

Peculiarities of Lake Baikal water level regime

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Abstract. A 15-year-old low-water period in the basin of Lake Baikal established an endurance record in the entire history of observations. It began in the mid 90s of the last century. With some probability it may continue in the following years. An analysis of meteorological series of air temperature and precipitation in the region is conducted. A statistically significant trend of increasing temperature and decreasing rainfall is revealed. Atmospheric precipitation affects the long-term fluctuations in the river run-off to a greater extent than the other elements of the water balance. An analysis of the inflow of water into Lake Baikal is performed. It is found that the water level of the lake almost directly depends on the water content of the Selenga River. The minimal run-off in dry periods, as well as the annual run-off, tends to decrease. It is a continuous series of low run-off, which provided the negative trend in the minimal run-off. A dendrochronological reconstruction of the Selenga River run-off is made. A statistically significant trend of decreasing Selenga River run-off is revealed in the recent decades, and an analysis of temperature and precipitation for the basin on the Russian side is made.

1. Introduction

Lake Baikal is the largest freshwater lake by volume in the world, containing roughly 20 % of the world's unfrozen surface fresh water.

With a volume of 23.6 thousand km³ of fresh water, it contains more water than all the North American Great Lakes together. With a maximum depth of 1642 m, the Baikal is the world's deepest lake. It is considered to be one of the clearest lakes and it is the world's oldest lake – 25 million years old. It is the seventh-largest lake in the world by surface area.

Known as the 'Galapagos of Russia', its age and isolation have produced one of the world's richest and most unusual freshwater fauna, which is of exceptional value to evolutionary science.

Lake Baikal together with the adjacent territories in 1996 was included in the UNESCO World Heritage List. In connection with this, the problem of the protection and conservation of lake water resources is acquired exclusively acute [1].

The Baikal Lake basin is located almost in the center of the vast Asian continent and covers an area of 545 km² (excluding water area of Lake Baikal), 45 % of which lies within the Russian Federation, the rest is on the territory of Mongolia. About 73 % of river waters are formed on the territory of Russia, 27 % – Mongolia [1].

Lake Baikal and its basin is a peculiar and very fragile natural ecosystem, which provides a natural process of water formation, famous for its transparency and purity.

Comprehensive study of the lake has a particular importance due to the problem of acute shortage



of fresh water. And according to experts, the world may face it in the coming decades. The most significant man-made interference with the natural state of the lake system was the construction of the Irkutsk hydroelectric stations and Baikal cardboard mill [2].

Because of the global warming in Transbaikalia the temperature of air limit layer increases, precipitation decreases [3]. All this has led to the low water content of the rivers flowing into the Baikal. There has been steady declining trend of the main flow of the Baikal tributary – the Selenga River due to the lack of rainfall [4, 5].

2. Materials and methods

An analysis of the meteorological series of air temperature and precipitation was held along the whole basin of Lake Baikal based on the initial data of weather stations and a global database of geospatial meteorological parameters Climate Research Unit – CRU (spatial resolution of 0.5×0.5 of angular degree) [6].

The Analysis of the hydrometeorological information was held on the basis of historical data and weather gauging stations of the Republic of Buryatia, Transbaikalia region and Mongolia.

3. Climate change in the Baikal region

On the basis of the annual CRU data a statistically significant trend of increasing temperature and decreasing rainfall in the basin of Lake Baikal was found.

Two humidification periods were allocated: 1980-1998 years – wet period (figure 1, a); 1999-2015 years – dry period (figure 1, b). The wet period is characterized by positive trends of precipitation totals for almost the entire basin of Lake Baikal, with the highest growth rate observed for Khamar-Daban ridge – 14 mm, and for the area of the Middle Baikal – 10 mm for the period under review (figure 1).

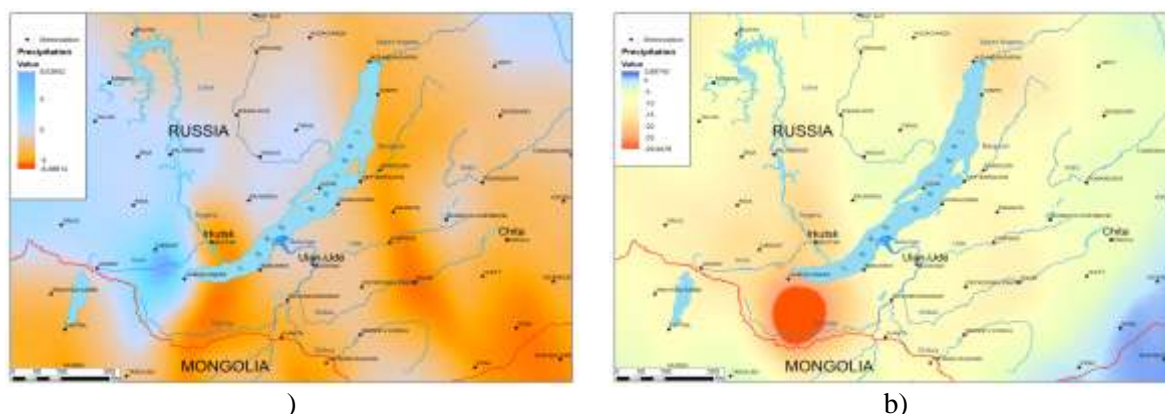


Figure 1. Map of linear trends of precipitation, mm for the period under review : a) 1980-1998 years; b) 1999-2015 years.

During the dry season in 1998-2015 years there is a negative trend in the amount of precipitation for the basin of Lake Baikal. Extreme reduction in moisture for the dry period under review is marked for Khamar-Daban ridge and amounts to -30 mm. In the Upper Angara and the Barguzin river basins the rate of decreasing reaches -18 mm. Atmospheric precipitation effects the long-term fluctuations in river flow to a greater extent than other elements of the water balance.

From 1885 to 2012 years the average annual air temperature in the Trans-Baikal region increased by 2.0 °C [5] (note that at the same time, the annual average temperature around the globe increased by 0.85 °C) [7]. The temperature increase is observed for the entire catchment area of Lake Baikal, while the areas with low growth rates of surface temperature are interspersed with areas with high growth rates, both in latitudinal and longitudinal directions (figure 2).

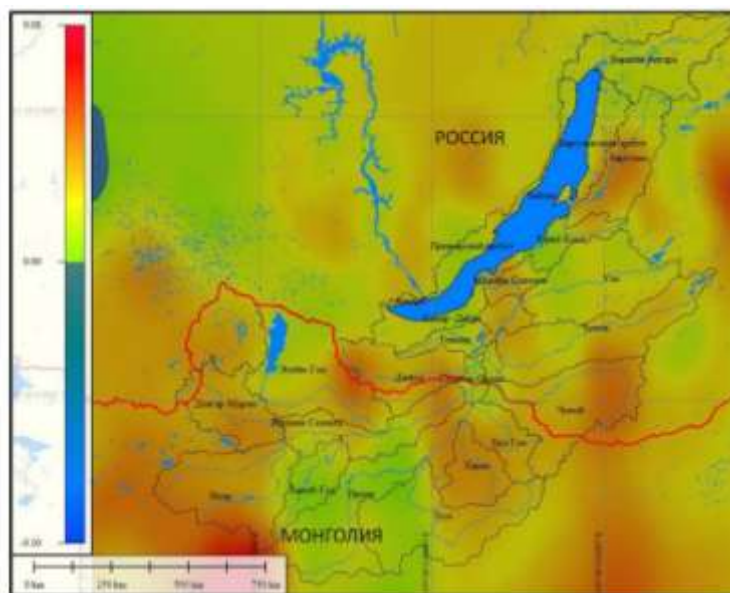


Figure 2. Map of linear trends of surface air temperature 2000-2014 years. (Winter months), °C/year.

4. Peculiarities of Lake Baikal water level regime

After the construction of the Irkutsk hydroelectric station (1956) Lake Baikal became an artificial water reservoir, as its level is being determined, to a greater extent, not by natural factors but the interests of the hydropower industry [2].

It should be noted that since 1996 Lake Baikal is UNESCO World Natural Heritage site. Due to the fact that the Baikal is an artificial reservoir, it can lose this honorary status, which may lead to the risk of inclusion of Lake Baikal to the list of World Heritage in Danger.

The actual water levels of Lake Baikal in vivo (1900 – 1956 yrs.) ranged from 454.93 m (historical minimum was recorded in 1904) to 457.10 m (maximum was recorded in 1869). In regulated conditions (1960 – 2015 yrs.) the minimum mark was registered in 1982 – 455.27 m, the maximum in 1988 – 457.42 m (hereinafter used Pacific Heights system).

Average annual useful inflow into the lake during the observation period (1900-2015) is 1872 m³/s, in vivo – 1916 m³/s, minimum average annual inflow into the lake was observed in 1903 – 1106 m³/s, the maximum was in 1932 – 3251 m³/s; over-regulated in the period – 1824 m³/s, the minimum inflow was recorded in 1979 – 1244 m³/s, the maximum – in 1973 – 2848 m³/s [8].

If the outflow of Lake Baikal will be controlled, it may gradually lose its uniqueness and over the time this can lead to the loss of biodiversity up to the complete disappearance of many species. When the level exceeded 457.0 m, during the high-water years in the middle of the 90-ies of the last century, low-lying coastlines of the east coast were destroyed (coastal forests, recreation zones, beaches and coastal constructions), it caused environmental damage throughout the natural and biological complex of lake system [9]. It should be noted that the real threat of complete destruction of Yarki island ridge that separates the open Baikal from Verkhneangarsky shallows exists. When approaching the lake level to the mark 457.0 m and a corresponding wave of activity for 3-5 days Yarki island group would be flooded, as a result Lake Baikal would increase to the north up to 40-50 km and Verkhneangarsky sor and the delta of the Kichera River, the Upper Angara River will completely disappear. Cold Baikal water will destroy all unique ecosystems of shallow waters in the delta of the Upper Angara and the Kichera including Verkhneangarsky omul race. At the same time the parameters of the lake water bowl and consequently the level regime will change [10].

If the level of Lake Baikal is extremely low, we can observe changes in the groundwater regime and groundwater lowering; violation of the existing mechanisms of Baikal water purification; reduction in water exchange of the sor system with open Baikal, the increase in average temperatures

and heavy overgrowth of shallow water; the death of aquatic organisms on the shore of the lake and the coastal system as a result of drying and freezing of the habitats, which are responsible for the processing of organic matter; peat fires in the Selenga River delta [11].

The spring-and-summer period in 2015 was characterized by great losses of forests from fires in the Republic of Buryatia. The dynamics of forest fires on the lands of the State Forest Fund of the Republic for the period from 1936 to 2015 was analyzed. According to the Federal Forestry Agency of the Republic of Buryatia from April to October of 2015 Forest fires caught the area of 750,500 hectares, that exceeds the long-term annual average by 12 times. The total damage caused by the forest fires was 20.46 billion rubles (according to the minimum rates of payment for standing timber) and 203.36 billion rubles (according to the auction prices of standing timber). It should be noted that the calculations do not include the basic costs of firefighting.

Before the construction of the Irkutsk hydroelectric complex (in natural conditions) the level of the lake varied in the range up to 2.17 m. During the period of operation of the Irkutsk hydroelectric station until 2001 the level of the Baikal was 17 times higher than the mark of 457.0 m and 18 times it fell below 456.0 m [12]. After acceptance in March 26, 2001 of the Russian Federation Government Decree № 234 "On the limit values of the water level in Lake Baikal in the implementation of economic and other operations" the level fluctuated in the meter range (456.0–457.0 m), but on 25.02.2015, for the first time since 2001, it fell below the mark of 456.0 m. This is primarily the result of the low water period, which was established in the middle of the 90-ies of the last century and was the highest rate ever recorded. The situation with the low-water level of Lake Baikal basin escalated in June of 2014, continued throughout the summer and autumn of the last year and continues in 2016. With a certain degree of probability it can continue in the following years.

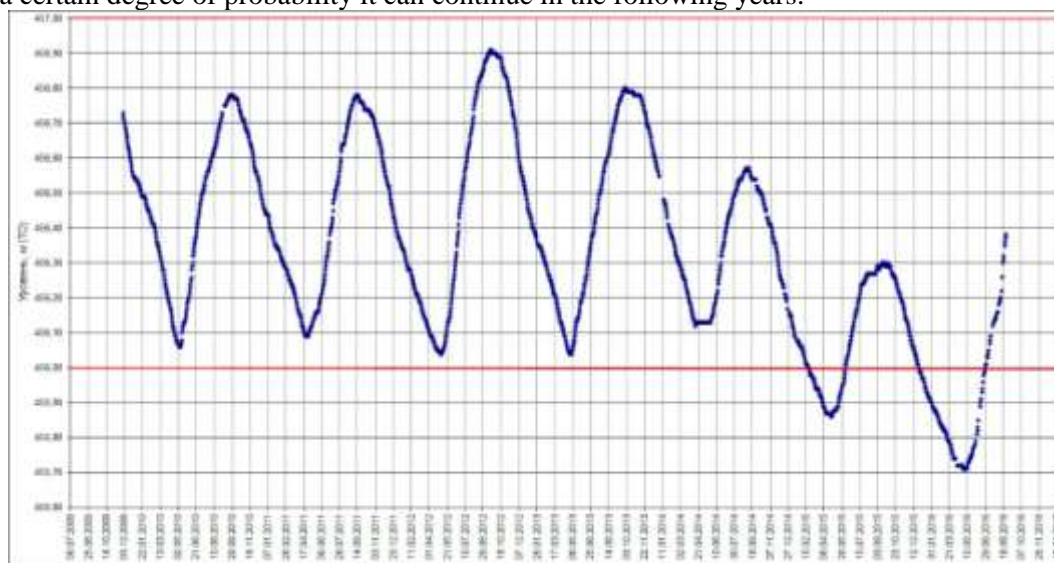


Figure 3. Average water level of Lake Baikal (2009-2016).

Due to the anomalously high air temperatures and almost complete absence of rainfall, inflow of water into the lake in the last 2015 was extremely low. The volume of inflows in 2015-2016 aquicultural years expected to be close to a minimum, which observed in the 1903-1904 years and amounted 34.7 km^3 . In the current aquicultural year, inflow is expected to reach 35.3 km^3 at long time average annual value of the normal equal to 61.9 km^3 . Thus, the useful inflow deficit could reach more than 26 km^3 .

It should be noted that in 2015 the level below 456.0 m was observed (with a recession) from February 19 to (at rise) June 5, 108 days duration. The Minimum level mark 455.86 m was detected on April 26-28. The maximum level of Lake Baikal water was 456.30 m, which is the lowest value since 2001. In 2016 the level below 456.0 m was observed (with a recession) December 26 to (at rise) June, 29, 184 days duration. The Minimum level mark 455.71 m was detected on April 28 to May 06.

An analysis of the inflow of water into Lake Baikal was carried out. The minimum and maximum water flow, volume of the flow of the major rivers of Lake Baikal basin were studied. It was found that the run-off of the Upper Angara and the Barguzin rivers in the last 20 years has remained within the long-term average rate, the Selenga run-off was reduced and now stands at 65 % of the normal value. Together, these three rivers provide 70 % of the annual inflow of water into Lake Baikal. The level of the lake almost depends on the water content of the Selenga. A good alignment between the inflow fluctuations in Lake Baikal and the Selenga river run-off was determined, which was confirmed by the high values of correlation of the coefficients between these variables: for the observation period (1934-2014) – 0.85, during the dry periods (1954-1958, 1976-1982, 1996-2014) – 0.68 [8].

The formation of water resources in the catchment area of Mongolia which accounts 67 % of the watershed district of the Selenga was studied. The dynamics of the Selenga and the Orkhon rivers flow, its main tributary, was studied. High-water period of the Selenga River was observed from 1979 to 1995. In recent years shallow period in the Selenga River basin is observed. Thus for the last 20 years about 700 rivers and 450 lakes dried up in Mongolia according to the Institute of Meteorology and Hydrology of Mongolia (Ulaanbaatar). The Government of Mongolia intends to start the construction of hydroelectric power station "Shuren", designed in the middle reaches of the main riverbed of the Selenga. Besides "Shuren" HPS it is planned to build hydroelectric power plants on the tributaries of the Selenga – Orkhon, and Delgermuren and Egiin-Gol. Let us note that such actions of Mongolia and the World Bank violate international convention on transboundary waters and a number of other international agreements.

The minimum flow during the dry periods, as well as the annual flow, tends to decrease. It is a continuous period of low flow which provided a negative trend of the minimum flow. Thus, the inflow of water into Lake Baikal in recent years is the record-breaking minimum for the whole period of instrumental observations.

5. Reconstruction of the water flow of the Selenga river basin

Unfortunately, for a full analysis of the history of the Baikal fluctuations, we have a too short period of instrumental observations – only 110 years. Considering that our object under study is Lake Baikal, which is the oldest lake in the world (20-35 Million years), this short period of observation data does not allow us to get a more or less objective picture of the changes in its level for a longer time. In this regard, only long-term series of observations will allow to define changes in moisture regime correctly. An analysis of trees annual rings will allow to extend essentially climatic characteristics data [14-18]. For example, the reconstruction of the Baikal level dendrochronological data is presented in the work of Andreev SG [19].

According to gauging stations and dendroclimatic stations, a spatio-temporal reconstruction of river flow parameters in the Selenga river basin was conducted [20]. As a result, water flow model reconstruction of the Selenga River and its tributaries – rivers: Uda, Khilok, Chikoy, Dzida, Orkhon and Kharaa was obtained (figure 4).

For individual watercourses the time-series until 1666 have been restored. This allowed us to reveal regularities of moisture fluctuations in Baikal Asia in retrospective.

In general, figure 4 shows that there is a spatial and temporal coherence of growth of trees with water flow dynamics of the Selenga River and its tributaries. This is particularly evident in the dry and humid periods. The correlation values for individual tributary basins are analyzed. The maximum value of 0.66 is a generalized chronology obtained through 8 local chronologies and "responsible" for the valley of the Jida River. Jida River Valley is an isolated area, surrounded by high mountain ranges. Here, the formation of run-off is within the valley. This explains the close relationship with the growth of water consumption of trees, depending in turn on the incoming water from the atmosphere. High correlation can be traced to the small rivers in the steppe and forest steppe zones.

For the Chikoy River connection with wood rings is smaller ($R = 0.47$). This value can be explained by the fact that the formation of the Chikoy river flow is under the influence of the Pacific air masses coming in the second half of the summer on the east and affecting the upper catchment

area, thereby weakening the bond dendrochronological series of stations located in middle and lower parts of the valley.

It should be noted that the reconstruction of the Kharaa River water flow, built on the same stations as for the Chikoy River, shows a similar picture while taking into account that Kharaa basin is located 300 km to the south. This coupling is determined by the general laws of the Chikoy and Haran rivers run-off formation.

Annual fluctuations in water of the Orkhon River flow showed a close relationship ($R = 0.53$) with stations located in the Jida River Basin. The values obtained for the correlation between the indices of growth of annual rings and instrumental measurements of river flows on Mongolian part of the Selenga River Basin (for the river Kharaa - 0.47 for the Orkhon River - 0.53) allow us to expand our network of stations in the basins of these rivers and get more reliable model reconstruction.

XX century in comparison with the previous was provided with water. The general trend of the XX century has the following character: until mid-century, water availability has increased, reaching a peak in the mid-1940s, and then began to slowly drop. The modern period is characterized by an increase in water content.

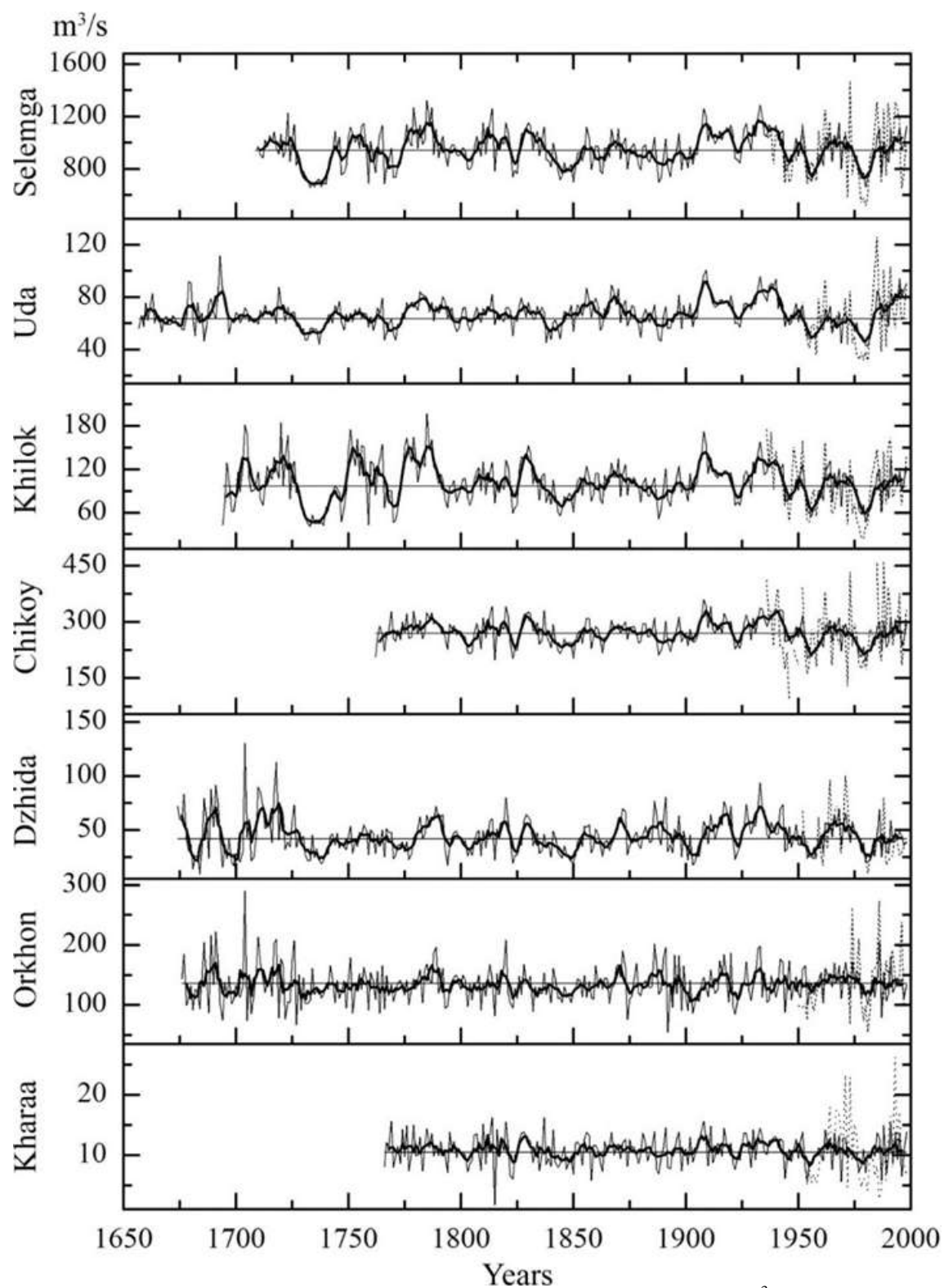


Figure 4. The reconstruction of the Selenga River basin rivers water discharge (m³/s). Legend: dashed line – instrumental measurements of water flow for gauging stations, thin curve – year-by-year reconstruction, bold curve – smoothed reconstruction over 5 years, the horizontal line – water flow rate during the instrumental period.

It is interesting to compare the data of historical chronicles with the reconstructed series of water flow.

6. A comparison of the historical chronicles with a time series of water discharge

Detailed chronological comparison of historical records and moisture regime on the basis of the reconstruction of the water regime was carried out [21]. Analysis of historical records is an indirect verification of the received time-series for the reconstruction of water flow in the Selenga River Basin.

There was a relatively high-water period from 1700 to 1725. For example, 1715 - "is a very rainy year in Mongolia", falls on the peaks of the reconstructed water consumption [21]. From another source [22] we know that Petropavlovskaya Fortress was built at the confluence of the Chikoy and Selenga rivers and it was first mentioned in 1713. Due to regular annual flooding in 1726 S.L. Vladislavich-Raguzinsky ordered the transfer settlement on 2 mile upstream of the Chikoi River. In 1727, I.D. Buchholz built Petropavlovskaya Fortress in a new place. Petropavlovskaya Fortress increasingly served not as a military target, but as trading posts, where caravans were formed for trade with China.

The period 1726-1745 was characterized as arid and is marked on our reconstructions. In the historical sources for the West Transbaikalia and Mongolia, these years are marked as dry and barren ("great drought") for decades [21]. A similar period, but for a shorter development time was observed in the modern period - in the late 70's - early 80's of the XX century.

Period 1746 - the end of the 50s of the XVIII century was marked by floods in the Selenga River. They peak in 1751, when the great flood was recorded.

Time intervals 1758-1761, 1778-1810 - periods of drought in Mongolia.

The following period was characterized by registered floods. The peak recorded in 1830 - "... great flood on the Selenga River. In Selenginsk most of the right-bank structures were washed away. As a result, in 1841 the city had to be moved to the left bank ... "[21].

1860 year is a year of the summer drought in Central Mongolia. 1862 year in the Trans-Baikal region was marked by the drought: "... unbearable heat, terrible drought, so the crops are bad, a little grass ...". It is noteworthy that in the same year on the Gusinoe lake islands had disappeared, that is, the lake was filled. This fact is explained by the intensification of tectonic processes in the Baikal region during this period (the formation of the Gulf of failure, etc.), and is not related to moisture regime. There was a "great flood on the territory of Buryatia" in the spring and summer of 1866. In 1869: "... the unusual flooding in Irkutsk Province and West Transbaikalia, the level of the lake rose nearly seven feet under the usual ..., ... a great flood on the Selenga ..., ... level in Verkhneudinsk increased up to 1.81 fathoms, part of the city and many villages were flooded ..." [23]. The end of the XIX century as a whole is characterized by the historical chronicles as a dry period. The beginning of XX century was characterized by a sharp increase in water consumption values, which is consistent with our obtained reconstructed series of streamflow.

Thus, considering the high correlation of the Selenga run-off and the lake level, we can indirectly have an idea of the fluctuation of the water level (inflow of water) in the lake for the last 300 years. For example, we already have the opportunity to respond specifically, whether high or low water levels in the lake have been observed in the middle of the XVIII and XIX centuries. This good correspondence of water level in the lake with a volume of annual runoff of the Selenga opens up new opportunities for data on the level of the lake regime over the past three centuries.

5. Conclusions

Thus, a significant transformation of the natural environment is currently observed in the Baikal Lake basin.

In particular, a statistically significant trend of increasing temperature and decreasing precipitation is established with the identification of wet and dry periods. In recent years, due to abnormally high air temperatures and almost complete absence of atmospheric precipitation, water flow into the Lake Baikal has been extremely low during the whole period of instrumental observations. As a result, there

were problems with the level of the Baikal Lake regime.

There is a high year and seasonal growth in response to the current draft in the dendrochronological series for specific areas. Spatio-temporal coherence growth trees with water flow dynamics of the Selenga River and its tributaries was revealed. So statistical models of reconstruction of water flow in the article show good correlation ($r = 0.47 \dots 0.66$) between the increase in the annual rings of Scots pine and annual consumption of water.

For example, the Mongolian part of the Selenga River Basin shows that the spatial relationship between the water drain and dendroclimatic stations located on the territory of Russia, can be traced for hundreds of kilometers. The data flow rates for a large time interval can serve as a basis for the planning of water resources management. This aspect is particularly relevant for the Selenga River, because of its cross-border location.

It was found that for forest-steppe regions of the Baikal Asia as limiting factor for tree growth are the atmospheric precipitations which form the water flow of the Selenga River Basin rivers.

These historical records without pretending to accuracy of the tool are an illustration of indirect, fragmentary verification of the received time series for the reconstruction of water flow in the Selenga River Basin. However, a significant correlation in the reconstruction of models allows you to use the data for retrospective analysis of periods of droughts and floods.

6. Acknowledgments

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