

# Environmental impact of geothermal fluids on surface water, groundwater and streambed sediments in the Akarcay Basin, Turkey

M. S. Dogdu · C. S. Bayari

**Abstract** In this study, the impact of geothermal water on ground and surface waters has been investigated in Akarcay Basin, Turkey. The release of thermal return water from district heating in the city of Afyon and from thermal baths has a considerable environmental impact on the main stream. Historical analyses of stream water quality data show that the present pollution is associated primarily with thermal return water of district heating system. Currently, about 6% of stream water comprises of thermal water. The pollution seems to degrade the water quality in Lake Eber. Streambed sediments were found to be in equilibrium with polluted water and may lead to additional pollution in lake water. Thermal groundwater intrusion to fresh water production wells was detected mainly at sites close to geothermal fields. Solutions to remove thermal water from surface environment are suggested.

**Keywords** Afyon · Environmental impact · Geothermal · Pollution · Turkey

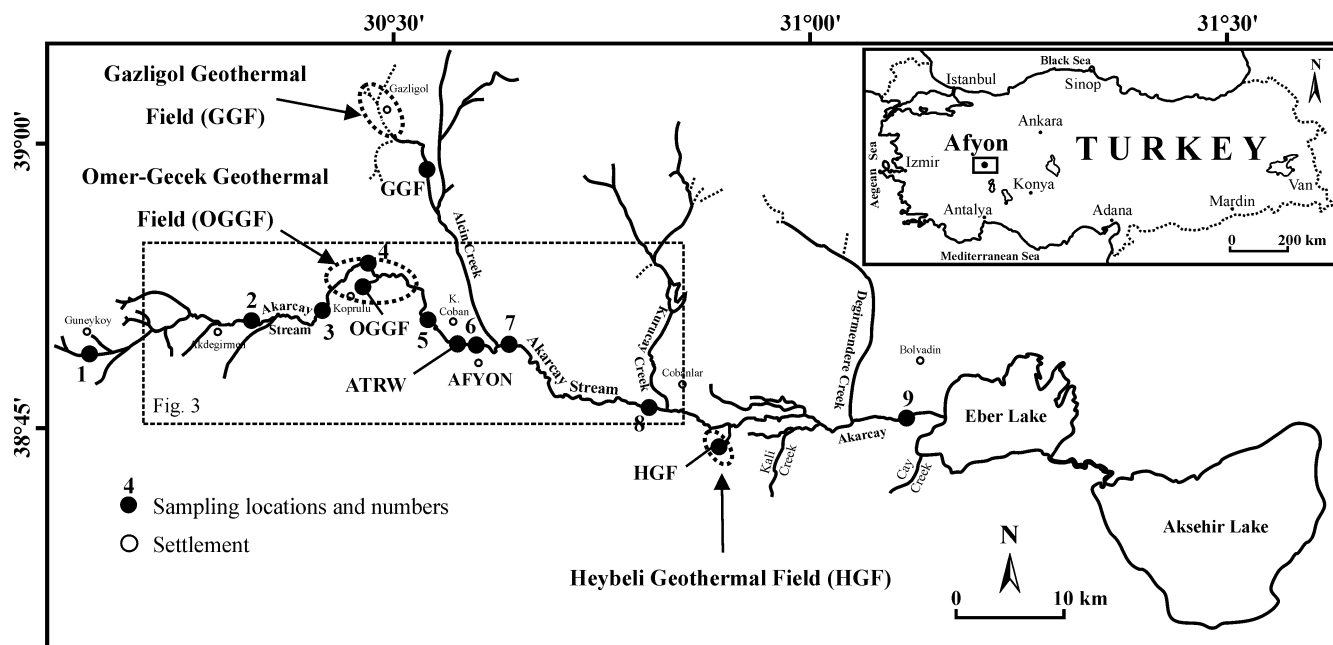
## Introduction

Geothermal groundwater is often regarded as an environmentally-friendly energy resource with respect to fossil

fuels. However, this argument may not be valid if this resource is not used properly. In the liquid-dominated geothermal systems, the geothermal fluid is rich in dissolved constituents with concentrations that are usually above the environmental limits. These chemicals have to be properly isolated from the environment after the heat capacity of the fluid is utilized. The discharge of geothermal fluid into the natural environment may lead to serious environmental damages with costs that could well exceed the benefits gained (e.g. Loppi 2001; Birkle and Merkel 2000; Beker 1999; Webster 1995, 1999; Hunt and Brown 1996; Nicholson 1992; Sabadell and Axtmann 1975). As a geographic bridge between Europe and Asia, Turkey is located on the Alpine-Himalayan orogenic belt where continuing tectonic activity leads not only to devastating earthquakes but also to the formation of widespread thermal water discharges. Low-to-medium enthalpy geothermal fields with a total estimated energy equivalent of 2,600 MWt (Batik and others 2000) are scattered throughout the country. As a result, geothermal energy has long been regarded as a potential alternative to fossil fuel use, particularly in the field of district heating. About 87% of the country's geothermal energy potential is found to be suitable for this purpose (Celik and Sabah 2000) and plans for geothermal district heating projects have long been underway. The Afyon Geothermal District Heating Project (for which "Afjet" is used for an acronym) is among the major projects that aim to provide heat energy for about 20,000 people living in approximately 4,500 residences in Afyon, the major city in the Akarcay Basin. The project involves geothermal fluid production via deep wells in the Omer-Gecek geothermal field located 15 km to the west of the city, a pipeline for geothermal fluid transport to heat exchangers in the city, and a hot-water distribution network to supply the residences. The production wells of the Afjet system were drilled between 1971 and 1997 and the district heating system was partly operational as of the winter of 1997, the system uses 170 l/s of geothermal liquid at a temperature 95 °C between the months October and April (Celik and Sabah 2000). In the future, fluid production will be gradually increased to 625 l/s in order for the heating system to become fully operational (Yilmaz 1999). Efforts aiming to dispose the thermal return water into the thermal aquifer have been

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**Fig. 1**

Geothermal fields, stream water and sediment sampling stations (ATRW Afjet thermal return water; GGF Gazligol geothermal field; HGF Heybeli geothermal field; OGGF Omer-Gecek geothermal field; numbers are keyed to Table 1)

unsuccessful because of the high pressure encountered in the re-injection wells (L. Tezcan 2003, personal communication). Consequently, the geothermal return water from heat exchangers has been discharged into the Akarcay Stream since 1997. Besides, evidence of pollution due to geothermal water contribution has also been reported in the irrigation water wells located around the geothermal fields. Such quality degradations are attributed to the change in hydraulic balance between fresh water and thermal water aquifers that seem to have existed due to increasing freshwater abstraction since the 1990s (Atilla 2002; Meric 2003).

This study aims to determine the impact of geothermal water on the quality of stream water, groundwater, and the streambed sediments, and focuses on part of the Akarcay plain between the source of the Akarcay Stream and its junction to Lake Eber. This paper begins with brief information on the study area and the extent of geothermal pollution is explained on the basis of physical and chemical data obtained. The causes of pollution are evaluated and countermeasures are discussed.

## Study area

Akarcay is a closed basin covering an area of 7,300 km<sup>2</sup> in the western Anatolia (lat. 38–39°N, long. 30–32°E), Turkey (Fig. 1). The basin is occupied largely by the Akarcay plain that extends roughly in an east–west direction and comprises an almost flat-lying bottom of a Pleistocene lake. The plain slopes gently towards the east, where Aksehir Lake is situated. Internal drainage is maintained by the

perennial Akarcay Stream flowing from west to east. It is connected to Lake Eber at the east, and then feeds into Lake Aksehir, a brackish water body. Several tributaries originating from northern and southern heights are also connected to the main river.

A semiarid climate with a mean annual temperature of 11.2 °C dominates the basin. Based on the last 30 years of observation, the mean annual precipitation and potential evapotranspiration rates are 437 mm/year and 1,170 mm/year, respectively. Groundwater is principally fed by precipitation over the volcanics and carbonate rocks that form the heights around the plain. Underground recharge from these units feed the thermal and freshwater aquifers located underneath the plain (Fig. 2). The Plio-Quaternary alluvial and lacustrine sediments underlying the plain make up the principal freshwater aquifer, which is underlain in part by volcanic units composed of the thermal groundwater aquifer. Both aquifers are separated by a Pliocene aquitard (i.e. silt-clay) of 200-m thickness. The freshwater aquifer is also confined from the top by the Pleistocene-Holocene sediments of lacustrine origin. Because of limited surface water, water demand for agricultural, drinking and other needs is met mostly from groundwater in the basin. Annual groundwater use for irrigation is about 50 million m<sup>3</sup> (Meric 2003), which is abstracted mostly during the period between April and September. Groundwater contamination from the surface is not anticipated because of the impermeability of sediments covering the plain surface. Field observations reveal that irrigation return water does not contribute to stream water in appreciable amounts because of the extensive evaporation during the irrigation season. The recharge of Akarcay Stream is mainly supplied by overland flow after precipitation and the long-term maximum and minimum flow rates at the outlet to Lake Eber are 18.58 m<sup>3</sup>/s (4.39 l/s km<sup>2</sup>) and 0.33 m<sup>3</sup>/s (0.078 l/s km<sup>2</sup>), respectively. Thermal return waters of the Afjet system and of Gazligol and Heybeli geothermal fields provide perennial contribution

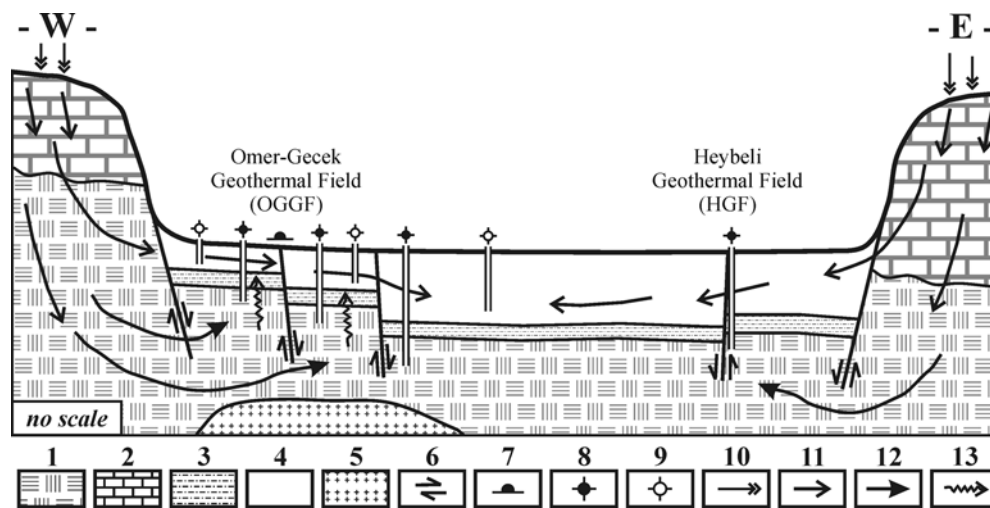


Fig. 2

Schematic cross section of the groundwater flow system in the Akarcay Basin (1 Paleozoic schist and marble (thermal water aquifer), 2 Mesozoic limestone (fresh water aquifer), 3 Pliocene silt-clay (aquitard-cap rock), 4 Plio-Quaternary sediments (fresh water aquifer), 5 magmatic intrusion (heat source-heat transport by conduction), 6 normal fault, 7 thermal spring, 8 thermal water well, 9 fresh water well, 10 recharge, 11 inferred groundwater flow, 12 inferred thermal water flow, 13 seepage)

to Akarcay Stream and its tributaries. The year-round discharge-weighted thermal water contribution to Akarcay Stream is around 6%.

In the Akarcay Basin, thermal groundwater exists in the Omer-Gecek, Gazligol and Heybeli regions (see Fig. 1) where thermal water uprise either through volcanic host rocks or through the intersection of active faults that also dissect Plio-quaternary freshwater aquifer. Several thermal springs existing in these fields with individual discharge rates between 0.1 and 3 l/s have ceased during the last decades after new thermal water production wells for therapeutical baths have been drilled. The Omer-Gecek geothermal field, located 15 km to the west of Afyon, is the source of hot water for the Afjet project. In this field, 25 wells were drilled to abstract hot water between 1971 and 1997. The depth, temperature, and discharge rate of these wells ranges between 125–905 m, 50–98 °C and 5–100 l/s, respectively.

## Materials and methods

Physical and chemical characteristics of Akarcay Stream and groundwater from irrigation water wells have been studied to determine the extent of thermal water pollution in the basin. Akarcay Stream has been investigated at nine locations in wet (March 1999) and dry (July 1999) seasons. Observation sites were selected to characterize the effect of known and probable thermal water discharge sites.

Groundwater samples were collected from 26 irrigation water wells, five thermal water wells and one mineral water well scattered along the plain. Temperature, pH, electrical conductivity (EC) and dissolved oxygen (DO) parameters have been determined in situ. Water samples for laboratory analyses were collected in polyethylene bottles. After filtering through a 0.45- $\mu\text{m}$  membrane, samples for cation and heavy metal analyses were acidified to  $\text{pH} \leq 2$  with analytical grade  $\text{HNO}_3$ . Samples for anion analyses were kept in an icebox at +4 °C and analyzed within 3 to 5 days. The major cation, heavy metal and trace elements analyses

were performed with an atomic absorption spectrophotometer and a UV-visible spectrophotometer was used for the  $\text{SO}_4$ , B and F analyses. Br and As concentrations were determined by ion selective electrode and hydride atomic absorption spectroscopic methods, respectively. End-point titration methods were used for the Cl,  $\text{HCO}_3$ , and  $\text{CO}_3$  analyses. Standard procedures suggested by APHA and others (1989) were followed in all stages of the hydrochemical studies. All analyses have electroneutrality values greater than 5%. Hydrochemical data are presented in Tables 1 and 2.

Streambed sediments were collected from the top 25 cm of the same localities where hydrochemical sampling and measurement activities were carried out. Samples were taken with a plastic shovel and kept in polyethylene bags to avoid contamination. Cation exchange capacity (CEC) and the amount of major cations held by these sediments were determined by ammonium acetate ( $\text{NH}_4\text{OAc}$ ) method (USDA 1996) after rinsing with bidistilled water and drying. Previous stream-water chemistry data available from the State Water Authority (State Hydraulic Works of Turkey, SHW) have also been used to demonstrate the historical changes in stream-water chemistry and to make comparisons with those collected in this study. SHW data were screened for anion-cation balance, and only those with electro-neutrality values (APHA and others 1989) less than 5% were used.

## Results

### Endmember waters in the basin

Groundwater in the Akarcay Basin belongs to one of the two end-member water types. Fresh groundwaters are characterized by  $\text{Ca-CO}_3$  facies while chemically enriched thermal groundwaters represent the  $\text{Na-Cl}$  water type (Fig. 3). Fresh groundwaters approach  $\text{Na-Cl}$  facies depending on the rate of thermal water contribution. Thermal groundwater contribution is also indicated by higher electrical conductivity value, warmer temperature,

**Table 1**

Physical and chemical properties of Akarcay Stream at various sections and of thermal waters (March 1999 and July 1999)

	Sample number and location	Temp. (°C)	pH	EC <sup>1</sup> (μS/cm)	DO <sup>2</sup> (mg/l)	Concentration (mg/l)			
						Na	K	Ca	Mg
March-1999	1-Akarcay (Güneykey)	3.4	8.18	366	9.3	2.76	2.35	35.07	3.28
	2-Akarcay (Akdegirmen)	5.7	8.09	444	8.4	4.37	5.08	41.08	4.01
	3-Akarcay (Koprulu)	6.3	8.08	411	8.5	6.21	3.91	33.87	4.01
	4-Akarcay (Gecek)	6.0	8.01	430	8.7	6.44	3.91	39.28	4.01
	5-Akarcay (K.Cobanlar)	5.7	8.05	430	8.9	8.51	3.91	33.07	4.74
	6-Akarcay (After ATRW)	6.7	8.04	594	7.8	39.54	10.17	40.88	4.25
	7-Akarcay (Akcin)	7.5	7.80	516	7.3	28.97	12.51	32.46	4.25
	8-Akarcay (Cobanlar)	7.4	7.82	570	6.1	41.84	5.87	31.06	4.01
	9-Akarcay (Bolvadin)	9.0	7.62	614	4.6	46.21	9.38	30.86	4.74
	ATRW <sup>3</sup>	47.6	7.70	7,197	1.6	1,445.15	162.66	96.39	7.53
HGF <sup>3</sup>	60.0	6.68	3,795	0.9	491.07	53.96	196.19	21.99	
July-1999	1-Akarcay (Güneykey)	16.3	7.93	559	8.6	4.14	1.56	48.50	5.22
	2-Akarcay (Akdegirmen)	16.8	7.98	618	7.1	8.51	3.13	51.30	6.56
	3-Akarcay (Koprulu)	18.0	7.90	639	6.0	11.50	5.08	47.29	7.78
	4-Akarcay (After OGGF)	20.9	7.89	640	6.8	25.75	7.04	43.49	6.32
	5-Akarcay (Before ATRW)	25.0	8.13	2,370	7.0	345.08	59.82	67.13	23.57
	6-Akarcay (After ATRW)	26.2	7.37	1,543	1.4	185.99	114.95	35.07	12.03
	7-Akarcay (Akcin)	28.7	7.65	1,244	4.2	145.07	16.03	37.68	9.48
	8-Akarcay (Cobanlar)	24.7	7.69	1,624	1.0	200.01	21.90	47.90	10.08
	9-Akarcay (Bolvadin)	30.6	9.37	1,676	-	211.97	37.54	35.67	16.04
	OGGF <sup>3</sup>	28.2	8.18	5,546	4.7	1,150.19	82.11	62.52	10.08
	ATRW <sup>3</sup>	34.0	7.46	6,660	1.8	1,437.56	107.92	87.57	12.51
	GGF <sup>3</sup>	33.5	7.53	2,325	1.9	456.12	36.36	42.28	8.02
	HGF <sup>3</sup>	35.5	7.44	2,862	1.0	326.92	28.54	118.24	22.48

1 Specific electrical conductivity, 2 dissolved oxygen, 3 thermal return water from geothermal field, ATRW Afjet thermal return water, HGF pH ( $\pm 0.2$  pH units), EC ( $\pm 1\%$  of range), DO ( $\pm 0.2$  mg/l), Na ( $\pm 0.01$ ), K ( $\pm 0.01$ ), Ca ( $\pm 0.002$  mg/l), Mg ( $\pm 0.0001$  mg/l), CO<sub>3</sub> ( $\pm 3$  mg/l), HCO<sub>3</sub> As ( $\pm 0.1$  ng/l)

and elevated trace element (i.e. Fe, Li, B, Br, Mn, Al, I and As) concentrations as well as Na and Cl contents (see Table 2). Typical fresh surface and groundwaters have an EC less than 1,000  $\mu\text{S}/\text{cm}$  whereas, thermal water's EC is more than 4,000  $\mu\text{S}/\text{cm}$ .

#### Impacts on groundwater chemistry

To determine the extent of thermal water contribution, 26 evenly distributed irrigation water wells were investigated. A visual analysis of the areal distribution of the groundwater's chemical composition reveals that thermal water contribution primarily affects the freshwater wells located around geothermal fields (Dogdu and Bayari 2002a). Although this impact is more pronounced

around the Omer-Gecek field (e.g., wells 4 thru 9), some wells located around Gazligol (e.g., well 14) and Heybeli fields (e.g., wells 28 thru 32) have also apparent indications of thermal water contribution as their temperature and electrical conductivity reveal (Fig. 4a, b, see also Table 2). Chloride and lithium ions, as typical indicators of thermal water contribution, also show a similar distribution to those of temperature and electrical conductivity (Fig. 5a, b).

Conservative mass-balance calculations, based on average concentrations of thermal water, fresh groundwater and mixed water, indicate ca. 10% thermal water contribution to mixed waters (12.4% for Na, 9.2% for Cl). It is noteworthy that some irrigation water wells (e.g., 21

											(ng/l)
CO <sub>3</sub>	HCO <sub>3</sub>	Cl	SO <sub>4</sub>	Fe	Mn	Li	Al	B	F	Br	As
14.10	155.60	5.32	12.49	0.43	0.03	0.01	0.56	0.67	1.01	0.18	2.15
14.10	184.28	10.64	16.33	0.87	0.06	0.01	0.73	1.92	1.17	0.20	2.15
10.20	169.03	8.86	18.25	3.81	0.16	0.01	3.80	2.11	1.15	0.21	4.55
10.20	173.91	14.18	19.69	0.30	0.04	0.01	0.29	2.03	1.25	0.35	3.21
10.20	173.91	12.41	18.73	0.64	0.04	0.01	0.56	1.87	1.22	0.28	2.68
11.70	200.15	53.18	20.17	0.65	0.04	0.07	0.90	2.01	1.94	0.91	2.68
9.00	173.91	39.00	18.73	2.92	0.12	0.06	3.54	1.02	1.41	0.78	4.01
10.20	181.84	42.54	21.13	0.71	0.08	0.07	1.19	0.00	1.53	0.76	5.87
20.40	163.53	44.31	23.53	0.93	0.10	0.07	1.46	0.00	1.89	0.78	3.75
71.70	903.71	1,737.05	214.69	0.32	0.05	2.68	0.00	10.64	13.20	18.20	165.38
56.10	1,210.03	194.98	280.01	0.57	0.03	1.10	0.00	2.22	8.43	2.65	142.11
22.50	228.21	7.09	9.61	0.12	0.03	0.00	0.00	0.27	159.00	0.24	6.94
25.20	245.30	19.50	11.05	0.42	0.05	0.00	0.66	0.11	101.00	0.52	8.01
25.20	233.71	17.73	13.93	2.00	0.20	0.01	2.24	0.29	82.30	0.30	8.54
22.50	222.11	39.00	11.05	1.00	0.10	0.03	2.09	0.38	53.80	0.45	39.43
23.70	410.66	514.03	72.53	0.61	0.47	0.59	1.88	2.08	21.20	3.23	159.52
0.00	484.50	216.25	24.98	0.39	0.19	0.25	0.81	0.00	23.70	1.73	97.48
0.00	470.46	152.44	21.61	0.39	0.15	0.19	0.45	0.15	35.40	1.89	61.26
0.00	610.20	191.43	18.73	0.19	0.27	0.24	0.00	0.00	25.50	2.15	81.23
39.30	290.46	233.97	36.98	0.75	0.22	0.15	1.47	0.00	31.60	2.39	80.44
50.40	661.46	1,382.55	140.73	0.72	0.06	1.74	0.78	6.59	6.34	6.40	176.56
0.00	1,214.30	1,843.40	145.53	2.69	0.14	2.41	0.00	2.95	2.86	9.78	173.90
61.80	1,260.06	23.04	9.13	0.74	0.12	1.27	0.00	5.50	13.40	0.89	17.86
0.00	1,214.30	186.11	82.13	0.20	0.05	0.61	0.00	0.00	11.40	1.43	168.58

Heybeli geothermal field,GGF Gazligol geothermal field, OGGF Omer-Gecek geothermal field. Analytical uncertainty: temperature ( $\pm 0.15$  °C), ( $\pm 3$  mg/l), Cl ( $\pm 2.5$ ), SO<sub>4</sub> ( $\pm 5$ ), Fe ( $\pm 0.004$  mg/l), Mn ( $\pm 0.002$  mg/l), Li ( $\pm 0.008$  mg/l), Al ( $\pm 0.03$  mg/l), B ( $\pm 0.7$  mg/l), F ( $\pm 2$ ), Br ( $\pm 2$ ),

and 25), which are located away from the known geothermal fields, also have indications of thermal water contribution. Such locations should be including buried faults, which create hydraulically more conductive zones for thermal groundwater uprising. The cool and thermal groundwaters in the basin are characterized by temperatures around 15 °C (EC=500  $\mu$ S/cm) or less and 50 °C (EC=4,500  $\mu$ S/cm) or higher, respectively. Elevated temperature and EC values are encountered in some of the wells drilled for freshwater production near the Omer-Gecek geothermal field (e.g., wells 8, 9, and 11 in Figs. 4, 5). It appears that these wells are located along the extension of buried fault(s) through which Afjet thermal water production wells were also drilled.

#### Impacts on surface-water chemistry

Two probable ways that the thermal water may influence the water quality in Akarcay Stream are direct manmade or natural discharge of thermal water and the seepage of thermal or mixed groundwater along streambed. Stream water quality has been observed at nine stations that were chosen by considering the known and probable thermal water contribution zones. The thermal return waters from Afjet (ATRW) and from Gazligol geothermal field (GGF) discharge directly in Akarcay Stream and Alcin Creek, respectively (see Fig. 1). Return waters from thermal baths in Omer-Gecek and Heybeli geothermal fields also discharge in Akarcay Stream (see OGGF and HGF in Fig. 1). Observations carried out in wet (March 1999) and dry (July 1999) seasons reveal that stream-water quality is

**Table 2**

Physical and chemical properties of thermal and freshwater production wells (July 1999)

Well name and number	Te-mp. (°C)	EC <sup>1</sup> (µS/cm)	pH	DO <sup>2</sup> (mg/l)	Concentration (mg/l)					
					Na	K	Ca	Mg	HCO <sub>3</sub>	
1	Irrigation well 50544	11.9	568	7.30	6.07	5.06	5.47	86.57	12.03	313.64
2	Irrigation well 11254	10.6	692	7.24	8.56	8.05	3.91	113.03	9.96	356.36
3	Irrigation well 22312	14.2	365	7.24	3.49	22.30	7.82	38.08	9.96	182.45
4	Ozerler thermal water well	65.0	5,668	6.56	1.48	1,180.08	91.89	121.04	14.94	1,009.27
5	OGGF thermal water AF-7 <sup>A</sup>	92.0	7,186	7.61	1.85	1,500.10	121.21	102.00	16.04	912.25
6	OGGF thermal water AF-9	48.0	4,299	6.18	1.56	722.12	57.09	192.58	31.95	1,014.76
7	Orucoglu thermal bath well	25.8	3,634	5.98	3.53	610.15	52.39	157.51	30.01	812.18
8	Irrigation well 45810	19.2	604	6.50	5.69	52.42	7.43	44.49	12.51	211.13
9	Irrigation well 31882	24.0	1,704	6.45	5.15	114.95	12.51	72.95	20.05	279.47
10	Irrigation well 34230	22.3	1,327	7.16	5.28	186.91	12.12	107.01	45.44	501.58
11	Irrigation well 34429	14.8	1,039	6.96	5.71	97.02	12.51	89.98	11.54	376.49
12	Irrigation well 53026B	14.9	202	7.78	3.08	11.95	1.56	20.44	4.01	79.94
13	Irrigation well 42670	11.8	1,178	7.33	5.72	112.42	13.69	94.59	17.98	438.73
14	GGF G1 <sup>A</sup>	65.0	3,872	7.20	1.94	913.16	77.42	112.42	25.03	2,907.60
15	Irrigation well 30513	14.1	974	7.34	5.9	148.29	12.90	53.91	9.96	533.31
16	Irrigation well 47854B	17.5	252	7.05	6.6	11.95	7.43	33.07	7.05	136.68
17	Irrigation well 33039	15.2	597	6.98	6.22	46.44	5.47	55.91	11.06	284.96
18	Irrigation well 15947	14.0	346	7.20	6.68	11.27	6.65	40.48	11.06	173.91
19	Irrigation well 40939	15.1	537	7.30	7.02	26.90	3.13	63.93	11.06	267.88
20	Irrigation well 36442	19.4	276	6.93	4.07	11.50	8.60	36.47	7.05	159.87
21	Irrigation well 13324	15.9	1,683	6.45	4.19	173.11	18.38	121.04	18.95	627.29
22	Irrigation well 51980	14.9	518	7.79	7.02	15.86	1.56	63.53	12.03	228.21
23	Irrigation well 49179	16.5	577	7.36	9.02	23.91	4.69	54.91	22.96	267.88
24	Irrigation well 38720	14.8	395	7.40	7.52	6.90	5.47	62.52	6.44	211.13
25	Irrigation well 32590B	18.4	1,357	6.55	3.98	66.44	12.12	144.09	31.47	576.03
26	Irrigation well 35599	16.1	645	7.40	4.7	27.82	3.91	66.93	20.05	296.56
27	Irrigation well 41068	14.6	612	7.45	5.56	44.60	7.04	52.91	18.95	349.03
28	Irrigation well 49758	13.8	629	7.39	6.87	7.36	2.35	81.96	18.95	273.98
29	Irrigation well 30082 <sup>A</sup>	21.5	3,817	6.31	1.06	800.05	75.85	91.98	44.96	2,651.32
30	Irrigation well 15022	16.5	486	7.39	7.85	6.90	2.35	70.94	9.96	216.62
31	HGF H2	60.0	3,596	7.13	2.3	474.05	55.13	330.46	72.54	1,573.71
32	Irrigation well 19277	16.1	546	7.42	7.63	37.24	3.13	56.51	9.96	250.79

1 Specific electrical conductivity, 2 dissolved oxygen, ATRW Afjet thermal return water, HGF Heybeli geothermal field, GGF Gazligol geothermal temperature ( $\pm 0.15$  °C), pH ( $\pm 0.2$  pH units), EC ( $\pm 1\%$  of range), DO ( $\pm 0.2$  mg/l), Na ( $\pm 0.01$ ), K ( $\pm 0.01$ ), Ca ( $\pm 0.002$  mg/l), Mg ( $\pm 0.0001$  mg/l), ( $\pm 0.03$  mg/l), I ( $\pm 2\%$ ), As ( $\pm 0.1$  ng/l)

strongly affected by the contribution of thermal water (Fig. 6a, b). These effects are more pronounced at stations 3, 5 and 6. Stations 5 and 6 are located downstream of the Omer-Gecek geothermal field and at the downstream of

ATRW discharge site, respectively. There is no visible thermal water discharge around station 3. Thermal water contribution in this area seems to be associated with the thermal groundwater seepage, which used to feed several thermal springs around. These springs ceased within the

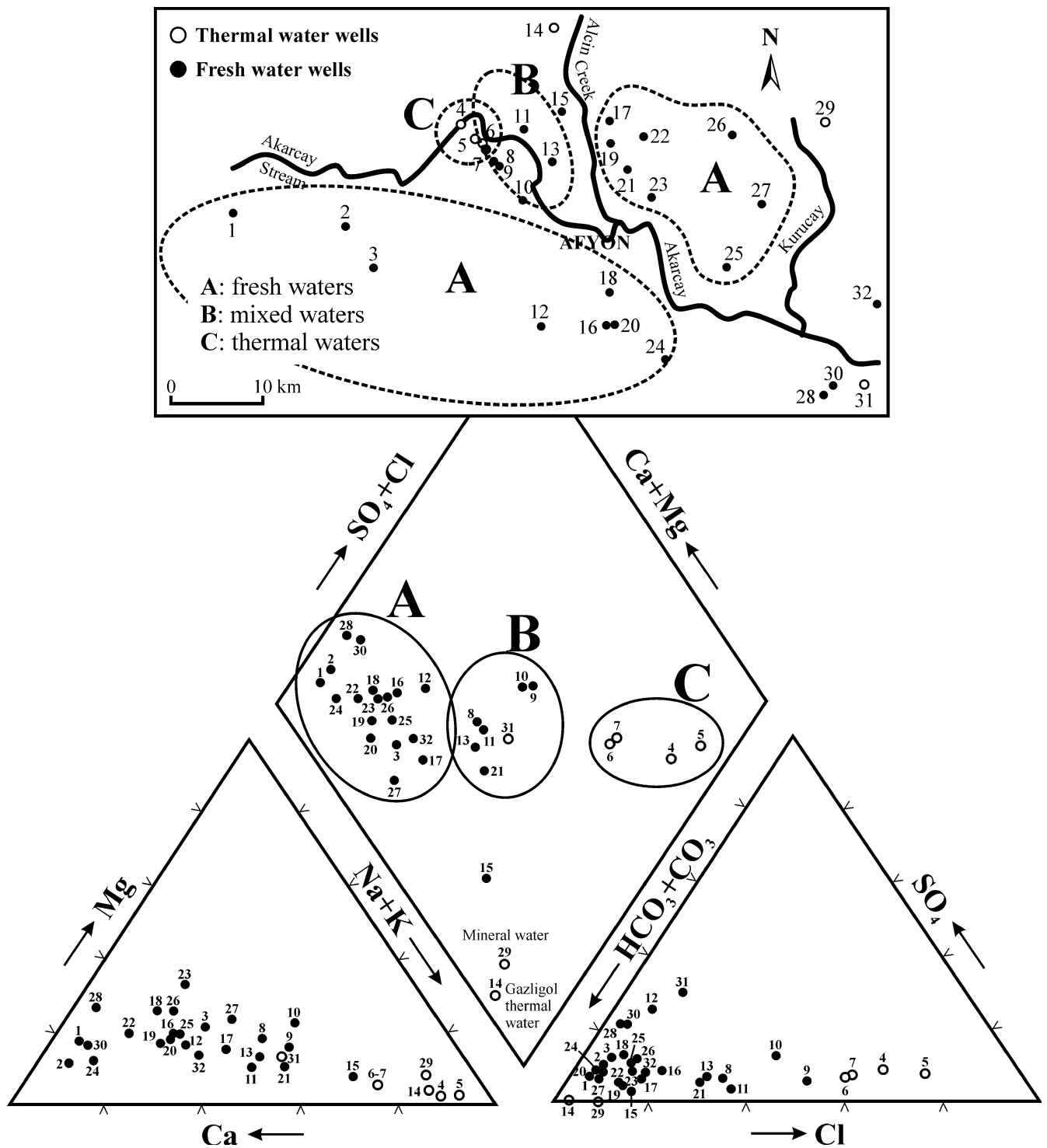
Cl	SO <sub>4</sub>	Fe	Li	B	Br	Mn	Al	I	(µg/l) As	Well depth (m), filter depth (m) and lithology
12.41	17.29	0.05	0.00	0.31	0.29	0.00	0.00	0.01	0.01	(140), (50–135), gravel
15.95	35.06	0.00	0.00	0.38	0.37	0.00	0.00	0.01	0.01	(175), sand-gravel
8.86	22.57	0.11	0.02	0.18	0.27	0.01	0.00	0.01	0.01	(150), gravel-tuff
1,347.10	261.28	4.26	2.09	5.83	8.65	0.10	0.41	0.11	0.18	n.d.
1,878.85	281.46	0.13	2.45	8.84	9.32	0.10	0.00	0.15	0.18	(210), (152), marble- schist-conglomerate
921.70	158.02	3.39	1.22	2.69	5.56	0.42	0.00	0.07	0.18	(320), (185), basalt- sandstone- conglomerate
779.90	137.85	0.16	0.98	0.89	4.50	0.05	0.00	0.05	0.17	n.d.
62.04	20.17	0.22	0.08	–	0.48	0.02	0.00	0.01	0.06	(100), (30–100), gravel-tuff-trachyte
184.34	26.42	2.36	0.15	–	1.51	0.07	0.61	0.02	0.07	(134), (40–90), gravel-agglomerate
248.15	100.38	1.35	0.24	–	2.75	0.44	0.00	0.10	0.06	(532), (28–60), gravel; 155–222 gravel
125.85	20.17	0.06	0.18	–	0.94	0.00	0.00	0.02	0.05	(80), (20–75), gravel
5.32	23.53	0.06	0.02	–	0.18	0.01	0.00	0.03	0.01	(193), (25–190), gravel-trachyte
109.90	33.62	0.06	0.23	–	1.03	0.01	0.00	0.02	0.04	(85), (23–80), gravel
33.68	3.84	0.32	2.85	10.20	0.92	0.09	0.00	0.03	0.01	(138), quartzite- calcschist
51.40	17.29	0.00	0.27	0.59	0.55	0.02	0.00	0.01	0.01	(80), (30–75), sand-gravel
21.27	12.01	0.29	0.00	–	0.20	0.02	0.00	0.01	0.03	(190), (50–185), gravel-sand
33.68	16.81	0.12	0.09	–	0.38	0.01	0.00	0.01	0.01	(85), (40–80), gravel
10.64	21.61	0.02	0.00	–	0.19	0.01	0.00	0.01	0.01	(205), (30–187), sand-gravel-tuff
23.04	12.97	0.56	0.02	–	0.24	0.04	0.76	0.01	0.01	(86), (20–80), gravel
8.86	11.05	0.05	0.00	–	0.14	0.01	0.00	0.01	0.03	(111), (40–105), trachyte-sand
145.35	31.22	0.02	0.38	1.06	1.15	0.03	0.00	0.02	0.01	(187), (60–140), gravel
17.73	13.45	0.97	0.02	–	0.17	0.04	1.30	0.01	0.01	(110), (32–95), gravel
23.04	24.50	1.19	0.04	–	0.27	0.06	1.75	0.03	0.02	(158), (40–152), gravel
8.86	16.33	0.69	0.00	1.35	0.23	0.04	0.00	0.01	0.01	(190), andesite- trachyandezite- gravel
46.09	60.52	0.15	0.17	–	0.50	0.04	0.00	0.01	0.03	(153), (35–145), gravel
30.13	33.62	0.04	0.03	–	0.53	0.02	0.00	0.01	0.01	(173), (32–162), sand-gravel
17.73	17.77	0.09	0.05	–	0.37	0.01	0.00	0.01	0.02	(70), (20–65), gravel- conglomerate- limestone
10.64	62.92	0.08	0.00	0.16	0.24	0.01	0.00	0.01	0.01	(145), (40–105), trachyte-sand
86.85	0.00	1.55	2.83	6.59	0.83	0.07	0.00	0.02	0.01	(35), (15–34), schist
7.09	48.99	0.30	0.03	0.37	0.21	0.02	0.00	0.01	0.00	(192), (40–130), gravel-limestone
177.25	634.96	0.83	0.88	–	1.92	0.04	0.00	0.02	0.18	(292), (237–248), calcschist-marble
26.59	21.61	0.03	0.02	0.02	0.36	0.00	0.00	0.01	0.01	(91), (48–62), limestone

field, OGGF Omer-Gecek geothermal field, A flowing artesian water, –: no analysis/measurement, *n.d.* no data available. Analytical uncertainty: CO<sub>3</sub> (±3mg/l), HCO<sub>3</sub> (±3 mg/l), Cl (±%2.5), SO<sub>4</sub> (±%5), Fe (±0.004 mg/l), Li (±0.008 mg/l), B (±0.7 mg/l), Br (±%2), Mn (±0.002 mg/l), Al

last two decades because of thermal water production wells drilled for thermal baths. During the course of this study, thermal return water from Afjet's heat exchanger has been discharged in Akarcay Stream at the upstream of station 6 both in wet (170 l/s) and in dry (3 l/s) periods while the

stream water discharge rates were 9,000 l/s and 28 l/s, respectively.

Variation of physical and chemical parameters during the wet season indicates that ATRW discharge is the main source of pollution in the stream. The temperature shows a



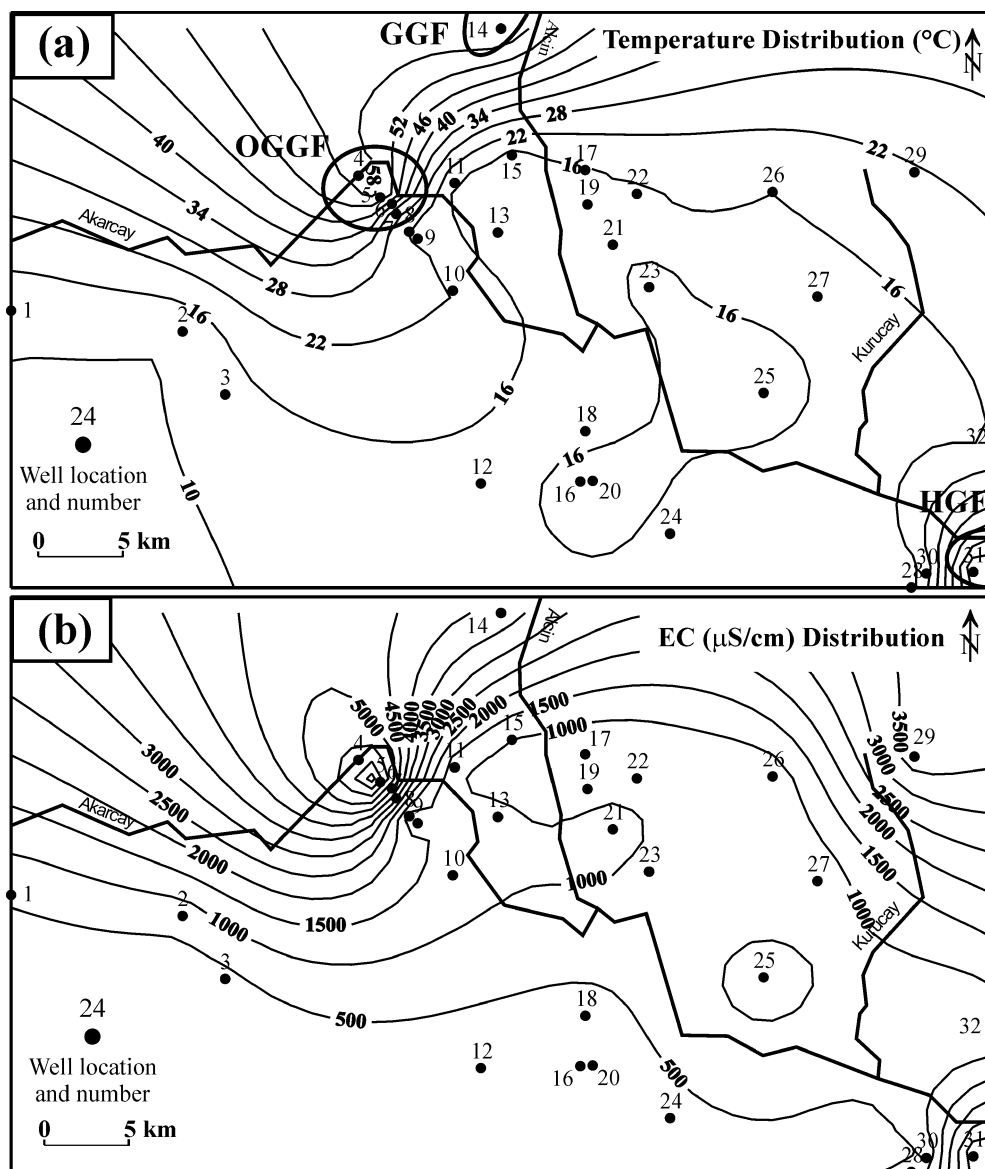
**Fig. 3**

Piper's diagram of groundwater samples of various hydrochemical facies (numbers are keyed to Table 2)

slight increase towards the downstream in both periods, mainly because of the thermal equilibration with atmospheric temperature, which increases as the elevation decreases. Variation of dissolved oxygen implies that the gas content is in equilibrium with atmosphere at the water's temperature and salinity. The decline in dissolved oxygen content that occurs after ATRW discharge is

attributed to the decreased gas solubility because of the salinity rise that is caused by this discharge. ATRW's effect on salinity is also apparent from the electrical conductivity shift at station 6. This effect is also observed in major- and trace-ion concentrations. The contribution of ATRW causes a drastic increase in Na and Cl contents, which persists along the rest of the stream. Ca and alkalinity does not show appreciable variation as one may expect from a solution, which is in equilibrium with atmospheric carbon dioxide partial pressure.



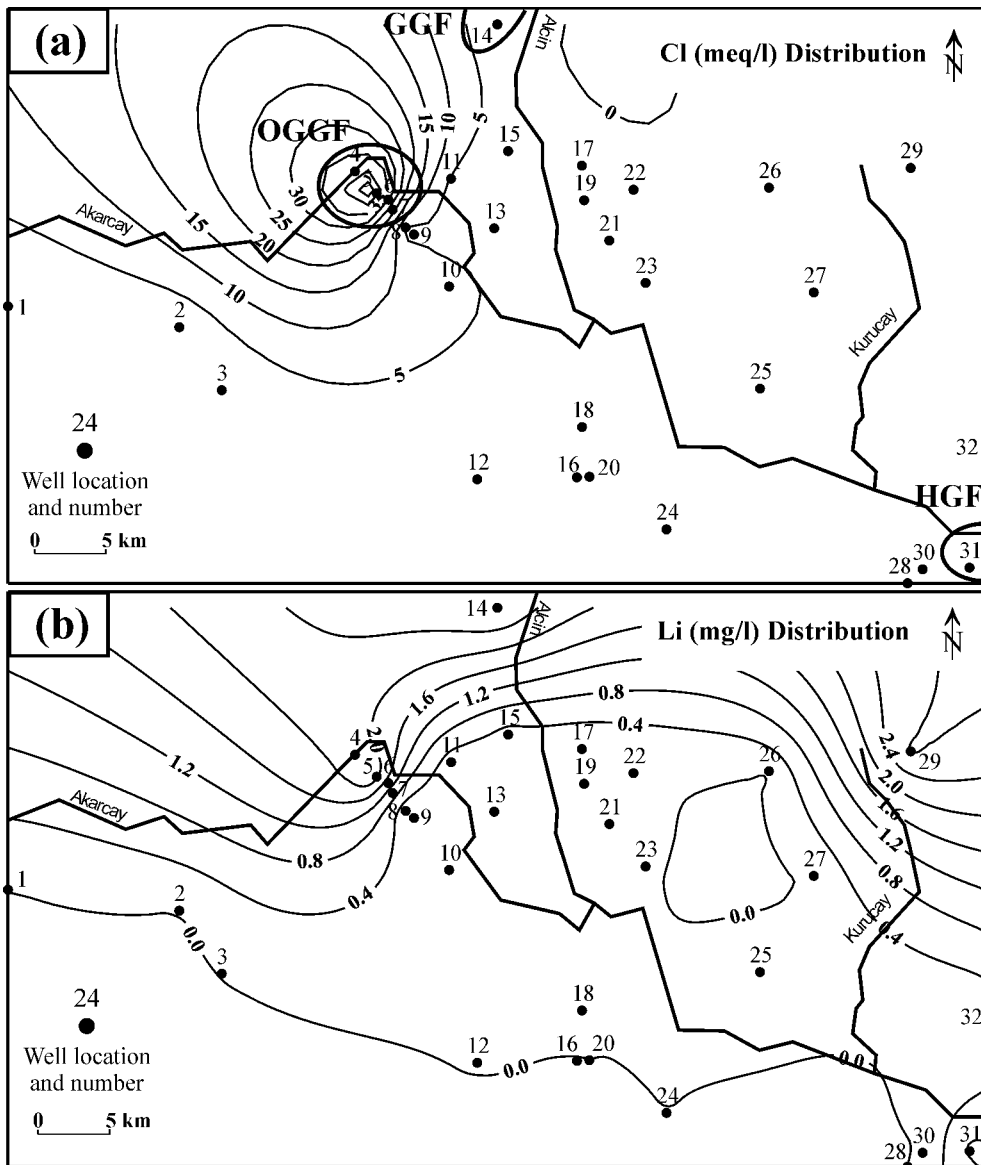


**Fig. 4** Temperature (a) and specific electrical conductivity (b) distribution in groundwater (numbers are keyed to Table 2)

Trace-element concentrations in the wet period show that contributions other than ATRW discharge are also effective in determination of the stream water chemistry. Although, ATRW discharge causes an increase in trace element concentrations, a significant rise is also observed at station 7 where Alcin Creek joins the Akarcay Stream (see Fig. 1). Apart from overland flow, the thermal bath return water in the Gazligol geothermal field feeds this creek as well. However, the comparison of trace-element compositions of bath return water (see item GGF in Table 1) and Akarcay Stream at station 7 (see item 7 in Table 1) reveals that water contributions of unknown origin and geochemical processes along the stream should also be effective in determining the Akarcay composition at this station. Station 7 is located downstream from Afyon through which Akarcay Stream passes. It seems probable that domestic and small-scale industrial return waters may also be affecting the stream-water quality. However, the Na-Cl-type ATRW discharge

seems to be the primary cause of stream water quality degradation in between the stations 6 and 9 during the wet season.

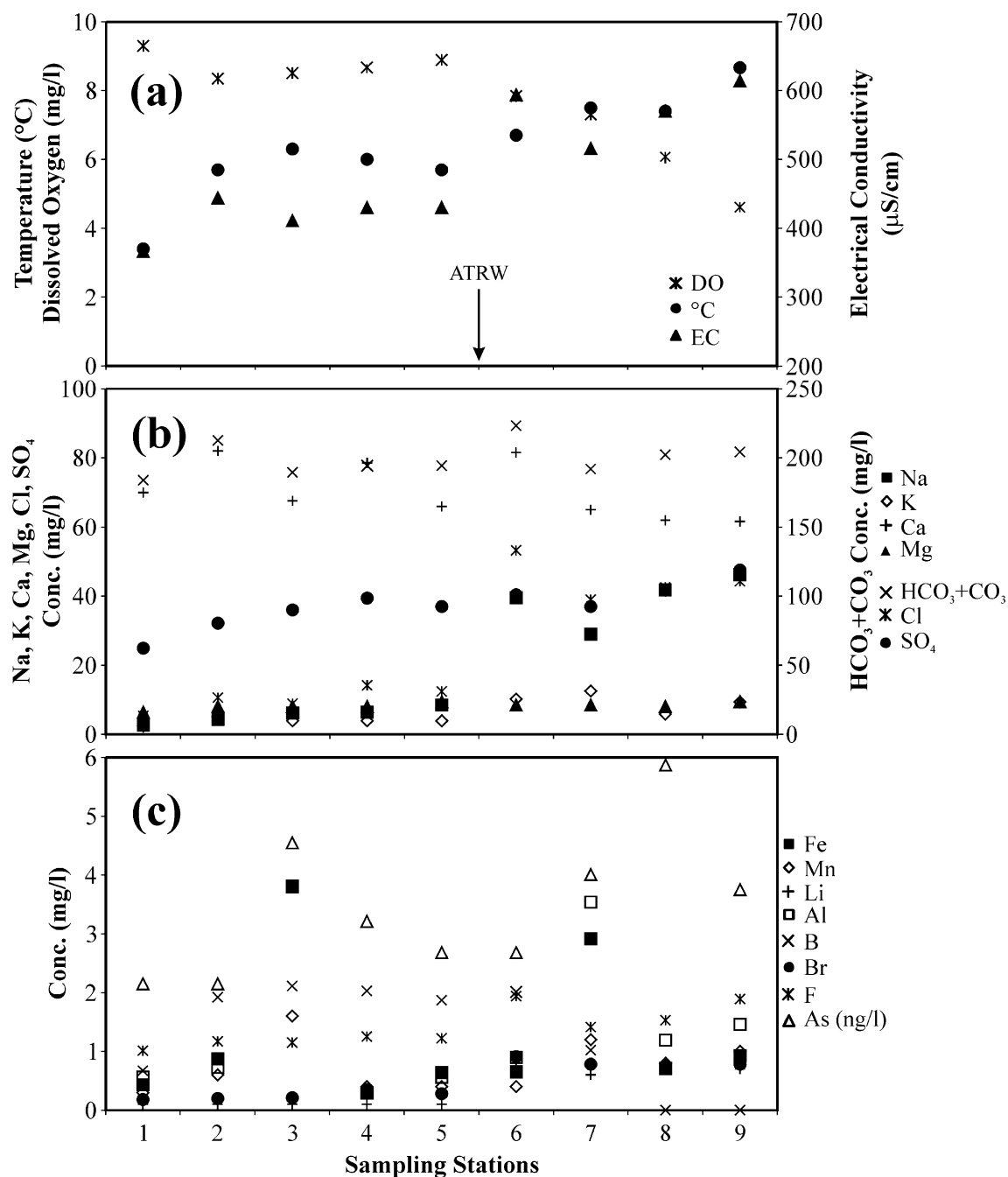
The anomalous rise in As, Al, Fe and Mn concentrations as observed at station 3 is also surprising because neither thermal nor other types of visible surface discharge to Akarcay Stream exist in this area. Because this site is located upstream from the Omer-Gecek geothermal field, the observed anomaly may be attributed to leaching of the near-surface geologic material, which might include mineral precipitates of hydrothermal origin. Alternatively, uprising geothermal water from Omer-Gecek geothermal field may be extending toward the upstream of station 3. If these trace-element contributions are due to thermal water influx, which is normally anoxic, then removal from liquid phase by complex and precipitate formation upon oxygenation would be expected. In such a case, high concentrations of trace elements in liquid phase can only be explained by slow redox chemistry.



**Fig. 5**  
Lithium (a) and chloride (b)  
distribution in groundwater  
(numbers are keyed to Table 2)

The variation of physical and chemical parameters along the Akarcay Stream during the dry period is similar to that of the wet period, though much higher concentrations are observed due to the increase in the volumetric ratio of thermal water to stream water. The decrease in the stream's discharge rate and probable water loss due to evaporation causes less dilution of thermal water that contributes the stream. The major difference between the trends of wet- and dry-season water quality profiles is the location of concentration increase. During the dry period, Na and Cl concentrations increase at station 5, while it happens at station 6 in the wet period. Because the ATRW discharge is reduced to a few l/sec during summer, its contribution to stream-water quality after station 6 decreases. The increase observed at station 5 seems to be associated with thermal water discharges from the Omer-Gecek geothermal field. Although, there is no need for geothermal fluid production during the dry season, the

wells are not shutdown completely to eliminate the scaling risk in well casing and in transport pipelines. Like in the wet period, thermal water contribution in the dry season persists along the rest of the stream. Variations in stream-water quality after station 5 seem to be influenced by the cation holding capacity of streambed material and by the dilution effect of irrigation return waters and tributary streams. Similar to the wet period, the anomalous increase in Fe and Al concentrations observed at station 3 is attributed to leaching of hydrothermal minerals. Historical data at stations 5, 6, and 9 have also been used to determine the impact of thermal water contribution on the Akarcay Stream water quality in the long term. Figure 7 shows the change of major ion composition on various dates between January 1991 and January 1999. Stations 5, 6, and 9 represent the condition at the downstream of Omer-Gecek geothermal field, downstream of ATRW discharge point, and the site where Akarcay Stream



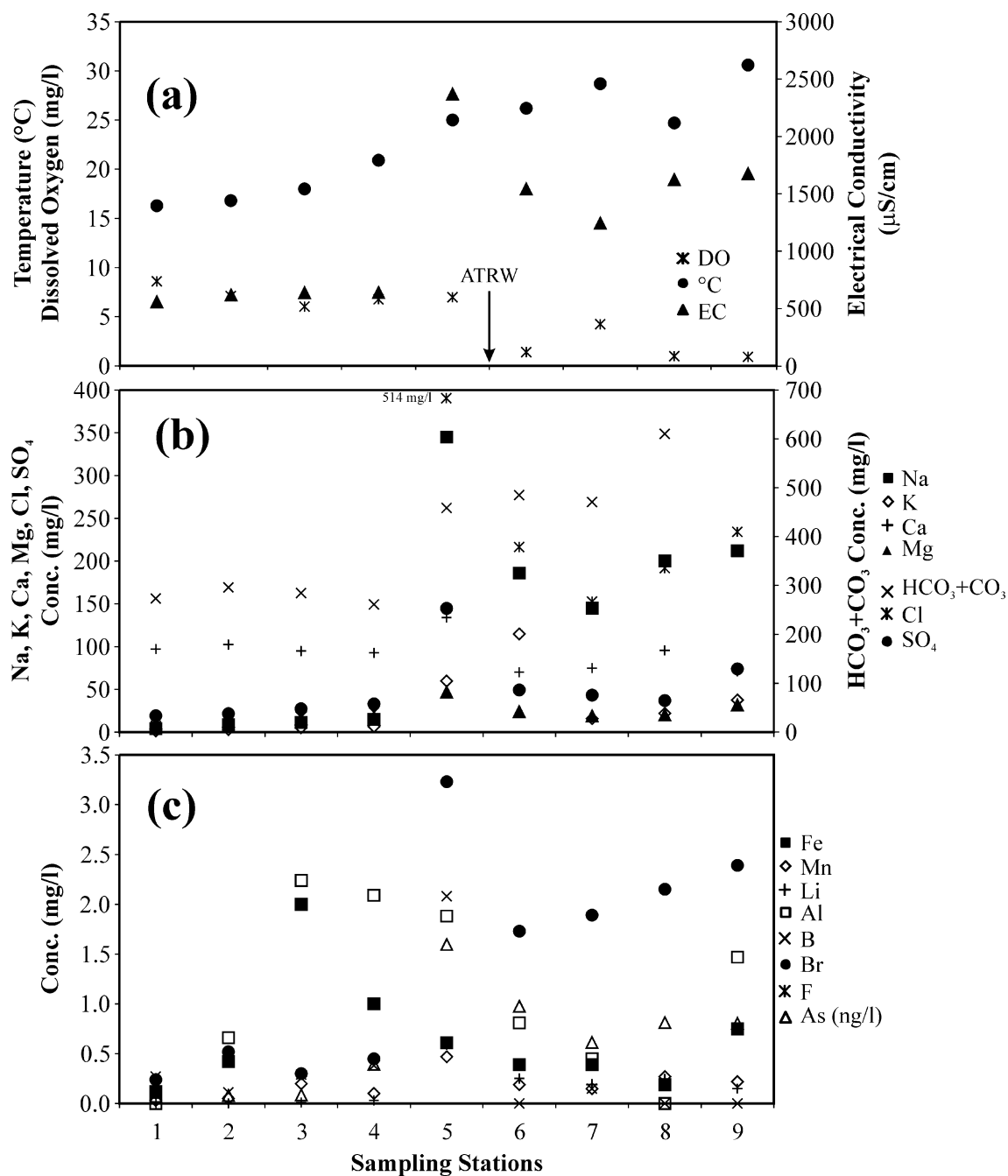
**Fig. 6**

a Variation of physical parameters (a), major ions (b) and, trace elements (c) along the Akarcay Stream in wet period (March 1999) (Mn and Li concentrations have been exaggerated ten times); b Variation of physical parameters (a), major ions (b) and, trace elements (c) along the Akarcay Stream in dry period (July 1999) (As concentration has been exaggerated hundred times)

joins the Lake Eber, respectively. Na and Cl are the primary ions that show anomalous peaks in all stations. First historical anomaly observed at all stations in September 1991 and January 1992 is due to thermal water release during the test runs in the wells of Omer-Gecek geothermal field. Elevated Na and Cl concentrations caused by thermal water discharge just before station 5 continued to affect the water quality along the whole

downstream course of Akarcay Stream. Similar peaks are also observed in the winters of 1997, 1998, and 1999 at stations 6 and 9. These anomalies correspond to ATRW discharges that occurred due to test or regular operation runs of district heating system.

Overall evaluation of the data presented indicates that thermal water discharge has always strongly affected the water quality in Akarcay Stream along its course to Lake Eber. Although observations carried out (not presented in this study, see Dogdu and Bayari 2002b) reveal no significant quality degradation yet in the lake water, the continuing thermal water discharge will eventually have a strong negative impact. It appears that present freshwater recharge supplied by tributary streams and by groundwater seepage along the southern shore of the lake is able



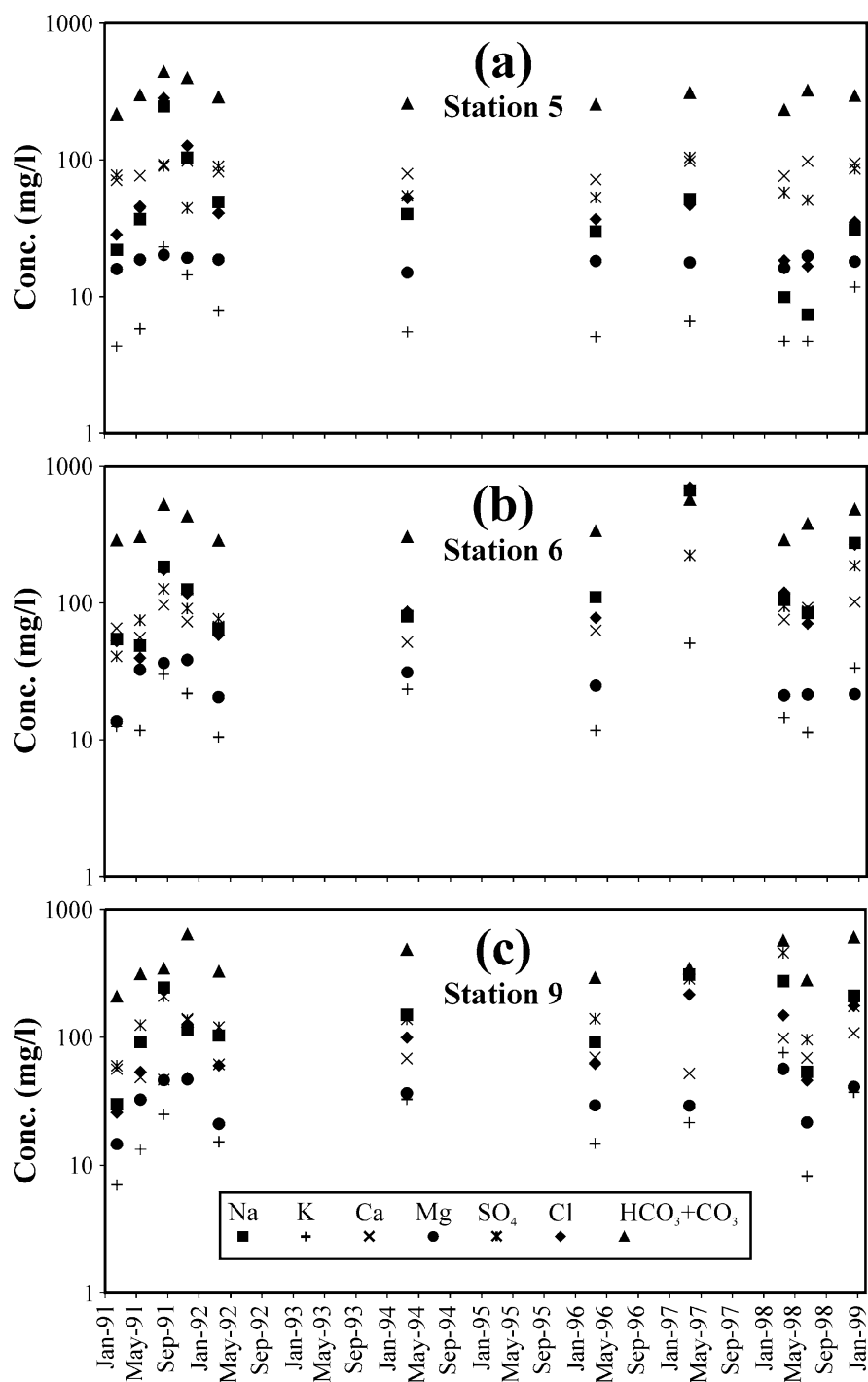
**Fig. 6**  
(Contd.)

to maintain the water quality by diluting the input by Akarcay Stream (Dogdu 2001). As discussed below, some of the Na in the stream water is held by streambed sediments before its arrival at the lake. However, once the stream sediments attain exchange equilibrium with stream water that is polluted by thermal discharge, the contamination in the lake water is expected to be more pronounced.

#### Impacts on streambed sediments

In order to infer the long-term water quality changes in Akarcay Stream and its probable effect on Lake Eber,

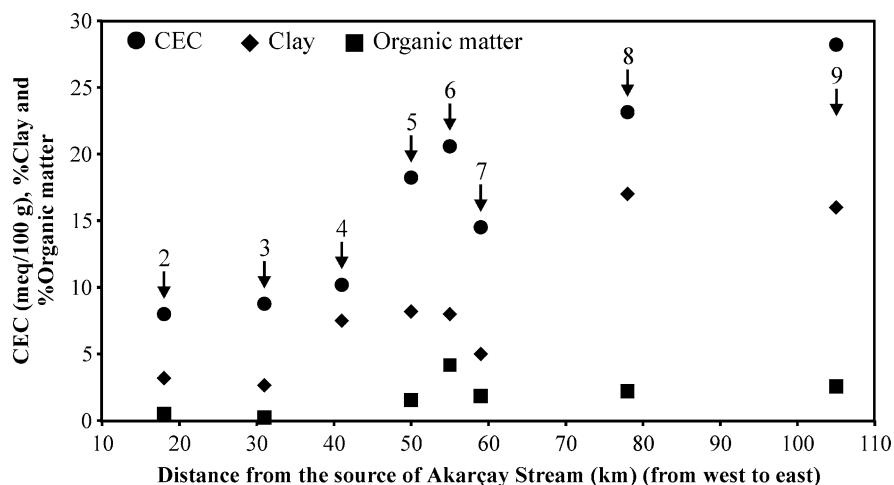
the streambed sediments were also investigated for their cation exchange capacity (CEC) and the amount of cations held as of the summer of 1999. Sediments (and the organic matter contained in them) have strong ion-exchange and sorption capacities. In general, decreasing particle size and increasing amount of organic matter and clay increase the ion-exchange capacity (Appelo 1994). Ion exchange and sorption equilibrium processes are fast and are realized within the time scale of seconds to days. Whether sediment will hold (or exchanged) cations or anions is determined by its mineral composition and the pH of stream water. X-ray powder dif-



**Fig. 7**  
Historical variation of major ion composition at stations 5, 6 and 9 along the Akarçay Stream

fraction analyses of sediments collected from stations 1 thru 9 revealed that montmorillonite and kaolinite are the dominant clay minerals. These minerals act as cations exchangers under the pH of Akarçay Stream (i.e., 7.5 to 8.5). Therefore, only cation exchange seems plausible. Because the sediment tends to be in equilibrium with the existing stream water chemistry, ions are held with approximately the same proportional distribution in water. This leads to a hold of pollution ions (e.g., Na) by sediment and causes a buffering for the spread of pollution in stream water. However, if the

stream-water chemistry is returned back to its natural composition by preventing the entrance of pollution ions, the system will tend to establish a new equilibrium with natural stream water composition by releasing the previously held pollution ions. To determine the magnitude of the problem in Akarçay Stream, CEC and the amount of cations held in sediments have been determined in nine sections. The CEC values range between 8.7 meq/100 g dry sediment and 28.2 meq/100 g dry sediment, and show a general increase trend towards downstream (Fig. 8).



**Fig. 8**  
Variation of clay and organic matter abundance and CEC along the Akarçay Stream (labels refer to station number)

This increase seems to be associated mainly with the increasing amount of clay in the streambed. The decrease in the grain size of the streambed is caused by the decreasing thalweg slope as the stream approaches Lake Eber. Increasing and decreasing CEC anomalies, observed at stations 6 and 7, respectively, are related to the disturbance of the streambed at these locations that led to fine-grained matter accumulation at station 6, and to removal at station 7. In all stations it was found that the sediments were in exchange equilibrium with the chemical composition of the stream water, which has been affected by ATRW (Fig. 9). The increase in Na and K amounts held in sediments is observed between stations 7 and 9 (Fig. 10).

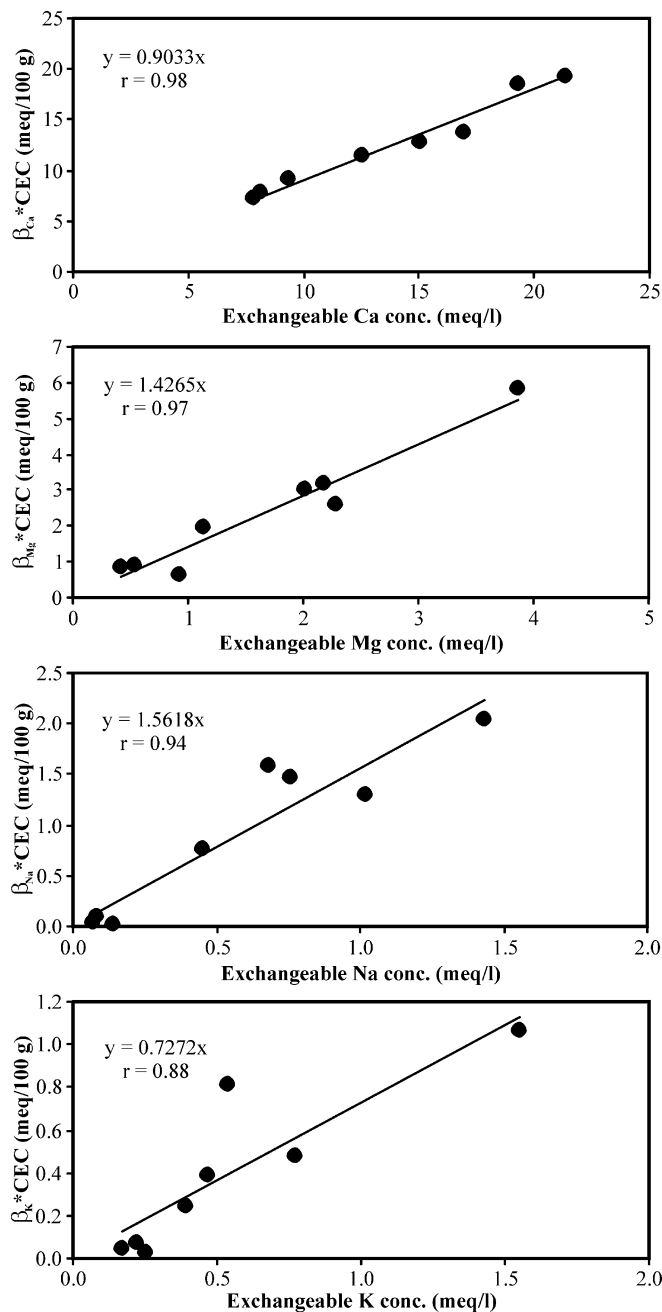
It appears that if ATRW discharge is stopped, the sediment will release Na to reach in equilibrium with Ca-CO<sub>3</sub>-type stream water. The released Na ions will eventually reach in Lake Eber and degrade its quality. By using the average values of streambed CEC (22 meq/100 g), length of the streambed between ATWR and outlet to Lake Eber (50 km), streambed width (10 m), sediment thickness (25 cm), porosity (35%) and particle density (2.5 g/cm<sup>3</sup>), the amount of Na ions to be released from sediments are estimated to be 60.4 t (Dogdu and Bayari 2002b). Similar calculations for other cations showed that re-equilibrium of stream water with Ca-CO<sub>3</sub>-type water will cause 0.05 t of Li, 1.13 t of Fe and 0.66 t of Mn could be released from streambed sediments to Lake Eber.

## Discussion

Geothermal energy is often promoted as an environmentally-friendly and low-cost alternative to fossil fuels that are in common use. Countries like Turkey, where geothermal energy potential is widely available, will tend to use this resource in increasing amounts in the future. However, the geothermal fluids used for their heat content are almost always rich in elements with which our natural environment is not familiar at elevated concentrations.

Release of geothermal fluids in surface environment will apparently lead to damages whose cost may far exceed the benefits gained from the heat energy. For this reason, geothermal fluids brought to surface for any purpose have to be removed from the surface environment by using the most economically feasible way. The cost of removal of these fluids has to be included in any project that aims to utilize this resource. It should be kept in mind that a feasible-looking project aiming to use geothermal heat energy could be unfeasible if the cost of removal is considered.

In the case of Akarçay Basin, the present study shows that release of ATRW has already caused water quality degradation at the current level of operation (i.e., 170 l/s of TW production). When the Afjet project becomes fully operational (i.e., 625 l/s of TW production), environmental consequences will be very detrimental. Removal by re-injection studies, which should have been in operation since 2000, seems to have failed due to the high pressure encountered in injection wells (L. Tezcan, personal communication). Economically and technically feasible alternative removal methods should be implemented within shortest time frame possible. For example, chemical treatment methods may be employed to remove compounds of Na, Li, K, and As etc. Such an approach will not only remove the contaminants from the surface environment, but would also result in additional economic gains. The chemical composition of ATRW (e.g., Li=2.68 mg/l, B=10.64 mg/l, F=13.20 mg/l, Br=18.20 mg/l) allows production of 7.1 t of Li, 28.1 t of B, 34.9 t of F and, 48.1 t of Br per year. Another technically feasible but environmentally questionable solution could be the transport ATRW to Lake Akşehir via a pipeline or a lined channel. Currently, the discharge from Lake Eber to Lake Akşehir is prevented by a weir structure. However, a water release may be possible in the future, if Lake Eber rises to flood neighboring agricultural lands or Lake Akşehir starts to dry up. Although, Lake Akşehir is a salty (EC=6,150 µS/cm), terminal water body, it hosts migrating birds and hence has an ecological value. The consequences of such a



**Fig. 9**

The relationship between exchangeable cations and respective “β<sub>cation</sub> \* CEC” (β<sub>cation</sub>: equivalent fraction) value

solution have to be investigated in detail, in order to not lead to other environmental damage. Another alternative solution to removal of ATRW seems to be sequential precipitation of minerals via evaporation as applied in salt pans. Such techniques have been successfully applied in the Salt Lake located to 200 km to the east in the Central Anatolian Closed Basin where a similar climate prevails. Groundwater chemistry data obtained in this study show that thermal water invades the freshwater aquifer in some places by leakage through overlying aquitard. Proper measures should be taken to eliminate (or slow down) this process. For example, irrigation

water wells already having thermal water contribution could be abandoned and plugged with impermeable material. In addition, the extension of buried faults in the geothermal fields should be taken into account when choosing the locations for new irrigation water wells. Delicate hydraulic head balance between fresh and thermal water aquifers should also be taken into account in basin-wide irrigation water production schemes. In addition, the cessation of thermal water production or re-injection of thermal water to prevent pollution in stream water may also lead to elevated hydraulic pressure in thermal aquifer, which in turn may increase the upward leakage to the freshwater aquifer. Thus, any activity involving these measures should be investigated in detail.

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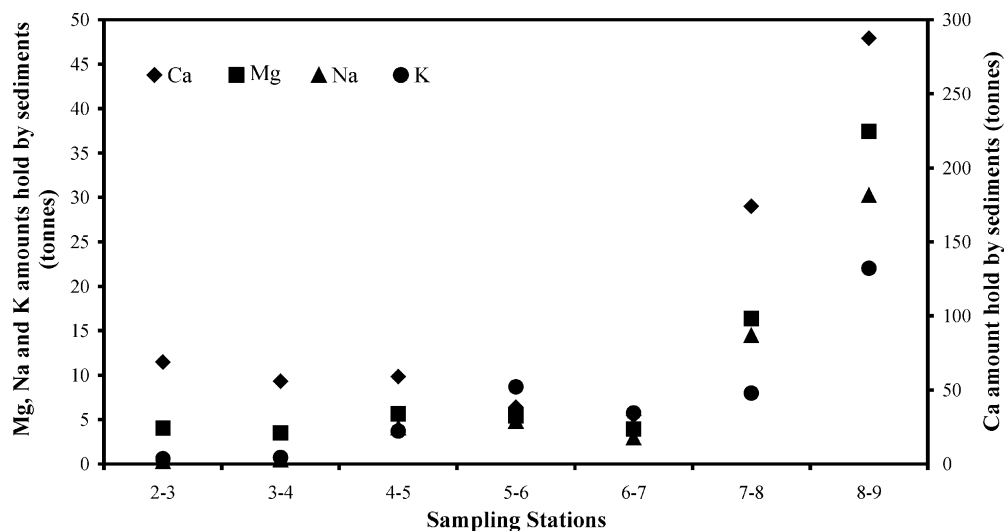


Fig. 10

Variation of sediment-held major cations between successive sections of the Akarcay Stream

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