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# The Sediments Flow of the Main Baikal Rivers and Its Sensitivity to the Environmental Change (East Siberia, Russia)

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**Abstract**
The results of the analysis of water and sediments flows' changes of main inflowing Baikal rivers over the observation period are presented. Long-term observation record of sediments flow is divided into two periods differ with average values and a scale fluctuations of annual averages values. During the first period dynamics of sediments flow of rivers is determined by hydro-climatic factors, i.e. fluctuations of sediments flow, in general, are synchronous to fluctuations of water flow. During the second period (from the second half of 1970s) there is the downward trend of sediments flow's change (decrease by 48 – 81%) against the background of increased water content of rivers. This trend is caused by both anthropogenic influence in basins of rivers under review and natural processes, connected to global and regional changes of climatic characteristics. In general, natural processes of sediments flow's changes in the different areas of Baikal basin are adjusted by anthropogenic factors to a greater or lesser extent. The present article can be used as information and analytical material for the further research and forecast of sediments flow's changes in Baikal basin as well as in other rift-valley lakes of the world.
**Keywords:** Lake Baikal, water and sediments flow, trends, antropogenic factor, climate change

## 1. Introduction

Baikal is the largest fresh water lake in the world, located almost in the center of Asian continent. Around 500 rivers flow into the lake, brining detrital material from the water catchment basin as well as pollutants. Natural and anthropogenic changes of the lake's basin clearly affect the water and sediments flow's regime. Formation of river sediments flow is determined by interaction of a number of natural factors (relief, surface roughness, composition of rocks, nature of soil and flora, climate conditions, etc.). Quite a significant and, at times, a leading factor of multidirectional changes of sediments volumes is human activity, different in nature and intensity. As a consequence, during last decades of global climate change, enhancing anthropogenic pressure on the landscape of the lake's basins, the scientific interest in the study of the on-going changes in the rivers flow regime and, in particular, sediments flow has been increased. The present article gives the determination of trends and the role of anthropogenic and natural factors and their interaction in the formation of sediments flow of major Baikal rivers over the observation period.

## 2. Study area

Baikal is a rift-valley lake. It's approximate age is 25 million years. Его возраст около 25 млн. лет. The volume of Baikal basin is 23000 km$^3$, water surface area is 31500 km$^2$. Объём котловины Байкала 23 тыс. км3, площадь водного зеркала 31,5 тыс. км2. The lake's length is 636 km, width varies from 25 to 80 km (Fig. 1). Total basin area (excluding water area of Baikal) is 545000 km$^2$. Approximately 90% of basin area is located in the east side of the lake. On the territory of Russia there is 45% of Baikal water catchment area, the rest of it – on the Mongolian territory (Surface Water Resourses, 1973). The correlation of basin area and water catchment area of Baikal is 1:17, which means there is a sufficient role of the land in the feeding process of the lake. And the main link of this prosses is a river flow.

Baikal basin has mainly a mountain relief. Altitude marks vary from 456 meters to 2840 meters. Mountain ridges are elongated parallel to the lake basin and oriented mainly from south-west to north-east.

The lake basin's territory is substantially consist of forest-steppe and forest (taiga) zones. However, highly dissected relief caused altitudinal belts in the vegetation's distribution (from steppe to goltsy).

Baikal basin is located in a temperate climate zone with a continental type of climate. The climate conditions on the study territory are determined by the nature of the atmospheric circulation and radiation regime, terrain's relief and the influence of water masses in the coastal areas of the lake. Average annual air temperature over a long-term observation period in Baikal basin is –3, 7˚ (Surface Water Resourses, 1973). The most **amount** of **precipitation** in the lake's basin has place in the mountain area (average annual amount is 1293 mm), minimum (250 – 300 mm) – in valleys of rivers Selenga, Barguzin, Uda, on the Olkhon island and in Selenga's delta. 80 – 90 % of the annual precipitation amount occurs during the warm season (May – September). The rock permafrost is widespread in the lake's basin. The most of the basin consists of the insular permafrost area (thickness is up to 50 m) and the area of the change from insular to continuous distribution of rock permafrost (thickness 50-100 m). Areas of continuous (thickness is over 100 m) distribution of rock permafrost are located in the easternmost and north-east territory of the lake's basin (Surface Water Resourses, 1973).

Baikal basin has a well-developed river system. There are about 500 rivers flow directly into the lake, but monitoring observations of sediments flow have place only on 5 of them (Table 1). At the same time, water-catchment areas of major rivers, where suspended sediment discharge is measured, cover over 90% of Baikal basin: Selenga (82,8%), Barguzin (3,7%), Upper Angara (3,6%). Therefore, the ongoing changes in the whole Baikal basin are objectively characterized by the long-term data of water and sediments flow of these rivers.

## 3. Materials and methods

The monitoring observations (by Federal Service for Hydrometeorology and Environmental Monitoring) of water and sediments flow of major Baikal rivers – Selenga, Barguzin, Upper Angara, Utulik and Khara-Murina have been analyzed in the study. The monitoring data of air temperature, subsoils and precipitation also has been used in the study. Satellite images of estuarine areas of rivers (provided by "Google Earth"), cartographic documents, author's own researches (Potemkina and Fialkov, 1993; Potemkina, 1998, 2004, 2011; Potemkina et al., 2012 et al.) and scientific publications were analyzed in the study.

Long-term records of annual water (further – WD) and suspended sediment discharge (further – SSD) cover the periods: on Selenga river (monitoring station Mostovoj) – 1934–2008 (WD) and 1941–2008 (SSD); on Barguzin river (monitoring station – village Barguzin) – 1933–2008 (WD) and 1943–2008 (SSD); on Upper Angara river (monitoring station – village Upper Zaimka) – 1939–2005 (WD) and 1946–2005 (SSD); on Utulik river (monitoring station – village Utulik) – 1941–2005 (WD and SSD); on Khara-Murin river (monitoring station – village Murino) – 1971–2005 (WD) and 1972–2005 (SSD).

Dynamics charts of the annual water and suspended sediment discharge over the observation periods are analyzed, trends are determined, correlation coefficients between WD and SSD are calculated. The long-term SSD observation was divided into two periods, differ with average values and their scale fluctuation. Changes of annual values of WD and SSD are detected and correlation coefficients between them are calculated for the selected periods. For validation estimation of the difference between values over the observation periods the statistical Student t-test was used. The flow of bedload sediments was not considered because its percentage relative to the flow of suspendedsediments is small (about 4% for the plain rivers and 20–25% for the mountain ones) and doesn't change the long-term dynamics (Gusarov, 2004; Panin, 2005).

## 4. Results and discussion

Selenga, Upper Angara and Barguzin – the largest rivers with their length, water and sediments flow – are selected in the large feeding province of Baikal. Their basins are connected to the water-body only via river estuaries. Rivers of the coastal strip area and of the facing-the-lake mountainsides of surrounding mountain range are selected into the small feeding province. Most of rivers of the small province are mountain rivers. The climate conditions of the small feeding province are original and determined by the high influence of Baikal water body. Utulik and Khara-Murin rivers are selected in the small feeding province; they are notable for relatively long-term observation periods. According to the ratio of the main feeding sources Utulik and Khara-Murin rivers are predominated by rainfall runoff, Barguzin and lower Selenga have nearly equal ratio of rainwater and meltwater (snow). Meltwater runoff predomination is typical for Upper Angara (Surface Water Resourses, 1973).

Average values of water and sediments flow of the examined rivers over the observation period are presented in the Table 1. Water and sediments flow of Baikal rivers is measured on monitoring stations, which are usually located well above estuaries. It shows an inflow of water and sediments to the estuaries, not the actual transfer of fluvial material into the deep-lake area. The most important characteristics of estuarine areas – their hydro-morphological type, which has an influence on a transfer of fluvial material into the lake. According to the classification by V. N. Mikhailov (2012) the mouth area of Barguzin river has estuarial type – no delta and the mixing of river and lake waters has place in Barguzin bay, jutting far into the land – estuary. Upper Angara river has estuarine-deltiac river mouth. The main element of river mouth – delta, which is adjacent to estuary – lagre estuarine lagoon Angarsky Sor, separated from the lake by the shore bar Yarki. The delta of Upper Angara is a bay-head delta. Estuarine area of Selenga river has a protruding delta, which is developed in the open estuarine zone of the lake. River mouths of Utulik and Khara-Murin are also deltaic type, but their deltas are little protruded in the lake. River mouth areas (especially deltaic) – it's a kind of marginal filters – a system of restructuring of fluvial material runoff on a river – lake border. For example, there is 59% of suspended sediments average in a year deposists in Selenga detla and 50% - in Upper Anagara delta (Potemkina, 2004; Potemkina et al., 2012). The Barguzinsky Bay estuary functions as a marginal filter in the mouth area of Barguzin river, about 60% of fluvial sediments deposits there. Therefore, in the study of river runoff and sedimentary processes in the lake it is necessary to take into consideration the role of river mouth areas as marginal filters which is rarely done by scientists.

The analysis of annual water and sediments discharge dynamics over the observation period in the under-study rivers of small and large feeding provinces of Baikal (Fig. 2) has revealed the following trends. There are negative trends of annual suspended sediments flow in all rivers – a reduction of volume of fluvial material has place. The changes of water content in the rivers Barguzin, Upper Anagara, Utulik has a positive trend, in Selenga and Khara-Murin – a little negative trend.

There are two periods in the long-term course of sediments flow in the under-study rivers. On Selenga and Barguzin – the break point of these two periods is the beginning of 1980s, in author's opinion. This term concurs with the term of two phases of water content changes in Baikal basin: low-water (1974-1982) and high-water (1983-1996). These phases are most noticeable in Selenga and Barguzin, less noticeable – in Khara-Murin and Utulik and unnoticeable at all in the long-term course of water content in Upper Angara. Obviously, the conditions of river runoff's forming are different and depend on relief features and climate characteristics in different parts of Baikal water catchment area. The break point for Upper Anagara river is 1976 year; after that (in the second period) there is a rapid change of sediments flow regime. The break point for Utulik river is 1975 year, for Khara-Murin – 1982, separated two phases of water content in the lake's basin. During the first period, the sediment flow's dynamics in the rivers of large feeding province shows the general course of water runoff, which means the fluctuations of sediments flow are synchronic to the fluctuations of water flow. It is proved by high correlation coefficients between SSD and WD (Table 2). During the second period, there is a strong decrease of suspended sediments flow in the course of slightly changing water content. Correlation coefficients decreased (Table 2), however for Selenga rivers it was insignificantly and for Barguzin and Upper Angara the correlation between WD and SSD in the second period is very weak. For the rivers of small feeding province – Utulik and Khara-Murin – the correlation between water flow and sediments flow is insignificant. The observation record on Khara-Murin river is quite short and mostly falls within the second period (when correlation coefficients between WD and SSD are not high). Only 11 years of the observation record fall within the first period. The prevail feeding source of Utulik and Khara-Murin rivers is rainfall runoff, which helps mudflows of variable intensity and, therefore, increases the annual volume of river alluvium. It is obvious that there is a high influence of random disastrous phenomenas (downfalls, mudflows) on an interannual allivium dynamics of these rivers.

The Table 3 shows that in the second period a sediments flow of rivers had 48-81% decrease comparing to the first period (almost by 2-5 times). The water content of rivers, at the same time, either increased or slightly decreased. Must be noted that the trend of sediments flow decrease of Selenga and Barguzin rivers began with the low-water phase (1974-1982). During that phase as well as during the whole first period, fluctuations of the annual flow were mainly caused by hydro-climatic factors. In the second period, an anthropogenic activity influenced on natural processes. It's effect in Selenga and Barguzin basins was not alike, which is proved by correlation coefficients between WD and SSD. Before the low-water phase (before 1974) the correlation coefficients of Selenga and Barguzin rivers were 0,76 and 0,60, after 1974 – 0,57 and 0,02 respectively. Anthropogenic factors, contributed to decrease of sediments volume, were caused by regress of agriculture during socioeconomic macro-reformations in Russia. In Buryatia, which covers about 34% of Baikal basin's area, plough lands reduced down to 84% by 1999 (as to 1983), pasture-lands area reduced by 2,6%, meanwhile haying territories expanded by 9,3%, countryside population decreased (Raldin, 2003). These processes have contributed to the weakening of the erosion in Barguzin and Selenga rivers basins and, therefore, to the decreasing of suspended sediment discharge. As for Selenga river – the decrease of the intensity of erosion processes (due to socio-economic reformations) had less effect than in Barguzin basin, which territory is more used for agriculture. Correlation coefficients between WD and SSD in Selenga river (Table 2) are the proof of the high influence of hydroclimatic factor on a river sediments flows (during the whole second period and during long-term observation period).

The Upper Angara basin is used very little for agriculture (< 1%) (Molotov and Shagshiev, 1999). However, during the second period the suspended sediment discharge of the river decreased by 71%, and water content, at the same time, increased. The two phases of water content, as mentioned above, were not revealed here in the long-term course of the water flow. Hydroclimatic factors were not the main reason of the start of sediments flow reduce in 1970s (for both Selenga and Barguzin rivers). At this time the anthropogenic pressure on the landscape of the Upper Angara basin was strong. This pressure was caused by the start of Baikal-Amur Mainline Railway construction. The railway crossed rivers channels and floodplains, bridge crossings were built, railway embankments in floodplains, dams for different purposes were made etc., construction camps were settled - all of these made a barrier to transit of denudation material. Quarrying in channels of Kichera and Upper Angara rivers for the use of the alluvium for railway construction caused the decrease of sediments transfer into Baikal and, thereby, the decrease of sand-wash on the shore bar Yarki, which is significantly eroded now (Potemkina, 2011). As the study shows (Vershinin, 2005), quarrying of river alluvium can cause the change of channel operation (channel deformation, sediments flow) and hydraulic characteristics (water surface slope, stream velocity). Sush situation, apparently, was noted in Upper Angara. Besides, the decrease of mudflow activity in the region has been noted nowadays. According to the data (Laperdin, 2008) from 1971 to 2007 years there were no disastrous mudflows on the rivers, that could change the value of the average annual sediment discharge. The disturbance of sediments flow's regime is also caused by lowering of Upper Anagara basin's bottom (0,5 mm/year), increasing of swampiness, interception of partial river sediments by large swapm masses (Geology, 1988). Changes of climatic charasteristics in the region, caused by global warming, also influence on sediments flow. Thus, a combination of natural processes and socio-economic activities in the basin of the Upper Angara River caused the reduce of the river sediments volume and the establishment of a different regime, which is confirmed by the use of Student t-test (at a significance level by 0,95).

In the second period the volume of sediments in the Utulik and Khara-Murin rivers decreased by 81% and 69% respectively (Table 3). In the author's opinion, the crucial importance in this trend is not an anthropogenic factor but natural conditions. Although an anthropogenic pressure in the Utulik and Khara-Murin basins gets more intense, landscapes of the most of territory are close to natural (large forested area, small ploughed area) and slightly altered by man. In the south-east of Baikal area, where the basins of these two rivers are, there were no disastrous mudflows for over 40 years (Laperdin, 2008). This period caused the decrease of sediments volume in the rivers Utulik and Khara-Murin. Accumulated denudation material over this period of time in the basins can generate, under certain meteorological conditions, disastrous mudflows, that will increase the annual volume of river sediments. Therefore, during the second observation period there were small volumes of sediments in Utulik and Khara-Murin, and the main element in this situation – the natural conditions and processes.

Global warming processes influenced on climate characteristics in the region and on the main Baikal rivers runoff. With the mid temperature of the global warming 0,75° C warming in Baikal region was 1,65° C over 100 years (1907-2006 yy.) (Valuation report…, 2008). Growth rate of warming in Baikal region is almost 2 times higher than the growth rate of global temperature. The warming climate, which was most intense in the second half of 1970s, should has helped to increase an evaporation, to reduce the water flow and, as a result, to reduce sediment flow. However, against the progress of warming over the last 30 years there was a phase of increased water content over the major Russia's territory (Shiklomanov et al., 2010). In the authors opinion (Shiklomanov et al., 2010) it happened due to the rise of humidity, which was mostly caused by intensifying of circulation processes in North Atlantic that influenced on moisture transporting cyclones. In Baikal there has also been noted a rise of water inflow into the lake with a positive trend by 300 $m^3$/sec over 100 years as the climate warms (1,2˚ C over 100 years). In authors opinion this trend was caused by the change of types of atmospheric circulation processes in the region and the increase of precipitation (Shimaraev et al., 2002).

The main trend of precipitation change in the Baikal region (1966-2010 yy.) was it's increase with a slight positive trend against a high increase of air temperature, which is common since the beginning and mid 1970s for all regions of Eastern Siberia. An exception is Selenga basin, within which there are areas with both positive and negative precipitation trend (Batima et al., 2005; Gunin et al., 2008; Miach et al., 2011; Report…, 2011). As noted above, there is a positive trend in the water content changing in Baikal rivers, except Selenga. Correlation coefficient between average values of water flow and precipitation on Barguzin, Upper Angara, Selenga, Utulik and Khara-Murin is 0,75, 0,37, 0,58, 0,54 and 0,74 respectively. The weakest link between precipitation and water runoff was observed on the Upper Angara.

In addition to precipitation, a change of runoff is affected by particular natural conditions in rivers basins. The basin of Selenga mostly consists of forest-steppe, steppe and desert natural areas, where evaporation from the surface of the land exceeds the amount of precipitation. The global warming intensifies evaporation and increases moisture deficit, which highly worsens the water balance of the territory and eventually affects the water flow of a river (Gunin et al., 2008). The basins of the Upper Angara, Barguzin, Utulik and Khara-Murin are located on the territory surrounded by mountains, with enough moisture and expansion of permafrost. The warming causes a degradation of frozen rocks, that helps to bring in an additional moisture into the feeding process of rivers. The timing of a soil temperature changes on the depth of 80 and 160 meters is mostly similar to the timing of an air temperature changes in Baikal area, as to the basins of the Upper Anagara and Barguzin – a soil temperature on 160 meters rose abobe zero during the cold period. In the North the temperature of permafrost on the depth of 19-20 meters rose by 0,9˚ C over 1987-2005 years period (Miach et al., 2011). There is a deglaciation by 3,2-11,7 sm/year in Baikalian caves. The rate of melting varies from 1,7 to 12,9 sm/year (Trofimova, 2006). Therefore, degradation of glaciation, obviously, contributes to the changes in a water flow of Baikal rivers. There is a decrease of sediments flow in the lake's rivers against the background of increasing water content. Must be noted, that due to the global warming and degradation of permafrost in different regions of the world there is a translocation up by 30-60 meters of alpine distribution limits of woody vegetation in the last 60-80 years (Iashina, 2011). In the Altay-Sayan mountain region (next to Baikal region) there is a rise of upper border of forest communities by 20-80 meter in height and by 100-900 meter on slope (Moiseev et al., 2010). Most likely, there are similar processes in Baikal area. Due to this, the territory of goltsy area, which is a source of detritus material for sediments flow and mudflow formation, decreases. A part of water catchment area of rivers is in a goltsy zone. Distribution of vegetation in this zone decreases a formation of detritus material and blocks it's transfer – and this creates conditions of the decrease of rivers' sediments flow.

To conclude, the current data of sediments flow of Baikal rivers lets to assume that the main element in the decrease of sediments flow in the lake's basin is natural processes, that are more or less corrected by anthropogenic factors in different parts of the region (it is most typical for rivers of large feeding province).

## 5. Conclusion

According to the annual sediments flow dynamics of major Baikal rivers there are two periods over the long-term observation record. During the first period the sediments flow dynamics on rivers is determined by hydro-climatic factors, i.e. fluctuations of sediments flow, in general, are synchronous to fluctuations of water flow. Since the second half of 1970s, there is the downward trend of the change of suspended sediments volume against the background of increased water content of rivers. This trend is caused by geological and geomorphological, hydro-climatic and anthropogenic factors, which differs in different areas of Baikal basin.
The reason of this trend in Selenga and Barguzin basins was more distinct revealing of socio-economic reformations against the background of natural processes. The combination of anthropogenic impact on basin's landscape and natural factors caused the rapid change of sediments volumes on the Upper Angara. The main element of the trend of sediments volume decrease in Khara-Murin and Utulik rivers is natural conditions and processes.

Earlier obtained results on sediments balance in Selenga's estuary, on river sediments transfer to the coastal area and their distribution in the lake (Potemkina and Fialkov, 1993; Potemkina, 1998) will require clarifications and additional research due to the changes of sediments flow of major Baikal rivers. The study can be used for further research and forecast of sediments flow's changes in Baikal basin and in other world rift lakes.

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Table 1. Characteristic of major Baikal rivers

| River | River length /water catchment area, km/km$^2$ | Average over observation period | |
|---|---|---|---|
| | | Water flow, km$^3$/year | Sediments flow, 10$^3$ tons/year |
| Small feeding province | | | |
| Khara-Murin | 86/1150 | 0,72 | 14,5 |
| Utulik | 86/965 | 0,53 | 31,5 |
| Large feeding province | | | |
| Selenga | 1024/447060 | 28,2 | 1735 |
| Upper Angara | 438/21400 | 8,26 | 274 |
| Barguzin | 480/21100 | 3,97 | 107 |

Table 2. Correlation coefficients (K) between water discharge and suspended sediments discharge over a long-term observation record and it's periods

| River | Lonr-term record, K | First period | | Second period | |
|---|---|---|---|---|---|
| | | years | K | years | K |
| Selenga | 0,61 | 1941-1982 | 0,80 | 1983-2008 | 0,68 |
| Barguzin | 0,23 | 1943-1982 | 0,62 | 1983-2008 | 0,28 |
| Upper Angara | 0,23 | 1946-1976 | 0,68 | 1977-2005 | 0,11 |
| Khara- Murin | 0,15 | 1972-1982 | 0,14 | 1983-2005 | 0,30 |
| Utulik | 0,31 | 1941-1975 | 0,50 | 1976-2005 | 0,31 |

Table 3. Changes of water flow (Q, km$^3$ /year) and sediments flow (R, 10$^3$ tons/year) over periods

| River | First period | | | Second period | | | Changes, % | |
|---|---|---|---|---|---|---|---|---|
| | years | Q | R | years | Q | R | ΔQ | ΔR |
| Selenga | 1941-1982 | 28,4 | 2129 | 1983-2008 | 28,0 | 1101 | – 1,4 | – 48 |
| Barguzin | 1943-1982 | 3,82 | 145 | 1983-2008 | 4,26 | 44,2 | + 12 | – 69 |
| Upper Angara | 1946-1976 | 8,14 | 419 | 1977-2005 | 8,48 | 120 | + 4,2 | – 71 |
| Khara-Murin | 1972-1982 | 0,73 | 29,6 | 1983-2005 | 0,71 | 9,15 | – 2,7 | – 69 |
| Utulik | 1941-1975 | 0,53 | 53,6 | 1976-2005 | 0,53 | 10,1 | 0 | – 81 |

 

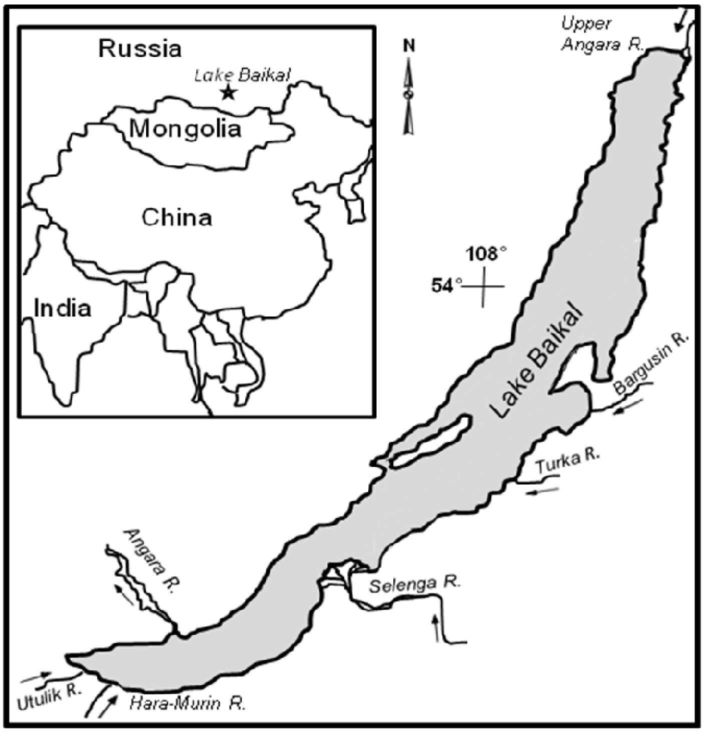


Figure. 1. Location of the Study Area.

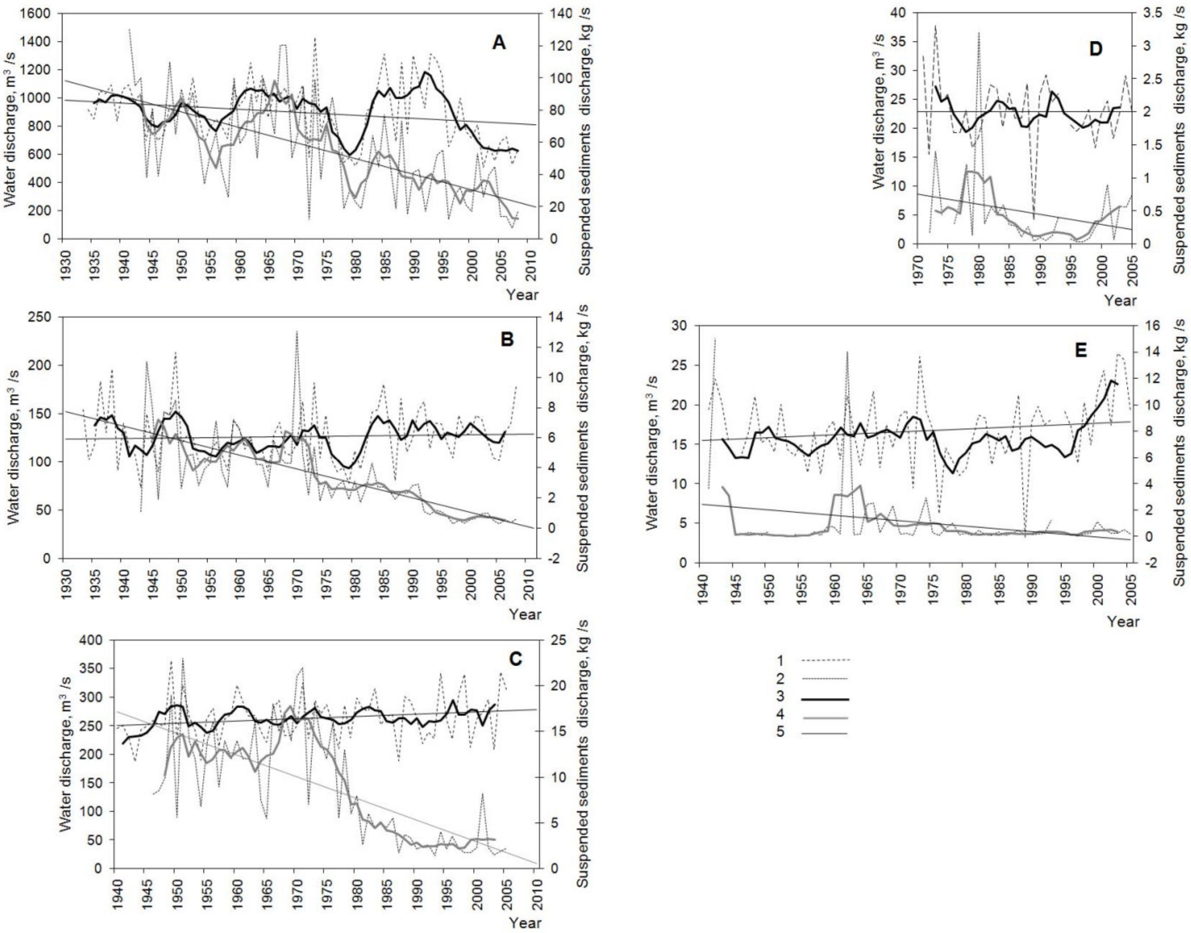


Figure 2. Long-term changes of water and suspended sediments discharge on Baikal rivers: **A** - Selenga, **B** – Barguzin, **C** – Upper Angara, **D** – Khara-Murin, **E** – Utulik. Average annual water discharge (1) and suspended sediment discharge (2), their current values smoothed for five-year periods (3, 4), linear trends (5).