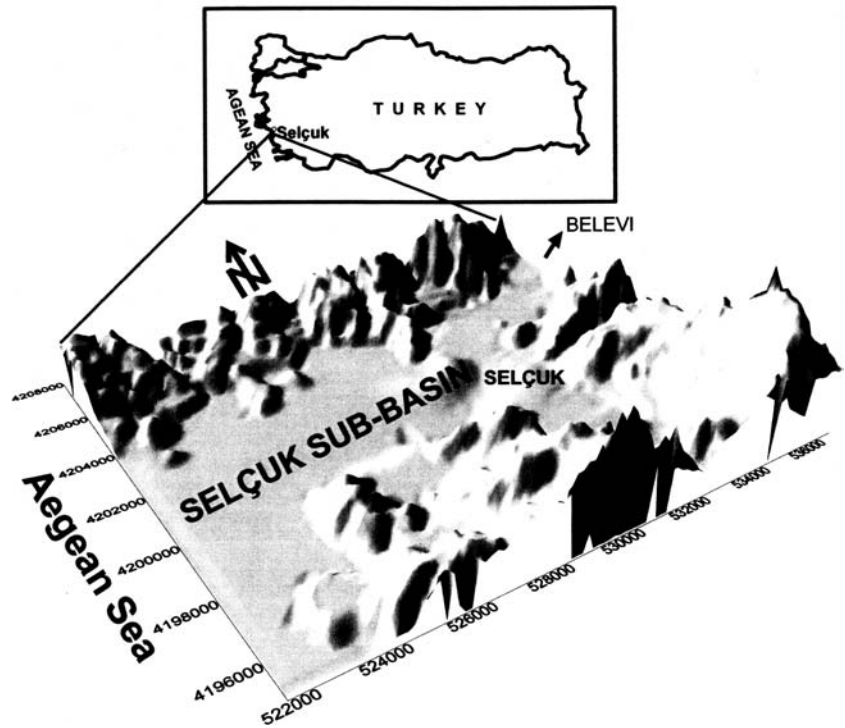
The Selçuk sub-basin plain, bounded by the Aegean sea in the west and by mountains from almost all other directions, is located in western Turkey (Fig. 1). The sub-basin is linked to the other sub-basins of the Küçük Menderes River Basin by a narrow valley through Belevi in the Northeast.

An artificial water canal opening is planned for purposes of tourism between the Aegean Sea and the historical ephesus site which lies at present about 6 km

inland in the Selçuk sub-basin. The location of the planned canal is shown in Fig. 2. The idea is to recreate historical conditions that existed in the seventh to third centuries BC for ephesus, which was a harbor city at that time (Erinç 1978). However, there exists a concern that such a canal construction may cause seawater intrusion in the sub-basin aquifer to the extent that groundwater resources, currently used for irrigation and domestic use in the area, will be contaminated.

The purpose of this study is to predict the effects of the planned canal on freshwater–seawater interface and

**Fig. 1** Location and elevation maps of the study area



related contamination in the aquifer through 3-D numerical density-dependent flow and solute transport simulations.

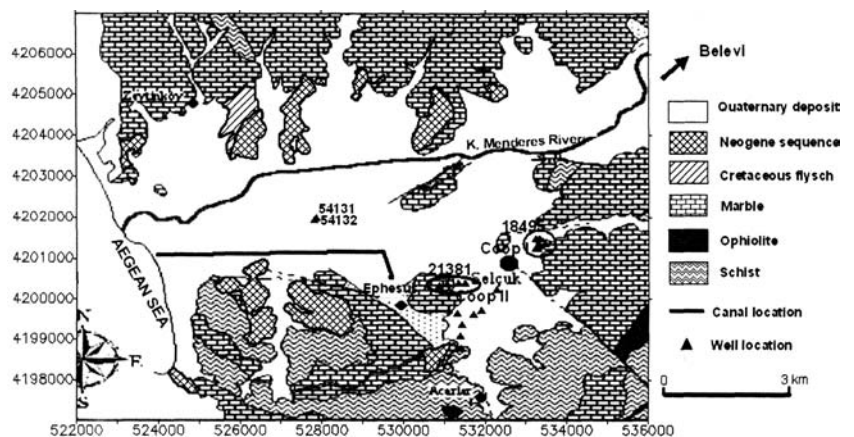
**Geology**

Geological characteristics of the Selçuk sub-basin summarized in this section are based on the work of Yazıcıgil et al. (2000b). Metamorphic rocks, the oldest rock unit in the study area, belong to highly metamorphosed rock complex called the Menderes massif. These basement rocks are overlain by either the Cretaceous Flysch,

and/or the Neogene sedimentary rocks and/or the Quaternary alluvial deposits as shown in the geological map of the study area (Fig. 2). The boundaries between the Cretaceous Flysch and the Neogene units are unconformable.

There are three main groups comprising the Menderes Massif complex in the study area: schist-phylites, ophiolitic rocks, and marbles, stratigraphically the youngest unit of the metamorphic sequence. The Cretaceous Flysch, which is generally characterized by a sequence of dark colored greywacke-conglomerate at lower parts, grades into gray, massive dolomitic limestones toward the top. The Neogene units are

**Fig. 2** Geological map of the Selçuk sub-basin. Coop I: irrigation cooperative I, Coop II: irrigation cooperative II. The coordinates are the UTM easting and northing



characterized by a sedimentary sequence grading from clastics to limestone. The quaternary sediments include alluvial fill and alluvial fans. The alluvial fill is the most widely distributed geological unit in the Selçuk sub-basin and is composed of alternations of clay, silt, sand, and gravel (Fig. 2).

## Hydrogeology

### Hydrogeological characteristics of units

Hydrogeological characteristics of the units in the study area were obtained from well logs of the State Hydraulic Works of Turkey and the Selçuk Municipality. Areal distribution of these wells in the sub-basin is shown in Fig. 2. Schists and ophiolites of the metamorphic complex are impervious rocks and do not show aquifer characteristics. Although the marble unit is a part of the metamorphic complex, the secondary porosity and permeability produced by the presence of fractures and solution cavities in some locations, make it a very productive aquifer. The intrinsic permeability of the marble unit ranges from  $0.22 \times 10^{-11} \text{ m}^2$  to  $497 \times 10^{-11} \text{ m}^2$  with an average of  $156 \times 10^{-11} \text{ m}^2$ . The marble unit has the highest average intrinsic permeability among all the other units present in the sub-basin. However the unit is permeable only at the southeastern section of the sub-basin.

There is only one well (no: 54132) which penetrates the Neogene unit groundwater in the sub-basin. The intrinsic permeability of the unit in this well location is about  $0.37 \times 10^{-11} \text{ m}^2$ . The intrinsic permeability of the Neogene unit in the other sub-basins of the Küçük Menderes River Basin ranges from  $0.24 \times 10^{-11} \text{ m}^2$  to  $2.4 \times 10^{-11} \text{ m}^2$  (Yazicigil et al. 2000a).

The alluvial fill deposits constitute the main unconfined aquifer in the sub-basin and cover the entire plain area. According to the wells located at the southeastern section where alluvium fans are present, the average intrinsic permeability is about  $0.8 \times 10^{-11} \text{ m}^2$ . The intrinsic permeability ranges from  $0.08 \times 10^{-11} \text{ m}^2$  to  $1.7 \times 10^{-11} \text{ m}^2$  in this area. In the alluvium fill, there is only one well (no: 54131) located at the middle of the plain of the sub-basin. The intrinsic permeability of the alluvial unit in this area is about  $0.38 \times 10^{-11} \text{ m}^2$  which is very similar to that of the Neogene unit in the same location. The intrinsic permeability of the alluvium unit

in the other sub-basins of the Küçük Menderes River Basin ranges from  $0.6 \times 10^{-11} \text{ m}^2$  to  $2.4 \times 10^{-11} \text{ m}^2$  (Yazicigil et al. 2000a). The storativity data in the area are scarce. The available data indicate specific yield of 0.1 for alluvial deposits and 0.4 for the marble units at the southeastern section.

### Recharge

The Selçuk sub-basin is located in the Aegean Sea climatic zone where it is hot and dry in summer and mild and rainy in winter. Data collected at the Selçuk meteorological station in the last 40 years indicate that annual means of temperature, precipitation, pan evaporation and humidity are about  $16^\circ\text{C}$ , 688 mm, 1,344 mm, and 63%, respectively. Monthly distribution of average precipitation determined by Gündoğdu (2000) are listed in Table 1.

State Hydraulic Works (1973) reports total of  $8 \text{ hm}^3$  net precipitation recharge to the sub-basin. Average precipitation net recharge to the aquifers in the Selçuk sub-basin was also calculated by Gündoğdu (2000) based on the hydrological budget method using data collected between the years of 1970 and 1995. In this work,  $8 \text{ hm}^3$  net recharge was reported for  $71.8 \text{ km}^2$  plain area and  $6 \text{ hm}^3$  net recharge was reported for  $205.6 \text{ km}^2$  highland area of the sub-basin.

Additional recharge to the sub-basin aquifers takes place from the neighboring Bayındır-Torbalı sub-basin at the northeast. Groundwater flow flux of  $5.567 \times 10^3 \text{ m}^3$  /day to the Selçuk sub-basin alluvial aquifer was reported by Yazicigil et al. (2000a). The K. Menderes River equipotential lines and base flow calculations suggest a very low-level flow interaction between the river and groundwater in the study area.

### Artificial discharge

Artificial discharge of groundwater in the sub-basin has been continued for irrigation and domestic water supply since late 1970's. Wet season (Nov–Apr) and dry season (May–Oct) discharges per  $\text{km}^2$  area are calculated as 1 kg/s and 16.7 kg/s, respectively for irrigation using the plant irrigation water need of Nippon 1996. Since 1978, irrigation water at the southeastern section of the sub-basin has been supplied to 240 ha area using the

**Table 1** Monthly mean precipitation values in the Selçuk sub-basin (Gündoğdu 2000)

|                    | January | February | March | April | May  | June | July | August | September | October | November | December |
|--------------------|---------|----------|-------|-------|------|------|------|--------|-----------|---------|----------|----------|
| Precipitation (mm) | 116.8   | 103.6    | 88.8  | 49.7  | 24.8 | 7.2  | 1.6  | 1.8    | 15.0      | 41.2    | 89.0     | 149.0    |
| (Percentage)       | 17      | 15       | 13    | 7.2   | 3.6  | 1    | 0.2  | 0.2    | 2.2       | 6       | 13       | 21.6     |

irrigation cooperative I wells (18495, 20045, 20046, and 20047) (Fig. 2). In the year 1989, the cooperative II wells (21381, 24853, 24854, and 24855) were also added to the discharge to irrigate 185 ha additional area at southeast. Irrigation water needed at the northern section of the sub-basin is pumped out using private wells in limited areas.

Municipality water discharge is reported to be 82.2 kg/s for the year of 1997 (Yazicigil et al. 2000a). Eighty-five percent of this need is pumped out in the dry season and the remaining is pumped out in the wet season from wells located at the southeastern section of the sub-basin near the cooperative wells. Although there is no industrial discharge in the sub-basin, some establishments (e.g. gasoline stations, slaughter house, fire department) located at the southern section pump out groundwater from the alluvium unit especially during the dry season through their private wells whose discharge amounts are unknown.

### Hydrochemistry

The electrical conductivity (EC) of groundwater in the sub-basin increases toward the shoreline. The EC values of the composite well waters from the depth interval of 30–80 m depth range from 700  $\mu\text{S}/\text{cm}$  to 3,000  $\mu\text{S}/\text{cm}$ . Depthwise EC profile measurements were carried out from well waters of 54131 and 54132 in May 2002 (Fig. 3). Both profiles indicate the existence of saltwater interface in the alluvium and Neogene units at the well locations. As it can be seen from the fig, the EC values in the alluvium unit groundwater (well no: 54131) increase steadily from 2,250  $\mu\text{S}/\text{cm}$  to 5,000  $\mu\text{S}/\text{cm}$  down to a depth of about 90 m. Then, the values increase sharply from 5000  $\mu\text{S}/\text{cm}$  to 30,000  $\mu\text{S}/\text{cm}$  between the depths of 90 m and 115 m. The values level up again and reach to about 37,000  $\mu\text{S}/\text{cm}$  at a depth of 150 m. Well water of 54131 was also sampled at depths of 65 m, 110 m, and 140 m in May 2002. Chloride concentrations measured in these samples are 855 mg/l, 3,660 mg/l and 14,120 mg/l, respectively. The EC values in well water of 54132, filtering the Neogene unit groundwater only at depth interval of 160–270 m, is between 10,000  $\mu\text{S}/\text{cm}$  and 11,000  $\mu\text{S}/\text{cm}$  down to the depth of 84 m. Then, the values increase sharply to about 25,000  $\mu\text{S}/\text{cm}$  at the depth of 85 m. Steadily increasing EC values down to the depth of 105 m reach to 38,000  $\mu\text{S}/\text{cm}$  between 105 m and 110 m (Fig. 3).

The EC of the Küçük Menderes River is about 1,522  $\mu\text{S}/\text{cm}$  which is about the average EC of the sub-basin groundwaters. The EC of the Kazancı spring, situated in the marble unit at the northwest corner of the sub-basin nearby Zeytinköy village about 2 km away from the shoreline, is about 5,750  $\mu\text{S}/\text{cm}$ , indicating high

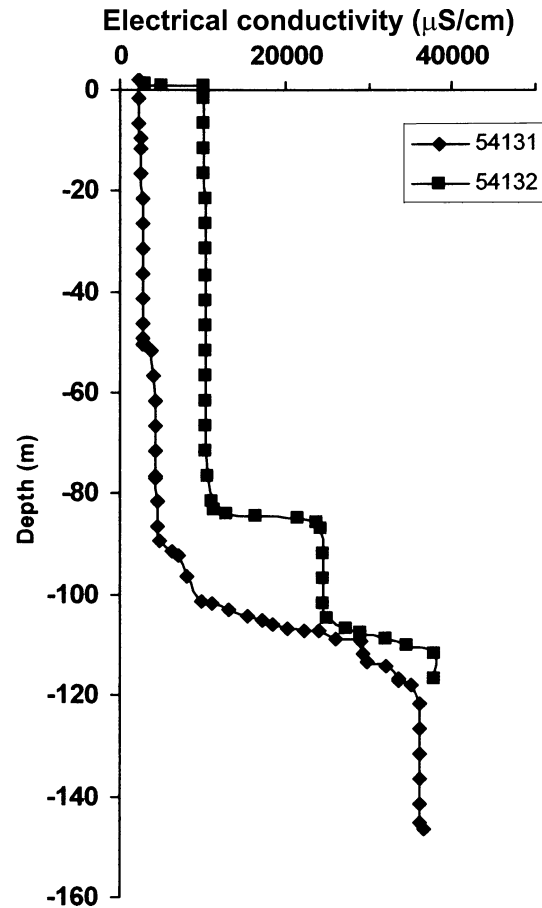


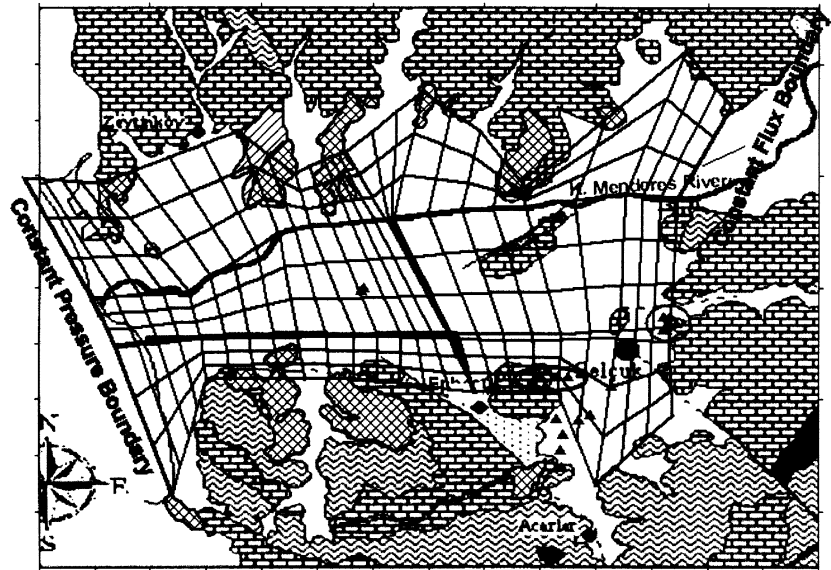
Fig. 3 Observed electrical conductivity profiles in wells 54131 and 54132 in May 2002

salinity in comparison to the salinity of groundwater pumped out from the wells in the sub-basin. Annual mean amounts of the EC and chloride in the Aegean seawater is 56,725  $\mu\text{S}/\text{cm}$  and 22,262 mg/l, respectively (Tarcan 1989).

### Numerical model

The effects of the canal on the freshwater–seawater interface in the sub-basin aquifer were simulated using density-dependent 3-D saturated flow and solute transport numerical model using SUTRA software of Voss (1984) and Voss and Provost (2003) in Argus One graphical user interface environment. Such prediction simulations require present groundwater level and solute distributions to be known in the area. In order to calibrate the model to present conditions, two sets of calibration simulations were carried out covering the pre-pumping period and pumping period. During the pre-pumping simulations no artificial discharge was assigned to the model domain.

**Fig. 4** Areal view of the 3-D model mesh and model boundary conditions



### Conceptual model

The domain of the model covers plain area of the sub-basin as shown in Fig. 4. The Marble, Neogene, and Alluvium units in this plain area are treated as a single aquifer having different hydrogeological characteristics. Thickness of the aquifer is 270 m (thickness of the Alluvium plus the Neogene units as determined from the well logs of 54131 and 54132) plus the topographic elevation at a given location. The aquifer is subjected to precipitation recharge in the domain area. Along the northeastern side, influx occurs from the neighbouring Bayındır-Torbali sub-basin. There is no flow relation between the modeled aquifer and the impermeable marble units composing highlands along the northern and southern boundary of the domain. It is also assumed that no flow relationship exists between the Küçük Menderes River and the aquifer modeled as suggested by Yazıcıgil and others (2000a).

### Discretization of the domain and boundary conditions

Three dimensional irregular finite element mesh was created in the domain (Fig. 4). Depth discretization of the aquifer is about 10 m. Widths of the elements at the locations of the planned canal were taken as about 40 m. Total number of elements and nodes present in the mesh are 7722 and 9072, respectively.

Three types of flow boundary conditions were used in the model: (1) constant pressure boundary, which is assigned along the western boundary of the domain where shoreline is present extending down to the depth of  $-270$  m (Fig. 4), (2) constant flux boundary, which is assigned to the northeastern boundary representing the

recharge from the Bayındır-Torbali sub-basin extending down to a depth of  $-270$  m (Fig. 4), (3) no flow boundary, which is assumed to exist along northern, southern and bottom boundaries of the model domain.

### Aquifer parameters

Permeability, porosity, water compressibility, solid matrix compressibility, molecular diffusion coefficient, dispersivity and recharge values used in the model are listed in Table 2. The value of solid matrix compressibility is so chosen that the value of specific yield becomes about 0.1–0.3, as suggested by the well data. Molecular diffusion coefficient of chloride in fluid is determined from the literature (Rowe et al. 1988; Baron et al. 1989; Voss and Andersson 1993). The parameters governing magnitude of dispersion were fixed at the minimum possible value that give stable solutions to the transport equation for the mesh used.

### Pre-pumping period calibration

In the beginning of the pre-pumping period runs, representing no artificial discharge conditions, the whole aquifer was assumed to be saturated and related hydrostatic pressure condition is assigned as initial pressure condition. Initial chloride concentration is assumed to be zero in the aquifer.

The pre-pumping calibration runs were carried out for 100 years with one month time increment using 10 year output option. It is observed that pressure values practically do not change after about 80 years. In these runs, observed versus calculated pressure

**Table 2** Parameters used in the model

| Parameter                                      | Value  | Unit        |
|--|--|-------------|
| Intrinsic permeability                         | $0.08 \times 10^{-11}$ – $1.0 \times 10^{-10}$ | $m^2$       |
| Porosity                                       | 20–25  | %           |
| Total recharge                                 | 94   | kg/s        |
| Molecular diffusion coefficient of Cl in fluid | $7.0 \times 10^{-10}$                          | $kg/m^3$    |
| Dispersivity (longitudinal)                    | 15   | m           |
| Dispersivity (transverse)                      | 1.5  | m           |
| Water compressibility                          | $4.47 \times 10^{-10}$                         | $1/kg/ms^2$ |
| Solid matrix compressibility                   | $2 \times 10^{-7}$ – $7.0 \times 10^{-8}$      | $m^2/N$     |
| Seawater chloride concentration                | 0.0225   | kg/kg       |

**Table 3** Average discharge values used in the pumping period runs

| Total average discharge kg/s | Period            |
|------------------------------|-------------------|
| 42                           | 1976–1977         |
| 98                           | 1978–1988         |
| 143                          | 1989–1990         |
| 155                          | 1991–Oct 2001     |
| 16.8                         | Nov 2001–May 2002 |

comparisons were performed by calibrating permeability and recharge values. Groundwater level measurements representing the pre-pumping period are only available from wells 18495 and 21381 (Fig. 2). Comparison of the observed and simulated groundwater levels at these well locations are 1.81–1.67 m and 1.80–1.65 m, respectively. The simulated head values are about 15 cm lower than the annual average of the observed values.

Because the pre-pumping period chloride concentration data for the aquifer are not available, no calibration

was performed related to the solute transport parameters (dispersivity, molecular diffusion coefficient) during the pre-pumping period simulations. Concentration calibration was carried out later in the pumping period runs.

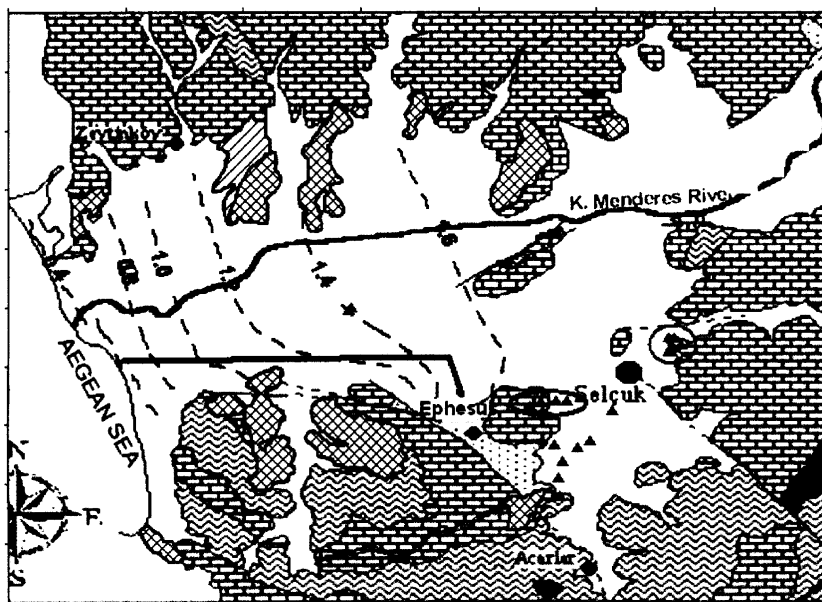
### Pumping period calibration

The discharge values based on irrigation and domestic water needs were determined for the pumping period runs and are summarized in Table 3. Domestic need discharge for a given period was approximated using population versus discharge relationship based on 1997 population and municipality discharge data. The discharge is assigned to the area at the southeastern section of the sub-basin where pumping wells are located. Discharge occurs at a depth interval of 30–75 m, representing filter depths of the pumping wells. Chloride dispersivity and storativity values were calibrated during the pumping period runs. The pumping runs were carried out in monthly increments by taking into account the changing discharge conditions in the sub-basin between the years of 1975 and 2002.

Groundwater level distribution obtained at the end of the pumping period runs is shown in Fig. 5. Observed versus calculated groundwater levels at May 2002 at well location of 54131 (only monitoring well in the plain area) is equal to 1.25 and 1.41 m, respectively. Comparison of the observed and calculated groundwater levels at well locations of 18495 and 21381 are 1.67–1.63 and 1.51–1.62, respectively.

Measured and simulated chloride concentrations at depths of 65, 110 and 140 m are 855–627 mg/l, 3,660–3,700 mg/l, 14120–12250 mg/l in May, 2002,

**Fig. 5** Simulated groundwater levels (above sea level in meters) in the sub-basin at the end of pumping period simulations



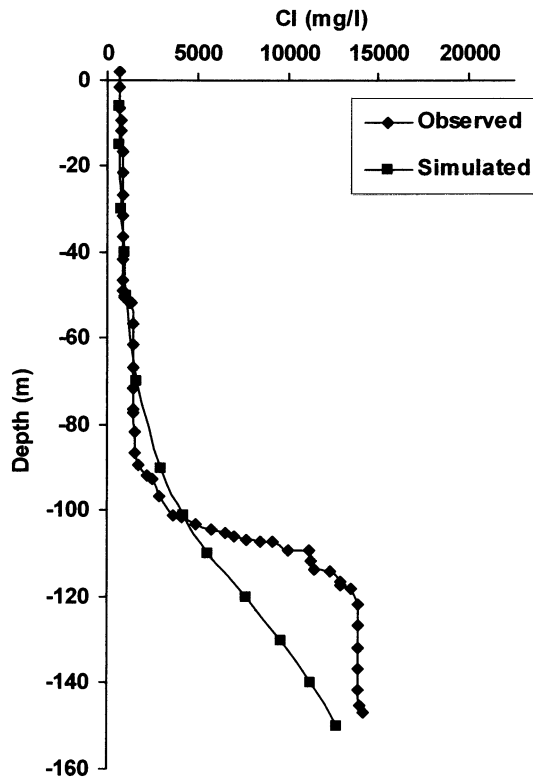


Fig. 6 Comparison of observed versus simulated chloride concentration profile in well location of 57131 at May 2002

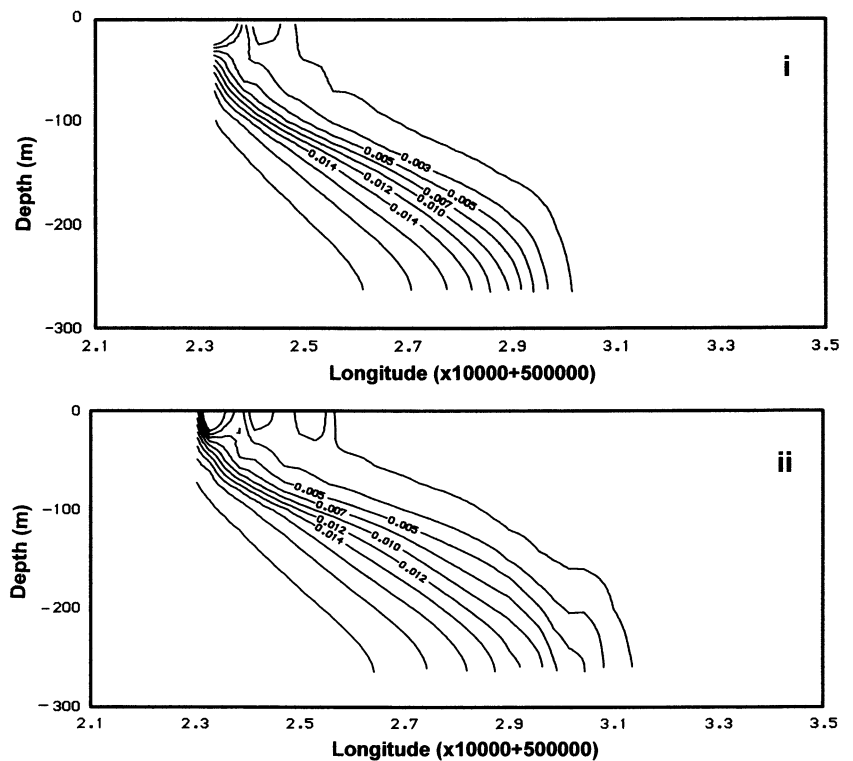
respectively. Chloride concentration distribution estimated from May 2002 EC data at well location of 54131 is compared with the pumping period May 2002 simulation results in Fig. 6. The chloride concentration cross-sections (taken along W–E direction from the middle of the sub-basin passing through well no. 54131) both at the end of the pre-pumping period and at the end of the pumping period are shown in Fig. 7. The pumping period simulations indicate that present pumping conditions in the Selçuk sub-basin have caused seawater intrusion in the aquifer.

### Results of prediction simulations

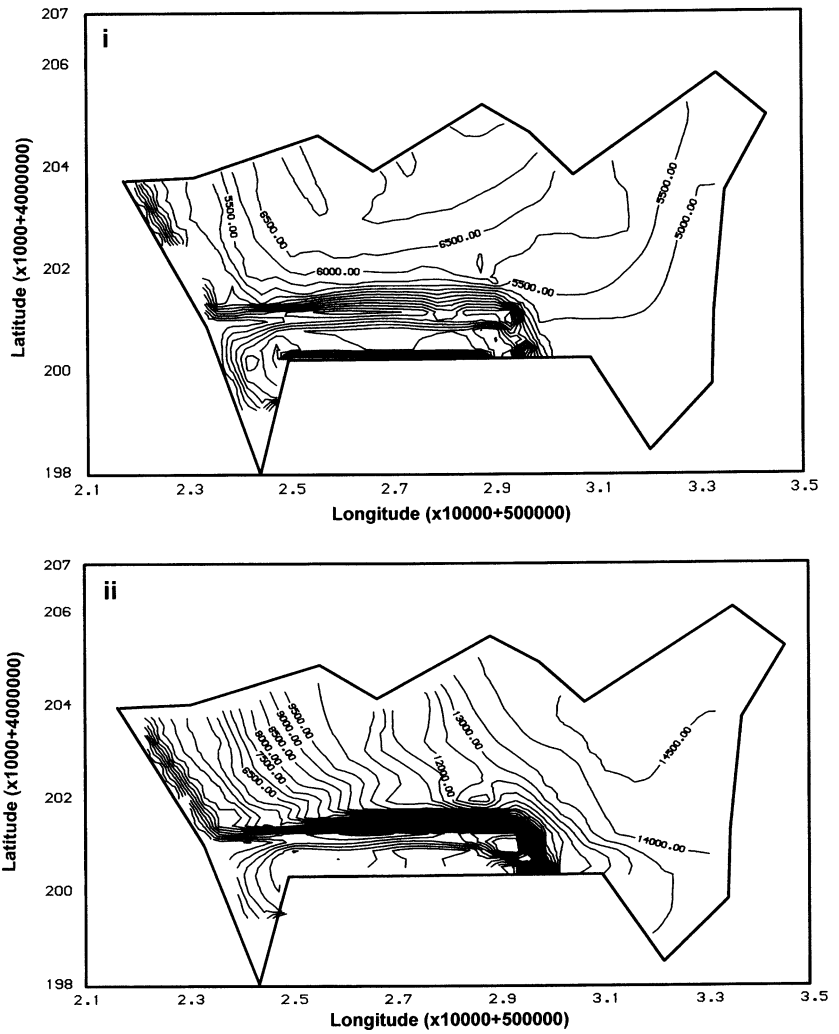
During prediction simulations, additional constant pressure boundary condition was applied to the elements covering the planned canal domain. The canal is planned to have a width of about 40 m and depth of about 10 m. Pressure and concentration results of the pumping period were taken as initial conditions for prediction simulations which cover 20 years. Present recharge and artificial discharge conditions were maintained during the prediction simulations.

At the end of the first year, about 1 m drawdown was observed in the groundwater levels. Groundwater flow direction was changed from east–west direction to north–south direction at north of the planned canal and to south–north direction at south of the canal (Fig. 8a).

Fig. 7 a Pre-pumping period chloride (kg/kg) distribution in the aquifer. b The pumping period chloride (kg/kg) distribution in the aquifer. The cross-sections are along 4201875 latitude passing through well no: 54131



**Fig. 8** Groundwater pressure distribution at sea level in the aquifer obtained (a) after 1 year of prediction simulation and (b) after 10 years of prediction simulation

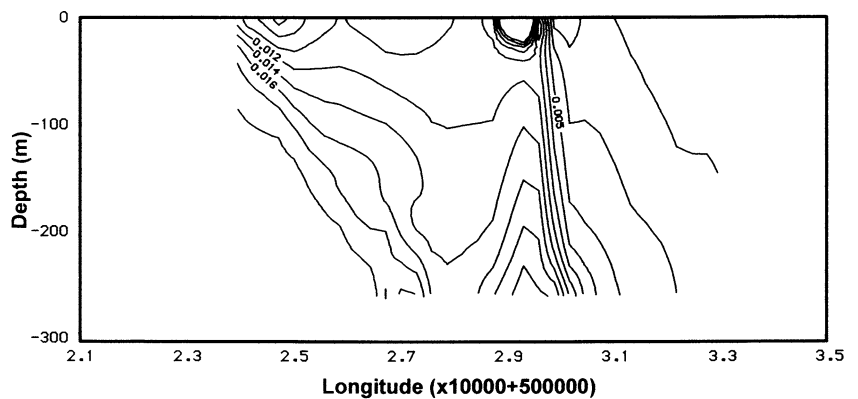


In the following years, groundwater level increased about 25 cm per year. Meantime, groundwater flow direction away from the canal area started to recover the pre-canal directions. The recovery took place from sea shore toward inland. By the end of the tenth year,

overall drawdown in the basin was about 20 cm with respect to the pre-canal levels (Fig. 8b).

Further seawater intrusion took place after the canal opening. Chloride concentration does not exceed the usable irrigation water caution limits (710 mg/l) of the

**Fig. 9** Chloride (kg/kg) distribution in the aquifer at the end of 10 years of prediction simulation. The cross-section is along 4200400 latitude passing through the cooperative II wells area





ministry of environment of Turkey until the seventh year of the simulation at a depth of about 100 m where the irrigation cooperative II wells are present. At the end of the tenth year chloride concentration was about 1,450 and 750 mg/l at depths of 100 and 50 m, respectively, in the cooperative II area (Fig. 9). At the end of the twentieth year of simulation, chloride concentration is about 3,750 and 2,890 mg/l at depths of 100 and 50 m, respectively, in the same area. On the other hand, seawater intrusion does not pollute the groundwater where the cooperative I wells are present even at the end of twentieth year of simulation. The municipality well waters located farther south of the cooperative II wells area would be unfit to use for drinking purpose after the tenth year of the canal opening because chloride amount

at 100 m depth would exceed the maximum admissible concentration limit of 600 mg/l.

In conclusion, the planned canal opening could lower the groundwater levels in the area and could change the groundwater flow directions in the first four years. Then the levels and flow directions will nearly recover. However, the canal opening would cause further seawater intrusion in the aquifer to the extent that groundwater would be unfit to use for irrigation after the seventh year of the canal opening in the cooperative II wells area and would be unfit to use for drinking purposes after the tenth year in the municipality wells area located south of the cooperative II wells. The cooperative I wells location, on the other hand, would not be affected from the canal opening.

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