ISSN 0097-8078, Water Resources, 2022, Vol. 49, Suppl. 2, pp. S113–S122. © Pleiades Publishing, Ltd., 2022.
Russian Text © The Author(s), 2021, published in Geoekologiya. Inzhenernaya Geologiya. Gidrogeologiya. Geokriologiya, 2021, No. 4, pp. 41–52.

Interaction between River Water and Groundwater in the Lower Reaches of the Tom River, Tomsk Oblast, Russian Federation

O. N. Vladimirova[a], * and O. G. Savichev[a], **

[a] *National Research Tomsk Polytechnic University, Engineering School of Natural Resources, Tomsk, 634050 Russia*
**e-mail: onv-2018@yandex.ru*
***e-mail: OSavichev@mail.ru*

Received September 21, 2020; revised January 19, 2021; accepted May 28, 2021

Abstract—Relationships between the amount and chemistry of atmospheric water, river water, and groundwater are analyzed in the catchments of six small tributaries of the Tom River near Tomsk City (Russian Federation, West Siberia, Ob R. basin) using data of long-term hydrogeological and hydrological observations (from the 1970s to 2019). A decrease in the rate of water exchange was shown to cause an increase in the interaction time in the water–rock system and, accordingly, in the total concentration of dissolved salts in groundwater. For the first time for the lower reaches of the Tom R., it was shown that the intensity of interaction between river water, subsoil water, and artesian water can be evaluated with the use of the coefficient of variation $Cv(Y_m)$ of the monthly runoff depth values of small rivers—the greater the value of $Cv(Y_m)$, the greater the closeness of deep aquifers and groundwater TDS. The processes of rock leaching and dissolution were found to dominate in areas with considerable replenishment of water reserves in the warm season of the year (on the right side of the Tom R. catchment), while the input of substances from outside, e.g., with precipitation, dominates in the area were groundwater resources are mostly replenished during snow melting.

Keywords: water balance, geochemical balance, river water and groundwater, Altai-Sayan hydrogeological folded area, West Siberian artesian basin, Tom River tributaries, Tomsk

DOI: 10.1134/S0097807822080139

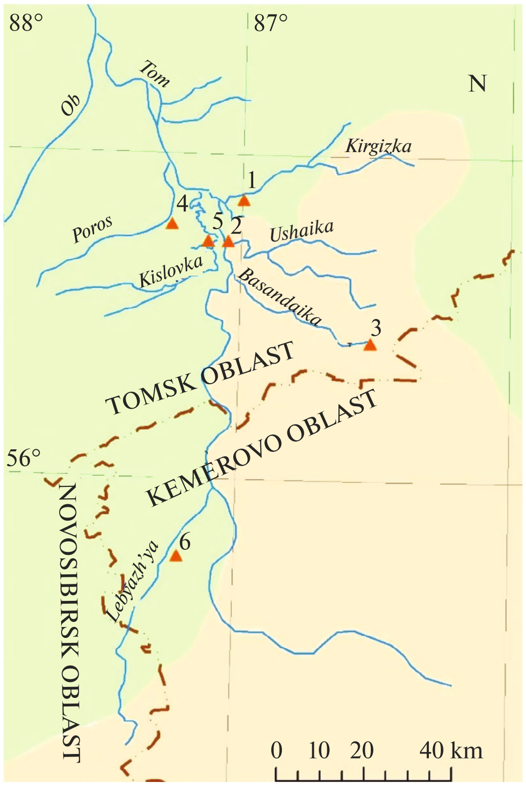
INTRODUCTION

The problem of high-quality drinking water supply to the population is of importance in many regions, including Tomsk—the administrative center of Tomsk oblast (Russian Federation, Siberian Federal District). Therefore, it is of importance to study the formation conditions of water resources and the state of groundwater used for drinking water supply. Water supply to Tomsk is based on the Tomsk subsurface water intake (in the volume of ~200 thous. m^3/day) and some lesser water intakes and individual wells [15, 29].

In the recent years, the built-up area has been increasing, resulting in a problem of ensuring groundwater quality, in particular, through the organization and control of the state of sanitary zones of water intakes and water-protection zones of rivers, the drainage basins of which completely or partially coincide with the areas of groundwater recharge and discharge. This is of importance because the intake of groundwater, which hydraulically interacts with rivers, can cause a decrease in river flow and the input of pollutants into aquifers from land surface and the aeration zone (surface flow, leaks from the systems of water and heat supply, sewerage, motor-vehicle refueling complexes, and other production facilities). In addition, the development of a territory changes the formation conditions of the surface water and groundwater flow, the recharge of deeper aquifers, and, hence, deterioration of groundwater quality [5, 27, 37].

These are some reasons why the Tomsk Polytechnical University (TPU), in cooperation with some research and production organizations, carries out long-term studies of subsurface and surface sources of water supply to Tomsk and the conditions of their formation [16, 17, 30]. Given below are the results of one stage of these studies as a part of works aimed to assess the level of protection of groundwater used for water supply to Tomsk and Tomsk region; it was focused on the identification of relationships between the chemistry and flow of groundwater and river water.

The objects of the study are groundwater and river water in the catchments of small tributaries of the Tom River in a segment of its lower reaches: the right tributaries: the rivers of Kirgizka (Bol'shaya Kirgizka), Ushaika, and Basandaika; the left tributaries: the rivers of Poros, Kislovka, and Lebyazh'ya (Fig. 1). The choice of these rivers was based on the following considerations.



Legend

Hydrological gages

Rivers

Boundaries of RF constituent territories

Hydrogeological zoning

Altai–Sayan hydrogeological folded area

West-Siberian Artesian Basin

Fig. 1. Layout of hydrological observation sites (the numbers of the sites are given in Table 1).

The area under consideration contains two hydrogeological structures of the I order: the West-Siberian artesian basin (WSAB) and the Altai–Sayan hydrogeological folded area (ASHFA). The latter structure includes a hydrogeological structure of the II order—Altai–Tomsk hydrogeological massif [33].

The catchments of the right tributaries (the rivers of Basandaika, Uskhaika, and a part of the Bol'shaya Kirgizka) lie in ASHFA at the boundary of the southern taiga. The catchments of the left tributaries (a part of the tributary of the Bol'shaya Basandaika R. and the rivers of Poros, Kislovka, and Lebyazh'ya) belong to WSAB and forest steppe. The approximate geohydrological structure can be represented in the form of a combination water-bearing deposits (top to bottom):

(1) the left bank of the Tom R.—neogene–quaternary and Paleogene (underlain by Cretaceous system, bearing groundwater with appreciable concentration of dissolved salts; Paleozoic formations reach the surface near the Tom; the drainage basin of the Lebyazh'ya R. shows wider occurrence of Neogene water-bearing deposits);

(2) the right bank of the Tom R.—deposits of Quaternary, Paleogene, Cretaceous, and Paleozoic age.

According to data published in bulletins on the conditions of the geological environment in the territory of SFD (Gidrospetsgeologiya and Siberian Regional Center of Gidrospetsgeologiya), the geological section of WSAB contains a distinct folded basement, composed of rocks of pre-Jurassic age, and a mantle consisting of platform gently sloping terrigenous sediments of Mesozoic and Cenozoic. The section of the Mesozoic–Cenozoic basin contains two hydrogeological stages with distinctive features of groundwater formation. The stages are separated by a thick regional aquiclude of Upper Cretaceous–Paleogene age, which wedges out in the marginal part of the basin. The top hydrogeological stage is a multilayer, facially varying stratum, containing more than 30 aquifers in Paleogene, Neogene, and Quaternary deposits. This stage features free water exchange, the rate of which decreases with depth and becomes hampered in the bottom part of the stage [33].

The hydrogeological conditions of ASHFA (Altai–Tomsk GM of the II order) also feature the presence of two hydrogeological stages (the upper on is confined to loose Meso-Cenosoic deposits, and the lower, to Paleozoic and Proterozoic rocks of various genesis) and a wide occurrence of fissure-vein waters. Pore water is mostly present in Quaternary deposits in river valleys and nearby areas. The geological and hydrogeological data are presented in greatest detail in many publications of various authors and institutions [2–4, 8, 19, 25, 33].

The Tomsk Groundwater Intake develops aquifers in Paleogene deposits within the Ob–Tom interfluve, in particular, within the drainage basins of the rivers of Kislovka and, especially, Poros. The drainage basin of the Lebyazh'ya river lies south of the recharge area of the Tomsk water intake. The Severskii Groundwater Intake lies in the drainage basin of the Kirgizka R., a right tributary of the Tom, and it also develops the Paleogene complex. The Ushaika R. runs through the entire Tomsk, and its drainage basin contains a large water intake (Akademicheskii) and many single wells. TheKirgizka and Ushaika rivers receive surface runoff from urban territories, suburban populated localities, large plants along with a considerable volume of wastewater (from treated to a standard level to non-treated). In the water intake of the Basandaika R., the intake of river water and groundwater and the discharge of wastes is carried out, but to a lesser extent than in the Ushaika and Bol'shaya Kirgizka rivers [8, 17, 30, 33].

Thus, the area under consideration (~5000 km^2) shows appreciable diversity of the natural and anthropogenic conditions of groundwater and river water formation, and the number of water intakes corresponds to the lower boundary of the applicability of statistical methods according [34]. This allows us to try to find quantitative relationships between groundwater used for water supply to more than half a million people and the water of small rivers. The number of the latter is objectively fixed and cannot be increased.

MATERIALS AND METHODS

The hydrological observations on Roshydromet network are now carried out on the Basandaika R. at Basandaika Settl. (now the southern part of Tomsk), the Poros R. at Zorkal'tsevo V., and the Lebyazh'ya R. at Bezmenovo V.; previously, they were carried out on the Ushaika R. at Stepanovka Settl. and on the Kirgizka R. at Kuzovlevo Settl. Hydrological studies on the Poros and Kislovka rivers were carried out before at the reevaluation of the reserves of the Tomsk water intake by experts of the Siberian Regional GMSN Center (a branch of Hidrospetsgeologiya), Tomskgeomonitoring, and Tomsk Geological Survey Expedition (TGSE). The same institutions carry out observations of groundwater level and chemistry in the state and local observation networks [1, 10, 16, 17, 33, 38]. A considerable volume of geochemical data was obtained in TPU and the Tomsk Branch of the Institute of Geology and Geophysics of Oil and Gas, Siberian Branch, Russian Academy of Sciences (TB IGGOG SB RAS) [8, 9, 11, 12, 14, 30, 39, 40]. These materials formed the information basis for the study.

The concept of the study is based on the analysis of relationships between the amount and chemistry of atmospheric and river waters and groundwater under the assumption that the winter river runoff in the area under consideration (seasonal snow cover and freezing of top ground layer to a depth of 2.0–2.2 m) forms by groundwater. In the composition of atmospheric precipitation, rain and snowmelt waters are considered, and in the composition of groundwater (according to the concepts given in [40]), phreatic (unconfined and weakly confined water of the top aquifer in the zone of full saturation) and artesian water (confined water between aquicludes), including phreatic and artesian water in the fractured zone. In the composition of atmospheric precipitation, the authors considered rain and snowmelt waters, and in the composition of groundwater (according to concepts presented in [40]), subsoil (unconfined and weakly confined water in the top aquifer in the zone of full saturation) and artesian (confined water lying between aquicludes), including phreatic and artesian water of the fractured zone.

The study procedure included five main stages:

(1) calculating the mean values of the chemistry characteristics of groundwater (phreatic and artesian), river and atmospheric (rain and snowmelt) water;

(2) assessing water balance elements for the drainage basins of the rivers under consideration on the average over a long period;

(3) evaluating the groundwater component of the total river flow and identifying in it the fracturs of water inflow from the main aquifer systems;

(4) evaluating elements of geochemical balance of catchments on the average over a long-term period;

(5) identification of relationships between elements of water and geochemical balances.

The first stage included the generalization of data on the concentrations of the principal ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, CO_3^{2-}, SO_4^{2-}, Cl^-), Fe, Si, NO_3^-, NO_2^-, NH_4^+, the values of permanganate oxidability (PO), pH, dry residue, and specific conductance, obtained in accredited Roshydromet laboratories, TPU, TGRE, AO Tomskgeomonitoring by comparable or identical certified methods. More detail data on the procedures of sampling and sample processing, as well as the methods of analyses are given in [24, 30].

The statistical analysis of the geochemical information included:

(1) evaluating the arithmetic mean A, the coefficients of correlation r, and the errors of their estimates δ_A and δ_r (1, 2);

(2) testing the homogeneity of samples from different catchments in terms of the sum of principal ions with the use of (3) Student and (4) Fisher tests at a significance level $\alpha = 5\%$;

(3) identifying regression relationships of the type

$$f(\Phi) = k_0 + \sum_{i=1}^{m} k_i f(Ar_i)$$

under the conditions: $|k_i| \geq 2\delta_k$, $|r| \geq 0.7$, where $f(\Phi)$ and $f(Ar)$ are functions of the variable sought-for and its arguments; k_i and δ_k are regression coefficients and their calculation errors, , $i = 0, \ldots, m$ [26, 34]:

$$\delta_A \approx \frac{\sigma}{\sqrt{N}}, \quad (1)$$

$$\delta_r \approx \frac{1 - r^2}{\sqrt{N-2}}, \quad (2)$$

$$Kr_S = \frac{|A(\Phi_1) - A(\Phi_2)|}{\sqrt{N_1\sigma_1^2 + N_2\sigma_2^2}} \sqrt{\frac{N_1 N_2 (N_1 + N_2 - 2)}{(N_1 + N_2)}}, \quad (3)$$

$$Kr_F = \frac{\max\left(\sigma_1^2; \sigma_2^2\right)}{\min\left(\sigma_1^2; \sigma_2^2\right)}, \quad (4)$$

where Kr_S and Kr_F are the actual values of Student and Fisher tests; N is sample size; subscripts 1 and 2 correspond to arbitrarily chosen numbers of the compared samples, for each of which the arithmetic mean $A(\Phi_j)$ and standard deviation σ_j are calculated.

The second stage included the use of equations (5)–(9) under the assumption that there are no significant changes in moisture reserves on the drainage basin on the average over the long period:

$$P_y - E_y - Y_y = P_r + P_{sn} - E_{wp} - E_{cp} - Y_g - Y_{sf} \approx 0, \quad (5)$$

$$E_{cp} = \sum_{T_a<0} 0.34 d_{ai} m_i, \quad (6)$$

$$E_{wp} = \left(P_y - Y_y\right) - E_{cp} = E_y - E_{cp}, \quad (7)$$

$$Y_{gi} = \begin{cases} Y_i, & i = (12, 1, 2, 3) \\ Y_3 + \left(Y_{12} - Y_3\right)\dfrac{(i-3)}{9}, & i = (4-12), \end{cases} \quad (8)$$

$$Y_{sf} = Y_y - \sum_{i=1}^{12} Y_{gi}, \quad (9)$$

where P_y, P_r, P_{sn} is the precipitation depth over the year, as well as that in the form of rain and snow, respectively, mm/year; E_y, E_{wp}, E_{cp} is the total evaporation depth from the catchments surface over the year as a whole, in the worm (tentatively, by the condition $T_a \geq 0°C$; T_a is the mean monthly temperature of the surface atmospheric layer) and the cold period ($T_a <$ 0°C), mm/year; i is month number; Y_y, Y_i are the depths of the total annual runoff, mm/year, and that over the ith month of the year, mm/month; Y_g, Y_{sf} are the subsurface and surface components of the total river runoff over the year, mm/year; Y_{gi} is groundwater runoff depth over the ith month of the year, mm/month; d_{ai} is the saturation deficit of the atmospheric air over the ith month, GPa; m_i is the number of days in the ith month.

The depth of river runoff was calculated by the measured monthly water discharges Q_i over the period from 1970 to 2000, or up to the end of monitoring [28]. The data on atmospheric precipitation, air temperature and saturation deficit were taken from [20], with requirements in [35] taken into account, for the rivers of Kirgizka, Ushaika, Basandaika, Poros, and Kislovka—by the Tomsk weather station, and for the Lebyazh'ya R., by the Bolotnoe weather station.

At the third stage, the method of mixing was used in the form:

$$Q_{g2} = Q_g \frac{\left(S_{rw} - S_{g1}\right)}{\left(S_{g2} - S_{g1}\right)}, \quad (10)$$

$$Q_{g1} = Q_g - Q_{g2}, \quad (11)$$

where $Q_g = Y_g$ is the annual average groundwater discharge, calculated by (8); Q_{g1} and Q_{g2} are groundwater runoff components, corresponding to the inflow of phreatic water and artesian groundwater; for all examined rivers, Q_{g1} corresponds to the inflow from water-bearing deposits of Quaternary and Neogene–Quaternary age (in the case of the Lebyazh'ya R.), and Q_{g2}, to the flow from the water-bearing system of Paleogene with possible inflow of water from Cretaceous deposits (the rivers of Kirgizka, Poros, and Kislovka) and the formations of Carboniferous period (partly, the rivers of Kirgizka and Kislovka; to a large extent, the rivers of Ushaika and Basandaika); S_{rw}, S_{g1}, S_{g2} are the mean values of the sum of principal ions in river water in winter, in phreatic and artesian groundwater.

The calculations use measured concentrations of Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, CO_3^{2-}, Cl^-, SO_4^{2-} in river water in the spring, summer–autumn, and winter periods (the boundaries of the seasons were chosen in accordance with the recommendations of the State Hydrological Institute of Roshydromet: the spring season from April to June, the winter season from December to March, when ice firmly forms on rivers along with a stable snow cover in the drainage basin), the concentrations of principal ions in phreatic and artesian water (the division into phreatic and artesian water was based on data on wells). The main database on the results of chemical analyses of samples was formed using the data from monitoring and exploration wells. The information on them was taken from the data of the Tomsk Exploration Expedition (works of N.A. Ermashova), AO Tomskgeomonitoring, and Siberian Regional Center Gidrospetsgeologiya. The data on individual points considered in the studies were taken from published works [8, 9, 11, 12, 14]. The measurement data on principal ion concentrations were used to calculate their sums by observation periods, which, in turn, were used to calculate the mean values of S_{rw}, S_{g1}, and S_{g2}.

The choice of the sum of principal ions as a hydrochemical characteristic of mixing of groundwater from various water-bearing deposits was determined by its relative tolerance to variations of the concentrations of individual ions and errors in their determination.

The calculations by the method of mixing for the area under consideration were carried out for the annual budget on the average for a long period. For the conditions of a specific year, the proportions of phreatic and artesian waters vary within a year. The seasonal variations on the average over the long period are much less than the seasonal variations of river water chemistry [16].

The fourth stage of the study includes the derivation and analysis of geochemical balance of the catchment in the form:

$$\begin{aligned} G_Y = S_Y Q_Y t b_1 &= F\left(P_r S_r + P_{sn} S_{sn}\right) b_2 \pm \Delta G \\ &= G_r + G_{sn} \pm \Delta G, \end{aligned} \quad (12)$$

where G_Y is the total annual runoff of dissolved salts in the outlet section of the examined river, t/year; Q_Y is the mean annual water discharge, m^3/s; t is the number of seconds in the calculation period (year); F is

Table 1. Mean annual sums of principal ions in river water and groundwater and errors in their determination (1) (1), mg/L (S_Y, S_{rw}, S_{g1}, S_{g2} are the mean values of the sum of principal ions in river water on the average over a year, in winter, in phreatic and artesian groundwater by the results of generalization of archive data in TPU and published data [11, 17, 22, 24, 30, 31, 40]; the mean values of the sum of principal ions in rain S_r and snowmelt S_{sn} water were taken using TPU archive data and published data [30] overall for the territory under consideration: $S_r = 90.7 \pm 9.1$ mg/L; $S_{sn} = 21.6 \pm 2.5$ mg/L)

No.	River – site	S_Y	S_{rw}	S_{g1}	S_{g2}
1	Kirgizka R. – Kuzovlevo Settl.	366.4 ± 24.9	509.4 ± 64.5	460.8 ± 24.4	540.2 ± 27.2
2	Ushaika R. – Stepanovka Settl.	406.0 ± 19.9	568.0 ± 78.8	457.4 ± 25.6	572.7 ± 19.1
3	Basandaika R. – Basandaika Settl.	453.8 ± 25.6	497.3 ± 38.5	375.2 ± 59.0	527.9 ± 20.4
4	Poros R. – Zorkal'tsevo Settl.	185.2 ± 23.1	509.2 ± 63.4	504.7 ± 32.9	535.0 ± 11.2
5	Kislovka R. – Timiryazevo Settl.	330.3 ± 11.6	385.1 ± 22.6	223.7 ± 6.6	444.5 ± 26.7
6	Lebyazh'ya R. – Bezmenovo V.	502.7 ± 34.0	559.5 ± 37.8	326.9 ± 47.4	566.8 ± 67.7

catchment area, km^2; S_Y, S_r, S_{sn} are the mean values of the sums of principal ions in the river, rain, and snowmelt water, respectively; P_r, P_{sn} are the same as in (5); ΔG is the result of salt input from soils, bogs, economy facilities, and their accumulation in the catchment; b_1, b_2 are dimensional factors.

The positive value of ΔG in the first approximation implies the predominance of the processes of rock dissolution and leaching, while its negative value, the predominance of matter accumulation in the catchment. The values of S_Y, S_r, S_{sn} were obtained by the generalization of archive and published data of Roshydromet, TPU, Tomskgeomonitoring, TGRE [30] under the same conditions as those for S_{rw}, S_{g1}, S_{g2}.

The equation of geochemical balance on the average for homogeneous period should be equilibrated; however, the balance equation for the drainage area under consideration does not include some elements, because an indirect evaluation of the lacking elements is supposed.

At the final, fifth stage, statistical analysis of the obtained data was carried out taking into account (1)–(4).

DISCUSSION OF RESULTS

The examined groundwater, river water, and atmospheric water are, on the average, fresh, hydrocarbonate, calcium. The total concentration of dissolved salts is, naturally, the least in atmospheric water and the highest in groundwater, commonly, in artesian (Table 1). In this case, we have to note that the test for heterogeneity in terms of the mean and variance suggests the statistical comparability of groundwater (either phreatic or artesian) in terms of the sum of principal ions (as well as in terms of the modulus of total water flow) only for the drainage basins of the Ushaika and Basandaika rivers (Table 2). For river water, the highest values of the sum of principal ions (Σ), comparable with the values for groundwater, are typical for freeze-up period.

The analysis of water balance elements for the drainage basins of the examined rivers showed that a considerable portion of the total and, especially, surface runoff has been formed by snowmelt water, and those for the rivers of Poros, Kislovka, and Lebyazh'ya, completely by such water. This is due to the fact that, first, the major portion of precipitation in the warm season is spent for total evaporation (with the involvement of snow reserves that have formed during snow melting). Second, the total evaporation in the drainage basins of the left tributaries of the Tom River in the forest zone, the total evaporation is higher than in those for the right tributaries (Table 3). This affects the absolute values of runoff (Fig. 2) and its annual variation, which was evaluated with the use of the coefficient of variation of the monthly runoff the coefficient of variation of the monthly runoff $Cv(Y_m)$.

We have to note that an increase in $Cv(Y_m)$ is accompanied by a pronounced increase in the proportion of the surface runoff and, accordingly, an increase in the proportion of the groundwater runoff $\frac{Q_g}{Q_a}$ (%):

$$\frac{Q_g}{Q_a} = (75.02 \pm 7.03) - (33.00 \pm 4.53)Cv(Y_m), \quad r = -0.96 \pm 0.04, \tag{13}$$

where $r \pm \delta_r$ is the correlation coefficient and the error of its determination, evaluated by (2). Also, an increase in the subsurface component of phreatic water contribution $\frac{Q_{g1}}{Q_g}$ (%) and a decrease in the contribution of confined water $\frac{Q_{g2}}{Q_g}$ (%) was observed, which may be due to the deterioration of the conditions of groundwater inflow from deeper horizons at a decrease in the total groundwater runoff:

$$\frac{Q_{g1}}{Q_g} = (43.25 \pm 18.44) + (25.73 \pm 11.88)Cv(Y_m), \quad r = 0.73 \pm 0.23, \tag{14}$$

Table 2. Proportions of the actual *f* and critical (at a significance level of 5%) values of Student Kr_S and Fisher Kr_F tests at the comparison of data on the sum of principal ions in phreatic and artesian groundwater in the drainage basins of Tom tributaries and the moduli of the total water flow (calculation of the actual values of Student and Fisher tests by formulas (3), (4); when $Kr(f)/Kr(5\%) > 1$, the homogeneity hypothesis is rejected with a significance level of 5%

The compared drainage basins		Criterion	The sum of principal ions		Modulus of total runoff
			phreatic water	artesian water	
Kirgizka	Ushaika	$Kr_S(f)/Kr_S(5\%)$	0.05	0.48	0.06
		$Kr_F(f)/Kr_F(5\%)$	0.40	1.09	0.28
Kirgizka	Basandaika	$Kr_S(f)/Kr_S(5\%)$	0.74	0.17	0.20
		$Kr_F(f)/Kr_F(5\%)$	0.79	1.11	0.44
Basandaika	Ushaika	$Kr_S(f)/Kr_S(5\%)$	0.70	0.79	0.28
		$Kr_F(f)/Kr_F(5\%)$	0.75	0.48	0.54
Poros	Kislovka	$Kr_S(f)/Kr_S(5\%)$	4.65	1.68	1.68
		$Kr_F(f)/Kr_F(5\%)$	0.57	0.60	0.92
Poros	Lebyazh'ya	$Kr_S(f)/Kr_S(5\%)$	1.40	0.39	2.45
		$Kr_F(f)/Kr_F(5\%)$	0.34	1.71	1.36
Lebyazh'ya	Kislovka	$Kr_S(f)/Kr_S(5\%)$	1.43	0.90	0.90
		$Kr_F(f)/Kr_F(5\%)$	0.73	0.93	0.64
(Ushaika–Basandaika)	(Kislovka–Lebyazh'ya)	$Kr_S(f)/Kr_S(5\%)$	–	–	6.21
		$Kr_F(f)/Kr_F(5\%)$	–	–	2.72

Table 3. Normal annual values of water balance elements for the drainage basins of the rivers of Bol'shaya Kirgizka, Ushaika, Basandaika, Poros, Kislovka, and Lebyazh'ya and the sum of principal ions in river water, groundwater, and atmospheric water (F is drainage area; Q_a is normal annual water discharge; $Cv(Y)$ is the coefficient of variation of monthly runoff; Q_g/Q_a is the subsurface component of the normal annual water discharge; Q_{g1}/Q_g and Q_{g2}/Q_g are the shares of phreatic and confined groundwater in the subsurface runoff; Y_g and Y_{sf} are the subsurface and surface components of the annual runoff depth, respectively; E_y and $E_{\geq 0}$ are the total evaporation over a year and a warm season, respectively; $(P-E)_{\geq 0}$ and $(P-E)_{<0}$ is the difference between atmospheric moistening and evaporation in the warm and cold seasons, respectively)

River – gage	F	Q_a	$Cv(Y)$	Q_g/Q_a	Q_{g1}/Q_g	Q_{g2}/Q_g	Y_g	Y_{sf}	E_y	$E_{\geq 0}$	$(P-E)_{\geq 0}$	$(P-E)_{<0}$
	km^2	m^3/s	–	%			mm/year					
Kirgizka R. – Kuzovlevo Settl.	825	5.14	1.32	36	61	39	70	126	395	366	40	156
Ushaika R. – Stepanovka Settl.	713	4.25	1.67	16	96	4	30	158	403	374	32	156
Basandaika R. – Basandaika Settl.	402	2.61	1.47	23	80	20	47	158	386	358	48	156
Poros R. – Zorkal'tsevo Settl.	316	0.45	1.31	30	85	15	13	32	546	517	–111	156
Kislovka R. – Timiryazevo Settl.	458	0.75	1.08	42	73	27	22	30	539	510	–104	156
Lebyazh'ya R. – Bezmenovo V.	1390	3.57	2.21	5	97	3	4	77	445	420	–48	129

$$\frac{Q_{g2}}{Q_g} = (56.75 \pm 18.44) - (25.73 \pm 11.88)\,Cv\,(Y_m), \quad (15)$$
$$r = -0.73 \pm 0.23.$$

Parallel to the decrease in $Cv(Y_m)$, a decrease in the groundwater component and the contribution of confined water, the sum of the principal ions in river water in winter and confined groundwater increases (Table 3).

This indicates to an inverse dependence of the total concentration of dissolved salts on the rate of water exchange, which, under the conditions under consideration (the excessive or normal moistening of the territory) is related with the share of groundwater flow $\frac{Q_g}{Q_a}$: the greater this share, the closer the interaction between different aquifers and surface water bodies.

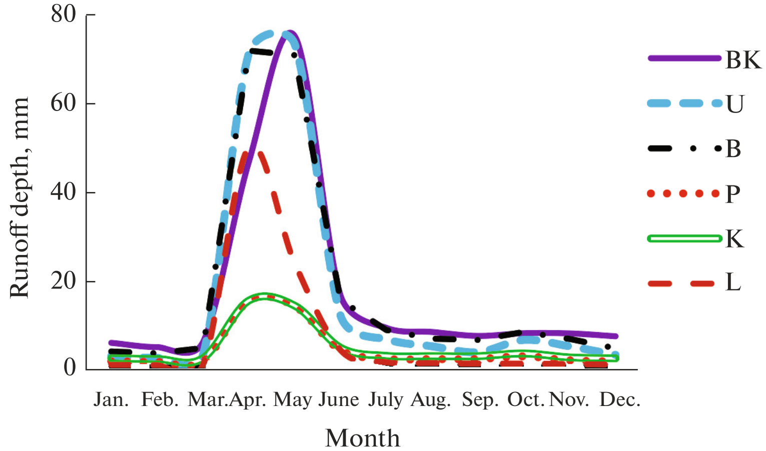


Fig. 2. Annual variations of the monthly runoff depth in the rivers of Kirgizka (Bol'shaya Kirgizka – BK), Ushaika (U), Basandaika (B), Poros (P), Kislovka (K), and Lebyazh'ya (L), on the average over a many-year period.

Conversely, at a decrease in $\frac{Q_g}{Q_a}$, the closeness of deep aquifers increases, as does the time of interaction between the water of those aquifers and rocks and, accordingly, increase the sum of principal ions in the artesian groundwater S_{g2}:

$$S_{g2} = (146.58 \pm 48.35) - (0.23 \pm 0.09)\frac{Q_g}{Q_a}, \quad (16)$$
$$r = -0.78 \pm 0.19,$$
$$S_{g2} = (402.21 \pm 62.31) + (85.46 \pm 40.16)Cv(Y_m), \quad (17)$$
$$r = 0.73 \pm 0.23.$$

An interesting feature was revealed in the structure of geochemical balance—the values of ΔG in (12) for the drainage basins of the left tributaries of the Tom (the Poros, Kislovka, and Lebyazh'ya) is much less than that for the right tributaries (the Kirgizka, Ushaika, and Basandaika), and positive values of ΔG were obtained for the surface runoff depth $Y_{sf} > 63$ mm/year and negative values of $(P–E)_{\geq 0}$ (Fig. 3; Table 3, 4).

The negative values of ΔG can be interpreted as the general predominance of the accumulation processes of substances arriving with atmospheric precipitation in the left-bank part of the Tom drainage basin. Conversely, the positive values of ΔG in the drainage basins of the rivers of Kirgizka, Ushaika, and Basandaika, may indicate to a greater role of the processes of rock leaching and dissolution against the background of significant replenishment of water reserves in the warm period, at which not only groundwater resources are supplemented, but the surface runoff is formed.

At the same time, it should be mentioned that several ore manifestations and deposits of solid minerals are located on the right-bank side of the Tom R. with the presence of rare earth elements (REE) in ground composition. No ore manifestations were found in the left northern part of the Tom drainage basin, but the presence of REE was found in groundwater and deposits that have formed in the process of groundwater deironing in the Ob–Tom interfluve (including the drainage basins of the Kislovka and Poros rivers) [7, 21, 23, 24, 36]. It can be supposed that a similar mechanism has been functioning in the previous geological periods, including periods with the hydrographic network different from the present one [18]. Because of this geochemical plumes have formed with centers in the northern part of the Kolyvan–Tomsk folded zone and, possibly, the northern part of the Kuznetskii Alatau.

The horizontal projections of these plumes are in general agreement with the conclusions made in the TPU regarding the regularities in the transformation of the mineral and chemical composition of bottom sediments in the rivers of the Northern and Southeastern Asia:

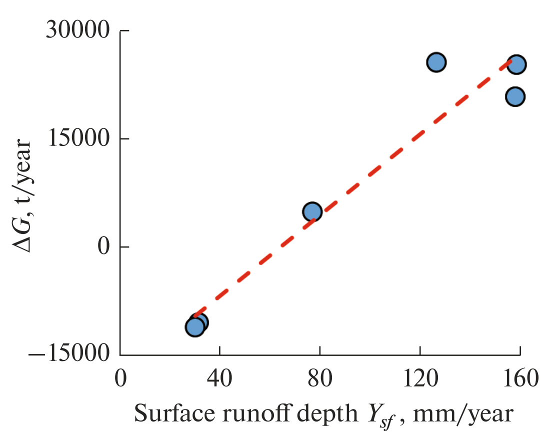


Fig. 3. Relationship between ΔG value and the surface runoff depth Y_{sf} in the drainage basins of the Tom tributaries in its lower reaches.

Table 4. Normal annual values of water balance elements for the drainage basins of the Kirgizka, Ushaika, Basandaika, Poros, Kislovka, and Lebyazh'ya rivers, t/year (G_r and G_{sn} are the input of dissolved salts into the drainage basin with rain and snowmelt water; $G_{Y\text{sum}}$, G_{Yg}, and G_{Ysf} is the total runoff of dissolved salts in the outlet section of the river, its subsurface and surface components; ΔG is the result of rock dissolution and leaching and matter accumulation in the drainage basin)

River – site	G_r	G_{sn}	$G_{Y\text{sum}}$	G_{Yg}	G_{Ysf}	ΔG
Kirgizka R. – Kuzovlevo Settl.	30380	3297	59345	29421	29923	25668
Ushaika R. – Stepanovka Settl.	26256	2849	54448	12111	42337	25343
Basandaika R. – Basandaika Settl.	14803	1606	37337	9386	27951	20927
Poros R. – Zorkal'tsevo Settl.	11636	1263	2635	2161	474	–10264
Kislovka R. – Timiryazevo Settl.	16865	1830	7851	3830	4021	–10845
Lebyazh'ya R. – Bezmenovo V.	46899	4624	56544	3202	53342	5021

(1) the main changes in the mineral composition of bottom sediments are due to an increase in the proportion of quartz from the sources to the mouths of rivers more than 11 km in length and a decrease in the contributions of the minerals for which the logarithm of the product of density and hardness is not greater than 1.27;

(2) river segments with conventionally homogeneous mineral composition of bottom sediments are shifted downstream relative to areas with conventionally homogeneous (or weakly changing at a long-time scale) chemical composition of river water by up to 100 km [31].

CONCLUSIONS

Data on six small rivers—tributaries of the Tom R. (the second largest tributary of the Ob R., Western Siberia) confirmed the well-known conclusions that a decrease in the rate of water exchange leads to an increase in the interaction time in the water–rock system and, accordingly, the total concentration of dissolved salts in groundwater [13, 39, 65].

For the first time for the segment of the lower reaches of the Tom R., it was shown that, first, the interrelation level of river, subsoil, and artesian waters can be evaluated with the use of the coefficient of variation $Cv(Y_m)$ of the monthly values of the runoff depth of small rivers, i.e., the greater $Cv(Y_m)$, the greater the "closeness" of the aquifers and the TDS of groundwater.

Second, in territories with a considerable replenishment of moisture reserves in the warm season of the year, in which both the subsurface and surface runoff is forming, the processes of rock leaching and dissolution dominate over the accumulation of salts entering the catchment area with atmospheric precipitation.

For the territories in which groundwater replenishment is mostly due to snow melting, the formation of groundwater chemistry is mostly due to the processes of matter input from outside; this should be taken into account in the designing of the zones of sanitary protection of groundwater intakes and the control of economic activity within groundwater recharge zones.

Third, by a system of geochemical, hydrological, and hydrogeological characteristics in the drainage area of the lower reaches of the Tom river (within the Tom oblast), taking into account the earlier studies [9, 11, 12, 30, 40], we can identify three regions by the TDS and chemistry of phreatic and artesian water and their interaction with river water:

(1) the right side of the Tom R. from the boundary between the Tomsk and Kemerovo oblasts to the water divide between the Ushaika and Kirgizka rivers (tentatively, the Irkutsk highway within the boundaries of Tomsk City);

(2) the right side north of the Kirgizka R. drainage basin (inclusive);

(3) the left side of the Tom River.

FUNDING

This study was supported by the Russian Foundation for Basic Research, project no. 18-55-80015, the RSCF, no. 23-27-00039 and under the Program of increasing the competitive advantage of the Tomsk Polytechnic University.

REFERENCES

1. Balobanenko, A.A., Geochemical features of groundwater for household and drinking purposes in the south of the West Siberian artesian basin, *Extended Abstract of Cand. Sci. (Geol.-Mineral.) Diss.*, Tomsk, Tomsk Polytechnic Univ., 2018, 22 p.
2. *Gidrogeologiya SSSR. T. 16. Zapadno-Sibirskaya ravnina (Tyumenskaya, Omskaya, Novosibirskaya i Tomskaya oblasti)* (Hydrogeology of the USSR. Vol. 16. The West Siberian Plain (Tyumen, Omsk, Novosibirsk and Tomsk regions)], Nudner, V.A. (Ed.), Moscow, Nedra Publ., 1970.
3. *Gidrogeologiya SSSR. T. 17. Kemerovskaya oblast i Altayskii krai* (Hydrogeology of the USSR. Vol. 17. Kemerovo region and Altai krai), Moscow, Nedra Publ., 1972.

4. Gudymovich, S.S., Rychkova, I.V., and Ryabchikova, E.D., *Geologicheskoe stroenie okrestnostei g. Tomska (territorii prokhozhdeniya geologicheskoi praktiki* (The Geological Structure of the Tomsk City Vicinity (Geological Field Practice Area), Tomsk, Tomsk Polytechnic University, 2009.
5. Grinevskii, S.O., *Gidrogeodinamicheskoe modelirovanie vzaimodeistviya podzemnykh i poverkhnostnykh vod* (Hydrogeodynamic Modeling of the Interaction between Groundwater and Surface Water), Moscow, Infra-M, 2019.
6. Guseva, N.V., The formation mechanisms of natural water chemical composition in various landscapes and climatic zones of orogenic areas in central Eurasia, *Extended Abstract of Doctoral Sci. (Geol.-Min.) Diss.*, Tomsk, Tomsk Polytechnic University, 2018, 43 p.
7. Domarenko, V.A., Savichev, O.G., Peregudina, E.V., Lepokurova, O.E., and Vil'gel'm, E.A., The material composition of bottom sediments of the Omutnaya River within the Tugan placer deposit (Tomsk region), *Razved. Okhr. Nedr*, 2020, no. 4, pp. 48–53.
8. Dutova, E.M., Vologdina, I.V., Pokrovskii, D.S., and Zamorovskaya, L.V., Changes in the hydrogeochemical conditions during the operation of an Academic deposit, *Izv. Tomsk. Politekh. Univ.*, 2008, vol. 312, no. 1, pp. 59–63.
9. Dutova, E.M. and Nalivaiko, N.G., Features of the chemical and microbiological composition of groundwater in the territory of the Tomsk City, *Izv. Vuz. Geol. Razved.*, 2011, no. 5, pp. 56–61.
10. Ermashova, N.A., Natural hydrogeochemical background of the upper hydrodynamic zone of the Middle Ob region as the basis for assessing its ecological state, *Obskoi Vestn.*,1999, no. 3–4, pp. 106–112.
11. Kolokolova, O.V., Groundwater geochemistry of the Tomsk water intake area, *Extended abstract of Cand. Sci. (Geol.-Mineral.) Diss.*, Tomsk, Tomsk Polytechnic Univ., 2003, 21 p.
12. Kolubaeva, Yu.V., Shvartsev, S.L., and Kopylova, Yu.G., Geochemistry of water in the northern part of the Kolyvan-Tomsk folded zone, *Geol. Razved.*, 2010, no. 2, pp. 50–58.
13. Krainov, S.R., Ryzhenko, B.N., and Shvets, V.M., *Geokhimiya podzemnykh vod. Teoreticheskie, prikladnye i ekologicheskie aspekty* (Groundwater Geochemistry. Theoretical, Applied and Ecological Aspects), Laverov, N.P., Ed., Moscow, Nauka, 2004.
14. Lepokurova, O.E., Ivanova, I.S., Shvartsev, S.L., Kolubaeva, Yu.V., and Nalivaiko, N.G., The chemical and microbiological composition of groundwater in decentralized water supply in the southern and central parts of the Tomsk region, *Izv. Tomsk. Politekhn. Univer. Inzhin. Geores.*, 2016, vol. 327, no. 5, pp. 29–41.
15. Lisetskii, V.N., Bryukhantsev, V.N., and Andreichenko, A.A., *Ulavlivanie i utilizatsiya osadkov vodopodgotovki na vodozaborakh g. Tomska* (Collection and Disposal of Water Treatment Sludge at Tomsk Water Intakes), Tomsk, NTL Pub., 2003.
16. L'gotin, V.A., Savichev, O.G., Makushin, Yu.V., and Kamneva, O.A., Long-term variability of groundwater chemistry in the Tomsk region, *Geograf. Prirod. Resur.*, 2012, no. 1, pp. 74–79.
17. L'gotin, V.A., Savichev, O.G., and Nigorozhenko, V.Ya., *Sostoyanie poverkhnostnykh vodnykh ob'ektov, vodokhozyaistvennykh sistem i sooruzhenii na territorii Tomskoi oblasti v 2000–2005 gg.* (The State of Surface Water Bodies, Water Management Systems and Structures in the Tomsk Region in 2000–2005), Tomsk, OAO Tomskgeomonitoring, AGRAF-PRESS, 2006, no. 88.
18. Maloletko, A.M., *Evolyutsiya rechnykh sistem Zapadnoi Sibiri v mezozoe i kainozoye* (The Evolution of River Systems in Western Siberia in Mesozoic and Cenozoic), Tomsk, Tomsk State Univ. Publ., 2008.
19. Manankov, A.V., and Parnachev, V.P., Geoecological aspects of the state of surface water and groundwater in Tomsk, *Obskoi Vest.*, 1999, nos. 1–2, pp. 105–116.
20. *Nauchno-prikladnoi spravochnik po klimatu SSSR. Seriya 3. Mnogoletnie dannye. Chasti 1–6, Vyp. 20. Tomskaya, Novosibirskaya, Kemerovskaya oblasti, Altaiskii krai* (Scientific and Applied Reference Book on the |USSR Climate. Series 3. Perennial data. Parts 1–6, vol. 20, Tomsk, Novosibirsk, Kemerovo regions, Altai Territory), St. Petersburg, Gidrometeoizdat, 1993.
21. *Nedra Rossii* (Bowels of Russia), vol. 1, *Mineraly* (Minerals), Mezhelovskii, N.V. and Smyslov, A. A., Eds., St. Petersburg, Moscow, Mining Institute, Mezhregion. Tsentr Geol. Kartogr., 2001.
22. Pasechnik, E.Yu., *Ekologo-geokhimicheskoe sostoyanie prirodnykh sred territorii goroda Tomska* (Ecological and Geochemical State of Natural Environment in Tomsk City), *Vest. Tomsk. Gos. Univ*. 2008, vol. 306, pp. 149–154.
23. Pasechnik, E.Yu., Guseva, N.V., Savichev, O.G., L'gotin, V.A., et al., The microelement composition of groundwater in the upper hydrogeodynamic zone in the Upper Ob basin as a factor in the formation of their ecological and geochemical state, *Bull. Tomsk Polytech. Univ. Geo-Resour. Eng.*, 2020, vol. 331, no. 4, pp. 54–63.
https://doi.org/10.18799/24131830/2020/4/2593
24. Pasechnik, E.Yu., Savichev, O.G., Domarenko, V.A., and Vladimirova, O.N., Rare earth elements in the surface water and groundwater of the upper hydrogeodynamic zone in the basin of the Upper and Middle Ob (Western Siberia), *Izv. Irkut. Gos. Univ. Ser.: Nauki o Zemle*, 2020, vol. 32, pp. 113–127.
25. Pokrovskii, D.S. and Kuzevanov, K.I., Hydrogeological problems of the construction development of the Tomsk territory, *Obskoi Vestn.*, 1999, nos. 1–2, pp. 96–104.
26. *Posobie po opredeleniyu raschetnykh gidrologicheskikh kharakteristik* (A Guide to Determining the Estimated Hydrological Characteristics). Leningrad, Gidrometeoizdat, 1984.
27. Ratkovich, D.Ya., *Aktual'nye problemy vodoobespecheniya* (Actual Problems of Water Supply), Moscow: Nauka, 2003.
28. Rogov, G.M., Popov, V.K., and Osipova, E.Yu., *Problemy ispol'zovaniya prirodnykh vod basseina reki Tomi dlya khozyaistvenno-pit'evogo vodosnabzheniya* (Problems of Using Natural Water of the Tom River Basin for Drinking Water Supply). Tomsk, Tomsk State Architecture and Construction University Publ., 2003.

29. *Regional'naya elektronnaya gidrograficheskaya set' dlya arkticheskogo regiona* (A Regional Electronic Hydrographic Data Network for the Arctic Region). Available at: http://www.r-arcticnet.sr.unh.edu/v4.0/index.html
30. Savichev, O.G., *Vodnye resursy Tomskoi oblasti* (Water Resources in the Tomsk Region), Tomsk, Tomsk Polytechnic University, 2010.
31. Savichev, O.G., Domarenko, V.A., Peregudina, E.V., and Lepokurova, O.E., Transformation of the mineral composition of bottom sediments from sources to river mouths, *Izv. Tomsk. Politekhn. Univer. Inzhin. Geores.*, 2018, vol. 329, no. 7, pp. 43–56.
32. Savichev, O.G. and Ivanov, A.O., Atmospheric precipitation in the Middle Ob River basin and its effect on the hydrochemical flow of rivers, *Izv. RAN. Ser. Geogr.*, 2010, no. 1, pp. 63–70.
33. *Sostoyanie geologicheskoi sredy (nedr) na territorii Sibirskogo federal'nogo okruga v 2017 g. Informatsionnyi byulleten'* (The Condition of the Geological Environment (Bowels) in the Siberian Federal District in 2017. News Bulletin), Tomsk, Branch "Sibirskii regional'nyi tsentr GMSN," FGBU "Gidrospetsgeologiya," 2018, vol. 14.
34. *SP 33-1010-2003. Opredelenie osnovnykh raschetnykh gidrologicheskikh kharakteristik* (Determination of the Main Calculated Hydrological Characteristics), Moscow, Gosstroy of Russia, 2004. URL: http://sniprf.ru/sp33-101-2003.
35. *SP 131.13330.2018. Stroitel'naya klimatologiya* (Building Climatology), Moscow: Standartinform, 2019. URL: http://base.garant.ru/72239302.
36. *Tsirkon-il'menitovye rossypnye mestorozhdeniya kak potentsialnyi istochnik razvitiya Zapadno-Sibirskogo regiona* (Zircon-Ilmenite Placer Deposits as Potential Development Source of the West Siberian Region), Tribunskii, E.N. and Parovinchak, M.S., Eds., Kemerovo, OOO Sars, 2001.
37. Cherepanskii, M.M., Regional hydrogeological forecasts of the effect of groundwater withdrawal on river flow, *Extended abstract Doctoral (Geol.-Min.) Diss*. Moscow, NIA-Priroda, 2007, 49 p.
38. Yankovich, E.P., Kopylova, Yu.G., and Guseva, N.V., The prevalence of geochemical types of groundwater in the Ob-Tomsk interfluve, *Politematicheskii setevoi elektronnyi zhurnal Kubanskogo agrarnogo universiteta* (Polytechnical Web Journal of the Kuban Agrarian Univercity), 2015, no. 107, vol. 03. URL: http://ej.kubargo.ru/2015/03/pdf/96.pdf.
39. Shvartsev, S.L., Geochemistry of fresh groundwater in the main landscape zones of the Earth, *Geochem. Int.*, 2008, vol. 46, no. 13, p. 1285–1398.
40. Shvartsev, S.L., Serebrennikova, O.V., Zdvizhkov, M.A., Savichev, O.G., and Naimushina O.S., Geochemistry of wetland waters from the lower Tom basin, Southern Tomsk oblast, *Geochem. Int.*, 2012, vol. 50, no. 4, pp. 367–380. https://doi.org/10.1134/S0016702912040076

Translated by G. Krichevets