DYNAMICS OF LAKE KÖYCEĞIZ, SW TURKEY: AN ENVIRONMENTAL ISOTOPIC AND HYDROCHEMICAL STUDY

C.S. BAYARI, T. KURTTAS, L. TEZCAN
International Research & Application Center for
Karst Water Resources,
Hacettepe University,
Ankara, Turkey

Abstract

Lake Köyceğiz, located in southwestern Turkey, is a meromictic lake with a surface area of 55 km^2. Impermeable ophiolitic rocks, and groundwater bearing alluvium and karstified limestone are the major geologic units around the lake. Köyceğiz lake, fed mainly by rainfall and stream flow, discharges into the Mediterranean Sea via a 14 km long natural channel. The average water level is estimated to be slightly above the sea level and the estimated lake volume is 826 million m^3. Lake level fluctuations are well correlated with rainfall intensity. Lake Köyceğiz comprises two major basins; Sultaniye basin (-32m) at the south and Köyceğiz Basin (-24m) at the north which are connected by a 12m deep strait. Environmental isotopic and chemical data reveals that the Lake Köyceğ has complicated mixing dynamics which are controlled mainly by density-driven flow of waters from different origins. The lake is fed mainly by rainfall and stream flow as low density waters and by high density thermal groundwater inflow at the southern coast. Complete annual mixing can not be achieved, because of the density difference between mixolimnion and recharge. Continuous high-density thermal water input into the Sultaniye basin is the major factor controlling the lake dynamics. The high density thermal groundwater discharging into the lake sinks to the bottom of Sultaniye basin and overflows toward the north along the bottom surface. During its travel, dense bottom water is mixed with mixolimnion water and as the distance from the thermal water inflow increases, the density tends to decrease throughout the lake. Calculations based on long-term average electrical conductivity data reveal that about 60% of mixolimnion in both basins is replenished annually, whereas the annual mixing with mixolimnion for Sultaniye and Köyceğiz Basins is 20% and 30%, respectively. Turn-over times for mixolimnion and monimolimnions of Sultaniye and Köyceğiz Basins are estimated to be 2 years, 5 years and 3.5 years, respectively.

1. INTRODUCTION

Lake Köyceğiz, located in southwestern Turkey, is among the "Specially Protected" areas because of its natural beauty and ecological and archeological importance. The lake is connected to the Mediterranean Sea coast, Iztuzu, where endangered sea turtle species, *Caretta caretta*, nest and breed (Figure 1). Studies for the protection of this environment which is also among the promising touristic development sites, from anthropogenic activities have been initiated in the 1980's Biological inventory of the area has been prepared, and some preliminary information regarding the hydrochemical structure has also been produced in these studies [1, 2].

However, since the proper design and management of the activities directed to develop the touristic potential of the region need more accurate and reliable information on the hydrologic system, a detailed study has been initiated by the International Research and Application Center for Karst Water Resources (UKAM) of the Hacettepe University, Ankara, Turkey. International Atomic Energy Agency (IAEA) supported these activities under the scope of Coordinated Research Program entitled "Isotope Techniques in Lake Dynamics Investigations". National institutes such as, Electrical Power Resources Research Authority (EİE) which is in charge with the operation of national hydrometric observation network, and the Technical and Scientific Research Council of Turkey (TUBİTAK) has also participated to/contributed in the project.

Because of the complicated geologic, hydrologic and hydrogeologic nature of the area, wide variety of investigation techniques such as, hydrometric measurements, in-site hydrochemical measurements/analyses, spatial depth-specific physical and chemical observations, environmental isotopic evaluations etc. have been employed to produce most reliable data that characterize the hydrologic system [2].

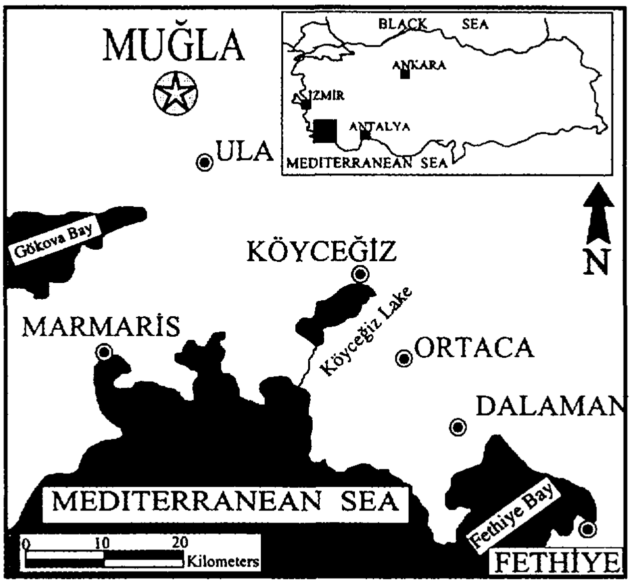


Figure 1: Location map of the Lake Köyceğiz.

2. MORPHOLOGIC CHARACTERISTICS OF LAKE KÖYCEĞİZ

Lake Köyceğiz has a shape of slightly distorted rectangle extending in NNE-SSW direction (Figure 2). Maximum length and width of the lake are 12km and 6.5km, respectively. The average surface area is 55 km^2. The lake is permanently stratified in terms of distinct chemical and isotopic composition and thus, it is classified as meromictic. Lake level does not fluctuate to a great extend and usually is at its equilibrium level which is ca. 2 m asl. During episodic winter rainfalls and streamflow fed by these events, the lake level rises temporarily about 1m above its normal, but the excess water is rapidly discharge into the Mediterranean Sea via a 14km long naturally formed channel which is a part of estuary located between the lake and the sea.

The area where Lake Köyceğiz is located is a tectonically active horst-graben region. The Asia Minor "or the Anatolian Plate" has been pushed northward by the Arabian plate toward "Russian Plate" located to the north. Since the "Russian Platform" forms a resistant barrier, the Anatolian Plate moves westerly against "European Plate" which is another relatively stable crustal component. The Anatolian and European plates meet along the Aegean Sea where, the weaker Anatolian Plate spreads in north-south direction to form horst and graben structures along the coastal zone. Horst-graben tectonics in the western Anatolia is characterized by ridges and plains extending perpendicular to the sea. Deep faults and hydrothermal activity associated with these faults are common in this area. Two of these graben structures form the Köyceğiz and, to the east, Dalaman Plains. The Lake Köyceğiz extend in the Köyceğiz plain between the mountains in the northeast and the Mediterranean Sea in the southwest.

Current geomorphologic features suggest that the formation of Lake Köyceğiz is a result of interplay of tectonic and fluvial processes. Whereas, the plain is being filled by alluvium brought from mountainous part via large rivers, such as, Namnamçay and Yuvarlakçay, horst-graben faulting causes the plain surface to subside continuously. Echo-sounding profiles indicate active fault lines along the lake bottom.

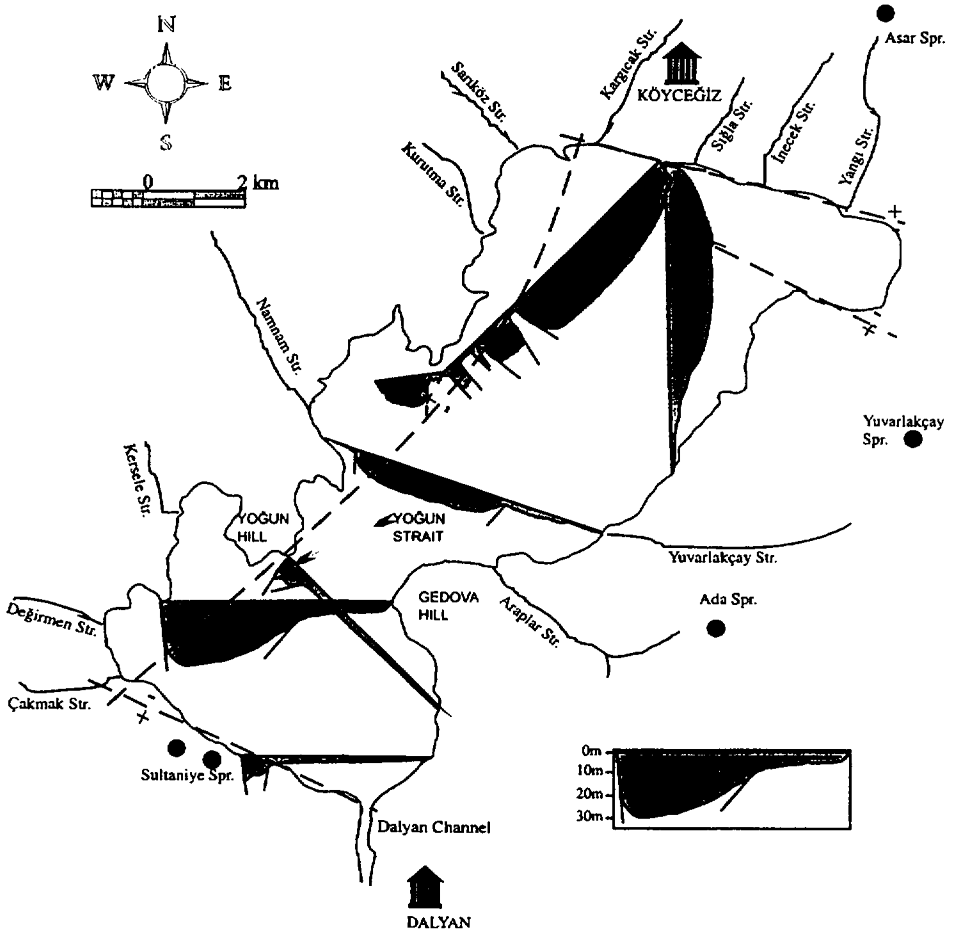


Figure 2: Bathymetric profiles and the site names mentioned in the text.

The lake comprises of two basins; first located at the northern part named as "Köyceğiz Basin" and, secondly located at south, named as "Sultaniye Basin". These names have been attributed from the settlements situated nearby the respective basins. The maximum depths in the Köyceğiz and Sultaniye basins are 24m and 32m from the mean lake surface, respectively. The basins are connected by the Yoğun Strait that extends between Cape Yoğun and Gedova Hill where the distance between the facing coasts of lake reduces to 1,750m. The lake depth becomes shallow (max. 6 m) in most parts of the Yoğun Strait, but suddenly deepens at the western end (Cape Yoğun) where a normal fault extending in NNE-SSW direction passes through. Here, the lake bottom comprises the down-thrown block of the fault, and the maximum depth is 12m. Three years' observation carried out in this study indicated that the depth of Cape Yoğun has a drastic control over the permanent stratification of lake water, especially in the Sultaniye basin. The boundary between mixolimnion (top water zone) and monimolimnion (bottom water zone) passes along 12m depth in both basins of the lake during most of the year. However, the thickness of mixolimnion in Köyceğiz Basin deepens up to 16m in high water season, whereas it is absolutely constant at 12m in the Sultaniye Basin.

3. DATA COLLECTION AND QUALITY

A vast amount of hydrologic, chemical and environmental isotopic data has been collected in this investigation. Since the volume of data is well beyond the limits of this paper, only a brief summary is given here. Readers willing to access all the data should refer to progress reports prepared under IAEA Research Contract RB/7997 [2, 3]. However, in order to provide an insight for the quality of data which have been evaluated in this paper, detailed explanations regarding the data collection, field measurements and analyses are given in the following paragraphs.

Stream flow-rate measurements based on the velocity-area method were carried out once a month in all streams discharging into the lake. In the wet season, when episodic floods occur, the sampling frequency was increased up to four measurements per site per month. The quality of measurement is +/- 10% of the measured value. Meteorological observation data have been collected from the records of nearby stations operated by the State Meteorological Affairs (DMI). Locations of hydrometric measurement and meteorological observation stations are shown in Figure 3.

Water samples for in-situ measurements and laboratory analyses of hydrochemical and isotopic parameters have been collected from thermal and cool karstic springs, streams, sea, rainfall and the lake. Seasonal (four times a year) samples have been collected from thermal and cool karstic springs located around the lake. Sampling procedures suggested by APHA et al. [4] such as filtration through 0.45micron filter, acidification of cation samples etc. have been followed in these studies. Depth-specific water samples from the lake have been collected in two ways. At

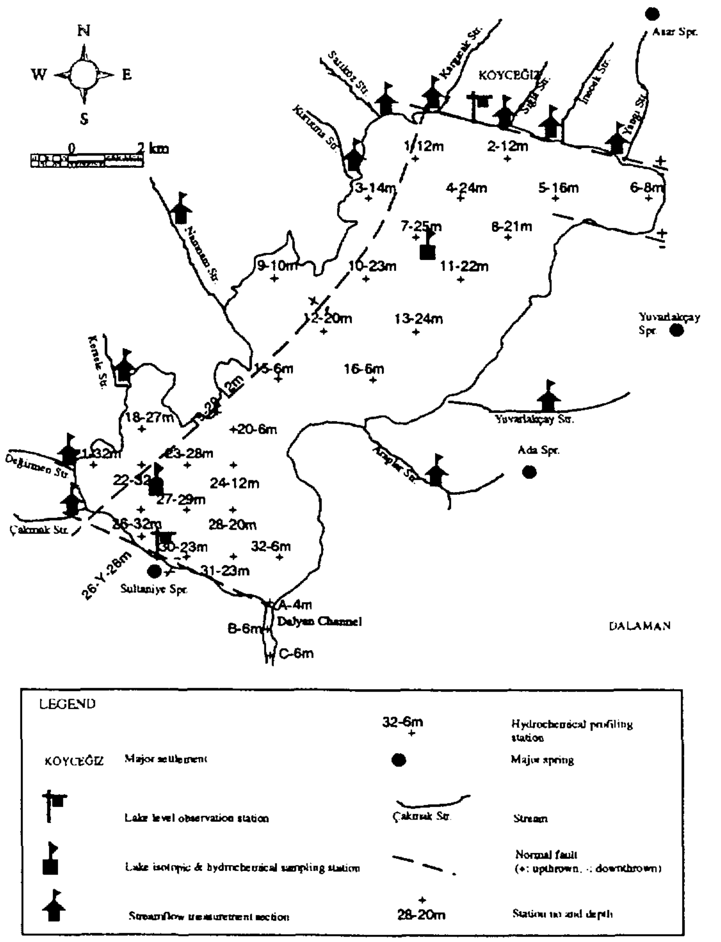


Figure 3: Map of hydrometric, meteorological and lake hydrochemical / isotopic sampling and profiling stations in and around Lake Köyceğiz.

the initial stage of research, a "Ruttrier type" sampler made of PVC (polyvinylchloride) has been used. In order to assure a better sampling quality, later on, a peristaltic pump with tygon tubing has been used. The inlet end of tubing has been fixed to Hydrolab Data Sonde 3 TM multiparameter water quality probe which is equipped with a depth gauge to determine the sampling depth within +/- 0.5m. Because of the permanent stratification in lake water, utmost care has been spent to collect water samples exactly from the pre-determined depths. Usually but not always, sampling works have been carried out when the lake water stands still in order to increase the sampling quality. Maximum error of sampling depth is estimated to have been +/- I meter. Lake water sampling locations have been pre-determined on a 1/25000 scale topographic map by considering the echo-sounding profiles obtained in a previous study by Bayari et al. [2]. A Global Positioning System (GPS) navigator has been used to locate the sampling sites within +/- 100m.

Physical and chemical parameters such as temperature, pH, specific electrical conductivity, dissolved oxygen, redox potential and turbidity have been measured in-situ. At the initial stage, these parameters were measured in water samples brought to the boat. However, after the fifth (inclusive) field campaign, they are measured in-situ, that is at the desired depth by means of a water quality probe equipped with relevant sensors. YSI (Yellow Springs Instruments™) Model 33 Salinity-Conductivity-Temperature (SCT) meter, YSI Model 54 Dissolved Oxygen Meter, ORION™ Model 290A digital pH meter have been used for the in-boat measurements. All instruments have been precisely calibrated according to manufacturers' instructions which conforms to APHA et al. Standards [4]. Alkalinity which is subject to rapid change upon CO_2 equilibration with atmosphere, has been measured in the field by means of Gran's potentiometric method [5].

Major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and anions (Cl^-, SO_4^{2-}, CO_3^{2-}/HCO_3^-) have been analyzed from samples collected at each campaign, whereas trace metals (Fe, Mn, Cr, Cu, Pb, Zn) and nutrients (PO_4^-, NO_3^-, NO_2^- and NH_3^+) have analyzed when needed. Major cations and trace metals have been analyzed on a Perkin Elmer™ Model 280 Atomic Absorption Spectrometer according to the methods suggested in APHA et al. [4]. Nutrients and SO_4^{2-} have been analyzed on a Bausch Lomb™ Model Spectronic 21 UV-visible spectrometer following the methods given in APHA et al. [4]. Chloride analyses have been performed by means of Argentometric method [4]. Water samples collected for environmental isotope content (^2H, ^3H and ^{18}O) have been analyzed IAEA's Vienna laboratories.

4. HYDROLOGY, GEOLOGY AND HYDROGEOLOGY

4.1. Hydrology

Most of the surface water into the Lake Köyceğiz is supplied by two perennial streams, which are Namnam Çay and Yuvarlakçay discharging into Köyceğiz Basin. Namnam Çay having the largest drainage area that lays over impermeable ophiolitic rocks supply most of the surface inflow, whereas Yuvarlakçay stream, fed mainly by a karstic spring, has a relatively small contribution. Mean annual discharges of Namnam Çay and Yuvarlakçay streams are 11 m^3/sec and 4.5 m^3/sec, respectively. Other streams distributed around the lake discharge intermittently only in wet season. The only outflow of Lake Köyceğiz is via Dalyan Channel, which is a 14km natural channel that connects the lake to the Mediterranean Sea. Simultaneous flow rate measurements carried out in flowing streams and the lake outlet indicates that the outflow exceeds the total inflow by streams and the difference is supplied by direct rainfall input over the lake surface.

Most of the annual inflow to the lake is provided between November and May. Accordingly, most of the discharge from the lake occurs in this period when the lake level reaches its maximum (Figure 4a and b). The response of lake level to the rainfall and streamflow input is rather fast, and the lake level reduces to its normal within several days. During summer

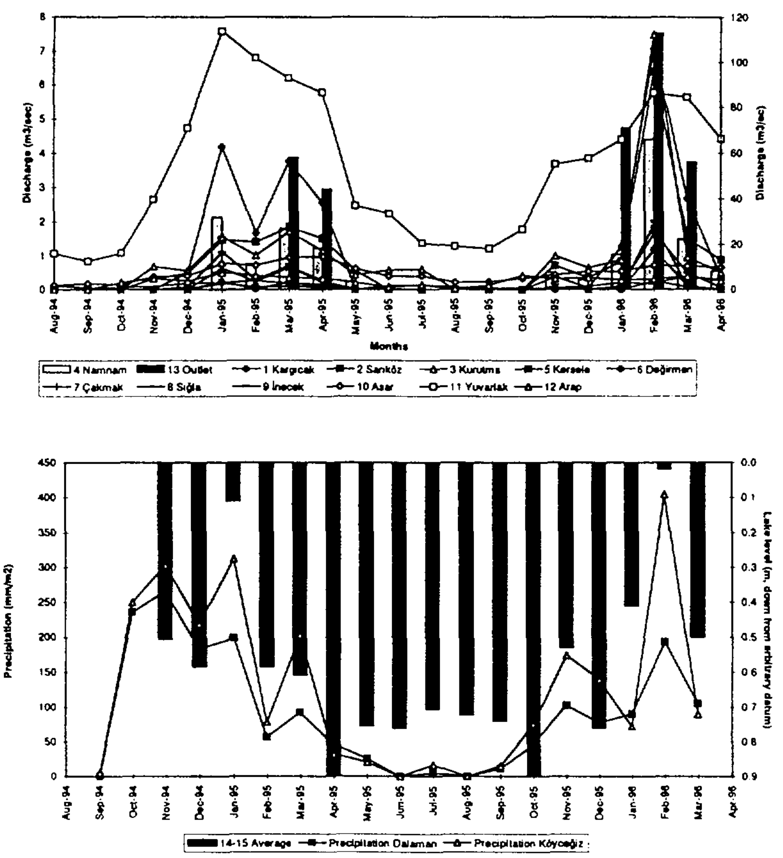


Figure 4: a: Variation of the rates of inflowing streams and the outlet (top). Discharge scale on the right is for Namnamçay and Outlet. b: Correlation of the outflow rate from the Lake Köyceğiz and the monthly precipitation of surrounding meteorological stations (bottom). Average lake level is given as "14-15 Average".

months, when the lake is fed only by small contributions from Namnam Çay and Yuvarlakçay streams, the lake level stands still slightly above the sea level. In Figure 4b, variation of mean lake level (average of northern and southern stations) is shown together with the monthly precipitation values of neighboring meteorological observation stations (i.e. Dalaman and Köyceğiz). Comparison of Figures 4a and 4b reveals that the lake level is more closely related to precipitation amount rather than flow rate of feeding streams.

4.2. Geology and Hydrogeology

The Köyceğiz Lake Basin is located at the western end of the Taurus mountain ridge which is a part of Alpine-Himalayan orogenic belt. As this tectonic belt has formed as a result of compression tectonics during the closure of Tethys ocean, the geologic structure comprises mainly of imbricated units. The geology of the Köyceğiz Lake basin has been studied by Graciansky [6]. Geologic structure comprises of three structurally different sequences of rock units, namely autochthonous carbonates and detritics, allochthonous Lycien Nappes, and ophiolite nappe (Figure 5). This tectono-stratigraphic sequence is overlain by the post-orogenic sediments of Plio-quaternary that expose in lowlands such as, riverbeds and Köyceğiz and Dalaman Plains.

The tectono-stratigraphic sequence starts with the metamorphic basement rocks belonging to Menderes metamorphic massive located to the northwest. Metamorphic rocks are covered by slightly metamorphosed carbonate rocks which in turn overlain by autochthonous Beydağları carbonates of Cenomanian-Early Miocene age. This formation is made up of thinly bedded

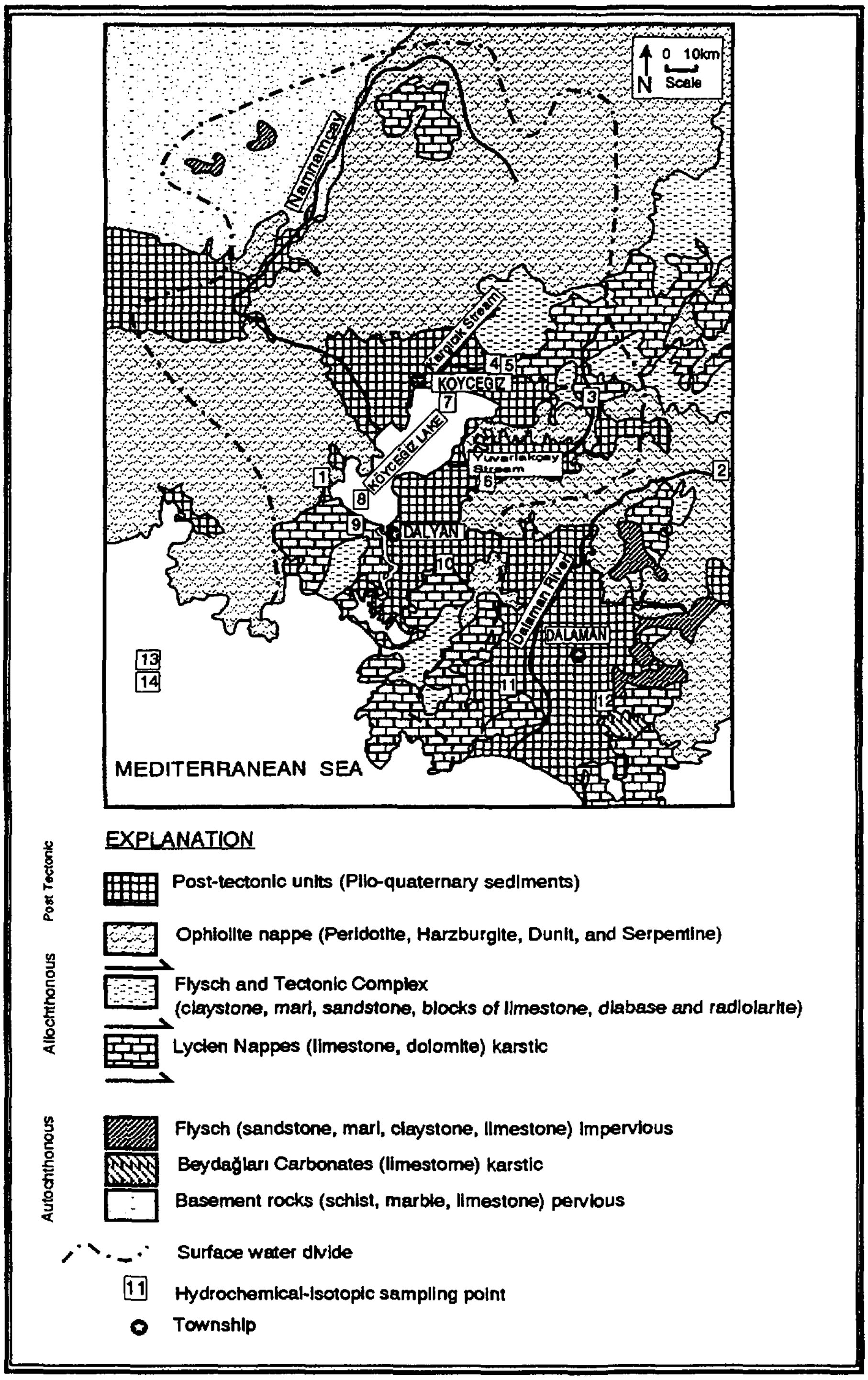


Figure 5: Geologic map of the Lake Köyceğiz Basin.

micritic limestone and thick bedded calcarenite. A Miocene flysch, comprising of alternating sequences of claystone, marl, sandstone and limestone, conformably overlies the Beydağları carbonates. Small outcrops of autochthonous sequence are observed in the northwestern 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 [6]. Another nappe unit, called the tectonic complex, lies tectonically in between the Lycien Nappes and the overlying ophiolite nappe. The tectonic complex is made up of limestone, radiolarite and diabase blocks. The ophiolite nappe, containing peridotite, dunite, harzburgite and serpentine locally overlie the former geologic formations, where they form lowlands during the emplacement of the ophiolite nappe.

Two major tectonic phases that contributed the geologic evolution of the area is inferred [6]. At the initial stage, lateral tectonic movements were dominant and this phase were resulted in the settlement of allochthonous units over the basement rocks and autochthonous carbonates. After the Late Miocene period when the nappe settlement terminated, vertical (mostly normal) faulting leading to today's horst-graben morphology started to develop. As a result of the horst-graben tectonics, a number of normal faults trending NE-SW and forming horst-graben structures throughout the basin occurred. The present day thermal springs located in and around the basin are associated with recent faulting extending possibly down to the basement rocks. During the Pliocene, the lowlands (grabens), which form 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 terrigenous material deposition between the lake and sea.

Allochthonous limestone formations (Lycien Nappes) and the Plio-quaternary alluvium are the major water-bearing units in the Köyceğiz Basin. Alluvium surrounding the lake is fed directly from rainfall and from the karstic limestone by means of seepage. The allochthonous limestone exposing to the north of lake is also fed by underground drainage from the northern part of the Dalaman Basin located to the northeast [7, 8]. The ophiolite nappe, which crops out in many parts of the basin, is practically impermeable and, therefore is not significant from the hydrogeological 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 northeastern part. Hydrogeology of Köyceğiz Lake Basin has been studied in detail by Güner [9].

5. ENVIRONMENTAL ISOTOPIC EVALUATIONS

5.1. Data

Environmental isotopes (^{3}H, ^{2}H and ^{18}O) have been utilized in this study to identify the inter-relation among waters of different origin and to understand the interaction between monimolimnion and mixolimnion waters. Apart from the data produced from the samples collected in this study, those given by previous studies [2, 8] have also been used. All environmental isotope samples have been analyzed by the IAEA under various research projects.

5.2. End-Members and Lake Water

Variation of oxygen-18 and deuterium composition of all water samples imply that there exist four isotopically distinct water types in the study area (Figure 6). Starting from the one most isotopically depleted, these are 1: Sea water, 2: Thermal waters, 3: Lake waters (3a: monimolimnion, 3b: mixolimnion), 4: Local precipitation and fresh groundwater fed by this precipitation. Sea water (group 1) and fresh waters (group 4) represent the isotopic end-members in the area. Samples from group 4 scatter around a Local Meteoric Water Line (LMWL) with a deuterium excess value of +16 which is apparently higher than that of Global Meteoric Water Line (GMWL). Same deuterium excess value has also been reported by Yurtsever [10] for the precipitation observed in Antalya IAEA-WMO network station which is located 250 km to the east of study area.

Water samples other than fresh waters and precipitation deviate from the LMWL indicating a mixing between fresh waters (group 4) and sea water (group 1). Thermal waters (Kubbeli Hamam: Dommed Bath and Çamur Banyosu: Mud bath) are more closely located to sea water samples. Position of thermal water samples on the ^{18}O/D graph implies that the thermal waters should have formed as a result of mixing of fresh water (group 4) and sea water (group 1) with dominant sea water component. This argument is supported by the chemical composition of water samples. Thermal waters have electrical conductivity values (35000 microS/cm) in between those of fresh water (max. 1000 microS/cm) and sea water (55000 microS/cm). Although, some of the ionic composition of thermal water should have been gained from the aquifer rock by dissolution, it is apparent that there is also substantial sea water contribution to the evolution of thermal waters. Considering the geologic structure in the area, it is concluded that the deep circulating fresh groundwater comes in contact with sea water (either connate or recent) and rises to the surface through the deep fault planes to form thermal springs in the area. Two of the thermal water samples (Kubbeli Hamam: Dommed Bath and Çamur Banyosu: Mud bath) deviate from the "mixing line" connecting fresh waters, lake waters,

thermal waters and sea water. Even if, these deviations may be explained by measurement errors, it is also possible that they may have undergone oxygen isotope shift because of exchange between thermal aquifer rock and water. However, degree of isotope shifty observed in these samples is also much greater than those observed in waters in major geothermal fields of Turkey where reservoir and fluid temperatures as much as 130 °C and 250 °C have been observed, respectively.

Lake water samples which deviate from LMWL and cluster around the mixing line that connects these samples to thermal waters comprise of two groups each representing waters from mixolimnion (Group 3a) and monimolimnion (Group 3b). Monimolimnion (bottom) waters are more depleted isotopically and therefore, located more closely to thermal waters. The deviation of mixolimnion waters implies that they have subject to evaporation as expected from such an open water body. However, their shift from the original water located on the LMWL is also follows the mixing line between fresh water and thermal water. In other words, the mixing and evaporation effects upon isotopic composition of lake waters can not simply be separated on the ^{18}O/D graph.

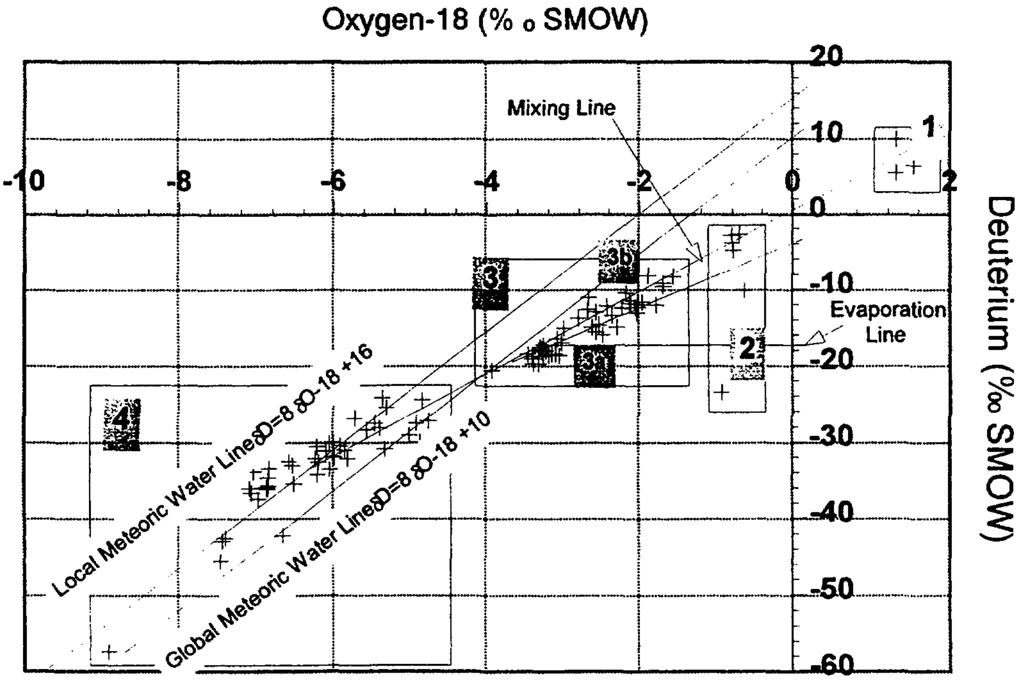


Figure 6: Meteoric water, evaporation and mixing lines fitting to waters samples collected from various points in and around the Lake Köyceğiz.

Closer inspection of $^{18}O/D$ indicates although, the samples from monimolimnion and mixolimnion are clustered roughly in separate groups, the monimolimnion samples from Sultaniye Basin are more depleted compared to those of from Köyceğiz Basin. It is clear that amount of stable isotopic depletion of monimolimnion samples increase with increasing depth. Similarly, isotopic depletion of mixolimnion waters from both basin also increases with increasing depth even if they are less depleted than those of monimolimnion waters. The difference between monimolimnion and mixolimnion waters in Sultaniye Basin is much more apparent than that of in Köyceğiz Basin. These observations imply that i) relatively good mixing occurs in Köyceğiz Basin, ii) most depleted waters are found in the deeper part of Sultaniye basin implying that the source of depleted water should be more closely located to this part of the lake. These arguments are also correlated well with the hydrochemical data as will be discussed in the following chapters.

5.3. Isotopic Profiles and Lake Water

Stable isotope profiles of lake waters from Sultaniye and Köyceğiz Basins are shown in Figure 7. These profiles indicate that the monimolimnion waters in both basins have more distinct isotopic compositions than those of respective mixolimnion waters which are less isotopically depleted. Relative isotopic enrichment observed in mixolimnion waters is attributed to the contribution from group-4 waters (i.e. precipitation, stream flow and rainfall). It appears that at least part of the monimolimnion waters mix with group-4 waters to form isotopic composition of the mixolimnion. The deuterium content in the mixolimnion in both basins is between -17 and -20 per mil SMOW, and does not show an appreciable variation along the depth. The isotopic homogeneity of mixolimnion water suggest that, after the formation of this water by mixing of group-4 and monimolimnion waters, the mixolimnion is well mixed.

The oxygen-18 composition of mixolimnion in both basins is between -3 and -3.5 per mil SMOW and like deuterium, the oxygen-18 content is also homogenous. The transition zone between monimolimnion and mixolimnion is rather sharp and extends along ca. 13m depth in this sampling period (December 1994). In succeeding field campaigns, it is well established that the transition zone is nearly constant at this depth in the Sultaniye Basin, whereas it fluctuates between 13m and 16m in the Köycegiz Basin. The reason for this-fluctuation is believed to be the increasing inflow of Namnamçay and Yuvarlakçay streams discharging into the Köyceğiz Basin, and recent rainfall input. Both the deuterium and the oxygen-18 contents in the monimolimnion of Sultaniye Basin is nearly constant except the deepest sample (-32m from mean lake level). Deuterium and oxygen-18 contents range between -10.5 and -11.5 per mill SMOW and -2 and -2.5 per mill SMOW, respectively. However, in the Köyceğiz Basin, the monimolimnion is not isotopically homogenous as it is in Sultaniye Basin, and the stable isotope content is enriched linearly from the bottom water to transition zone. The stable isotope composition of bottom water (24m) in the Köyceğiz Basin is less depleted than that of bottom (32m) water of Sultaniye Basin but more or less the same as the sample collected from the same depth (24m) at the Sultaniye Basin.

The presence of most isotopically depleted samples at the deepest points of both basins may be accepted as an indication of the inflow of water that is isotopically most depleted. Except the sea water, the most isotopically depleted waters in the area are of thermal origin. Sea water intrusion via the Dalyan Channel toward the Lake Köyceğiz has not been observed during the observation period between 1993 and 1997; neither was such evidence presented in the studies carried out previously. Therefore, the most plausible source of isotopically depleted water in the monimolimnion of the Sultaniye Basin should be the thermal water contribution. Sultaniye spring, located just along the shoreline to the south of Sultaniye Basin, has an average temperature of 40°C and any such thermal water inflow that may discharge through the lake bottom is expected to have been influenced by this high temperature. However, no such evidence has been obtained from extensive spatial temperature measurements carried out in various field campaigns, probably because of diffuse inflow of thermal water. It is inferred that some of the thermal water ascending to the Sultaniye Spring (which is more depleted than monimolimnion water) discharge into the lake through fractures/joints located on the southern bank of the lake. As will be demonstrated later in this paper, this water has higher density than that of any water in the Sultaniye Basin and sinks to the lake bottom to form monimolimnion water.

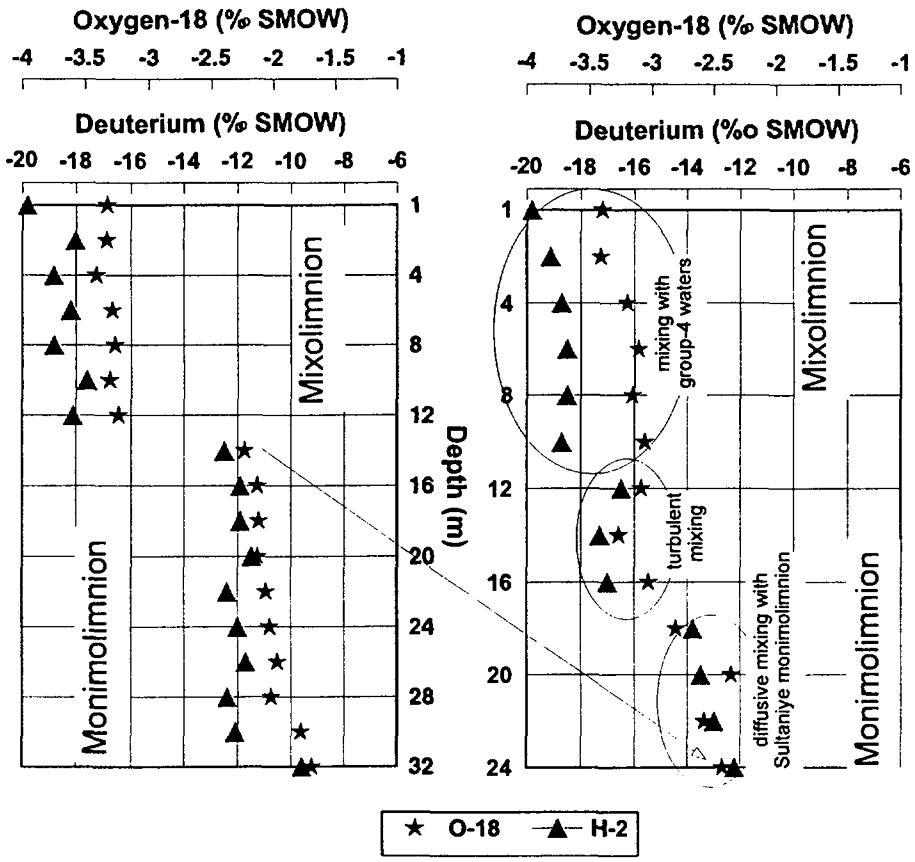


Figure 7: Deuterium vs. oxygen-18 profiles from two major station on the Lake Köyceğiz (Left: Köyceğiz Basin, Right: Sultaniye Basin).

The rate of isotopic depletion in the Sultaniye monimolimnion decreases upward with a sudden shift at –12m from the average lake surface where the transition zone between mixolimnion and monimolimnion in this basin is located. Bathymetric profiles of Sultaniye Basin indicates that the isotopically depleted monimolimnion water can outflow only toward the Köyceğiz Basin via Yoğun Strait where the lake bottom rises to –12m below mean lake level (m.l.l.) because the bottom elevation of the lake outlet to the Dalyan Channel is at 6 to 7m below m.l.l. It appears that the high density thermal water sinking into the bottom of Sultaniye Basin is subject to diffusive mixing as the infilling dense water rises to transition zone. At the top of monimolimnion of Sultaniye basin, the stable isotopic composition is enriched with respect to deeper parts. The outflowing Sultaniye monimolimnion water is still denser than the mixolimnion waters of both basins. Therefore, the outflowing water tend to sink into the bottom of monimolimnion of Köyceğiz Basin. The similarity between the isotopic compositions of outflowing water (that is, Sultaniye monimolimnion water with O-18= -2.23 ‰ and deuterium = -12.5 ‰ at 12m/13m depth) and the bottom water of Köyceğiz Basin (with O-18= -2.43 ‰ and deuterium = -12.2 ‰ at 24m depth) is quite striking. This similarity implies that the dense water outflowing from Sultaniye monimolimnion keeps its isotopic composition during its travel to the bottom of Köyceğiz basin. This is somewhat surprising, because the mixolimnion water from Köyceğiz basin flows in opposite direction and is expected to cause turbulent mixing along the transition surface. Absence of such a turbulent mixing can be accepted as a sound evidence of very low flow velocities along the mixolimnion and monimolimnion surface at the Yoğun Strait or the presence of a connection between two basins that is located below the transition surface.

The depth of transition zone at 12m in the Sultaniye Basin is a dominant characteristic as revealed by the hydrochemical data obtained in all field campaigns. The endurance of transition zone at 12m in the Sultaniye Basin is believed to be due to the physical (bathymetric) barrier created by the depth of Yoğun Strait connecting both basins (see Figure 2). It seems, even though the surface water inflow into the Köyceğiz Basin causes a mixing of monimolimnion and mixolimnion to some extend, the resultant water is still less dense than the monimolimnion of Sultaniye Basin and most of the this water leaves the lake via Dalyan Channel by flowing over the monimolimnion of Sultaniye Basin.

Three distinct regions are observed in the stable isotopic composition of the Köyceğiz Basin. The bottom water which expose isotopic similarity to the upper most monimolimnion water of Sultaniye Basin, becomes increasingly enriched as the transition zone located at 16m depth is approached. Between the bottom of monimolimnion and the transition zone the isotopic enrichment is linear and correlated well with the depth. Between 12m and 16 m depths, the isotopic composition is almost homogenous implying that turbulent mixing is effective. Above 12m depth up to the surface, the isotopic composition becomes increasingly enriched probably because of the recent surface and rainwater input in to the lake. The isotopic composition of mixolimnion in both basins are very similar especially in the surface (-1m) samples.

5.4. Tritium profiles

Tritium composition of lake water has been determined in dry (August 1994) and wet (February 1994) seasons (Figure 8). Although, the variation of tritium content with depth in both basins suggests a small decrease, systematic variation observed in stable isotope profiles is not clearly demonstrated here. Even though, this irregular variation can be attributed to measurement error which is roughly around +/- 0.5 TU, it is apparent that there is no large difference between the tritium composition of monimo and mixolimnion waters. In both periods the relatively low tritium contents are observed in the bottom waters confirming the deductions made on the basis of stable isotope content. The Sultaniye thermal spring's water which is believed to sink to the lake bottom in this sector has also low tritium content (0.4 +/-0.3 TU in August 1994 and 0.5 +/-0.3 TU in February 1994).

Because the degree of measurement error does not allow to make deductions on the evolution of Sultaniye monimolimnion water, a rough mixing calculation was made based on the average stable isotope, electrical conductivity values of assumed end-members. Table x shows that when Sultaniye thermal spring and Sultaniye mixolimnion are mixed at 40% and 60%, respectively, the electrical conductivity and stable isotope composition of hypothetical mixing water resembles well enough to monimolimnion water in this basin. To maintain the obtained mixing ratio, the tritium content of the mixolimnion is calculated to be 10.4 TU. It may be assumed that the error associated with this figure is, like real measurements, +/- 0.5 TU. Although, the calculated tritium content is above the measured values in the lake, it can still be accepted as a plausible value. Previously measured mixolimnion tritium contents (Köyceğiz basin = 13.2 +/-0.6 TU, Sultaniye basin = 12.5 +/-0.5 TU; [8]) and those measured in local springs which are fed from annual rainfall (Marmarlı spring, 9.1+/-0.5 TU in August 1994 and 15.0+/-0.3) suggest that the calculated tritium content for mixolimnion is within acceptable limits.

Table 1: Major components contributing to monimolimnion of Sultaniye Basin.

End-member	Conductivity	Oxygen-18	Deuterium	Tritium
	microS/cm	%o SMOW	%o SMOW	TU
Thermal water (A)	30000	-0.8	-3.9	0.5
Sultaniye mixolimnion (B)	4900	-3.33	-18	10.4*
Sultaniye monimolimnion	14750	-1.78	-12.1	6.4
Mixing (%40 A + %60 B)	14940	-2.318	-12.36	6.4

Note: * Calculated mixolimnion tritium content.

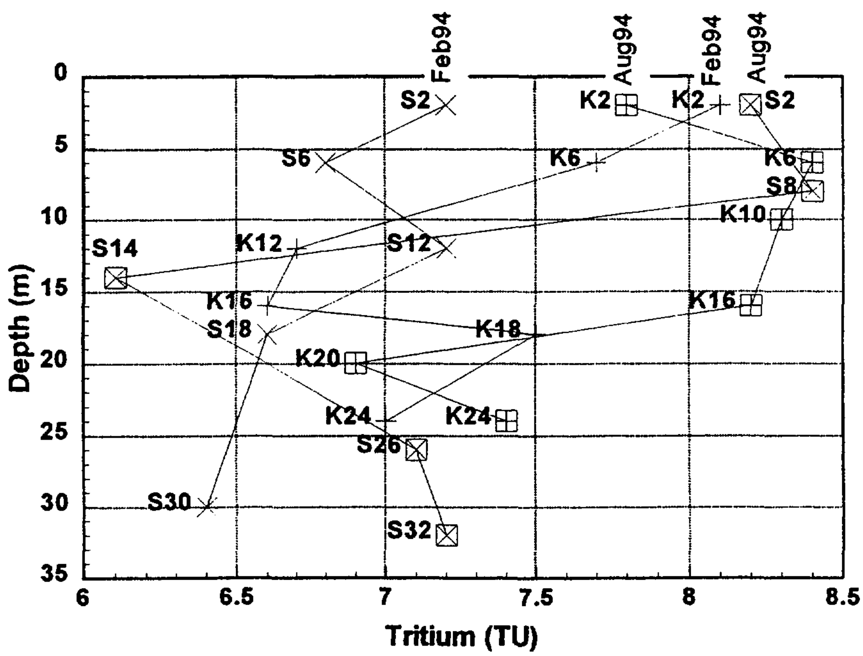


Figure 8: Tritium profiles from Köyceğiz and Sultaniye Basins.

6. HYDROCHEMICAL EVALUATIONS

6.1. Data

In order to have a complete picture of the dynamics of Lake Köyceğiz, and to provide supporting evidence for evaluations made on isotopic data, 6 hydrochemical field campaigns have been carried out. Evaluation of field data is given in the following paragraphs. At this point, method of data collection should be mentioned to explain the reliability of field data. In the first 5 sampling campaign the field parameters have been measured on the boat just after the depth specific sample has brought to the boat via "Ruttner" sampler. Although, the time between the closure of Ruttner sampler at the desired depth and the measurement on the boat has been tried to be minimum, it has been between 5 and 10 minutes depending on the sampling depth. During this time interval, it is possible that properties of sample could have been changed because of the temperature equilibration with the upper levels of the lake. Furthermore, those properties, evidently, changes during measurements made on the boat, because the water sample tends to equilibrate with atmosphere. Inspite of the fact that utmost care has been spent in these measurements, the measured parameters should have had slightly different values from those at the sampling depth. However, these problems have been minimized to instrument's accuracy level in the last field campaign by the use of "Hydrolab Datasonde 3" multiparameter water quality probe with which measurements have been made at the desired depth. As will be shown in the following paragraphs, the field data provide good evidences on the dynamics of interaction between the monimolimnion and mixolimnion waters.

6.2. End-Members and Lake Water

Like the isotopic data, hydrochemical data suggest also the same end-members as shown in trilinear diagram which is based on data from second field campaign (August 1995) (Figure 9). Figure 9 implies that the typical regional groundwater is represented by Yuvarlakçay karstic spring. Other groundwater samples (such as, Marmarlı, Asar and Ada springs) which are more closely located to the Lake Köyceğiz exhibit local chemical variations such as sulfate reduction and cation exchange, but stay within the region of fresh (group-4) waters. Thermal waters are located closely the Sea Water region which is located to the right-hand end of central diamond, and the lake waters are located in between sea water and thermal waters. A general view of the hydrochemical composition of water samples from Lake Köyceğiz and surrounding sampling points is given in Figure 10.

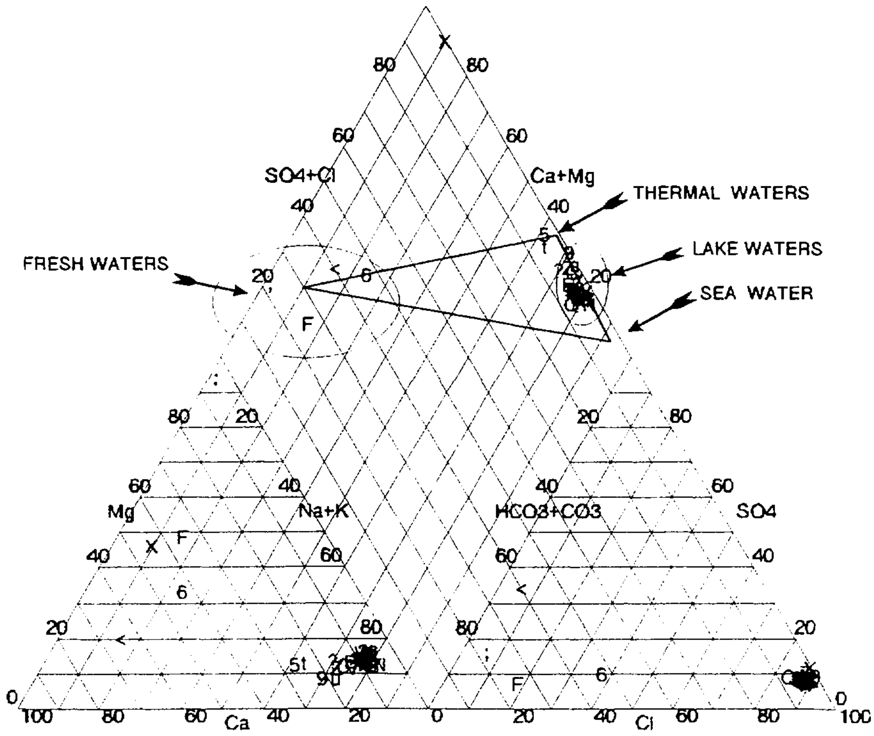


Figure 9: Trilinear diagram of water samples collected in and around Lake Köyceğiz (data from August 1994 field campaign).

6.3. Temporal Hydrochemistry of Lake Water

Temporal variations in the physical and chemical characteristics of lake water have been investigated with a number of field measurements carried out in typical wet and dry months. Apart from the parameters that have been measured in the field, water samples have also been collected for the determination of major ion, trace element and nutrient composition. The variation of both the field and laboratory parameters are in good agreement with those inferred from isotopic evaluations. The following evaluations are based on field measured parameters carried out two lake stations that represent the hydrochemistry of Köyceğiz and Sultaniye Basins. The locations of temporal measurement stations were chosen to reflect deepest profiles in both basins.

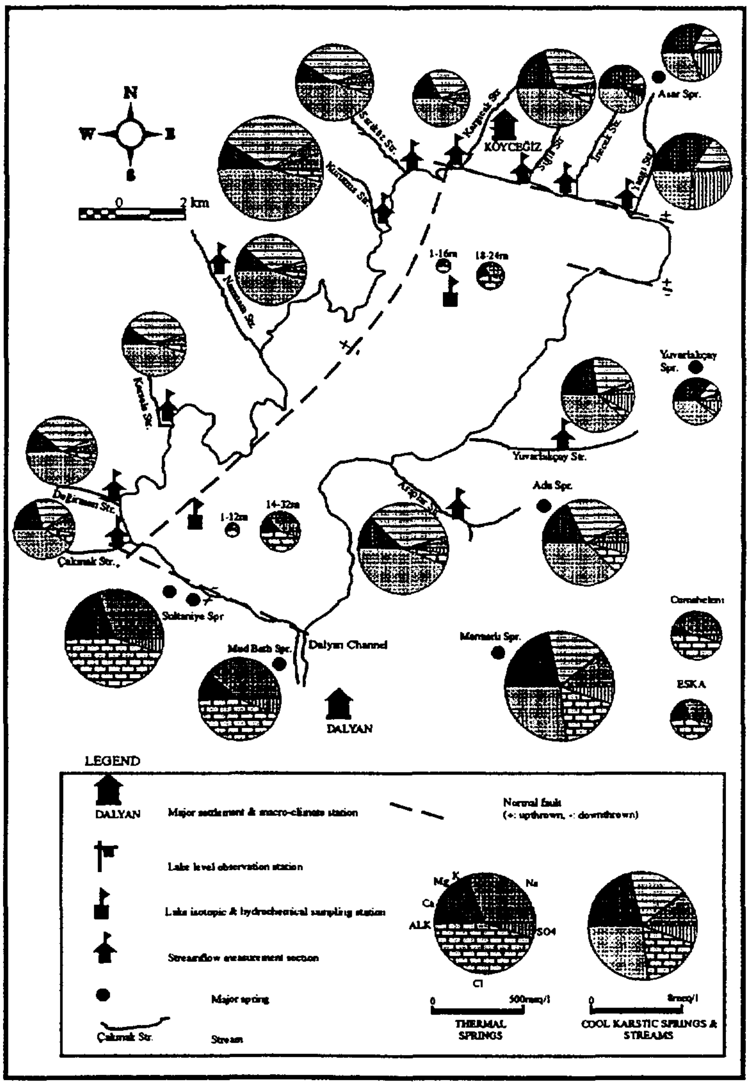


Figure 10: Circular diagrams showing hydrochemical character of sampling points (data from August 1994 field campaign).

6.3.1.Temperature :

Mixolimnion temperature in the Lake Köyceğiz varies depending on the equilibration with atmospheric temperature (Figure 11). As indicated earlier the depth to transition zone between monimolimnion and mixolimnion in both basins is controlled by the depth of Yoğun Strait that connects both basins. Temperature measurements from all campaigns indicate that the monimolimnion temperature in the Sultaniye Basin is rather stable and show only slight variations which may partially be attributed to measurement and calibration errors. However, the mixolimnion temperature of Sultaniye basin fluctuates all year round apparently because of temperature equilibration with air. High and low mixolimnion temperatures are observed in summer and winter months. According to temperature profiles, the mixolimnion extends to -12m whereas, the transition zone is located between –12m and –14m. Stability of monimolimnion profile indicates clearly that the permanent stratification is dominant in the Sultaniye Basin.

However, temperature profiles observed in Köyceğiz Basin is less stable in the monimolimnion region. Mixolimnion temperatures fluctuates annually as observed in Sultaniye Sector. Interestingly, temperature values observed in the bottom water of Köyceğiz Basin's monimolimnion and the monimolimnion of Sultaniye Basin. This supports the idea that the monimolimnion water from Sultaniye Basin flow toward the bottom of Köyceğiz Basin due to its higher density which is maintained by continuous thermal water sink and overflow.

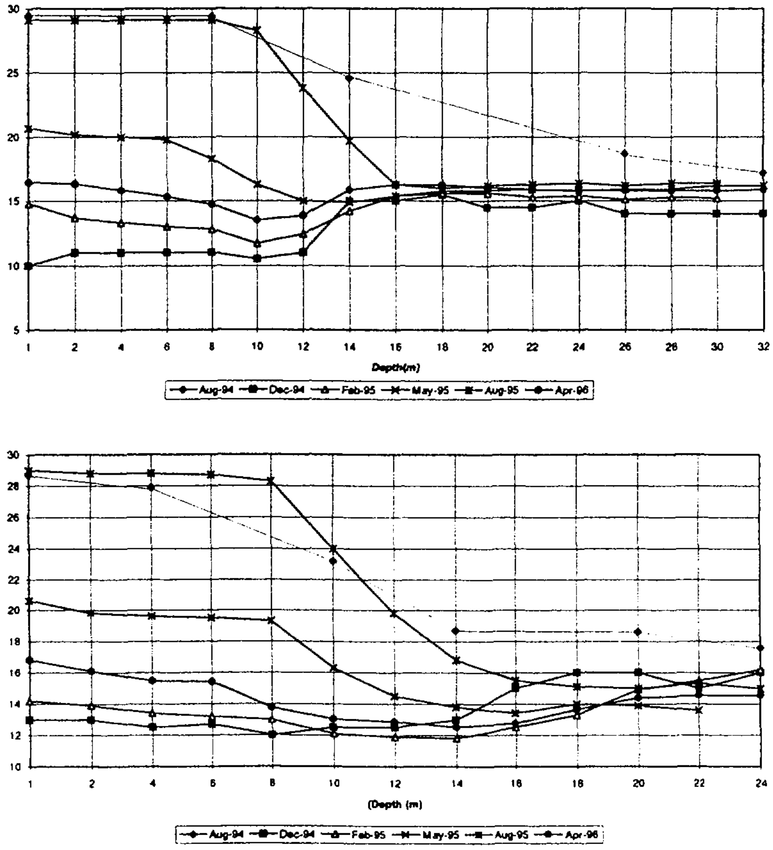


Figure 11: Temperature profiles in Lake Köyceğiz (Values are in °C. Top: Sultaniye Basin, Bottom: Köyceğiz Basin; August 1994 data is based on measurements made in samples brought to the boat).

6.3.2. Specific Conductivity:

Specific conductivity as a measure of total ion content is one of the best indicators of the interaction between monimolimnion and mixolimnion. In the Sultaniye Basin, alike temperature profiles, the specific conductivity profiles of monimolimnion and mixolimnion are separated sharply. Here the mixolimnion extends between surface and 8/12m. Depth to transition zone changes as a result of fresh water input from surface flow and rainfall, and the thickness of mixolimnion increases as expected when this input occurs (e.g. in December 1994 and April 1996). Contrary to the variations in Köyceğiz Basin, the top of monimolimnion in Sultaniye Basin is fixed at 14m depth regardless of the time of the year. The specific conductivity profiles in the mixolimnion of Köyceğiz Basin are nearly the same except that of December 1994 (Figure 12). This suggest that the mixolimnion water is chemically stabilized (or gets homogenized) within a very short period. In contrast to mixolimnion, specific conductivity profiles in the monimolimnion vary in a wider range suggesting that, although mixolimnion gets homogenized rapidly, mixing of mixolimnion with monimolimnion occurs gradually. As a result of this gradual mixing, the depth of monimolimnion reduces to 20m and the transition zone is thicker (i.e. between 8m/12m and 20m).

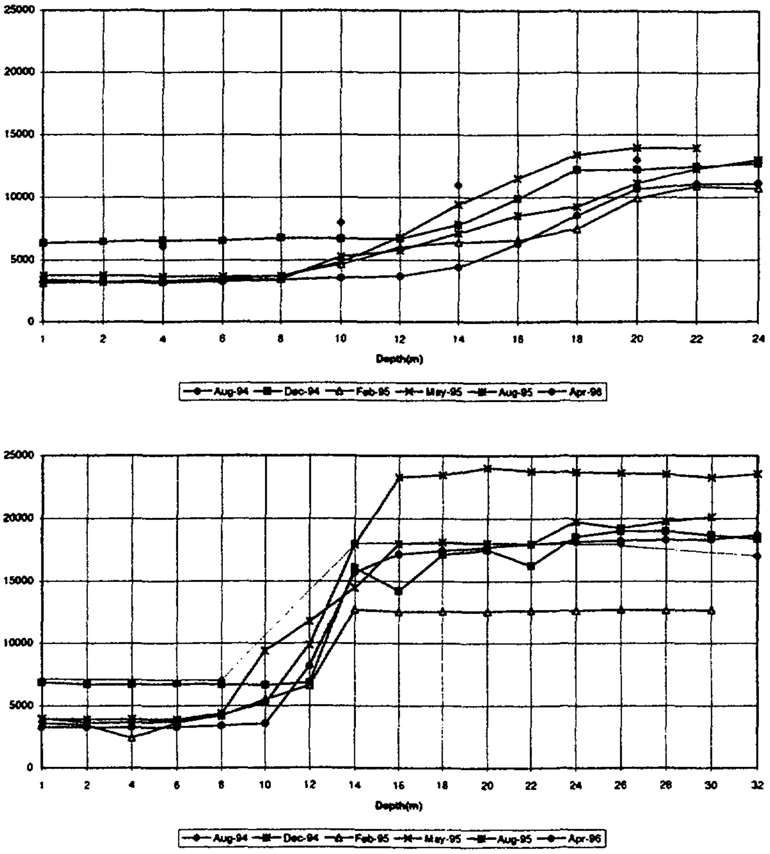


Figure 12: Specific conductivity profiles in Lake Köyceğiz (Values are in microSiemens/cm.. Top: Köyceğiz Basin, Bottom: Sultaniye Basin).

Comparison of specific conductivity profiles of Köyceğiz and Sultaniye Basins reveals that, even if the specific conductivity of mixolimnion in both basins are nearly the same, there is an apparent difference between the specific conductivity's of monimolimnions. The higher monimolimnion specific conductivity in the Sultaniye Basin should be due to continuous thermal water sink into this basin. Alike the stable isotope and temperature data, the specific conductivities of the waters of monimolimnion of Sultaniye Basin and that of Köyceğiz Basin's bottom water have similar values suggesting that monimolimnion water at 13m depth in the Sultaniye basin flows toward the bottom of Köyceğiz Basin.

6.3.3. Dissolved Oxygen:

Dissolved oxygen is among the primary field parameters that helps to identify the stratification variations in Lake Köyceğiz. Dissolved oxygen in the mixolimnion of both Basins varies between 5 mg/l and 10 mg/l (Figure 13). Dissolved oxygen content of monimolimnion is less than 2 mg/l. Lowest dissolved oxygen values in the of monimolimnion have been recorded in April 1996 campaign during which the measurements were made "in-site" by using multiparameter water quality probe. In these measurements it is believed that the maximum accuracy has been obtained since a magnetic stirrer fitted to the end of dissolved oxygen probe has also been used. It appears that dissolved oxygen content of mixolimnion is controlled both by water temperature and the intensity of biologic activity. Higher values are observed in colder periods when the oxygen solubility is increased but the biologic and chemical activities consuming oxygen is depressed. Dissolved oxygen profiles reveal that monimolimnion in Sultaniye and Köyceğiz Basins start at depths 12m/14m and 14m/16m, respectively. Accordingly, mixolimnion extends down to 6m/8m in Köyceğiz Basin, and to 10m in Sultaniye

Basin. Previous observations suggesting inflow from Sultaniye Basin's monimolimnion towards the bottom of Köyceğiz Basin are also supported by the dissolved oxygen data.

6.3.4. pH:

The pH provides also a robust portrait of the interaction between monimolimnion and mixolimnion in both basins. In the mixolimnion of both basins, the pH range between 8.4 and 8.8 as expected from an open water body which is abound with nutrients and photosynthetic organisms (Figure 14). Although seasonally changes, the pH does not show any drastic variation along the depth of mixolimnion, indicating that mixolimnion water is homogenized well. This is also the case for monimolimnion in both basins even if lower pH values observed there. The major factor controlling the value of pH in the mixolimnion is the biologic activity of floral species such as, alga. During higher biogenic activity periods, because of the photosynthetic use of dissolved carbon-dioxide, higher pH values are observed. According to pH values, the mixolimnion extends down to 8m in the Köyceğiz Basin, whereas it continues to 8m/10m in the Sultaniye Basin. The monimolimnion starts in the Köyceğiz and Sultaniye Basins at 20m and 16m, respectively. The decrease of pH in the monimolimnion of both basins may be attributed to several reasons: i) thermal water input (which virtually has no oxygen) into the monimolimnion and, ii) chemical reduction processes occurring due to depletion of oxygen by inorganic/organic reactions. Normally, the depletion of oxygen in aquatic systems leads to reducing conditions which result in proton (H^+) release into the water. Here, again the similarity between the pH values of the monimolimnion water of Sultaniye Basin and that of bottom water in Köyceğiz Basin is noteworthy. This may be accepted another evidence for the outflow of Sultaniye Basin's monimolimnion toward the bottom of Köyceğiz Basin.

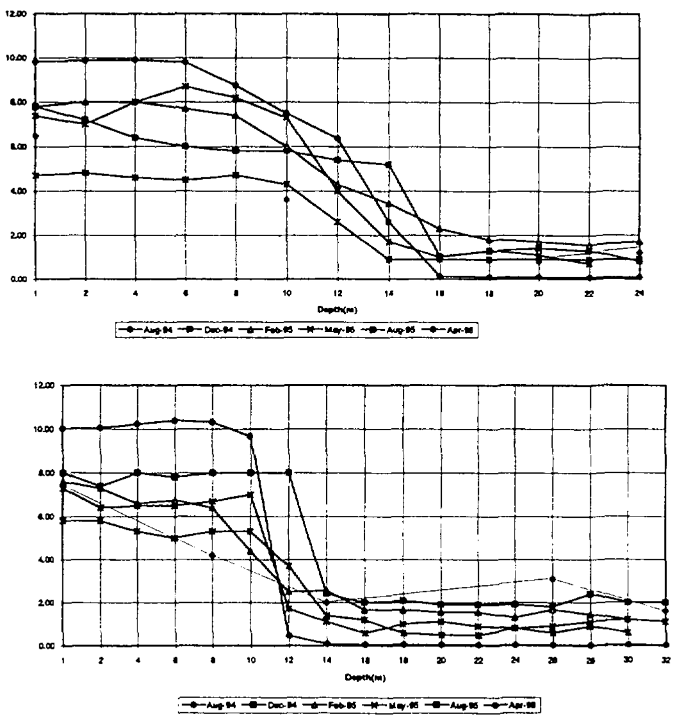
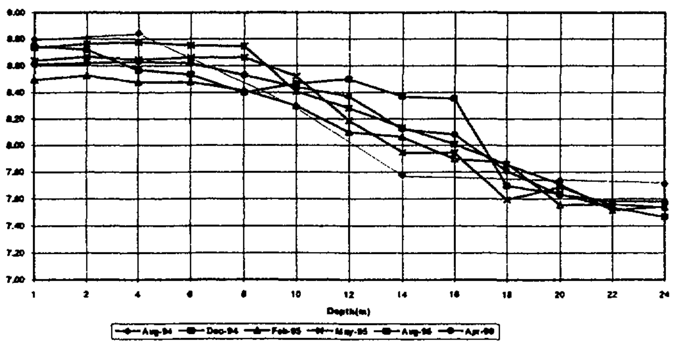


Figure 13: Dissolved oxygen profiles in Lake Köyceğiz (Values are in mg/l. Top: Köyceğiz Basin, Bottom: Sultaniye Basin).



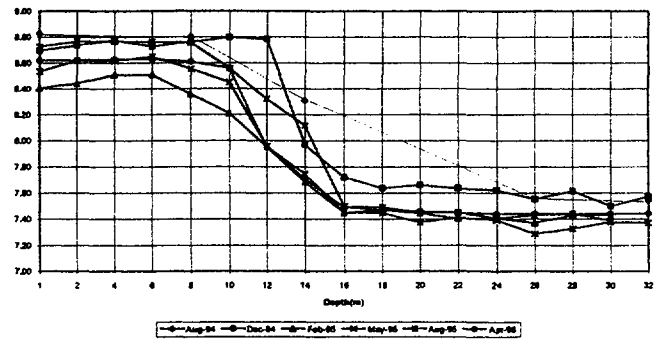


Figure 14: pH profiles in Lake Köyceğiz (Values are in standard units. Top: Köyceğiz Basin, Bottom: Sultaniye Basin).

6.3.5. Major Ion Composition

Major ion, trace element and nutrient data produced in all field campaigns expose a portrait that is in accordance with the deductions made on field measured data (i.e., electrical conductivity, dissolved oxygen and pH). Detailed evaluation of laboratory data will be given elsewhere and only the temporal variation of chloride ion, as a conservative species, is discussed here.

Variation of chloride composition in the Lake Köyceğiz suggest that the chemical composition of lake water do not show any substantial variation in the long run (Figure 15). The highest chloride content is observed in the monimolimnion of Sultaniye Basin where there is thermal water sink chemically resembling to Sultaniye thermal spring of which average chloride content varies around 400 mg/l. The chloride content of the Sultaniye Basin's monimolimnion is rather stable around 200 mg/l and reduces to 150 mg/l at the top of this zone at 14m depth. As expected, the chloride content of the bottom water in Köyceğiz Basin is similar to this value.

6.4. Spatial Variation of Chemical and Physical Parameters in Lake Köyceğiz

Spatial variation of some physical and chemical parameters have been measured "in-situ" by using a "Hydrolab Data Sonde 3 ™" multiparameter probe. Use of this instrument not only helped to increase the number of profiling stations (from 2 to 31, see Figure 3 for station locations and their depths), but also enhanced the quality of data because the measurements have been made at the desired depth without bringing water samples to the surface. Although, 7 parameters including temperature, pH, dissolved oxygen, specific electrical conductivity, redox potential and turbidity have been measured, because of the scarcity of space, only the variation of temperature and specific electrical conductivity are evaluated briefly here. More detailed evaluations including other parameters will be given elsewhere (see also [3]).

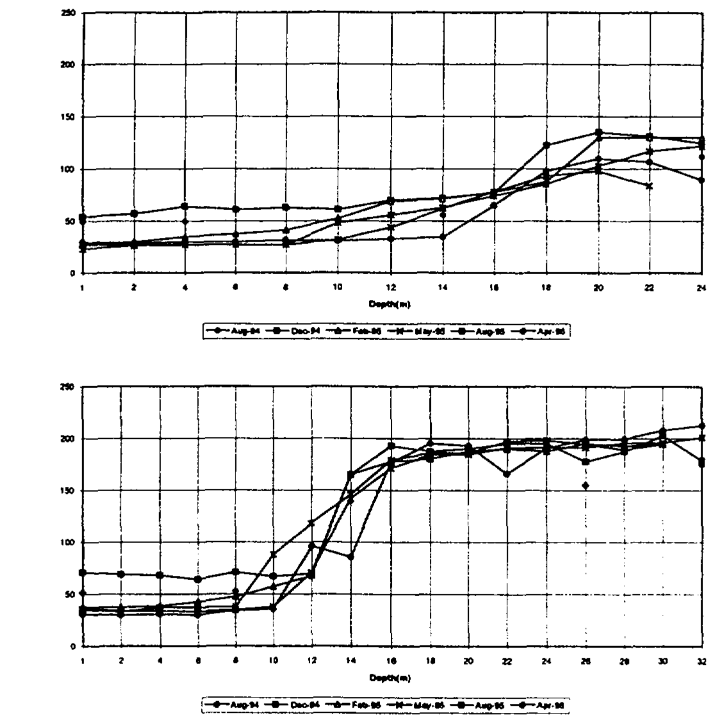


Figure 15: Cl profiles in Lake Köyceğiz (Values are in meq/l Top: Köyceğiz Basin, Bottom: Sultaniye Basin,).

6.4.1.Temperature:

Three main features in the temperature profiles are noteworthy (Figure 16). First, the monimolimnion temperatures in the Sultaniye Basin is apparently higher than those of Köyceğiz Basin, second temperature profiles in both monimolimnion have different shapes, third the mixolimnion temperature profiles vary in a wider range compared to those of monimolimnion. The difference between the shapes of temperature profiles in the monimolimnion of both basins suggests that, the monimolimnion in Sultaniye Basin is more stable in terms of heat balance. In both basins, the monimolimnion temperature becomes stable below 20m depth. Moreover, the monimolimnion temperature profiles of Sultaniye Basin also reveals that only the top 6m (between 14m and 20m) is influenced by the mixolimnion temperature variations.

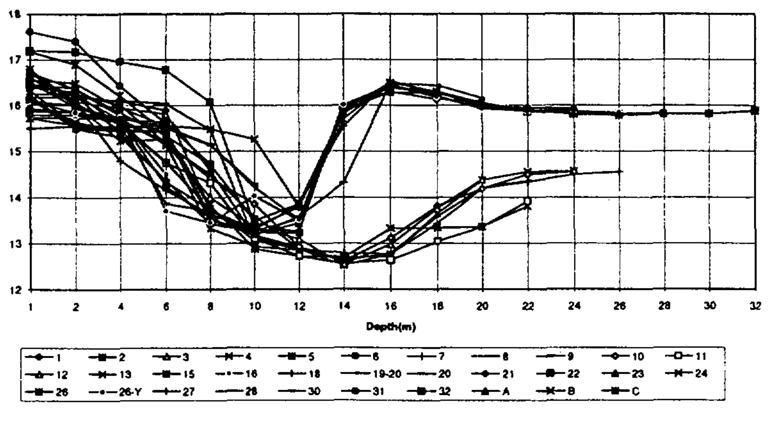


Figure 16: Variation of temperature at 31 stations in the Lake Köyceğiz (Values are in °C, Data from April 1996 campaign).

6.4.2. Specific electrical conductivity:

Alike temperature profiles, specific conductivity profiles as well suggest the same depiction. That is, the specific conductivity of mixolimnion is nearly the same all over the lake and the specific conductivities in the monimolimnion of either basins are apparently different, with higher values belonging to the Sultaniye Basin (Figure 17). According to specific conductivity profiles, the transition zone extends between 10m and 20m in both basins. Below 20m, the specific conductivity apparently does not change to a great extend. On the other hand, specific conductivities observed in the monimolimnion of Sultaniye Basin is more homogenous than those of Köyceğiz Basin, implying that mixing of mixolimnion and monimolimnion is more important in the Köyceğiz Basin.

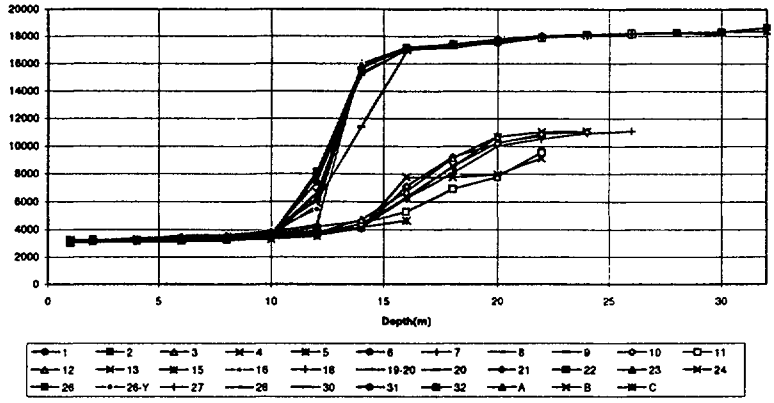


Figure 17: Variation of specific electrical conductivity at 31 stations in the Lake Köyceğiz (Values are in microSiemens/cm, Data from April 1996 campaign).

7. DENSITY VARIATIONS

In order to have a better under standing of the mixing dynamics, density variation in the Lake Köyceğiz has been investigated by means of "sigmatee" data for selected profiling stations. The "sigmatee (τ_t)" is the difference between the density of a water sample and that of pure water. Since, the density variations are small numerically, by convention, the sigmatee values are multiplied by 1000 to have a better expression. The pure water has a sigmatee value of zero and the higher the density of water the higher the sigmatee values. The "international equation of state for sea water" that accounts for the effects of salinity, temperature and hydrostatic pressure upon density has been used for the calculation of sigmatee values. Variation of lake waters' density in vertical direction for all stations is shown in Figure 18 which is based on the data collected in April 1996 field campaign. Data from other field studies reveals similar portraits in terms of density variations. Variation of sigmatee values in April 1996 indicates that the waters with highest density are found in the monimolimnion of Sultaniye Basin where dense thermal water sink is suggested by chemical and isotopic data. Slightly lower sigmatee values are observed in the monimolimnion of Köyceğiz Basin. Densities observed in the bottom of Köyceğiz Basin are similar to those of 12m depth of Sultaniye Basin. This observation is accepted as another supporting evidence for the fact that the monimolimnion water in Sultaniye Basin flows through 12m deep Yoğun Strait toward the bottom of Köyceğiz Basin.

A simplified view of sigmatee variation in Lake Köyceğiz is given in Figure 19 for stations located between station no.2 (offshore of Köyceğiz town at the north) and station "a" (lake outlet at the south). Figure 19 reveals that the lowest density in the Lake Köyceğiz is observed in station 2 whereas, the highest density is observed at the bottom of station 31 that penetrates into the monimolimnion of Sultaniye Basin. Lake water density in the mixolimnion increases progressively from station 2 toward station 'a' which is most closely located to the sea.

However, it appears that the density of Sultaniye monimolimnion originates from thermal water sink rather than sea water intrusion because the density observed in this station is substantially lower than those observed in Sultaniye monimolimnion.

The argument that suggests monimolimnion owerflow toward the bottom of Köyceğiz Basin from the Sultaniye monimolimnion is also supported by Figure 19. Densities observed in the transition zone between monimolimnion and mixolimnion of Sultaniye Basin at the depth of 13 m (i.e. in between 12m and 14m depths) correspond to density of bottommost water of profile 12 in the Köyceğiz Basin. From this profile toward those located to the north, denisty of lake water in the top and bottom waters reduces progressively indicating that the main source of dense water in the Köyceğiz Basin is the monimolimnion of Sultaniye Basin.

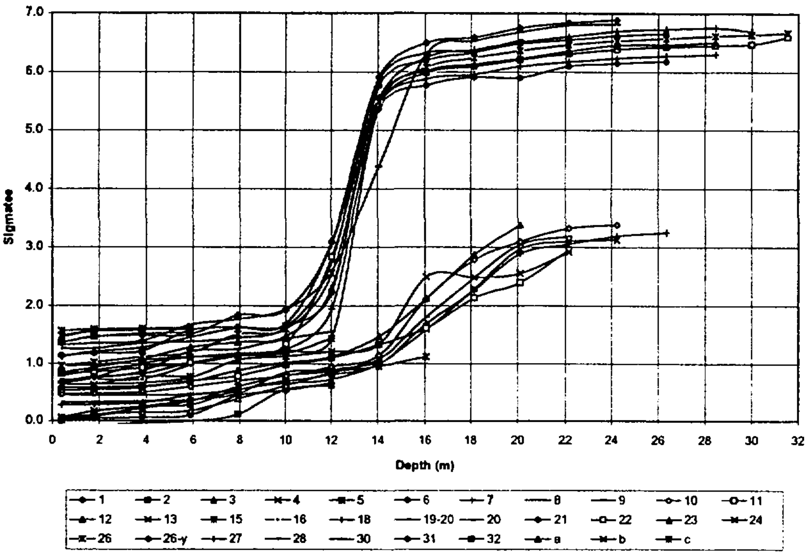


Figure 18: Variation of sigmatee values among profiling stations in the Lake Köyceğiz (data based on April 1996 field campaign).

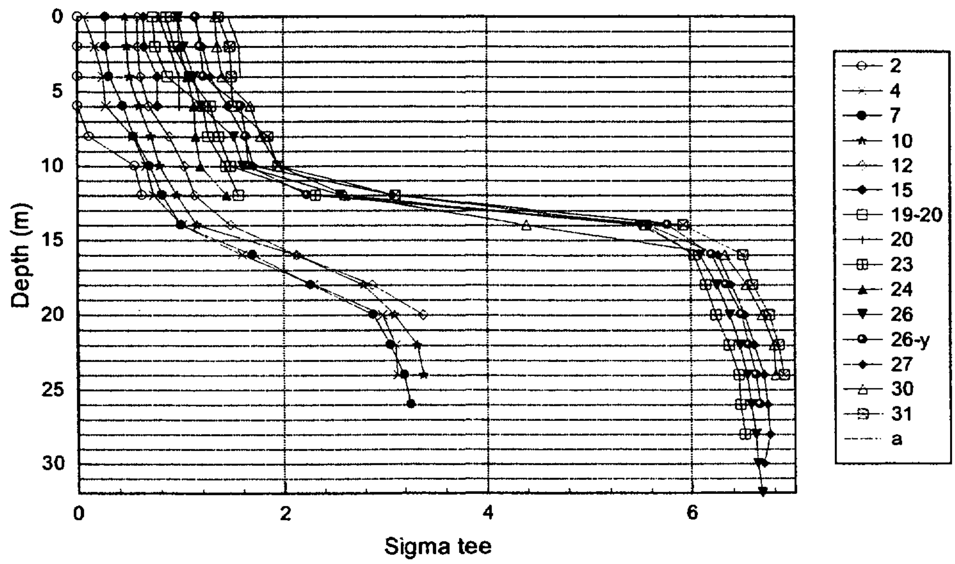


Figure 19: Variation of sigmatee values along profiling stations located between station no.2 (Köyceğiz town offshore at the north) and station "a" (lake outlet at the south).

8. EPILOGUE: LAKE DYNAMICS MODEL

Overall evaluation of isotopic, chemical and density data collected in this study reveals that the Lake Köyceğiz has a complicated mixing dynamics which is controlled mainly by density-driven flow of waters from different origins (Figure 20). The lake is fed mainly by rainfall and streamflow as low density waters and by high density thermal groundwater. Apart from the streamflow brought by two major streams Namnamçay and Yuvarlakçay which discharge into the northern part, the main source of low density water input is the rainfall. However, because of the density difference between mixolimnion and recharge, it appears that complete annual mixing in the lake can not be achieved.

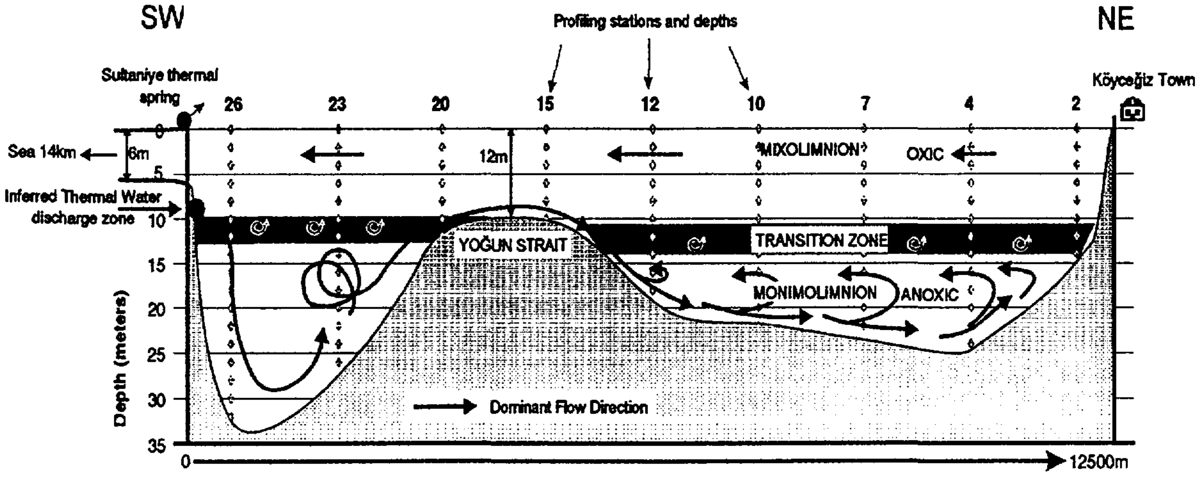


Figure 20: Conceptual lake dynamic model.

It appears that there is continuous high-density thermal water input into the southern (Sultaniye) basin of the lake where along thermal springs are located along the coast. Some of the thermal groundwater discharge into the lake from a depth of 8m to 10m along this coast line. Because of the high density, the thermal groundwater discharging into the lake sinks into the bottom of Sultaniye basin where the highest density among all lake waters is observed. The infilling of southern basin is controlled by the bottom topography. Since, this basin has two outlets, one located at 12m depth toward the northern basin, and another located at 6m depth toward the sea, the bottom (monimolimnion) water tends to overflow toward the northern basin. It appears that this overflowing water follows the bottom surface in the northern basin and is accumulated at the deepest point. During the travel of dense bottom water current, it is mixed with top (mixolimnion) water and as the distance from the high density water increases, the density tends to decrease. Consequently, highest and lowest density waters in the top water are found in the most southern and northern ends of the basin, respectively. These conclusions are in good agreement with those drawn from isotopic and chemical data. Isotopically most depleted waters in the area are represented by thermal groundwater discharges located on the southern shore of the lake. The variation of the stable isotopic composition of the lake water is also in good agreement with density-driven flow scenario. Most isotopically depleted lake water are found in the bottom water of southern basin and the bottom water becomes progressively less depleted toward the north of the lake. Due to mixing with recent recharge, the top water is isotopically more enriched. The same conclusions are also valid for the variation of other physical and chemical parameters of the lake water. It is difficult to arrive at firm conclusions on the turn-over rates of bottom and top waters in both basins. However, rough calculations based on long-term average electrical conductivity data reveal that about 60% of mixolimnion in both basins is replenished by annual recharge where as the annual mixing of monimolimnion with mixolimnions in Sultaniye and Köyceğiz Basins are 20% and 30%, respectively. Therefore, the turn-over times for mixolimnion and monimolimnions of Sultaniye and Köyceğiz Basins are estimated to be 2 years, 5 years and 3.5 years, respectively.

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