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WATER RESOURCES AND THE REGIME OF WATER BODIES

Many-Year Variations of River Runoff in the Selenga Basin

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Abstract—Many-year variations of river runoff in the Selenga basin are analyzed along with precipitation, potential evapotranspiration, and basin water storages. Data of ground-based (1932–2015) and satellite observations, as well as the analysis of literature data suggest the presence of within-century cycles in the series of annual and minimum runoff. Compared with 1934–1975, the Selenga Basin shows a general tendency toward a decrease in the maximum (by 5–35%) and mean annual (up to 15%) runoff at an increase in the minimum runoff (by 30%), a decrease in the mean annual precipitation (by 12%), and an increase in potential evapotranspiration by 4% against the background of a decrease in evaporation because of lesser soil moisture content and an increase in moisture losses for infiltration because of permafrost degradation. The observed changes in water balance may have unfavorable environmental effects.

Keywords: runoff variations, climate changes, Selenga basin, Lake Baikal, low-water period

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INTRODUCTION

The global warming since the late XX century has a considerable effect on the hydrological cycle and therefore, on river runoff dynamics [5, 40]. Air temperature rise can cause an increase in evaporation and a decrease in snow river nourishment in temperate latitudes. These changes involve the precipitation, its amount, and the character of distribution over both space and time. The expected effects include an increase in the number of extreme hydrometeorological events because of the intensification of water turnover [38, 40, 48]. The global climate change, which started in the early 1970, has an appreciable effect on the hydrological processes, in particular, in the basin of the largest lake on the planet, Lake Baikal, as well as on the river runoff in its basin [10, 21]. The year-to-year and seasonal variations of water inflow into Lake Baikal determine the conditions of its ecosystem functioning and the management strategy of its water resources. Changes in river water flows causes changes in the discharges of suspended and dissolved substances. Changes in river water regimes have an effect on the functioning of aquatic ecosystems by changing the magnitudes, duration, passage time, the frequency, and the rate of changes in water flows in the river [30].

The key factor of ecosystem stability in Lake Baikal is the regime of the Selenga R., which carries up to 50% of water and more than 50% of the chemical runoff [6]. Selenga water resources are of great importance for the water management activity in Mongolia and Buryatia, and determine a considerable part of the hydropower potential of HPPs in the Angara chain [43].

Studying many-year variations of river flow in the Selenga basin has become of particular importance because of the long dry period, which has led to a considerable drop in Baikal water level [2, 14, 18, 19]. The dry period, lasting since 1996, requires an improvement in the operation regime of the Angara HPP chain, which has been regulating regulated water flow from Baikal since 1963. In addition, the need for studies is due to the anticipated construction of HPPs on the Selenga and its tributaries in accordance with plans of Mongolian Government.

The objective of this study is to analyze the space and time variations of various characteristics of river runoff in the Selenga Basin in the XX–XXI centuries. The main tasks are as follows: the collection and treatment of the up-to-date ground and remote-sensing hydrometeorological information, statistical analysis of hydrological data series, analysis of formation conditions of Selenga runoff in periods of medium and extreme water abundance.

MATERIALS AND METHODS

Study Area

The Selenga is a transboundary river, the largest tributary of Lake Baikal. On the average, it discharges into Baikal ~30 km^3 of water, i.e., half of the total inflow into the lake. Forty six percent of Selenga annual runoff forms in Mongolian territory. The length of the river is 1024 km, its drainage area is 447.06 thousand km^2, of which 148.06 thousand km^2 are in the territory of Russia.

The Selenga Basin lies in the zone of extremely continental climate; and a considerable portion of the basin is occupied by permafrost [50]. Runoff formation conditions in the Selenga Basin are very diverse. The southern part of the Selenga Basin shows low soil moisture content and steppe vegetation, while its northern part is covered by dense taiga vegetation and permafrost—an important source of soil water in summer. The large elevation difference (from 600 to 3000 m) also has its effect on runoff formation conditions.

Rains are the main source of Selenga R. nourishment. Snow cover in its drainage basin is not rich, hence the low share of snow in river nourishment. About half of Selenga annual runoff is the runoff over the summer (June–August), the role of groundwater in river nourishment is also small [2]; therefore, its runoff varies mostly because of variations of summer precipitation.

The rivers of the Selenga Basin show pronounced winter low-water period from November to March (3–10% of the annual runoff volume), a relatively low spring snow-melt flood and a series of rain floods in summer and autumn. Many rivers freeze through in winter.

Meteorological Data on the Study Region

The article uses mean monthly data on precipitation P and potential evapotranspiration (PET) over 1934–2014, taken from a database of East Anglia University CRU TS 3.23, which had been constructed based on weather station data and which has a resolution of 0.5°. The completeness and representativeness of the data in this database for the Selenga Basin are analyzed in [50].

Hydrometric Data on the Study Region

The statistical analysis of the many-year series in the Selenga Basin was carried out on the data of 29 gages, chosen in Russian territory by the longest runoff observation series, and eight gages in Mongolia (Fig. 1).

Data on 2013 [37] were used in the Russian part of the basin (Table 1). Selenga runoff at the Mostovoi gage in 2014 and 2015 was evaluated by short-term observation data. Data on Mongolian gages are available only up to 2005–2011.

In this study, the authors analyzed only series of annual and maximum water discharges as well as minimum winter 30-day discharges for rivers not freezing through.

Terrestrial Water Storage

The terrestrial water storage (TWS), comprising surface and soil water, groundwater, and water storages in snow and permafrost were evaluated using data of GRACE project (Gravity Recovery and Climate Experiment). GRACE provides data on mean monthly TWS values in the nodes of the grade grid, three of which have been published [36] by the Geophysical institute GFZ (Potsdam, Germany), Center of Space Researches CSR (Austin, USA), and Jet Propulsion Laboratory (Pasadena, USA). These massifs were used to calculate the averaged TWS values in Selenga basin over 2002–2015. In addition, the results of the authors of [55] were used. To do this, multichannel singular spectral analysis (MSSA) was used to filter data and to identify principal components with different periods (many-year and seasonal variations of water storage). Data of the GRACE project are in wide use for hydrogeological studies at both global and regional levels [9, 29, 35, 47, 52].

Statistical Analysis of Runoff Series

The analysis of many-year variations of river runoff in the Selenga Basin includes the assessment of quasiperiodicity and autocorrelation, trend, and statistical homogeneity of the series.

The characteristics evaluated for the series under study included expectation Q_0, variance S^2, standard deviation S, the coefficient of variation C_v, the coefficients of autocorrelation between the runoff in successive years in the examined series r_1 and their errors [20]. The estimates were based on the method of moments. Corrections for bias were introduced for autocorrelation. To identify the phases of higher and lower water abundance, cumulative integral curves were used. Anderson's parametric test and the nonparametric series test were used to test the series for independence [3, 20].

Spearman trend test was used to check the series for monotonous (upward or downward) trend.

The homogeneity (stationarity) of the series was checked by t-test and F-test. The t-test is used to assess the homogeneity of hydrological series in terms of their expectation, while the F-test is used to assess their homogeneity in terms of variance. To apply t-test and F-test, the examined series is divided into two parts. In this case, the boundary years were taken to be 1975–1976 because of changes in the character of atmospheric circulation over the Selenga Basin, con-

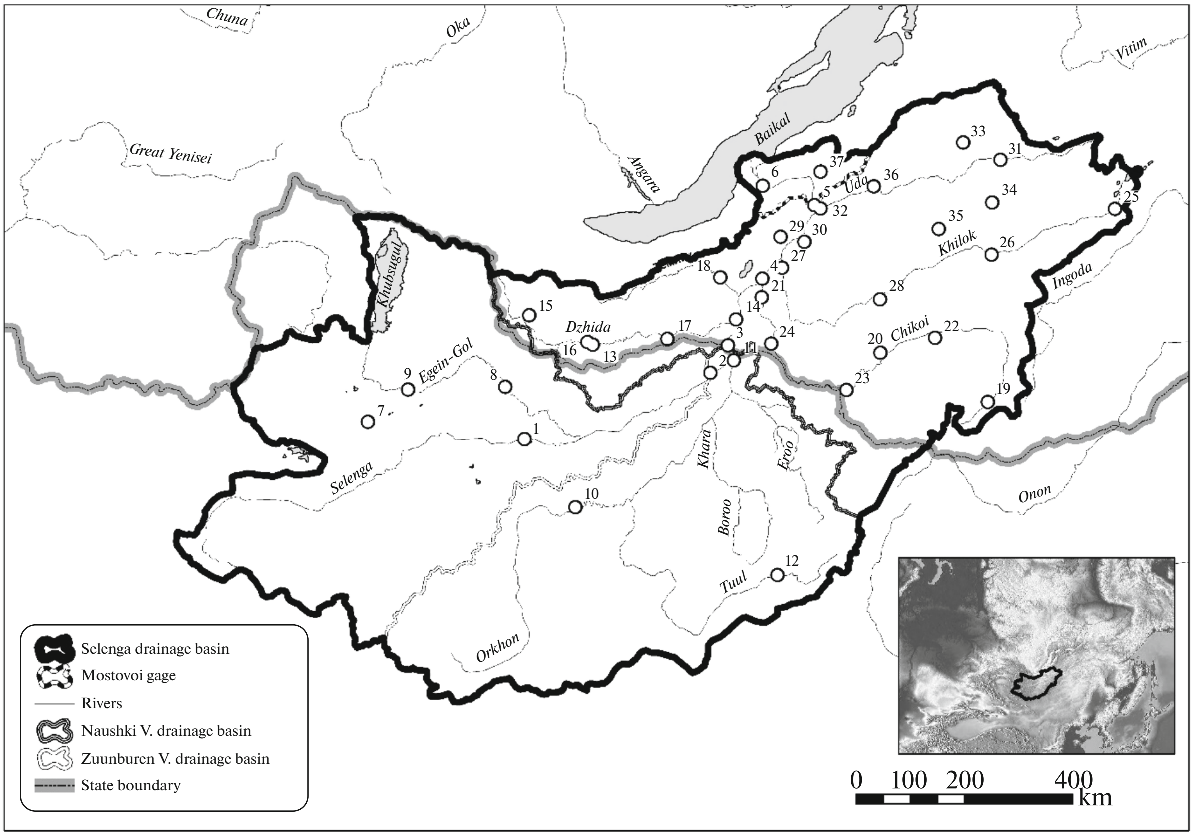

Fig. 1. Location of gages used in the study (Table 1).

sisting in a decrease in the intensity of the East Asian monsoon and the westward transport over this territory [2, 14]. In addition, according to [5], the period after 1976 shows the most rapid rise in surface air temperature, both all over the world and over Russian territory.

As *F*-test is intended for the analysis of independent series with normal distribution, only skewness C_s and autocorrelation r_1 were taken into account [8].

RESULTS OF THE STUDY

Assessment of Variations in Precipitation and Potential Evaporation

According to [50], the rate of increase in the mean annual air temperature over Baikal Basin (by 1.6°C) over 1938–2009 was almost twice as large as the growth rate of the global temperature (0.72°C over 1951–2012 [40]). As shown in [21], short (2–7 years) and long (~20 years) cycles with distinct phases of rise and drop can be identified in annual air temperature variations in Baikal region. Two complete cycles of annual air temperature (1912–1936 and 1937–1969) along with phases of two incomplete cycles, i.e., a decrease between 1896 and 1911 and an increase since 1971, can be seen in the XX century. The most recent ascending phase (since 1971) is anomalously long (~25 years) with an increase in temperature by 2.1°C. The general tendency toward an increase in air temperature near Baikal is typical of all seasons, though with different rates. The largest warming was taking place in winter and spring (the temperature rise was 2.0 and 1.4°C within 100 years, respectively); in summer and autumn, its velocity was 2–4 times less (0.8 and 0.5°C, respectively).

The present-day climate changes in Mongolian territory, where the basin of the upper and middle reaches of the Selenga R. lie, were studied in [44, 45]. In the territory of the Inner Mongolia, the warming rate was 0.29°C over 10 years for the period from 1980 to 2010 [45]. Overall, the mean annual air temperature in the eastern regions of Mongolia increased by 2.03°C over the recent 70 years. In period 1991 to 2009, it increased by 0.05°C per year [44].

From 1936 to 2010, precipitation in Transbaikalia decreased by 50–100 mm, though in some places (mostly in the northern part of the basin), it increased by 50 mm. The increase in the mean annual air temperature in Transbaikalia is in agreement with the tendency toward a decrease in the total, especially, lower cloud; it determines an increase in the duration of the warm season and a decrease in the under-snow period on the major portion of Transbaikalia [11].

The authors used CRU TS 3.23 to study the dynamics of changes in precipitation P, potential evaportanspiration PET, and the aridity index I_A ($I_A = P/PET$) both for the Selenga Basin as whole (SB) and for its subbasins: a basin up to Zunnburen V. section (HZ), from Zunnburen V. to Naushki V. (ZN), and from Naushki V. to Mostovoi sidetrack (NM) (Table 2).

The results of calculations, in accordance with UNESCO classification [41] show that the segment of Selenga watershed down to Zunnburen V. and its segment from Naushki V. to the mouth lie in subhumid zone, while the segment from Zunnburen V. to Naushki V., to semiarid zone. Note that none of the subbasins has passed into another gradation in terms of aridity in the period under consideration. However, an important feature is a decrease in precipitation depth and an increase in potential evaporation in all subbasins, resulting in a decrease in the aridity index I_A. The increase in PET is largest down to Naushki V., i.e., in the highest mountain regions. Earlier [28, 39], it was noted that the rate of temperature increase is higher in high-mountain regions.

According to Andersen and series tests, the series of annual and seasonal precipitation for all subbasins and seasons can be regarded as independent from their previous values. However, as can be seen from these tests, such dependence exists for PET in winter, seemingly, because of the effect of the Atlantic Multidecadal Oscillation [22], the influence of which is maximum in winter. In other seasons, Andersen tests shows some cyclicity in PET series. This may be due to the increasing trend in PET.

The variance of the seasonal and annual averages of precipitation and potential evaporation has not changed significantly by F-test over 1976–2014 compared with 1934–1975.

The decrease in precipitation mentioned above no doubt contributes to the decrease in runoff; however, the extent of this decrease has different manifestations in different periods.

Thus, while the mean annual runoff depth in the Selenga Basin in 1977–2014 was 10.7 mm (2.9%) less than that in 1934–1976, the runoff depth (according to data on Mostovoi gage, Selenga R.,) decreased by 8.4 mm (12.4%). The respective values for period 2002–2014 are 25.3 mm (6.7%) and 20 mm (29.6%). Note that, in the outlet section, the coefficient of correlation between the mean annual runoff and annual precipitation, both averaged over the entire basin, is 0.75.

Assessing Changes in the Annual, Maximum, and Minimum Runoff. Analysis of Annual Runoff Variations

The analysis of the runoff dynamics of the Selenga and its tributaries shows that runoff variations are of cyclic character (Fig. 2), as was mentioned by many researchers of Southern Siberia rivers [1, 12, 21, 22]. The high-water phases, lasting 12–17 years, give place to dry phases with a duration of 7 and more years. Two complete cycles were identified in the Selenga runoff in the period of hydrological observations (1932–1958 and 1959–1982). The high-water phase of the third cycle lasted from 1983 to 1995, and a transition to a low-water phase took place in 1996 (Table 3). The present-day low-water phase is the longest (20 years) all over the history of instrumental observations. In this period, the least mean annual dischages were recorded at the Selenga mouth (2002, 2007, and 2015). Selenga runoff at Mostovoi gage in 1996–2015 was 1.4 time less than that in the WMO reference period (1960–1990).

In Mongolian territory, the decrease in runoff in the same period was largest (more than twice) in the Orkhon and Tuul rivers. No considerable drop in runoff was recorded in the Delger–Muren R. in Selenga upper reaches. Overall, the runoff of the Selenga in the Mongolian part of its basin decreased 1.5 times in 1996–2013 compared with the average runoff over 1961–1990.

The comparison of annual runoff dynamics of large right- and left-hand tributaries of the Selenga within Russian territory shows their variations to be asynchronous (Fig. 3). In particular, the runoff of the Dzhida R. (a left tributary) after 1995 was 22% higher than it was in 1961–1990. On the other hand, the runoff of the largest right-hand tributaries of Khilok, Chikoi, and Uda (their total runoff amounts to 47% of the Selenga runoff at its mouth) was relatively high since the late 1970s to the early 1980s, as can be seen from the higher water abundance up to 1995–1998 and a synchronous drop in water abundance in the later years by a factor of 1.2–1.3 on the average.

Overall, runoff variations in the nearby right-hand Selenga tributaries are synchronous (pair correlation coefficient $r > 0.5$, and that between the large tributaries of Chikoi and Khilok is $r = 0.8$). No significant correlation was found to exist between the annual runoff of the Uda R. in Ulan-Ude C. and other rivers nor even the upstream section ($r = 0.4$).

The runoff of the rivers of Chikoi, Khilok, and Itantsa shows a close correlation with Selenga runoff in its lower reaches (Mostovoi gage, Kabansk V.). The coefficient of determination with Chikoi R. runoff, which accounts for almost one third (on the average, 29%) of the Selenga runoff, is 73%. Similarly, the dynamics of the Khilok R. (10% of inflow) accounts for 56–64% of Selenga runoff variance.

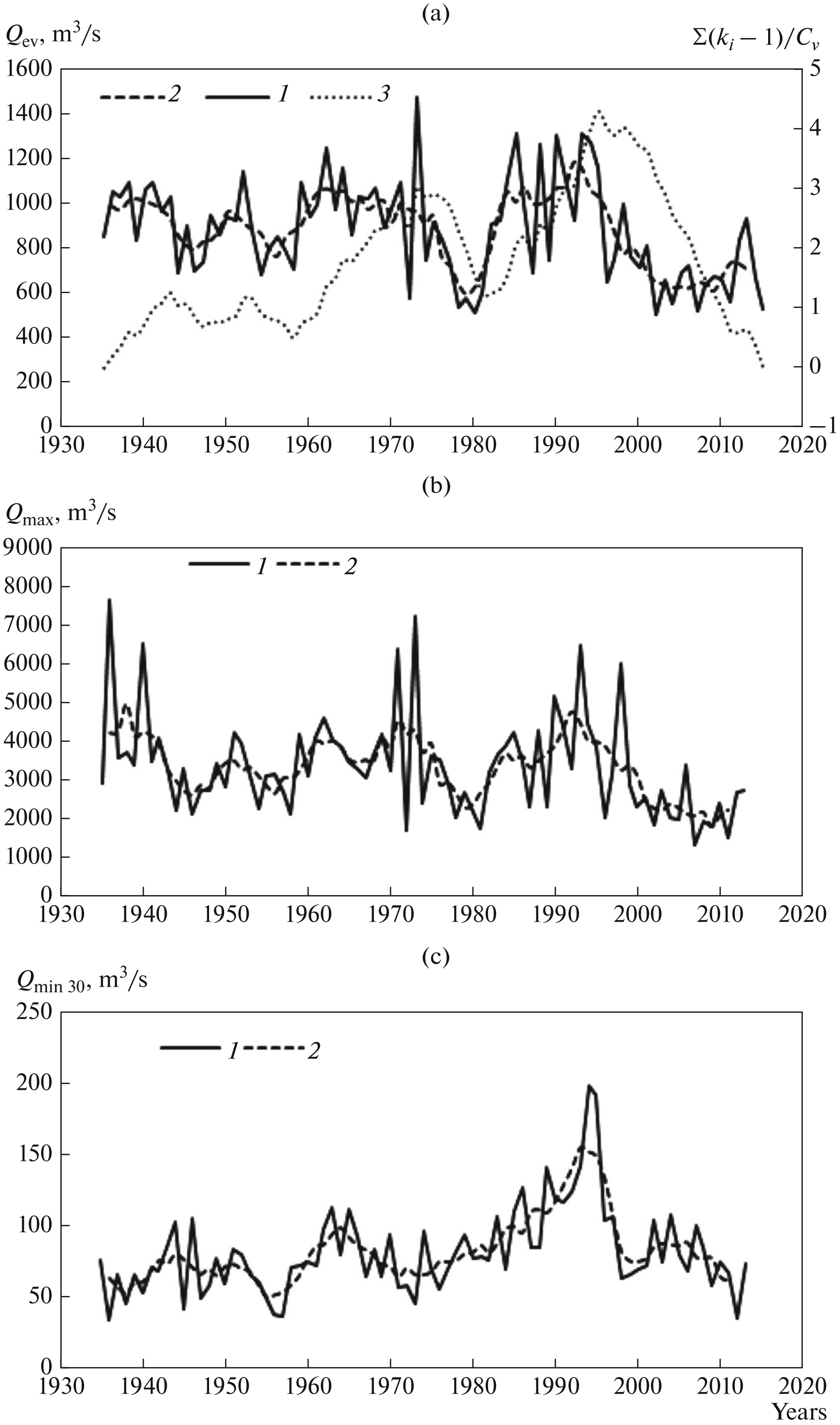

Fig. 2. Variations of (a) mean annual, (b) maximum measured, and (c) minimum winter 300-day discharge in the Selenga R. at Mostovoi gage ((*1*) measured values, (*2*) 5-year running window, (*3*) cumulated difference curve).

The tendency of runoff to cyclicity is confirmed by various statistical tests. The relationships within a series (a significant autocorrelation within a series, the rejection of the hypothesis regarding the independence of series terms) has been studied with the use of parametric Anderson test and a test less particular about the probability distribution function, i.e., series test. The majority of gages on the Selenga R. and many

Table 1. Characteristics of gages in the Selenga R. Basin

Gage no.	River	Gage	Distance to the mouth, km	Observation period	Series length	Area, km^2	Mean elevation of the basin, m
1	Selenga	Khutag V.	811	1945–2010	66	92300	1910
2	Selenga	Zuunburen V.	503	1975–2013	39	148000	–
3	Selenga	Naushki V.	402	1973–2013	41	282000	–
4	Selenga	Novoselenginsk V.	273	1932–2015	72	360000	–
5	Selenga	Mostovoi sidetrack	127	1934–2015	70	440000	–
6	Selenga	Kabansk T.	43	1971–2013	43	445000	–
7	Delger-muren	Muren V.	66	1950–2010	61	18900	2020
8	Eg	Erdenebulgan V.	260	1973–2004	32	15300	1860
9	Eg	Khantai T.	48	1960–2004	45	41000	1710
10	Orkhon	Orkhon V.	432	1945–2011	67	36400	1900
11	Orkhon	Sukhe-Bator C.	25	1950–2005	56	132000	–
12	Tuul	Ulan-Bator C.	547	1945–2011	67	6300	1850
13	Dzhida	Khamnei V.	318	1935–1942, 1955–2013	67	8480	1520
14	Dzhida	Dzhida V.	21	1939, 1943–1946, 1953–2013	67	23300	1200
15	Tsakirka	Sanaga hm st.	31	1958–2013	56	1030	1700
16	Khamnei	Khamneiskii bridge	1.2	1971–2013	43	3600	1500
17	Zheltura	Zheltura V.	2.2	1978–1979, 1981–2013	35	5120	–
18	Temnik	Ulan-Udunga ulus	59	1940–1943, 945–1949, 1954–1964, 1966–1968, 1971–2013	66	4240	1320
19	Chikoi	Semiozer'e V.	707	1980–2013	34	1340	1600
20	Chikoi	Gremyachka V.	385	1943–2013	71	15600	1300
21	Chikoi	Povorot V.	22	1936–1947, 1949–1950, 1952–2013	76	44700	1230
22	Atsa	Atsa V.	17	1949–2013	65	2010	1320
23	Katantsa	Khilkotoi V.	9	1953–2013	61	2120	1330
24	Kiran	Ust'-Kiran V.	2.5	1964–1980, 1982–1985, 1987–2013	48	1130	860
25	Khilok	Sokhondo St.	773	1952–1997	46	1900	1040
26	Khilok	Khilok T.	522	1947–2013	68	15400	1080
27	Khilok	Khailastui V.	22	1936–2013	78	38300	990
28	Ungo	Ust'-Ungo V.	8.2	1950–2013	64	2290	1100
29	Orongoi	Orongoiskii bridge	16	1939–1940, 1942, 1947, 1950–2013	68	1840	920
30	Kuitunka	Tarbagagai V.	12	1959–2013	55	1060	850
31	Uda	Ust'-Egita V.	328	1956–2013	58	3900	1010
32	Uda	Ulan-Ude C.	5.1	1936–2013	78	34700	940
33	Ona	Nizhnyaya Maila V.	66	1968–2013	46	2660	1180
34	Kudun	Mikhailovka V.	104	1955–2013	59	3300	990
35	Kizhinga	Novokizhinginsk Settl.	81	1960–2013	54	820	970
36	Kurba	Novaya Kurba V.	4.7	1948–2013	66	5500	1080
37	Itantsa	Turuntaevo V.	22	1961–2013	53	2120	920

Table 2. Precipitation, potential evaporation, and aridity index in the Selenga Basin over 1934–2014

Sub-basin		1934–1975	1976–2014	1934–2014
HZ	P	426	418	422
	PET	608	633	619
	I_A	0.68	0.70	0.66
ZN	P	324	307	316
	PET	700	737	717
	I_A	0.44	0.46	0.42
NM	P	358	346	353
	PET	615	633	623
	I_A	0.57	0.58	0.55
SB	P	376	364	370
	PET	637	664	650
	I_A	0.57	0.59	0.55

other rivers of its basin (the Orkhon with Tuul, Khilok, Uda in its upper reaches, Kizhinga, and Itantsa) show a considerable autocorrelation ($0.31 < r_1 < 0.59$) and the violation of Anderson independence test at the significance level of 1%. The autocorrelation ($r_1 = 0.65$) was highest for the Eg R. (Erdenbulgan gage), which is most likely due to the river nourishment from Lake Khubsugul. In the rivers with considerable autocorrelation, mentioned above, the series test statistics also showed a statistically significant trend toward grouping of years with higher or lower water abundance at a significance level of 1%. The hypothesis of independence of the terms in annual runoff series was accepted for the rivers of Delgermuren and Chikoi.

The identified runoff cyclicity can be due to both the regulating capacity of watersheds and other factors (such as atmospheric circulation specifics and evaporation regime).

The presence of series with higher and lower water abundance can be due to both a correlation between runoff values in different years and the presence of a statistically significant negative linear trend according to Spearman test. In the case of a negative trend, wet years will occur in the beginning of the period, while dry years, in its end.

A trend was observed in four out of six runoff gages on the river (the only exceptions are the gages at the villages of Zunnburen and Kabansk, where the series are shortest). The manifestation of a trend is also due to a long dry period in the end of the series: a significant negative trend with $\alpha = 5\%$ was observed since 2008, and that at $\alpha = 1\%$, since 2010.

The series of mean annual discharges were tested for homogeneity (stationarity) with the use of Fisher's variance ratio F-test and Student's t-test of the equality of expectations. The situations when the homogeneity condition was not true at the significance level $\alpha = 5\%$, were regarded as dubious, and the final conclusion regarding homogeneity hypothesis for the series was made at $\alpha = 1\%$. The series were divided into 2 periods: before 1975 and after it.

The identified periods show a statistically significant increase in the variation (variance) of the mean annual discharges in four gages: at Khutag V. on the Selenga R., in the lower reaches of the Orkhon R., in the middle reaches of the Khilok R., and on the Kizhinga R. The situation with the Khilok R. is discussed in [6], where the increase in variance is attributed to the extremely wet years of 1983–1985 in the observation series. The considerable increase in the variance in the upper reaches of the Selenga and Orkhon is also due to the extremely high-water 1993, with an outstanding maximum discharge. However, if we take into account the considerable within-series correlation in the Selenga and Orkhon runoff (violation of the independence condition) and the violation of the series normality condition (the high value of skewness) and introduce appropriate corrections to the calculation of the critical value of F-test [16], the established increase in the variance will cease to be statistically significant.

The statistically significant descending trend by Spearman test was observed in 10 out of 35 gages. It is only at two gages that the trend of the mean annual Ыdischarges is positive (at Khilkotoi V. on the Katantsa R. and Dzhida gage on the Dzhida R.). The rank correlation coefficients for the mean annual discharge vary within the range from 0.45 at Dzhida gage

Table 3. Low- and high-water periods in the Selenga R. at Mostovoi gage

High-water periods			Low-water periods			Cycle duration, years	Mean discharge over the period, m^3/s
period, years	duration, years	mean discharge, m^3/s	period, years	duration, years	mean discharge, m^3/s		
1932–1943	12	1051	1944–1958	15	837	27	932
1959–1975	17	1004	1976–1982	7	674	24	908
1983–1995	13	1086	1996–2015	20	692	33	847

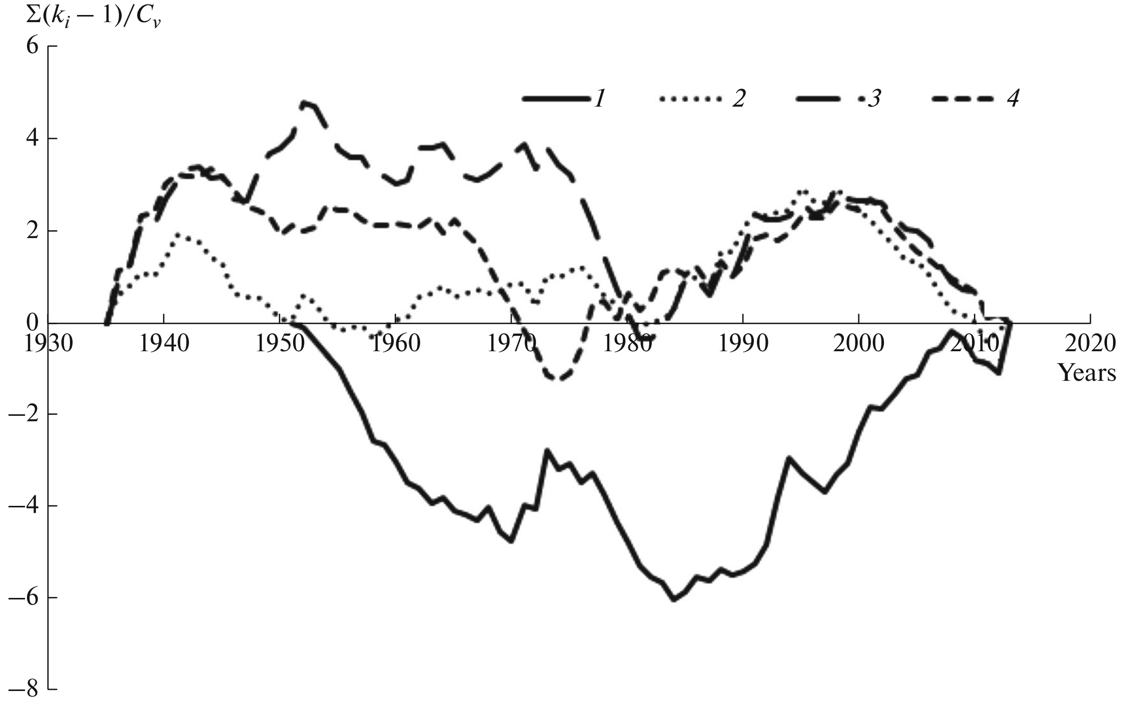

Fig. 3. Cumulated difference curves for annual runoff in major Russian tributaries of the Selenga. (*1*) Dzhida R. at Dzhida St., (*2*) Chikoi R. at Povorot V., (*3*) Uda R. at Ulan-Ude C., (*4*) Khilok R. at Khailastui V.

on the Dzhida R. to –0.62 at Tarbagatai V. on the Kuitunka R.

A reliable descending trend at a significance level of $\alpha = 1\%$ was observed at six gages. In the case of mean annual discharges these are the gages of Dzhida on the Dzhida R., Tarbagatai on the Kuitunka R., Orkhon on the Orkhon R., and gages on the Selenga R. (Naushki Settl., Novoselenginsk Settl., and Mostovoi).

Analysis of Maximum-Runoff Variations

Variations of maximum water discharges are closely correlated with mean annual discharges [6], especially, in large rivers, because of the effect of flood wave superposition. The general decrease in water abundance in the Selenga basin is followed by a decrease in maximum discharges (Fig. 2b). The lowest maximum water discharges in the Selenga within the Russian part of the basin were recorded in 2007; while those in its tributaries, in 2007 and 2011 or to the period from 1972 to 1981. The highest discharges in the upper reaches of the Selenga were recorded in 1993; in 1998, an absolute maximum was recorded in the Khilok R. No large floods were recorded in the Selenga Basin after 1998.

A statistically significant negative trend in the maximum water discharges was recorded at 14 out of 35 gages. Of these, seven gages show a significant trend in terms of both maximum and mean annual discharge. In the case of maximum water discharges, all trends are negative. The values of the coefficient of rank correlation for maximum discharges vary from –0.25 at Khailastui V. on the Khilok R. to –0.58 at Tarbagatai V. on the Kuitunka R.

A statistically significant descending trend at the significance level $\alpha = 1\%$ in the case of maximum individual discharges was recorded at seven gages: Zunnburen V., Naushki Settl., Novoselenginsk V., and Mostovoi on the Selenga R.; Orkhon V. on the Orkhon R.; Ust'-Ungo V. on the Ungo R.; Tarbagatai V. on the Kuitunka R.; and Turuntaevo V. on the Itantsa R.

Analysis of Variations of Minimum Runoff

Variations of minimum winter runoff in rivers of the Selenga basin are governed by two factors: water abundance in the basin in the previous warm season and low air temperature, which cause the cessation of groundwater nourishment and through freezing of many rivers with drainage area of up to 4 thousand km^2. Variations of minimum runoff show a statistically significant correlation with the annual runoff, though lesser than that of the maximum runoff. The many-year dynamics of winter runoff shows a steady increase, which may be due to an increase in air and soil temperatures [12].

The minimum 30-day runoff generally has a high within-series interdependence. The values of autocorrelation coefficients and Anderson test statistics demonstrate statistically significant within-series interdependence of nonfreezing gages in the majority of rivers in the basin, except for the Khilok and Selenga rivers in Mongolian territory. Series criterion showed a statistically significant tendency toward grouping of winters with higher and lower water abundance at $\alpha = 5\%$ for a half of the gages under consideration.

The significance of changes in minimum runoff was checked by Spearman nonparametric trend test. A significant positive trend at $\alpha = 5\%$ was found in the Lower Selenga (Mostovoi gage), Eg, Dzhida, Chikoi, and Khilok rivers. However, the changes in the minimum winter discharges cannot be regarded as a steady increase (Fig. 2c). The minimum runoff in rivers in the Selenga Basin has been decreasing since 1995 because of both the general decrease in water abundance and a drop in winter air temperature since 1988 [13]. Thus, while the minimum winter 30-day discharges over 1976–2013 at Mostovoi gage on the Selenga R. are 31.4% greater than those in 1934–1975, the similar excess in 1996–2013 is as little as 10.2%.

Nevertheless, the many-year increase in winter runoff has already led to a considerable disturbance of the homogeneity of the series. The statistics of Student's *t*-test for the equality of expectations for Selenga runoff in Novoselenginsk and Mostovoi and for the Dzhida and Chikoi were in excess of the critical value of 2 at the significance level of 5%, i.e., the mean minimum winter runoff over 1976–2013. *F*-test also showed a statistically significant increase was also obtained in the variance of minimum 30-day winter discharges.

DISCUSSION OF RESULTS

In period from 1934 to 2015, the heat and water regime in Selenga Basin changed significantly, including, primarily, an increase in the mean air temperature and a decrease in precipitation (especially, extreme summer precipitation), which caused a decrease in soil moisture content [46], an increase in its winter temperature, and permafrost degradation [54].

In this study, 10 out of 35 examined gages showed statistically significant changes in the mean annual water discharges, of which 8 (including the outlet section of the Selenga R.) showed a decrease in runoff. The inverse tendency at Dzhida gage on the Dzhida R. is likely due to the greater amount of precipitation [51]. The decrease in runoff was largest in the Orkhon R. basin.

Fourteen gages showed a statistically significant descending trend in the maximum water discharges. Estimates show that the decrease in the mean annual runoff is mostly due to the decrease in the summer freshet discharges. This conclusion is supported by both significant decrease in the mean precipitation in summer by Student's *t*-test (Table 2) and a decrease in the extreme precipitation [46]. The decrease in the maximum discharges also caused a significant decrease in their variances. A change in the minimum winter discharges, i.e., an increase in their magnitude and variations in the Selenga Basin, is also typical of the entire Northern Eurasia [34, 49], mostly because of an increase in winter air temperature [12, 31]. However, because of the strong dependence of minimum winter discharges on the discharges in summer freshet period [6] and a decrease in winter air temperature since 1998 [12], the mean water discharges over the most recent period of 1996–2013 are close to the mean values over 1934–1975 (Fig. 2c). The increase in the minimum water discharges has a positive effect on water quality through the dilution of industrial and municipal wastewaters.

The increase in air temperature allows some researchers to consider the increase in evaporation as a factor of river runoff decrease in the Selenga Basin [50]. However, the authors' studies suggest a decrease in evaporation in the Selenga Basin in the present-day dry period, as compared with 1934–1975, because the decrease in precipitation compared with this period is greater than that of runoff. However, notwithstanding the decrease in evaporation, the runoff coefficient for 1996–2014 was 0.14, compared with 0.18 for 1934–1975. The leading factors in the decrease in evaporation for the Selenga Basin seem to be a decrease in soil moisture content [46] and an increase in seasonally thawed layer [49, 53, 54]. Because of this, a decrease in evaporation takes place, notwithstanding the increase in potential evaporation.

As the increase in the seasonally thawed layer leads to a decrease in evaporation through an increase in the share of groundwater inflow, the groundwater storages also increase. A confirmation of this is the relative stability (Fig. 4, curve *1*) or even increase by 40–60 mm (Fig. 4, curve *2*) of the total water storages in the Selenga Basin, estimated by GRACE gravimetric data since 2002.

If curve *2* in Fig. 4 is correct, this implies that 3.1–4.6 mm of precipitation depth in 2002–2014 were spent for increasing the basin water storage (i.e., 7–9% of the average long-term runoff over this period).

Figure 4 clearly demonstrates the intense increase in TWS in 2012–2013, when Selenga runoff was nearly equal to its mean many-year value. The minimum TWS value was recorded in 2002 (the driest year over 1934–2015). The increase in the estimated basin water storage against permafrost degradation and a decrease in soil moisture content may be due to both errors in precipitation depth over the periods under consideration [1, 2] and the replacement of ice in soils by denser water.

A considerable uncertainty exists in the forecasts of the future river runoff regime in the Selenga Basin, even if the mean annual values are meant [26, 46, 50]; this refers to both the magnitude and direction of such changes. At the same time, the tendency toward a

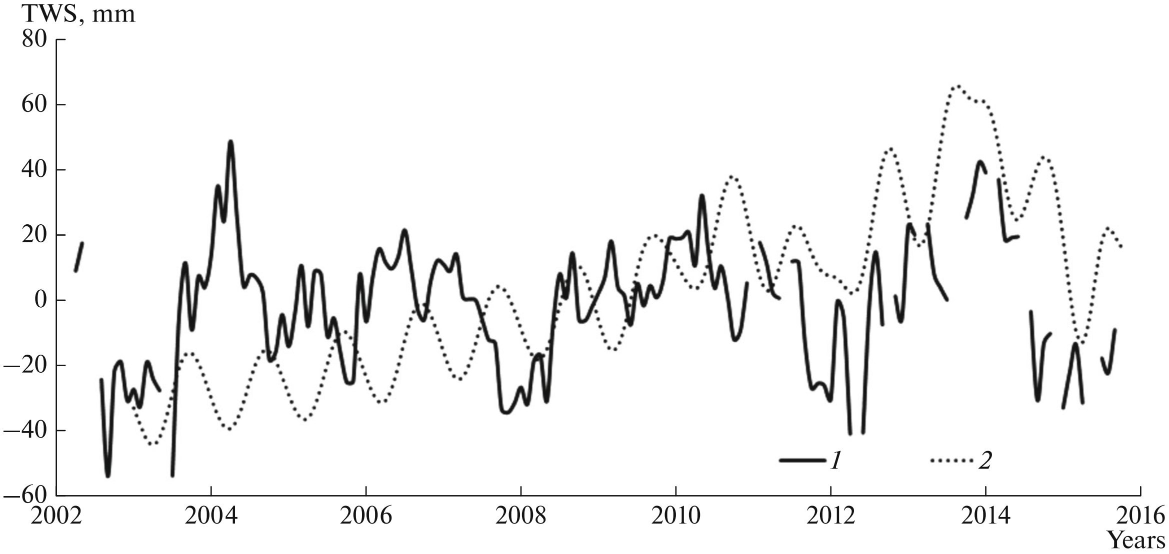

Fig. 4. TWS variations in Selenga R. Basin from April 2002 to September 2015: (*1*) mean by CSR, GFZ, JPL; (*2*) the authors' calculations based on MCCA [9, 55].

decrease in the summer precipitation still persists, at least on the Mongolian part of the basin [46]. On the other hand, an increase in both the annual runoff of rivers and the annual precipitation is expected [50]. However, no water resources deficiency is forecasted for the Selenga Basin [25, 27], even under a negative scenario of precipitation decline, because of the poor economic development of the territory [6].

If the Mongolian plans of HPP construction on the rivers of Egiin-Gol, Chargait, Orkhon, and the Selenga itself (Egiin, Chargait, Orkhon, and Shuren HPPs) is implemented, the runoff from Mongolian territory will decrease by 0.11 km^3 because of an increase in evaporation from reservoir surfaces (the additional water intake not taken into account), amounting to ~0.5% of the Selenga runoff at its mouth. The largest changes may take place in the within-year runoff redistribution: winter runoff will increase and maximum discharges will drop [7], resulting in changes in the runoff regimes of dissolved matter and sediment, which form the unique delta.

Quasi-cyclic oscillations play an important role in many-year runoff variations in the Selenga Basin [4, 12, 15, 21]. The analysis of Selenga Runoff dynamics at Mostovoi gage since the early 1930s shows that annual runoff variations are cyclic with a period of 20–30 years. Currently, the runoff is in its low-water phase, which began in 1996 and which shows the longest duration and the lowest water all over the period of instrumental observations. All gages on the Selenga (except for Zunnburen V., where, however, the input data may contain errors) show a significant coefficient of correlation $0.31 < r_1 < 0.59$ and a tendency toward grouping of years with higher and lower water abundance. The most recent dry period (Fig. 3) had a considerable effect on the extent of within-series correlation. The series of maximum water discharges in Selenga Basin rivers can be considered independent both by Anderson test and by series test.

The dendrochronological reconstructions of the runoff in the upper reaches of the Selenga (Khutag V. gage) [32, 33] in the recent four centuries show a wide range of river runoff variations compared with the period of instrumental observations. Overall over the XX century, the Selenga runoff in its upper reaches featured higher water abundance compared with the mean, calculated for the four centuries. The droughts and dry periods on the Selenga, according to the reconstruction, could have longer duration and lesser water abundance, a situation that can occur again in the future.

The annual runoff of the Selenga largely determines Baikal level variations. After the commissioning of the Irkutsk HPP in 1958, the runoff from the lake through the Angara has been regulated and Baikal mean level has risen by 80 cm [17, 18]. A specific feature of the present-day low water abundance is the increase in the contribution of northern Baikal tributaries with snow and mixed nourishment (the rivers of Upper Angara, Barguzin, and others) to the river water inflow into the lake. The mean share of the Selenga R. decreased from 50–55% in high-water periods of 1983–1995 to 35–40% in 2000 (at the mean annual value of 48%) [2]. The low water abundance in the Selenga caused a decrease in the general river water inflow into the lake.

CONCLUSIONS

A typical feature of the rivers in the Selenga basin is runoff cyclicity with a period of 15–30 years. The present-day low-water period (since 1995) is unprecedented in both the depth and duration throughout the observation period.

A significant decrease is taking place in both mean annual and maximum water discharges. Note that, in this case, the decrease in the mean annual discharges is due to the lesser discharges in the summer freshet period. This is caused by a decrease in the total and extreme precipitation in summer.

The minimum winter water discharges show a significant increase because of an increase in the winter air temperature in the recent decades. However, in the current low-water period, the increase in the minimum discharges has a lesser effect than it had in the previous 20-year period; this is due to the lesser discharges in the summer freshet period an a drop in winter air temperature.

The decrease in the mean annual river runoff and precipitation and an increase in potential evaporation are accompanied by a decrease in evaporation caused by lesser soil moisture content and greater infiltration losses because of permafrost degradation. No significant changes in TWS have taken place since 2002.

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