

## Chemical tracing of salinity sources in Lake Kinneret (Sea of Galilee), Israel

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### *Abstract*

Lake Kinneret is a freshwater lake in northern Israel that receives a major part of its salt input from unmonitored springs that discharge through the lake's bottom. We attempt to characterize the nature of these springs by estimating their chemical composition. While the springs around Lake Kinneret are subject to wide spatial and temporal variations in their ionic concentrations, specific sodium (Na), potassium, magnesium (Mg), strontium, bromine, and lithium to chlorine (Cl) ion ratios are almost constant within individual springs and spring groups. The radium:Cl ratio and the  $\delta^{18}\text{O}$ -Cl relationship confirm the notion that the spring waters result from recent mixing between saline brines and freshwater.

Available compositional data from past years along with new analyses of the lake and its known springs allow identification of the salinity source that causes the observed deficit in the lake's salt budget (e.g., 91–93% chloride). The relative contributions from these saline springs are different for different ions; this contribution is highest for bromide (95%), decreases to 84% for Na, and is less than 50% for Mg.

Two independent approaches have been used for balancing the salts in the lake, and they are as follows: (1) an annual mass balance between salt removal and supply of the different ions, assuming a steady-state lake; and (2) simulation of the lake's evolution from 1964 (the beginning of salt removal from the lake via the Salinity Diversion Channel) until the present. Both methods predict very similar ionic ratios for the (yet unknown) average saline spring(s), testifying to the reliability of both approaches. The ionic ratios so obtained closely resemble Fuliya ( $\pm$  Tabgha)-type waters, excluding the Tiberias and eastern shore springs as significant salt sources. This inferred composition of the average unmonitored springs depends strongly on present-day diversion of saline springs (this diversion thus prevents their flow into the lake). The different ionic ratios that identify the various spring groups reflect the respective compositions of the brine pockets that feed them. Our simulation also shows that the layered structure of Lake Kinneret enhanced the evolution rate of the lake after the implementation of the salt diversion program in 1964.

Lake Kinneret (LK; Lake Tiberias or the Sea of Galilee) is a lake of immense historical and religious significance. It is also the only freshwater lake in Israel and the main water reservoir for the National Water Carrier (NWC)—the water supply system that transfers freshwater to central and southern Israel. About 30% of the country's water supply was pumped from LK in 1995. Furthermore, with the water shortage in the Middle East becoming more and more acute, LK is also a waterbody of great political significance.

The lake is monomictic; it is stratified between mid-March and December. The mixing of a fully stratified to a fully mixed lake takes about 4–5 months. Though it is a flow-through lake, it is significantly saltier than the Jordan River, which is its major water source (Table 1). The composition

of LK dissolved salts is different from that of these same Jordan River salts (Tables 1, 2); whereas the sodium:chlorine (Na:Cl) equivalent ratio in the Jordan is around 1.3, it is significantly lower ( $\sim 0.78$ ) in LK. The major sources of the lake's salinity are surrounding and underlying saline springs. Furthermore, both salt content and salt composition are different in the epilimnion and hypolimnion (Table 1).

The lake volume is  $4.1 \times 10^9 \text{ m}^3$ , of which about  $650 \times 10^6 \text{ m}^3$  of water are exploitable. At the beginning of the century, the concentration of chloride in the lake was below  $300 \text{ mg Cl liter}^{-1}$  (Serruya 1978). Artificial decrease of the lake-water output during the 1940s increased the chloride concentration to some  $350\text{--}395 \text{ mg liter}^{-1}$ . In 1964, the NWC began to operate, thereby increasing the freshwater throughput. This action was supplemented by the southward diversion from the lake of several saline springs (via a Salinity Diversion Channel [SDC]); these springs were thus diverted into the Jordan River (Fig. 1). Consequently, the chloride concentration in LK started to drop toward its present level of some  $230 \text{ mg liter}^{-1}$  (Table 1).

The source of the saline waters around LK has been attributed by Mazor and Mero (1969) to an intrusion of seawater into the region that occurred during the Neogene. Goldschmidt et al. (1967) and Starinsky (1974) explained that the origin of the saline water was evaporated seawater that had precipitated evaporites such as gypsum and halite.

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Table 1. The chemical composition of Lake Kinneret, the Jordan River, and the eastern runoff (in mg/liter).

Chemical	Lake Kinneret (1996)*		Lake Kinneret (1964)†	Arik Bridge Jordan (1997)	Eastern Runoff‡
	Upper	Lower			
Na	122.7	112.6	163	12.4	40.4
K	6.21	6.06	8.0	1.53	2.5
Mg	28.8	27.9	34	11.0	22.5
Ca	46.2	59.2	68	58.3	31.0
Sr	0.660	0.678	1.0	0.179	0.25
Cl	241.1	223.8	347	14.7	32.5
Br	1.58	1.53	2.9	0.054	0.11
SO <sub>4</sub>	50.6	38.0	68	30.3	7.4
HCO <sub>3</sub>	143.6	213	154	194	260
Li	0.0108	0.0098	0.0065	bd§	<0.001

\* Location: UTM 744314/634848; Sampling on 13 Nov 1996; Profile #108. Upper water mass (Epilimnion), 21.7°C; lower water mass (hypolimnion), 16.1°C.

† See Nissenbaum (1969, p. 25): 20-m depth.

‡ Average of the Yahudia and Meshushim streams was taken as representing runoff from the eastern watershed.

§ bd, below detection limit.

Mazor and Mero (1969) divided the waters into several geography-composition groups. In the present study, we have applied their classification to our own data. The isotopic composition of the waters was measured by Gat et al. (1969); they explained the  $\delta^{18}\text{O}$  of the spring waters by mixing two end-members: (1) seawater evaporated by a factor of two to three and (2) freshwater of meteoric origin.

Saline waterbodies occur all around, and probably beneath, LK. It is, therefore, of interest to recognize those waterbodies that are chiefly responsible for the chemical composition of the modern lake. In the present study, we attempt to achieve this recognition by comparing the ratios of the different chemical constituents of the salt inputs—the monitored saline springs, the Jordan River, and the surface runoff into the lake. The results of this comparison are then tested against an integrative approach that describes the recent (1964–1996) evolution of the lake.

#### Overall water and salt balances

The extent of salt spring contributions to LK salinity became clear in the 1960s as a result of a series of studies that centered on water and salt balances. Assouline (1993) presented a detailed treatment of the salt balance. Several additional researchers have reported calculations of the salt sources for LK using a mass-balance approach (e.g., Nishri et al. in press). The amount of chloride supplied by the saline springs was estimated based on the difference between the amount of salts removed from the lake  $T_{\text{out}}$  (pumping, usage, and overflow to the southern Jordan river) and the amount of salt supplied to the lake by the monitored sources  $T_{\text{in}}$  (northern Jordan inflow and other runoff).

The various fluxes of chloride are routinely estimated by measuring chloride concentration profiles as well as inflowing waters at several sites in LK and by measuring both water discharges into the lake and amounts of water pumped

Table 2. Ionic ratios (in equivalents) in Lake Kinneret and its surface supply sources (based on data from Table 1).

	Lake Kinneret (1996)		Kinneret (1964)	Jordan (1997)	Eastern runoff (1997)
	Upper	Lower			
Na/Cl	0.785	0.776	0.72	1.30	1.92
K/Cl	0.0230	0.0246	0.021	0.094	0.070
Mg/Cl	0.349	0.364	0.29	2.18	2.02
Ca/Cl	0.339	0.470	0.35	7.02	1.69
Sr/Cl	0.0022	0.0025	0.0023	0.010	0.0062
Br/Cl	0.0029	0.0030	0.0037	0.0016	0.0014
Mg/Na	0.444	0.469	0.40	1.68	1.05
Li/Cl ( $\times 1,000$ )	0.229	0.224	0.096	nd*	nd*

\* nd, not determined.

from the lake. The chemical composition of the waters that leave the lake has been assumed to be identical to the lake's composition. In the analysis below, we rely heavily on the published water balances for LK (Table 3). Error analyses

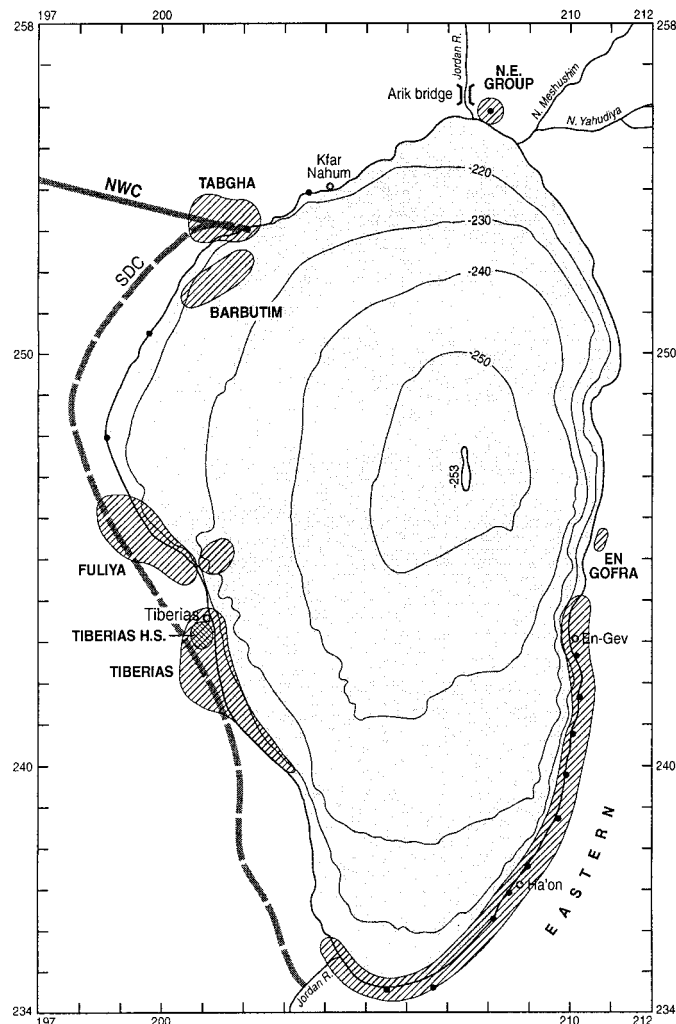


Fig. 1. Location map. The distribution of the major saline spring groups is indicated. Modified after Simon and Mero (1992).

Table 3. Water and chloride balance for the hydrological year 1996–1997 (from Rimmer and Shaw 1997).

	Water (mm <sup>3</sup> )	Cl <sup>-</sup> (tons)
Inputs		
Jordan	396	7,748
Runoff + rain	124	1,841
Saline springs	68	101,959
Stream diversion	27	3,011
Total annual	615 (T <sub>in</sub> )	114,559
Outputs		
Evaporation	242	0
NWC	376	86,078
Usage	86	19,677
Outflow (at Degania)	15	3,385
Total annual	719 (T <sub>out</sub> )	109,140

of such balances were presented by Assouline (1993) and by Rimmer and Shaw (1995).

The total supply of chloride into LK, T<sub>in</sub>, is provided by monitored, onshore sources (i.e., known springs, Jordan River, etc.) and by subaqueous, unmonitored sources, the number and specific site and composition of which are unknown. The latter, unmonitored sources are designated by “US1.” In contrast, the total output of salts from the lake, T<sub>out</sub>, is known and monitored. During periods of steady state, T<sub>in</sub> = T<sub>out</sub>, and these terms can be interchanged. Hence,

$$T_{US1} = T_{out} - T_{in} \quad (1)$$

Consequently, US1 represents the average contribution of the sublacustrine, or onshore, unmonitored inputs into the Lake.

*Sampling and analyses*—Between 1995 and 1997, we sampled and analyzed water from several stations in and around LK, from 14 saline springs on the lake’s shore, as well as from the Jordan River at the Arik Bridge, close to its inflow into LK (Fig. 1). Most of the sources were sampled about 8 to 10 times within the 2 yr of study. We also sampled water from the Yahudiya and the Meshushim streams (Fig. 1), which represent the major runoff supply from the east into the lake (Tables 1, 2).

Chemical analyses were performed at the Geochemical Laboratory at the Institute of Earth Sciences, The Hebrew

University of Jerusalem. Initially, Na, potassium (K), and lithium (Li) were measured by atomic absorption spectroscopy (Perkin Elmer 5000). Calcium (Ca), magnesium (Mg), strontium (Sr), and SO<sub>4</sub> were determined by plasma emission on a Perkin Elmer model 6000 ICP spectrometer. Later, all the above elements were analyzed on a Perkin Elmer Optima 3000 ICP spectrometer. Cl and bromine (Br) were determined using a Quickchem, Model AE Automatic Flow Injection Analyzer, manufactured by Lachat. HCO<sub>3</sub><sup>-</sup> was determined by titration with 0.02 M HCl, using a BDH 4460 indicator.

In addition to chemical analyses, we also measured the activity of <sup>226</sup>radium (Ra) (t<sub>1/2</sub> = 1,600 yr). Ra was determined by equilibrating it with its daughter, <sup>222</sup>radon, and then measuring the latter emanometrically in a “Lukas Cell” (Mathieu et al. 1988; Moise 1996).

## Results and discussion

The most important result (Table 4) is that the ionic (and isotopic) ratios characteristic of every group of springs (Fig. 2) vary only within a rather limited range, whereas for a given source, chemical and isotopic compositions may differ in time, and between closely related saline springs, they may differ in space. The characteristic values of ionic and isotopic ratios for spring groups are interpreted to reflect mixing relationships between a “brine end-member” and a “freshwater end-member” (Fig. 2). The reason for the narrow variation of the ionic ratios is the insignificant contribution of salts from the freshwater end-member.

The existence of a Ca-chloride brine in the subsurface of the Jordan Valley, which could be interpreted as the cause of its saline springs, was suggested by Starinsky (1974). Starinsky also presented a detailed mechanism for the evolution of such a brine. The crux of his explanation is that these brines formed in a marine lagoon by evaporation of seawater beyond the halite precipitation point, and these brines were subsequently modified by mineral–water interaction in the subsurface, mainly via dolomitization of carbonate sediments and/or limestone. The variability of elemental ratios between geographically separated groups of springs suggests that the brine end-member varies in its composition between different geographic localities, probably reflecting isolated brine pockets. The similarity of the <sup>226</sup>Ra-

Table 4. Ionic ratios in the saline water sources (eq liter<sup>-1</sup>).

Group	Na/Cl	Mg/Cl	K/Cl	Mg/Na	Br/Cl	Li/Cl × 1,000	Sr/Cl × 1,000
NE of Kinneret	0.59	0.26	0.0039	0.43	—	0.0160	0.80
Eastern shore	0.60–0.64	0.26–0.33	0.017–0.018	0.39–0.53	0.0052–0.0058	—	—
En Gofra	0.71–0.75	0.23–0.25	0.026–0.029	0.32–0.33	0.0043	0.27–0.29	3.1–3.4
Tiberias	0.54–0.64	0.17–0.23	0.017–0.018	0.29–0.41	0.0048–0.0061	—	—
Tiberias Hot Springs	0.57–0.61	0.10–0.12	0.017–0.020	0.17–0.20	0.0053–0.0057	0.33–0.36	2.8
Tabgha	0.69–0.73	0.11–0.15	0.016–0.017	0.16–0.20	0.0052–0.0058	0.35–0.39	3.0–3.1
Barbutim	0.66–0.68	0.13–0.15	0.015–0.017	0.19–0.23	0.0034–0.0037	—	—
Fuliya	0.73–0.78	0.12–0.14	0.015–0.016	0.17–0.19	0.0025–0.0029	0.12–0.18	1.5–1.7
SDC (1975)	0.66	0.131	0.016	0.20	—	—	3.0
SDC (1997)	0.66	0.129	0.016	0.20	0.00435	0.37	3.1

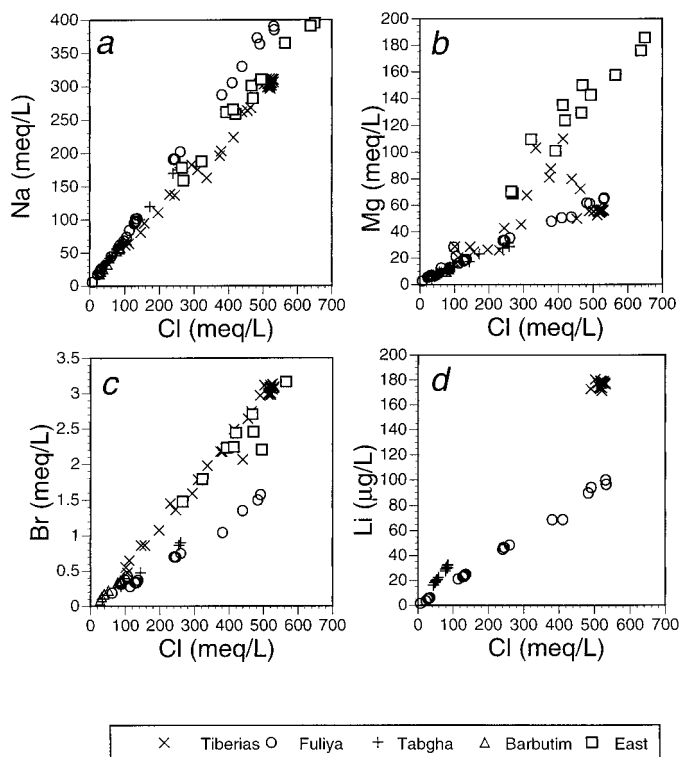


Fig. 2. Chloride-ion relationships in saline springs. (a) Na-Cl, (b) Mg-Cl, (c) Br-Cl, and (d) Li-Cl. For (a), (b), and (c), data are from Mazor and Mero (1969), Moise (1996), and this study. For (d), data are from this study. All plots of this figure can be interpreted to represent mixing relationships between saline end-members (of a different composition for every group) and a freshwater end-member.

Cl plots (Fig. 3) to the other ion-Cl plots indicates recent mixing on a scale of  $10^3$  years (Moise 1996).

According to Gat et al. (1969), the waters of the Tiberias group fall on a mixing line, with Cl ranging between 3,000 and 18,000 mg liter<sup>-1</sup> and with  $\delta^{18}\text{O}$  ranging between  $-3$  and  $-4\text{‰}$ . Figure 3 shows the  $\delta^{18}\text{O}$ -Cl relationship in the Fuliya and Tiberias groups. It is noteworthy that the freshwater end-member is practically identical for the two groups, and it probably possesses a chloride content of about 50–100 mg Cl liter<sup>-1</sup> and a  $\delta^{18}\text{O}$  of about  $-4.6\text{‰}$ . On the other hand, the saline end-members are significantly different: for a salinity of 18,000 mg Cl liter<sup>-1</sup>,  $\delta^{18}\text{O}$  of the Fuliya group is  $-1.8\text{‰}$ , whereas that of Tiberias is  $-3.5\text{‰}$ . These differences can be explained by multistage dilution of an original brine, as first suggested by Gat et al. (1969). Furthermore, the discernible difference in elemental and isotopic ratios between groups of springs and wells suggests the possibility of “fingerprinting” the different groups. The question of whether the analogous chemical and isotopic ratios in LK reflect an overwhelming contribution from a specific group of springs or rather are a combined contribution from a small number of groups is addressed below.

*Ion ratios in US1*—The ion ratios in the total salt input of US1 could, in principle, be calculated with Eq. 1 for every

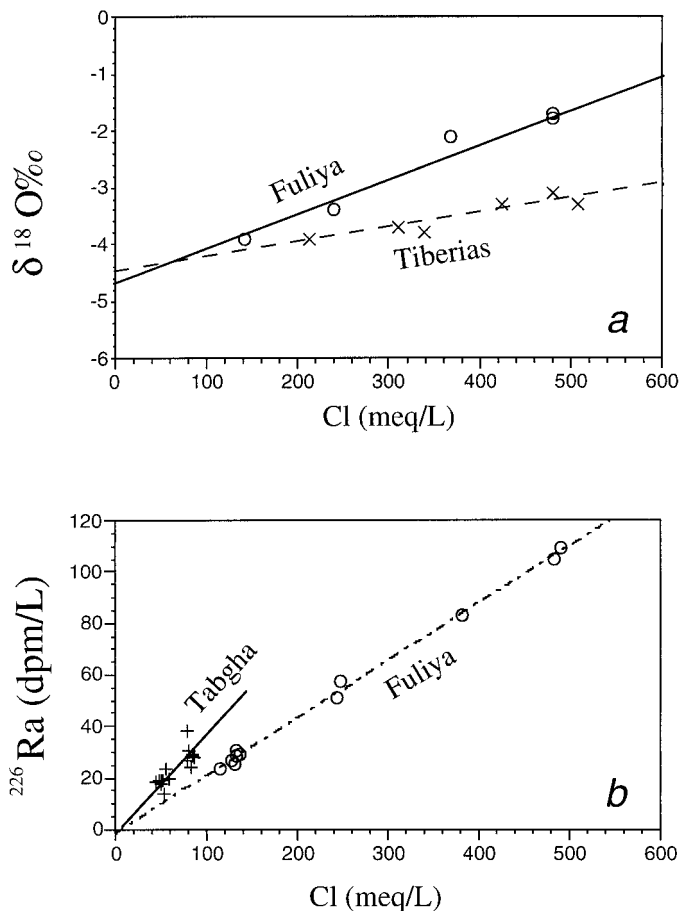


Fig. 3. (a)  $\delta^{18}\text{O}$ -Cl. Data from Gat et al. (1969) and Moise (1996). Note that this plot suggests a single freshwater component mixing with two brine end-members. (b)  $^{226}\text{Ra}$ -Cl. Data from Moise (1996).  $^{226}\text{Ra}$  behaves as a conservative element, suggesting mixing, which is recent on a  $10^3$ -yr time scale.

conservative ion by evaluating  $T_{\text{in}}$  and  $T_{\text{out}}$  from the product of the concentration of an ion in a reservoir (i.e., LK, the Jordan, surface flow) by its volume. Such a procedure would, however, be rather prone to error, because this product is sensitive to both volume (and discharge) estimates as well as to concentration variations. Since ratios are much more stable in all reservoirs and because chloride balances as performed by Tahal (Water Planning for Israel Ltd.) and Mekorot are much more reliable, we chose to multiply ion: Cl ratios in LK and the Jordan River by the corresponding chloride concentrations. It is assumed that within a year, the chloride concentration in the lake remains reasonably constant; hence, the input of chloride into the lake is equal to the amount removed. The following variables are used (Table 3): (1)  $T_{\text{out}}$ , the total annual Cl supply to the lake (in tons), is calculated from the chloride concentration in the lake multiplied by the volume of the chloride-bearing water leaving the lake annually (i.e., the sum of the quantities leaving by the NWC and that pumped from the lake for local consumption); and (2)  $T_{\text{in}}$ , the Cl<sup>-</sup> concentration in the Jordan River times the Jordan River annual discharge plus a similarly calculated product for “average runoff.”

Table 5. Chemical characteristics of the US1 as calculated from data for the hydrological year 1996–1997, assuming surface layer composition as LK chemistry. Calculations were performed both including runoff and neglecting it. The table includes the mass of elements supplied by the US1 and the fraction of the US1 (in %) from the total input of the element to LK. The right hand columns give the ionic ratios in the US1.

Element	Chemical composition				Ratio studied (element/Cl)	No runoff (ionic ratio)	Runoff included (ionic ratio)
	No runoff		Runoff included				
	(tons)	(%)	(tons)	(%)			
Na	49,008	88.2	46,719	84.1	Na	0.7453	0.7236
K	2,005	71.3	1,863	66.3	K	0.0179	0.0170
Mg	7,239	55.5	5,965	45.8	Mg	0.2083	0.1748
Ca*	-9,815	-46.9	-11,571	-55.3	Ca	-0.1712	-0.2056
Sr	204	68.4	190	63.7	Sr	0.0016	0.0015
Br	687	96.0	681	95.2	Br	0.0030	0.0030
Li	4.5	91.9	4.5	91.3	Li	0.0002	0.0002
Cl	101,392	92.9	99,551	91.2	—†	—	—

\* Ca is an example of nonconservative behavior in the lake; in our balancing, the principal process of calcite precipitation has been neglected.

† For Mg/Na, the ionic ratio not including runoff was 0.2795; including runoff, the ratio was 0.2416.

A sample balance calculation (similar to the one carried out for chloride) has also been performed for  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{Sr}^{2+}$ ,  $\text{Li}^+$ , and  $\text{Br}^-$  for the hydrological year 1996–1997 (Table 5). Each of the listed ion:Cl ratios has been calculated for LK, the Jordan River, and runoff. The masses of each ion were then obtained by multiplying the respective ratio by the amount of chloride in each reservoir. Thus, the amounts of each element that must be supplied to the lake by US1 were calculated. The results of these calculations are presented in Table 5. About 102,000 tons of chloride (or 91–93% of the total chloride supply) were introduced into the lake by the US1. A similar or even higher percentage of bromide was contributed by the same springs (680 tons, or 95–96%). The contribution of the US1 to the balance of the other ions is lower, amounting to 84–88% for Na (46,000–49,000 tons) and to 45–55% for Mg (6,000–7,000 tons). The mass of each ion contributed by the US1 is calculated by difference; therefore, its value depends on the assumed initial parameters, notably, on whether the supply term includes only the Jordan River or whether the runoff salt supply is also included and whether the concentrations assumed for LK are epilimnic or hypolimnic. Table 5 was constructed assuming LK surface chemistry, and it presents the resulting expected ionic ratios in the US1. Table 5 also illustrates the dependency of the US1 composition on runoff. The latter, in turn, depends on ion concentration, error in flux estimates, etc.

Ca,  $\text{SO}_4^{2-}$ , and  $\text{HCO}_3^-$  were omitted from the balance calculations because they are nonconservative in LK, thus showing a deficit in all our salt balances. For these three ions, there are additional sinks rather than a source in the lake: Ca and bicarbonate are precipitated as calcite (biogenic and/or inorganic), and sulfate is partially reduced.

*Thirty-year chemical evolution*—The contribution of solutes to LK from the unmonitored salt springs can be estimated alternatively from the change in the lake's composition, brought about by the 1964 diversion of several salt springs that had previously discharged into it.

An infinitesimally small change in the dissolved mass ( $m$ ) of a solute in LK can be described by the following equation:

$$dm_K = dm_J + dm_{RO} + dm_{US2} - dm_M, \quad (2)$$

In this equation, the subscript K represents LK, J represents the inputs of the solute from the Jordan River, RO the solute from the runoff, US2 the solute from the unmonitored salt springs (to avoid confusion, we will designate it as US2 when calculated as below), and M represents the sum of the outputs through the NWC system, etc.

The masses of a solute in Eq. 2 can be expressed as the products of the respective volume ( $V$ ) and concentration ( $C$ ); hence,

$$dm_K = V_K dC_K \quad (3)$$

$$dm_J = C_J dV_J \quad (4)$$

$$dm_{RO} = C_{RO} dV_{RO} \quad (5)$$

$$dm_M = C_M dV_M \quad (6)$$

Let us assume constant (but not necessarily equal) rates of supply (or removal) of solutes for each source and outlet from LK (Jordan River, runoff, NWC, and US2). If so, the ratios between their respective fluxes must also be constant. Hence,

$$dm_{RO}/dm_J = C_{RO} dV_{RO}/C_J dV_J \quad (7)$$

By substituting  $A = C_{RO} dV_{RO}/C_J dV_J$  into Eq. 7 and by then rearranging, we obtain

$$dm_{RO} = A dm_J \quad (8)$$

Similarly, a constant ratio  $P$  can be defined, such that

$$dm_{US2} = P dm_J \quad (9)$$

By designating that the ratio between the volume of water output from LK via the NWC ( $V_M$ ) and its input to the lake through the Jordan River ( $V_J$ ) will be represented by  $R$  yields

Table 6. The inputs of Na, K, Mg, and Cl into Lake Kinneret via saline springs (US2) calculated by Eqs. 15–17. Surface layer composition was assumed for LK chemistry.

Element	Input				Ionic ratios		
	No runoff		Runoff included		Ratio studied (element/Cl)	No runoff (ionic ratio)	Runoff included (ionic ratio)
	P*	Tons yr <sup>-1</sup>	P*	Tons yr <sup>-1</sup>			
Na	8.96	56,207	8.00	50,207	Na/Cl	0.755	0.705
K	3.07	2,376	2.59	2,006	K/Cl	0.019	0.017
Mg	1.63	9,091	1.04	5,810	Mg/Cl	0.231	0.154
Cl	15.4	114,865	14.76	109,808	— <sup>†</sup>	—	—

\* P, see Eq. 10 in text. Assumed volumes (10<sup>6</sup> m<sup>3</sup>) and fluxes (per annum): Kinneret: 4,100; Jordan River: 506; runoff: 145; National Water Carrier (NWC): 510.

<sup>†</sup> For Mg/Na, the ionic ratio not including runoff was 0.306; including runoff, the ratio was 0.219.

$$dV_M = RdV_J \quad (10)$$

By substituting Eqs. 3–10 into Eq. 2, we obtain

$$\begin{aligned} V_K dC_K &= C_J dV_J + PC_J dV_J + AC_J dV_J - RC_K dV_J \\ &= (C_J + PC_J - RC_K) dV_J, \end{aligned} \quad (11)$$

which, after rearrangement becomes:

$$\begin{aligned} V_K \frac{dC_K}{(C_J + PC_J + AC_J - RC_K)} \\ = V_K \frac{dC_K}{(aC_K + b)} = dV_J, \end{aligned} \quad (12)$$

where

$$a = -R$$

and where

$$b = C_J(1 + P + A).$$

Hence,

$$V_K \int_{C_{K_i}}^{C_{K_f}} \frac{dC_K}{(aC_K + b)} = \int_{V_{J_i}}^{V_{J_f}} dV_J \quad (13)$$

and,

$$\frac{V_K}{R} \left[ \ln \frac{(C_J(1 + P + A) - RC_{K_i})}{(C_J(1 + P + A) - RC_{K_f})} \right] = V_{J_f} - V_{J_i} \quad (14)$$

Setting  $V_{J_f} - V_{J_i} = \Delta V_J$  and rearranging eq. (14) yields

$$P = \left[ \frac{R \left( C_{K_i} - C_{K_f} \exp \left( \frac{R \Delta V_J}{V_K} \right) \right)}{C_J \left( 1 - \exp \left( \frac{R \Delta V_J}{V_K} \right) \right)} - 1 - A \right]. \quad (15)$$

The term  $\Delta V_J/V_K$  in Eq. 15 is a measure of the amount of Jordan River water, given in lake-volume units, that passed through LK during the integration time (1964–1997).

Equation 15 yields a specific  $P$  value for each solute, for which the following data is available: a) its initial ( $i=1964$ ) and final ( $f=1967$ ) concentration in LK. b) its constant concentrations in the Jordan River and in the runoff. The mass

of the solute contributed by US2 into LK during the same period is then obtained by multiplying its  $P$  value by its respective mass imported via the Jordan River.

We have carried out a calculation for Cl, Na, K, and Mg by integrating over the period from 1964 to 1997. The data used, the resulting mass inputs through the average saline spring, and some important resulting ionic ratios are displayed in Table 6.

The US2, as calculated in Table 6, is the average integrated spring, which should flow into LK and is compatible with the observed change in the lake chemistry after the diversion of the SDC. Therefore, it is instructive to compare both the composition and the ionic ratios of this US2 with those of the US1, calculated from a 1-yr budget. The comparison is presented in Fig. 4. The agreement between these independent methods is sufficiently strong to warrant our trust in both. The size of the bars for the two sets of calculations in Fig. 4a–f represents the estimate of the error on a calculated ratio. Because the values used in the calculations represent the extreme limits (composition of the upper versus the lower water layers, with or without the consideration of runoff contributions, etc.), the bar lengths designate the maximal range of variation of the specific ratios.

The evolution of the concentrations of Na, K, Mg, and Cl in the lake during the years from 1964 to 1997 is displayed in Fig. 5a and that of the corresponding ratios of Na:Cl, Mg:Cl, and K:Cl is displayed in Fig. 5b. The graphs were calculated as follows.

The concentration of a specific solute in LK at any given time during the 1964–1997 period is defined in Eq. 15 by the term  $C_{K_f}$ . In the same equation, the time is represented by the function  $\Delta V_J/V_K$  (the amount of Jordan River water, given in lake-volume units, that entered LK during the integration time). Using the data from Table 6, the weekly increment,  $W$ , for the integration period is obtained as follows:

$$W = \left( \frac{\Delta V_J}{V_K} \right)_{\text{week}} = \frac{506 \cdot 7}{365 \cdot 4100} = 2.367 \cdot 10^{-3} \text{ week}^{-1}. \quad (16)$$

By substituting  $(P + 1 + A)C_J = G$  in Eq. 15 (for any given solute) and by then rearranging, the required relation for  $C_{K_f}$  is thus yielded:

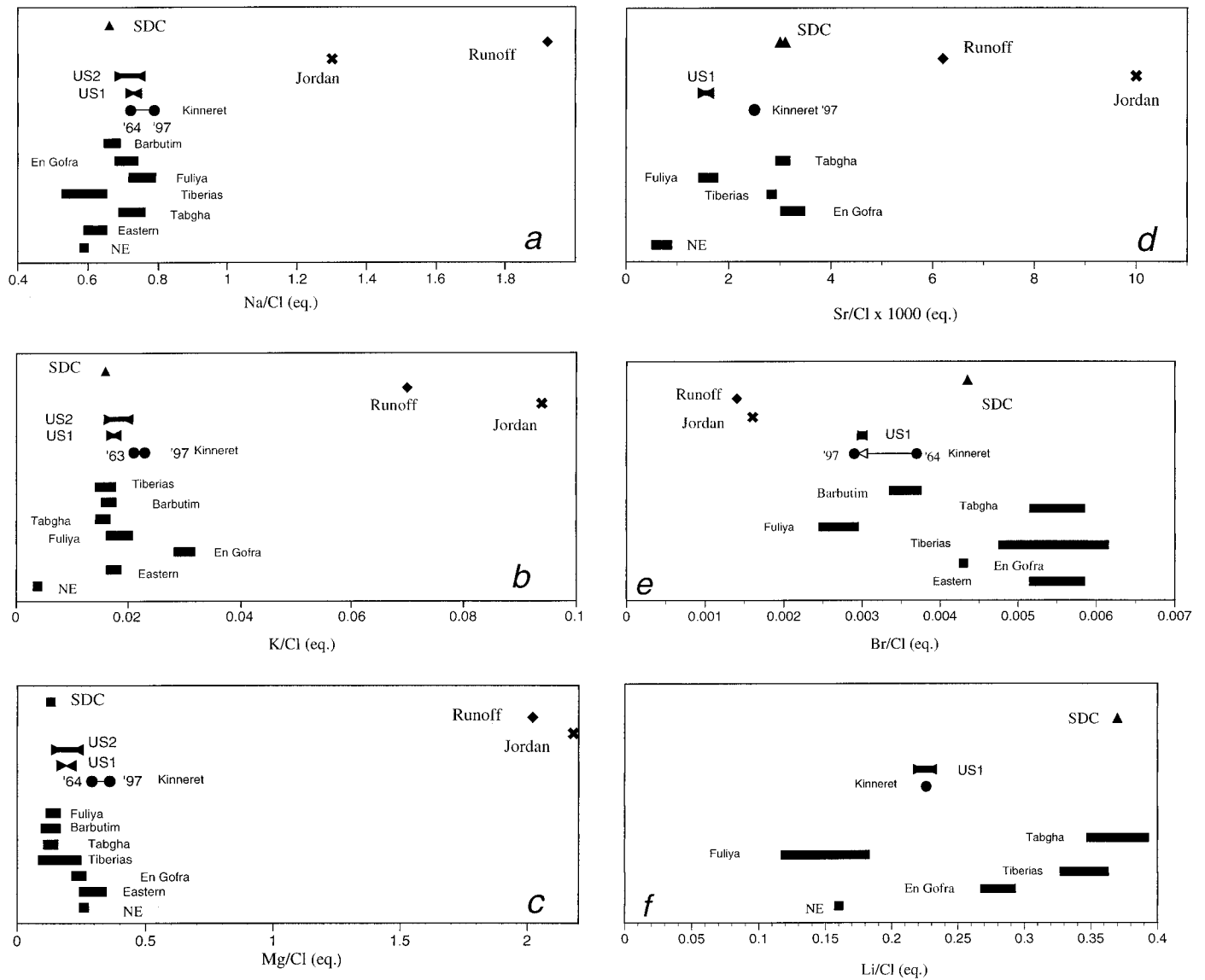


Fig. 4. Ionic ratios of the saline springs (US1 and US2, see text) LK, the Jordan River, and runoff: (a) Na:Cl, (b) K:Cl, (c) Mg:Cl, (d) Sr:Cl, (e) Br:Cl, and (f) Li:Cl (in equivalent units). Vertical axis is an arbitrary separation for readability.

$$C_{K_r} = \frac{1}{\exp(nRW)} \left[ C_{K_i} - \frac{G}{R} (1 - \exp(nRW)) \right] \quad (17)$$

where  $n$  is the incremented week number. The corresponding ratios of Na:Cl, Mg:Cl, and K:Cl are calculated in parallel for each integration step.

The asymptotic nature of the compositional change imposed on LK by the diversion of salts via the SDC (as of 1964) is obvious from Fig. 5. Most of the change occurred within a few years following the implementation of the SDC project, thus reflecting the efficient flushing of the LK system by the Jordan River and the consequent short residence time of the water and solutes in LK. The shape of the curves in Fig. 5 depends on the flushing efficiency of LK by the influx of freshwater (Jordan River and runoff), which is represented in Eq. 15 by the term  $(\Delta V_f/V_K)$ .

The graphs in Fig. 5 are insensitive to the inclusion or

omission of runoff in the calculations. This is a result of the constraint imposed on the US2 in order to compensate for all of the solutes in the system that are not supplied by the known sources. Therefore, if the runoff contribution of any solute is omitted, US2 automatically compensates to maintain mass balance.

Despite significant annual fluctuations, no a priori reason exists that allows one to assume that the lake's volume, or the freshwater influx into it, have dramatically changed between the starting and ending integration times (1964 and 1997, respectively). However, the ample chloride data for the investigated period shows (Fig. 6) that the real situation would be better represented by a somewhat steeper, slightly lower curve. The discrepancy between the prediction and the data probably stems from two causes. First, we have imposed on the calculated evolution lines (Fig. 5) the chloride concentration measured in November 1996, which is signif-

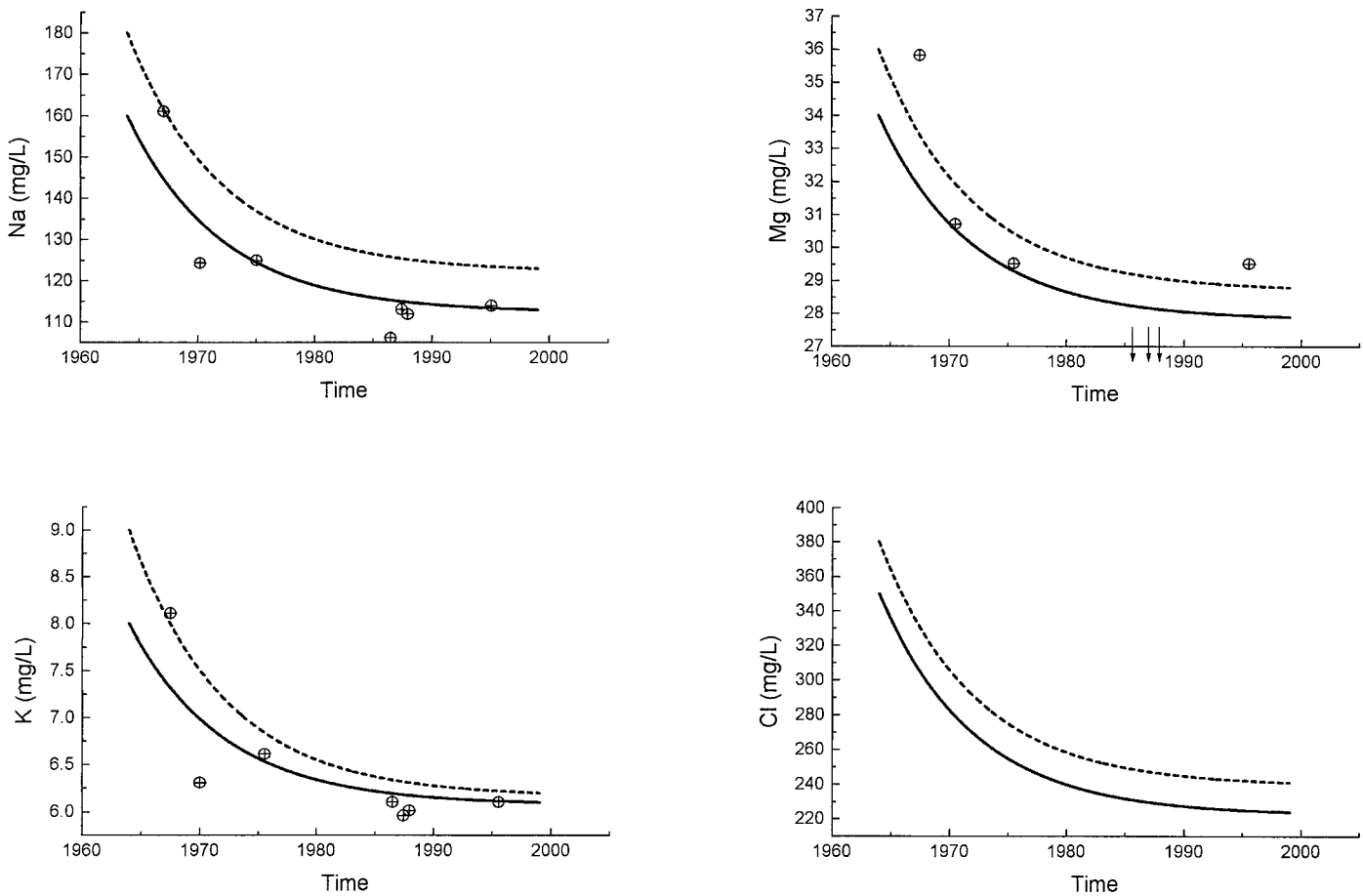


Fig. 5a. The evolution (as calculated from the integrated model) of (a) Na, K, Mg, and Cl concentrations and (b) Na:Cl, K:Cl Mg:Cl, and Mg:Na ratios in LK from 1964 through 1997. Two curves are given for each of these solutes: a dashed line for the lower water layer and a full line for the upper water layer. The resultant area between the two curves represents the feasible concentration range in the lake for the different solutes. Actual concentrations of Na, K, and Mg as well as the relevant ionic ratios were plotted on the curves from the literature for several years between 1966 and 1995. These data points represent single analyses, not averages. Note that the deviations are parallel for all elements (including Cl). For instance, in 1986–1987, the concentrations were low, reflecting dilution of the lake water relative to the calculated curves. Data points are after Serruya (1978), Nishri (pers. comm.), and Sandler (pers. comm.).

icantly higher than concentration values in the preceding years (Fig. 6). This results in an upward shift of the line. Secondly, the shape of the calculated curve strongly depends on the rate constant  $W = \Delta V_j/V_K$  in Eq. 16 and exhibits steeper curvature as this ratio increases. The layering of the lake combined with the fact that the main input and output of water are located in the upper water mass possibly result in a larger effective  $W$  compared with the one we used ( $2.37 \times 10^{-3}$  per week).

*The chemical nature of US1 and US2*—The next step in our study was to compare the calculated ion ratios from the US1 and US2 models and those observed in springs around LK. As noted above (Table 4, Fig. 4), the ion:chloride ratios in each group of springs are confined to narrow ranges.

**Na:Cl:** The Na:Cl ratio of 0.69–0.75, calculated for US1 and US2, excludes both the Tiberias hot springs (Na:Cl = 0.58–0.59) and the LK eastern coast springs, as the chemical analogues of the unmonitored coasts. This ratio corresponds

to the Fuliya and Tabgha groups on the west shore and to the En Gofra spring on the east shore. The saline water that is now being removed from the Kinneret system via the SDC is a mixture of Tabgha, Fuliya, and Tiberias groups. The removal of solutions with a low Na:Cl ratio to the SDC has resulted in an increase of this ratio in LK, an increase from a value of 0.72 in 1964 to one of 0.78 in 1997. This latter ratio corresponds to the highest value of the Fuliya group. This correspondence agrees with the result (Table 5) that 85–90% of the Na is contributed by the saline springs and that <15% is contributed by the Jordan River, even though the Na:Cl in the Jordan is high (1.3).

**K:Cl:** The K:Cl ratio in the saline springs, as calculated by the two methods, is between 0.016 and 0.020. This ratio is similar to most saline sources in the Kinneret region, except for the En Gofra (K enriched) and the northeast (K depleted). K:Cl in the SDC is 0.016. The removal of SDC solutions in the last 33 yr has changed this ratio in LK relatively little: i.e., from 0.021 in 1963 to 0.024 in 1997. The

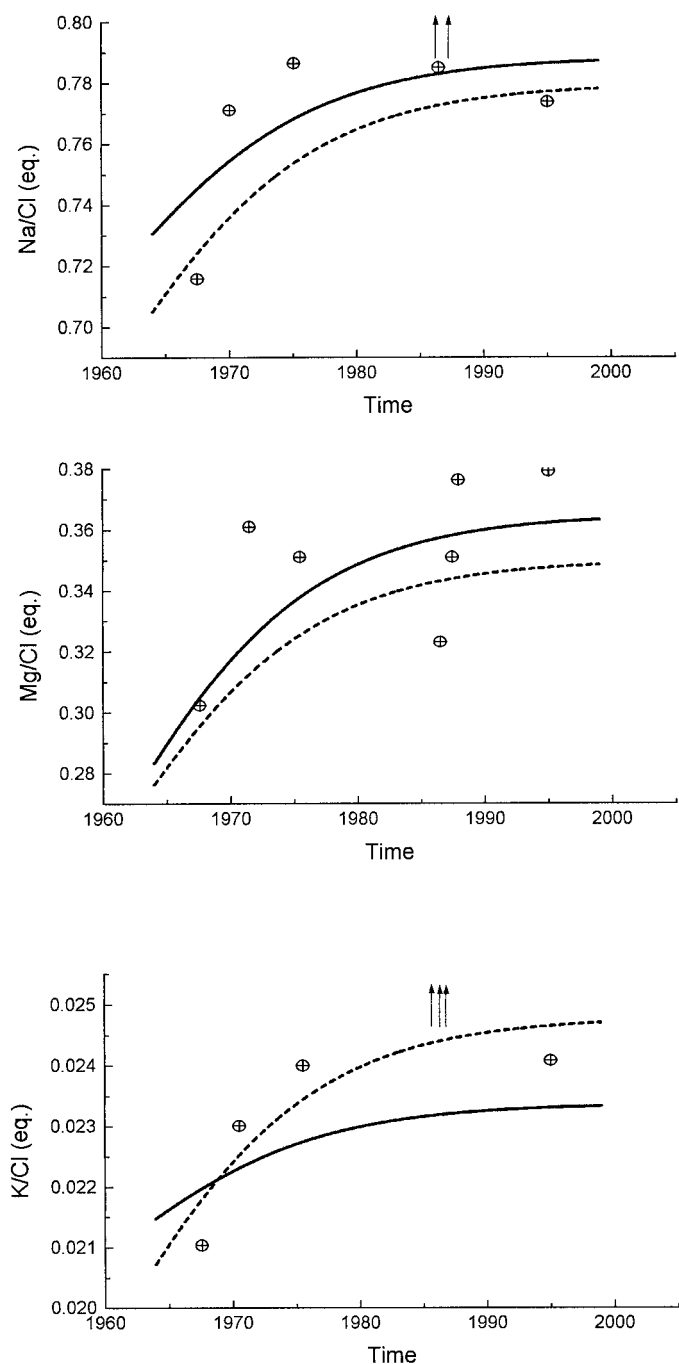


Fig. 5b. Continued.

K contribution of the saline springs to the LK budget is about 70% (Table 5). Obviously, the similarity between K:Cl in most sources makes it a poor source discriminator.

Mg:Cl: The Mg:Cl ratio in US1 is between 0.17 and 0.21. For the US2 33-yr integration period, this ratio is 0.15 to 0.23 (Fig. 4, Tables 5, 6). Unlike the other ionic ratios, the Mg:Cl ratio varies over a large range in the saline springs: in the west, it varies between 0.10 and 0.23, and in the east, it varies between 0.23 and 0.33. The calculated ratio

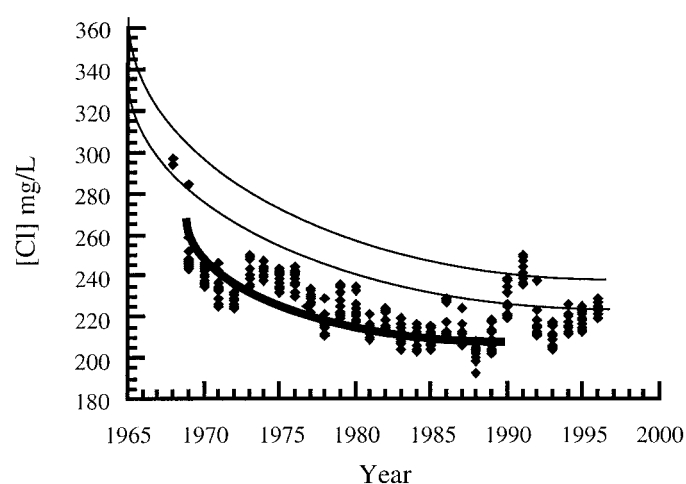


Fig. 6. Variation of average  $\text{Cl}^-$  content in LK water between 1965 and 1997 (data from Rimmer pers. comm.). Compare the thin curves to the general shape of curves on Fig. 5a and see text. The thick curve is a smoothed fit to the real data. The increase in chloride concentration in 1990–1991 was most probably caused by two consecutive dry years, a lower input of Jordan River water, and a lower amount of salt removal via the SDC.

in the average spring is, hence, compatible with that observed in the west. The Tiberias group is the one that best fits the unmonitored ratio, whereas Barbutim, Fuliya, and Tabgha correspond to the lower end of the range or are below it (0.11–0.15). The SDC Mg:Cl ratio is 0.13, similar to the latter three groups. About one-half of the Mg in LK is contributed by the saline springs (Table 5). The removal of the very low Mg:Cl brine by the SDC caused the Mg:Cl ratio in the lake to increase from 0.29 in 1964 to 0.35 in 1997.

Br:Cl: Lack of historical data constrained us so that we were only able to obtain a calculation of the US1 ratio for Br:Cl of about  $3 \times 10^{-3}$ . This ratio results when the run-off contribution is included or neglected. The US1 Br:Cl ratio is similar to the upper range of Fuliya (Fig. 4). The SDC value ( $4.4 \times 10^{-3}$ , Table 4) is between Fuliya and Barbutim on the lower side and between Tabgha and Tiberias on the high side. As with the Mg:Cl ratio, Br:Cl demonstrates a large variance between the different spring groups. Br is the element with the highest supply fraction from the saline springs (95%); hence, it is not surprising that this ratio dropped from  $3.5 \times 10^{-3}$  in 1964 to  $3.0 \times 10^{-3}$  in 1997.

Li:Cl: All the ratios that have been presented above were determined for the different groups on the basis of the large number of saline sources that have been analyzed, starting with sources analyzed in the late 1950s and 1960s. The Li:Cl ratio, on the other hand, is much less representative: it has been analyzed in fewer sources and only during the last 3 yr. Having noted this, the Li:Cl ratio in the US1 was about  $0.2 \times 10^{-3}$ . It is about midway between the values for Fuliya and the Tiberias springs. The Li:Cl ratio in the SDC is similar to that of the Tabgha sources, which is probably ex-

plained by the fact that Li was analyzed in recent years, when the Tabgha springs constituted the main contribution to the SDC. The percentage of Li contributed to LK by the saline springs is about 91% (Table 5).

Sr:Cl: Just as in the case of Li:Cl, Sr:Cl was also determined only in the last 3 yr and with the use of a small number of sources. The Sr:Cl ratio in the US1 is about 0.0015–0.0016, similar to that ratio's value in the Fuliya group. The SDC Sr:Ca ratio is similar to those of the Tabgha, Tiberias, and En Gofra. The Sr:Cl ratio remained constant in LK from 1963 to the present—at about 0.0024. Ca:Cl remains similarly constant at  $\approx 0.4$ . The examination of the Sr:Ca ratio may, however, be misleading. Ca is removed from the lake by calcite precipitation and shows a “negative contribution” by the US1 (i.e., there is a Ca sink rather than a source in the lake). Sr, on the other hand, is removed only slightly with calcite precipitation. Sr behaves conservatively, with US1 contributing about 60–70% of this element to the lake.

Both the ionic ratios and a simple balance calculation indicate that the US1 is dissimilar to both the Tiberias hot springs and the springs on the eastern shore of LK. Similar calculations can be performed for other periods in the past, but they are somewhat hampered by the availability of good analytical, historical data for both the lake and the Jordan River.

### Summary and conclusions

The chemical composition of the “theoretical” saline spring that is responsible for the salinization of LK was estimated by two independent approaches. The first estimate, US1, is an annual balance between removal and supply of the different ions, and it assumes a steady-state lake. The second estimate, US2, is the result of a simulation of the chemical evolution of the lake from 1964 to the present.

The different springs around LK exhibit a rather large variability in terms of chemical composition, both in time and between springs; yet, each spring group is characterized by a narrow range of ionic ratios. These ratios are used as fingerprints for identification of the nature of salts in US1.

The bulk of the salt is contributed to LK via springs or saline groundwater of the western lakeshore type. In the natural, anthropogenically undisturbed LK system, the major sources of salt supply to the lake are of chemical types Tiberias, Tabgha, Fuliya, and Barbutim. The relative contribution from these springs is different for different ions. The contribution is highest for bromide (96%) and decreases to about 85% for Na and to 45–55% for Mg.

Since a significant portion of the west-shore saline water sources have recently (within about the last 30 yr) been pre-

vented by the SDC (via diversion) from entering LK, the contribution of the Tabgha and Tiberias springs has decreased. Therefore, at present, Fuliya and Barbutim springs are the major source of the LK salinity.

We propose that the different ionic ratios in the spring groups are a reflection of different subsurface brine pockets in the different areas. Hence, if the Fuliya (chemical)-type springs represent, at present, an essential component of the saline spring contribution, it is reasonable that the Fuliya block is (geographically) the major site of such springs.

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