

# Runoff fluctuations in the Selenga River Basin

Natalia L. Frolova<sup>1</sup> · Pelagiya A. Belyakova<sup>1,2</sup>  · Vadim Yu. Grigoriev<sup>1,3</sup> · Alexey A. Sazonov<sup>1,3,4</sup> · Leonid V. Zotov<sup>5,6</sup> · Jerker Jarsjö<sup>7</sup>

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**Abstract** The Selenga River has historically provided 50% of the total freshwater water input to the Lake Baikal, transporting substances and pollutants that can considerably impact the unique lake ecosystem. In the context of on-going regional to global change, we here aim at identifying and understanding mechanisms behind spatial and temporal variability and trends in the flow of the Selenga River and its tributaries, based on hydrological and meteorological station data (since the 1930s), remote sensing, and statistical analyses. Results show that the flow of the Selenga River exhibits cycles with phases of high flows lasting 12 to 17 years and phases of low flows that historically lasted for about 7 years. However, despite an asynchronous behavior between right-bank tributaries and left-bank tributaries, the flow of the Selenga River near its delta at Lake Baikal has now been

low (30% below the 1934–1975 average) for as long as 20 years, due to reduced input from precipitation, particularly during the summer season. Observed decreases in annual maximum hourly flows and decreases in annual minimum 30-day flows are consistent with increasing activation of the groundwater system due to thawing permafrost, and higher winter temperatures that support increased winter flows by preventing rivers to freeze from top to bottom. These recent and relatively large changes have implications for regional water planning and management, including the planned large-scale hydropower expansion in the upper part of the Selenga River Basin.

**Keywords** Runoff fluctuations · Climate change · Selenga River · Lake Baikal · Low flow period

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✉ Pelagiya A. Belyakova  
hydropolya@gmail.com

Natalia L. Frolova  
frolova\_nl@mail.ru

Vadim Yu. Grigoriev  
vadim308g@mail.ru

Alexey A. Sazonov  
sazonov.lesha@gmail.com

Leonid V. Zotov  
wolftempus@gmail.com

Jerker Jarsjö  
jerker.jarsjo@natgeo.su.se

<sup>1</sup> Department of Land Hydrology, Lomonosov Moscow State University, Leninskie Gory 1, 119911 Moscow, Russia

<sup>2</sup> Hydrometcentre of Russia, B. Predtechensky per. 11-13, 123242 Moscow, Russia

<sup>3</sup> Water Problems Institute of the Russian Academy of Sciences, ul.Gubkina 3, 119333 Moscow, Russia

<sup>4</sup> S.I.Vavilov Institute for the History of Science and Technology of the Russian Academy of Sciences, ul.Baltiyskaya 14, 125315 Moscow, Russia

<sup>5</sup> National Research University Higher School of Economics, Myasnitskaya ul. 20, 101000 Moscow, Russia

<sup>6</sup> Sternberg State Astronomical Institute, Universitetsky pr. 13, 119234 Moscow, Russia

<sup>7</sup> Department of Physical Geography, and the Bolin Centre for Climate Research, Stockholm University, SE-106 91 Stockholm, Sweden

## Introduction

Global warming that has become apparent in the second half of the twentieth century can greatly influence fluxes of water and substances of the hydrological cycle, including the dynamics of river runoff (Hartmann et al. 2013; Second 2014). Higher air temperatures can for instance lead to increased evapotranspiration, reduced spring-time snow melt, and lower average river flow during the growing season. Greenhouse gas-driven changes in precipitation patterns have furthermore impacted on absolute amounts of precipitation received in drainage basins, as well as spatio-temporal distributions within the basins. In particular, the water cycle is expected to intensify, which can also lead to an augmentation of extreme hydrological and meteorological events (Huntington 2006; Schneider et al. 2013; Hartmann et al. 2013).

For example, global warming has considerably affected hydrological processes in the drainage basin of Lake Baikal, which contains 25% of the world's unfrozen surface waters and is the largest fresh water lake in the world. The observed changes notably include the flow characteristics of the principal rivers of the Lake Baikal Basin (Shimaraev et al. 2002; Latysheva et al. 2009). In turn, such changes also impact the riverine transport of suspended and dissolved matter, including carbon, nutrients, and pollutants (Thorslund et al. 2012; Chalov et al. 2015), as well as the functioning of aqueous ecosystems (Bunn and Arthington 2002).

These on-going changes have important implications for management strategies for water resources of the Lake Baikal Region. The largest river of the Lake Baikal Basin, the Selenga River, discharging up to 50% of all freshwater water input to Lake Baikal and more than 50% of the total dissolved matter (Garmaev and Khristoforov 2010), is hence of major importance for the Lake Baikal ecosystem. Furthermore, the water resources of the Selenga River are of great importance for economic activities of Mongolia and Buryatiya (Mun et al. 2008), since its drainage basin is relatively densely populated, including for instance the Mongolian Capital of Ulan Baator, and the principal Buryatian town of Ulan-Ude. Analysis of long-term fluctuations of water flow in the basin of the Selenga River becomes especially important because of the long duration of low flow period which has led to a significant decrease of water level of the Baikal (Berezhnykh et al. 2012; Sinyukovich et al. 2013). The Selenga River also plays a significant part in the hydraulic energy potential of hydraulic power plants (HPP) of the Angara cascade; Mongolia intends to build several HPP on the Selenga and its tributaries. In addition, prolonged periods of low flow would require a reconsidering of the existing Angara reservoir cascade in Russia, which since 1963 controls the water outflow from Lake Baikal.

From a scientific viewpoint, the Selenga River provides an important example as one of the world's major rivers that is still essentially unregulated, although its drainage basin contains large cities. Water intake in Mongolian and Russian parts of the basin changed together with economic growth till the end of 1980s. Annual water withdrawal in Russian part of the basin reached maximum  $0.96 \text{ km}^3$  in 1982 ( $0.37 \text{ km}^3$  irretrievable water consumption) and then, because of economic crisis, decreased to  $0.48 \text{ km}^3$  by 2001, with subsequent stabilization at  $0.5 \text{ km}^3$  ( $0.065 \text{ km}^3$  irretrievable) (State 2016). In Mongolian part, there has been notable increase of water intake in last 20 years by 29% due to urbanization and growing mining activities. In the mid-2000s, irretrievable water consumption in both the Russian and Mongolian parts of the basin was about  $0.23\text{--}0.25 \text{ km}^3$  which corresponds to  $0.8\text{--}0.9\%$  of the Selenga River runoff measured at Mostovoy gauge (Mun et al. 2008). Indirectly, the amount of river runoff is affected by the landscape change in the catchment area. At present, the area under agricultural use is more than  $34,000 \text{ km}^2$ , the area disturbed by mining is  $2214 \text{ km}^2$ , and the area of settlements is about  $900 \text{ km}^2$  (in 1960, it was about  $600 \text{ km}^2$ ), and the area of forests is about  $180,000 \text{ km}^2$  (Mun et al. 2008).

Consequently, whereas its water discharge and sediment yield respond to climate change and human pressures (Korytny et al. 2003), it is not being artificially altered by flow regulation schemes. There is hence a large potential to study river characteristics in the context of greenhouse gas-driven climate change, land-use change, and water use change, which have overlapping and interacting effects that despite their significance are in general not yet fully understood (Jarsjö et al. 2012; Törnqvist et al. 2015; Karthe et al. 2015). This is for instance reflected in state-of-the-art climate models (or earth system models), which despite their use in projecting future hydro-climatic conditions of river basins across the world have unresolved problems regarding their ability to reproduce historical changes (Bring et al. 2015). Clearly, an important step for increasing the understanding of underlying change mechanisms is to analyze and critically evaluate spatio-temporal characteristics of such historical hydro-climatic data, e.g., distinguishing random fluctuations in the records from actual trends.

Our working hypothesis is that the Selenga River system has already undergone unreported hydro-climatic shifts that are significant in the context of understanding regional change. We therefore aim at identifying spatial and temporal variability and trends regarding different runoff characteristics of the Selenga River and its tributaries, during the twentieth and twenty-first centuries. We address these aims through collecting and processing recent surface and remote hydrological and meteorological data, and statistical analysis of time series of hydrological characteristics, including analysis of extreme flows.

## Materials and methods

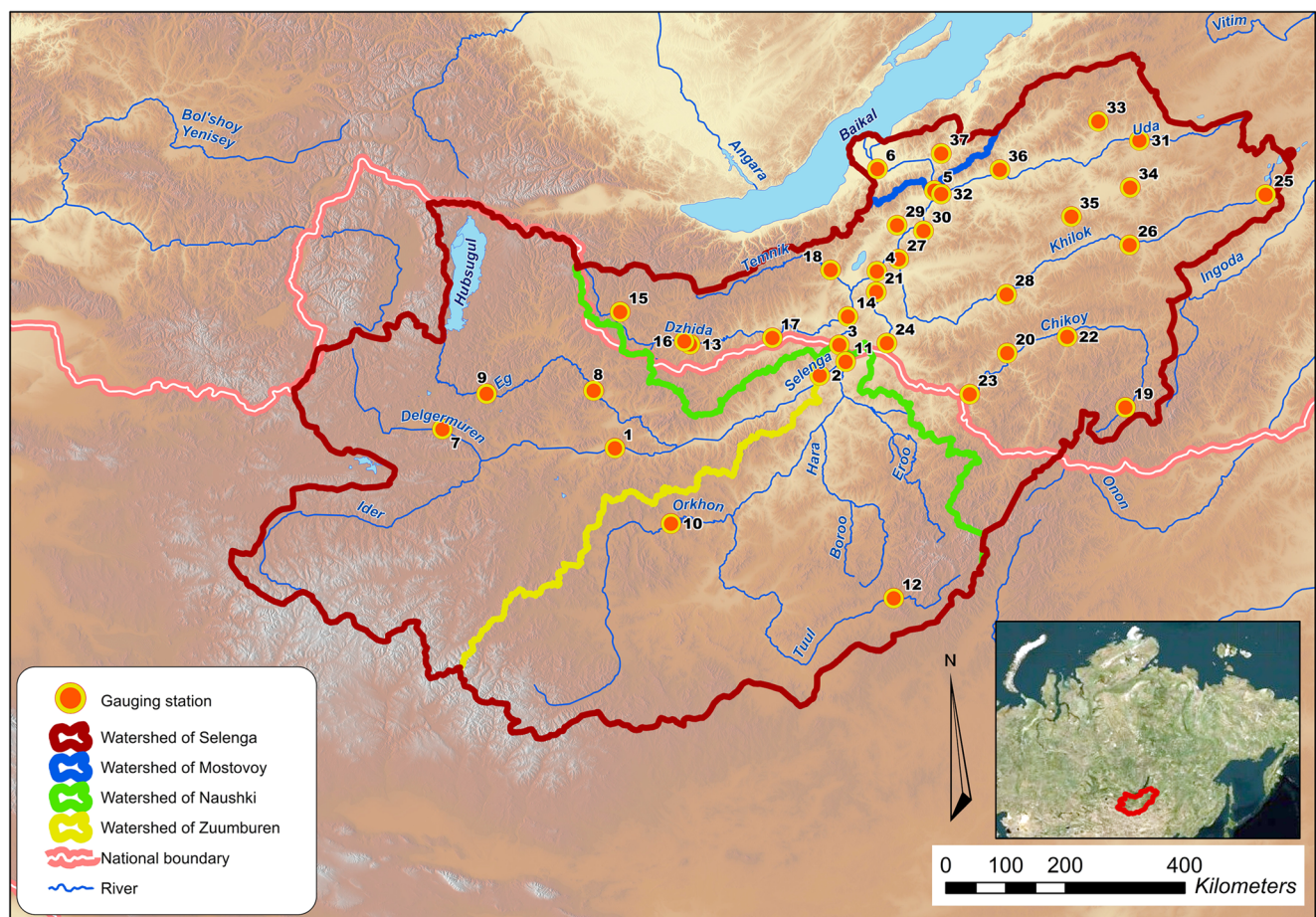
### Site description

Since the 1930s, the average discharge into Lake Baikal of the transboundary Selenga River (shared between Russia and Mongolia) is nearly  $28 \text{ km}^3 \text{ year}^{-1}$ , of which the main part is formed in Russia (63%). The length of the river is 1024 km, and the drainage area is  $447,060 \text{ km}^2$  of which the main part is located in Mongolia (67%; Garmaev and Khristoforov 2010; Fig. 1).

The basin of the Selenga is located in a region of extremely continental climate. It is covered by isolated and sporadic permafrost, and has largely variable conditions of runoff formation. The southward hill slopes are covered by steppe vegetation and have low humidity of soil, whereas the northward slopes have dense taiga vegetation and frozen ground which is an important source of groundwater recharge in the summer season. The large elevation range between 600 and 3000 m also influences the hydro-climatic conditions. Departing from a historical annual average air temperature of  $-3 \text{ }^\circ\text{C}$  in the Selenga River Basin, the increase between 1938 and 2009 of  $1.6 \text{ }^\circ\text{C}$  (Törnqvist et al. 2014), which is accompanied by an

increase in cloudiness, corresponds to a rate that is more than one and a half times higher than the global average temperature increase ( $1.05 \text{ }^\circ\text{C}$  for 1951–2012; Hartmann et al. 2013). This is consistent with large temperature changes seen in Mongolia during the past 70 years (e.g., by  $2.0 \text{ }^\circ\text{C}$  in the past 70 years, and at rates of between  $0.03$  to  $0.05 \text{ }^\circ\text{C}$  per year since the 1980s; Quandin et al. 2013; Otgonsuren and Erdenesukh 2013). Furthermore, variations in the annual average temperature around Lake Baikal have been identified to occur in short cycles of 2 to 7 years and long cycles of about 20 years (Shimaraev et al. 2002). In the past century, two complete cycles (1912–1936 and 1937–1969) were displayed, in addition to other deviations such as a low-temperature period during 1896 to 1911.

Most of the annual precipitation in the Selenga River Basin (of about  $450 \text{ mm year}^{-1}$ ) falls as rain. Whereas diverging precipitation trends during the period 1936 to 2010 are reported for different parts of the Lake Baikal region, ranging from decreases of  $50$ – $100 \text{ mm}$  to increases of  $50 \text{ mm}$  (mainly in the north), overall long-term trends ( $>30$  years) within the Selenga River Basin are reported to be insignificant (Törnqvist et al. 2014). The modest snow cover shows decreasing trends in most parts of the basin (Meshcherskaya



**Fig. 1** Location of hydrological gauging stations in the Selenga River Basin used in the present study



et al. 2009), and accordingly, snow melt has only minor part in the water budget of the Selenga River. About half of the annual flow of the Selenga River is the flow of the summer season (June–August), and groundwater dynamics are such the main cause of flow variation is related to rainfall characteristics of the summer season (Berezhnykh et al. 2012). Winter flow of the Selenga River and its tributaries is consistently low with only between 3 and 10% of the annual flow occurring between November and March. Many tributaries freeze to the bottom in the winter season.

### Meteorological data

We here consider the area averaged monthly data of air temperature (T) and evapotranspiration (ET) for the period of 1934 to 2014 from the Climatic Research Union high-resolution gridded datasets—CRU TS3.23 (CRU 2015). The dataset covers all land areas of the Earth and incorporates mean daily temperature (TMP), diurnal temperature range (DTR) and air maximum and minimum temperatures (TMX and TMN), precipitation total (P), vapor pressure (VAP), cloud cover (CLD), rain day counts (WET), ground frost frequency (FRS), and potential evapotranspiration (PET). The CRU dataset is based on meteorological measurement data and has a resolution of  $0.5^\circ$  by  $0.5^\circ$ . Within and in the vicinity of the Selenga River Basin, approximately 40 T and P measurement stations have been used (details given in Törnqvist et al. 2014). For calculation of PET, a version of the Penman–Monteith method was used, based on the gridded TMP, TMX, TMN, VAP, and CLD (Harris et al. 2014; Mohammad et al. 2015). An analysis of the completeness and representativeness of the chosen database for the Selenga River basin was previously presented in Törnqvist et al. (2014).

### Hydrological data

Twenty-nine hydrological stations within Russia that had the longest periods of river flow gauging records among the available stations and eight stations in Mongolia (Fig. 1) were selected in the Selenga River Basin for the statistical analysis. River flow data from the Russian stations cover a period up to 2013. These data originate from digitizing the official printed publications of the Russian Hydrometeorological Agency (from 1932 to 2007) and online data from the Russian Federal Water Resources Agency (from 2008 to 2013) (Automated 2015) (Table 1). For the assessment of the Selenga flow at the Mostovoy gauging station in 2014 and 2015, operational data obtained from the Hydrometcentre of Russia were utilized. From the Mongolian hydrological stations, data were only available for the period 2005–2011; at present, there is no organized mechanism for official hydrological data exchange between Mongolia and Russia, which affects data availability. Trends and variations in the annual

average flow, annual maximum hourly flows, and annual minimum 30-day flows were also analyzed. Time series are limited to stations with non-zero minimum flows.

### Satellite gravimetry

For the assessment of terrestrial water storage (TWS), consisting of water storage as surface water, soil water, groundwater, snow, and permafrost, data from the Project Gravity Recovery And Climate Experiment (GRACE) have been used. GRACE data are widely used for hydrological assessments, at regional to global scales (Frappart et al. 2011; Schmidt et al. 2008; Bulychev et al. 2012; Zotov et al. 2015a; Yang et al. 2015). GRACE provides gridded data of monthly average values of TWS. Four different gridded GRACE hydrology products (GRACE 2015), three of which are published by the Centre for Space Research (CSR), by the Geo Forschungs Zentrum (GFZ), and by the Jet Propulsion Laboratory (JPL), were employed to derive TWS variations over the Selenga River Basin for 2002–2015. In addition, the calculation results of TWS by Zotov (2015b) were used. For this purpose, a multichannel singular spectrum analysis (MSSA) technique was applied to filter GRACE data and separate its principal components (PCs) at different frequencies.

### Hydro-climatic assessment methods

The conducted analysis of long-term fluctuations of the annual river flow includes an assessment of quasi-frequency and autocorrelation, a trend and statistical uniformity of data time series. For the data time series under study average assessments ( $Q_0$ ), variances ( $S^2$ ), standard deviation ( $S$ ), and variation factor ( $C_v$ ) have been received. Coefficients of autocorrelation of the data time series between the runoff of adjacent years  $r_1$  and their errors have been calculated (Khristoforov 1994). In the autocorrelation analyses, an allowance for shift corrections was introduced. Difference integral curves were used to separate phases of high flow conditions and low flow conditions. To check the data time series for independence, the Anderson's test for independence (Khristoforov 1994) was applied. This test assumes that the data are normally distributed. For identifying the presence of consistent trends in time series data, a special case of Spearman's rank correlation test was used, comprising a rank-based test for correlation between two variables.

Uniformity (stationarity) of the time series data was checked by the application of the Student's  $t$  test and the Fisher's  $F$ -test. The Student's  $t$  test is used to check the uniformity of hydrological time series with respect to the expected value. The Fisher's  $F$ -test provides an estimate of the uniformity of time series with respect to the variance. Since the Fisher's  $F$ -test is designed for time series that follow the

**Table 1** Gauging stations used in analysis and their characteristics

Station no.	River	Station	Distance to mouth, km	Period	Number of years	Drainage area, km <sup>2</sup>	Mean basin altitude, mamsl
1	Selenga	Khutag	811	1945–2010	66	92,300	1910
2	Selenga	Zuunburen	503	1975–2013	39	148,000	–
3	Selenga	Naushki	402	1973–2013	41	282,000	–
4	Selenga	Novoselenginsk	273	1932–2015	72	360,000	–
5	Selenga	Mostovoy	127	1934–2015	70	440,000	–
6	Selenga	Kabansk	43	1971–2013	43	445,000	–
7	Delgermuren	Muren	66	1950–2010	61	18,900	2020
8	Eg	Erdenebulgan	260	1973–2004	32	15,300	1860
9	Eg	Khantai	48	1960–2004	45	41,000	1710
10	Orkhon	Orkhon	432	1945–2011	67	36,400	1900
11	Orkhon	Sukhebator	25	1950–2005	56	132,000	–
12	Tuul	Ulaanbaatar	547	1945–2011	67	6300	1850
13	Djida	Khamney	318	1935–1942, 1955–2013	67	8480	1520
14	Djida	Djida	21	1939, 1943–1946, 1953–2013	67	23,300	1200
15	Tsakirka	Sanaga	31	1958–2013	56	1030	1700
16	Khamney	Khamneiskiy most	1.2	1971–2013	43	3600	1500
17	Zheltura	Zheltura	2.2	1978–1979, 1981–2013	35	5120	–
18	Temnik	Ulan-Udunga	59	1940–1943, 1945–1949, 1954–1964, 1966–1968, 1971–2013	66	4240	1320
19	Chikoy	Semiozer'e	707	1980–2013	34	1340	1600
20	Chikoy	Gremyachka	385	1943–2013	71	15,600	1300
21	Chikoy	Povorot	22	1936–1947, 1949–1950, 1952–2013	76	44,700	1230
22	Atsa	Atsa	17	1949–2013	65	2010	1320
23	Katantsa	Khilkotoy	9	1953–2013	61	2120	1330
24	Kiran	Ust'-Kiran	2.5	1964–1980, 1982–1985, 1987–2013	48	1130	860
25	Khilok	Sokhondo	773	1952–1997	46	1900	1040
26	Khilok	Khilok	522	1947–2013	68	15,400	1080
27	Khilok	Khailastuy	22	1936–2013	78	38,300	990
28	Ungo	Ust'-Ungo	8.2	1950–2013	64	2290	1100
29	Orongoy	Orongoiskiy most	16	1939–1940, 1942, 1947, 1950–2013	68	1840	920
30	Kuytunka	Tarbagatay	12	1959–2013	55	1060	850
31	Uda	Ust'-Egita	328	1956–2013	58	3900	1010
32	Uda	Ulan-Ude	5.1	1936–2013	78	34,700	940
33	Ona	Nizhnyaya Maila	66	1968–2013	46	2660	1180
34	Kudun	Mikhailovka	104	1955–2013	59	3300	990
35	Kizhinga	Novokizhinginsk	81	1960–2013	54	820	970
36	Kurba	Novaya Kurba	4.7	1948–2013	66	5500	1080
37	Itantsa	Turuntuevo	22	1961–2013	53	2120	920

normal distribution, the coefficients of skewness ( $C_s$ ) and autocorrelation  $r_1$  were taken into account in the analysis (Evstigneev and Magritskiy 2013; Bol'shev and Smirnov 1983; Rozhdestvensky et al. 2010). In applying the Student's  $t$  test and the Fisher's  $F$ -test on the available series, they were divided into two parts. The break-point 1975–1976 was chosen because the characteristics of the atmospheric circulation over the Selenga River basin have been reported to change at that time. This change brought to the decrease of

intensity of the East Asian monsoon and the western air motion over this terrain (Berezhnykh et al. 2012). Besides, according to Second Roshydromet Assessment Report on Climate Change and its Consequences in the Russian Federation (2014), the period after 1975 is characterized by the most intensive warming in the time series of annual average anomalies of temperature of ground air, averaged both in global time series and on the terrain of Russia.

## Results

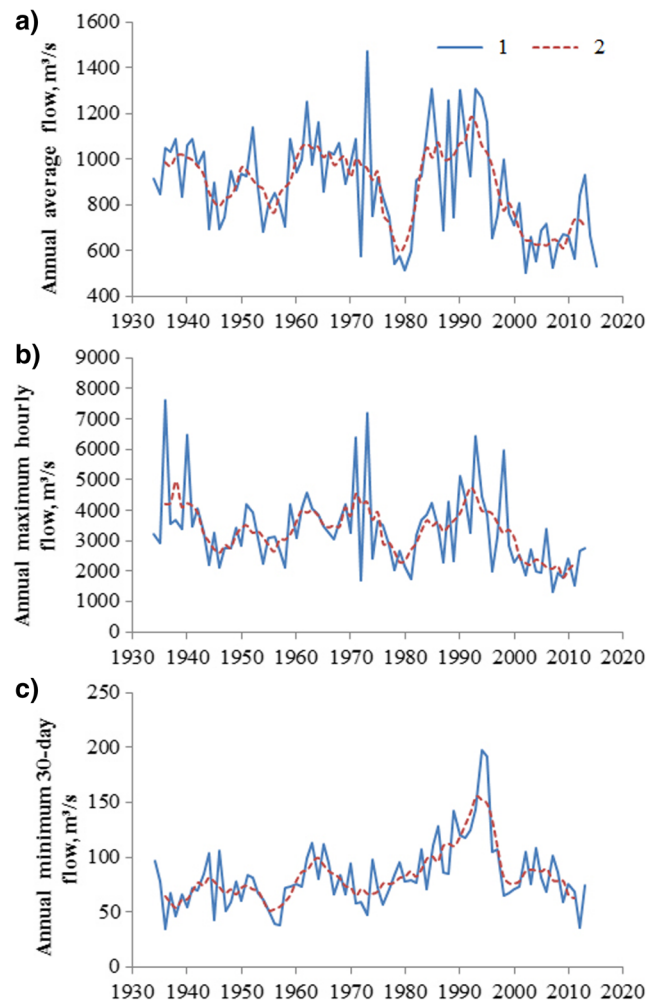
### Precipitation and potential evapotranspiration

For the Selenga River Basin, results show a relatively small decrease by 10.7 mm (2.9%) in annual average precipitation in the more recent period (1976–2014) compared to the period 1934–1975. In the last decade (specifically 2002–2014), the corresponding values are considerably larger at 25.3 mm (6.7%). Furthermore, the dynamics of change of the potential evapotranspiration PET and the index of aridity IA ( $IA = P/PET$ ) were studied both for the whole Selenga River Basin and for its sub-basins: the basin upstream the hydrological gauging station Zuunburen (HZ), from Zuunburen to Naushki (ZN) and from Naushki to Mostovoy (NM) (Supplementary Table 1). Results show that HZ, NM, and SB belong to the sub-humid zone and ZN to the semi-arid zone. None of the sub-basins has shifted to another aridity class during the considered period, compared to the UNESCO classification from 1979 (Map 1979). However, reduced precipitation and increased potential evapotranspiration in all sub-basins have led to decreased values of the aridity index IA. The greatest increase of PET is observed in HZ and ZN, which are the most high-mountainous areas. This is consistent with global warming being generally more pronounced at higher altitudes (Immerzeel et al. 2009; Bradley et al. 2006).

For all sub-basins and seasons, the Anderson's test showed that annual and seasonal precipitation is independent of the precipitation characteristics in the previous seasons. However, a dependency was found for PET in the winter season. This has possibly to do with an influence of the Arctic fluctuation (Shimaraev and Starygina 2010), which is strongest during the winter season. A cyclicity in the series of PET is also traced by Anderson's test during other seasons. The variance of the seasonal and annual precipitation and PET has, however, not changed between the periods 1976–2014 and 1934–1975, according to Fisher's *F*-test.

### Annual average flow

The flow of the Selenga River and its tributaries show cyclical variations (Fig. 2), which is consistent with flow characteristics of South Siberian Rivers (Afnas'ev 1967; Shimaraev et al. 2002; Obyazov and Smakhtin 2012). Phases of high water flow with duration of 12 to 17 years are replaced by low flow phases, which historically have lasted for about 7 years. The here considered flow data of the Selenga River comprises two complete flow cycles including high and low flow phases (1932–1958 and 1959–1982). High water flows of the third cycle proceeded from 1983 to 1995. The current low flow phase that started in 1996 (Table 2) is the longest (20 years) during the whole history of instrumental



**Fig. 2** Fluctuations of **a** annual average, **b** annual maximum, and **c** annual 30-day minimum flow of the Selenga River at the Mostovoy gauging station (actual values (1) and moving (2) 5-year average)

measurements. The three lowest annual average water flows on record at the mouth of the Selenga River occurred during this period (2002, 2007, and 2015; recorded at the Mostovoy station) (Fig. 2). A flow decrease is also seen when considering longer time periods, as reflected in the Selenga River Basin runoff yield that decreased by 8.4 mm (12.4%) when comparing the 39-year period 1976–2014 to the period 1934–1975. For the period of 2002–2014, the corresponding value is 20 mm (29.6%). We note that the correlation coefficient between annual average runoff (Selenga-Mostovoy) and annual precipitation, averaged for the whole basin, is equal to 0.75.

In the Mongolian part of the Selenga River Basin, the largest flow decreases are seen in the Orkhon River (by 2.8 times near its outlet) and at the Tuul River (by 57% near its outlet). However, in the upper reaches of the Selenga River Basin, in the Delger-Muren River, essential reductions of flow are not observed.

As a whole, flow fluctuations of the right bank tributaries to the Selenga River are synchronous (coefficient of correlation

**Table 2** Low and high flow periods at the Selenga River at Mostovoy

High flow phase			Low flow phase			Duration of the cycle, years	Mean discharge of the cycle, m <sup>3</sup> /s
Year	Duration	Mean discharge, m <sup>3</sup> /s	Year	Duration	Mean discharge, m <sup>3</sup> /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

exceeds 0.5 as a rule; being 0.8 for the large tributaries of Chikoy and Khilok). Furthermore, the Chikoy, Khilok, and Itantsa tributaries reveal a close relationship with the flow of the lower Selenga River (Mostovoy and Kabansk stations). Flow fluctuations of the Chikoy River that contributes to almost one third (on the average 29%) of Selenga River flow can explain up to 73% of the Selenga River flow variability. Similarly, the Khilok River that contributes to 10% of the Selenga River flow on average can explain between 56 and 64% of its flow variability.

This pattern can in part be explained by the fact that, for the majority of gauging stations on the Selenga River and many rivers of its basin (e.g. the Orkhon, Tuul, Khilok, and Uda Rivers in the upper part of the basin, and the Kizhinga and Itantsa Rivers in the middle part), the coefficient of autocorrelation is considerable ( $r^1$  from 0.3 to 0.6). Consequently, with some exceptions including the Delgermuren and Chikoy Rivers, the Anderson's test shows a failure of the criterion of independence at a significance level of 1% (Supplementary Table 2). The results also show that years of either high flow conditions or low flow conditions are clustered, at the significance level of 1%. The revealed high autocorrelation of river flow series can be explained by contributions from watershed storage, in addition to the influence of other factors, such as the characteristics of atmospheric circulation, and evapotranspiration (Ratkowich 1976).

### Annual maximum flow

Related to the general decrease of flow in the Selenga River Basin, a reduction of peak flow (Fig. 2b) is observed, which is consistent with typical behaviors of large rivers, as described in Garmaev and Khristoforov (2010). After the observations started in the 1930s, the lowest annual peak flow of the Selenga River within the lower, Russian part of the basin occurred in 2007. For the tributaries of the Selenga River, corresponding minima for annual peak flow occurred in 2007, 2011, and between 1972 and 1981, with few exceptions. The greatest peak flow in the upper Selenga occurred in 1993. A few years thereafter, in 1998, the Selenga River Basin was subject to a major inundation event with an absolute

maximum in the Khilok River. However, after 1998, large inundation events have been absent in the basin.

More specifically, statistically significant negative trends of the annual maximum flow occur at 14 of 35 hydrological gauging stations. For the following seven stations, this negative trend had a significance level of  $\alpha = 1\%$ : Zuunburen, Naushki, Novoselenginsk, Mostovoy (all four at the Selenga River main branch), Orkhon settlement (at the Orkhon River), Ust-Ungo (at the river Ungo), Tarbagatay (at the river Kuytunka), and Turuntaevo (at the river Itantsa). There were also seven stations which had authentic trends of both the annual maximum and the annual average flows. Coefficients of rank correlation for the peak flows are in the range from 0.25 at Khilok-Hailastuy to 0.58 at Kuytunka-Tarbagatay.

### Annual minimum 30-day flow

The annual minimum 30-day flow of the rivers in the Selenga Basin occurs in the winter season and are mainly governed by two factors: storage of surplus water from the previous warm season and winter air temperatures, which can be low enough to freeze the river water bodies from top to bottom and terminate groundwater discharge into the rivers along extensive stretches. Changes of the annual minimum flow of the Selenga Basin Rivers are correlated with the annual average flow (0.2–0.7) at statistically significant levels, however, to a lesser degree than the annual maximum flow. There is a clear long-term trend of increasing minimum winter flows, which is related to increasing temperatures of air and soil (Obyazov and Smakhtin 2013).

As a rule, the minimum 30-day flow values have high autocorrelation coefficients. For streams that do not freeze to the bottom, such high autocorrelations are statistically significant over their gauging reaches, as shown by Anderson's test criteria for coefficients of autocorrelation. The exceptions are the Khilok River and the Mongolian part of the Selenga River. More generally, for as much as 50% of the analyzed rivers, there is a statistically significant tendency (at  $\alpha = 5\%$ ) that winters of either high flow or low flow conditions are clustered.

The apparent trend of increasing minimum 30-day flow values over time is proved to hold true by the Spearman rank



correlation test. There is a significant positive trend at  $\alpha = 5\%$  for the Selenga River in its lower part (Mostovoy), as well as for the Eg, Dzhida, Chikoy, and Khilok Rivers. However, despite this overall increasing trend, the results become ambiguous when considering refined time periods between 10 and 20 years (Fig. 2c). Notably, from 1995 to present date, there has been an overall decrease of the minimum 30-day flow of the rivers of the Selenga Basin compared to the 1980s and the early 1990s. This is likely related to both the general decrease of runoff and the decrease of winter air temperatures after 1998 (Obyazov and Smakhtin 2012). In summary, considering the minimum 30-day flows at the Selenga-Mostovoy gauging station during the historical period 1934–1975, they were on average exceeded by a considerable 31.4% during the period 1976–2014, whereas they were only moderately exceeded by 10.2% during the period 1996–2014.

Nevertheless, the long-term trend of increasing winter flows contributes to a significant failure of the tested hypothesis regarding the uniformity of the time series. For the Selenga River at the Novoselenginsk and Mostovoy gauging stations, and for the Dzhida and Chikoy Rivers, the Student's  $t$  test of the equality of averages showed that the average minimum winter flow for 1976–2014 significantly exceeded the one for the previous 40-year period, at a significance level of 5%. For the Selenga River, there was also a statistically significant increase in the variance of the minimum 30-day winter flows, according to Fisher's  $F$ -test.

## Discussion

Between 1934 and 2015, heat and water flux balances of the Selenga River Basin have undergone substantial changes. These are mainly expressed in increased average air temperature and decreased precipitation (especially during the summer season; Berezhnykh et al. 2012). This is also reflected in reduced soil humidity (Sato et al. 2007) and increased soil temperature during the winter season and permafrost degradation (Zhao et al. 2010). The precipitation deficiency in the Selenga River Basin since 1996 can more generally be related to climatic changes in Asia-Pacific region. In particular, there is coherence between hydrological drought, seasonal anomalies of atmospheric pressure, and surface heat fluxes of the Pacific and Indian Oceans (Ponomarev et al. 2015).

This study revealed that 10 out of the 35 investigated stream gauging stations showed statistically significant changes in the annual average flows. In 8 out of these 10 cases, the river flows were reduced, including the Selenga River at its outlet gauging station. The most pronounced flow decrease was observed in the Orkhon River. The reverse tendency, observed at the gauging station of the Dzhida River, is possibly caused by a local to regional increase of precipitation (Vrba 2013).

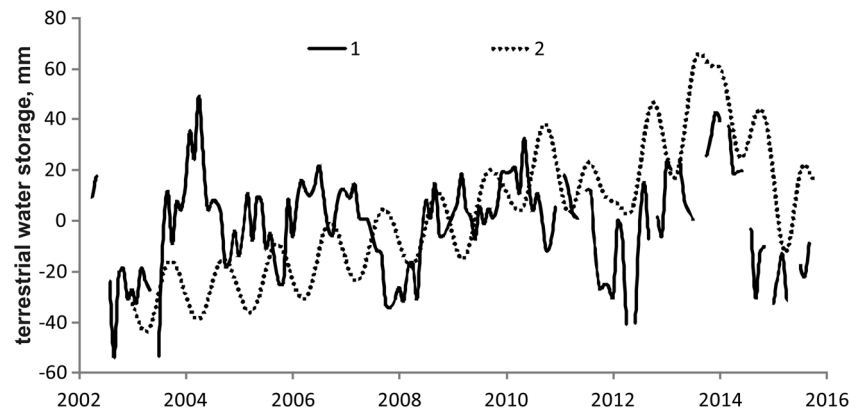
At 14 gauging stations, statistically significant decreasing trends of peak flows were observed. Assessments show that the reduction of annual average flows is mainly related to reduced flows during summer floods. This conclusion is supported by a significantly reduced average precipitation during the summer season, as shown by Student's  $t$  test results (Supplementary Table 1). The conclusion is also supported by reported reductions of extreme precipitation (Sato et al. 2007). Since a large part of the transport of sediments and of heavy metals occur during high flow and peak flow conditions (Chalov et al. 2015), on-going reductions in peak flows can significantly impact such transport. In addition, reduced water flows imply redistribution of flow between the branches of the Selenga River delta, including a potential “dying off” of small branches and lakes with their filtering functions, as well as changed sediment accumulation in the delta. Taken together, this impacts the barrier functions of the delta (possibly adversely; Chalov et al. 2016). Besides, there is an on-going deterioration of the quality of waters originating from the upstream Mongolian part of the river basin with respect to both hydrochemical and hydrobiological indices (Sorokovikova et al. 2013).

The trend of increased magnitude and variability of minimum water flows in the Selenga River Basin is shared with most major rivers of northern Eurasia (Smith et al. 2007; Dzhamalov et al. 2015) and can largely be explained by increased air temperatures during the winter (Dashkhuu et al. 2015; Obyazov and Smakhtin 2013). However, not least since air temperatures for the winter period started to decrease again in the Selenga River Basin after 1998 due to changes in seasonal dynamics (Obyazov and Smakhtin 2013), the minimum winter water flows for the most recent period of 1996–2013 were actually lower than during the previous 20-year period, being only slightly higher than the average value for the reference period 1934–1975 (Fig. 2c).

Previous results from closure of long-term water balances have shown that annual average evapotranspiration has exhibited relatively small historical changes, which may in part may be explained by contrasting seasonal trends (increasing evapotranspiration during the spring and summer seasons and decreasing evapotranspiration during the autumn season; Törnqvist et al. 2014). The present results emphasize that annual average evapotranspiration has been reduced during the most recent 20-year period (1996–present), under current conditions of low precipitation and runoff in the Selenga River Basin. This can be understood from water balance considerations, given the observation that the recent runoff decreases are not as large as the precipitation decreases. Major factors behind this reduction of evapotranspiration (besides the reduced precipitation) are the reduction of the humidity of soil (Sato et al. 2007) and the augmentation of seasonally thawed bedrock layer (Zhao et al. 2010; Yoshikawa and Hinzman 2003; Smith et al. 2007; Kopp et al. 2016).



**Fig. 3** Fluctuations of terrestrial water storage (TWS) in the Selenga River basin from 04.2002 to 09.2015. 1 1 – Averages by Centre for Space Research (CSR), the Geo Forschungs Zentrum (GFZ), and by the Jet Propulsion Laboratory (JPL) data 2 – multichannel singular spectrum analysis filtered JPL data (Zotov et al. 2015a, b)



Regarding long-term trends in water storage within the Selenga River Basin, gravimetric data from GRACE (Fig. 3) shows a maintained (solid curve, no. 1) or even increased (by 40–60 mm; dashed curve, no. 2) total terrestrial water storage TWS in the Selenga River Basin since 2002. The minimum values of TWS are observed in 2002, which had the lowest annual average runoff during the period 1934–2015. The increase in TWS for 2002–2014 (dashed curve) corresponds to an annual storage increase of 3.1–4.6 mm of precipitation surplus (i.e. 7 to 9% of the average runoff yield for this period). Such considerable increases of storage have been observed in other Eurasian regions with thawing of sporadic permafrost, such as in the Lena River Basin (Velicogna et al. 2012). A plausible reason is that permafrost thaw increases the infiltration, which implies reduced evaporative losses and correspondingly increased amounts of surplus water that may be subject to storage. Furthermore, since the active layer becomes thicker as permafrost thaws, subsurface ice can be replaced by water with higher density, hence contributing to increased storage.

There is significant uncertainty in projections of future runoff in the Selenga River Basin, including overall trends in annual average values (Arnell 1999; Sato et al. 2007; Törnqvist et al. 2014). This uncertainty regards both the magnitude and direction of change. There is, however, a tendency of reduced summer precipitation, at least on the Mongolian part of the basin (Sato et al. 2007), whereas annual average precipitation and runoff is projected to slightly increase. Despite increasing water demands due to economic development, an overall deficiency of water resources is not foreseen (Alcamo and Henrich 2002; Arnell et al. 2011). Nevertheless, water quality issues are likely to need increased attention in the future (Törnqvist et al. 2011; Thorslund et al. 2016).

If current plans are realized regarding hydropower plant construction in Mongolia (at Egiin, Chargajt, and Shuren) on the Eg River (Egiin Gol), the Orkhon River, and the main branch of the Selenga River, the outcome is estimated to be a reduction of annual average flow by 0.11 km<sup>3</sup> due to evaporative losses of surface water in the reservoirs, which corresponds to about 0.5% of the runoff at the Selenga River outlet.

However, more notable changes are expected due to seasonal redistribution of flow. For instance, the expected augmentation of winter flows and reduction of peak flows (Grechushnikova and Edelshtein 2016) imply, together with the expected trapping of sediment in the reservoirs, changes in sediment delivery as well as in the associated erosion–deposition patterns that have shaped and maintained the Selenga River delta.

Along with the overall trends, the cyclic changes (Obyazov and Smakhtin 2013; Shimaraev et al. 2002; Ptitsyn et al. 2010; Voloshin et al. 2006) play an important role. The flow data from the Selenga River at its downstream Mostovoy gauging station, starting in the 1930s, show a cyclicity with a phase duration of 7–20 years. The current low-flow period, which began in 1996, is the longest one during the history of instrumental measurements. For all the gauging stations on the Selenga River (except for the Zuunburen station), there is a significant coefficient of autocorrelation ( $r(1)$  between 0.31 and 0.59) and a tendency for clustering of years that have either high flow conditions or low flow conditions. The high autocorrelations are largely caused by the last low flow period (Fig. 2a, b). In comparison with this period of instrumental measurements, dendrochronological reconstructions of the hydroclimate during the last four centuries in the upstream part of Selenga at Khutag (Davi et al. 2006, 2010) imply a large variation of river flow. Compared to the estimated average hydroclimate during these four centuries, the twentieth century is characterized by high flow conditions. According to the reconstruction, there have been extended droughts and low water periods in the Selenga River Basin in the past; such shifts cannot be excluded in the future.

## Conclusions

Since instrumental measurements started in the 1930s, the annual average flow of Selenga Basin Rivers has shown cyclicity, comprising phases of high water flow lasting between 12 and 17 years and phases of low water flow that historically have lasted for about 7 years. However, the current low flow

period has lasted for 20 years and is unprecedented in the measurement record, regarding both duration and magnitude of flow deviation. Compared to the historical period 1934–1975, the most recent period 2002–2014 showed a significant flow reduction of 30%, in comparison with a moderate average reduction of 12% for the longer period 1976–2014. This recent and significant flow reduction is caused by reduced input from precipitation and is also accompanied by reduced evapotranspiration. In particular, river flow has been reduced during the summer season due to a reduction in total and extreme rainfalls.

The minimum flow of rivers in the Selenga Basin occurs during the winter season and has increased significantly due to increasing winter temperatures of air, which can partially hinder the freezing of rivers from top to bottom. However, during the current low flow period, the increase of minimum flows has been much less pronounced. In contrast, the general trend of decreasing maximum flows has been further accentuated during the current low flow period. Furthermore, the observed trends of increasing minimum flows and decreasing maximum flows are consistent with expected impacts of the ongoing thaw of the basin's permafrost.

Although associated with uncertainty, estimates of the total water storage within the Selenga Basin suggest that (if anything) it may have increased since 2002, which in that case would be consistent with observed water storage increases in other Eurasian regions characterized by sporadic or discontinuous permafrost. Taken together, these trends and recent changes have implications for and need to be considered in water planning and management, not least in the context of the planned large-scale hydropower expansion in the upper part of the Selenga River Basin.

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