ISSN 1995-4255, Contemporary Problems of Ecology, 2016, Vol. 9, No. 5, pp. 590–599. © Pleiades Publishing, Ltd., 2016.
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Hydrochemical Balance of Itkul–Shira Lake System (Khakassia, Russian Federation)

N. V. Guseva* and O. G. Savichev

Tomsk Polytechnic University, pr. Lenina 30, Tomsk, 634050 Russia
**e-mail: Guseva24@yandex.ru*

Received December 7, 2015; in final form, February 10, 2016

Abstract—The water and hydrochemical balance of Shira and Itkul lakes, located in the arid (steppe) zone in the Republic of Khakassia (Russian Federation), has been calculated. It is shown that Lake Itkul can be considered a drained lake, which significantly determines the basic differences of the hydrochemical balance in the two water bodies. The outflow of water from Itkul to Shira is, on average, 6791000 m^3/year, and the average outflow of dissolved salts is 35697 t/year. Lake Shira can be considered a drainless water body with an evaporation mechanism of formation of the chemical composition of its waters, and Lake Itkul is considered a flowing water reservoir. The salt concentration in Itkul is not as high as that in Shira due to the lower influence of evaporation on the formation of the chemical composition of waters and time of their interaction. It has been assumed that this phenomenon is regular, rather than exceptional, for the arid zone of Northern and Central Asia.

Keywords: Lake Shira, Lake Itkul, Khakassia, steppe zone, hydrochemical and water balance, interaction of water with rocks, arid ecosystems

DOI: 10.1134/S1995425516050061

INTRODUCTION

Identifying the mechanisms of formation of the chemical composition of lake waters in the arid zone is a difficult problem whose solution is important for the development of geochemistry and geoecology. The peculiarity of this problem can be illustrated based on the example of lakes of Khakassia. The lakes are located at a relatively small distance from each other (up to 4–5 km); however, the mineralization and chemical composition of their waters can be radically different: from fresh hydrocarbonate calcium waters to sulfate–chloride magnesium–sodium brines. Some of these lakes have been studied and used for balneological and recreational purposes for a long time (*Prirodnye vody*..., 2003; Banks et al., 2004; Guseva et al., 2012); however, detailed morphometric and hydrological studies of these lakes have still not been carried out.

Taking this into account, integrated studies of lakes Shira and Itkul (or Itkol, according to a number of sources), located in the steppe zone at a distance of 3–4 km from each other (Figs. 1, 2) have been carried out at Tomsk Polytechnic University for a number of years (*Prirodnye vody*..., 2003; Guseva et al., 2012; Guseva and Kopylova, 2013). The total content of dissolved salts in waters of the first lake (Shira) is 12–31 g/kg, while waters of the second lake (Itkul) in total contains only 0.6–0.7 g/kg; at the same time, the morphometric characteristics of these lakes are generally comparable. Specifically, the average depth of Lake Shira is 11.0 m (with the maximum being 24.0 m) against the average depth of lake Itkul of 9.1 m (with the maximum being 17.0 m). The area of the surface of Lake Shira is 35.90 km^2 against the area of the surface of Lake Itkul of 23.25 km^2. The Son River runs into Lake Shira; no runoff from the water body was found. Karysh River and minor Karasuk and Shel-Sukh watercourses run into Lake Itkul, and, during a high-water period, a runoff along the course of the disappearing Tushinsky stream to the Tuim River (through Lake Orlovo) may be observed. The elevation mark of the average long-term annual water edge is 352.9 m (in the system of elevations of Baltic Sea) in Lake Shira and 456.2 m in Lake Itkul. A more detailed characteristic of the natural conditions and water balance of the lakes under study is given in (*Prirodnye vody Shirinskogo*..., 2003; *Prirodnyi kompleks*..., 2010, 2011).

The authors and B.D. Abdullaev previously calculated the water balance of these lakes (Savichev et al., 2015). As a result it was concluded that, first, the lakes are hydraulically bound. Second, Lake Itkul can be considered a drained lake, and the outflow of water from it enters Lake Shira in the volume of 5433000–8149000 m^3/year (6791000 m^3/year, on average). Third, only Lake Shira can be considered a drainless water body with an evaporation mechanism of forma-

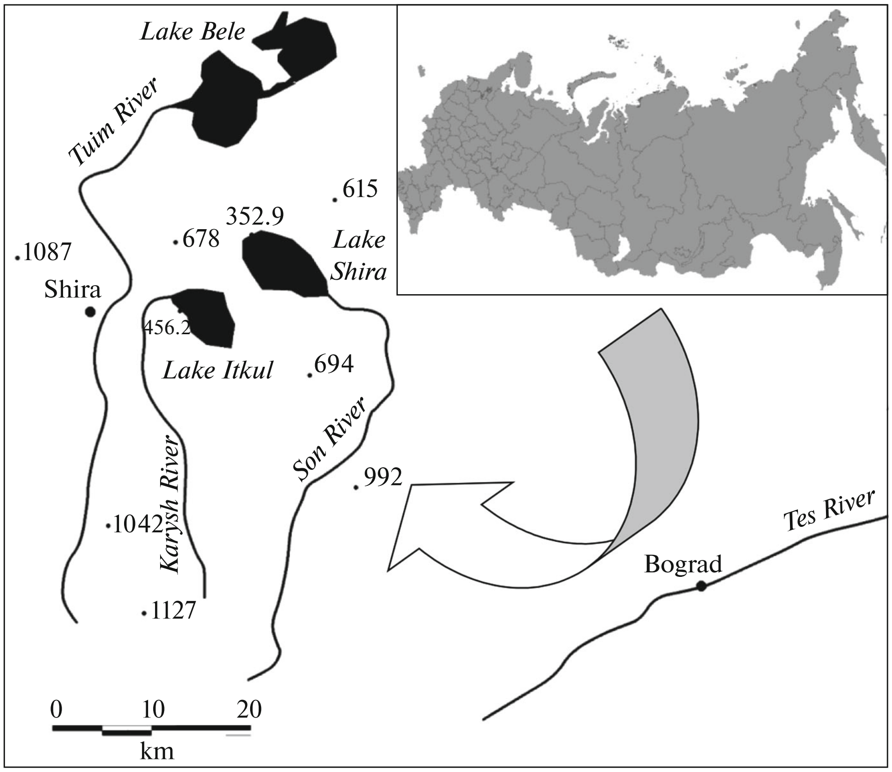

Fig. 1. Layout of lakes Shira and Itkul and elevation marks of the catchment surface (values of the average water edge in lakes: Shira, 352.2 m; Itkul, 456.2 m).

tion of the chemical composition of its waters, while Lake Itkul is characterized by a more intensive water exchange leveling the effect of salt concentration in lake waters in the process of water evaporation from the water area in June–July (Savichev et al., 2015). The following stage of investigations and the objective of this work are to calculate and analyze the hydrochemical balance of lakes Shira and Itkul for substantiating the mechanisms of formation of their chemical composition.

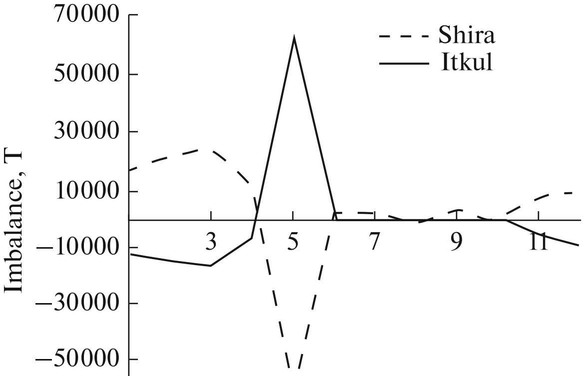

Fig. 2. Interannual distribution of the hydrochemical imbalance of lakes Shira and Itkul (according to (*Melioratsiya*..., 1988); the calculation error is about 20%).

METHODS

The research included the development itself and analysis of the long-term annual average (over the last 50 years) hydrochemical balance, collection of lake water samples, determination of their chemical composition, and thermodynamic calculations for clarifying the validation of conclusions obtained during the analysis of the water and hydrochemical balance of the Shira–Itkul lake system.

In general terms, the mathematical model of the water balance of an area has the form (1), and the hydrochemical balance model has the form (2), (3):

$$X_t + Z_t - E_t - Y_t \pm \Delta U_t + A_{1,t} - A_{2,t} \pm I_t = \eta_W, \tag{1}$$

$$\begin{aligned} &M_{X,t} + M_{Z,t} - M_{E,t} - M_{Y,t} \pm M_{U,t} \\ &+ M_{A1,t} - M_{A2,t} \pm M_{I,t} + R = \eta G, \end{aligned} \tag{2}$$

or

$$\begin{aligned} &V_{X,t}C_{X,t} + V_{Z,t}C_{Z,t} - V_{E,t}C_{E,t} - V_{Y,t}C_{Y,t} \\ &\pm V_{U,t}C_{U,t} + V_{A1,t}C_{A1,t} - V_{A2,t}C_{A2,t} \\ &\pm V_{I,t}C_{I,t} \pm R = \eta_G, \end{aligned} \tag{3}$$

where Y_t and $V_{Y,t}$ are the layer and volume of total water runoff (surface runoff $Y_{s,t}$ and subsurface runoff $Y_{g,t}$)

from the area under consideration (water object) over the time period t (over a month Y_m or a year Y_y); X_t and $V_{X,t}$ are the layer and volume of atmospheric moistening; Z_t and $V_{Z,t}$ are the layer and volume of the water inflow from adjacent catchment areas; E_t and $V_{E,t}$ are the layer and volume of evaporation from the surface of catchment (E_W) or lake (E_L), taking into account water condensation (over a month Em or a year E_y); ΔU_t and $V_{U,t}$ are the variation of the layer and volume of moisture content in the catchment (ΔU_W) or lake (ΔU_L) over a month (ΔU_m) or a year (ΔU_y); $A_{1,t}$, $V_{A1,t}$ and $A_{2,t}$, and $V_{A2,t}$ are the layer and volume of wastewater discharge and water intake; I_t and $V_{I,t}$ are the layer and volume of water losses for ice formation (or inflow of water formed during ice melting in spring; for months with positive average monthly air temperatures and for the whole year, $I_t = 0$); $C_{Y,t}$, $C_{X,t}$, $C_{Z,t}$, $C_{E,t}$, $C_{U,t}$, $C_{A1,t}$, $C_{A2,t}$, and $C_{I,t}$ are the concentration of substance in the runoff in the area under study, as well as in precipitation, the runoff from adjacent areas, evaporating moisture, moisture content in the catchment or lake, waste waters, intake water, and in freezing or thawing water; $M_{Y,t}$, $M_{X,t}$, $M_{Z,t}$, $M_{E,t}$, $M_{U,t}$, $M_{A1,t}$, $M_{A2,t}$, and $M_{I,t}$ are the mass of substance in the runoff from the area under consideration, as well as in precipitation, the inflow from adjacent areas, evaporating moisture, moisture content in the water catchment or lake, runoff waters, intake water, and in freezing or thawing water; and R is the variation in the amount of substance due to physicochemical, chemical, and biochemical processes. η_W and η_G are the water and hydrochemical imbalances; on the whole, the lower index X corresponds to atmospheric moistening, Y to the water runoff, E to evaporation, A to the anthropogenic effect, Z to the entry from adjacent areas, and I to ice formations (Alekin, 1970; Loucks and Van Beek, 2005).

Calculation of the water balance (Savichev et al., 2015) involved the following methods of assessing the water-balance elements and assumptions on their application: (1) from the long-term annual average perspective, it is approximately assumed that the variation of moisture content during the year is $\Delta U_y \approx 0$; (2) the I_t value in the first approximation can be calculated depending on the sum of negative temperatures of atmospheric air by the Bydin formula (Savichev et al., 2015); (3) monthly "effective" atmospheric moistening is determined as the sum of liquid precipitation and water yield from seasonal snow cover (Savichev et al., 2015)—water yield from snow cover is determined by the method of temperature coefficients, depending on atmospheric air temperature with moisture content restrictions in the snow cover formed at negative air temperatures (Gel'fan, 2007); (4) monthly evaporation from the catchment surface when snow cover is absent is determined by the method of M.I. Budyko in the interpretation of (*Metodicheskie*..., 1986)—calculation of soil moisture content is made according to the data obtained from the first month during which thawed soils or their intensive melting are generally observed (in the case under consideration, from April) and evaporation from the surface of snow cover was calculated by Kuz'min (according to (*Resursy*..., 1972)); (5) evaporation from the water surface was determined according to (*Metodika rascheta*..., 2007); (6) the layer of the monthly underground component of the river runoff $Y_{g,m}$ was determined by interpolation between the values of runoff in February and December—from December to March the underground runoff is assumed to be equal to the river runoff and for areas beyond the catchments of Son or Karysh rivers, the subsurface runoff in the first approximation is determined as the product of the respective area by the rate of subsurface runoff that was obtained for the respective rivers; and (7) provided that the data on levels of water (in Lake Shira) are available, the water variation in the lake, $\Delta U_{L,m}$, is determined by the truncated pyramid formula according to (Bogoslovskii, 1960).

A more detailed description of the mathematical catchment model and the simulation algorithm are given in (Savichev, 2012) and results of calculation of the water balance of lakes Shira and Itkul are presented in (Savichev et al., 2015). The data on the average monthly values of air temperature and water-vapor pressure, moisture deficit, wind velocity, and monthly precipitation volumes that were obtained at the Shira weather station at a distance of several kilometers from the lakes under study were used as source data (*Prirodnyi kompleks*..., 2010, 2011; *SNiP* 23-01-99*; *Resursy*..., 1973). The moisture content in the meter-deep soil layer as of the beginning of April (152.3 mm) and the temperature coefficient for calculating snow melting (0.43 mm/(day °C)) were determined by trial and error. The average monthly values of Son River water discharges were calculated based on the data of observations in the watercourse under consideration, near the village of Spirinskaya Zaimka, over 1967–1985, taking into account the full catchment area. The water runoff of Karysh River was calculated by multiplying the area of water catchment of this river by the rate of water runoff, which was calculated for the geometric catchment center as the weighted mean between the values of rates of the water runoff of Son River near the village of Spirinskaya Zaimka and Tuim River near the village of Tuim. Water catchment from Lake Itkul was assumed to be at the rate of 135000 m^3/month (*Prirodnyi kompleks*..., 2010), and the discharge of waste waters into Lake Shira was assumed to be approximately equal to the water intake from Lake Itkul (Savichev et al., 2015) (taking into account mutual compensation of water intake from underground sources and waste water infiltration).

The hydrochemical balance was calculated for the sum of principal Σ_{mi} ions (sum of Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, CO_3^{2-}, SO_4^{2-}, and Cl^- concentrations). Published data of hydrochemical observations of Rosgidromet (Russian Federal Service for Hydrometeorology and Environmental Monitoring) (*Resursy..*, 1973) and file and published materials of Tomsk Polytechnic and Tomsk State Universities (*Prirodnyi kompleks...* 2010, 2011; Guseva et al., 2012) served as source materials.

Mean Σ_{mi} values are assumed according to the published and file materials of Tomsk Polytechnic University, Tomsk State University, Rosgidromet, and a number of other organizations (*Prirodnye vody Shrinskogo...*, 2003; *Prirodnyi kompleks...*, 2010, 2011; Guseva et al., 2012; *Resursy...*, 1973; Rogozin et al., 2010) and are as follows: 605.4 mg/dm^3 for the Son River, 401.5 mg/dm^3 for Karysh, and 7.2 g/dm^3 for water formed during ice melting in Lake Shira. The mean vertical Σ_{mi} value for Lake Shira (as a result of linear interpolation between measurements in the 0.5 and 20–21 m layer below the surface for the average depth of 11 m) is calculated by regressional dependence: $C_i = 0.33\ C_{i,0.5} + 13947.30$, where C_i and $C_{i,0.5}$ are the average monthly concentrations of substance in the central vertical layer and in the 0.5 m layer below the surface; the squared correlation ratio $R^2 = 0.55$ at critical ratio $R^2_{\text{critical}} = 0.36$.

An estimate of the interannual distribution of the sum of principal ions in river waters was made with respect to the regressional dependence obtained for the steppe zone of Western Siberia: $C_i/C_b = 0.81\ (Q_i/Q_b)^{-0.152}$, where C_i and C_b are the average monthly and average long-term annual concentrations of substance, Q_i and Q_b are the average monthly and average long-term annual water discharges, and $R^2 = 0.55$; the characteristic of the initial data is given in (Savichev, 2014). In the underground water inflow, the Σ_{mi} value for each month is calculated by the same dependence; however, it now determines the discharge of underground waters. The Σ_{mi} values of waters formed during ice melting in Itkul are assumed to be equal to the sum of principal ions in the waters of this water body.

The sum of principal ions in precipitation (and in evaporating moisture) was determined according to the data of (Savichev and Ivanov, 2010) that were obtained for snow and rain (when calculating the hydrochemical balance of the lakes under study, a certain value is chosen depending on negative or positive atmosphere air temperature). The content of dissolved salts in domestic waste waters discharged into Lake Shira is assumed to be equal to the respective indicator for waters of Lake Itkul on the premise that the waste waters have been treated to standard quality and correspond to waters of the source by their composition.

In August 2015, five lake water samples were additionally selected from the 0.3–0.5 m layer below the surface at a distance of 3 m from the shore. The chemical composition of lake waters was determined at the accredited Fundamental Research Hydrochemistry Laboratory of Tomsk Polytechnic University using the following methods: pH, potentiometric method; specific conductivity, conductometric method; solution density, aerometric method; Ca^{2+}, Mg^{2+}, HCO_3^-, and Cl^-, titration method; Si, photometric method; SO_4^{2-}, Na^+, and K^+, ion chromatography; Al, atomic absorption; and dissolved organic carbon Corg, high-temperature catalytic oxidation.

Thermodynamic calculations for determining the index of water saturation L (4) with secondary minerals and compounds were made using the Solution+ software package developed on the basis of the method of constants and calculation of activity coefficients by Davis equation (Savichev et al., 2002):

$$L = \log PA - \log K_{\text{nost}}, \qquad (4)$$

where PA is the product of activities of the group of substances; K_{nost} is the instability constant. Negative values of index L indicate potential solution undersaturation, while positive values indicate solution oversaturation with minerals.

RESULTS AND DISCUSSION

The calculations allowed us to obtain a general picture of the formation of the hydrochemical balance of lakes Itkul and Shira which, on the whole, coincides with the previous results of analysis of the water balance (Savichev et al., 2015). The basic features of the hydrochemical balance of the water bodies under study are as follows.

On average, over a multiyear period, moisture content is accumulated in the catchments of the Son River and Lake Shira during the spring–summer period, while in autumn and winter they get empty; it should be noted here that the highest average monthly evaporation from the catchment surface is confined to August (77 mm/month), while the highest evaporation from the water surface is confined to June (132 mm/month) and July (131 mm/month). Accordingly, the period from April to October also covers the entry of salts generated by liquid precipitation and salt concentration during water evaporation, while the period from March to May covers the entry of salts generated by snow melting in catchment (Tables 1, 2).

The discharge of water inflow into Lake Itkul is covered not only by evaporation and saturation of the near-bottom and nearshore zones, but also by runoff from the lake to Lake Shira along the Tushinsky stream. The latter assumption is based on the fact that, first, the specified water body (Lake Shira) is located 3–5 km from Lake Itkul, and the levels in the first water body are approximately 100 m lower than those in the second one. Second, the underground flow from Lake Itkul to Lake Shira is in good agreement with the results of calculation of the water and hydrochemical balances of the two water bodies and aligns moisture imbalance.

Table 1. Long-term annual average water and hydrochemical balance of Lake Shira (water volume *V*, thousand m^3; dissolved salt mass *M*, *t*)

Month	Precipitation on lake surface		Evaporation from water surface		Total Son River water inflow		Underground drift, except for the Son River and Lake Itkul		Waste-water discharge		Water losses for ice formation		Water inflow from Lake Itkul or interaction with the geological environment	
	V_X	M_X	V_E	M_E	$V_{Z(C)}$	$M_{Z(C)}$	V_{Zg}	M_{Zg}	V_{A1}	M_{A1}	V_I	M_I	$V_{Zg(I)}$	$M_{Zg(I)}$
I	200	5	0	0	169	109	109	70	0	0	23708	170700	22878	17284
II	100	2	0	0	117	78	75	51	0	0	28065	202066	28125	21670
III	0	0	0	0	320	187	93	61	0	0	30072	216520	30895	24233
IV	1272	65	1791	91	1660	752	99	64	0	0	11670	84023	14776	11780
V	1109	56	3579	182	1441	670	111	71	0	0	–121608	–875580	–118351	–59285
VI	1784	91	4755	242	1396	649	116	74	135	77	0	0	3884	2215
VII	2771	141	4696	239	1863	833	129	81	140	86	0	0	2093	1288
VIII	1957	100	3560	181	1637	747	138	86	140	91	0	0	–2181	–1416
IX	955	49	1968	100	1306	613	143	88	0	0	0	0	2788	1887
X	632	32	845	43	1157	556	157	96	0	0	0	0	–1257	–880
XI	0	0	0	0	535	288	161	97	0	0	10219	73577	9810	7071
XII	200	5	0	0	271	162	175	105	0	0	17874	128694	13330	9851
I–XII	10982	545	21194	1079	11871	5644	1506	944	414	253	0	0	6791	35697

V is the water volume; *M* is the mass of dissolved salts; in the case of evaporation, *M* is the mass of dissolved salts that enters the water body during evaporation of water with mineralization being equal to precipitation mineralization; the volume of water inflow from Lake Itkul is assumed to be equal to the water imbalance; the water balance was calculated by the authors in (Savichev et al., 2015).

Table 2. Long-term annual average water and hydrochemical balance of Lake Itkul (water volume V, thousand m^3; mass of dissolved salts M, t)

Month	Precipitation on the lake surface		Evaporation from the water surface		Total water inflow of the Karysh River		Subsurface inflow from catchment (except for the Karysh River)		Water intake		Water losses for ice formation		Outflow to Lake Shira or interaction with the geological environment	
	V_X	M_X	V_E	M_E	$V_{Z(K)}$	$M_{Z(K)}$	V_{Zg}	M_{Zg}	V_{A2}	M_{A2}	V_I	M_I	$V_{Zg(I)}$	$M_{Zg(I)}$
I	130	7	0	0	442	158	369	132	0	0	15556	11752	22878	17284
II	65	3	0	0	370	134	309	112	0	0	18347	14136	28125	21670
III	0	0	0	0	477	168	346	125	0	0	19636	15401	30895	24233
IV	824	42	1160	59	1215	370	338	122	0	0	7718	6153	14776	11780
V	718	37	2318	118	1056	330	352	127	0	0	–80174	–61294	–118351	–59285
VI	1156	59	3079	157	877	280	344	123	135	77	0	0	3884	2215
VII	1795	91	3041	155	1182	363	359	129	140	86	0	0	2093	1288
VIII	1267	64	2306	117	1076	335	362	130	140	91	0	0	–2181	–1416
IX	618	31	1275	65	963	304	354	126	0	0	0	0	2788	1887
X	409	21	547	28	906	290	369	132	0	0	0	0	–1257	–880
XI	0	0	0	0	566	194	360	128	0	0	7075	5099	9810	7071
XII	130	7	0	0	449	160	376	134	0	0	11843	8752	13330	9851
I–XII	7112	362	13726	699	9580	3085	4239	1518	414	253	0	0	6791	35697

The water outflow from Lake Itkul is assumed to be equal to the water imbalance of Lake Shira, and the change in the volume of lake waters is calculated by Eq. (1); the change in the volume of water in Lake Itkul presumably has a systematic error due to the failure to take account of the runoff to the Tuim River and Lake Berezovoe; calculation of the water balance was performed by the authors in (Savichev et al., 2015).

Table 3. Physicochemical and hydrochemical indicators of waters of lakes Itkul and Shira as of August 3, 2015, mg/dm^3

Component	Lake (sampling from the 0.5 m layer below the surface)	
	Itkul	Shira
pH	8.6	8.8
Specific conductivity, μS/cm	705	22400
Water density	998	1012
Ca^{2+}	24	60
Mg^{2+}	62	1196
Na^+	47	3429
K^+	4.9	37.0
HCO_3^-	293	848
CO_3^{2-}	12.2	116
SO_4^{2-}	76	7970
Cl^-	32	1802
Mineralization	551	15458
Si	3.70	8.60
Fe	0.05	0.29
Al	0.05	0.91
C_{org}	9.6	23.9

If we assume that water exchange with the bottom and shores is correlated with variations in moisture content (ΔU_t) in water catchment and, on the whole, tends towards zero during the year, the value of the annual water imbalance can be interpreted as a characteristic of the filtration water flow from Lake Itkul to Lake Shira (Tables 1 and 2). According to the obtained data, its volume is 6791000 m^3/year, or about 0.22 m^3/s, which is comparable with long-term annual average water discharges of the Tuim River near the village of Tuim and the Tes River near the village of Bograd (0.23 m^3/s each) and the Son River near the village of Spirinskaya Zaimka (0.31 m^3/s). Taking into account calculated estimation errors (about 20%, according to (*Melioratsiya*..., 1988) or 1358000 m^3/year), the average annual water runoff from Lake Itkul into Lake Shira is about 5433000 to 8149000 m^3/year (the water discharge is from 0.17 to 0.26 m^3/s). The width of the flow from Lake Itkul to Lake Shira is about 6 km, the average thickness of water-bearing deposits is 75 m, and the surface slope (presumably, also including the water surface slope) is 0.00295 (m/m). Based on these values, one can approximately estimate the average velocity of the motion of underground waters to be 0.041 m/day and the filtration coefficient to be 1.391 m/day (Savichev et al., 2015).

According to (Mikhailov et al., 2005), if we use ratio (5) as a water-exchange characteristic, we can estimate the rates of conventional water exchange for lakes Shira and Itkul to be 0.05 and 0.10, respectively, based on the abovementioned average values of the depth and size of water areas. Consequently, the intensity of water exchange in Lake Itkul is approximately two times as high as that in Lake Shira.

$$K_w = (V_E + V_Y + V_{A2})/V_L, \tag{5}$$

where K_w is the rate of conventional water exchange, V_L is the lake volume obtained by multiplying the average values of the water area by the (average) depth, and the other notations are the same as those for Eqs. (2) and (3).

The average hydrochemical runoff from Lake Itkul to Lake Shira is 35698 t/year, which significantly exceeds the entry of principal ions from all other sources in Lake Shira (Table 1). The values of the basic elements of the hydrochemical balance of Lake Shira are as follows (t/year): entry with precipitation, 545; outflow with evaporating moisture, 1079; inflow with the Son River waters, 5644; subsurface inflow (in addition to the inflow through the channel network and from Lake Itkul), 944; domestic waste-water discharge, 253; filtration flow from Lake Itkul, 35697; and imbalance, 41498.

The hydrochemical imbalance for Lake Shira can be presumably explained not only by errors of determination of entry and discharge components, but also by the elimination of chemical elements from the water medium with low-soluble compounds that are generated during interaction with dissolved organic matter and suspended silts and as a result of processes of secondary mineral formation. A certain role may also be played by processes of concentration and dilution during the formation and melting of ice cover.

To confirm this hypothesis, the authors selected and analyzed water samples from lakes Shira and Itkul (Table 3) and calculated indices of saturation of lake waters with rock minerals in August 2015.

The waters of Lake Itkul are fresh, weakly alkaline, and hydrocarbonate sodium–magnesium. The concentration of dissolved organic carbon is 9.6 mg/dm^3. The silicon concentration is not high, being 3.7 mg/dm^3.

The waters of Lake Shira are also weakly alkaline; however, they are characterized by higher mineralization, being 22400 mg/dm^3. The ion composition is dominated by sulfate ion and sodium, while magnesium occurs more rarely. Higher concentrations of rock-forming silicon, iron, and aluminum elements are recorded in waters of Lake Shira (Table 3). The concentration of dissolved organic carbon is 23.9 mg/dm^3.

According to the estimate of the degree of saturation with rock minerals, the waters of the lakes under consideration are saturated with clay minerals and cal-

Table 4. Index of saturation (L) of lake waters with some minerals and organo-mineral compounds

Reaction	Lake Itkul	Lake Shira
$CaCO_{3(calcite)} = Ca^{2+} + CO_3^{2-}$	–0.13	0.23
$CaCO_{3(calcite)} + CO_2 + H_2O = Ca^{2+} + 2HCO_3^-$	0.33	0.09
$CaMg(CO_3)_{2(dolomite)} = Ca^{2+} + Mg^{2+} + 2CO_3^{2-}$	1.49	2.71
$CaMg(CO_3)_{2(dolomite)} + 2CO_2 + 2H_2O = Ca^{2+} + Mg^{2+} + 4HCO_3^-$	2.41	2.43
$MgCO_{3(magnesite)} + CO_2 + H_2O = Mg^{2+} + 2HCO_3^-$	–1.87	–1.61
$Ca(HC) = Ca^{2+} + HC^{2-}$	0.18	0.28
$Mg(HC) = Mg^{2+} + HC^{2-}$	1.62	2.22
$CaSO_4 = Ca^{2+} + SO_4^{2-}$	–3.10	–1.74
$CaSO_4 \cdot 2H_2O = Ca^{2+} + SO_4^{2-} + 2H_2O$	–2.89	–1.53
$SiO_{2(quartz)} + 2H_2O = H_4SiO_4^0$	–0.23	0.26
$2NaAlSi_3O_{8(albite)} + 11H_2O + 2CO_2 = Al_2Si_2O_7 \cdot 2H_2O_{(kaolin)} + 2Na^+ + 2HCO_3^- + 4H_4SiO_4^0$	–9.38	–4.28
$3KAlSi_3O_{8(orthoclase)} + 2H^+ + 12H_2O = KAl_3Si_3O_{10}OH_{2(muscovite)} + 2K^+ + 6H_4SiO_4^0$	–23.48	–18.39
$CaAl_2Si_2O_{8(anorthite)} + 2H^+ + 6H_2O = Al_2O_3 \cdot 3H_2O_{(gibbsite)} + 2H_4SiO_4 + Ca^{2+}$	–4.74	–3.28
$CaAl_2Si_2O_{8(anorthite)} + 2H^+ + H_2O = Al_2Si_2O_7 \cdot 2H_2O_{(kaolin)} + Ca^{2+}$	–18.97	–20.14

cium and magnesium carbonates; at the same time, they are nonsaturated with primary rock-forming minerals, namely, albite, anortite, and orthoclase, and sulfate minerals, namely, gypsum and anhydrite (Table 4), which are the principal sources of entry of chemical elements into waters. Saturation with calcium and magnesium humates is also observed in the lakes under consideration. An analysis of the results (Table 4) showed that an increase in water mineralization leads to a growth in saturation with calcite (in the absence of or at low content of CO_2), dolomite, calcium and magnesium humates, and quartz. Therefore, the waters being considered have a geochemical barrier for the accumulation of basic salt-forming elements in the solution, i.e., calcium, magnesium, hydrocarbonate ion, and carbonate ion, which are eliminated together with the secondary mineral phase being formed, whose deposit is directly observed in the lake (Tret'yakov et al., 2012).

In addition to processes of interaction in the water–rock system, a significant role in the formation of arid areas is played by evaporating concentration processes. Thus, according to the presented calculations, the water and hydrochemical balance of the lakes under study in June to July is characterized by prevailing evaporation from the water surface compared with that from entering components, which indicates a significant role of the evaporation mechanism of the formation of the chemical composition of lake waters. However, among the lakes being considered, this is true only for Lake Shira. On the whole, Lake Itkul cannot be recognized to be a drainless water body due to the significant outflow of water and salts dissolved in it to the Tuim River through the channel network and to Lake Shira in the form of a filtration flow. Accordingly, evaporation has significantly lower influence on the formation of the hydrochemical balance and chemical composition of waters of Lake Itkul than that of Lake Shira, which is the primary cause of the difference in mineralization between the two water bodies.

It should also be noted that significant water volumes are withdrawn for ice formation and an additional increase in the concentration of principal ions is observed in lake waters in winter months, while in April and May a relatively sharp decrease in concentrations of dissolved salts in lake waters is observed due to the entry of water with a lower content of dissolved salts into the water body. As was assumed in (Rogozin et al., 2010; Savichev et al., 2015), as a result of this difference, a stable stratification of water masses is maintained in Lake Shira due to the fact that the upper layers are less dense than the lower ones. However, for fresh Lake Itkul, this difference is not as significant and is compensated by wind mixing and intralake currents.

Therefore, the substantiation of mechanisms of formation of the chemical composition of waters of lakes Shira and Itkul should take into account that these water bodies are an integrated hydrochemical system in which the evaporation mechanism of formation of water composition is mainly characteristic of Lake Shira, while Lake Itkul plays the role of a flowing reservoir of water and dissolved salts. An analysis of the data of published and file materials on the composition of waters of a number of other lakes in the Asian arid zone (Guseva et al., 2012; Kolpakova, 2014; Shvartsev et al., 2014) indicates that this situation is common rather than exceptional for this region. Lake Bele can be considered an example of such lake systems, which is located north of the water bodies being considered. The feature of this lake is the presence of two parts that are located at different altitudes and connected by a branch. Since the flow between parts of Lake Bele has a significantly higher intensity than that in the Itkul–Shira system, the mineralization gradient is also significantly lower in the case under consideration; however, it is rather noticeable.

CONCLUSIONS

In the arid zone of northern Asia, under approximately the same physicogeograhical conditions, significant differences can be observed in the formation of the water balance of large lakes that are associated with strong variability in evaporation and intensity of water exchange. In turn, the latter value (intensity of water exchange) determines differences of lake waters in terms of their mineralization and chemical composition, which is due to different time of interaction of lake waters with rock minerals.

In the above-considered case, lakes Shira and Itkul are a hydraulically bound system of water bodies; the latter plays the role of a drained water body. As a result, the intensity of water exchange is approximately two times higher in it than that in Lake Shira. The volume of evaporation is also significantly higher (21200000 m^3 in Lake Shira and 13700000 m^3 in Lake Itkul). Accordingly, the average mineralization of waters of Lake Shira is approximately 28 times higher than that in Lake Itkul. Since the growth in mineralization also leads to changes in the ratio of principal ions (Kazantsev, 1998, Shvartsev, 1998; Krainov et al., 2004), the geochemical type of waters also changes: from hydrocarbonate sodium–magnesium waters in Lake Itkul to sulfate magnesium–sodium waters in Lake Shira.

In addition, waters of Lake Shira are oversaturated with calcium and magnesium carbonates and humates, but they are unsaturated with gypsum and primary aluminosilicates. It can be assumed that the further decrease in the intensity of water exchange (due to an increase in evaporation as the water inflow decreases) will lead to changes in the chemical composition of waters up to chloride or sulfate–chloride sodium brines, which is observed, for example, in Lake Tus in Khakassia (Guseva et al., 2012), Dus Khol in Tuva (Kopylova et al., 2014), or lakes of Mongolia (Kolpakova, 2014).

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research, project no. 14-05-31387, and by the State Assignment “Science,” project no. 5.1931.2014/K.

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Translated by D. Zabolotny