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Hydroclimatic development and anthropogenic impact on sediment loads in the Selenga catchment

Abstract: The present study focuses on the relationships between fluvial processes, climate and land-use changes in the Selenga River catchment. The results indicate that high sediment loads were reported both for altered and natural rivers. The reported multidecadal declines in sediment loads in the downstream part of the Selenga River can be attributed to the abandonment of cultivated lands and changing hydroclimatic factors, in particular a climate-driven decrease in water flows and intensified water use for irrigation purposes. Empirical sediment rating curves show that a series of peak flow events during spring and summer contributes to the main part (up to 98%) of the annual sediment and pollution loads. The highest contribution of flood sediment loads was determined for specific wet years and the lowest – for dry years, which generally reflects the increase in water runoff during high floods in the annual flow. While sediment flows are connected with hydroclimatic conditions in the catchment, the elemental composition of mass flows is mostly related to soil/petrologic conditions. With the exception of small impacted rivers where water quality effects associated with mining were observed, the formation of elemental composition and sediment-associated chemical constituents generally reflects catchment characteristics.

Keywords: fluvial processes, climate changes, land use, sediment loads, water quality, influence of mining, Selenga River

1. Introduction

Recent studies indicate a strong relationship between river discharges, climate oscillations and land use (Syvitski, 2003). Human-induced changes have significantly altered both the composition and magnitude of allochthonous material entering the rivers. The latter leads to a significant shift in geochemical fluxes and water quality. While sediment transport rates are also a function of sediment availability (Asselman, 1999), the climate oscillations and land-use changes have a profound impact during flood events when physical and biological processes operate to increase the export of matter. In this respect,the close relationship between climate, land use, vegetation cover density, and erosion rates remains the key question in both global and regional estimates of the sediment and contaminant loads.

Changes in the sediment availability during floods result in so-called hysteresis effects. Clockwise (positive) hysteresis loops (type II), anti-clockwise hysteresis (type III) as well as single (direct, no hysteresis effect) (type I) or complicated type (IV) of S=f(Q) relations may occur (Gellis, 2013). The export of land-derived constituents from drainage basins as a result of episodic discharges could exert the first-order control on the cycling of sediment and contaminant loads in rivers (e.g. Zwolsman et al., 1997; McKee et al., 2004). Research on the effect of floods (Table 1) in the context of a relationship between catchments and rivers are usually based on:

- sediment rating curves and hysteresis effect analyses,
- intensive detailed basin-wide investigations in small catchments,
- detailed investigations on long-term observation data for discharge stations in large catchments as a substitute measure of catchment/river interface.

With some exceptions (e.g. Asselman, 1999), large river basins are well described by data from discharge stations, whereas

Table 1. Some examples of regional studies of land-derived constituents during floods

Study area and scale	Methods	Datasets (station, time, variables)	Catchment properties	Reference
10 sub-catchments of the Geba River, northern Ethiopia (F=from 121 to 4,592 km^2)	Basin-wide sediment rating curves analyses, determination of grain size distribution (sieve-pipette method)	41 monitoring stations, 2004–2007 rainy seasons (July–September), pressure measurement every 10 min (TD-diver) + manual measurements of flow depth, runoff discharge and sampling of suspended sediments (2-3 times per week in 2004, and daily in 2005–2007)	Topography, size, land use, vegetation cover, lithology	Vanmaercke et. al., 2010
Rhine catchment between Kaub and the German–Dutch border (165,000 km^2)	Basin-wide sediment rating curves analyses, "supply-based" model (computes sediment transport as a function of water discharge and the amount of sediment stored)	Stations along the Rhine River and its main tributaries, 1975-1990 – daily discharge and suspended sediment concentrations	The base of slopes, drainage area, distance from the river source, sediment travel time	Asselman, 1999
4 catchments of Puerto Rico (F=from 3.5 to 20 km^2)	Sediment rating curves analyses using factor analysis and stepwise regression on the factor scores.	1 site per catchment characterized by varied land use, storm-generated sediment loads and concentrations	Type of land use	Gellis, 2013
Wadi Sebdou catchment (256 km^2)	Graphical analysis method based on features of hysteresis loops	31-year period (1973–2004) at the outlet of the basin	Seasonality of flood types and sediment sources	Megnounif et. al., 2013
16 in Northern Siberia and the Russian Far East (large and medium-sized rivers)	Sediment rating curves analyses, plots grouped over the water regime phases	27 gauges (1-2 stations per catchment) with chronological plots of S=f(Q) relationship	Duration of events (spring flood, freshet period), sediment sources, seasonal permafrost, topography, soil types, sediment travel time	Tananaev, 2011
Selenga catchment (F = 447,000 km^2)	Basinwide accounting segment	150 grab sampling sites around the catchment with daily water discharges and more than 50 chemical variables; 7 monitoring stations	Topology, land use and land cover, population density, climatic factors	Present study

the behaviour of chemical elements during a hydrological event has been much less studied (e.g. Audry et al., 2004; Horowitz et al., 2008, Ollivier et al., 2011). On the other hand, much more detailed studies in terms of observational data have been carried out for small catchments (e.g. Roussiez et al., 2013; Gellis, 2013) (Table 1). For both scales,a relatively small number of studies have addressed the composition and magnitude of the material supplied during short-lived events.

The key issue that still remains open is how to separate the impact of climate change and related changes in floods and episodic discharges from that of other changes in the catchment conditions (first, land-use drivers). Less is known about the relationship between the flood sediment transport magnitude,the hysteresis effect and the magnitude and structure of geochemical fluxes.

The present study is focused on detailed analysis of geochemical fluxes and the role of single floods in suspended sediment dynamics due to climatic, hydrological and land use impact within the relatively large Selenga River Basin (Table 1). The Selenga River, which originates in Mongolia, contributes about 50% of the total inflow into Lake Baikal. The catchment still has no soil and water conservation, sediment control programmes or reservoirs, which, in the global perspective, lead to a decrease in sediment fluxes (e.g. Walling and Fang, 2003). The main anthropogenic inputs are related to mining, industrial and agricultural activities within the Selenga drainage basin. At the same time, the region is reported to experience the warming trends with acceleration since the 1970s (Unger-Shayesteh et al., 2013), which has a profound impact on the components of the hydrological system in the area. Elevated sediment-associated chemical concentrations were reported for the area (Chalov et al., 2015).

The main objectives of this study were (i) to determine long-term changes inhydroclimatic drivers of sediment delivery into the river channel, (ii) to investigate the impact of hydrological peak-flow events on the total annual load contributions and their implication for geochemical fluxes, (iii) to determine the importance of export of land-derived constituents and related human activities on the cycling of sediment and contaminant loads into the rivers.

2. Methods

The study is based on data from the national gauging network of the Selenga River Basin, which is implemented by the Russian and Mongolian hydrometeorological surveys for their corresponding parts of the basin. The long-term hydrological changes in the selected rivers were calculated based on the reference period of 1975-1995 for average values for 1996-2011:

$$\Delta Q = \frac{Q_{1996-2011}}{Q_{1975-1995}}$$

Regional climate modelling of land use impact on air temperature and precipitation was performed based on COSMO-CLM (Consortium for Small-scale Modeling) tool (Böhm et al., 2006) with a spatial resolution of 14 km. The modelled approach was based on the comparative study of predicted precipitation and temperature inthe central part of the Selenga catchment (Northern Mongolia) simulated for 2 scenarios:

1. Scenario of modern landscapes to predict actual recent values of precipitation P_0 and temperature fields T_0
2. Scenario of landscapes extremely disturbed by mining operations to predict precipitation $P_{\text{disturbed}}$ and temperature $T_{\text{disturbed}}$ fields in altered conditions. The disturbed lands were determined according to areas allocated to mining, recently approved by the Mongolian Government (Fig. 1).

The difference inmodelled values between undisturbed and disturbed conditions were calculated as follows:

$$\Delta P = P_0 - P_{\text{distrubed}} \text{ and } \Delta T = T_0 - T_{\text{distrubed}}$$

Suspended sediment monitoring data included daily averages for the period of 1970–2010, which were used to obtain S=f(Q) relationships (Table 2) between daily suspended sediment concentrations S and daily water discharges Q for the flood season that covers both the melting period (April–May) and rainfall floods (June–August). Each flood event was characterized by specific relationships. The representative equation for a given gauging station was used in further analyses to estimate the contribution of aflood season to the annual sediment yield.

Table 2. Representative S=f(Q) relationships during the flood season (April to August)

River – station	Type of S(Q) relation	Relationship	
		rising limb	falling limb
Selenga – Mostovoi	IIIb	$S = 0.043Q^{1.05}$	$S = 0.0002Q^{1.7}$
		$R^2 = 0.84$	$R^2 = 0.64$
Chikoy –Gremyachka	IIIb	$S = 0.011Q^{1.58}$	$S = 0.0027Q^{1.7}$
		$R^2 = 0.78$	$R^2 = 0.63$
Khilok – Khaylastuy	IIa	$S = 6.81e^{0.009Q}$	
		$R^2 = 0.68$	
Uda – Ulan-Ude	IIIb	$S = 2.29Q^{0.79}$	$S = 0.02Q^{1.66}$
		$R^2 = 0.71$	$R^2 = 0.79$
Khara – Burunkhara	Ib	$S=17.6Q+87.3$	
		$R^2 = 0.73$	

(Source: Author own study)

For the detailed investigation of geochemical patterns, novel screening campaigns were conducted in June–September 2011–2014 in both the Russian and Mongolian parts of the Selenga River Basin. The study focused specifically on the episodic rainfall discharges and the associated geochemical fluxes, which were analysed on the data coming from 3 monitoring stations located in the upper Orkon River (near Kharokhorin), the Tuul River (near Ulan Baatar) and the Khara River (near Burunlhara) (Fig. 1). Water discharge and water sampling were performed during 3-4 week campaigns in 2011, 2012, 2013 and 2014. Water samples for suspended sediment data analysis were collected manually using 2000–4000 mL plastic sampling bottles, including optical turbidity measurements by Hach 2100P along the rising and falling limb of a storm hydrograph. Water samples were filtered through pre-weighed filter papers with a pore size of 0.45 µm. Filter papers were oven-dried, weighed, and suspended sediment concentrations were calculated using the gravimetric method. Moreover, water samples were also collected during rainfall-runoff events in 2012 at intervals of 5 minutes at the Khara River (near Burunkhara) by a YSI automatic sampler operated by the Momo project (Karthe et al., 2014).

Discharge and suspended sediment concentration (SSC) data were combined to yield estimates of daily and monthly water discharges, suspended load averages at more than 150 locations. All samples (suspended and streambed sediments and filtered water) were analysed for 62 elements by inductively coupled plasma–mass spectrometry ICP-MS (ICP-AES) using a semi-quantitative mode and a 10-fold automated dilution during the analysis. Elemental analyses were conducted on filtered samples without an additional treatment. For a fully quantitative analysis, the instrument was calibrated with a series of known standards for each element. Corrections were applied for potential interferences, and more comprehensive quality assurance/control measures were performed for each element.

The spatial variability of geochemical fluxes was evaluated based on environmental surveys conducted in 2011-2014. The surveys targeted sites located along the Tuul River (T), the Orkhon River (O), the Eg River (EG), the Yeroo River (ER), the Khangal River (H), the Selenga River (S) and the Kharaa River (Hr) in Mongolia (Fig. 1). In Russia, the observational sites were located along the main Selenga riverbed (S) and its main tributaries – Dzhida (D), Temnik (TM), Chikoy (CHK), Hilok (HK), Orongoy (OR), Uda (U), Itantsa (IT), Kiran (KR), Kudara, Zheltura (G), Udunga (UD), Suhara (SH), Tugnui (TG), Menza (MZ), Buy, Bryanka (BK), Ilka (IK), Chelutay, Kurba (KB), Kodun (KD), Kizhinga (KG), Ona (Fig. 1).

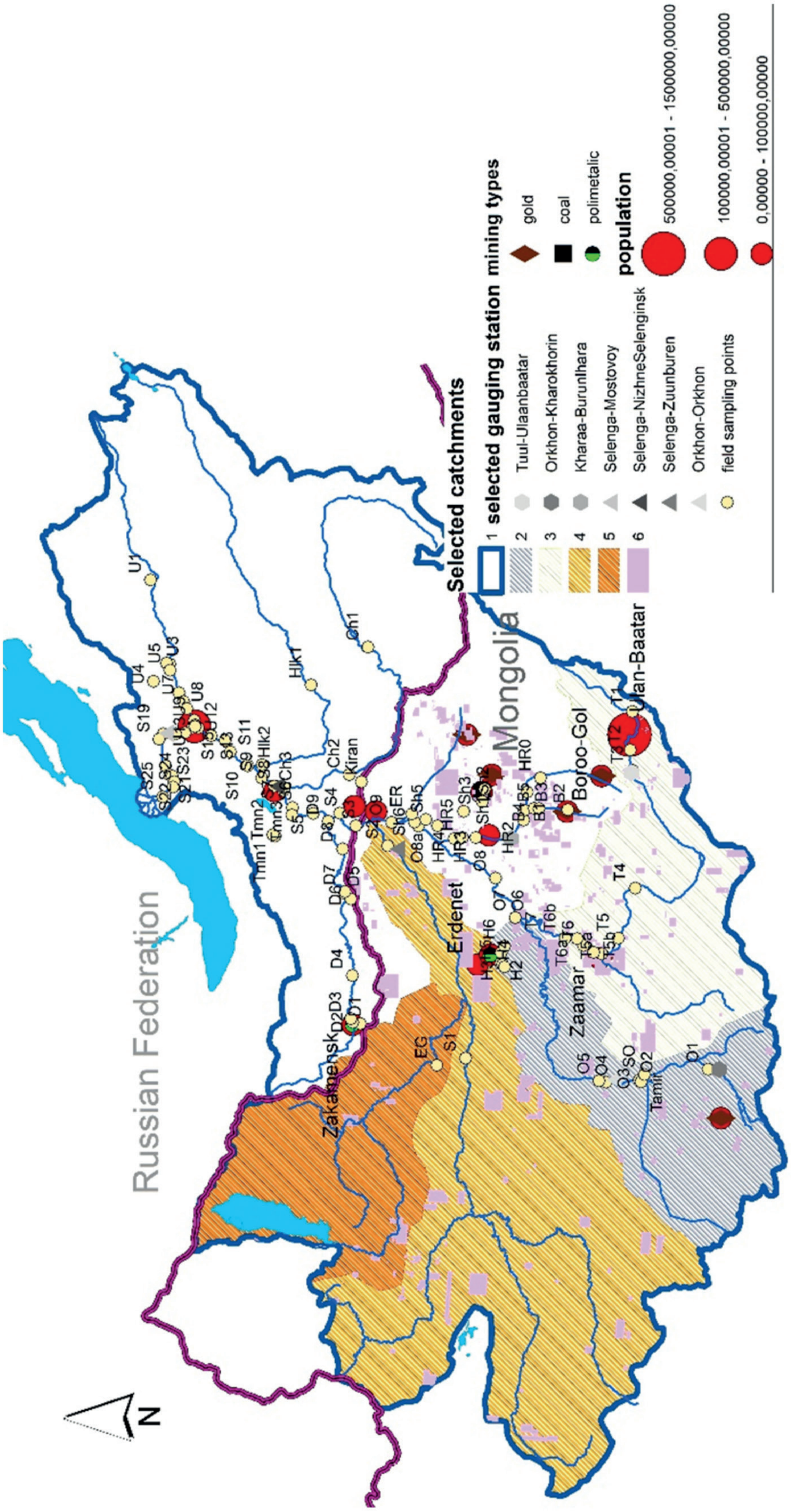

Figure 1. The Selenga River Basin with the sampling sites, major mining sites and main sub-catchments: 1 – the whole Selenga catchment; 2 – the Orkhon River, the upper part; 3 – the Tuul River; 4,5 – the upper Selenga River with the Eg River and Lake Khovsgol; 6 – areas allocated to mining in Mongolia (Source: prepared by Author)

3. Discussion and results

3.1. Hydroclimatic drivers of sediment delivery

Climate variability and climate change are one of the major drivers of hydrological trends in dry lands. In Mongolia, air temperature has increased by 1.8^0C since the 1940s, and precipitation decreased in some parts of the country, including the western slopes of the Khentii Mountains. The latter is regarded as the main reason behindthe long-term low-water period (since around 1989) reported for the Selenga River. The runoff records for the downstream Selenga (Mostovoy) show a statistically significant downward trend from 903 $m^3 \cdot s^{-1}$ (for the period from 1941 to 1982) to 888 $m^3 \cdot s^{-1}$ (for the period from 1983 to 2011), or even more drastic for the recent decades – from 940 $m^3 \cdot s^{-1}$ (for the period from 1975 to 1995) to 689 $m^3 \cdot s^{-1}$ (for the period from 1995 to 2011). The mean annual discharge at some gauging stations within the Mongolian part of the basin demonstrated even greater decreases during the last decades, from an average of 53.3 $m^3 \cdot s^{-1}$ during the period of 1975-1995 to only 18.1 for the years 1996-2011 at the upper Orkhon River (Orkhon–Orkhon) and from 35.3 $m^3 \cdot s^{-1}$ to 14.9 $m^3 \cdot s^{-1}$ for the Tuul River at UlaanBaatar, respectively. The changes were caused mostly by intensive rainfall floods which determined thehigh-water period in the late 1970s and early 1990s (Fig. 2). This decrease primarily caused a reduction in precipitation and an increase in evapotranspiration during that period, though intensified water use for irrigation purposes may have contributed as well.

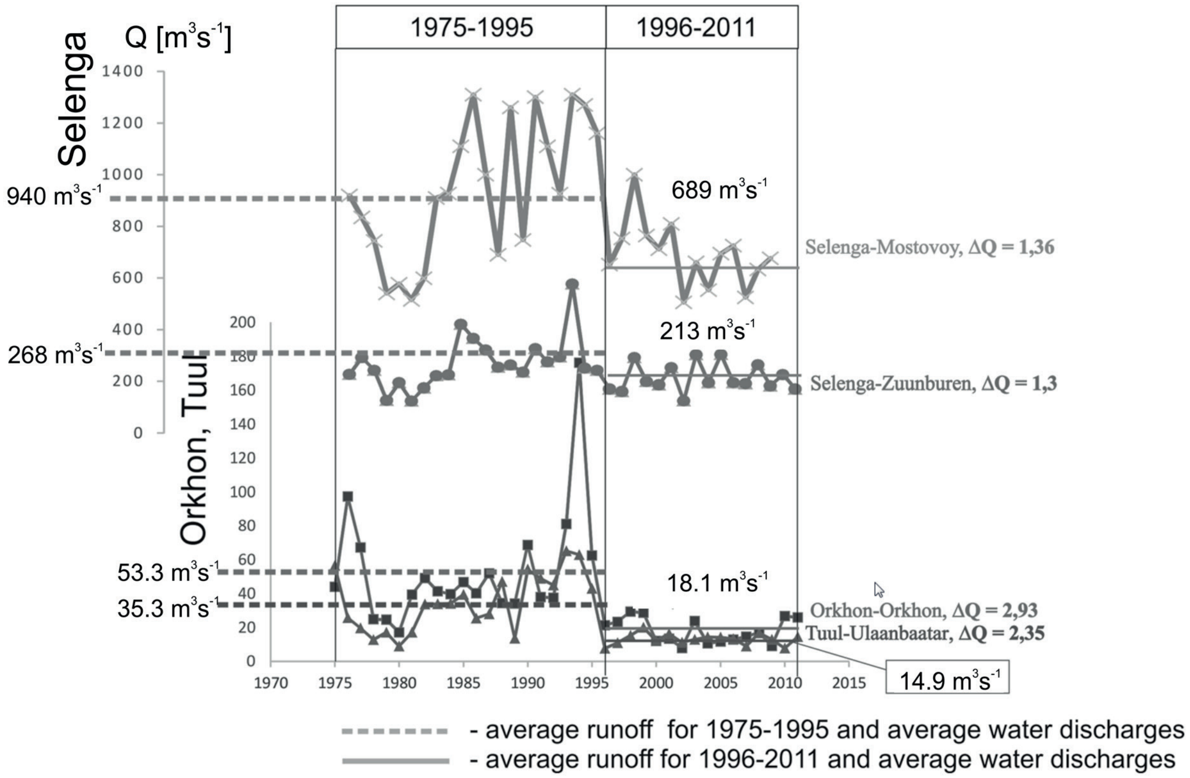

Figure 2. Long-term changes in average runoff in the Selenga catchment (location of the gauging station – see Fig. 1) (Source: Author own study)

The observed decrease inthe mean annual Q since 1990 is largely due to the decreased peak discharge in summer. The above-mentioned climatic variability has significantly affected the maximum discharges over the last decades (Fig. 3) and the flood contribution became smaller than in the mid-20th century (average annual difference between maximum and

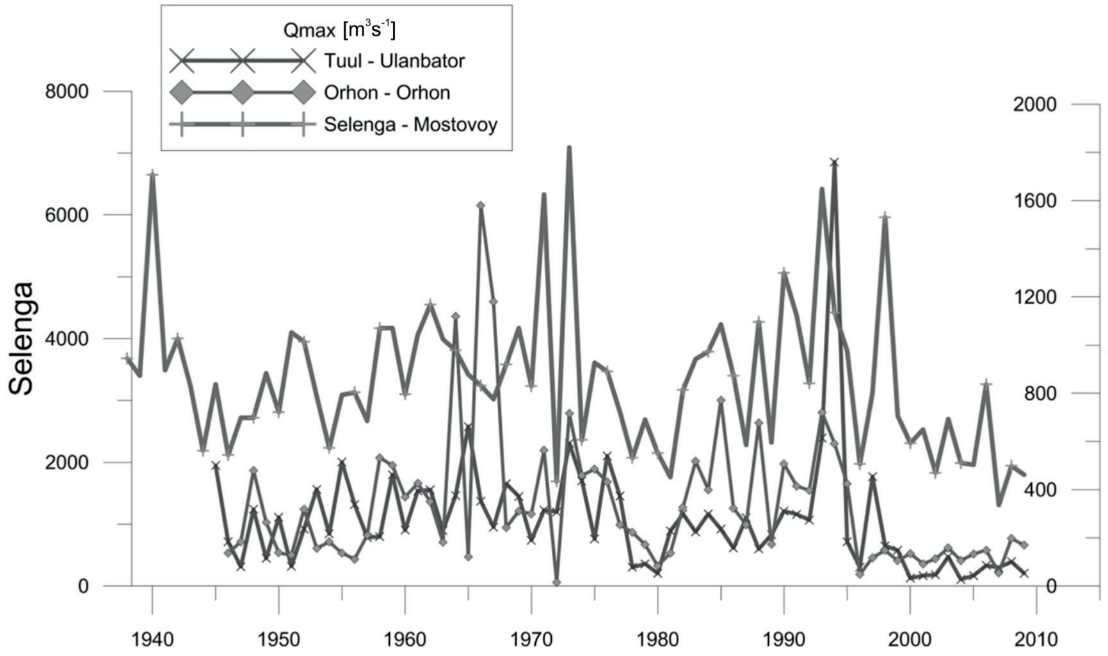

Figure 3. Long-term changes in the maximum annual discharges Qmax ($m^3{\cdot}s^{-1}$) atthe Tuul, the Orkhon and the Selenga River (Source: Author own study)

minimum discharges Qmax–Qmin decreased from 3,740 to 2,920 $m^3{\cdot}s^{-1}$). This corresponds to the highest warming rate in the Selenga River Basin during the last 20 years (1989–2009; 0.048⁰C per year). Land disturbance, on the other hand, especially resulting from mining operations, could significantly influence the water balance components due to changes in regional evaporation patterns. The results of the COSMO-CLM model application indicated spatial redistribution of both precipitation and temperature fields with maximum shifts in the annual summer precipitation of ΔP=300 mm. The most significant shifts will occur during dry years.

The above-mentioned changes in climatic conditions were followed by a considerable decline in the sediment yield of the Selenga River (from 5,832 t per day to 3,015 t per day) and its main tributaries in the Russian part of the river basin. In the upper part of the basin where statistical analysis of the sediment trends is not possible due to the lack of routine monitoring of sediment loads, there is little evidence of a sediment yield decrease based on the comparison between SPM concentrations measured during the campaigns of 2011-2014 and historical field campaigns of 1934-1936 (Kuznetsov, 1955). In the upper reaches of the Selenga, above the Eg River (S-1), SSC varied between 1.2 $mg{\cdot}L^{-1}$ (20 February) and 1,193 $mg{\cdot}L^{-1}$ (8 August) in 1934, whereas it was 11.5 $mg{\cdot}L^{-1}$ in 2001 (18-24 August). During our field campaigns, SSC ranged from 9.51 $mg{\cdot}L^{-1}$ (16 June 2012) to 114 $mg{\cdot}L^{-1}$ (2 August 2011). At the confluence of the Orkhon and the Tuul, a 65-fold increase in SSC was observed during summer floods for the Tuul River (T-9) (from 11 $mg{\cdot}L^{-1}$ on 19 October 1934 to 716 $mg{\cdot}L^{-1}$ on 26 August 1934) and a 43-fold increase for the Orkhon River (O-6) (from 23.3 $mg{\cdot}L^{-1}$ on 17 June 2012 to 1,000 on 7 May 1934).

Taking into account the CMIP 5 ensemble mean future projections, according to which T is expected to increase by as much as 5⁰C until the end of the 21st century (Törnqvist et al., 2014), also anincreased runoff isexpected in the near future. This implies shifts in sediment transport patterns, particularly during event conditions. Shifts in soil temperature and moisture are among the main driving forces of the water and sediment transport. They exert a strong impact on the soil aggregate stability, and thus on the soil erosion intensity; permafrost thawingwill likely to continue. The recent mining impact on sediment loads were observed mostly during relatively short hydrological events, when intensified slope wash near floodplain mining activities could flush large amounts of turbid water into the river. A significant suspended sediment load increase was reported for the Tuul River at sites located near the Zaamar placer gold mining area. During the flood season in 2011, a 2.3-fold sediment load increase from 307 to 710 t per day was recorded. During base flow periods in 2012, a 1.2-fold increase from 115 to 143 t per day was determined.

3.2. Impact of hydrological peak-flow events

The long-term flood season has usually a significant impact on the annual sediment loads. Up to 98% of the annual sediment loads in the river are transported during the flood season (April to August) (Table 3). The highest contribution of flood sediment loads was determined for specific wet years and the lowest – for dry years, which generally reflects the increase in water runoff during high floods in the annual flow. The temporal variability in the sediment discharge within individual basins indicates that the maximum role of floods, in terms of sediment transport events, relates to small rivers. Changes in the sediment transport rates correspond with changes in the SPM size, which is probably related to the intensive slope wash during rainfall events that dominate in the flood period. They may furthermore be related to seasonal changes in the vegetation cover and its characteristics, temperatures (that influence the concentration of suspended matter), colloids, and organisms.

Table 3. Flood contribution (R, tons and % of the year) to the annual sediment yield W for selected gauging stations in the Selenga River catchment (Source: Author own study)

River – station	Year	Flood contribution		Duration of the period, days/% of the year
		R, tons	R/W % of the year	
Selenga –Mostovoi	1976 (dry)	2,720,000	98	183/50%
	1967 (average)	3,120,000	82	183/50%
	1973 (wet)	13,900,000	99	264/67%
Chikoy–Gremyachka	1972 (dry)	28,100	52	183/50%
	1963 (average)	138,000	89	183/50%
	1962 (wet)	431,000	99	183/50%
Khilok–Khaylastuy	1977 (dry)	43,300	72	188/52%
	1967 (average)	87,900	94	266/73%
	1973 (wet)	345,000	99	217/59%
Uda – Ulan-Ude	1977 (dry)	30,300	96	183/50%
	1963 (average)	104,000	97	216/59%
	1973 (wet)	267,000	99	218/60%
Khara–Burunkhara	2002 (dry)	4,340	97	189/52%
	1992 (average)	27,900	97	245/67%
	1990 (wet)	38,300	97	253/69%

Changes in the sediment load during short-term hydrological events (rain floods) can have an even greater effect on sediment transport patterns and depend on different synoptic situationsas well as geological and geomorphological conditions in the catchments. In June–August 2012, rain floods in the downstream of the Khara River (KH-4) were relatively small (the maximum change in the sediment concentrations in 2012 within two consecutive days was 22%). Heavy rains in the upper mountain part of the catchment (KH-2),with the total precipitation of 28.1 mm between 20 and 22 June (7% of the annual value), lead to the SSC increase from 13.3 to 518 $\mathrm{mg \cdot L^{-1}}$. The same effects of rain floods in the mountain valley induce rather fast changes in sediment transport rates for the Orkhon River upstream (O-1, Fig. 2). A 15-fold increase in the sediment load during the day was reported as a response to heavy rainfall that amounted to a total of 50 mm (29–31 July 2011), corresponding to 20% of the annual average precipitation.

These findings provide an important conclusion that the long-term changes in the sediment yield have been caused by climatic drivers of water runoff deficitswith the related flood reduction. Fluctuations in sediment fluxes in a given catchment are determined by changes in sediment patterns during event conditions (seasonal variability). Even a relatively small ($\Delta = 1.3$, or 30%) decrease in the annual runoff has a large impact (almost 50% decrease) on the sediment yield due to the river's flood response. This gives quantitative thresholds for the global behaviour of sediment fluxes, evidencing that one of the greatest effects of climate change occurs through changes in the overall water balance with subsequent effects on land cover density and thus erosion rates (Knox, 1993). On the other hand, our results based on the COSMO-CLM model indicate that the land-use changes (e.g. land disturbance by mining operations) may have an impact on water balance and could lead to an increased instability of the summer precipitation fields (Fig. 4). The modelled ΔP values of up to 300 mm in certain grid cells reflect the importance of changes in evaporation rates due to land cover disturbance. The future runoff increase will be associated with the growth of maximum discharges and the magnitude of floods, and may imply the increased transport of sediments and contaminants (e.g. Chalov et al., 2014).

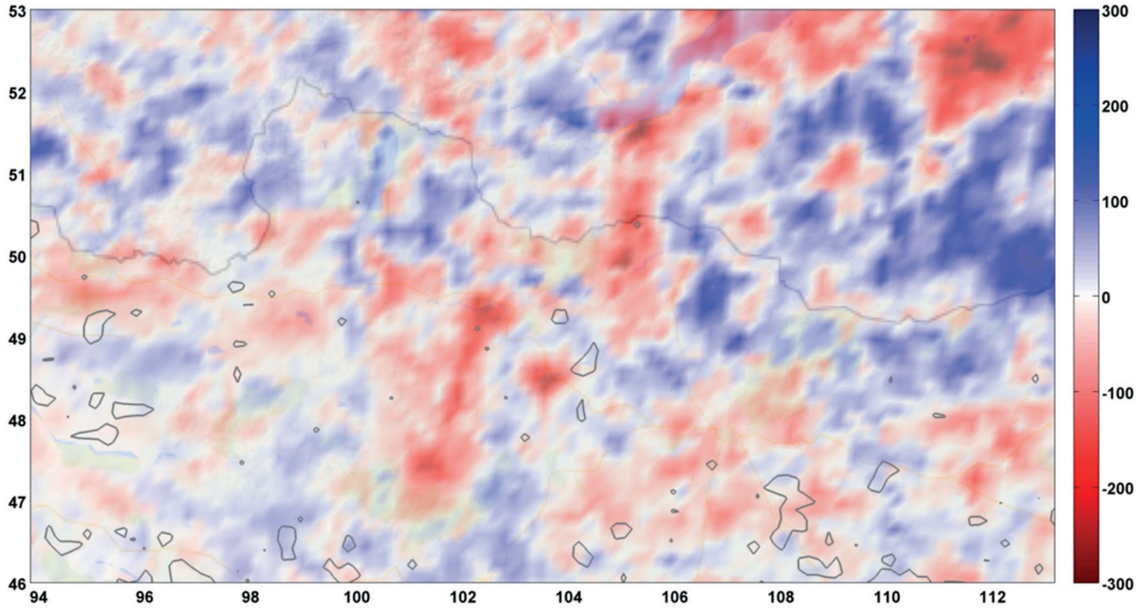

Figure 4. Hypothetical changes in precipitation fields due to possible mining impact in Selenga–Baikal catchments (modelled values between undisturbed and disturbed conditions)

(Source: Author own study)

$$\Delta P = \frac{P_0}{P_{disturbed}} \text{ (for wet summer conditions)}$$

Blue colour indicates a precipitation increase (ΔP > 0), red colour – a precipitation decrease (ΔP < 0).

3.3. Importance of export of land-derived constituents and their relationships with hydroclimatic conditions

In many cases, the sediments contain relatively high concentrations of metals from e.g. mining operations (Thorslund et al., 2012), hence shifts in sediment transport patterns from altered hydrology within the Selenga River Basin may also influence the heavy metal loading to Lake Baikal. Thus, the historical trends discussed above suggest smaller loads of metals in recent years, with all other conditions unchanged. A slight increase in the total dissolved solids and a twofold increase in SO4 (from 6.2-8.6 mg·L^{-1} in 1950–1970 to 10.6-16.4 mg·L^{-1} in 1995–2011) was caused by the sustained low-water period. The origin of metals and sediment-associated chemical components could be related both to natural and anthropogenic drivers. The examples of the upper Orkhon, the upper Selenga and the Tuul River, as well as downstream reaches of the Selenga River represent contrasting environmental conditions (Table 4). The upper Selenga catchment is relatively undisturbed with a typical distribution of pastures as the only dominant type of land use. This is a forested part of Mongolia. The upper Orkhon has a few small towns and mining sites. The Tuul River drains the driest and mainly steppe part of the Selenga catchment, with the largest mining and industrial centre of Mongolia and is regarded as the most polluted river in the region. Half of the Mongolian population is concentrated in its capital

Table 4. Seasonal changes in geochemical patterns related to hydroclimatic and anthropogenic changes (Source: Author own study, The discharge data are according to the following stations: Selenga–Mostovoy, Selenga–Zuunburen, Orkhon–Orkhon, Tuul–Ulaanbaatar)

Concentration of chemical elements in the particulate form	Orkhon catchment		Tuul catchment		Selenga catchment, upstream		Selenga catchment, downstream	
	July 2011	June 2012	July 2011	June 2012	July 2011	June 2012	July 2011	June 2012
> 75%	V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Pb	-	Mn, Fe, Co, Zn, Pb	-	V, Mn, Fe, Co, Zn, Pb	Fe	V	V, As
50-75%	As, U	Fe, Cu	V, Ni, Cu	Fe	Ni, Cu	Cr, Mn, Co, Cu, Pb	Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Pb	Mn, Fe, Co, Ni, Cu, Pb
25-50%	B	V, Mn, Co, Ni, Pb	-	V, Mn, Co	B, As	V, Ni, Zn	-	B, Cr, Zn
< 25%	Mo	B, Cr, Zn, As, Mo, U	B, Cr, As, Mo, U	B, Cr, Ni, Cu, Zn, As, Mo, Pb, U	Cr, Mo, U	B, As, Mo, U	B, Mo, U	Mo, U
ΔQ		2.93		2.35		1.3	1.46	
Average elevation, m	1,750		1,375		1,750		-	
Afforestation (%)	32		32		50		-	
Population	50,000		1,300,000		5,000		2,500,000	
% of mining areas	0.7		0.7		<0.1		-	

(Ulaanbaatar). Due to poor maintenance, lack of spare parts, outdated equipment, and frequent power outages, waste water from the wastewater treatment plants in Ulaanbaatar may be released directly into the Tuul River without treatment. Geochemical patterns in various parts of the catchment are determined by both natural and technogenic factors. Regional petrology causes general enrichment of suspended matter and sediments with As, Cd, Sn, Sr, W, Pb compared to the lithosphere averages. The common feature of the basin consists in the prevailing transport of dissolved forms of chemical elements that are highly mobilein the alkaline environment (Table 4). The contribution of dissolved forms of B, As, Mo, Cr, U increases (in some cases up to 98%), mostly during the low-water period (June 2012). The high-water period (July 2011) is characterized by increasing turbidity of river water and the growing importance of particulate forms of heavy metals (Fe, Mn, Ni, Co, Pb, Cu, Zn).

The reported individual storm events were associated with changes in heavy metal concentrations. During a storm event reported for the Orkhon River (O1) on 29–31 July 2011, the mass concentrations (mg·kg^{-1}) in the suspended load decreased for the main part of the chemical constituents during the peak flow, and increased again on the falling limb, with the exception of Ag and Br. Bulk concentrations (mg·L^{-1}) increased during the peak flow, becauseSPM concentrations also peaked. The only exception was As that showed lower values during the highest discharges. The highest increase in bulk concentrations during this individual flood event was reported for Fe and Al (2.3 and 2.4 times, respectively) (Chalov et al., 2015).

The observed absolute metal concentrations in the suspended sediments of the Tuul River at Ulan Bator also significantly increased during high-flow events in 2011 and 2012. Figure 5 also shows that the overall trends are consistent among different heavy metals, although the magnitude of change is varied. While some heavy metals (Be, Ag and Mo) clearly increased during high flows, the others (Se, Cd, W, Hg and Bi) demonstrated greater variability between different flow conditions.

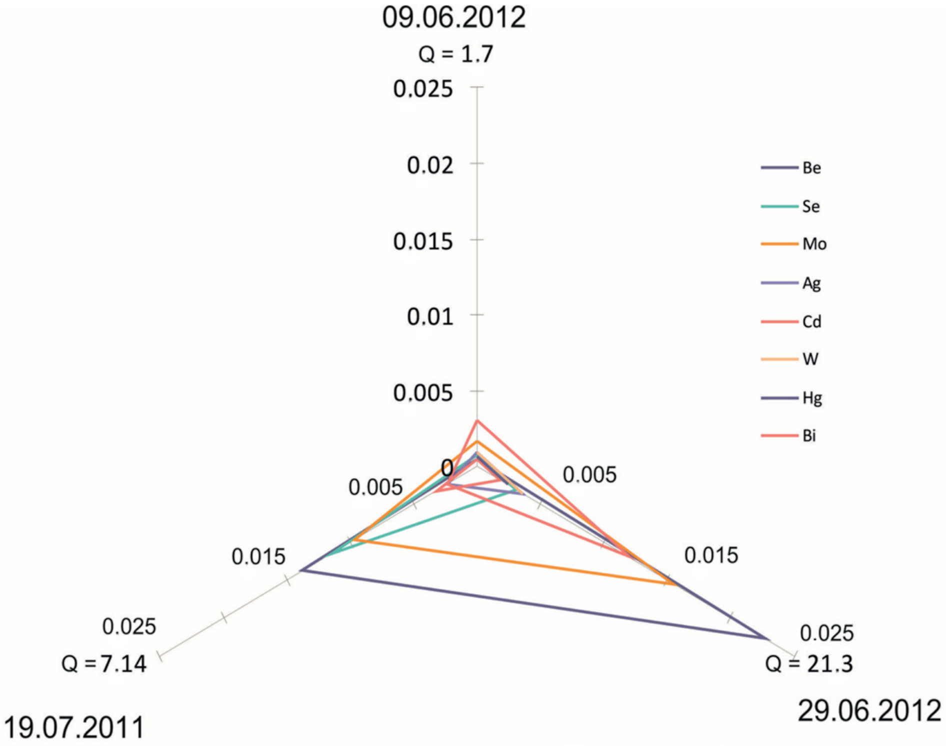

Figure 5. Observed changes in particulate heavy metal concentrations (mg·L^{-1}) in 2011 and 2012 due to flow fluctuations in the Tuul River (near UlanBaatar) (Source: Author own study)

These findings lead to an important conclusion that, due to hydroclimatic and land use development, a significant decrease in the elemental export to Lake Baikal has been observed for almost 20 years, e.g. AS (total): 1.8-2-fold decrease, Fe (total): 2-3-fold decrease, carbon (POC and DOC): 1.2-1.4-fold decrease. The afore mentioned values should be considered as the first approximation. They take into account the rates of the flood magnitude decrease over the last 20 years (Fig. 3), the observed changes in elemental behaviour before and during flood events (Fig. 5) and are based on sediment rating curves (Table 1).

4. Conclusions

The hydroclimatic development determines the multidecadal declines in sediment loads and elemental delivery to Lake Baikal. The reported multidecadal declines in sediment loads in the downstream part of the Selenga River can be attributed to the abandonment of cultivated lands and changing hydroclimatic factors, in particular a climate-driven decrease in water flows and intensified water use for irrigation purposes. Changes in flood magnitude are of primary importance to the mass export along river systems.

Whereas sediment flows were connected with the hydroclimatic conditions in the catchment, the elemental composition of mass flows was mostly related to soil/petrologic conditions. Except for small impacted rivers, where water quality effects associated with mining were observed, the formation of elemental compositions and sediment-associated chemical constituents generally reflects the catchment characteristics. The heterogeneity of catchments with associated soil geochemical anomalies has a significant impact on the compositions of chemical elements and their forms as well as sediment-associated chemical constituents.

The results indicate that future shifts in geochemical patterns due to hydroclimaticchanges and (less evident on a catchment scale) land-use changes will influence (e.g.) the heavy metal and carbon loading to Lake Baikal.

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