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A preliminary assessment of the geochemical dynamics of Issyk-Kul Lake, Kirghizstan

Abstract—Issyk-Kul Lake is one of the largest brackish water lakes in the world. Being a closed-basin lake, it is susceptible to volume changes caused by natural climatic variability, as well as human-induced water diversion from the basin. Long-term lake level records indicate that lake levels are declining and that salinity is increasing because of evapoconcentration. We present the first trace element data for this important lacustrine system and, using both ours and previously published data, investigate the geochemical dynamics within the watershed.

Issyk-Kul Lake, lying between 76° and 78°15′E and 42°10′ and 42°40′N, is the deepest lake in central Asia (maximum depth of 668 m) and the fourth largest saline/brackish water lake in the world. The lake is located in the northeast portion of the country of Kirghizstan (Fig. 1). The lake basin occupies a depression in the northern Tien Shan Mountains at an altitude of 1,609 m, making it the second largest mountain lake in the world (Grosswald et al. 1994). The lake basin was formed during the Carboniferous period, and the lake, in its present form, is at least as old as the Late Pliocene (Tsigelnaya 1995). It is very much a "superlative" lake in the same way as Lake Baikal (Weiss et al. 1991).

Although the biology of the lake (especially its fisheries) has been investigated since the 1920s, there is much less information regarding the lake's physical and chemical characteristics, and only since 1992 have there been results published in the western literature (Savvaitova and Petr 1992;

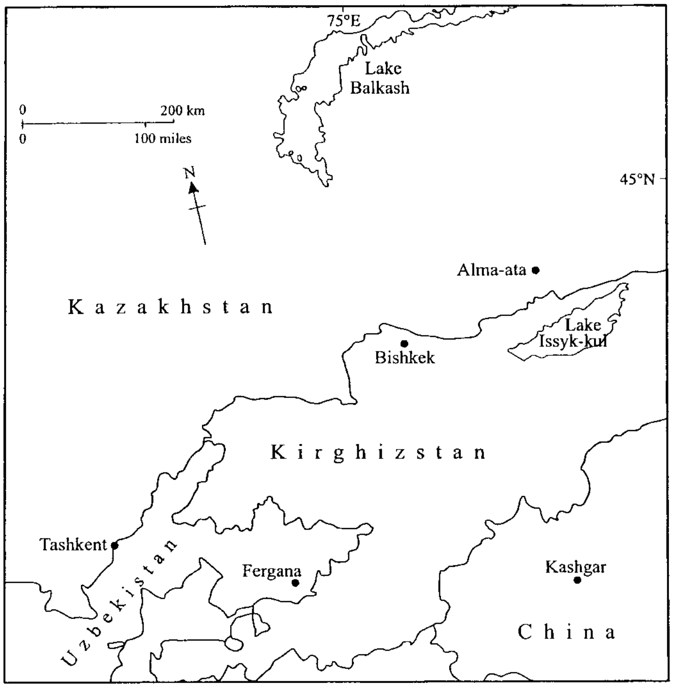

Fig. 1. Map of Central Asia.

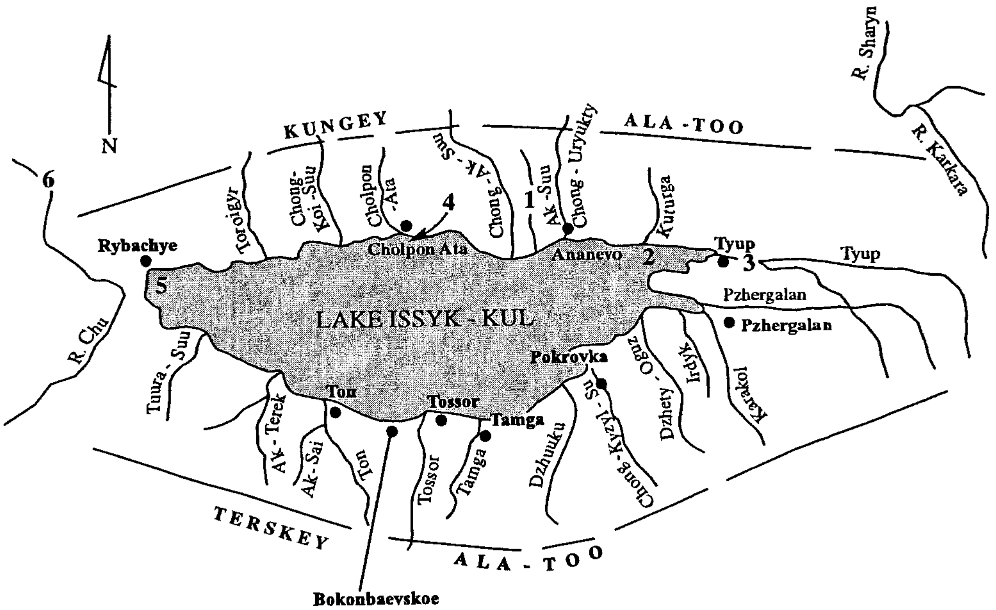

Fig. 2. Sampling locations in Issyk-Kul watershed (from Savvaitova and Petr 1992).

Tsigelnaya 1995; Zektser 1996). Given its world-class status, relatively little is known about the geochemistry of the lake or its geochemical dynamics. In addition, the information that is available is contradictory, or at least, not always comparable.

The major goal of this study was to assess and characterize the geochemistry of the lake as a baseline for future work. This will be needed as future anthropogenic activity within the lake basin proceeds. As part of a preliminary study to assess the influence of anthropogenic activities on the lake, we present data from a suite of near-shore lake and stream samples. These data provide the first measurements of trace elements within the lake and its watershed. The chemical data, used in collaboration with water balance data collected in the 1970s by scientists from the former Soviet Union, have allowed us to compute elemental residence times within the lake in an attempt to improve our understanding of the general geochemical dynamics of the watershed/lake system.

Table 1. Environmental setting of Lake Issyk-Kul. From Savvaitova and Petr 1992 and Tsigelnaya 1995.

Lake area	6,236 km^2	
Watershed area	22,080 km^2	
Maximum depth	668 m	
Mean depth	278 m	
Lake volume	1,738 km^3	
Total water input	162 m^3 s^{-1}	(818 mm yr^{-1})
Precipitation		(280 mm yr^{-1})
Stream discharge		(208 mm yr^{-1})
Groundwater		(330 mm yr^{-1})
Total evaporation	161 m^3 s^{-1}	(814 mm yr^{-1})
Surface-water temperature variation	4–20°C	
Mean air temperature in January	3°C	
Mean air temperature in July	12°C	

Background—The most definitive studies on Issyk-Kul published in English are those of Savvaitova and Petr (1992) and Tsigelnaya (1995). These authors have pointed out that the lake water has a salinity of ~6 g L^{-1} with $Na^+ + K^+ > Mg^{2+} > Ca^{2+}$ and $Cl^- \geq SO_4^{2-} >> HCO_3^-$ ionic composition. In addition, the nutrient concentrations within the lake are very low, and it is considered ultra-oligotrophic (Savvaitova and Petr 1992). The ionic composition of Issyk-Kul is similar to that of the Aral Sea (before input water diversion) and the Caspian Sea, its two larger Asian counterparts (Savvaitova and Petr 1992). The pH of the lake ranges from 8.70 to 8.75 and, due to its well-mixed nature, the dissolved O_2 concentrations are high throughout the 668-m deep-water column, especially in October–February (Savvaitova and Petr 1992). It has been argued that the ultra-oligotrophy of the lake is due to the very low ratio (0.2%) of stream freshwater discharge to total lake-water mass (Savvaitova and Petr 1992). Savvaitova and Petr (1992) report that 300 phytoplankton taxa and 117 zooplankton taxa have been identified within the lake. The fish populations include both endemic and introduced species. The current fish catch that is permitted is 320 ta^{-1} (Savvaitova and Petr 1992).

Because of the aridity of this region (Table 1), the ecology of the lake, as well as the local agricultural economy, is dependent on the water supply from streams originating from snow and glaciers within the Tien Shan ranges. Maximum runoff is in the spring due to snowmelt from higher elevations (Aizen et al. 1995). Konovalov and Shchetinnicov (1994) have suggested that there has been a loss of ~13% of the total ice volume in portions of Central Asia to the west of Issyk-Kul from 1950 to 1980. This has not led to large-scale changes in river runoff during this time, however. In fact, annual runoff is characterized by considerable consistency, with only minor annual variations (Tsigelnaya

Table 2. Major element data for Issyk-Kul (in mM) and three major streams (in μM).

	Na^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	HCO_3^-
Streams							
Ak-Suu	105	21	73	496	25	110	1,000
Tyup	494	34	326	1,580	230	370	3,340
Chu	451	40	373	1,300	251	375	2,820
Lake							
Eastern	55.4	1.5	11.1	3.2	38.4	19.2	8.2
Central	60.8	1.7	12.1	3.4	43.2	21.5	6.6
Western	59.3	1.6	11.8	3.3	41.3	20.7	7.8
Lake mean	58.4	1.6	11.7	3.3	41.0	20.4	7.5
	(64.4*)	—	11.8*	3*	45*	22*	5.2*

* From Kadyrov 1995. He reported Na and K as a sum, so individual values cannot be compared.

1995). A major present-day concern by local fishing and tourist industries, as well as environmentalists, is over the future of the lake and how its water resources should be managed (Savvaitova and Petr 1992). A number of anthropogenic activities impinge upon the lake and could potentially affect its geochemistry. These include the discharge of industrial and agricultural wastes that contain human-produced organic compounds as well as nutrients (Savvaitova and Petr 1992; Zektser 1996). The most serious potential perturbation of the lake comes from the continued lake level decline (~5 cm yr^{-1}, according to Savvaitova and Petr 1992), due, in part, to the diversion of stream inflow for irrigation. Currently, ~160,000 ha in the basin are under irrigation. Given the fate of the Aral Sea (Williams and Aladin 1991), this activity and its potential impact on the lake should not be taken lightly. Savvaitova and Petr (1992) argue that ''it is essential'' that if irrigated agriculture in the region is to expand, it should not be achieved through stream diversion. Presently, irrigation return may be a significant source of pesticides and nutrients to the lake.

Previous work by Soviet scientists has produced conflicting results regarding the ''age'' of the most recent stage of lake development, i.e., the time of the formation of its closed-basin nature (Grosswald et al. 1994). Geomorphologic research has shown that in some past time during the Pleistocene, the lake emptied into the River Chu to the west (Fig. 2). The age of lake isolation from the River Chu ranges from <26,000 yr B.P., by glacial ice damming of the lake, to early Quaternary ages resulting from tectonic readjustments (Grosswald et al. 1994). The lake levels have fluctuated through time with 10–12-m higher stands in the seventeenth and eighteenth centuries and submerged settlements found at ~8-m depths in the lake (Aladin and Plotnikov 1993). The periodic highstands have allowed for outflow into the Chu at times in the past, with the last occurring early in the nineteenth century (Tsigelnaya 1995). These past highstands are thought to be due to increases in precipitation and concurrent glacial advances in the mountains (Tsigelnaya 1995).

Cl^- ages of the lake have been used in past studies to establish the age of isolation of the lake. Using this technique, ''isolation'' ages for Issyk-Kul have ranged from 6,300 to ~135,000 yr (Tsigelnaya 1995). Uranium isotopic techniques calculated ''isolation'' ages of 110,000 ± 40,000–310,000 ± 40,000 (Tsigelnaya 1995). Kadyrov (1975) first raised the issue that these ''ages'' were all incorrect because groundwater fluxes had been ignored. He recalculated the Cl^- age as 50,000 yr.

Sampling and analytical methods—Samples were collected in mid-September 1996. During this time, three river samples (samples 1, 3, and 6) and three near-shore samples (samples 2, 4, and 5) were obtained (Fig. 2). Trace metal samples were obtained in precleaned Teflon™ bottles. Cleaning and shipping procedures can be found in Bonzongo et al. (1996). The trace metal samples were collected using ultra-clean techniques. The sampler took all samples facing into the flow (for rivers) or into the current/wave action (for the coastal lake). Upon return to the U.S., the samples were first split into two aliquots. One of these aliquots was filtered through precleaned filters, acidified with Optima™ HCl, and analyzed immediately for mercury using the cold vapor atomic fluorescence spectrometry (CVAFS) technique of Gill and Fitzgerald (1985). The other aliquot was used for analysis of minor cations and trace metals, other than mercury, by inductively coupled plasma mass spectrometry (ICP-MS) with a Perkin Elmer Elan 6000. Precautions were taken to minimize sample contamination, in that trace metal samples were either stored under a Class 100 clean hood or maintained in their double-bagged state when not being manipulated. Water samples for major cations and anions were collected, processed, and analyzed following procedures described in Welch et al. (1996). Alkalinity was determined on the samples by titration. Reactive silicate (H_4SiO_4) was measured colorimetrically (Mullin and Riley 1955).

Aliquots of samples were sent from the University of Alabama for Sr isotope and tritium analyses at MIT and the University of Rochester, respectively.

Results—Lake and river concentrations are shown in Tables 2–4. As previous authors have observed, the lake-water chemistry is an Na > Mg, Cl = SO_4 (in equivalents) (Table 2) type of water. The HCO_3^- and Ca^{2+} concentrations are low, because $CaCO_3$ is supersaturated in the lake and is rapidly lost to the sediments (Tsigelnaya 1995). Our Ca^{2+}, Mg^{2+}, and HCO_3^- values are slightly higher, relative to Na^+,

Table 3. Minor and trace element concentrations for Issyk-Kul and three major streams in the region.*

	V	Mn	Co	Cu	Mo	U	Ba	Sr	Rb	Cs	Sb	Hg	H_4SiO_4	Br	F	NO_3	Li	$^{87}Sr/^{86}Sr$
Lake																		
Eastern	11.2	<0.06	0.30	3.04	70.0	52.6	44.0	6,260	5.08	—	0.305	2.82	68	1,620	12,200	—	150	—
Central	12.1	0.10	0.30	4.86	81.0	59.9	40.7	6,890	4.75	0.09	0.429	4.46	66	1,710	13,990	—	150	0.712411±1.3×10⁻⁵
Western	12.5	<0.06	0.35	4.34	81.5	63.6	41	6,900	4.90	0.10	0.385	1.67	27	1,780	13,470	—	150	—
Lake mean	11.9	<0.07	0.32	4.08	77.5	58.7	41.9	6,680	4.91	0.10	0.373	2.98	54	1,700	13,220	—	150	—
Streams																		
Ak-Suu	0.36	1.14	0.03	<0.37	4.43	4.12	13.0	63	0.46	0.02	0.094	2.23	65	<10	370	30	<10	—
Tyup	0.64	0.34	0.07	0.39	1.90	4.32	83.3	395	0.47	<0.015	0.075	2.02	330	10	530	41	10	0.711113±1.1×10⁻⁵
Chu	0.84	0.25	0.05	<0.37	3.30	8.56	69.5	347	0.77	0.015	0.112	1.85	390	20	320	103	<10	—

* All values in $\mu g\ L^{-1}$ except for Hg ($ng\ L^{-1}$) and H_4SiO_4 and NO_3 (μmol).

Table 4. Hg speciation data in $ng\ L^{-1}$.

	Total Hg	Total Me-Hg	Total dissolved Hg	Reactive-Hg
Lake				
Eastern	2.82	0.018	0.33	0.27
Central	4.46	0.032	0.10	0.28
Western	1.67	0.044	0.10	0.10
Lake mean	2.98	0.031	0.18	0.22
Streams				
Ak-Suu	2.23	0.008	0.19	0.09
Tyup	2.02	0.023	0.28	0.42
Chu	1.85	0.010	0.07	0.18
Stream mean	2.03	0.014	0.18	0.23

SO_4^{2-}, and Cl^-, than those of Kadyrov (1975), but this may be because our samples were collected closer to shore and demonstrate a greater influence of input sources (Tsigelnaya 1995). The absolute values of the major elements, when compared to the available data of Kadyrov (1975), are very similar (Table 2).

The vast majority of surface-water inflow to the lake originates in the eastern portion of the watershed, with >50% coming from the Tyup and Dzhergalan Rivers (Fig. 2) (Savvaitova and Petr 1992). The Tyup discharges the largest amount of water entering the lake. Rivers and streams in the central portion of the basin are the second largest source of water to the lake. Ak-Suu is a rapidly flowing, ‘‘white-water’’ stream that is directly fed by glacier melt water. Although the River Chu currently does not flow into Issyk-Kul, it is representative of the western basin streams/rivers that deliver the least amount of total water to the lake (Savvaitova and Petr 1992). All these rivers are dominated by Ca^{2+} and HCO_3^- as their major constituents (Table 2). Ak-Suu has higher $HCO_3^- : Cl^-$ and $Ca^{2+} : Na^+$ ratios than the other two rivers that were sampled, but the stream chemistry is very similar both to runoff from the more eastern portion of the Tien Shan, in China, and from waters entering Lake Baikal to the northeast (Kenison Falkner et al. 1991; Williams et al. 1992; Kenison Falkner et al. 1997). The lower $HCO_3^- : Cl^-$ and $Ca^{2+} : Na^+$ ratios in the River Chu may suggest increased transit times or thermal water input, or both. There are at least 20 ‘‘mineral’’ waters in the basin; some are thermal, but most are of low salinity (Tsigelnaya 1995).

The lake is enriched in V, Co, Cu, Mo, U, Sr, Sb, Cs, Br, F, and Li and depleted in Mn, Ba, Si, and NO_3 relative to the rivers entering it (Table 3). The Hg concentrations are similar. The U and Mo concentrations are higher than observed in most other rivers, globally. This may reflect local sources of these elements within the watershed or input from thermal waters, as has recently been observed in high-elevation lakes in the Pamirs, to the southwest of Issyk-Kul (Volkova 1998). Edgington et al. (1996) also observed relatively high U concentrations in Lake Baikal at ~475 ng L^{-1}, with the Selenga River having more than double that value in some sampling locations. The lake has a more radiogenic $^{87}Sr/^{86}Sr$ value than its largest riverine source, the

Table 5. Estimated residence times in Issyk-Kul* (in years).

Na^+	K^+	Mg^{2+}	Ca^{2+}	HCO_3^-	F^-	Cl^-	Br^-	SO_4^{2-}	H_2O
120,000	42,000	37,000	2,100	2,450	21,000	190,000	190,000	55,000	~800

* Considering only surface input.

Tyup (Table 3). The dissolved Hg and total methyl-Hg concentrations in both the rivers and the lake are low (Table 4), reflecting both their relatively pristine and the lake's oligotrophic nature (Gill and Bruland 1990; Mason et al. 1994). The ^3H concentrations from near-shore surface waters from the lake have a value of 11.9 TU.

Discussion—The residence times of the major and some of the minor ions were calculated using the average water budget of river water put forward by Savvaitova and Petr (1992). The River Tyup data were used as a representative of the chemistry of the eastern rivers, the Ak-Suu data were used as a representative of the central rivers, and the River Chu data were used to represent the western rivers. Total river/stream discharges of 47, 24, and 1 $m^3\ s^{-1}$ were used for the eastern, central, and western streams, respectively (Savvaitova and Petr 1992). Residence times were calculated by simply multiplying the lake volume by the mean elemental concentration of the lake and dividing this by the mean riverine flux. The estimated residence times are shown in Table 5. Na^+, Cl^-, and Br^-, the most conservative elements, have similar residence times of $\sim 10^5$ yr; K^+, Mg^{2+}, F^-, and SO_4^{2-} have residence times of $\sim 10^4$ yr. Ca^{2+} and HCO_3^- have residence times of $\sim 10^3$ yr, and water has one of $< 10^3$ yr. These residence times are similar to the Cl^- ages, or isolation ages, previously calculated by Tsigelnaya (1995). However, groundwater discharge into the lake (Table 1) accounts for ~40% of the water balance input and should be considered in estimates of water and solute residence times (Zektser 1996). It is thought that the relatively large role of groundwater in the water balance is due to the seepage of stream water into alluvium and subsequent discharge into the lake (Savvaitova and Petr 1992). If the groundwater and associated groundwater solute fluxes estimated by Zektser (1996) are included in the flux considerations, the Cl^- residence time decreases to 39,000 yr, the Ca^{2+} to 1,050 yr, and the water to 460 yr, respectively. Ca^{2+} and HCO_3^- are undoubtedly being removed via $CaCO_3$, as observed in other Central Asian brackish water lakes (Kawabata et al. 1999) and recently, via sediment coring in Issyk-Kul itself (Ricketts et al. 1999). When groundwater is also considered, the water residence time becomes very similar to that of Lake Baikal, a much larger lake, but one with an outflow (Kenison Falkner et al. 1997). In comparison to Issyk-Kul, the residence times of the major solutes in Lake Baikal are of the same order of magnitude as the water (Kenison Falkner et al. 1997). Clearly, the closed-basin nature of Issyk-Kul has led to solute residence times longer than that of the water. In addition, solute fluxes, via groundwater input, may have a very important consequence with regard to the estimated ''age'' of the lake, as well as its overall water budget (Zektser 1996).

As mentioned above, the V, Co, Cu, Mo, U, Sr, Sb, Cs, Br, F, and Li concentrations are enriched in the lake, relative to the stream input. The relative enrichments of these elements can be compared to a more conservative element, such as Cl^-, using the flow-weighted Cl^- value of 162 μmol L^{-1} and the mean lake value of 40,900 μmol L^{-1}. The enrichments of V, Mo, and U are clearly much less than that of Cl^-, being 23, 29, and 14, respectively. These enrichments are a factor of 10 less than that of Cl^-, suggesting some form of geochemical or biogeochemical removal within the lake. The lake is thought not to develop anoxia at depth in the summertime, so that loss of these oxyanionic species through reduction and precipitation in the water column is highly unlikely. The buildup of oxyanionic metal species such as V, Mo, and U in closed-basin, alkaline lakes is not unusual and probably represents a natural, long-term process, rather than effects from any anthropogenic activities (Simpson et al. 1982; Domagalski et al. 1990). This seems to be particularly true for Mo and U, in part because of the relatively high fluvial input.

The Hg concentrations fall within the range of other surface waters throughout the world (Mason et al. 1994). The surface Hg_T values for Issyk-Kul are, however, a factor of 10 higher than those recently obtained in Lake Baikal (Kenison Falkner et al. 1997) but are similar to values observed in other alkaline, closed-basin lakes such as Pyramid Lake, U.S.A. (Gill and Bruland 1990). As in many aquatic systems (Bonzongo et al. 1996), the largest percentage of the Hg_T is associated with particulate matter (Table 4). Stream and lake waters have similar Hg_T concentrations with slightly higher particulate Hg in the lake. Total dissolved Hg and reactive Hg mean concentrations are essentially the same in both the streams and the lake. The lake has a slightly higher percentage of methyl-Hg than the streams do. There is little indication of major anthropogenic contributions to Issyk-Kul, as both Hg_T and dissolved Hg concentrations in the river waters are lower than streams entering Lake Michigan, for example (Hurley et al. 1996).

Conclusions—We have presented some of the first published data on the geochemistry of Issyk-Kul, a closed-basin, mountain lake in Central Asia. Estimated residence times of the major solutes entering the lake suggest a closed-basin ''age'' of over ~100,000 yr. The caveat of substantial groundwater flow into the lake, and hence, another source of solutes, exists, however. Previous work suggested a relatively large amount of groundwater input compared to other large lakes throughout the world. Certainly, future studies should focus on the quantification of this groundwater, especially if water resource issues are to be addressed. This is particularly true if diversion of water from both surface and shallow groundwater sources continue to increase as agricultural activity increases with the basin (Tsigelnaya 1995).

Our major, minor, and trace element data indicate that certain elements are evapoconcentrated in the lake, while others are removed via biogeochemical processes. This is similar to observations from other brackish closed-basin lakes around the world.

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