Effect of coal mining activities on the surface water quality

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Abstract

The hydrological and hydrochemical characteristics of Tugnui river basin, affected by coal mining activity were obtained. Water turbidity, concentrations of major ions, nutrients and trace elements have changed dramatically. During low water period the effect of mining has been traced over 24 km downstream, increased concentrations of toxic substances were found mainly in dissolved forms. The concentrations decreased in the lower part of the basin owing to dilution and complexation with organic matter, since the hydrochemical transformation was insignificant.

Keywords: coal mining, Baikal, water chemistry, trace elements, pollution, sediments

Introduction

Coal mining leads to a substantial change in water quality of rivers and lakes. Sewage and drainage water coming from the mining area contains high concentrations of toxic substances, which at low water period can lead to degradation of aquatic ecosystems for many kilometres downstream. The flow transports dissolved forms, and pollutants in suspended sediments and bedload. Suspended particles could accumulate in geochemical barrier zones, creating sources of contamination. These accumulative formations could be mobilized during substantial changes in hydrochemical regime or could preserve the contaminants for many years (Thorslund et al., 2016).

Tailing dumps and sedimentation ponds, where suspended particles enriched with toxic substances are concentrated in large amounts, pose a substantial danger. After the end of exploitation and dewatering, the bottom sediments of such water bodies are eroded, resulting in catastrophic discharges of toxic substances (Chalov et al., 2015).

The assessment of spatial scale of mining impact and the intensity of chemical transformation of river waters is often difficult due to insufficient monitoring data and a limited number of monitoring stations. The solution to this problem requires complex hydrological and hydrochemical studies.

This paper shows the results of research in the Tugnui river basin in the southeastern part of the Republic of Buryatia in august 2018. The environment in the upper part of the basin territory is strongly affected because of the Tugnui coal mine – one of the largest in Baikal region. The aims of the study are: (i) to characterize pollutant fluxes formation and transport from the mine into surface waters; (ii) to evaluate major physicochemical mechanisms, governing the attenuation and fate of pollutants downstream the mine.

The study of Tugnui water quality was carried out during summer low-water period. During this period all streams of the area are characterized by a small variability of hydrochemical characteristics. Wastewater discharges from the mining areas could be easily detected in such conditions, as their chemical composition is very different from that of river waters. The results of geochemical survey showed, that the main sources of pollution in Tugnui basin are: atmospheric dispersion of pollutants from thermal power plant, input of pollutants with wastewater, their leaching from waste rocks and mine tailings and sewage of local miner's village.

Study area

The basin is located in the southeastern part of Buryatia and is a part of the Selenga River basin (fig. 1). This territory is of great importance in Republic economy owing to substantial contribution in industrial and agricultural production. In the upper reaches, between the Tugnui River and its right tributary, the Kusota River, the largest in the Baikal region Tugnui coal deposit is situated. Its capacity is about 12.5 million tons of coal per year. The mine has been functioning since 1981. The mining complex also includes the Nikolsky open pit mine, which began to be developed in 2015. A coal processing plant is located in the northern part of Tugnui coal mine. Both excavation areas are equipped with a system of water-lowering wells and sump for accumulation of drainage water, which are then discharged into the Tugnui River. The volume of drainage water discharge from the Tugnui mine is 11860 thousand m^3/year. Municipal sewage (516 thousand m^3/year) from the coal processing plant and the nearby Sagan-Nur village enter the treatment plant, and then discharged into the sewage pond. At the same time, part of the sewage falls into the Olon-Sibir salt lake, which is located 4 km below the treatment plant. Downstream the Nikolsky mine industrial activities are absent. The rest of the valley territory is a valuable agricultural land, where the waters of the Tugnui River and the lakes are used for irrigation and as a source of water for livestock. Banks of the sedimentation pound on the Tugnui River (at station C16, fig.1) and the Olon-Shibir Lake (C24) are used as recreation centers and for fishery. These lakes, middle and lower courses of the Tugui River belong to the 2nd category of water bodies, intended for fisheries.

Materials and methods

Field studies in the basin took place during the summer low water period in 2018. A network of 29 representative stations including gauging station on the upper reaches of the Tugnui river (point C 12) was created. The main water chemical characteristics, such as pH, conductivity (EC), alkalinity

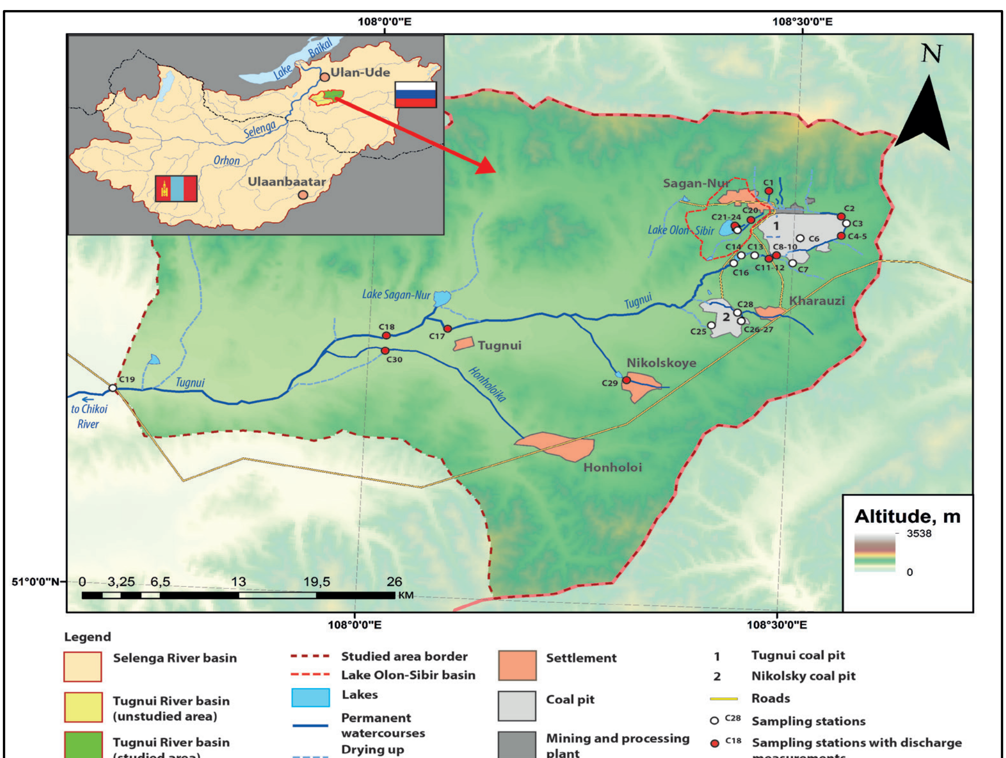

Figure 1 *Map of the studied part of Tugnui River basin*

(Alk), total organic carbon (TOC), main ion concentrations, and concentrations of nutrients and trace elements (TEs) were determined. Water discharges and turbidity were also measured. Solid and liquid fractions of TEs were separated by filtering of water sample through 0.45 μm Millipore membrane filter. The TE content was determined at the All-Russia Research Institute of Mineral Raw Materials by mass-spectral and atomic-emission methods with inductively coupled plasma (ICP-MS, ICP-AES). Ba, Cr, Pb, Mn, Fe, Co, Ni, Cu, Zn, As, Sr, Mo, Cd, Sn, Sb, W were detected as the most common and widespread TEs in this mining area. The hydrochemical characteristics were assessed using:

- solid–solution ratio Kd $=C_s/C_d$ (μg/L), where C_s; C_d (μg/L) is a content of an element in suspended sediments and in the dissolved phase, respectively;
- enrichment coefficient $EF_i = C_T/C_{Ref}$, where C_T, C_{Ref} (μg/L) is a content of the i-th trace element (TE) in suspended form in the Tugnui River and in the rivers of the Russian part of Selenga basin (Environmental … 2019), respectively;
- total pollution index $Zc = \Sigma EF_i - (n - 1)$, where n is the number of elements with $EF_i > 1$;
- hazard coefficient $K_0 = C_i/MPC$, where C_i (μg/L) is a content of the i-th TE in dissolved phase and MPC is its maximum permissible concentration according to (GN 2.1.5.2280-07; Prikaz … 2018).

Hydrology

During the survey period, the predominant source of feeding the rivers was groundwater, no precipitation was observed, which determines the hydrochemical conditions as stationary. Many watercourses of Tugnui basin flowing through Nikolsky pit were dried up because of the lack of precipitation. The maximum water discharge in Tugnui river was observed downstream the effluent of wastewater from the pit area (at station C8 – 0.18 m^3/s) and at the station in Tugnui village (C18 – 0.12 m^3/s). In August the erosion processes of Tugnui river banks are not pronounced. The main sediment flow is associated with channel erosion and the input of fine particles during coal mining. The obtained information on turbidity allows us to divide the Tugnui river basin into 4 areas: background (C1-C5); river water downstream coal mining (C6-C15); river water downstream treatment facility (C16-C19) and sewage (C20-C24). Results of grain-size analysis are represented on a figure 2.

Upper reaches of the Tougnui River are characterized by weak turbidity. The low transport capacity of the stream leads to the mobilization of only the smallest particles (d 0.0005-0.05 mm) with turbidity values of 5–20 mg/L. The river bed experiences vertical deformations, and the channel processes are

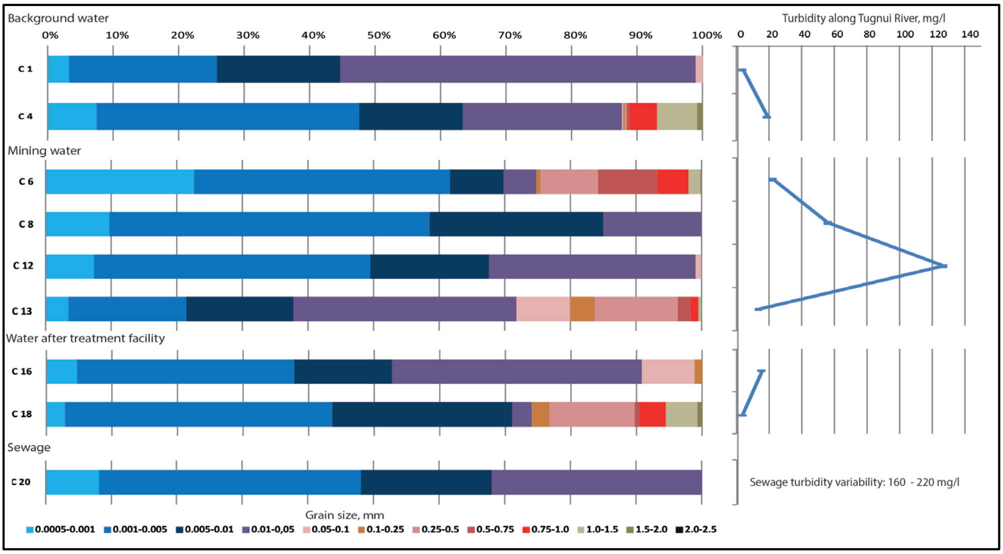

Figure 2 Grain-size distribution and turbidity values in Tugnui river basin

poorly developed. Downstream, within the coal pit, the river flows through the system of river-taps and sumps. The appearance of particles is connected both with the transfer of material from the mining area and with the vertical and horizontal channel deformations. Sediment composition in mine watercourses is mainly affected by flushing of waste rock dumps and by wastewater discharges. The last forms more than 80% of river flow (0.1 m^3/s at C12 station). Turbidity increases to120 mg/L. During wastewater discharge it reaches 300 mg/L at sampling station C12 which substantially exceed the MPC of turbidity equal 35 mg/L. From 75 to 100% of suspended particles belongs to silt and clay particles (<0.05 mm). The effect of the small fraction is expressed in clogging of river channels and prevention of benthic organism's growth. Contaminated water comes to sedimentation pound between Tugnui and Nikolsky mines. Substantial volumes of sediments accumulate in it, but the finest particles are transported downstream. The rate of fine particles (d <0.05 mm) downstream is quite high (70-75%) which provides turbidity 15-20 mg/L. According to Malinovsky et al. (2001), this fraction mostly determines pollutant's migration. TEs are concentrated predominantly in particles 0.001-0.05 mm and Zn and Cr migrate mainly in fractions of 0.0005-0.001 mm.

Table 1 *General hydrochemical characteristics and TE concentrations in Tugnui river basin*

Parameters and their units		MPC (Prikaz … 2018)	Background water (n*=5)	Water downstream coal mining (n =10)	Water downstream treatment plant (n=6)	Sewage of coal mine (n=5)
pH		-	7.8-8.2	8.5-9.3	8.1-8.3	8.3-8.5
EC**	µS/cm	-	175±25	910±140	860±410	570±40
Cl-	mg/L	-	1±0.4	4.4±1.9	22±20	40±10
SO_4^{2-}	mg/L	-	22±6.5	230±90	90±65	56±30
Alk	mg/L	-	120±7.5	280±30	530±280	277±4
Ca^{2+}	mg/L	-	25±1.5	65±32	60±20	85±4
Mg^{2+}	mg/L	-	6.1±0.5	23±3.5	41±25	23±1.5
Na^+	mg/L	-	7.7±2.6	100±9.8	110±74	85±6.8
K^+	mg/L	-	0.5±0.1	5±2.7	3.1±1.5	2.6±1.8
TOC	mgC/L	-	8.2±0.5	6.3±2.5	11.7±1.4	17.3±2.9
P_{tot}	µg/L	-	18±6	12±2	52±27	300±420
P-PO_4^{3-}	µg/L	-	16±8	8±3	37±25	270±260
Si	mg/L	-	8±0.5	4±2	7±3.5	310±500
Al $_{(iv)}$	µg/L	40	24±2.5	26.2±8.3	62±30	51.1***
As $_{(iii)}$	µg/L	50	0.05***	0.05*	0.05***	20.8***
Fe $_{(iv)}$	µg/L	100	35±10	48±40	80±65	41±30
Ba $_{(iv)}$	µg/L	740	15.5±2.7	53±15	35±12	51±17
Zn $_{(iii)}$	µg/L	10	5±0.5	10.3±7	39±70	8.3±2.3
Sr $_{(iii)}$	µg/L	400	236±80	3195±1520	1377±517	2904±1515
Mo $_{(ii)}$	µg/L	1	9±4.3	58±28	9.1±9	63±21
U $_{(ii)}$	µg/L	-	4±2.2	9.8±3	9.1±2.3	16±3.3
V $_{(iii)}$	µg/L	1	0.15*	0.15***	1.6*	6.4***
Mn $_{(iv)}$	µg/L	10	4±3.3	18.3±15	15.6*	3.1±2.6
Co $_{(iii)}$	µg/L	10	0.08±0.07	1±0.7	0.27±0.09	0.3±0.07
Ni $_{(iii)}$	µg/L	10	0.25***	6.4±4.3	1.2***	35***
Cu $_{(iii)}$	µg/L	1	1.1±1	0.7±0.8	2.4***	2.9±1.1
Cd $_{(ii)}$	µg/L	5	0.01***	0.08±0.07	0.01***	0.1±0.07
W $_{(iii)}$	µg/L	0,8	0.01***	0.03±0.03	0.041***	1.5±0.5
Pb $_{(ii)}$	µg/L	6	0.46±0.06	0.5±0.4	1.1±0.8	0.5±0.2
Sb $_{(iii)}$	µg/L	-	0.01***	0.4±0.5	0.12±0.08	0.3±0.1
Cr $_{(iii)}$	µg/L	70	1.1±1	1.9±2	2.5±1.4	4.3±1.5

Note. MPCs are given for dissolved form of TEs; *n – number of sampling stations; **EC – electrical conductivity, ***only single measurement; (iii) –hazard class of a TE.

General water chemistry

The study of chemical characteristics of surface waters in the Tugnui river basin is important as they allow understanding migration processes of such contaminating components as TEs (Table 1). Water of background areas is of hydrocarbonate-calcium type with mineralization 150–200 mg/L; pH 8–8.5. The differences in mineralization and content of the main water ions in background areas are small and related to the composition of the rocks prevailing in river basins and the relief features. High content of organic matter is caused by swamps that are situated on riversides. Increased Si concentrations are caused mainly by underground sources of water during low water period.

The water chemistry of inner mining water bodies and watercourses downstream the mine is similar. It belongs to hydrocarbonate type with alkaline pH values 8.5-9.3 and high mineralization (up to 1000 mg/L). Increased concentrations of SO_4^{2-} (up to 340 mg/L) and Na+ (up to 100 mg/L), which are 50-100 times higher than background, were found. These ions are leached from the coal, and due to explosion operations (NO_3- >50 mg/L).The lower part of Tugnui River basin (stations C16-C19) has hydrocarbonate–sodium waters due to mining influence and evaporation of river waters. Mineralization decreases because of dilution of contaminated waters. Total phosphorous concentration Ptot inside mining area is low. More than 80% of P is in mineral form. After water treatment facilities the content of phosphorous increases up to 37 μg/L. Organic forms of phosphorous dominate in these conditions due to wash out of organic matter from farms and fields.

Sewage water in the basin of Lake Olon-Sibir contain high concentrations of nutrients. Total phosphorous concentration reaches 300 μg/L, P-PO_4 share is 50%. The lake water is characterized by sodium type with increased content of Cl- that possibly comes from sewage water and underground sources. Lake Olon-Sibir has high content of P-PO_4 – 780 μg/L(90% of P_{tot}). Sewage pound, which stores contaminated water from Sagan-Nur has total phosphorous concentration up to 480 μg/L with very low content of P-PO_4 (<20%). High water temperature, nutrient supply and high content of organic matter (>19 mg/L) can cause an eutrophication of this water body.

The background concentrations of the main ions and TEs in the undisturbed parts of the basin do not exceed sanitary - hygienic and fishery MPCs (GN 2.1.5.2280-07; Prikaz … 2016), except for Mo and Cu (K0 = 9; 1.1). In the confluence of wastewater from the coal mine, the sanitary and hygienic MPCs are exceeded for Mo (K_0 = 1.2) and fishery MPCs – for Zn, Sr, Mn (K_0 = 1.1-8) and Mo (K_0 = 58). The waters downstream the mining area are also characterized by exceeding the fishery MPCs for Al, Zn, Sr, Mo, V, Mn, Cu (K_0 = 1.6-9.1). The fishery MPCs for Mo (K_0 = 60), Al, Sr, V, Cu, W (K_0 = 1.3-7.3) are also strongly exceeded in sewage. During the expedition near the treatment facilities and downstream dead fish was observed. In the closing section (station C19), values of hazard coefficient K_0 decrease to 1.5-2 as a result of dilution.

Forms of trace elements

The basin of the Tugnui River is distinguished by increased background concentrations of TEs in water (TDS) and in suspension (TSS) due to its complex geological structure. In comparison with the average TDS concentrations of TEs in world rivers (Gaillardet et al., 2003), the background content of Zn, Sr, Mo, U is increased. In the upper part of Tugnui basin TEs concentrations are determined by groundwater flow through fractures in the rocks, leaching of dumps, and also with atmospheric aerosols that come from settlement and coal producing plant.

To study the variability of TEs in dissolved phase, a correlation matrix (n=21, r>0.55) was calculated and two groups of elements were distinguished: Sr, Ba, U, Mo, Co, Ni and Fe, Al, Zn, V, Cr. Mn, Pb, Cu, Sb displayed a weak correlation with other metals (fig. 3).

All groups of elements have low concentrations in upper reach of the Tugnui River, which slowly increase downstream due to TEs washout from mining dumps and infrastructure operations in mining area. High enrichment factor was estimated for Co (EF_{water}: 500) and for Sb, Cd, Ni, Mo, Mn, Cu (EF_{water} 8-1,5). The intensity of sorption processes could also increase inside mining zone due to inflow of clay fraction and

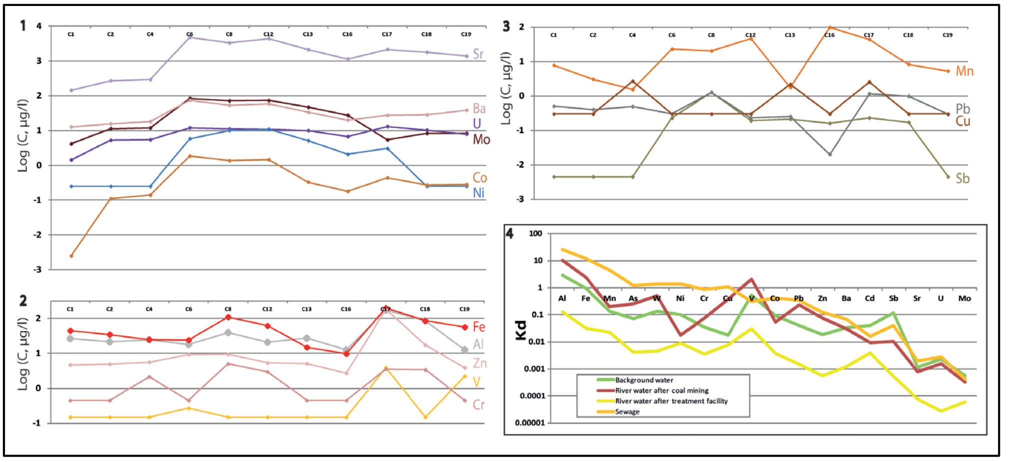

Figure 3 Trace metal distribution along the Tugnui river (1-3) and the ratio of suspended and dissolved forms of metals (Kd)(4)

dust, washed out from roads. Downstream, sedimentation pounds decrease the sediments concentration, dilution changes pH conditions (from 9 to 8), and decreases the TSS migration. Downstream the treatment plant a large part of other TEs tied with organic matter (TOC >11 mg C/l). This also causes the decrease of TE concentrations. Second group of elements has an upraise of concentrations close to Tugnui village in river lower reach. This is governed mainly by sewage inflow and pollution with TEs, washed out from the road.

The solid–solution partitioning of major and trace elements was quantified using the distribution coefficient *Kd* (fig. 3). Kd depends upon the abundance and speciation of elements in materials. Increased *Kd* values reveal that elements have high affinity for solid phases, while elements with low *Kd* values are more easily weathered, removed in soil solution and/or groundwater and transported in dissolved phases in the river (Ollivier et al., 2011). For the study area, the variability of Kd for elements in background, waste and transformed waters is rather large, but the main part of TEs is transported in dissolved form because of weak sediment flow. This situation can threat the ecosystems below mining area because the dissolved forms of TEs are the most bioavaliable. Local concentrations of TEs exceed the average global TEs values in TSS, with the exception of Ni and Cr. The multi-elemental pollution for contaminated waters is moderately dangerous (Zc 21-19). Concentrations of suspended V, Mn, Co, Ni, Cu, Zn, Mo, Cd, W, Pb exceed background concentrations (EF_{susp}: 6.37-1.09).

Analysis of TE migration in Tugnui river showed the predominance of suspended form in upper reach and in mining area for Al (>60%), V (>50%), Fe (40-50%). From 10 to 30% of Cr, Co, Cu, As, W, Pb is also in suspended form, but only upstream the treatment facilities. Sr, Mo, U migrate only in dissolved form. Using the data on the water consumption and concentrations of TEs, the share between the dissolved and suspended forms of element's flow was obtained. TEs are predominantly transported in dissolved form. The maximum intensity of transport in the solution was observed for Sr (42 mg/day), Mo (700 μg/day), Fe (600 μg/day), Mn (500 μg/day), Ba (400 μg/day). Aluminium (4 mg/day) and iron (2 mg/day) dominate in the suspended form.

Analysis of TEs in dissolved and suspended forms showed the exceptional role of mining water for the area. The influence of this factor can be traced for more than 24 km downstream and leads to the accumulation of toxic substances in bottom sediments mainly in artificial channel below mining and in sedimentation pound. The thickness of bottom sediments there exceeds 1.2 m.

Environmental impact

Coal mining has a strong effect on the Tugnui river basin, but it is relatively small throughout the Selenga River Basin. The average annual water discharge at the mouth of the Tugnui River is about 20 m^3/s. Pollutants are diluted by 2 times at the confluence of Tugnui into the Sukhara River, and even more substantially at the confluence of the Sukhara and Khilok River (its average water discharge is 120 m^3/s).

In the period of increased water flow in the upper reaches of the Tugnui River intensive discharge of drainage waters from the quarry area and activation of the migration of TEs downstream were observed and in the lower reaches of the river, increased concentrations of Fe, Pb, Zn, Co, V, Ni, Cr, Mo in water and suspended sediments were determined (Environmental … 2019). During the low water period the effect was traced in 20-30 km downstream. This time, most of the suspended pollutants accumulated in the upper and middle reaches of the Tugui River.

The negative effect of coal development on the Tugnui River can be reduced by upgrading the mine wastewater drainage system and by construction of another sedimentation pond downstream the treatment plant of the Nikolsky pit. This will provide additional purification of waters discharged from both quarries, especially when the development of the Nikolsky mine reaches its full capacity. Another effective measure would be the construction of a dam between the Olon-Shibir lake and the ditch into which the sewage of the Sagan-Nur village and the mining and enrichment plant is discharged. This dam will substantially reduce the flow of sewage into the lake. It is also important to create an effective system of hydrochemical monitoring in the section below the confluence of the Tugnui River with wastewater from the Nikolsky field.

Conclusions

Anthropogenic (industrial and agricultural) activities exert a strong effect on water quality in Tugnui River basin. Tugnui mining complex influence could be found in more than 24 km downstream. Water quality of the Olon-Sibir lake worsens due to sewage flow from non-effective water treatment systems.

Trace elements Ba, Cr, Pb, Mn, Fe, Co, Ni, Cu, Zn, As, Sr, Mo, Cd, Sn, Sb, W in waters of the Tugnui River have increased concentrations in comparison with other rivers of the Selenga basin.

Our study showed that the main source of TEs in the basin is mining activities and the concentration of elements decreases substantially in the sedimentation pond owing to sorption and organic complexation processes.

During low water period main part (45-50% in upper reach and 70-100% in lower reach) of TEs migrates in dissolved form. The rates of migration are high for Sr, Mo, Fe, Mn, Ba in TDS and for Al, Fe in TSS form. Sediments downstream mining area are largely represented by silt and clay fractions (<0.05 mm), which are the most chemically active. During high water period this particles could significantly increase migration of TEs in solid phase.

The major agent of water pollution in the area is sewage discharge from local settlements and coal production plant. They cause upraise in organic (in 2-5 times) and nutrient (in 100 times) flows. These conditions promote eutrophication of local freshwater lakes and sewage reservoirs.

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