ELSEVIER

Journal of Hydrology 166 (1995) 171–191

Journal of Hydrology

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Determination of the origin of the waters of Köyceğiz Lake, Turkey

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Received 30 July 1993; revision accepted 6 June 1994

Abstract

The Köyceğiz Lake in south-western Turkey is a meromictic lake, comprised of waters of both thermal and cold-karstic origin. The lake is principally fed from surface flow, ground water recharge from alluvium and thermal discharges located at the bottom of the lake. As indicated by physical and chemical observations, the lake is composed of two hydrochemically distinct water layers. There is a transition zone between these two layers at a depth of approximately 10 m. The bottom layer, which contains more mineralized water, is recognized easily by the smell of hydrogen sulfide gas. A decrease in pH and dissolved oxygen and an increase in specific conductivity and ionic constituents are observed at the transition zone in depth profiles at all measurement sites throughout the year. The isotopic compositions of the representative observation points widely scatter and indicate the mixing of thermal and cold-karstic waters. As indicated by satellite imagery data, the morphology of the lake shores are primarily controlled by structural elements, which are mostly normal faults. Echo-sounding profiles point out that some of the fault lines, along which the lake bottom springs seem to be located, extend through the lake bottom. Current velocity observations also indicate possible sites of thermal ground water discharges located at the lake bottom.

1. Introduction

The Köyceğiz Lake, between the towns of Köyceğiz and Dalyan in south-western Turkey (Fig. 1), stimulates international concern as it is included within the area where rare and endangered loggerhead turtles (*Caretta caretta*) nest (Baran and Kasparek, 1989).

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SSDI 0022-1694(94)02554-O

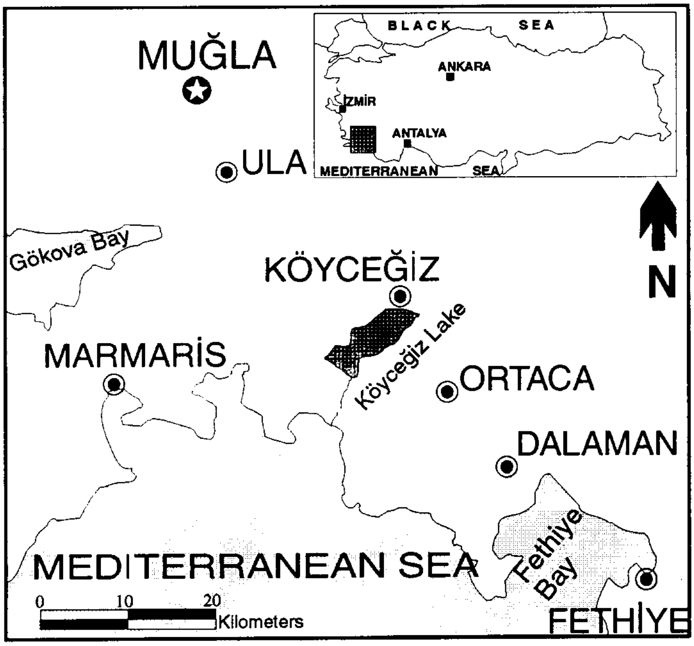


Fig. 1. Location map of the Köyceğiz Lake Basin.

The ecological value of the region was made public by Kinzelbach and Schemel (1987), and the area is designated as a national reservation area to be administrated by the Authority of Specially Protected Areas. As a result of its special ecological value and the natural beauty of the region, this area is among the most attractive tourist sites on the Mediterranean coast of Turkey. The Köyceğiz Lake, fed by a series of surface and ground water inflows, discharges through a meandering channel into the Mediterranean Sea. The zone between the lake and the sea, in which fish breeding is the major local activity, is a typical estuary.

The lake is in the downstream part of the Köyceğiz Lake Basin covering an area of 1160 km^2. The annual water level fluctuations of the lake is between 1.5 and 2.5 m and its average surface area is about 55 km^2. The average lake volume is around $860 \times 10^6 m^3$. The water depth generally ranges between 1 and 30 m, but several local depressions with depths of 70 m were also discovered. As the area has a complicated aquatic structure, it has been subject to many hydrobiological investigations (Kazancı et al., 1992a). The study by Kazancı et al. (1992b) determined the basic structure of the aquatic ecosystem in Köyceğiz Lake and showed that a dominant hydrogen sulfide-rich zone exists beneath the upper 10 m layer. This is in agreement with the existence of thermal springs scattered around the lake (Istanbul University, 1975; Yeşertener, 1986).

Although the previous hydrogeologic studies (Tansuğ and Öztunalı, 1976; Yeşertener, 1986; Eraslan, 1991) state that there are a number of karstic and thermal springs around the lake, the origin of the lake water has not been determined yet. The determination of the origin of waters is of utmost importance from the point of view of protecting the lake from pollution and understanding the effect of present conditions upon the existing aquatic ecosystem.

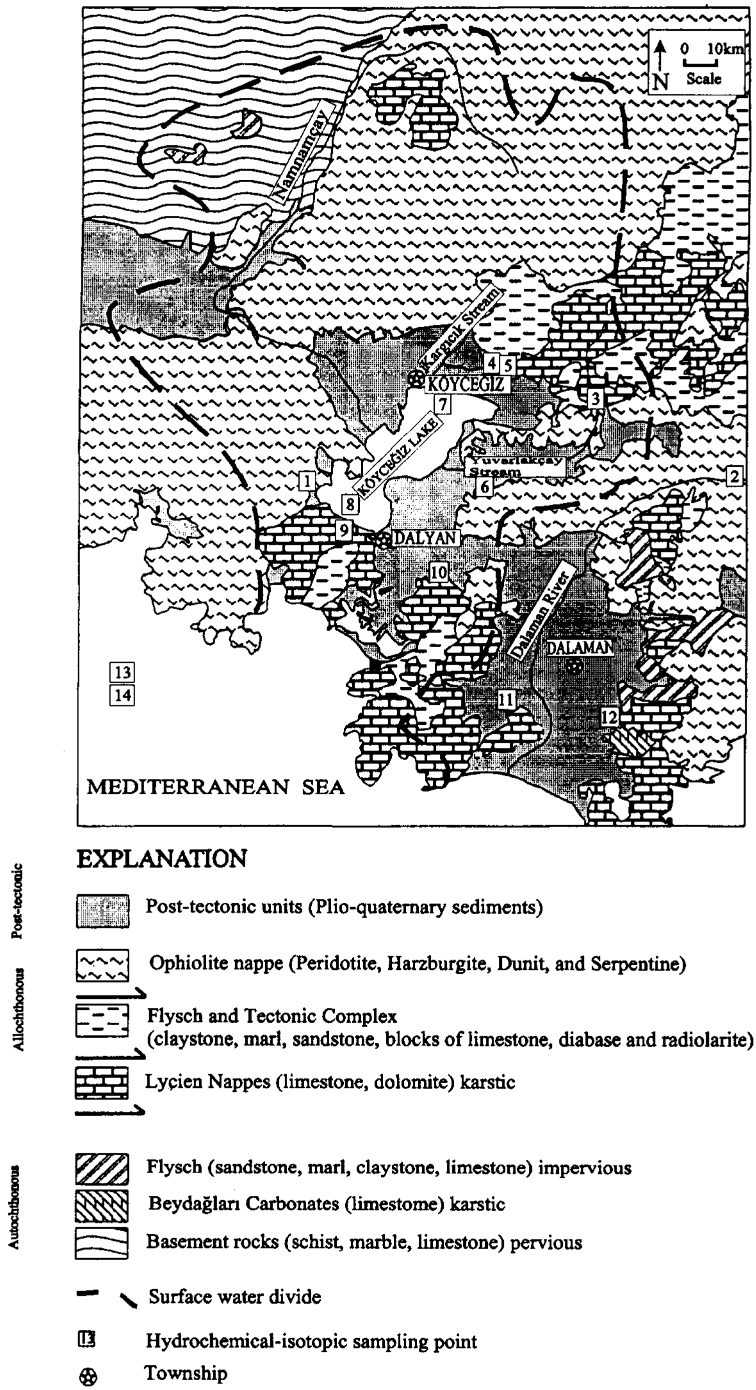
2. General geology, hydrogeology and hydrology

2.1. Geologic setting

The Köyceğiz Lake Basin is at the western end of the Taurus tectonic belt. Graciansky (1968, 1972), in his studies of an area covering the Köyceğiz Lake Basin, determined that the geologic structure is composed of three structurally different sequences of rock units, namely autochthonous carbonates and detritics, allochthonous Lycien Nappes, and ophiolite nappe (Fig. 2). The post-orogenic sediments of Plio-quarternary age overlie these units. The tectono-stratigraphic sequence starts with the autochthonous Beydağları carbonates of Cenomanian–Early Miocene age. This formation is made up of thinly bedded micritic limestones and thick bedded calcarenites. A Miocene flysch, comprised of alternating sequences of claystone, marl, sandstone and limestone, conformably overlies the Beydağları Formation. Small outcrops of autochthonous sequence are observed in the north-western part of the Köyceğiz Lake Basin. The Lycien Nappes, which tectonically overlie the autochthonous sequence, are made up of limestone formations, each coming from a different paleogeographic origin and containing various stratigraphic units (Graciansky, 1968; 1972). Another nappe unit, called the tectonic complex, lies tectonically over the Lycien Nappes. The tectonic complex includes blocks of limestone, radiolarite and diabase. The ophiolite nappe, comprised of peridotites, dunites, harzburgites and serpentine, locally overlies the former geologic formations, where they formed lowlands during the emplacement of the ophiolite nappe.

Graciansky (1972) stated that the lateral tectonic movements, which were responsible for the nappe settlement, terminated in the Late Miocene period and later on, the vertical (mostly normal) faulting started to occur. The present morphology of the basin was produced as a consequence of the vertical tectonic activities. As a result of the vertical tectonic movements, a number of normal faults trending NE–SW and forming horst–graben structures throughout the basin formed. During the Pliocene, the lowlands (grabens), which form the Köyceğiz and Dalaman Plains, were filled with terrigenous material comprised of marl, conglomerate and limestone. The Köyceğiz Lake started to form during the Plio-Quaternary time as a result of the clogging of the channel between the lake and the sea.

The region, which was characterized by extensive tectonic activity in geologic time was also struck by many earthquakes during historic times. Soysal et al. (1981) stated that numerous destructive earthquakes with intensities of VII–IX (Mercalli–Sieberg scale) had occurred during the period 2000 BC–AD 1900. Kocaefe and Ataman (1976) pointed out that the seismic activity is still going on and strike-slip faults extending NW–SE are still being formed as a result of the present tectonic activity.



0 10km
N
Scale
Namnamçay
Kargıcık Stream
KÖYCEGIZ
KÖYCEĞİZ LAKE
Yuvarlakçay Stream
DALYAN
Dalaman River
DALAMAN
1
2
3
4
5
6
7
8
9
10
11
12
13
14
MEDITERRANEAN SEA
EXPLANATION
Post-tectonic
Post-tectonic units (Plio-quaternary sediments)
Allochthonous
Ophiolite nappe (Peridotite, Harzburgite, Dunit, and Serpentine)
Flysch and Tectonic Complex
(claystone, marl, sandstone, blocks of limestone, diabase and radiolarite)
Lyçien Nappes (limestone, dolomite) karstic
Autochthonous
Flysch (sandstone, marl, claystone, limestone) impervious
Beydağları Carbonates (limestome) karstic
Basement rocks (schist, marble, limestone) pervious
Surface water divide
Hydrochemical-isotopic sampling point
Township

The thermal springs located in and around the basin could have been associated with recent faulting extending down to the basement rocks.

2.2. General hydrogeology

The major water-bearing formations within the Köyceğiz Basin are the allochthonous limestone formations (Lycien Nappes) and the Plio-Quaternary alluvium. While the alluvium is fed only by rain and seepage from limestone, the allochthonous limestone is also fed by underground drainage from the northern part of the Dalaman Basin located to the north-east (Tansuğ and Öztunalı, 1976; Yeşerterner, 1986). The ophiolite nappe, which crops out in most of the basin, is practically impermeable and is, therefore, not significant from the hydrogeologic point of view. The springs discharging from this unit are of local origin. The thermal and karstic springs discharge from allochthonous limestone where it is intersected by faults. The thermal springs are located in the southern part of the basin, whereas most of the karstic springs are located in the north-eastern part.

2.3. Regional hydrology and lake water budget

Typical Mediterranean climate with hot and dry summers and mild and wet winters prevails in the area. Based on the long-term average data, the mean annual precipitation over the basin is 1202 mm. The mean annual temperature is about 18°C. Major streams draining various geologic units discharge into the Köyceğiz Lake which in turn discharge its waters into the Mediterranean Sea via a 14 km long, meandering channel. The Namnamçay and Yuvarlakçay streams are the major surface waters in the basin. No serious long-term water level changes have been observed in the Köyceğiz Lake (Eraslan, 1991).

Streams, alluvial groundwater and rain are the important sources that feed the lake. On the other hand, the evaporation from the lake surface and the discharge into the Mediterranean Sea via the Dalyan Channel are the main component of the outflow from the lake. Eraslan (1991), on the basis of long-term meteorologic and streamflow data, found that the recharges from rain, stream flow, and loss by evaporation amount to 66.1×10^6, 636.4×10^6 and $56.1 \times 10^6\, m^3\, year^{-1}$, respectively. Tansuğ and Öztunalı (1976), considering the average values of hydraulic gradient, groundwater level changes and the transmissivity, stated that the recharge from alluvium is of the order of $14.2 \times 10^6\, m^3\, year^{-1}$. By using average values of roughness coefficient, hydraulic gradient and channel cross-section, the outflow through the Dalyan Channel was found to be $1031.2 \times 10^6\, m^3\, year^{-1}$ (Eraslan, 1991). The flow velocity values given in his calculations are in accordance with those measured by İller Bank (1983) at the exit point where the Köyceğiz Lake discharges into the Dalyan Channel.

Because no serious water level changes occur in the lake, the lake volume is

Fig. 2. Geologic map of the study area (modified after Eraslan, 1991; numbers are keyed to Table 1).

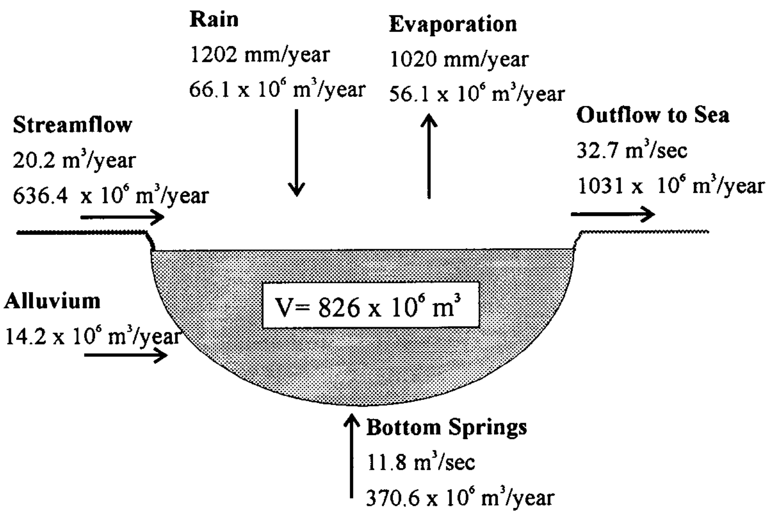


Fig. 3. The lake water budget.

assumed to be constant in the long-term. Hence the variation in storage is assumed to be zero and, the lake water balance equation can be given by the following equation:

$$S + R + Gw + Bs = Ep + Q_{\text{out}} \qquad (1)$$

where S is the streamflow into the lake, R is the rainfall over the lake, Gw is the groundwater inflow through the alluvium, Bs is the groundwater inflow through the lake bottom springs, Ep is the evaporation from the lake surface and Q_{out} is the outflow from the lake into the Mediterranean Sea.

The only unknown parameter in Eq. (1) is the groundwater inflow by lake bottom springs (Bs). As explained in the succeeding parts of this paper, the existence of the lake bottom springs has been proven by different approaches. However, because they are scattered along the lake bottom, it is not possible to determine their total discharge rate by means of the classical measurement techniques. By using average values of known parameters in Eq. (1), the amount of inflow through the lake bottom springs is calculated to be 370.6×10^6 m^3 year^{-1}. The components of the lake water balance are shown in Fig. 3. Although, the precision of the meteorological and streamflow data used in Eq. (1) is around 10% (Eraslan, 1991), it is obvious that an important amount of water must be supplied by lake bottom springs in order to balance the inflows and outflows.

3. Methods of study

A wide variety of investigation techniques and data were adopted and used for the determination of the origin of the Köyceğiz Lake waters. These include hydrochemical, environmental isotopic, satellite imagery, echo-sounding and water current velocity data.

Water samples were collected and analysed according to standard methods (APHA et al., 1989). The chemical data (three samples) taken from previous studies were also reported to be sampled and analysed according to standard methods (İstanbul University, 1975; UKAM, 1991). The existence of hydrogen sulphide in the water was determined qualitatively by using Merck's lead (II) acetate paper. Water samples for environmental isotopic analysis were also collected from the field according to procedures set by the International Atomic Energy Agency (IAEA) (UKAM, 1991). The isotopic analyses were made by the IAEA Isotope Hydrology Section, Vienna, Austria.

The SPOT imagery data, in the form of digital numbers (DNs) used in this study were extracted from SPOT1 HRV2 Sensor multispectral full scene data (imaged on 7 June 1990, WRS 102-276/0). The digital imagery data were processed on a PC-based digital image processing system, using ERDAS image processing program. The data were enhanced and interpreted for linear features and subtle reflectance variations over the lake, which might indicate possible sites of ground water inflow to the lake.

Echo-sounding profiles were taken to determine the physical variations along the lake bottom. For this purpose, and echo-sounder with an 8° narrow angle transducer was used. The current velocity and direction data were taken from a previous study performed by İller Bank (1983), and correlated with the results of this paper.

4. Results and discussion

4.1. Regional hydrochemistry

There are five hydrochemically different types of water in the study area. These are (i) cold karstic or associated waters, (ii) the Sultaniye thermal spring in the Köyceğiz Lake Basin, (iii) the thermal springs in the Dalaman Basin (iv) the lake waters and (v) sea water. Plausible interactions among the hydrochemically different types of waters existing in the study area are evaluated through the trilinear diagram given in Fig. 4.

4.1.1. Cold karstic and associated waters

Cold karstic and associated waters include Değirmenbaşı (1), Yuvarlakçay (3), Yangı (4), Asar (5), Ada (6) and, Marmarlı (10) springs (numbers are keyed in Table 1). These springs, which are located around the Köyceğiz Lake, are fed from karstic aquifers. Their chemical compositions (Ca > Mg > Na > K and HCO_3 > SO_4 > Cl) indicate a typical rock–water interaction observed in carbonate aquifers. These springs discharge either from limestones or along the contact between limestone and ophiolite or alluvium. The Dalaman River (2) is also assumed to be a karstic water, because its discharge is supplied by karstic discharges distributed along the stream bed. Yeşertener (1986) states that, except during the wet period when precipitation supplies some of the discharge, most of the discharge of Dalaman River is supplied by karstic discharges.

On the central diamond of the trilinear diagram (Fig. 4), the left-hand part is

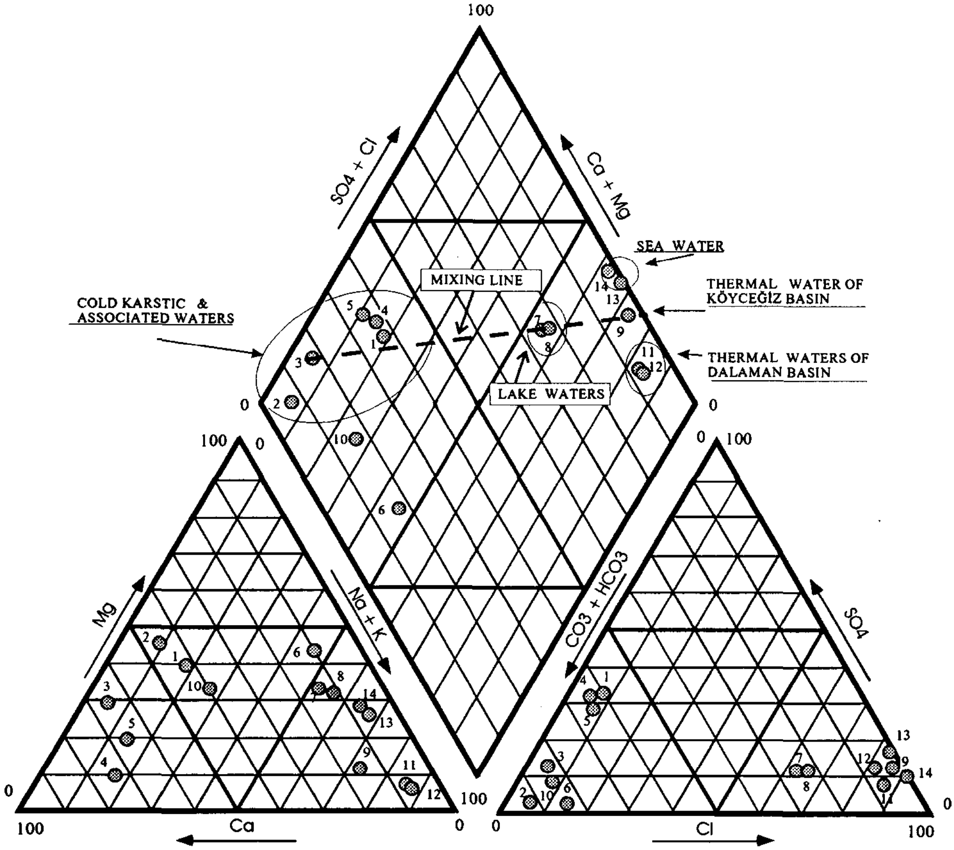


Fig. 4. Trilinear diagram of the selected water samples (numbers are keyed to Table 1).

occupied by cold karstic and associated waters comprising of samples from the Değirmenbaşı (1), Yuvarlakçay (3), Yangı (4), Asar (5), and Marmarlı (10) springs and the Dalaman River (2). The Ada spring (6), which is a member of this group, however, occupies a distinct position. Its position implies that this water has been subject to certain geochemical processes, such as cation-exchange and sulfate reduction. Since this spring discharges from the contact with limestone and alluvium, it is possible that some of the original calcium and magnesium may have been replaced by sodium present in alluvial deposits. On the other hand, it seems that some of the original sulfate might have been reduced by some means (e.g. bacterial activity).

4.1.2. Thermal waters of the Köyceğiz Lake and Dalaman Basins

There are three thermal springs in the area. The Sultaniye thermal spring (9) discharges from limestone and is located 50 m from the shore at the southern part of the lake. The Kükürtlüsu (11) and Cumabeleni (12) springs are located in the Dalaman River Basin. Although the chemical compositions of the thermal springs

(Na > Mg > Ca > K and Cl > SO_4 > HCO_3) are somewhat similar, the chemical composition of the Kükürtlüsu and Cumabeleni springs are more similar to each other. The Sultaniye thermal spring has slightly higher ionic composition. Yeşertener (1986) points out that the thermal springs in the Dalaman basin also emerge from the karstic limestone aquifer in which mixing with sea water occurs.

On the basis of several geothermometer equations given by Fournier (1989), the reservoir temperature of the Sultaniye thermal spring ranges between 117.3 and 148.5°C. Instabul University (1975) reports that this spring has the highest radon-222 content (12 612 pCi l^{-1}) when compared with the other thermal springs in Turkey. Moreover, all the thermal springs have considerable hydrogen sulfide content. The hydrogen sulfide content of thermal springs ranges between 8 and 11 mg l^{-1}.

The thermal springs are located on the right-hand part of the central diamond on Fig. 4. The positions of the thermal springs of the Dalaman Basin (11, 12) is quite close on the central diamond. The thermal water of Köyceğiz Basin, the Sultaniye spring (9), is located slightly above these waters. This indicates that, although they are fed from the same karstic aquifer, the geochemical processes affecting the evolution of thermal waters in the Dalaman and Köyceğiz Lake Basins are not similar. This conclusion is also supported by the environmental isotope data. As explained in the following sections, the isotopic compositions of the thermal springs in Köyceğiz Lake and Dalaman Basin are quite different.

4.1.3. Lake waters

The composite water chemistry of the Köyceğiz Lake in the northern and southern sectors is represented by samples 7 and 8. Their chemical composition (Na > Mg > Ca > K and Cl > HCO_3 > SO_4) differs remarkably from those of all the other waters. The ionic composition of the lake water samples suggests that they could be formed by the mixing of karstic and thermal discharges. The samples from Köyceğiz Lake occupy a distinct position among all the other waters on the trilinear diagram (Fig. 4). They plot along the mixing line between the Yuvarlakçay karstic spring (3) and the Sultaniye thermal spring (9), which are assumed to be typical karstic and thermal waters in the Köyceğiz Lake Basin.

4.1.4. Sea water

The sea water samples taken in autumn 1986 (14) and in spring 1987 (13) exhibit the typical chemistry (Na > Mg > Ca > K and Cl > SO_4 > HCO_3) of the Mediterranean Sea in the close vicinity of the study area. The chemical compositions of both samples are similar. The sea water samples are also closely located on the right-hand side of the central diamond (Fig. 4). Their proximity on the graph suggests that, although each sample represents the chemical composition of sea water in wet and dry seasons, the chemistry of sea water changes little with time. This is probably due to the buffering effect of sea water.

4.2. Hydrochemical stratification in the lake

The physical and chemical measurements made in the lake at various depths and

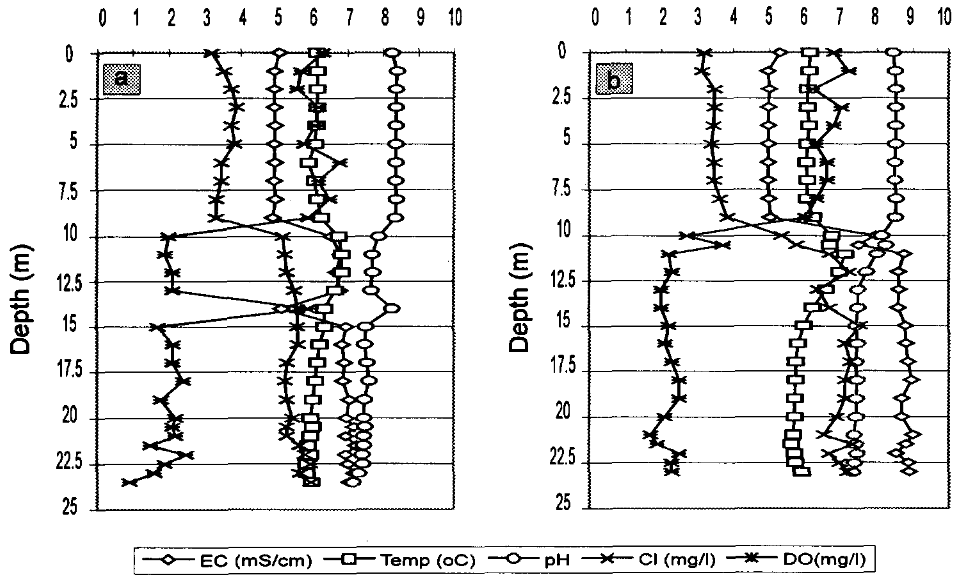


Fig. 5. Variation of some physical and chemical parameters with depth in (a) the northern and (b) the southern part of the lake. (Temperature and chloride data are reduced 3 and 1000 times respectively.)

times, indicate that the water body has two distinctive layers, separated by a transition zone (Figs. 5(a) and 5(b)). The first layer, extending from the lake surface to a depth of 10–12 m, is composed of relatively less mineralized water. The bottom layer, which begins at a depth of approximately 10–12 m beneath the surface, is characterized by hydrogen sulfide, and contains more saline water. Although the variation of physical and chemical parameters within each layer is relatively homogenous, there is an apparent shift along the transition zone between the top and bottom layers. Kazancı et al. (1992b) suggested that the lake can be classified as meromictic.

Figs. 5(a) and 5(b) show the typical summer-time variation of some physical and chemical parameters with depth at the northern and southern parts of the lake, respectively. Regardless of the time of measurement, the dissolved oxygen and pH values start to decrease just below the boundary between the top and bottom layers. However, the electrical conductivity and chloride content increase with depth. The variation of other ionic species is similar to chloride. Detailed evaluation of the ionic species with depth is given by Kazancı et al. (1992a). The increase in electrical conductivity and the decrease in pH and dissolved oxygen values in the bottom layer is attributed to the more saline water input occurring at the bottom of the lake. The possible sources of the waters that are more saline than the cold karstic waters are sea water and the thermal springs existing in the basin. The contribution of sea water to the bottom layer is not anticipated because the pH and dissolved oxygen values of this layer are lower than that of sea water. If a considerable amount of sea water had been contributed to the lake, higher pH and dissolved oxygen values would have occurred in this layer. The pH and the dissolved oxygen content of sea water are slightly above 8 and around 7.5 mg l^{-1}, respectively. However, the pH and dissolved oxygen values corresponding to the bottom layer are 7.1–7.2 and 1.0–2.2 mg l^{-1} respectively. Although some variation in dissolved oxygen content may be accepted due to the redox reactions that may occur in this zone, the pH should not change at all, because the sea water has a strong buffering effect against pH changes. On the other hand, the pH and dissolved oxygen content of the Sultaniye thermal spring (pH = 6.6, DO = 1 mg l^{-1}) located about 50 m away from the southern coast of the lake resemble those of the bottom layer (pH = 7.2, DO = 1–2 mg l^{-1}).

Another piece of hydrochemical evidence that supports the idea of thermal water input into the bottom layer is the presence of hydrogen sulfide along the lake floor. During all the depth-specific measurements, hydrogen sulfide has been determined semi-quantitatively within a zone of several meters above the lake bottom and along the 1 m deep transition zone between the bottom and top layers. Kazancı et al. (1992b) points out that the hydrogen sulfide content at the lake bottom (3–5 mg l^{-1}) is higher than that of the transition zone in which the hydrogen sulfide content decreases to 1–2 mg l^{-1}. Among the all cold and thermal ground waters in the area, only the thermal springs have considerable hydrogen sulfide content. For example, the hydrogen sulfide content of the Sultaniye thermal spring (9) was reported to be 11.06 mg l^{-1} (İstanbul University, 1975). Yeşertener (1986) states that the hydrogen sulfide content of the Cumabeleni and Kükürtlüsu thermal springs are in the ranges 3–5 and 6–8 mg l^{-1}, respectively. Therefore, the presence of hydrogen sulfide-rich water in the bottom layer can be accepted as evidence for thermal water input. As sea water is a slightly alkaline solution (Garrels and Christ, 1965), the hydrogen sulfide gas concentration in sea water cannot reach appreciable amounts under usual circumstances.

4.3. Environmental isotope data

In order to understand the relationships between the various types of waters existing in the Köyceğiz Lake Basin, environmental isotopic data of 14 water samples have been used (Table 1). Fig. 6, showing the δD and $\delta^{18}O$ values of water samples, gives some evidence on the possible physical processes influencing these waters. As inferred from the graph, the water samples are plotted in five different regions. These are (i) cold karstic and associated waters, (ii) thermal waters of the Dalaman Basin, (iii) Köyceğiz Lake waters, (iv) thermal water of the Köyceğiz Lake Basin (the Sultaniye thermal spring) and (v) sea water. It is interesting to note that the water samples show a similar grouping both in the trilinear diagram and in the $\delta D/\delta^{18}O$ graph.

The cold karstic and associated waters fit a straight line called the Local Meteoric Water Line (LMWL) with a deuterium excess value of +18. This value is higher than that of the global meteoric line with a deuterium excess value of +10 (Craig, 1961). High deuterium excess values are encountered in areas where clouds are formed as a result of fast evaporation from the sea surface (Gat and Carmi, 1970). Gat and Carmi (1970) determined that high deuterium excess values are observed in the eastern Mediterranean region. This suggests that the karstic springs in the basin are fed by

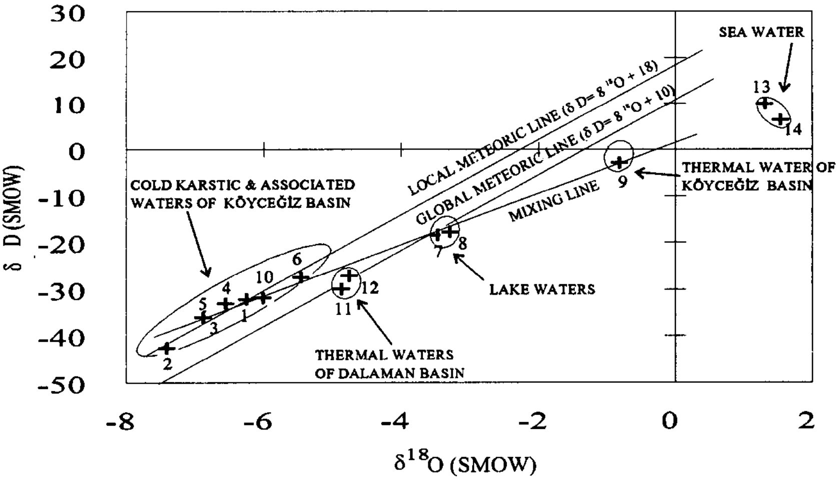


Fig. 6. Deuterium vs. Oxygen-18 plot of the water samples (numbers are keyed in Table 1).

precipitation formed over the Mediterranean Sea. As deuterium excess values ranging between +10 and +14 are observed in the inland parts of Turkey (Günay and Bayarı, 1989; Bayarı and Gürer, 1991), it appears that continental precipitation from the north and north-east does not make a significant contribution to the recharge of karst waters in the area.

The cold karstic and associated waters have tritium contents ranging between 7.9 and 15.0 TU. Tritium contents of these waters suggests that similar values are observed in springs that exhibit similar recharge and ground water circulation conditions. For example, the tritium contents of the Yuvarlakçay karstic spring (3) and the Dalaman River (2), which are fed from the same karstic aquifer (Yeşertener, 1986) extending to the northeast of the basin, are 14.0 and 13.8 TU, respectively. Similarly, the springs located around the Köyceğiz Lake (Yangı (4), Asar (5) and Değirmenbaşı (1)) also present similar tritium contents (10.5, 9.6 and 10.9 TU, respectively). Moreover, the Ada spring (6), which is also close to the Köyceğiz Lake, has a different hydrochemical and isotopic composition. It seems that there is a slight lake and/or thermal water contribution to this spring.

The thermal waters of the Dalaman Basin (Cumabeleni (11) and Kükürtlüsu (12) springs) plot slightly below the LMWL. This situation arises frequently in waters of geothermal reservoirs, where oxygen-18 exchange occurs between the aquifer and ground water, and in open water bodies where isotopic enrichment due to fast evaporation exists (Gat et al., 1968; Molinari, 1977). Water samples that have been altered by evaporation plot along straight lines with slopes ranging between 4 and 6 on the $\delta D/\delta^{18}O$ graphs (Gat, 1971). Because the pools that form at the discharge point of these springs are quite small, no serious isotopic enrichment owing to evaporation is anticipated for these waters. Therefore the thermal waters of Cumabeleni and Kükürtlüsu, which plot below the LMWL, might be evaluated as having the same origin as the cold karstic and associated waters which plot on the LMWL. This means that, if some portion of the karstic ground water feeding Değirmenbaşı, Marmalı and

Table 1
Physical, chemical and environmental isotopic data of the selected water points

Water point	T (°C)	pH	EC ($\mu S\,cm^{-1}$)	Ca	Mg	Na	K	Cl	SO_4	HCO_3	$\delta^{18}O$ (SMOW)	δ^2H (SMOW)	^3H (TU)	^3H error	H_2S ($mg\,l^{-1}$)	Source[b]
1 Değirmenbaşı spring	16.5	7.8	698	2.1	2.0	0.9	0.0	0.4	1.4	2.8	−6.25	−32.2	10.9	±0.6	nd	1
2 Dalaman River (at Akköprü)	21.0	8.2	560	2.9	2.8	0.4	0.1	0.4	0.1	5.3	−7.41	−42.6	13.8	±0.6	nd	1
3 Yuvarlakcay spring	13.2	8.0	328	2.4	1.1	0.1	0.0	0.2	0.4	3.0	−6.86	−35.8	14.0	±0.6	nd	1
4 Yangı spring	16.0	7.9	730	3.6	0.5	0.8	0.0	0.4	1.6	3.0	−6.55	−33.1	10.5	±0.6	nd	1
5 Asar spring	16.0	7.9	670	2.7	0.8	0.1	0.4	0.4	1.3	2.7	−6.88	−36.0	9.6	± 0.6	nd	1
6 Ada spring	20.0	8.5	656	0.6	2.7	2.8	0.0	0.7	0.1	4.2	−5.46	−27.5	7.9	±0.6	nd	1
7 Köyceğiz Lake (North)	18.4	8.3	5080	6.0	18.0	25.2	1.6	38.0	7.0	11.0	−3.47	−18.5	13.2	±0.6	1–5	2
8 Köyceğiz Lake (South)	18.4	8.4	5290	5.4	17.6	28.1	1.8	39.0	7.0	11.5	−3.29	−17.9	12.5	±0.5	1–5	2
9 Sultaniye thermal spring	41.9	6.6	41255	78.2	53.8	360.5	10.2	454.2	57.9	5.3	−0.81	−2.9	1.0	±0.5	11	3
10 Marmarlı spring	19.0	8.3	602	2.0	1.8	1.3	0.0	0.5	0.5	4.6	−6.01	−31.9	15.0	±0.3	nd	1
11 Kükürtlüsu thermal spring	30.0	6.6	18321	11.0	14.0	128.5	1.3	132.0	11.7	10.0	−4.87	−30.0	5.8	±0.6	5–7	1
12 Cumabeleni thermal spring	30.5	6.4	16361	9.3	11.5	112.1	1.1	109.6	15.6	8.4	−4.76	−27.2	3.3	±0.4	3–5	1
13 Mediterranean Sea May 87	17.5	8.3	50000	25.0	105.3	262.2	5.4	427.9	69.1	3.0	1.31	9.89	3.6	±0.4	nd	4
14 Mediterranean Sea Nov. 86	20.5	8.1	50000	25.3	106.7	242.2	1.2	387.1	42.0	3.2	1.54	6.38	3.0	±0.4	nd	4

[a] Chemical analysis are reported in $meq\,l^{-1}$.
[b] Chemical data sources are (1) Yeşertener (1986), (2) Kazancı et al. (1992b), (3) Istanbul University (1975), (4) IAEA, unpublished data 1988. Environmental isotope data were taken from UKAM (1991), nd: not detectable.

Yangı springs goes on to circulate through the deeper parts of the aquifer, their isotopic composition will be changed by geothermal exchange. When this ground water flows toward the surface, it could have a δD–$\delta^{18}O$ composition similar to those of the Cumabeleni and Kükürtlüsu thermal springs. Therefore, it may be assumed that the thermal waters of the Dalaman Basin were originally karstic in origin but have been enriched both chemically and isotopically during their travel through the karstic aquifer. Their relatively long residence time, as indicated by the low tritium contents (5.8 and 3.3 TU, respectively) and the relatively high temperature (30–30.5°C), also supports the idea that these waters have sufficient time to permit the isotopic exchange between the ground water and the aquifer rock. However, these waters may have also been formed as a result of local mixing of cold karstic waters with some higher temperature ground waters.

The Sultaniye thermal spring occupies a distinct position on the $\delta D/\delta^{18}O$ graph. Compared with the thermal springs in the Dalaman Basin, this spring obviously has a different origin. Considering its quite low tritium content (1.0 ± 0.5 TU), an accountable juvenile water contribution to this water can be suggested. Although it is located along the possible mixing line between the sea water and the other cold-karstic ground waters, it is not likely that this water was formed by the simple mixing of these end members. If such a mixing had occurred, the tritium content of the Sultaniye thermal spring (1.0 TU) should be in between that of the sea water (3.0–3.6 TU) and the cold karstic and associated waters (7.9–15.0 TU).

Like the thermal waters of the Köceğiz and Dalaman Basins, the lake water samples also plot below the LMWL on the $\delta D/\delta^{18}O$ graph. It is also interesting to note that the lake waters are located along a possible mixing line between the cold-karstic waters and the Sultaniye thermal spring. The tritium contents of the lake water samples (12.5 and 13.2 TU) are in between those of suggested end-members (7.9–15.0 and 1.0 TU). Assuming that the cold-karstic and the thermal waters around the Köyceğiz Lake can be represented by the Yuvarlakçay karstic (3) and the Sultaniye (9) springs, the mixing line can be drawn between these end-members (see Fig. 6). As the lake waters have been collected from depths of several meters below the surface, it is not expected that they have been subject to accountable evaporation. Therefore, their position on the $\delta D/\delta^{18}O$ graph is attributed to the mixing of end-member waters rather than isotopic enrichment due to evaporation.

The sea water samples occupy a typical position on the upper right-hand corner of the $\delta D/\delta^{18}O$ graph. As indicated above, the proximity of the sea water samples to that of the Sultaniye thermal spring is completely fortuitous, and any mixing between them seems impossible. However, some contributions of fossil sea water to this spring seems possible. The isotopic composition of pore water in the buried sediments or rocks may be markedly affected, if the amount of trapped sea water is similar to or smaller than that of the minerals. This situation may exist in the case of pore waters in relatively impermeable rocks or in sedimentary reservoirs with restricted circulation (Savin, 1980). The δD and $\delta^{18}O$ analysis of pore waters recovered from the cores of the Deep Sea Drilling Project (DSDP) indicates that there is a depletion of both ^{18}O and deuterium with increasing depth of burial (Friedman and Hardcastle, 1973). Considering the high discharge rate ($100\,l\,sec^{-1}$) and the radon-222 content

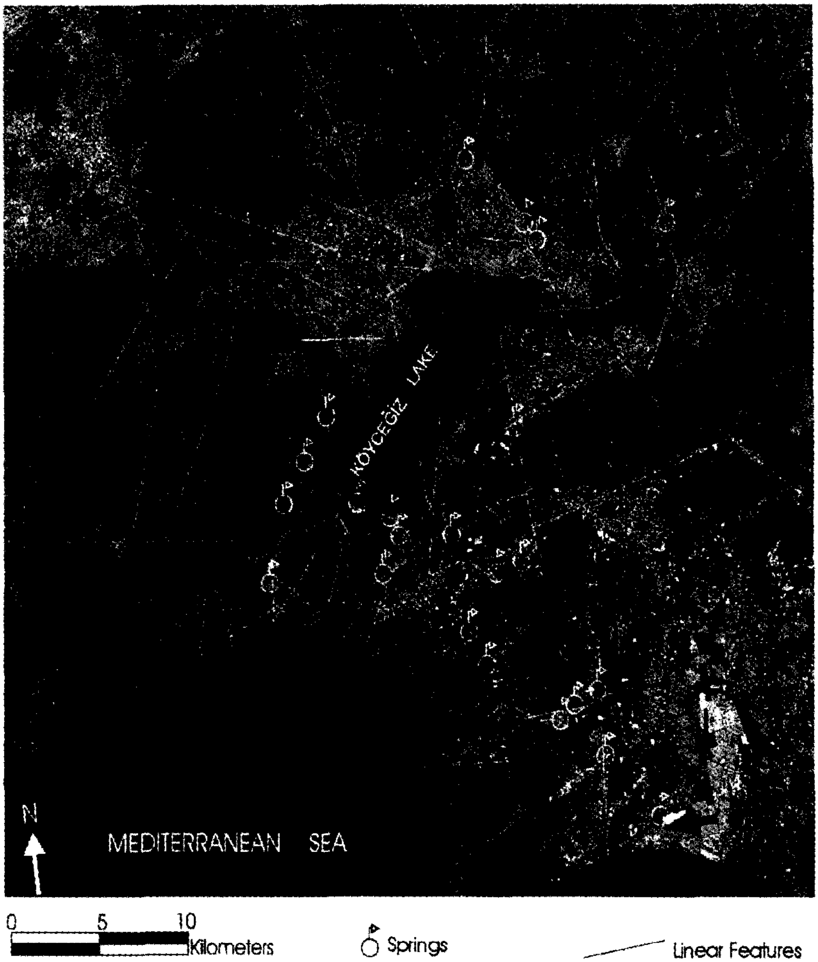


Fig. 7. SPOT-XS3 image showing the interpreted lineaments and the springs of the study area.

(12 612 pCi l^{-1}) of the Sultaniye spring, it may be concluded that this water is of deep-thermal origin, but there may also be some contribution from the fossil sea water.

4.4. Satellite imagery data

Possible sites of ground water inflow to the Köceğiz Lake were interpreted from the lineament analysis of the study area and vicinity. The lineaments observed on the enhanced satellite image show that the lake shores are shaped by regional fractures extending in the NE–SW and EES–WWN directions (Fig. 7). Most of these fractures were field checked and determined to be normal faults. On the other hand, it is interesting that all of the thermal and karstic springs in the basin discharge from allochthonous limestone at places where this unit is intersected by fractures. The observations suggest that there is a strong structural control on the ground water movement in the Köyceğiz Basin and its vicinity.

Spectral reflectance differences from the lake surface are strongly correlated with possible bottom spring locations, which are indicated by physical, chemical, echo-sounding and current velocity observations made in the lake. Places where physical, chemical and current velocity data strongly suggest the emergence of thermal water are darker on the satellite imagery. In conclusion, remotely sensed imagery data were found to be quite a useful tool in the analysis of hydrogeologic and geologic characteristics of the basin. The use of thermal infrared data, which is not available with SPOT, could help to locate the sites of bottom springs owing to anomalous temperature differences near the discharge points or areas.

4.5. Echo-sounding data

The normal faults determined on the satellite image are also seen in the echo-sounding profiles (Figs. 8(a) and 8(b)). These profiles evidently show that the northern, western and southern shores of the lake were formed as a result of normal faulting. A very young fault influencing the recent bottom sediments is clearly seen on profile D (indicated by 'b' in Fig. 8(a)). High current velocity values measured by İller Bank (1983) in places close to this fault were interpreted as an evidence for the ground water emergence (stations K-6 and K-10 in Fig. 9). A similar situation arises in another location in the southern part of the lake. An anomaly detected in profile F (see points indicated by 'g' on Fig. 8(b)), was interpreted as a major ground water emergence. This anomaly corresponds with the site where profile F crosses over the large fault extending NE–SW along the western shore of the lake (marked by 'X' in Fig. 9).

The layering that occurs due to the density differences of the top and bottom sectors of the lake is recognized clearly in all of the echo-sounding profiles. The upper layer where the density is lower is darker than the bottom layer which occurs below a depth of around 10 m. As the bottom layer contains hydrogen sulfide, it is easy to determine the extent of the hydrogen sulfide-rich zone throughout the lake. The dark colored upright triangular reflections (indicated by 'a' 'c' and 'g' on Figs. 8(a) and 8(b)) seen along the bottom are interpreted as ground water emergence points and uprising thermal water.

4.6. Current direction and velocity data

The current velocity and direction measurements made by İller Bank (1983) at some selected locations over the lake show that anomalous current velocities exist in some places (Fig. 9). Although there is no streamflow contribution to these areas, high current velocities are measured in the northern and southern parts of the lake. The high velocity zones determined with these measurements correspond to the darker areas from satellite imagery and correlate strongly with the tectonic elements (compare Figs. 7 and 9).

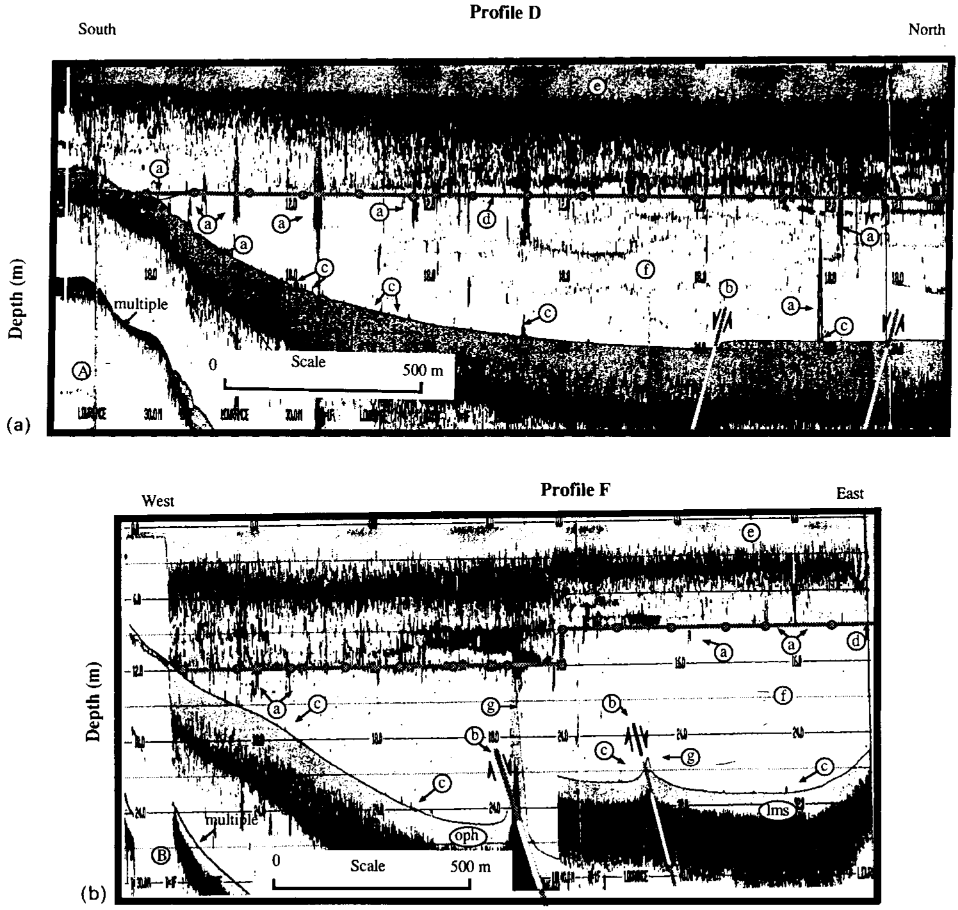


Fig. 8. Echo-sounding profile taken in (a) the northern and (b) the southern parts of the lake. (a: up-conning formed by upward moving ground water; b: recent normal faulting affecting bottom topography; c: possible ground water inflow sites; d: boundary of top and bottom layers; e: top layer; f: bottom layer; g: upright triangles possibly formed by turbidity that appears as result of extensive ground water inflow; alv: alluvium; lms: limestone; oph: ophiolite; the locations of the profiles are shown in Fig. 9.)

In an attempt to take depth-specific water samples at a location close to point K-16, it was observed that the water sampler, which weighs about 5 kg, was pushed strongly sideways by the high velocity current. It is also interesting to note that this point is very close to the location of the biggest upright triangular reflection on echo-sounding profile F (indicated by ‘g’ in Fig. 8(b)). As can be seen from Fig. 9, the current directions along the depth at site K-16 are towards the coast, which is located to the south-east. In all the measurements, taken at 5 m intervals, the current directions are nearly the same. Considering that this location is close to the Sultaniye thermal spring, it may be deduced that the ground water inflow in this site is of thermal origin. The measurements taken at stations K-16 and K-17, which are located close to the

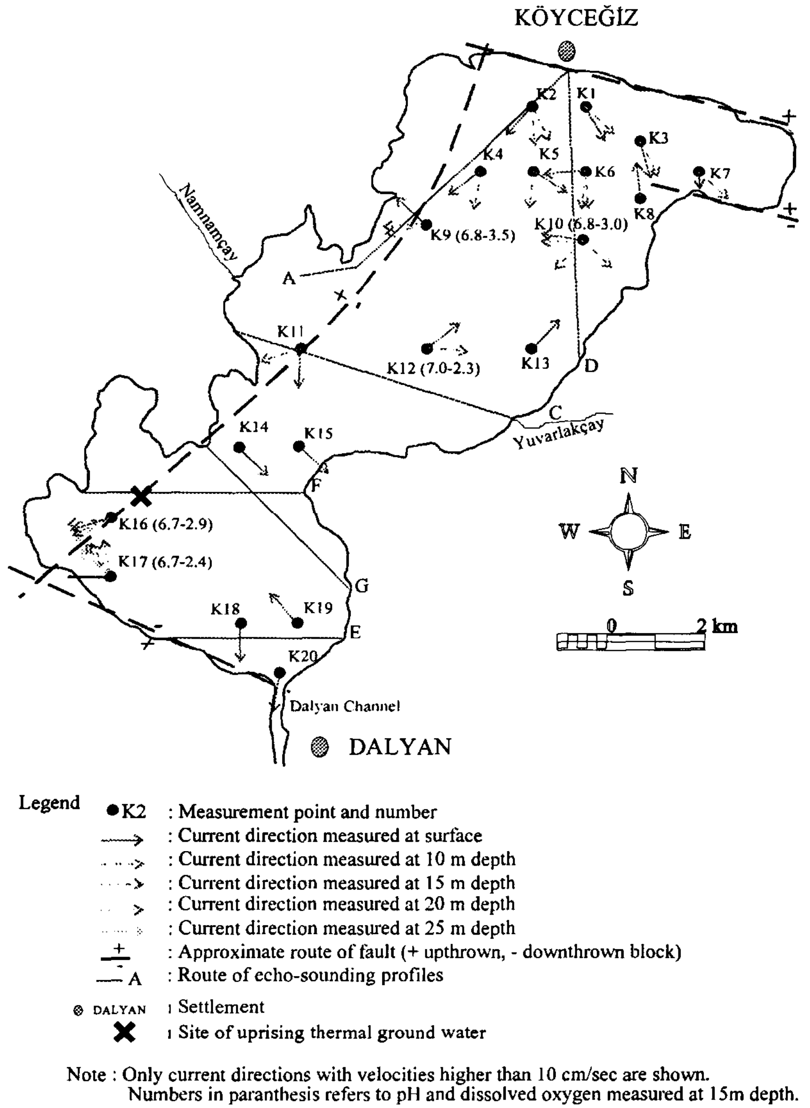


Fig. 9. Current directions measured at different locations and depths of the Köyceğiz Lake.

Sultaniye spring, indicate a slight increase in temperature as the lake bottom is approached. Additionally, the lowest pH and dissolved oxygen values have also been observed in these locations (see Fig. 9).

The current direction measurements taken at sites K-1 to K-10, located in the north-eastern part of the lake, indicate a current velocity variation with depth. In this area, the current directions below 10 m depth are mostly towards the south, while the velocities measured at the surface vary in all directions. The variation of current velocities with depth at points K-5, K-6 and K-10 may be attributed possibly to the ground water emergence points observed on echo-sounding profile D (see Fig. 8(a)).

5. Conclusions

Combined isotopic, hydrochemical, remote-sensing and echo-sounding data were proven to be useful in determining the origin of the Köyceğiz Lake water. Based on the results of this study the following conclusions can be drawn:

(1) The Köyceğiz Lake waters are comprised of contributions from rain, streams, seepage from alluvium, and bottom effluents associated with the present tectonic activity.
(2) Hydrologic budget calculations suggest that an accountable ground water inflow along the lake bottom must exist to balance the inflows and outflows. The difference between the mean annual inflow and outflow rates cannot be explained without taking into account such a contribution.
(3) The variation of physical and chemical parameters with depth indicates that the lake water comprises two hydrochemically distinct layers. Hydrochemical observations suggest that the water circulation between these layers is quite slow, indicating that the lake can be classified as meromictic.
(4) Analysis of hydrochemical and environmental isotopic data indicates the lake water is formed by mixing of thermal and cold-karstic waters.
(5) The evaluation of satellite imagery data suggests strong tectonic control over the hydrogeology of the lake. Most of the lake shores are shaped by structural elements. Some of the lineaments observed on land also extend along the lake bottom.
(6) Echo-sounding data clearly shows hydrochemically distinct layers, fault lines, and the ground water inflow sites, and also provides supporting evidence to the results obtained by hydrochemical, isotopic and remote-sensing studies.
(7) Current velocity data clearly indicates the possible sites of ground water discharges located along the lake bottom. At the sites where strong ground water emergence seems possible, the current velocities measured at 5 m depth intervals show a definite trend in a specific direction. High velocity sites are also correlated with the echo-sounding data.

This preliminary study of Lake Köyceğiz provides a framework for understanding the origin of the lake water. Further studies may be carried out to determine the details regarding the isotopic and hydrochemical characteristics and their relation to the regional hydrogeologic structure.

Acknowledgments

The authors wish to thank Messrs. Levent Tezcan, Özalp Harut and Onur Köse for their contributions to various parts of this study. Thanks are also due to Cahit

Yeşertener (Karst Research Center, Hacettepe University) and Yücel Yurtsever (IAEA, Isotope Hydrology Section) for providing us with the hydrochemical and isotopic data. The manuscript was improved by review comments from Prof. Vedat Doyuran, Prof. Hasan Yazıcıgil (Dept. of Geology, Middle East Technical University), and Prof. William Back (US Geological Survey, Reston, VA). Thanks also to an anonymous referee and to Dr. George H. Davis for their critical comments.

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