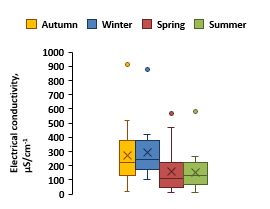
**Supplementary Material**

|  |  |
| --- | --- |
|  |  |
| **(a)** | **(b)** |
|  |  |
| **(c)** | **(d)** |

**Figure S1.** Box plot of median and IQR range (with outlies as dots) of electrical conductivity **(a)** in rivers; **(b)** in lakes; and DIC concentrations in the waters **(c)** in rivers; **(d)** in lakes (averaged across seasons)



**Figure S2.** Boxplots (median and IQR range) of specific conductivity during different seasons (lakes and rivers combined together)

|  |  |
| --- | --- |
|  |  |
| **(a)** | **(b)** |
|  |  |
| **(c)** |  |

**Figure S3.** Plots of DIC concentration (mg/L-1) as a function of specific conductivity in **(a)** large rivers; **(b)** small rivers; **(c)** and lakes.

**Figure S4.** The relationship between pCO2 and oxygen saturation degree for lakes and rivers of the Tyva region (all seasons together).

**(a)**

**(b)**

**Figure S5.** The relationship between **(a)** pCO2 and **(b)** fCO2 and thermokarst lakes water surface area of the Tyva region.

**(a)**

**(b)**

**Figure S6.** The relationship between **(a)** pCO2 and **(b)** fCO2 in river watershed surface of the Tyva region (all seasons together).

**Table S1.** Pearson correlation coefficients between major hydrochemical and microbiological parameters of the water column, including pH, O2, S.C., DOC, DIC and optical parameters of DOM reflecting DOM quality. Sarea, S.C., and TBC represent area of lake surface or river watershed, Specific Conductivity, and Total Bacterial Count, respectively.

Large rivers

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | E.C. | Twater | pH | O2 | pCO2 | TBC | DIC | DOC | SUVA254 | E2:E3 | E254:E436 | SR | fCO2 |
| Sarea | 0.05 | 0.28 | 0.04 | -0.11 | 0.18 | 0.27 | 0.12 | 0.80 | 0.14 | -0.23 | 0.55 | -0.47 | 0.08 |
| S.C. |  | -0.31 | 0.80 | 0.54 | -0.05 | -0.17 | 0.96 | -0.29 | -0.88 | 0.53 | -0.64 | 0.35 | 0.85 |
| Twater |  |  | -0.50 | -0.83 | 0.64 | 0.84 | -0.09 | 0.49 | 0.29 | -0.81 | 0.57 | -0.52 | -0.39 |
| pH |  |  |  | 0.66 | -0.41 | -0.22 | 0.73 | -0.42 | -0.74 | 0.78 | -0.69 | 0.52 | 0.64 |
| O2 |  |  |  |  | -0.47 | -0.77 | 0.31 | -0.44 | -0.48 | 0.78 | -0.60 | 0.78 | 0.61 |
| pCO2 |  |  |  |  |  | 0.29 | 0.06 | 0.15 | -0.02 | -0.69 | 0.22 | -0.37 | -0.01 |
| TBC |  |  |  |  |  |  | 0.10 | 0.41 | 0.09 | -0.60 | 0.38 | -0.57 | -0.41 |
| DIC |  |  |  |  |  |  |  | -0.20 | -0.87 | 0.37 | -0.55 | 0.15 | 0.72 |
| DOC |  |  |  |  |  |  |  |  | 0.54 | -0.52 | 0.90 | -0.64 | -0.16 |
| SUVA254 |  |  |  |  |  |  |  |  |  | -0.43 | 0.82 | -0.35 | -0.55 |
| E2:E3 |  |  |  |  |  |  |  |  |  |  | -0.67 | 0.66 | 0.54 |
| E254:E436 |  |  |  |  |  |  |  |  |  |  |  | -0.60 | -0.39 |
| SR |  |  |  |  |  |  |  |  |  |  |  |  | 0.44 |

Small rivers

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | E.C. | Twater | pH | O2 | pCO2 | TBC | DIC | DOC | SUVA254 | E2:E3 | E254:E436 | SR | fCO2 |
| Sarea | 0.54 | 0.38 | 0.52 | -0.01 | -0.53 | -0.43 | 0.63 | -0.20 | -0.52 | -0.03 | -0.30 | -0.01 | -0.58 |
| S.C. |  | 0.01 | 0.77 | 0.54 | -0.05 | -0.01 | 0.81 | -0.16 | -0.68 | 0.31 | -0.46 | 0.33 | -0.16 |
| Twater |  |  | -0.24 | -0.66 | -0.28 | -0.54 | 0.27 | -0.14 | 0.03 | -0.71 | 0.04 | -0.49 | -0.45 |
| pH |  |  |  | 0.67 | -0.32 | -0.13 | 0.57 | -0.04 | -0.83 | 0.46 | -0.44 | 0.35 | -0.22 |
| O2 |  |  |  |  | -0.02 | 0.30 | 0.02 | -0.01 | -0.49 | 0.71 | -0.32 | 0.50 | 0.04 |
| pCO2 |  |  |  |  |  | 0.21 | -0.11 | -0.38 | 0.27 | 0.32 | -0.27 | 0.49 | 0.94 |
| TBC |  |  |  |  |  |  | -0.10 | 0.30 | 0.31 | 0.23 | 0.23 | -0.07 | 0.17 |
| DIC |  |  |  |  |  |  |  | -0.06 | -0.50 | -0.04 | -0.28 | 0.00 | -0.22 |
| DOC |  |  |  |  |  |  |  |  | 0.42 | -0.16 | 0.89 | -0.59 | -0.28 |
| SUVA254 |  |  |  |  |  |  |  |  |  | -0.32 | 0.71 | -0.54 | 0.24 |
| E2:E3 |  |  |  |  |  |  |  |  |  |  | -0.38 | 0.73 | 0.40 |
| E254:E436 |  |  |  |  |  |  |  |  |  |  |  | -0.68 | -0.22 |
| SR |  |  |  |  |  |  |  |  |  |  |  |  | 0.51 |

Freshwater lakes

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | E.C. | Twater | pH | O2 | pCO2 | TBC | DIC | DOC | SUVA254 | E2:E3 | E254:E436 | SR | fCO2 |
| Sarea | 0.84 | 0.40 | 0.69 | -0.34 | -0.64 | 0.44 | 0.99 | 0.92 | -0.85 | 0.79 | -0.69 | 0.58 | -0.88 |
| S.C. |  | -0.14 | 0.89 | 0.08 | -0.81 | -0.02 | 0.89 | 0.93 | -0.62 | 0.97 | -0.19 | 0.91 | -0.85 |
| Twater |  |  | -0.31 | -0.86 | 0.29 | 0.73 | 0.31 | 0.16 | -0.61 | -0.23 | -0.94 | -0.42 | -0.26 |
| pH |  |  |  | 0.44 | -0.99 | 0.13 | 0.77 | 0.68 | -0.27 | 0.97 | -0.03 | 0.74 | -0.53 |
| O2 |  |  |  |  | -0.50 | -0.29 | -0.23 | -0.29 | 0.74 | 0.27 | 0.78 | 0.17 | 0.45 |
| pCO2 |  |  |  |  |  | -0.23 | -0.72 | -0.57 | 0.17 | -0.92 | 0.02 | -0.62 | 0.41 |
| TBC |  |  |  |  |  |  | 0.41 | 0.04 | -0.26 | 0.05 | -0.77 | -0.44 | -0.02 |
| DIC |  |  |  |  |  |  |  | 0.91 | -0.79 | 0.85 | -0.61 | 0.63 | -0.86 |
| DOC |  |  |  |  |  |  |  |  | -0.86 | 0.83 | -0.45 | 0.83 | -0.98 |
| SUVA254 |  |  |  |  |  |  |  |  |  | -0.46 | 0.78 | -0.46 | 0.92 |
| E2:E3 |  |  |  |  |  |  |  |  |  |  | -0.11 | 0.85 | -0.71 |
| E254:E436 |  |  |  |  |  |  |  |  |  |  |  | 0.14 | 0.51 |
| SR |  |  |  |  |  |  |  |  |  |  |  |  | -0.76 |

Thermokarst lakes

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | E.C. | Twater | pH | O2 | pCO2 | TBC | DIC | DOC | SUVA254 | E2:E3 | E254:E436 | SR | fCO2 |
| Sarea | 0.86 | 0.25 | 0.31 | -0.07 | 0.17 | -0.31 | 0.47 | 0.88 | 0.26 | 0.57 | 0.74 | -0.30 | 0.00 |
| S.C. |  | -0.22 | 0.71 | 0.41 | -0.25 | 0.15 | 0.62 | 0.96 | -0.05 | 0.90 | 0.51 | 0.13 | 0.24 |
| Twater |  |  | -0.84 | -0.72 | 0.52 | -0.99 | -0.56 | -0.23 | 0.24 | -0.61 | 0.16 | -0.98 | -0.77 |
| pH |  |  |  | 0.69 | -0.44 | 0.80 | 0.80 | 0.71 | -0.12 | 0.93 | 0.23 | 0.79 | 0.74 |
| O2 |  |  |  |  | -0.95 | 0.65 | 0.11 | 0.23 | -0.80 | 0.70 | -0.49 | 0.57 | 0.16 |
| pCO2 |  |  |  |  |  | -0.45 | 0.19 | -0.02 | 0.94 | -0.50 | 0.69 | -0.35 | 0.12 |
| TBC |  |  |  |  |  |  | 0.57 | 0.17 | -0.17 | 0.54 | -0.15 | 0.99 | 0.81 |
| DIC |  |  |  |  |  |  |  | 0.78 | 0.50 | 0.69 | 0.72 | 0.62 | 0.88 |
| DOC |  |  |  |  |  |  |  |  | 0.21 | 0.85 | 0.71 | 0.19 | 0.41 |
| SUVA254 |  |  |  |  |  |  |  |  |  | -0.23 | 0.83 | -0.07 | 0.43 |
| E2:E3 |  |  |  |  |  |  |  |  |  |  | 0.28 | 0.52 | 0.47 |
| E254:E436 |  |  |  |  |  |  |  |  |  |  |  | -0.07 | 0.42 |
| SR |  |  |  |  |  |  |  |  |  |  |  |  | 0.86 |

**Appendix**

*Detailed description of rivers and lakes of the Tyva Republic sampled in this work.*

The Yenisei River is one of the longest and deepest rivers in the world and Russia, flowing into the Kara Sea of the Arctic Ocean. The length is 3487 km, the catchment area is 2,580,000 km², and the annual flow is 624.41 km3. The flow velocity is from 0.3 to 5 m/s, depending on the location of the river [1]. The research was carried out in the upper reaches of the river. The river originates from the confluence of two sources — the Big Yenisei (Biy-Khem) and the Small Yenisei (Kaa-Khem). The main tributaries in the upper reaches are Elegest, Khemchik, Us, Kantegir. The city of Kyzyl and the Service-Khem kozhuun of the Republic of Tyva, together with the administrative center of Shagonar, is located in the river basin. The non-flooded channel of the Upper Yenisei (Service-Khema) on the territory of Tyva runs through the flat terrain of the Tuva basin with a pronounced steppe landscape, has many channels and islands [2].

The basin of the Bolshoy Yenisei River (Biy-Khem) is located in the wettest, taiga, teeming with lakes and wetlands of Tyva. In the center of it is the vast Todzhinsky basin. The Biy-Khem basin, in the area from the mouth of the Seiba to the mouth of the Uyuk, is characterized by the presence of high mountains with steep slopes and weak forest cover. Below, before the confluence with the Maly Yenisei River (Kaa-Khem), smoothed open landforms and a wide river valley are typical. The length of the river is about 560 km. The width of the riverbed The Yenisei varies from 20-80 m in the upper reaches to 120-290 m in the middle and lower reaches, depths, respectively, from 1-1.5 m to 1.5–4 m. The flow velocity varies from 1.4 to 2.4 m / s. The average long-term water consumption of the Yenisei River in the closing alignment (Kara—Haak village) is 594 m3 / s [2].

The Maly Yenisei River (Kaa-Khem) is formed by the confluence of two rivers: Kyzyl-Khem and Balyktyg-Khem. The source of Kyzyl-Khem is located on the territory of Mongolia, whereas Balyktyg-Khem originates from the northern slopes of the Sengilen Highlands. In the upper reaches of the Yenisei River, it is a typical mountain river, its bed abounds with rocky ledges that form numerous rapids and shivers. After entering the Ulugh-Khem basin, it flows in low steppe shores. Compared to Biy-Khem, Kaa-Khem has fewer tributaries. The right tributaries of the river are Unzhey, Honga, Uzhep, Derzyg; the left ones are Shivey, Sizim, Buren. The river is quite full-flowing, fast, the speed is 1.8-2.3 m / sec, the width of the channel is from 20 to 80 m. The water discharge is highly variable and depends on the amount of precipitation (Table 1). In May - early June, the spring flood comes, and in July-August, as a result of heavy rains, sometimes there is a summer flood. Groundwater takes part in feeding rivers all year round. The depth of groundwater is about 8-10 m, in floodplains of rivers and streams they come close to the surface [3].

The Tes-Khem River has a mountainous character, belongs to the Ubsu-Nur water system. The length of the river is 139 km, the width of the river is 10-100 m, the catchment area is 4390 km2. The river's feeding is predominated by rain. In summer, there is a high probability of rain floods. In winter, the river freezes. The river originates on the Tannu-Ola mountain range. The mouth of the river is at an altitude of 1067 m. To the west of Tes-Khem, beyond the sands of Tsugeer-Els, there is the lake Tore-Khol, formed by the damming of the former tributary of Tes-Khem.

The Khemchik River originates on the eastern slope of the Kozer ridge from a peak of 3122 m, belonging to the Shapshalsky ridge system, on the border with the Altai Republic. The entire river is located on the territory of the Republic of Tyva. It flows between two mountain systems — the Western Sayan from the north and the Western Tannu-Ola from the south, collecting all its runoff from them. The length of the river is 320 km, the catchment area is 27 thousand km2. The average water discharge is 102 m3/s [2]. All sources and tributaries are fed by runoff from high ridges, and therefore the river system in the Khemchik basin is widely used for irrigation [4]. The valley is narrow, with steep banks, and there are many boulders in the riverbed. In the Khemchik basin, the river has a flat character with bends. Large stone remains are not uncommon. The flow velocity is low. The river is essentially fed from underground discharge. The Khemchik’s flood occurs in summer, from June to August inclusive (with a maximum in July), and is the result of summer precipitation in the form of rain. In September, water consumption decreases significantly, and this decrease continues until the beginning of winter, along with a decrease in precipitation [5].

The Alash River, a left tributary of the Khemchik River, is formed by the confluence of the Chulcha and Kara-Khol rivers; its length is 125 km and the slope is up to 3.5 m/km. The catchment area is 4630 km. The width of the riverbed is up to 60-90 m. The valley of the river is wide. The river acquires a mountain-steppe character. Absolute elevation marks in the area of the river flow range from 1000 to 1200 m [6].

The Ak-Sug River (in the upper reaches of the Ak-Khem), a left tributary of the Khemchik River, originates in one of the lakes of the Dashtyg-Khem ridge at an altitude of 2115 m above sea level. The length of the river is 160 km, the area of its catchment area is 3170 km2. The average annual water discharge is 14 m3/s. Agriculture with irrigation is developed in the valley. Annual water consumption is 1% of the annual flow of the river (15 million m3). The river has 46 tributaries less than 10 km, the total length of which is 173 km, there are also 82 lakes in the catchment area, the total area of which is 10.23 km². The Kyzyl-Taiga Mountain is located at the headwaters of the Ak-Sug River [7]. The absolute heights of the terrain through which the Ak-Sug River flows vary significantly from 1320 to 2100 m. The width of the riverbed ranges from 2-5 m in winter, to 15-20 m in summer, the depth, respectively, from 0.2-0.3 m to 0.7-1.1 m. The river valley on the investigated section of the Ak-Sug river is forested, the lower parts of the slopes are relatively flat, the upper ones with rocky and shrubby tundra are steep and rocky. At the beginning of the lower third of this segment on the left bank of the Ak-Suga at absolute altitudes of 1350-1500 m there is an eponymous deposit of molybdenum-copper sulfide ores. The deposit was exposed by erosion and subjected to the movement of part of the ore material by a glacier [8].

The Chadan River is a right tributary of the Khemchik River. The source is located on the western ridge of Tannu-Ola. The length of the watercourse is 98 km, the catchment area is 2200 km². The absolute height of the terrain is 800 m [9].

The Durgen River is a left tributary of the The Yenisei of the 3rd order: flows into the Mezhegey River, a tributary of the Elegest River. The source is located in the highlands of the East Tannu-Ola ridge, then the river flows along its northern macro slope. According to the State Water Register, the total length of the river is 93 km. The speed of the river flow changes in accordance with the change in terrain. The river is distinguished by a rare cascade of waterfalls. The river is located within the Mezhegeysky coal deposit (Khomushku et al., 2019) [10]. In the middle course, the river flows through the territory of two villages in which there is no sewerage, the river is used for watering livestock. Part of the catchment area is occupied by a specially protected natural area - the Durgensky Nature Reserve.

The Chaa-Khol River, a right tributary of the The Yenisei River, flows through the territory of the Ulug-Khem and Chaa-Khol kozhuuns of Tyva. The total length of the river is 90 km. The catchment area has 1730 km². It begins on the northern slope of the Western Tannu-Ola ridge between the Tyndy-Ula and Hule-Bozh mountains. It flows in a northerly direction through a valley overgrown with larch forest in the upper reaches and across the steppe in the lower reaches. In the middle course it is divided into several channels. It flows into the Yenisei River at a distance of 3315 km from the mouth. The height of the mouth is 540 m above sea level [1].

The Khule River (Torgalyg), a right tributary of the Shagonar River, originates on the northern macroscline of the Eastern Tannu-Ola, flows through the Central Tuva Basin. The length of the river is 40 km, the width varies from 0.5 to 1.5 m, the catchment area is 610 km². Altitude above sea level: 535 m [11].

Anyyak-Chyrgaki River, a tributary of the Chirgaki River, a right tributary of the Khemchik River. The length of the watercourse is 52 km, the catchment area is 410 km². The bottom of the river is pebbly. During the study period, the water is transparent to the bottom, its color is bluish-green, the depth of the river ranges from 0.2 to 2.0 m. The absolute elevation of the terrain is 800 m. The source of the river begins on the north-western forested slopes of the Western Tannu-Ola [12].

The Biche-Bayan-Gol River is a right tributary of the Yenisei, into which it flows 12.5 kilometers from the mouth, 14 kilometers northwest of the city of Kyzyl. The length of the watercourse is 32 km [13].

The Adyr-Khem River flows through the territory of the Barun-Khemchik district on the Alash plateau. The width of the Adyr-Khem River is 1.5 m, the depth is from 0.25 - 1m, the flow velocity is about 0.25 m/s [14].

Lake Tore-Khol is the only large freshwater lake in the Ubsunur basin. The lake has no tributaries, receiving water from springs of sand dunes, which are located in a horseshoe-shaped bowl of the southern shore and drain into the lake in the form of a stream. The Torehole is located in a shallow depression with flat sides, the average depth is 7 m, the area is 42 km². The greatest depth (up to 40 m) was noted at the isthmus in the southern part (Fesenko, 1984) [15]. The absolute height of the terrain is 1149 m. The lake is oligotrophic, the least productive of all the lakes of the Ubsunur basin [16]. It contains a relatively small percentage of organogens and bacteria. Therefore, the lake is transparent, clean, rich in underutilized oxygen by organisms. In the summer, the surface layers warm up well, in the middle of August in the afternoon the temperature rises to 21 ° C at an air temperature of 32 ° C [17].

Lake Chagytai is the largest freshwater lake of the Tuva basin, located in its southern part on the border of the settled hilly foothills of the Vostochny Tannu–Ola ridge, at an altitude of 1003 meters above sea level. This is the largest freshwater lake in the Tuva basin. It has the shape of an almost regular circle with a diameter of about 6 kilometers, the length of the coastline is about 20 kilometers. The area of the lake is 2860 hectares, its maximum depth reaches 17 meters [1]. In the west and southeast of the reservoir, the slopes of the mountains are covered with taiga. The bottom of the lake is sandy and pebbly. The shores are mostly flat, sometimes rocky, sometimes sandy. The south-eastern shore is swampy, overgrown with talus, birches, larches. The only river flowing from the lake, the Mazhalyk River, originates here.

Lake Cheder is located 45 km south of the city of Kyzyl, in the south of the Tuva basin in a drainless depression, on board of which the sandy-clay rocks of the Jurassic come out. The depression is surrounded by a hilly, treeless plain. The lake is drainless, located in a shallow depression, within the vast Central Tuva basin, at an absolute mark of 706 m. The lake is fed by a stream flowing into the lake in the southern part, as well as groundwater from quaternary lake sediments. The lake has a slightly elongated shape. The water surface area is 430 ha, length - 4.5 km, width - 0.8 - 1.5 km, depth - 1.5 - 1.8 m [18]. The water in the lake is highly mineralized. The main component is sodium sulfate. The mineralization of water in the lake, depending on the level, ranges from 80 in April and May to 200 grams per liter in August. Potassium salts (0.250 g/l), fluorine (0.003 g/l), iodine (0.001 g/l), strontium (0.001 g/l) are present in small quantities. The shores and bottom of the lake are composed of silt mud with a thickness of up to 2 meters. The mud is gray or gray-black with the smell of hydrogen sulfide. On the territory of the lake there is 46-m deep well with mineral drinking water. The mineral water captured by the well is cold, low-mineralized chloride magnesium-sodium-calcium in composition and slightly alkaline in the nature of the reaction of the medium [19].

Thermokarst lakes are located in the Alash Highlands in the Barun-Khemchik district, 6.5 kilometers from the border with Khakassia and 150 km from the city of Ak-Dovurak. Absolute marks in the area of lakes range from 1800 to 2000 m. Absolute heights in the lakes range from 1840 to 1860 m . There are about 200 thermokarst lakes in the study area. Basically, the lakes are small, most of the lakes have a rounded, oval-elongated shape, some of the shores are overgrown and swampy. Two round-shaped lakes were selected for the study.

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