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Actual inflow of riverine sediment load into Lake Baikal: main tributaries – the Selenga, Upper Angara, and Barguzin Rivers (Russia)

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ABSTRACT. The sediment load delivery into Lake Baikal from its main tributaries – the Selenga, Upper Angara, and Barguzin Rivers has been reduced since the mid-1970s. This is explained by climate change and socioeconomic activities. Integrated analysis of changes in hydro-meteorological parameters (water discharge, sediment load, air temperature, precipitation) and their trends over the period 1946–1975 (baseline) and 1976–2017 (warming) is performed. Changes in natural processes and human activity were negligible during the baseline period. During the warming period, the greatest reduction of the sediment load inflow against the background of temperature rise and precipitation decrease occurred in the interval between 1996 and 2017 in the Selenga River, between 1985 and 2017 in the Upper Angara River, and between 1992 and 2017 in the Barguzin River. The flux of the sediment load into these rivers was 768×10^3, 88×10^3, and 29×10^3 t y $^{-1}$, respectively. This is 2–3 times less than the average multiyear values for all period of 1946–2017, which are usually used when characterizing sediment load runoff from these rivers. Currently the values in the given intervals correspond to the actual sediment load flux into Lake Baikal from the main tributaries.

Keywords: sediment load flux, Selenga River, Upper Angara River, Barguzin River, Lake Baikal

1. Introduction

The river fluxes affect the morpho-lithodynamics of the shore zone, its ecological state, sedimentation processes, and the health of the aquatic ecosystem of water bodies. The sediment loads play a crucial role in these processes, as they are able to accumulate and transfer various substances into water bodies. Currently, significant changes in the sediment load occur in many large rivers of the world. In general, the sediment load of many rivers diminished and, therefore, its inflow into water bodies decreased (Syvitski, 2003; Walling and Fang, 2003; Milliman et al., 2008). The decrease of sediment load supply into water bodies and its consequent impact on their aquatic and coastal systems have become a global topic (e.g., Dai et al., 2009; Wang et al., 2011; Lu et al., 2013; Zhao et al., 2015; Timpe and Kaplan, 2017; Dorjsuren et al., 2018). A decrease of the sediment load for the main tributaries of Lake Baikal – the Selenga, Upper Angara, and Barguzin Rivers, which bring the main volume of sediments to the lake, is also observed. The river sediment load runoff in Lake Baikal basin is defined by the interaction of a number of natural factors (relief, ruggedness and composition of rocks, type of soils and vegetation, weathering, and climatic conditions), as well as by anthropogenic activity.

At present, a special attention is paid to the ecological state of Lake Baikal and its shallow zone because of local negative ecological processes observed there, for example, blooms and increase of productivity of toxin-producing cyanobacteria and filamentous algae, disease of endemic Baikal sponges – a natural filter of the lake water, a fecal pollution of the shore waters, etc. (Timoshkin et al., 2016). These negative processes are likely connected with both climate changes and human activities (Potemkina et al., 2018). Therefore, the preservation of the world's largest lake – Baikal, containing about 20% of freshwater reserves of the world, the natural UNESCO World Heritage Site, requires a better understanding of the current trends in the natural processes and ecology, including the river runoff.

The catchments of the main tributaries – the Selenga, Upper Angara, and Barguzin Rivers – occupy more than 90% of the total catchment of Lake Baikal. The long-term data on their water and sediment load runoff characterize natural and anthropogenic changes in almost all territory of the lake basin. Usually, the sediment load runoff is characterized by an average value over all monitoring period. However, at present, this value differs from the actual sediment load supply into Lake Baikal. Therefore, this study is aimed: (1) to detect periods of temporal changes of the sediment

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load in the context of the climate and anthropogenic changes; and (2) to assess the actual sediment load supply from the main tributaries into the lake. The results of the study may be important for investigating processes related to hydrology, geomorphology, biogeochemistry, sedimentology, pollutant supply and ecology in the tributaries-Lake Baikal system. They are of relevant interest for other freshwater lakes in the world, too.

2. Materials and methods

We have analyzed long-term observation series of hydro-meteorological data (water discharge and sediment load, air temperature and precipitation). The long-term hydro-meteorological parameters cover the period from 1946 to 2017. The long-term hydrological data were obtained from the Hydro-meteorological Centre of Russia (Roshydromet). The long-term meteorological parameters (air temperature and precipitation) for the river basins were received from the NCEP/NCAR (The National Centers for Environmental Prediction/The National Centre for Atmospheric Research) global reanalysis database, which is accessible on the ESRL (The Earth System Research Laboratory) website (https://www.esrl.noaa.gov/). They are available in NetCDF (Network Common Data Form) format. The original data were the average monthly air temperature values with a regular grid step of $2.5 \times 2.5^{\circ}$ and monthly average precipitation values with a grid step of $1 \times 1^{\circ}$. For the further analysis, the data on the average monthly precipitation intensity were converted into the total precipitation per month.

Statistical methods were used to examine the relationships between the hydro-meteorological parameters and their tendencies (trend analysis, pair correlation, linear-trend coefficients). The non-parametric Mann-Kendall (M-K) test allowed determining the significance of a trend, which was considered to be significant at the $p < 0.05$ level. In addition, the M-K rank statistics and cumulative anomalies method (Feidas et al., 2004; Zhao et al., 2015) made it possible to detect the beginning of changes in the hydrological parameters of rivers.

Study area

The studied tributaries – the Selenga, Upper Angara, and Barguzin Rivers (the largest by water runoff and sediment supply) – are situated on the eastern shore of Lake Baikal. The Baikal tributaries bring about 60 km^3 of water into the lake annually, among them the studied tributaries account for 27.2, 8.48 and 3.82 $km^3\ y^{-1}$, respectively. These rivers are the main sources of river sediment load as well: the Selenga River – 1535×10^3 t y^{-1}, the Upper Angara River – 243×10^3 t y^{-1}, the Barguzin River – 90×10^3 t y^{-1}. The values are the mean annual water runoff and sediment load supply of main tributaries for the period of 1946–2017.

The catchments of the main tributaries are located in different natural conditions. The main general characteristics of the natural conditions in the basins of these rivers are an extremely continental climate and the presence of permafrost. There are significant differences, too. The drainage basins of the Upper Angara and Barguzin Rivers are framed by mountains and have a moderate humidity. The Selenga River drainage basin extends far southwards, to areas experiencing a moisture deficit (forest-steppe, steppe and desert areas). The main feeding sources of the Selenga and Barguzin Rivers are rain and melt waters with approximately equal contribution. Melt water is a typical feeding source of the Upper Angara River (Resursy…, 1973). The mouth areas of three main tributaries belong to different hydro-morphological types. The mouth area of the Selenga River is an open multi-arm advancing delta. The mouth area of the Upper Angara has a semi-closed delta that is formed in lagoon separated from the lake by a coastal bar. The Barguzin River has a delta-free one-arm mouth area. Water and sediment load enters directly the Barguzin Bay, which goes far into the shore.

3. Results and discussion

The hydrolithodynamics and ecology of the Baikal shore zone and of Lake Baikal mostly depend on quantity and quality of substances and pollutions supplied by main tributaries. Herewith, an essential importance in this issue belongs to river sediment loads (Chalov et al., 2016; 2018). The global warming recorded since the mid-1970s led to changes in the regional hydro-meteorological parameters and natural processes in the river catchments, including the sediment load. In addition, socioeconomic activities also contributed to the changes in the sediment load. Moreover, at present, negative ecological processes in the shallow zone of Lake Baikal are observed (Timoshkin et al., 2016). Therefore, it is very important to assess the actual sediment load supply into Lake Baikal from its main tributaries in the context of the climate instability and anthropogenic pressure for monitoring the ecological state and hydrolithodynamics of the lake and its shore zone.

An integrated analysis of changes of hydro-meteorological parameters, their values and trends during the monitoring period was performed. The period of 1946–2017 was divided into two: 1946–1975 (baseline) and 1976–2017 (warming) periods. Changes in natural processes and anthropogenic pressure were negligible during the baseline period, whereas they considerably increased during warming period. During the baseline period, the sediment load fluctuations were in general synchronous to the water discharge fluctuations, i.e., the sediment load dynamics was determined by hydro-climatic factors. During the warming period, this synchronization was broken.

The average temperature has risen by +1 °C in the river basins over the warming period having a statistically significant trend according to the M-K test. A decrease of precipitation (2–9%) in the river basins was observed during 1976–2017. Against the background of the increasing temperature and decreasing precipitation, the water discharge has a slightly negative trend (5–13%) for the Barguzin River and the Selenga River and a slightly positive trend (2%) for the Upper Angara River. However, the sediment load has decreased greatly (53–72%) since the beginning of the warming period (Table) and has a statistically significant trend according to the M-K test. Obviously, there are other processes caused by the warming and human activities. The main ones are permafrost degradation, changes in atmospheric circulation, evapotranspiration, soil erosion, upward movement of vegetation in mountainous areas, weathering of rocks, etc. (Törnqvist et al., 2015; Kasimov et al., 2017). Socioeconomic activities (changes in the agriculture, land use, various mining activities, construction of roads, urbanization, etc.) also contributed to the sediment load decrease.

The use of the M-K rank statistic and cumulative anomalies method made it possible to detect the beginning and the intervals of changes of the hydrological parameters during the warming period and to clarify the actual sediment load supply into Lake Baikal. The statistical methods showed that the sediment load changes had begun since 1976 and their greatest decrease had occurred in the Selenga River over the interval 1996–2017, in the Upper Angara River over the interval 1985–2017 and in the Barguzin River over the interval 1992–2017 (Fig. 1). For these intervals, the water discharge in the Upper Angara and the Barguzin Rivers changed little in contrast with the baseline period (Fig. 2). In the Selenga River, the water discharge decreased by 26% in 1996–2017 in comparison to the baseline period. It exceeds the moderate average reduction of 13% for the entire warming period. The sediment load flux of the Selenga River in the given interval was 768×10^3 t y $^{-1}$, thus being smaller than the average value for all warming period – 1048×10^3 t y $^{-1}$ (Table). For the Upper Angara River, these values were 88×10^3 t y $^{-1}$ and 119×10^3 t y $^{-1}$, for the Barguzin River – 29×10^3 t y $^{-1}$ and 49×10^3 t y $^{-1}$, respectively. Thus, the values in the given intervals correspond to the actual sediment load flux from the main tributaries into Lake Baikal. This is 2–3 times less than the average multiyear values for the period 1946–2017 (Table), which are usually used for characterizing the sediment load runoff from the main tributaries into Lake Baikal.

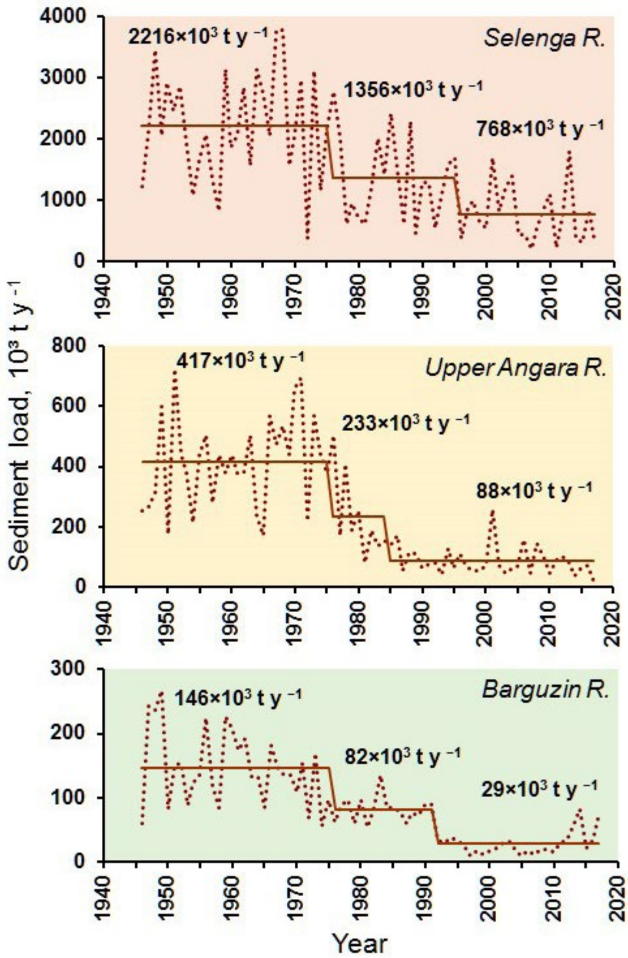

Fig.1. Actual sediment load supply from the main tributaries into Lake Baikal.

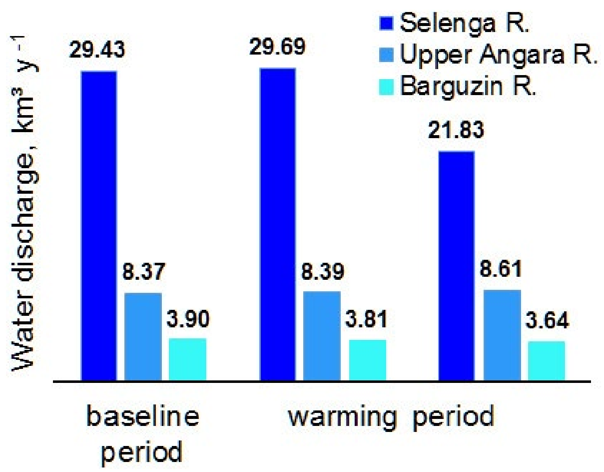

Fig.2. Changes of the water discharge at the given periods.

Table. Changes in the average annual water discharge (W, km^3 y^{-1}) and sediment load (S, 10^3 t y^{-1}) in the river basins in different periods

Period	Selenga R.		Upper Angara R.		Barguzin R.	
	W	S	W	S	W	S
1946–2017	27.18	1535	8.48	243	3.79	90
1946–1975	29.43	2216	8.37	417	3.90	146
1976–2017	25.57 (–13%)	1048 (–53%)	8.56 (+2%)	119 (–72%)	3.71(–5%)	49 (–66%)

Note. Data in parentheses indicate the relative change compared with the corresponding value in the baseline period (1946–1975); symbol '+' in the round brackets corresponds to the increase, whereas '–' represents the decrease.

4. Conclusions

The sediment load supply into Lake Baikal from its main tributaries – the Selenga, the Upper Angara and the Barguzin Rivers – has been considerably reduced since the mid-1970s. This is explained by climate change and socioeconomic activities. The statistical methods showed that the gradual sediment load decrease had begun since 1976 and its greatest reduction had occurred in the Selenga River over the period 1996–2017, in the Upper Angara River over the period 1985–2017 and in the Barguzin River over the period 1992–2017. The sediment load supply from the main tributaries into the lake during these periods was smaller than its average value for all warming period (1976–2017) and is only 35% of the baseline period (1946–1975) for the Selenga River, 21% for the Upper Angara River and 20% for the Barguzin River. Moreover, it is 2–3 times less than the average multiyear values for the period 1946–2017, which are usually used for characterizing the sediment load runoff from the Selenga, Upper Angara, and Barguzin Rivers into Lake Baikal. Thus, the values in the given intervals correspond to the actual sediment load flux from the main tributaries into Lake Baikal.

These results are important for further studies and forecast of the sediment load and pollutant supply from the tributaries into Lake Baikal, for analysis and evaluation of the ecological state and functioning of the shore zone and the whole lake. They can also be important for studying other lakes of the world that have similar natural conditions.

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Conflicts of 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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