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Ecological assessment of the Selenga River basin, the main tributary of Lake Baikal, using aquatic macroinvertebrate communities as bioindicators

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ABSTRACT

The Selenga River is the main tributary of Lake Baikal (Siberian, Russia). In 2015/2016, the water quality at previously identified contaminated hotspot regions in the lower Selenga River basin was evaluated using resident aquatic macroinvertebrate communities as bioindicators. Benthic macroinvertebrate communities within the Selenga River were found to be relatively sensitive to water pollution as was highlighted by three evaluated biotic indices:Average Score per Taxon (ASPT); Ephemeroptera-Plecoptera-Trichoptera density index (EPT); and Trent Biological Index (TBI). The human impact on the Selenga River basin water quality was evident due to the significant decrease of the biotic indices at several sample locations including downstream of the wastewater discharge point of Ulan-Ude city, in the Dzhida River downstream of the confluence of the Modonkul River, and especially in the Modonkul River near to the mining operations at Zakamensk. At the same time, our study revealed a high self-regeneration ability of the aquatic ecosystem throughout the basin; with resident benthic macroinvertebrate communities appearing to recover in both the Selenga River and the Dzhida River within two to five km downstream of the contamination source. The changes in the benthic communities at the Selenga delta sampling sites were shown to occur under the influence of natural factors such as hydrological conditions and benthic sediment type, which significantly changed from the upper to the lower regions of the delta. For the Selenga delta, a typology of benthic macroinvertebrate communities including a map of their spatial distribution is presented.

Introduction

Great Lake systems such as Ontario, Tanganyika and Baikal are significantly affected by their major tributaries (Karthe, 2018; Kasimov et al., 2017a,b,c; Makarewicz et al., 2012a,b; Sun et al., 2018). The ecosystems of large lakes and their self-regeneration capacities depend considerably on the hydrology, water quality and the adequate aquatic (and riparian) ecological functioning of their tributaries (Cech, 2005; Timoshkin et al., 2018). This in turn is influenced by the condition of the floodplain regions of their entire catchments. The Selenga River is the largest tributary of Lake Baikal, providing nearly half of the annual inflow of water into the lake (Sinyukovich et al., 2004). Over the last four decades, the ecological condition of the Selenga River basin has been severely impacted by the increased intensity in the number of anthropogenic activities including land clearing, livestock grazing, large scale and illegal mining and commercial agriculture. In addition to the expected impacts associated with climate change, the effects of these human activities across the basin have led to significant, and in many cases, irreversible damage to the sustainability and resilience of the Selenga River and other major boreal river ecosystems. (Antokhina et al., 2019; Frolova et al., 2017).

For a comprehensive assessment of the environmental conditions across the Selenga River basin, specific hydrochemical and hydrobiological data are required. The comparison of these data describing the hydrochemistry of water flows and the structure of their biota allows for an objective evaluation of the river system conditions (Beisel et al., 2003). Thus the objective of the current study is to determine if structural changes of benthic macroinver-

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tebrate communities clearly and temporally indicate an ecosystem transformation within the Selenga River basin. Therefore the specific aim of the current research was to make an ecological assessment of Lake Baikal's main tributary, the Selenga River basin, using resident benthic macroinvertebrate communities as bioindicators of aquatic ecosystem health. An additional aim was to determine the current trends of both natural and anthropogenic impacts influencing macroinvertebrate communities across several contaminated sites.

Materials & methods

Study site

The Selenga River (Fig. 1) has a large catchment area of 447,000 km^2 shared between Russia and Mongolia and is the largest tributary of Lake Baikal, providing nearly half of the total annual inflow of almost 30 km^3 per year (Sinyukovich et al., 2004). Within the river basin there is both steppe and taiga forest which have both been exposed to widespread anthropogenic impacts such as tilling of virgin and fallow lands, as well as exploitation of raw material deposits (Kasimov et al., 2017a,b,c; Chalov et al., 2014). Throughout the last decade, rapid economic development has resulted in significant urbanisation and population growth across the Selenga River basin, which has subsequently led to widespread expansion of agriculture, particularly in the upper catchment within Mongolia. Land clearing and overgrazing of floodplains are both anthropogenic factors that have significantly impacted water quality and flow regimes in recent years (Ilyicheva, 2008). Moreover, the anthropogenic transformation of terrestrial floodplains has caused significant changes to the transportation and concentration of organic elements and heavy metals from the growing agriculture and mining regions. Thus these catchment activities are having a direct influence on the water quality of the entire river system (Batbayar et al., 2019; Inam et al., 2011; Thorslund et al., 2012). Current climate change impacts have also led to decreased spring runoff, increased fine sediment intrusion into the river network and substantial hydromorphological changes (Frolova et al., 2017). Together these current and widespread changes have a high potential to negatively shift aquatic communities and ecosystem processes, and have already impacted one of the most populated parts of the Selenga River basin, the Kharaa River, in Mongolia (Hartwig et al., 2016; Kaus et al., 2017).

Samples were collected in 2015 and 2016 within the Selenga River basin in Russian territory (Fig. 1). Sampling sites were chosen relative to known anthropogenic impacts along various parts of the Selenga River basin. The Modonkul River was selected to represent rivers with a high level of impact from mining. Sampling was performed in 2016 in the Modonkul River (a tributary of the Dzhida

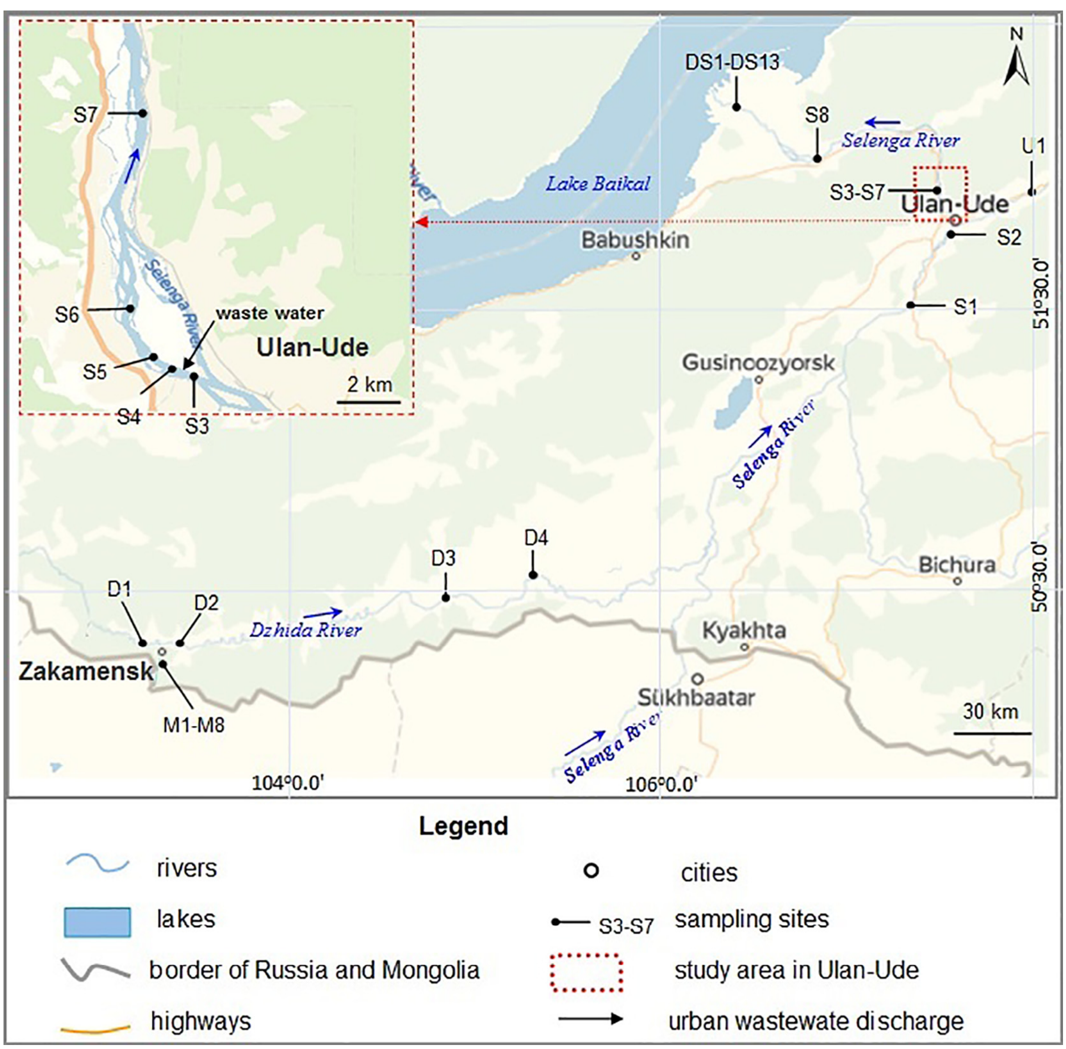

Fig. 1. Map of locations and sampling sites.

River) and its tributary the Inkur. Sampling points were chosen at various distances both upstream and downstream from the metal refinery where polymetallic ores are produced near the town of Zakamensk. This mining and processing factory produces tungsten and molybdenum and was in operation on the bank of the Modonkul River between 1935 and 1998. A large amount of production waste sand is deposited on the river bank and the contaminants contained in it continue to leach into the adjacent river course (Garmaev et al., 2019).

The Uda and Dzhida Rivers were sampled to determine the level of anthropogenic impact on large tributaries of the Selenga River. Four samples were taken from the Dzhida River: sites D1 and D2 were located upstream and downstream of the town of Zakamensk respectively, with site D1 being the control site, without anthropogenic load (Fig. 2). Sites D3 and D4 are located in the lower reaches of the Dzhida River catchment in the vicinity of the Nizhny Torey and Petropavlovka townships, respectively. The site on the Uda River is located upstream of the city of Ulan-Ude.

Biomonitoring of the Selenga River aquatic ecosystem was also carried out in the middle reaches, near the settlement of Ganzurino (sampling site S1) and Ulan-Ude city. The remaining sampling sites were located in Ulan-Ude upstream of the city's waste water discharge point (sampling site S2). Samples were taken directly before the discharge of waste water (sampling site S3), 400 m downstream of the discharge point (sampling site S4), and 900 m and 2.5 km downstream of the discharge point (sampling site S5 and S6 respectively). In addition, samples were taken downstream of Ulan-Ude (sampling site S7) and in the Selenga River delta (sampling site S8). The location of the sampling sites of the Selenga River is schematically shown in Fig. 1.

The Selenga River delta is the most dynamic and environmentally vulnerable natural complex region of the Lake Baikal catchment. Apart from its important biospheric value, the delta performs the function of a barrier filter in relation to the flows of various substances entering the river waters from the vast territory of the catchment (Chalov et al., 2016; Shinkareva et al., 2019). It is important to study the benthic communities of the river delta, as they take part in transformation of the flows of substances and of the energy carried by the Selenga River to Lake Baikal and thus

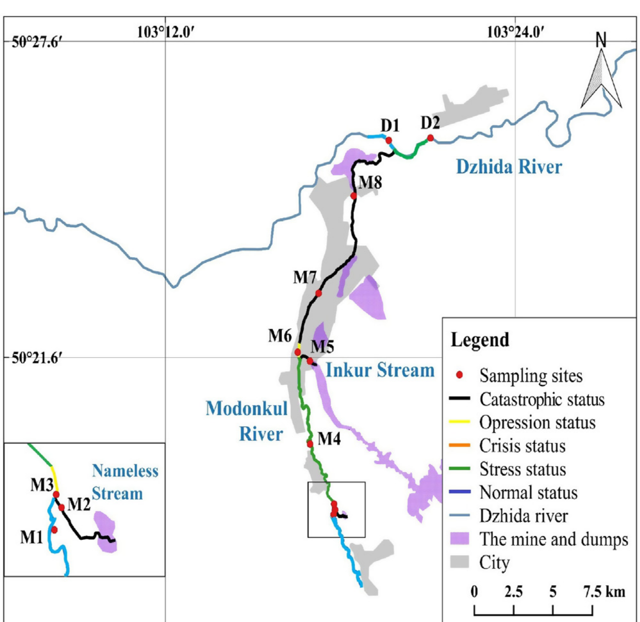

Fig. 2. Locations of sampling sites along of the Modonkul River near Zakamensk.

resident aquatic organisms can serve as bioindicators of the condition of the river (*i.e.* pollution levels). Therefore, in 2016, 14 samples were taken in the Selenga River delta from locations with different types of bottom sediment (Fig. 1).

Macroinvertebrates sampling and identification

At each sampling site, benthic macroinvertebrates were collected during a period of 30 min (GOST state standard of Russia 31861-2012). Samples were collected in the littoral zone, by disturbing the bottom sediments and catching the rising organisms with a scoop net. Then by multiplying the length of the disturbed area by the width of the scoop net, the area of the catch was calculated. Organisms in a measured area were picked off boulders individually with pincers. The collected samples were transferred to 5 ml plastic tubes and preserved in a 4% formalin solution. Organisms were identified to the lowest taxonomic level possible, usually species, in the laboratory according to several ID keys (Key to freshwater invertebrates, 1994–2004, Teslenko and Zhiltsova, 2009). Subsequently, organisms are reported as total number and biomass of individuals per m^2. Based on the data obtained, the density index of the species was evaluated and applied in further calculations (Zatsepin et al., 1948).

Data analysis

The assessment of water quality utilising macroinvertebrate community composition is a standard technique for aquatic ecosystem analyses. The use of aquatic macroinvertebrates is dependent on the life history and requirements of a number of key species. Most benthic macroinvertebrates are represented frequently by the amphibiont insect larvae stages which can last for several years and are strongly dependent on dissolved oxygen concentrations, the amount of organic nutrients and level of contamination in the water. That is why the selection of bioindicators based on macroinvertebrates allows the time integrated assessment of water. Hence, the age and the taxonomic structure of the benthic communities reflect the condition of the river system over recent time. Thus the use of these species to biomonitor a specific region allows for the identification of localized river transformations due to the exposure of anthropogenic activities. The resident macroinvertebrate community's taxonomic and structural composition, will over time reflect changes within the river ecosystem and thus ultimately indicate the water quality level (Kemp et al., 2011).

We used a number of biotic indices to determine water quality at each sample location. These included: Ephemeroptera-Plecoptera-Trichoptera density index (EPT); Trent Biological Index (TBI) and Average Score per Taxon (ASPT). The EPT index is a standard method using aquatic macroinvertebrates for monitoring and assessing river ecology, and has been previously used for biomonitoring studies of transboundary river basins throughout Eurasia (Bae et al., 2005; Heldt et al., 2017). This method is based on calculated relative abundances of the orders Ephemeroptera, Plecoptera and Trichoptera in the sample, compared to the total number of individuals in the sample (Cairns and Pratt, 1993). The higher the relative abundance of EPT taxa in the sample, the higher the water quality at the site. This index relies on the fact that most organisms belonging to these three orders are sensitive to organic pollution and dissolved oxygen concentrations (Resh and Jackson, 1993). The Trent Biotic Index (TBI) is based on an examination of key groups of benthic macroinvertebrates along riffle ridges. According to how many species and individual indicator organisms are present, the water is given a score in a range from 0 (grossly polluted) to 10 (unpolluted). The Biological Monitoring Working Party (BMWP) system considers the sensitivity of invertebrates to pollution, and families are assigned a score between 1 and 10, accordingly. The BMWP score is the sum of the values of all families present in the sample. Values greater than 100 are associated with clean streams, while the scores of heavily polluted streams are less than 10 (Mason, 2002). The average sensitivity of the families of organisms present is known as the Average Score Per Taxon (ASPT) and can be determined by dividing the BMWP score by the number of taxa present. A high ASPT score is considered indicative of a clean site containing large numbers of high-scoring taxa (Hawkes, 2016). In addition, we used a classic index of biodiversity to evaluate the condition of the watercourse: an index of species diversity known as the Shannon Index (SI) (Odum, 1986). It is considered that the better the physico-chemical conditions (the cleaner the water is), the higher is the biotic diversity. However, it should be considered that biodiversity also depends on the diversity of habitats present. For example, a river reach with substrate consisting of boulders and pebbles of various sizes would typically have a higher diversity of species compared to another river reach with a sandy substrate.

Results & discussion

Biomonitoring of the Modonkul River

The Modonkul River assessment results (Fig. 3) suggest that the status of the river ecosystem based on the TBI classification varies from normal: 10–9 to catastrophic: 1–2. Upstream of the town of Zakamensk, in section M1 (Fig. 3), the values of the ASPT and TBI indices indicate very clean water. The benthic communities here demonstrate a high degree of diversity, as is demonstrated by the high SI value (3.4). The top surfaces of the bottom stones are populated by attached passive filter-feeding organisms (Simuliidae larvae), scraper plant-feeders (mayflies *Rhitrogena* spp. larvae), and chironomid larvae midges grazing on algae (Chironomidae). The underside of the sampled stones were mostly populated by detritivore caddisflies larvae (*Erotesis*sp., *Rhyacophila* spp.) and predator organisms (stoneflies *Skwala* spp., dragonflies *Ophiogomphus* spp.).

In the section M2, the stream flowing past the abandoned mine where tungsten and molybdenum were quarried between 1934 and 1998, no benthic macroinvertebrates were found. This indicates very poor water quality with severe water pollution levels. Downstream in section M3, the condition of the Modonkul River changes abruptly: three species of benthic organisms were found and the indices TBI, EPT, ASPT improved, which resulted in the water being characterized as polluted. Two and a half kilometres downstream in section M4, the influence of mining on the stream again goes down considerably with the natural process of oxidation of salts occurring as the steam water becomes more diluted. The total number of species increases to 9, the EPT index grows to 77, the TBI index rises to 7, and the Shannon Index goes up to 2.7. At the same time, this is much less than in natural background levels at the control site (M1). Thus the condition of the benthic macroinvertebrate community there may be assessed as stressed.

The Inkur stream section (M5) originates from the mining tailings and as a result was found to be not populated with benthic organisms. Following the inflow of the Inkur stream into the Modonkul River, there is a substantial reduction in the abundance of macroinvertebrates. In section M6 the total number of species is four, and EPT, TBI, ASPT, and SI indices decreased in comparison to the upstream sites. In fact, the Modonkul River in the area of Zakamensk and downstream of this town becomes nearly lifeless with only a single species of Chironomidae detected. This seems to be caused not only by the inflow of the Inkur but also by the mining waste from which contaminants enter the river, especially during flooding events, which occurred during the study period. The overall environmental condition of the Modonkul River is shown in Fig. 3. Thus benthic river communities formed by invertebrate species, which are characteristic of this region, have been completely devastated due to the severe anthropogenic impact (in the Modonkul River downstream of the town of Zakamensk).

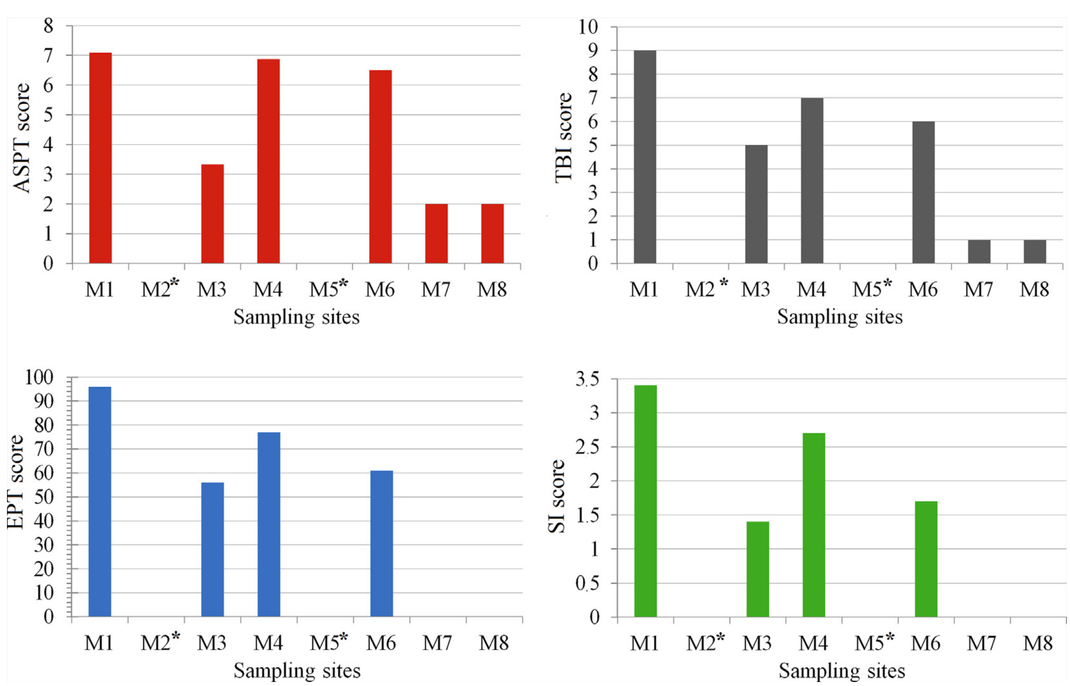

Fig. 3. Biomonitoring of the Modonkul River near Zakamensk. Symbols: M1 – Modonkul River upstream of the mine; M2 – a stream flowing from the mine; M3 – Modonkul River 10 m downstream of the stream influx; M4 – Modonkul River, 3 km downstream of the mine; M5 – Inkur Stream, mouth; M6 – Modonkul River, below the influx of the Inkur Stream; M7 – Modonkul River downstream of the waste treatment facilities; M8 – Modonkul River downstream of Zakamensk. * – site of contamination.

It has been previously reported that mountain rivers, such as the Modnkul River, have a large potential for self-purification. Therefore, it was unexpected that the benthic community displayed a degraded species diversity in Zakamensk (Fig. 3), even though the mining works stopped operating in 1998. At the same time, the results of the hydrochemical studies carried out in the region in 2009–2012 (Sanzhanova and Khazheeva, 2019) showed substantial contamination in the Modonkul River originating from the abandoned facilities of the former mine. For example, at monitoring station M2, in the stream flowing from a derelict mining site, the concentrations of copper (Cu), zinc (Zn), lead (Pb) and cadmium (Cd) reached ultrahigh values, such as 6.6 mg/l, 26.7 mg/l, 0.108 mg/l, and 0.132 mg/l, respectively. These values are hundreds of times higher than the concentrations recorded upstream of the Modonkul River at monitoring station M1 (Fig. 1). Three hundred metres downstream of the inflow of the stream, the concentration of contaminants in the Modonkul River decreased significantly, with the maximum concentration of contaminants not reaching more than tenfold above normal levels (Sanzhanova and Khazheeva, 2019). This was expected, as the stream flowing from the mine has a small discharge of about 5 l/s, and the contaminants would be diluted with the waters of the Modonkul River, where the water discharge was 3 m^3/s at the time of measurement. Such large scale dilution also explains the improvement in the condition of the benthic communities at monitoring station M4.

A downstream tributary of the Modonkul River, the Inkur, has a water discharge of approximately 0.5 m^3/s. Concentrations of Cu, Zn, Pb and Cd in the Inkur exceeded background values by several times, while the mineral content was elevated by nearly tenfold. The composition of the water changes drastically from the bicarbonate-calcium (magnesium) to sulphate-sodium (potassium) composition, with sulphate concentration of more than 800 mg/l detected.. This is the reason why benthic macroinvertebrates were not found in the Inkur stream, and why a clear reduction in the benthic fauna was observed in the Modonkul River downstream of confluence with the Inkur. Further, in the area of Zakamensk, the Modonkul River is almost lifeless, with only one Chironomidae species reported, due to the impact of not only the contaminated Inkur stream, but also exposed sites of the refuse ore located in the right-hand part of the water catchment of the Modonkul River (Fig. 2). Here two tailings storages are located, the Dzhida and Barun-Naryn pits, containing approximately 44.5 million tons of hazardous waste (Kasimov et al., 2017a,b,c). As the Modonkul River flows in a steep sided valley, the waste located above is easily transported into the river below where significant aeolian drift also occurs. Similar changes in the benthic fauna are described in the studies of other rivers and streams in the areas of mining operations (Stepanov, 2009).

Biomonitoring of the Dzhida and Uda Rivers

The Uda and Dzhida rivers were sampled to determine the level of anthropogenic impact in two large tributaries of the Selenga River. Larvae of amphibiont insects: Trichoptera, Ephemeropetra, Plecoptera and Diptera formed the basis of the benthic communities at these sites. The influence of pollutants originating from the Modonkul on the Dzhida River is limited as is evident by high EPT, ASPT, TBI, and SI indices (Fig. 4) at sampling site D2 (just downstream of the inflow of the Modonkul into the Dzhida). However, if we compare the characteristics of site D2 to the upstream site D1, we can see all the parameters of the Dzhida River are slightly reduced downstream of the Modonkul River, so that its condition may be defined as environmentally stressed (Fig. 4). Further downstream of the Dzhida River, at sites D3 and D4, the values of the biotic indices and of the biodiversity index return towards levels that were observed at the control site D1.

In the river above the city of Ulan-Ude (site U1), there is a high species diversity of benthic organisms. Twenty-two species of benthic invertebrates were found, including two species of Plecoptera, six species of Ephemeroptera, and three species of Trichoptera. This reflects the high water quality in this fast-flowing river section.

Biomonitoring of the Selenga River

Ulan-Ude is a large industrial and cultural centre with a population of over 400,000 people. Hence, widespread pollution of the

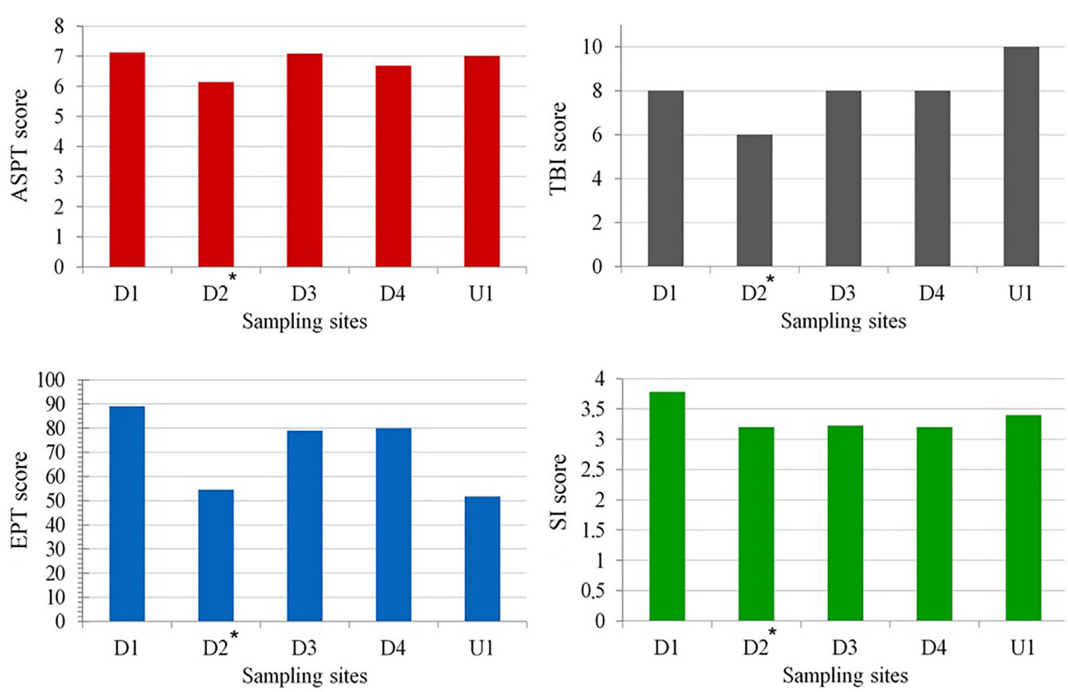

Fig. 4. Biomonitoring of the Dzhida and Uda rivers. Symbols: D1 – Dzhida River upstream of Zakamensk; D2 – Dzhida River downstream of Zakamensk; D3 – Dzhida River near Nizhny Torey; D4 – Dzhida River near Petropavlovka; U1 – Uda River upstream of Ulan-Ude. * – site of contamination.

Selenga River at this location might be expected with associated changes in the benthic fauna. However, the results (Fig. 5) indicate that the biotic parameters upstream of Ulan-Ude (sites S1 and S2) and downstream of the city (sites S6-S8) did not vary substantially from each other. Downstream of the city of Ulan-Ude, in the delta zone, where sampling site S8 is located, the values of the indices reach the values obtained from sampling sites S1 and S2, located upstream of Ulan-Ude. This suggests that the city of Ulan-Ude does not have a significant impact on the benthic communities downstream.

At the same time, in the city itself, at the place of the wastewater discharge from the water treatment plant (site S4), as well as downstream (S5), a reduction in the value of all parameters of benthic metrics was observed. The results of the study demonstrates that the condition of the benthic macroinvertebrate community changes dramatically following the discharge of the city's waste water (Fig. 5). The values of the SI, EPT, ASPT, and TBI indices essentially decrease at site S4, before gradually increasing again at subsequent downstream sites. Thus the number and variety of available benthic macroinvertebrates suggests a reduction in water quality in the Selenga River near Ulan-Ude, particularly following the waste water discharge location (S4). At the same time, the impact of the discharged waste water on the Selenga River does not last long as within 2.5 km downstream of the water treatment plant, there is evidence that the benthic communities have largely regenerated. This indicates local contamination, with which the river can process rather effectively. Such a conclusion is corroborated by the results of a number of similar studies. For example, the concentration of heavy metals in the benthic sediments of the Selenga River revealed that the total contamination of the sediments within Ulan-Ude and further downstream in the Selenga River is still within the permitted limits. This relatively good condition is a result of insignificant anthropogenic transformations and low levels of heavy metal contamination of river water, soil and snow in and around Ulan-Ude (Kasimov et al., 2017a,b). Continuous monitoring of water quality in the Selenga River at Ulan-Ude indicates that a major source of contamination in the river is the waste water discharged from the water treatment plant. The water purity standards used in Russia are exceeded there for nitrates 2.2 times, iron – 7.8 times, ammonia –2.7 times, fluorides – 1.6 times, five-day biological oxygen demand – 3 times, chemical oxygen demand – 2.7 times (The State Report, 2017).

Biomonitoring of the Selenga River delta

During the study conducted in the Selenga River delta, the values of the biotic indices underwent a transition (Fig. 6). Comparison of the delta's characteristics to the upstream site S8 indicated a reduction of the TBI and ASPT indices. The TBI and SI indices decrease in the areas of the delta composed of pure sand (sampling sites DS4 -DS6) and silt (DS11–DS14), while the EPT index also drops (Fig. 6) meaning that oxyphilic species from the orders Trichoptera, Plecoptera, Ephemeroptera disappear. This result suggests a general reduction of dissolved oxygen in the water.

If we compare Fig. 6 to the preceding figures, it is evident that such drastic changes in the biotic indices are characteristic only of the highly polluted Modonkul River in the vicinity of Zakamensk (Fig. 3). However, as the delta sites considered are not exposed to such severe anthropogenic impact; why then are there such clear differences among the sites in this area?

In our opinion, this is caused by the fact that whereas previously we dealt with biological indications of pollution in river sections which are similar in their hydrological parameters (flow velocity, type of bottom sediments, etc.), the situation in the delta is totally different. Here the hydrological conditions and the type of

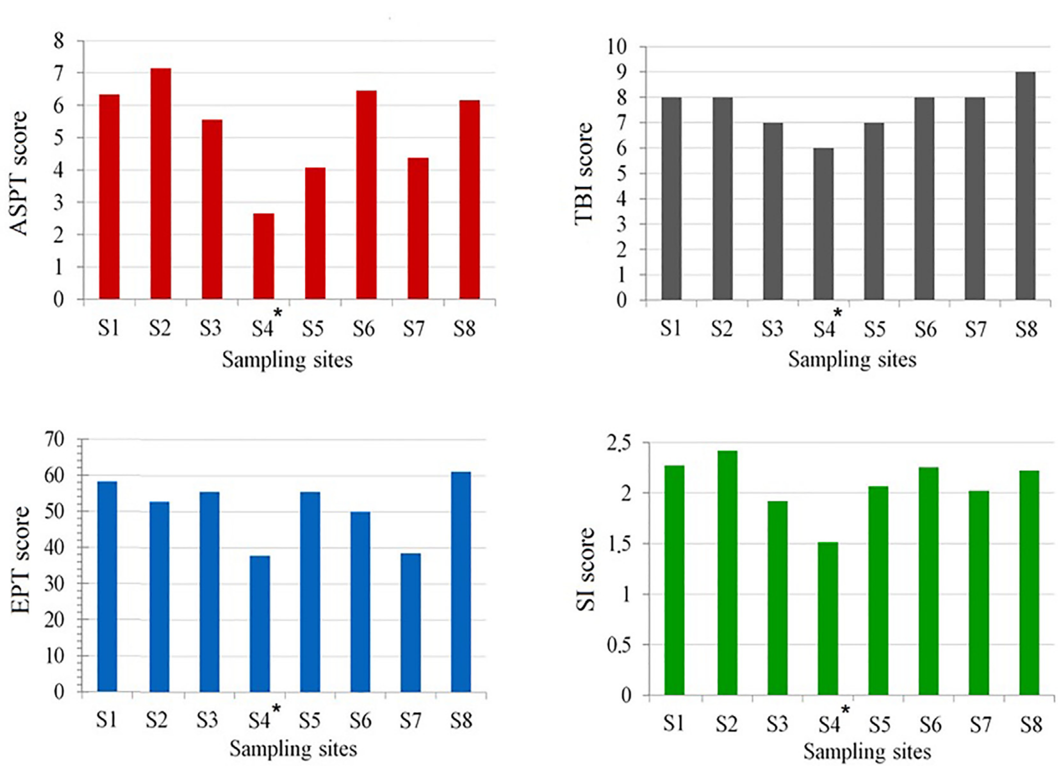

Fig. 5. Biomonitoring of the Selenga River; symbols: S1 – Selenga River upstream of the settlement of Ganzurino; S2 – Selenga River 2.5 km upstream of Ulan-Ude; S3 – Selenga River 200 m upstream of the discharge of the city's waste water; S4 – Selenga River 400 m downstream of the discharge of the city's waste water; S5 – Selenga River 900 m downstream of the city's waste water; S6 – the Selenga River 2.5 km downstream of the city's waste water; S7 – the Selenga River downstream of Ulan-Ude; S8 – the Selenga River near its delta. * – site of contamination.

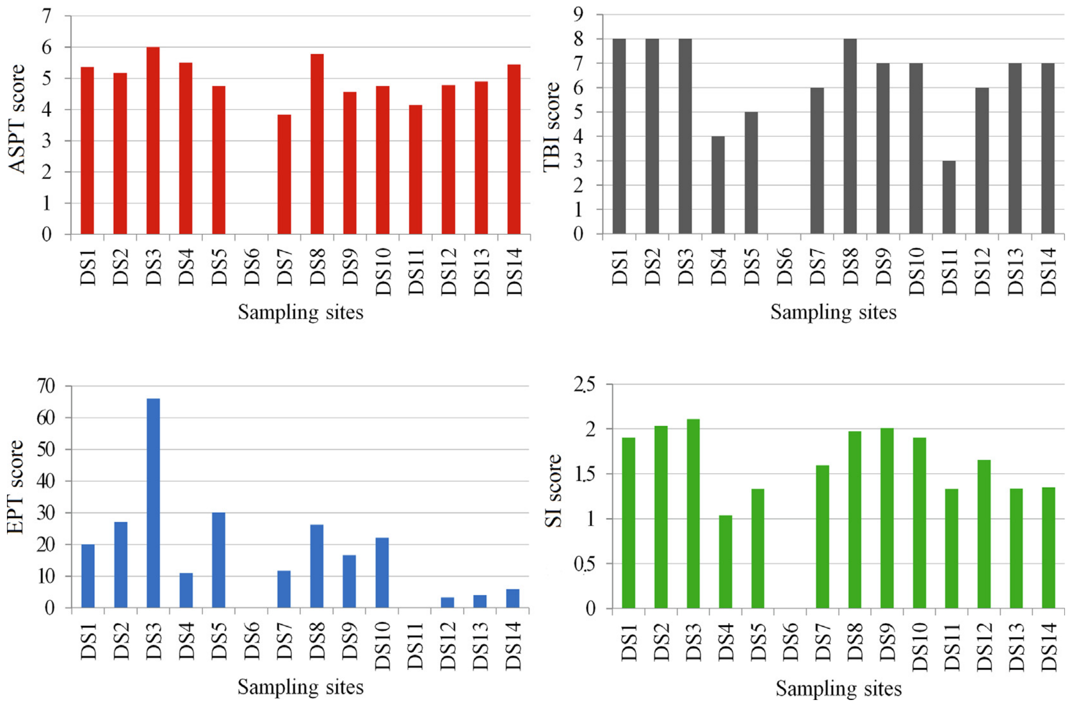

Fig. 6. Biomonitoring of the Selenga River delta. Symbols: DS1 – DS3 are sites located over pebble-sandy bottom sediments; DS4 – DS6 are sites located over pure sand bottom sediments; DS7–DS10 are sites located over sandy-silty bottom sediments, DS11–DS14 are sites located over silty bottom sediments.

substrate vary considerably from the upper to the lower part of the delta and now these substrata characteristics rather than contaminants, determine the structure of the benthic biotic communities (Pietroń et al., 2018).

Therefore, in relation to the delta, we also considered the local hydrological conditions in the river using the composition of the benthic macroinvertebrate communities. According to a map published in 2015 for the Selenga River delta (Assessment and forecast, 2015; Dong et al., 2019), the surface of the delta could be divided into zones corresponding to the type substrate, from which it is clear that the gravel-pebble sediments are replaced by sandy sediments and then by silty ones from the head of the delta to its lower sections. This is likely due to the reduction of the river flow velocity, which should also affect the benthic species community. Assuming the relation between the type of bottom sediments and the benthic communities living on them, we examined the communities in the left-hand relative to downstream (and most accessible) sector of the delta, encompassing all major types of substratum habitats (Fig. 7).

As a result, four types of benthic communities were identified for the Selenga River delta (Fig. 7), which varied in character from the substrate on which they were found: pelorheophilic (silt), pelopsammorheophilic (silted sand), psammorheophilic (sand), and lithorheophilic communities (on gravel-pebble bottoms with sand). Silty areas DS11-DS14 are located in the lower part of the delta and are characterized by the largest quantity of benthic organisms. Here the average biomass was 92 g/m^2, the occurrence is was 1000 organisms/m^2; molluscs, amphipods and oligochaetes prevail. There are much fewer organisms on pebble-sandy – sites DS1–DS3 and sandy-silty bottoms – sites DS7–DS10: where the density is 30–50 organisms/m^2 and the average biomass is 3–4 g/m^2; with many Ephemeroptera, Trichoptera and Plecoptera. There are fewer organisms in the regions of the delta composed of pure sand (sites DS4–DS6), where the average biomass was 0.3 g/m^2 and the density 3 organisms/m^2. The pebble-sandy reaches of the delta have the largest variety of species, while sandy substrates demonstrate the smallest variety of species (Table 1). In the regions composed of silty substrate the biomass of the benthic organisms was higher, while their variety was lower. However, oligochaetes of the Tubificidae family, chironomids larvae, amphipods and bivalve molluscs of the Pisidiidae family dominate. The biodiversity of organisms increased on silty substrates where vegetation occurred. The dominant species mentioned above now includes different groups of detritivores and scraper plant-feeders (mayflies of families Caenidae, Baetidae (*Cloeon* sp.), Heptageniidae (*Heptagenia* sp), dragonfly Coenagrionidae larvae, and leeches *Erpobdella* sp. On silty substrates with pond weed growth, communities including active-swimming organisms, such as mayflies *Baetis* sp., dragonflies *Coenagrion* sp., and creeping scraper plant-feeders (mayflies, caddis flies) were common. Amphipods, chironomids larvae, oligochaetes Tubificidae and bivalve molluscs Pisidiidae maintain their dominance on silty substrates. There was an evident correlation between the type of bottom sediment and the type of benthic communities in the left-hand segment of the delta; thus we applied the relation to the entire delta and schematically described the major types of the benthic communities throughout the Selenga River delta (Fig. 7).

The current study produced the first zoning map of the Selenga River delta based on sampled and predicted benthic macroinvertebrate communities. This result is important for the fishing industry, as it elucidates the conditions of fish nutrition. It is significant for understanding the relationship between living organisms inhabiting the river substrate (benthic populations) and their preferred habitat in terms of bottom sediments which are dictated by the inflow of the Selenga River. The information obtained may be useful for predicting the future conditions of the aquatic ecosystem, e.g. if the boundaries of the types of bottom sediments shift as a result of changes in the hydrological conditions (Fig. 7), we might expect responsive changes in the distribution of resident macroinvertebrate communities as well (Fig. 7).

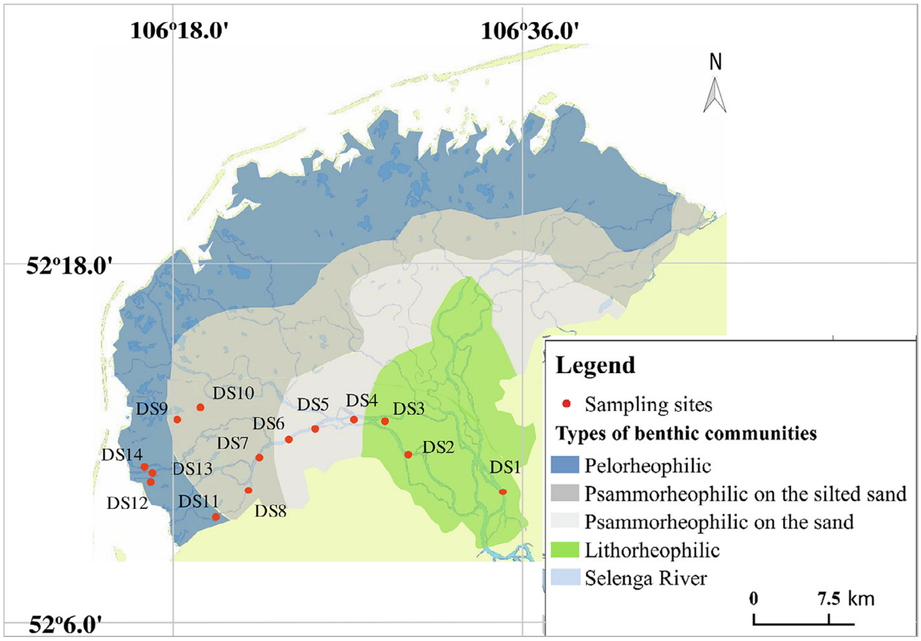

Fig. 7. Distribution of the major types of benthic communities in the Selenga River delta.

Table 1
Macroinvertebrates metrics in the Selenga River delta.

Number on the map	Type of bottom	Biomass, g/m^2	Number of organisms/m^2	Number of species/SI
DS1	Pebbles and sand	1.4	45	18/1.9
DS2	Pebbles and sand	2.4	73	17/2.0
DS3	Pebbles and sand	7	45	11/2.1
	Average	**3.6**	**54.4**	**15.3/2.0**
DS4	Sand	0.4	2	5/1.0
DS5	Sand	0.5	8	5/1.3
DS6	Sand	0	0	0/0
	Average	**0.3**	**3.3**	**3.3/1.15**
DS7	Silted sand	3	33	6/1.6
DS8	Silted sand	3.4	24	9/1.9
DS9	Silted sand	3.3	36	9/2.0
DS10	Silted sand	2.1	27	8/1.9
	Average	**2.9**	**29.9**	**8/1.85**
DS11	Silt	7.8	307	12/1.3
DS12	Silt	128.5	1202	9/1.6
DS13	Silt	208.6	2600	10/1.3
DS14	Silt	24.7	121	9/1.3
	Average	**92.4**	**1057**	**10/1.45**

Conclusions

The study of the benthic invertebrates of the Selenga River in the vicinity of Ulan-Ude has shown that the city currently makes an insignificant impact on the benthic communities downstream. Strong impact is manifested only in the area of the wastewater discharge from the sewage treatment plant and results in a decrease of the benthic community species diversity as well as in a reduction of the number of invertebrate species, particularly those more sensitive to water contamination.

The Modonkul River has evidently suffered from a prolonged anthropogenic impact. Although the large mining operations in Zakamensk have ceased for more than two decades, the impacts are still manifesting themselves in practically complete destruction of the local benthic communities. This is caused by the severely contaminated water run off which enters the river from the tailings dumps of refuse ore containing millions of tons of hazardous waste. The impact of the Modonkul River on the benthic invertebrates of the Dzhida River into which it flows, is comparatively low.

Benthic macroinvertebrate communities within the Selenga River delta are dictated not by anthropogenic impacts but by changes in the hydrological conditions that alter the type of substrate occurring between the upper and lower reaches of the delta. In accordance with this, a change takes place from the lithoreophilic communities, the richest in the number of the species present, to psammoreophilic and then to peloreophilic communities, which are characterized by the greatest amount of biomass.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Antokhina, O.Y., Latysheva, I.V., Mordvinov, V.I., 2019. A Cases Study Of Mongolian Cyclogenesis During The July 2018 Blocking Events. GEOGRAPHY, ENVIRONMENT, SUSTAINABILITY. 12 (3), 66–78. https://doi.org/10.24057/2071-9388-2019-14.

Assessment and forecast of transboundary movement of harmful (polluting) substances in the Selenga river – lake Baikal system. Stage 1: assessment of transboundary movement of harmful (polluting) substances in the Selenga river – lake Baikal system in modern climatic and technogenic conditions. Moscow, MSU, 2015, 1005 p.

Bae, Y.J., Kil, H.K., Bae, K.S., 2005. Benthic macroinvertebrates for uses in stream biomonitoring and restoration. KSCE J. Civil Eng. 9 (1), 55–63.

Batbayar, G., Pfeiffer, M., Kappas, M., Karthe, D., 2019. Development and application of GIS-based assessment of land-use impacts on water quality: a case study of the Kharaa River Basin. Ambio, 1–15. 10.1007/s13280-018-1123-y.

Beisel, J.N., Usseglio-Polatera, P., Bachmann, V., Moreteau, J.C., 2003. A comparative analysis of evenness index sensitivity. Internat. Rev. Hydrobiol. 88, 3–15.

Cairns, J., Pratt, J.R., 1993. A history of biological monitoring using benthic macroinvertebrates. In: Freshwater Biomonitoring and Benthic Macroinvertebrates. Chapman & Hall, New York, pp. 10–27.

Cech, T., 2005. Principles of Water Resources: History, Development, Management, and Policy. John Wiley & Sons Inc, New York, p. 468.

Chalov, S.R., Jarsjö, J., Kasimov, N.S., Romanchenko, A.O., Pietron, J., Thorslund, J., 2014. Spatio-temporal variation of sediment transport in the Selenga River Basin, Mongolia and Russia. Environ. Earth Sci. 73, 663–680. https://doi.org/10.1007/s12665-014-3106-z.

Chalov, S., Thorslund, J., Kasimov, N.S., Aybullatov, D., Ilyicheva, E., Karthe, D., Kositsky, A., Lychagin, M., Nittrouer, J., Pavlov, M., Pietron, J., Shinkareva, G., Tarasov, M., Garmaev, E., Akhtman, Y., Jarsjö, J., 2016. The Selenga River delta: a geochemical barrier protecting Lake Baikal waters. Regional Environ. Change 17 (7), 2039–2053.

Dong, T.Y., Nittrouer, J.A., Czapiga, M.J., Ma, Y., McElroy, B., Il'icheva, E., Pavlov, M., Chalov, S., Parker, P., 2019. Roles of bank material in setting bankfull hydraulic geometry as informed by the Selenga River Delta, Russia. Water Resour. Res. doi:10.1029/2017WR021985.

Frolova, N.L., Belyakova, P.A., Grigoriev, V.Y., Sazonov, A., Zotov, L., Jarsjö, J., 2017. Runoff fluctuations in the Selenga River Basin. Reg. Environ. Chang. https://doi.org/10.1007/s10113-017-1199-0.

Garmaev, E.Z., Kulikov, A.I., Tsydypov, B.Z., Sodnomov, B.V., Ayurzhanaev, A.A., 2019. Environmental Conditions Of Zakamensk Town (Dzhida River Basin Hotspot). GEOGRAPHY, ENVIRONMENT, SUSTAINABILITY 12 (3), 224–239. https://doi.org/10.24057/2071-9388-2019-32.

GOST State Standard 31861-2012, 2013. Water. General Requirements for Water Sampling. Standartinform, Moscow, 32 pp.

Hartwig, M., Schäffer, M., Theuring, P., Avlyush, S., Rode, M., Borchardt, D., 2016. Cause–effect–response chains linking source identification of eroded sediments, loss of aquatic ecosystem integrity and management options in a steppe river catchment (Kharaa, Mongolia). Environ. Earth Sci. doi:10.1007/s12665-015-5092-1.

Hawkes, H.A., 2016. Origin and development of the biological monitoring working party score system. Water Res. 32 (3), 964–968.

Heldt, S., Rodriguez, J.C., Dombrowsky, I., Field, C., Karthe, D., 2017. Is the EU WFD suitable to support IWRM Planning in non-European countries? Lessons Learnt from the Introduction of IWRM and River Basin Management in Mongolia. Environ. Sci. Policy 75, 27–37.

Ilyicheva, E., 2008. Geogr Nat Resour (4), 58–63. https://doi.org/10.1016/j.gnr.2008.10.011.

Inam, E., Khantotong, S., Kim, K.W., Tumendemberel, B., Erdenetsetseg, S., Puntsag, 2011. Geochemical distribution of trace element concentrations in the vicinity of Boroo gold mine, Selenge Province, Mongolia. Environ. Geochem. Health 3 (1), 57–69. https://doi.org/10.1007/s10653-010-9347-1.

Karthe, D., 2018. Environmental changes in Central and East Asian drylands and their effects on major river-lake systems. Q. Int. 475, 91–100.

Kasimov, N., Karthe, D., Chalov, S., 2017a. Environmental change in the Selenga River—Lake Baikal Basin. Regional Environ. Change 17, 1945–1949.

Kasimov, N.S., Korlyakov, I.D., Kosheleva, N.E., 2017b. Distribution and factors of accumulation of heavy metals in the benthic river sediments in the territory of Ulan-Ude // Bulletin of the Russian University of Peoples' Friendship. Ecol. Life Safety 25 (3), 380–395.

Kasimov, N.S., Kosheleva, N.E., Korlyakov, I D., Sorokina, O.I., Timofeev, I.V., 2017. Environmental geochemistry of the cities and industrial centres in the basin of the Selenga River // Geochemistry of Landscapes. A Tribute to Alexander Ilyich Perelman on the Occasion of his Centenary (N.S. Kasimov & A.N. Gennadiev). APR Moscow. p. 253–294.

Kaus, A., Schaffer, M., Karthe, D., Büttner, O., Tümpling, W., Borchard, D., 2017. Regional patterns of heavy metal exposure and contamination in the fish fauna of the Kharaa River basin (Mongolia}. Reg. Environ. Chang. 17 (7), 2023–2037. doi: 10.1007/s10113-016-0969-4.

Kemp, P., Sear, D., Collins, A., Naden, P., Jones, I., 2011. The impacts of fine sediment on riverine fish. Hydrol. Process. https://doi.org/10.1002/hyp.7940.

Key to freshwater invertebrates in Russia and adjacent lands. 1994–2004. (T. 1 – T. 6, ed. by S. J. Tsalolikhin), St. Petersburg.: Science.

Makarewicz, J.C., Booty, W.G., Bowen, G.S., 2012a. Tributary phosphorus loading to Lake Ontario. J. Great Lakes Res. 38 (S4), 14–20.

Makarewicz, J.C., Lewis, T.W., Boyer, G.L., Edwards, W.J., 2012b. The influence of streams on nearshore water chemistry, Lake Ontario. J. Great Lakes Res. 38 (S4), 62–71.

Mason, C.F., 2002. Biology of Freshwater Pollution. Prentice Hall, New York, USA, p. 400.

Odum, Yu., 1986. Ecology. Vol 1. Moscow, 328 pp. (in Russian).

Pietroń, J., Nittrouer, J.A., Chalov, S.R., Kasimov, N., Shinkareva, G., Jarsjö, J., 2018. Sedimentation patterns in the Selenga River delta under changing hydroclimatic conditions. Hydrol. Process. https://doi.org/10.1002/hyp.11414.

Resh, V.H., Jackson, J.K., 1993. Rapid assessment approaches to biomonitoring using benthic macroinvertebrates. In: Rosenberg, D.M., Resh, V.H. (Eds.), Freshwater Biomonitoring and Benthic Macroinvertebrates. Chapman & Hall, New York, pp. 195–233.

Sanzhanova, S.S., Khazheeva, Z.I., 2019. The impact of the derelict mine outflows into the Inkur Stream on the chemical composition of the waters of the Modonkul River. Issues Reg. Ecol. T.3, 42–46.

Shinkareva, G.L., Lychagin, M.Y., Tarasov, M.K., Pietroń, J., Chichaeva, M.A., Chalov, S. R., 2019. Biogeochemical specialization of macrophytes and their role as a biofilter in the Selenga delta. GEOGRAPHY, ENVIRONMENT, SUSTAINABILITY 12 (3), 240–263. https://doi.org/10.24057/2071-9388-2019-103.

Sinyukovich, V.N., Zharikova, N.G., Zharikov, V.D., 2004. The runoff of the Selenga River in its delta. Geografia i Prirodnye Resursy 3, 64–69.

Stepanov, L.N., 2009. Influence of the gravel gold deposits minings on the subpolar Ural mountain rivers zoobenthos. Bull. KrasSAU 12, 100–104.

Sun, S., Groll, M., Opp, C., 2018. Lake-catchment interactions and their responses to hydrological extremes. Q. Int. 475, 1–3.

Teslenko, V.A., Zhiltsova, L.A., 2009. Key to stoneflies (Insecta, Plecoptera) of Russia and adjacent countries. Imagines and Nymphs. Vladivostok: Dalnauka, 2009. 382 p.

The State Report on the Condition and Protection of the Evironment in the Buryat Republic in 2016-2017. Ulan-Ude.

Thorslund, J., Jarsjö, J., Chalov, S.R., Belozerova, E.V., 2012. Gold mining impact on riverine heavy metal transport in a sparsely monitored region: the upper Lake Baikal Basin case. J. Environ. Monitor. 14 (10), 2780–2792.

Timoshkin, O.A., Moore, M.V., Kulikova, N.N., Tomberg, I.V., Malnik, V.V., Shimaraev, M.N., Troitskaya, E.S., Shirokaya, A.A., Sinyukovich, V.N., Domysheva, V.M., Yamamuro, M., Poberezhnaya, A.E., Timoshkina, E.M., 2018. Groundwater contamination by sewage causes benthic algal outbreaks in the littoral zone of Lake Baikal (East Siberia). J. Great Lakes Res. 44 (2), 230–244.

Zatsepin, V.I., Zenkevich, L.A., Filatova, Z.A., 1948. Materials for quantification of the benthic fauna of the littoral of Kola Bay. Proceedings of the State Oceanography Institute. Iss. 6, p. 13–54.