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THEMATIC ISSUE

Spatio-temporal variation of sediment transport in the Selenga River Basin, Mongolia and Russia

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Abstract Many Asian rivers have been intensively used to boost economic growth, resulting in sudden and drastic changes in sediment transport patterns. However, a few rivers are still undisturbed. The present paper considers the unregulated Selenga River and its basin, located in Russia and Mongolia. The river contributes to 50 % of the total inflow to Lake Baikal. Pending scientific challenges include the quantification of sediment loads and erosion–deposition patterns along the Selenga River system, the understanding of suspended particulate matter composition and the importance of peak flow events for total sediment discharge and heavy metal transport. Field data and hydraulic modeling converge on showing that peak flow events during spring and summer contribute to the main part (70–80 %) of the annual sediment and pollution loads in upstream parts of the basin. The Selenga River carries mostly silt and sand. The average particle size differs by a factor of four between summer floods and base flow periods. The low amount of particulate organic matter (ranging between 1 and 16 % in the studied rivers) is consistent with the significant role of sediments originating from mining areas and in-channel sources. The bed load transport in the downstream part of the river basin is high (up to 50 % of the total transport), and channel storage plays an important role in the total sediment transport to Lake Baikal. Reported statistically significant multi-decadal declines in sediment fluxes in the downstream Selenga River can be attributed to the abandonment of cultivated lands and (most likely) to changing hydroclimatic factors.

Keywords Sediment transport · Sediment budget · Transboundary rivers · Suspended particulate matter · Lake Baikal

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Introduction

The role of the water cycle in transporting sediments and elements from inland basins to downstream recipients is considerable. The water cycling implies that human activities in inland areas can considerably alter the hydrological and hydrogeochemical conditions of downstream lakes, wetlands and coastal waters. Land pollution is mainly caused by the release of heavy metals associated with mining and ore excavation (Malmström et al. 2008), the spread of nutrients and pesticides over agricultural areas (Darracq and Destouni 2005), and the release of many different elements and chemicals, including persistent organic pollutants, in urban and industrial areas (Jarsjö et al. 2005). A result of basin-scale transport of heavy metals, nutrients, and persistent organic pollutants is that they can be found at elevated levels in groundwaters, rivers, lakes, coastal seawater and near-shore sediments worldwide. Associated accumulation of toxic substances in biota, which adversely affects the functioning of ecosystems and human health, is since long well-documented (Vitousek et al. 1997; Törnqvist et al. 2011).

The quantification of cause-and-effect relations that are needed to predict basin-scale substance spread and

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understand the net impact of inland sediment and pollutant sources on downstream recipients is scientifically challenging (Meybeck and Vörösmarty 2005; Rügner et al. 2013; Mouri et al. 2013), for instance due to the large heterogeneity in hydrological, hydrogeological, and geochemical parameters. Sediment erosion and deposition patterns can cause spatial variation of sediment loads along a stream, which can constrain the basin-scale transport (Alexeevsky et al. 2013). The suspended-phase transport of elements of anthropogenic origin can at some locations dominate the total transport (Chalov et al. 2012; Thorslund et al. 2012). The various anthropogenic impacts can be seen in the suspended particulate matter (SPM) structure [grain sizes, particulate organic matter (POM), sediment-associated chemical constituents].

The scientific understanding of such processes and their impacts on environment and human health is, furthermore, hampered by limited observational data on spatially extensive water systems (Törnqvist et al. 2011; Liu et al. 2011). Recent attempts to quantify the riverine sediment supply to the world's oceans (Walling and Fang 2003) have highlighted the degree to which river loads have been altered by human activities in drainage basins in the past two centuries (e.g., land use changes, damming, artificial levees and other river control works, etc.,). Fewer studies have been devoted to inland areas and continental fluxes to recipient lakes.

In this study, we consider the Selenga River and its basin, located in Russia and Mongolia. The Selenga River contributes to 50 % of the total inflow to Lake Baikal, which has earned UNESCO World Heritage status. However, the lake is now under pressure from pollution by heavy metals, as well as toxic and persistent organic pollutants. For instance, the dioxin and dibenzofuran (PCDD/Fs) levels in Lake Baikal seals were found to be as high as in seals of the Baltic Sea (Tarasova et al. 1997). Other pollutants include lead (found in lake sediments; Boyle et al. 1998), and PCBs (found in seal and lake water; Nakata et al. 1995; Mamontov et al. 2000). High pollutant loading is reported for some Mongolian rivers, such as the Tuul River below Ulan Bator and Zaamar Goldfield (Lee et al. 2006; AATA 2008; Bayamba and Todo 2011; Thorslund et al. 2012), the Boroo River (Inam et al. 2011) and the Khangal River below the copper–molybdenum mines of Erdenet (Lee et al. 2006). High loads are also reported for Russian rivers, such as the Modonkul–Dzhida River system below the wolfram–molybdenum mining and processing factory of Zakamensk (Chalov et al. 2013).

In recent years, exploration for natural resources has increased rapidly in the Selenga River Basin. Many sub-basins of the river are used intensively for mining of gold, silver, and coal, supplying also precious stones, gravel, and other natural resources. A total of 784 enterprises are engaged in mining in Mongolia, of which 204 small-scale gold mining companies are operating on 6,065,298 hectares of land (Batimaa et al. 2011). At the same time, Selenga River in-channel processes are still not heavily impacted by anthropogenic pressures. This is because dams and large-scale water abstractions for irrigation are absent in both the main river channel and its tributaries. However, there are plans by the Mongolian government in particular to develop hydropower and construct a number of reservoirs. Potentially significant cross-border impacts of dams on sediment flows highlight the importance of understanding sediment transport under the present natural conditions.

Whereas runoff (Semenov and Myagmarzhav 1977; Sinukovich 2008; Garmaev and Khristovorov 2010) and water quality (Khazheeva et al. 2004, 2008; Chebykhin et al. 2012) of Lake Baikal and its basin has been extensively studied, only a few studies have focused on sediment source locations and sediment transfer through fluvial systems of the basin (Thorslund et al. 2012; Theuring et al. 2013; Priess et al. 2014). Therefore, the relative contribution of different potential sources to the observed pollution of Lake Baikal and its surroundings is not understood in sufficient detail.

There are also several open questions regarding the importance of various possible spreading pathways. For instance, the relative contribution of pollution sources along the principal Selenga River to the total downstream sediment fluxes is not well known. Likewise, effects of filtering processes of sediments as they enter the Selenga River Delta on their way to the Lake Baikal are to large extent unknown (Lisitsyn 1995). More specifically, the delta-coastal area, acts as a marginal filter in which gravitational sedimentation, flocculation and biofiltration (Sholkovitz 1976) determine the removal of SPM. This emphasizes the importance of sediment delivery estimates from the transboundary river system to the Selenga Delta area. Besides, the unregulated nature of the Selenga River yields unique opportunities to quantify responses to hydrologic events and effects of seasonality, which can at least partially be masked in regulated rivers.

In particular, this study aims at (i) quantifying sediment loads along the Selenga River system and its long-term changes, (ii) resolving erosion–deposition patterns that can constrain suspended-phase transport distances, (iii) determining relative element concentrations transported in SPM and their possible event variations, and (iv) investigating the impacts of hydrological peak flow events on total annual load contributions. We carried out snapshot field campaigns on sediment loads and water chemistry to address objective (i) and (iii). Furthermore, data from these campaigns were used as a basis for developing numerical models for the interpretation of erosion and deposition according to objective (ii). Finally, overall questions on the contribution of the river system to element and pollution transport are discussed on the basis of suspended transport patterns from (i) to (ii) combined with element distribution data and variability over the hydrological year from (iii) to (iv).

Site description

The Selenga River, which originates in Mongolia (see the "Methods" section for location map), contributes to about 50 % of the total inflow to Lake Baikal and is geographically located in the center of Asia. The Selenga River Basin is characterized largely by mountain topography and has an area of 447,000 km^2. It contains the world's largest inland continental delta with an area of 5,000 km^2.

The mean annual water discharge of the Selenga River at the downstream Raz'ezd Mostovoy station (located close to the river delta at Lake Baikal) is 28.7 km^3/year. The maximum annual river discharge recorded at this location since observations started in 1936 is 46.4 km^3/year. The largest hourly discharge was observed on 11 of June 1936 (7,620 m^3/s), and the lowest summer one was observed between 6 and 7 July 1969 (518 m^3/s). At the Russian–Mongolian State border the mean annual discharge is 9.68 km^3/year. The maximum river discharge is driven by the spring melt of the accumulated snowpack. A second peak in the river hydrographs is observed in late summer, August or September, during the rainy season. In recent times (1996–2011), the low water period is observed during July and August. It is usually explained by rainfall decreases (Bereznykh et al. 2012) caused by reduced circulation at the air masses convergence of the mid-latitude and the East Asian cyclone.

The absence of large impoundments and dams within the Selenga River Basin implies that sediment loads are essentially natural. However, mining, industry and agriculture within the Selenga River Basin affect the sediment influx and transport along the river and its tributaries. The average suspended sediment concentrations were reported (Semenov and Myagmarzhav 1977) to range from approximately 100 to 250 g/m^3 in the midstream and downstream area of the Selenga right tributary Orkhon and Tuul rivers to 50 g/m^3 or less in the upstream area of the Orkhon and Selenga rivers.

The primary chemical composition of waters of the Selenga River and most of its tributaries follows the pattern of $Ca^{2+} > (Na^+ + K^+) > Mg^{2+}$, and $HCO^{3-} \gg SO_4{}^{2-} > Cl^-$. Aquatic systems of the Selenga River Basin in general are characterized by low salinity, slightly alkaline pH and a calcium bicarbonate composition of the water. More specifically, the pH in the upstream part of the Selenga River Basin is around 7.5–9 (Thorslund et al. 2012), whereas Lake Baikal itself is characterized by pH values of 7.3–7.4 (Chebykin et al. 2010). Acid rains over the Selenga River Delta may occasionally lower the pH below neutral (Plyusnin et al. 2008; Thorslund et al. 2012).

Methods

The present analysis is based on data from the national gauging network of the Selenga River Basin, which is implemented by the Russian and the Mongolian hydrometeorological surveys for their corresponding parts of the basin. We also report and discuss the results of novel field campaigns and environmental surveys conducted by Lomonosov Moscow State University and Stockholm University from July to August 2011 and June 2012. We particularly focus on the Tuul River, which is regarded to be the most polluted river in the region (Batimaa et al. 2011), arguably due to mining of placer gold deposits (at the Zaamar Goldfield) and urban pollution sources from the Mongolian capital Ulan Bator, which is located in the upstream part of the basin. The one-dimensional hydrodynamic model HEC-RAS was applied to the downstream and relatively disturbed part of the mentioned river.

Data from the national gauging network and historical field campaigns

There are currently 62 flow measurement stations in the Selenga River Basin, of which 44 belong to the Russian part of the basin, and 18 belong to the Mongolian part. For the present study, daily discharges were obtained from four gauging stations located in Mongolia and Russia for the period 2011–2012 (Fig. 1). Generally, the hydrographs show significant differences both in hydrological conditions of certain sub-basins during the considered periods. For instance, there are significant differences between the discharge patterns of the Selenga River (3, Fig. 1) and the Orkhon River (2, Fig. 1). Furthermore, the discharge of the Selenga River is one order of magnitude higher in 2012 than in 2011. Hence, while discharges differed considerably between the field campaigns in July–August 2011 and June 2012, differences in sediment transport properties can additionally be related to seasonal variations of catchment and in-channel processes and features.

Sediment loads have routinely been observed through a relatively dense gauging station network. In Mongolia, sediment load data were episodically obtained at six gauges that have been in use only occasionally. Previous historical studies (Stubblefield et al. 2005) reported sediment load measurements at Selenga, Orkhon, Tuul, Yeroo, Kharaa and Eg Rivers in 2003. In Russia, there are 12 gauging stations for measuring the sediment load at four rivers.

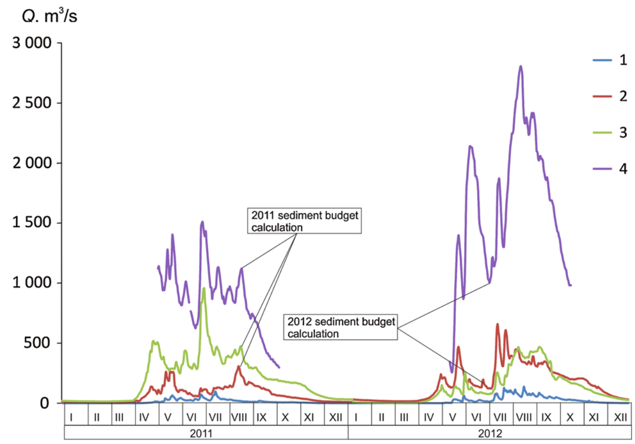


Fig. 1 Hydrographs showing the discharge Q of the Tuul River (*1* Ulan Bator, field point T2), the Orkhon River (*2* Suhabaator, field point O6), and the Selenga River (*3* Zuunburen, field point S2 and *4* Mostovoy, field point S16). The numbering of the field points is consistent with Fig. 2, in which their geographical locations are shown

Long-term trends in sediment loads were analyzed based on discharges and sediment loads obtained from six national gauging stations operated by Russian National Survey for Hydrometeorology (Roshydromet) with observation periods until 2011. Additional information was obtained from historical field campaigns focusing on sediment loads and water quality in different parts of the Selenga River Basin (Stubblefield et al. 2005; AATA 2008; Baljinnyam et al. 2009; MCA 2011).

Environmental surveys 2011–2012

The spatial variability of sediment loads was evaluated based on environmental surveys conducted in 2011 and 2012 (Chalov et al. 2012; Thorslund et al. 2012). 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. 2a). In Russia, the observational sites were located along the main stem of the Selenga River (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. 2a).

In-stream measurements of pH, conductivity (TDS) (both of water and streambed sediments) and turbidity (for water) were conducted. Discharge (Q, m^3/s) measurements were performed using a velocity current meter lowered from bridges. Depth-integrated water samples were collected with a GR-16M bottle sampler at midstream. Water samples were filtered through pre-weighed membrane filters (with pore size 0.45 µm) from the "Millipore" filtration system. The samples were then oven-dried and re-weighed to determine suspended sediment concentrations (SSC, mg/l = g/m^3). The sediment load (SL, g/s), defined as the mass of matter that passes through a river cross-section per unit time, is a product of the local concentration and the discharge:

$$\mathrm{SL} = Q\ \mathrm{SSC} \tag{1}$$

where Q is the water discharge through the control plane for the given time t (s). Available SL estimates were averaged over consecutive time periods of 1 day.

Using sediment load measurements to estimate daily sediment loads as W_{R} = SL 86,400, the sediment budget was calculated for the Orkhon–Selenga rivers as;

$$\Delta W_{\mathrm{R}} = W_{\mathrm{Rdown}} - (W_{\mathrm{Rup}} + W_{\mathrm{Rtrib}}) \tag{2}$$

where W_{Rdown} and W_{Rup} are the sediment loads at the downstream and upstream boundaries of a considered reach, respectively, and W_{Rtrib} is the sediment load from tributaries along the reach. $\Delta W_{\mathrm{R}} > 0$ corresponds to erosion–degradation patterns, whereas $\Delta W_{\mathrm{R}} < 0$ evidences deposition–aggradation patterns. The present study focuses on estimating sediment budgets during July–August 2011, which we refer to as the flood period, and June 2012, which we refer to as base flow (Fig. 1). Particularly, the base flow conditions (June 2012) were characterized by homogenous discharge periods (constant water discharge during the field monitoring; see Fig. 1).

Errors in the daily sediment balance calculations during the flood period (July–August 2011) were reduced by explicitly accounting for water discharge alterations. For this purpose, all discharge measurements between 20 July 11 and 15 August 11 were transformed to peak flow conditions by multiplying the discharge with a daily reduction coefficient k_n, which was determined using the daily discharges (Fig. 1) from control gauging stations as $k_n = Q_{n\ \mathrm{gs}}/Q_{\max\ \mathrm{gs}}$, where $Q_{\max\ \mathrm{gs}}$ is the maximum discharge during this period at the considered gauging station, $Q_{n\ \mathrm{gs}}$ is the discharge on the day of measurements at the gauging station, and n is the date of the field measurement. The maximum discharges at the considered gauging stations were 146 m^3/s on July 30th for the Orkhon River (O6–7), 443 m^3/s on August 6th for the Selenga River (S-2), and 1,119 m^3/s on August 15th for the downstream Selenga River (S-16).

The bed load measurements were collected by a bed load sampler at two to three locations along a cross-section of the river. The used sampler has a rectangular mouth that is 0.2-m high and 0.3-m wide. The sampler has a 0.1-mm mesh. It collects particles transported near the riverbed (the bed load) and likely the lower layer of the saltation load.

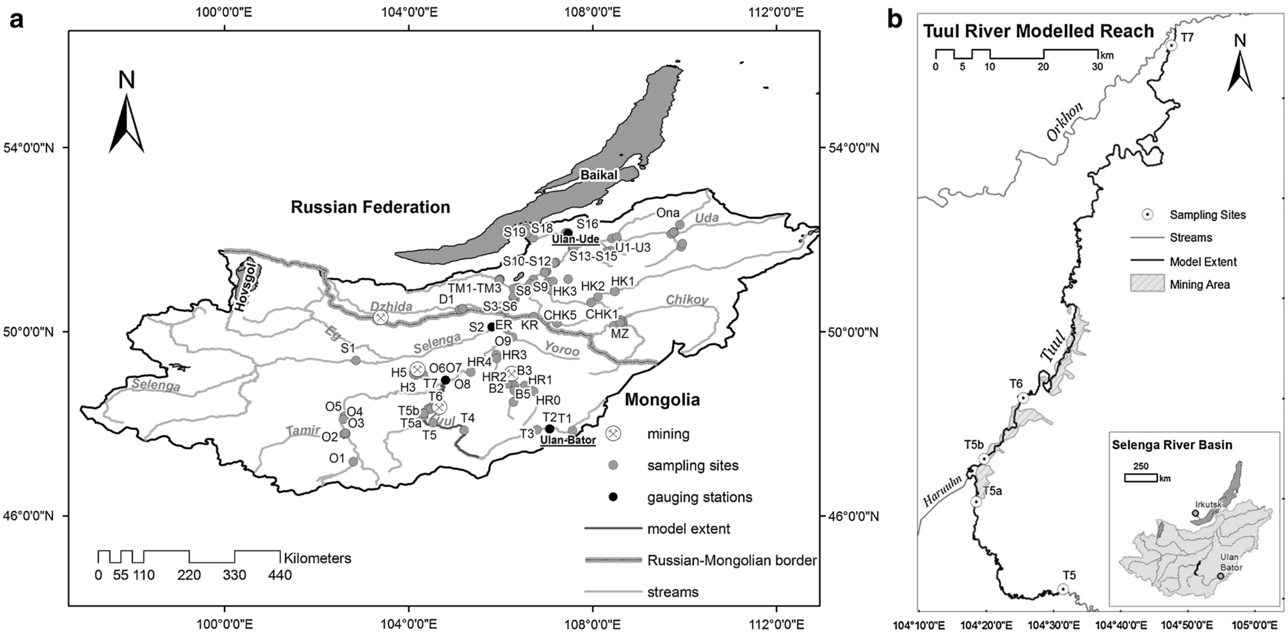


Fig. 2 **a** Selenga River Basin (*left*) showing sampling sites and major mining sites, and **b** modeled reach of downstream Tuul river (*right*)

For sediment quality parameters, the suspended and finer fractions ($d < 0.05$ mm) of the bed load samples were collected and returned to the laboratory for analysis.

In total, 120 samples of water and suspended matter and 140 streambed sediment samples were taken. All samples (suspended and streambed sediments and filtered water) were analyzed for 62 elements by inductively coupled plasma mass spectrometry ICP-MS (ICP-AES) using a semi-quantitative mode and a tenfold automated dilution during the analysis. Elemental analyses were conducted on the filtered samples without additional treatment. For a fully quantitative analysis, the instrument is calibrated with a series of known standards for each element. Corrections are applied for potential interferences, and more comprehensive quality assurance/control measures are performed for each element.

The contribution of various forms of transport to sediment-associated chemical constituents is

$$r_{\mathrm{s-d}} = C_{\mathrm{dissolved}}/C_{\mathrm{suspended}}; \quad r_{\mathrm{s-b}} = C_{\mathrm{suspended}}/C_{\mathrm{bed}} \tag{3}$$

where $C_{\mathrm{dissolved}}$, $C_{\mathrm{suspended}}$ and C_{bed} are concentrations of chemical elements in the dissolved and suspended phases, and the bed load. We also note that the mass flows in the dissolved and suspended phases can be expressed as $\mathrm{mf}_{\mathrm{dissolved}} = C_{\mathrm{dissolved}}\,Q$ and $\mathrm{mf}_{\mathrm{suspended}} = C_{\mathrm{suspended}}\,Q$, respectively, where Q is the river flow at the considered cross-section, it follows that the mass flow ratio between the dissolved and suspended phases $r_{\mathrm{s-d,mf}}$ equals the concentration ratio $r_{\mathrm{s-d}}$ of Eq. (3). In the present paper, sediment quality analyses were applied for the modeled reach of the Tuul River.

Grain size analysis of suspended sediments was conducted with the Laser granulometer Fritsch Analysette 22 and with sieving method for bed load samples. The D_{50} for suspended and bed load which corresponds to the diameters at which 50 % of the particles (in weight) are finer, respectively, were obtained. The POM in the suspended sediments was determined from cooling and weighing samples that had been filtered onto pre-washed and pre-weighed glass fiber filters and ashed at 400 °C for 1 h. Heating the filters to 400 °C prevented loss of water from clay minerals (vermiculite, kaolinite, chlorite, and mica) that can occur at higher temperatures (600 °C), while still burning off the organic matter. Dried samples were weighed on an analytical balance (accuracy to 0.0001 g).

Hydrodynamic modeling

The one-dimensional hydraulic modeling program, HEC-RAS 4.1, was used to model sediment transport patterns of the most downstream (245 km) reach of the Tuul River (Fig. 2b). The modeled reach contains the Zaamar placer mining area, which is distributed along a 60-km long river stretch (dashed, gray area in Fig. 2b) and is regarded to be largest placer mining in the Selenga River Basin.

The geometry of the model was developed using field measured cross-sections at three locations of the river, as well as open-source data such as SRTM 90 Digital Elevation Model (USGS 2012a) and LANDSAT images (USGS 2012b). The flow model component was calibrated by adjusting Manning's roughness coefficients of the channel using discharge–velocity information acquired from six locations along the studied reach. Information about the bed material in the model was based on riverbed sample data measured at 12 locations along the reach.

The bed material was divided into ten sediment size classes ranging from 0.0625 to 150 mm. While applying the sediment size classes to the model, the default HEC-RAS classes were changed. Thus, the "settling depth" factor, which controls vertical distribution of each class in the water column (Gibson et al. 2010), was adjusted for each new class. The specific gravity of the material was also changed from the HEC-RAS default value of 2.65–1.91. The latter value was obtained from measurements in the upstream part of the studied reach.

The model scenario was based on daily discharge data from 2011 of the Ulan Bator gauging station (Fig. 1), which is located 150 km upstream of the mining site. According to Battulga et al. (2009), the flow between the Ulan Bator gauging station and the location of the model is unchanged. Therefore, the inflow to the modeled area was assumed to equal the observed flow at the gauging station. Furthermore, long-term monitoring data showed that an average increase in discharge along the modeled reach of Tuul was consistent with independent observations of precipitation surplus, i.e., precipitation minus evapotranspiration, from the adjacent basin parts. Therefore, the flow was allowed to increase in the downstream direction along the model reach, according to the increase of contributing drainage basin area of the river. This increase was significant in the upstream part of the model due to a confluence of the Tuul River with its left tributary, the Haruuhn River (Fig. 2b).

The sediment load entering the model at its upstream boundary was automatically calculated using the "equilibrium load" upper boundary condition (USACE 2010a). Sediment transport was calculated using the Tofalleti equation (USACE 2010b). Out of several transport equations that are available in HEC-RAS 4.1, it was found that the Tofalleti equation is the most appropriate considering the studied sediment grain sizes. The river type "Exner 5" was chosen to estimate bed sorting in the model (USACE 1993).

Results

During the 2011 environmental survey, the SSC varied between 1.43 (in the downstream part of the Dzhida River, D2) and 2,850 mg/l (in the Orkhon River at Kharkhorin, O1). The average SSC values in the Mongolian part of the basin (270 mg/l) were 15 times higher than in the Russian part of the basin (19.0 mg/l). Within Russian territory, the maximum SSC was observed at the Selenga delta (70.5 mg/l), while all other SSC values were below 50 mg/l. In Mongolia, nearly 70 % of the values were higher than 50 mg/l. In 43 % of cases, they were higher than 100 mg/l. In 2012, the average SSC was 127 mg/l. The minimum value was 1.68 mg/l, observed in the Tuul River upstream of Ulan Bator (T1), and the maximum value was 1,249 mg/l, observed in the Tuul River downstream of the Zaamar Goldfield (T6–7). For the Russian part of the Selenga River Basin, the average SSC was half (63.6 mg/l) of the average SSC for the Mongolian part. The highest SSC was observed in the Tugnuy River in the Khilok basin (560 mg/l, TG) and at the Dzhida River outlet (200 mg/l, D2).

Silt (<0.05 mm) and sand (>0.05 mm) are primary constituents of the observed sediment load in the Selenga River Basin. Fine sediments that range in grain size from 0.01 to 0.05 mm represent more than 50 % of the total suspended sediment load. The volume of particles that have a grain size of <0.05 mm constitutes over 60 % of the total particle volume. During base flow periods, a longitudinal decrease in the average grain size was reported (Fig. 3). The SPM size was highest in samples from the upper parts of the Tuul, the Orkhon and the Uda rivers. The grain size was furthermore higher at sites in the Uda River (0.31 mm) compared to other sites. The average grain size of SPM was low (0.019 mm) at sites in the Selenga River mouth (S16). This provides evidence that the sedimentation behavior of grain size fractions >0.05 and <0.05 mm is different; the former consists mainly of sediment deposited in the channel.

Due to intensive slope wash during rainfalls that dominate the flood period (July–August), the SPM size was nearly four times as high as during the base flow period. On average, the silt fraction (0.001–0.05 mm) accounts for 80–90 % of the total sediment load. The highest values of the SPM size were found in the samples taken between storm events. They were generally associated with rivers in the upstream areas of the basin.

The organic matter content (POM) in the suspended sediment samples was determined only for the flood season 2011 and exhibited considerable variation. It ranged between 0 and 16.3 % in the Mongolian part of the Selenga River Basin. In general, POM increases along a river system. It varied between 2 and 3 % in the upstream part of the Kharaa, Selenga and Orkhon rivers. In the midstream part of the Orkhon, Selenga, Eg, and Tuul rivers the values varied between 5 and 8 %. In the downstream part of the Tamir and Orkhon rivers, the corresponding range was between 11 and 13 %.

The present measurements indicate that about 3,000 t/day of suspended sediments are discharged annually from the Selenga River to the delta area under current conditions, which is higher than the total sediment flux to Lake Baikal. This is due to retention in lakes and river branches located within the Selenga River Delta. About 1,800 t/day

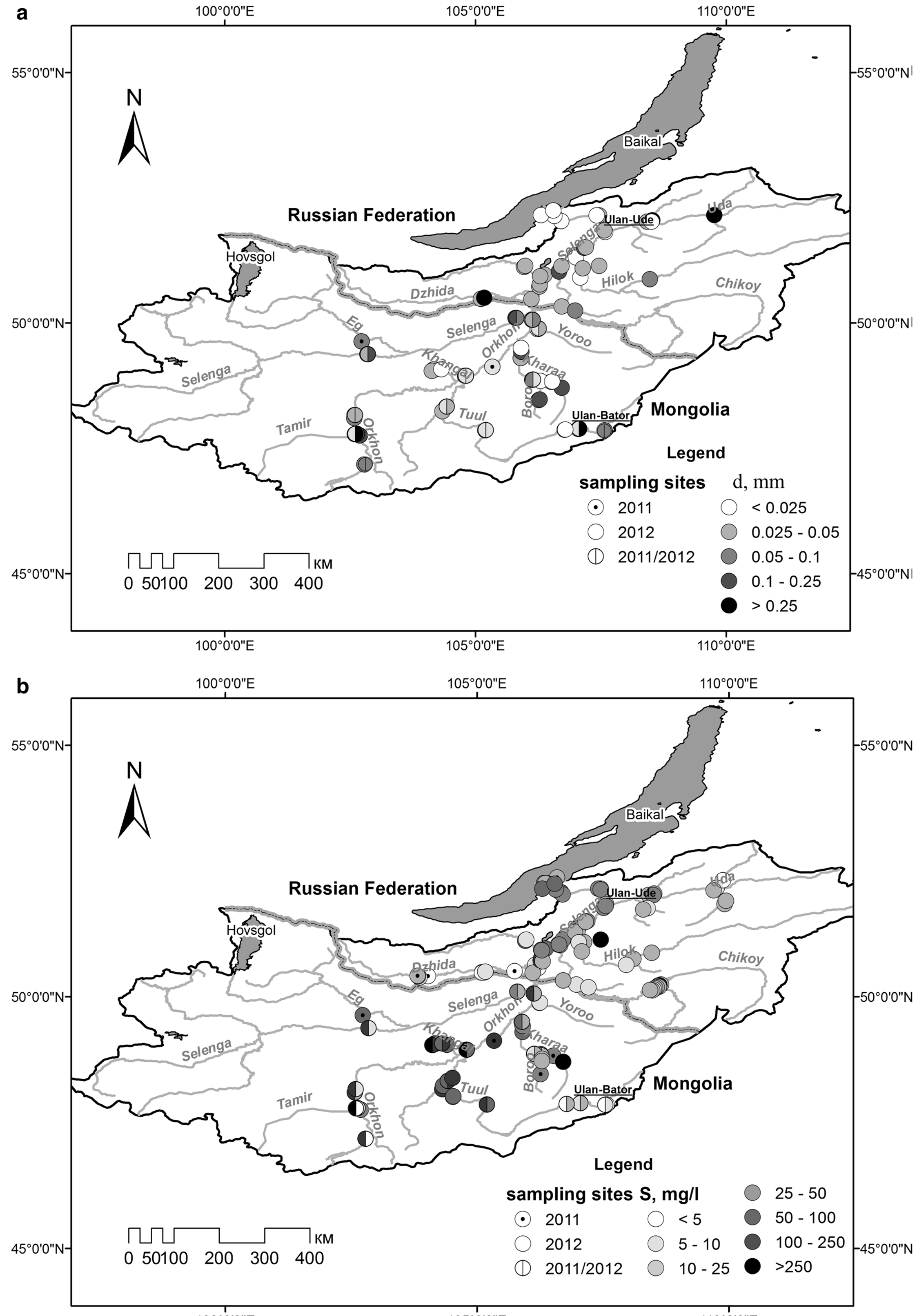


Fig. 3 Average grain size (**a**) and measured SSC (**b**) (2011–2012) in the Selenga River Basin

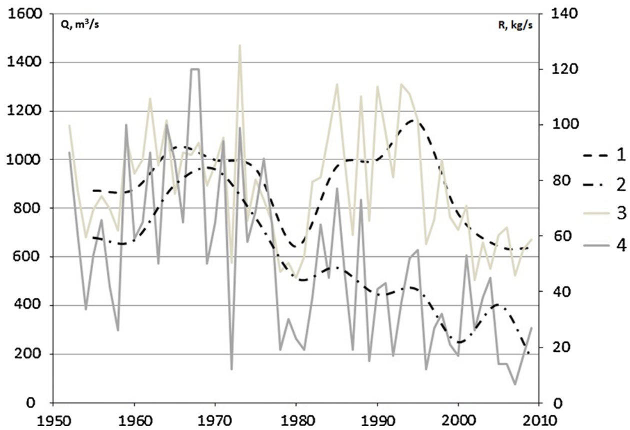


Fig. 4 Temporal changes in water and sediment discharges in the downstream Selenga River (Mostovoy gauging station, 50 km downstream of Ulan-Ude); 5-year running average of *1* water discharge *Q* and *2* sediment discharge *R*, and annual average *3* water discharge and *4* sediment discharge (data from Potemkina 2011)

of suspended sediments originate from the Mongolian part of the drainage basin, on average. Variability in water discharges and suspended sediment concentrations cause seasonal differences in the sediment fluxes. The suspended sediment flux at the Russian–Mongolian border was 83 % of its average annual value during the flood period of July–August 2011 and 8 % of its average annual value during the base flow period of June 2012. The total suspended sediment flux into Lake Baikal during the field campaigns 2011–2012 was below the corresponding annual averages (1,560 and 1,549 t/day, respectively).

Bed load measurements in small gravel-bed and sand-bed rivers conducted during the base flow period (field points O6, T7, Hr3, Hr4, ER) indicated small bed load transport. Measured bed load values accounted for about 2–4 % of the total sediment transport in the rivers. In the downstream sand-gravel reach of the Selenga River, repeated sonar surveys gave a velocity of the annual riffle movement of around 1,390 m/year (Garmaev and Khristovorov 2010). Considering bed topography survey data, the bed load transport was estimated at 0.7 Mt/year (or 2,130 t/day in average), accounting for 45 % of the total sediment flux in the downstream Selenga River.

During the past 30 years, there has been a substantial decline (about 50 %) of annual sediment loads in the downstream Selenga River (Fig. 4) and its main tributaries in the Russian part of the river basin (from 5,832 to 3,015 t/day). Decreasing trends in suspended sediment concentrations are well traced in the Uda and Chikoy rivers. Mean SSC in the Uda River was equal to 52 g/m^3 in the 1980s and 27 g/m^3 after that. In the Khilok River, the above trends are the least pronounced (Potemkina 2011).

Estimates using Eqs. (1) and (2) for the Tuul–Orkhon–Selenga River system showed that some river stretches are associated with patterns of both aggradation and erosion, whereas others are associated with channel erosion. In the upstream areas (Orkhon River), the longitudinal increase of W_R caused by erosion ($\Delta W_R > 0$) is due to river size increase. Downstream sites are frequently characterized by sediment deposition ($\Delta W_R < 0$). The channel aggradation–degradation patterns are also time dependent. In the Tuul River, the sediment load upstream of the Zaamar Goldfield (T5) varied between 307 and 115 t/day during high and low water periods, respectively. Sediment loads upstream of Ulan Bator (T2) ranged between 18.6 t/day in 2011 and 2.50 t/day in 2012 (Table 1).

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/day was recorded. During base flow periods in 2012, a 1.2-fold increase from 115 to 143 t/day was measured. In the 150 km long river reach downstream of the Russian–Mongolian border, the net annual loss (deposition) from the suspended sediment load is $\Delta W_R = -2{,}445$ t/day during the flood season (July–August 2011). During base flow conditions the following year (June 2012), the sum of river loads showed a longitudinal increase (erosion) of $\Delta W_R = 428$ t/day.

The results show significant differences between the dissolved and the suspended concentrations of heavy metals. Concentrations of suspended heavy metals were nearly twice as high as concentrations of dissolved metals. The pH of the Tuul River water during the 2012 environmental campaign ranged between 8.5 and 9.6 (average 9.0), indicating clearly alkaline conditions at all times and locations. Most of the As and Zn in the Selenga River Basin is transported as dissolved loads, whereas Bi, Cd, Mn, Pb, V, Fe, Al are almost completely adsorbed by suspended solids. Along the downstream reach of the Tuul River, Al has the highest suspended–dissolved mass flow ratio ($r_{s\text{–}d}$; Eq. 3) (Fig. 5), with an average $r_{s\text{–}d}$ of 178 for all locations and values close to 400 at the first two locations (T5, T5a).

This implies that the overall transport of Al is almost completely dominated by the suspended phase. For most considered heavy metals and cross-sections, $r_{s\text{–}d}$ is between 10 and 50, with suspended mass flows being on average approximately 60 times higher than dissolved mass flows at the five cross-sections. However, the spatial trends of $r_{s\text{–}d}$ for the various heavy metals differ. For instance, $r_{s\text{–}d}$ for Cu has a clear increasing trend along the studied reach (T5–T6) while results for Al mainly show an opposite trend with the suspended ratio decreasing from upstream (T5) to downstream reaches (T6a).

Table 1 Suspended sediment load along the Tuul River during the flood period of July–August 2011 and the base flow period of June 2012

Site	Location	Sediment load								
		Unit	Clay (<0.001 mm)		Silt (<0.05 mm)		Sand particles (>0.05 mm)		Total suspended sediment load	
			July–August 2011	June 2012	July–August 2011	June 2012	July–August 2011	June 2012	July–August 2011	June 2012
T1	20 km upstream from Ulan Bator	%	2.8	2.1	68.1	75.7	29.1	22.2	100	100
		t/day	0.12	–	2.91	–	1.24	–	4.28	–
T2	0.5 km upstream from Ulan Bator	%	4.6	0.6	92.3	24.6	3.1	74.8	100	100
		t/day	0.86	0.02	17.2	0.61	0.58	1.87	18.6	2.50
T3	0.1 km downstream from Ulan Bator	%	–	4.0	–	93.5	–	2.5	–	100
		t/day	–	1.79	–	41.8	–	1.09	18.7	44.7
T4	Downstream from Lun City	%	3.5	2.3	93.9	90.9	2.6	6.9	100	100
		t/day	6.91	1.13	185	45.0	5.16	3.39	197	49.5
T5	10 km upstream from Zaamar Goldfield	%	2.4	–	76.3	–	21.3	–	100	–
		t/day	7.32	–	235	–	65.5	–	307	115
T5a	Upper border of Zaamar Goldfield	%	–	2.7	–	91.1	–	6.2	–	100
		t/day	–	2.66	–	89.8	–	6.15	–	98.6
T5b	Midstream of Zaamar Goldfield	%	–	2.2	–	76.5	–	21.3	–	100
		t/day	–	1.80	–	62.7	–	17.4	–	81.9
T6	Downstream reach of Zaamar Goldfield	%	3.3	2.7	88.9	90.1	7.8	7.2	100	100
		t/day	23.4	3.91	632	129.1	55.2	10.33	710	143
T7	0.1 km upstream from the confluence with the Orkhon River	%	3.2	2.3	92.9	91.5	3.9	6.2	100	100
		t/day	14.9	2.02	432	79.5	18.1	5.35	465	86.9

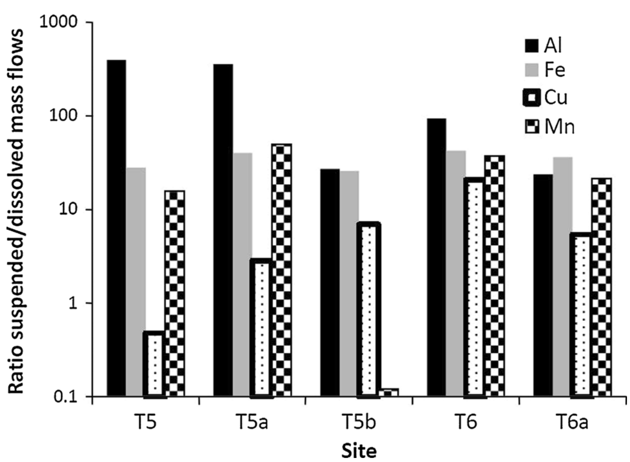


Fig. 5 Ratio between suspended and dissolved heavy metal (Al, Fe, Cu and Mn) mass flows across five cross-sections (T5, T5a, T5b, T6 and T6a) in the Tuul river (June 2012)

The averages $r_{s\text{–}d}$ of Fe, Mn and Cu are 34, 25 and 7, respectively, showing that the relative importance of dissolved transport is highest for Cu. Furthermore, two cross-sections (T5, T5a) show low $r_{s\text{–}d}$ values (below 3) for Cu and one for Mn (T5b); large fraction of these metals are hence in solution at those locations. However, despite spatial variability and differing characteristics of the different heavy metals, the suspended-phase transport is considerably higher than the dissolved transport in all cross-sections and for all considered heavy metals (Cu, Mn, Fe and Al), with only two exceptions (Cu in T5 and Mn in T5b). Using total sediment analyses (both suspended and bed load) for the rivers of Mongolia, we indicated that some elements dominate within bed load samples (Se, Hg, Bi), whereas Mn, Ag, Hg are associated with suspended load.

Significant increases of SSC and suspended sediment loads were observed at Kharkhorin at the Orkhon River (O1; July 2011) (Fig. 6) and at the Kharaa River (Hr2) upstream of Darkhan (June 2012) during a hydrological event resulting from a regional storm event. In the first case, the SSC increased 18 times from 160 to 2,800 mg/l. The load reached 3,000 t/day at peak flow. This was a response to an intense rainfall that amounted to a total of 50 mm, which corresponds to 20 % of the annual average precipitation. At the Kharaa River, the total precipitation between the 20th and the 22nd of June was 28.1 mm (7 % of the annual value), and the SSC increased from 13.3 to 518 mg/l.

The suspended load increased more than 110 times and reached almost 480 t/day. In particular, the coarse SPM concentrations (>0.05 mm) increased considerably in both

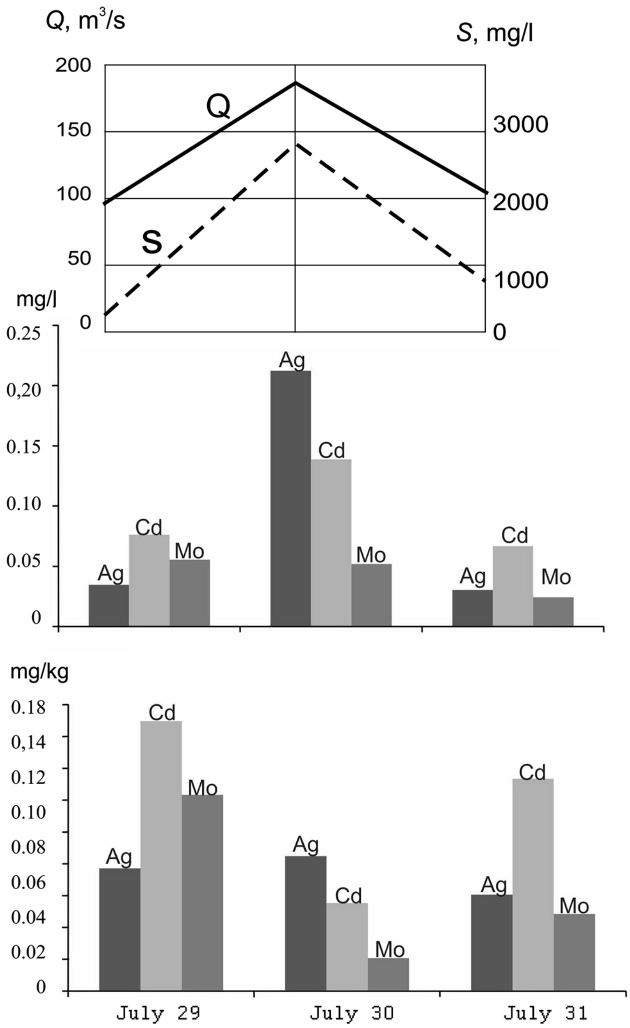


Fig. 6 Water discharge, *Q*, and sediment load, *S*, associated changes of mass (mg/kg) and bulk (mg/l) concentration in SPM of Ag, Cd and Mo in the Orkhon River during a storm event (29–31 July 2011)

the Kharaa and Tuul rivers. In the upper reaches of the Tuul River, the average grain size of SPM was 0.48 mm before the flood peak and 0.041 mm after, whereas it was 0.051 and 0.014 mm, respectively, in the Kharaa River. In the Orkhon River (O1; 29–31 July 2011), during the falling limb of the flood, the average SPM size increased from 0.03 to 0.12 mm.

The reported individual storm events were associated with changes in heavy metal concentrations. During a storm event reported for the Orkhon River (O1) in 29–31 July 2011, the mass concentrations (mg/kg) in the suspended load decreased for the main part of the chemical constituents during peak flow, and increased again on the falling limb of the hydrograph (Fig. 6), with exception of Ag and Br. Bulk concentrations (mg/l) increased during peak flow, since SPM concentrations also peaked. The only exception is As, which showed lower values during the highest discharges (Fig. 6). The highest increase of bulk concentrations during this individual flood event was reported for Fe and Al (2.3 and 2.4 times accordingly).

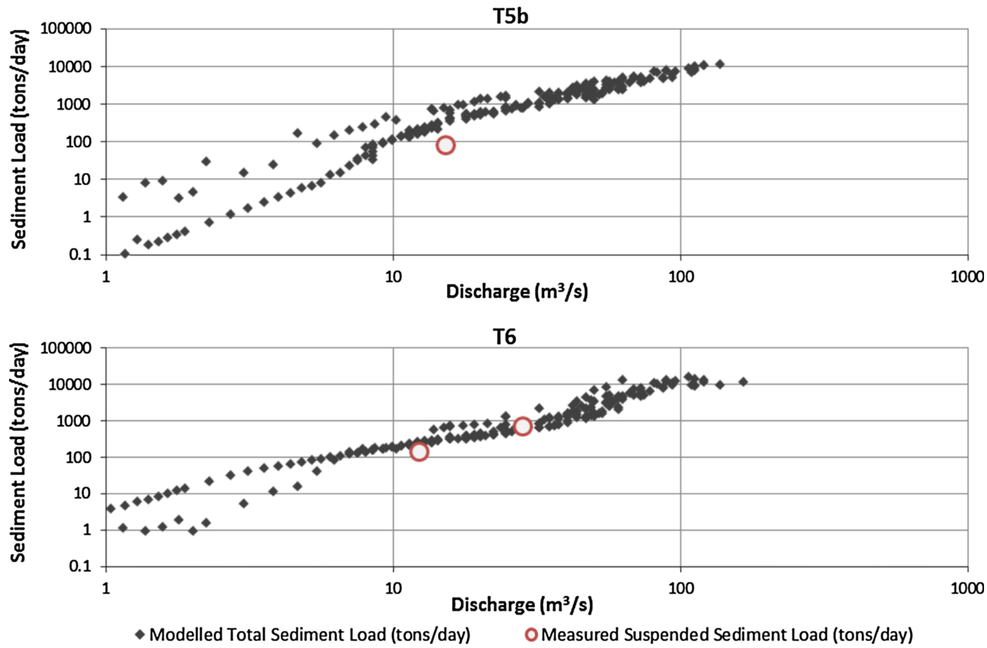
Hydrodynamic modeling was used to increase our understanding of the role of event flows in total sediment transport and sediment budget calculations. Figure 7 presents a comparison between the suspended sediment load data from the field measurement and the modeled total sediment load values for two locations (T5b and T6) along the studied reach. The figure illustrates that the modeled sediment load (black diamonds) ranges over at least five orders of magnitude for the considered range of discharges. The observed sediment loads (open red circles), which captured two discharge conditions in T6 and one in T5a, were within one order of magnitude of the observed one.

The agreement was better, that is with a difference smaller than one order of magnitude, for both observations made at T6. Overall, the comparison indicates that the model reasonably reproduces the observed sediment loads. However, it should be noted that the measurements at the considered Tuul stretch were conducted at average flow conditions and hence did not capture low flow and high flow conditions. Figure 7 also shows that the values of the modeled total sediment load at point T6 are slightly greater than the values at T5b. This is due to a calculated natural increase of the total sediment load in the vicinity of the mining sites. More specifically, this increase is associated with increased erosion of channel bed between points T5a–T5b which is rich in fine sediments. Hence, the model calculates an elevated mass inflow at point T6, which comes from upstream locations. An increasing channel slope from approximately 0.0005 at T5a to 0.001 at T6 can also contribute to the increase of sediment transport at this location.

In general, describing the sediment transport dynamics of the entire modeled reach, the parts of the reach most prone to erosion are those with the finest bed material, including the stretch between points T5a and T5b. At locations where there is no supply of erodible material from the riverbed (i.e., where the median of the bed material is high) deposition rates dominate over negligible erosion rates. Material is also frequently deposited at the floodplains of the reach during decreasing flow conditions. Flow events play an important role in both erosion and deposition of material. High deposition of the material most often occurs during the falling limb of a hydrological event. However, high flow events are mainly related to vast and rapid erosion of the fine material.

The role of event flows in total sediment transport was studied based on the hydrograph for the year 2011 at the Tuul River (Fig. 8). The hydrograph was separated into base flow and event flows (Fig. 8) using the local-minimum method (Sloto and Couse 1996). In total, the

Fig. 7 Measured suspended sediment load in July 2011 and June 2012 (*red dots*), and modeled total sediment load (*black dots*) at points T5b (upstream mining) and T6 (at mining)



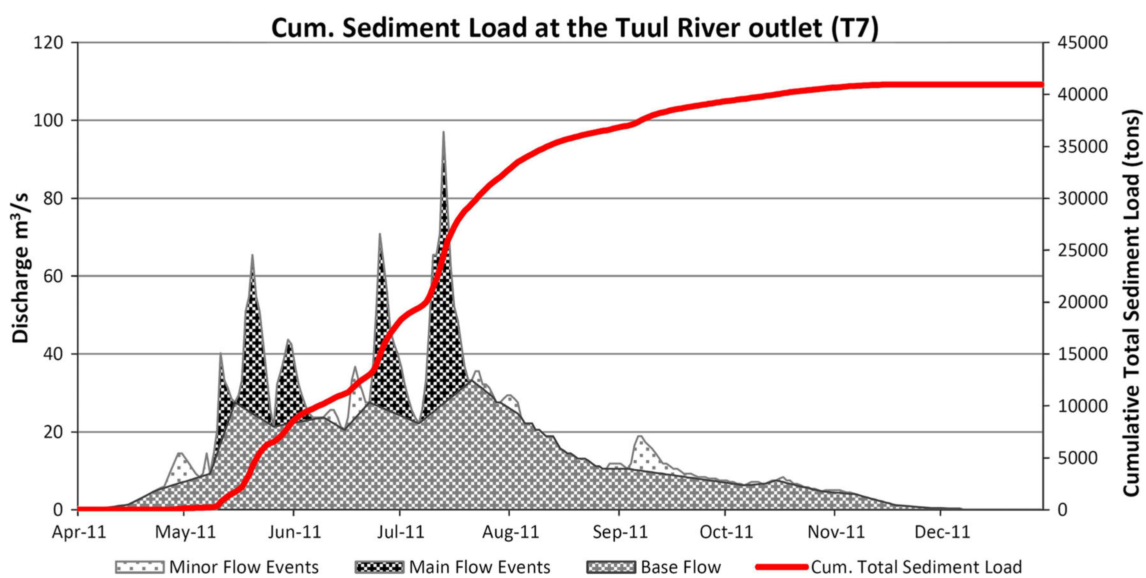
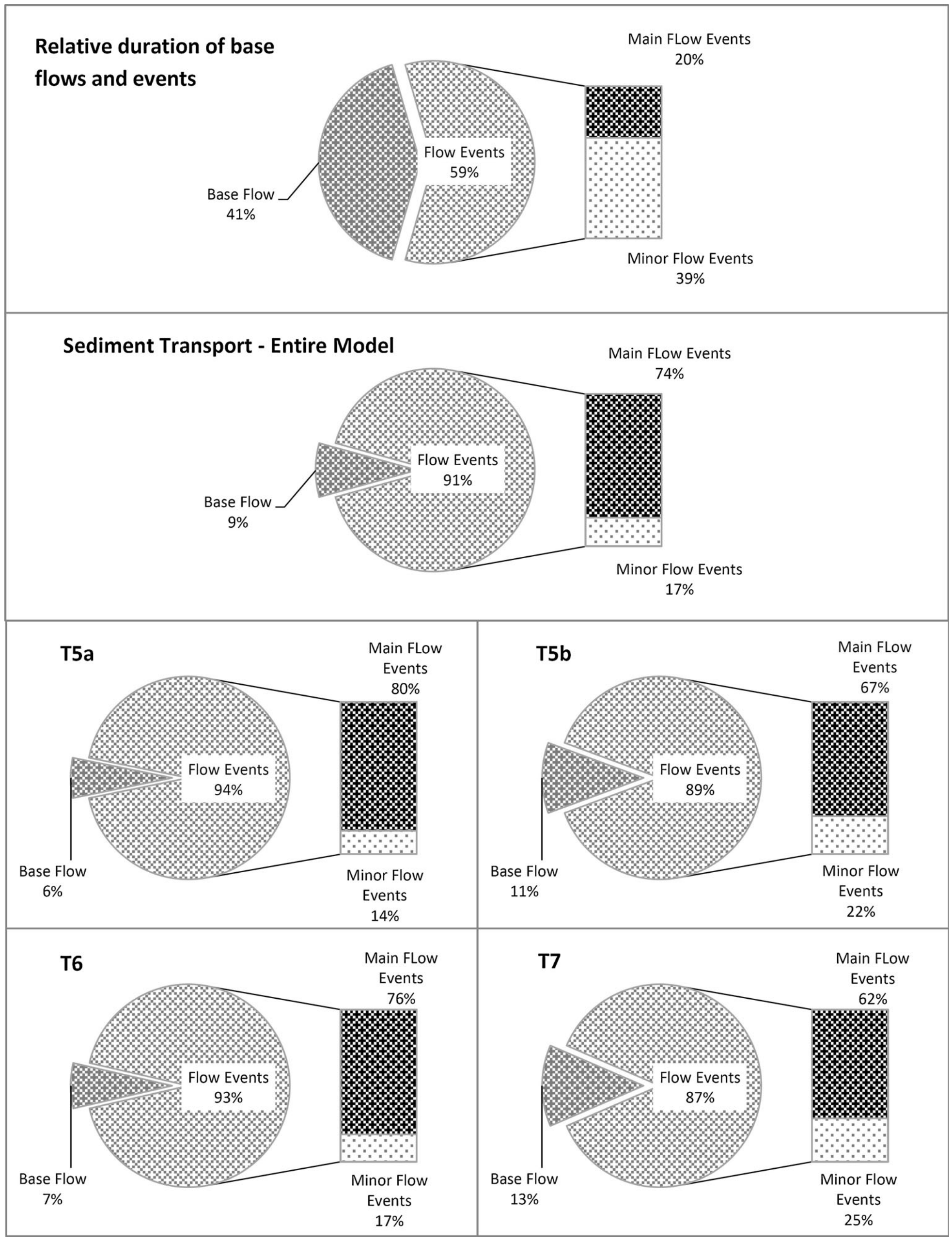


Fig. 8 Modeled cumulative total sediment load (tons) at the Tuul river outlet (point T7); hydrograph separation of the upper boundary discharge data applied in the model

separation gave 16 individual event flows (Fig. 8; dark gray areas) during the studied period. Five of those were classified as main flow events, during which the peak flows were at least twice as large as the prevailing base flow. The other 11 events were classified as minor flow events. The modeled cumulative total sediment load curve for the outlet of the Tuul River shown in Fig. 8 visualizes the contributions of hydrological events to sediment export from the Tuul River basin. Analyzing the cumulating total sediment load curve and the hydrograph, it can be noticed that the main flow events considerably contribute to increasing the cumulative outflow of the material (Fig. 8; thick curve) from the Tuul River basin.

For the downstream reaches of Tuul River, the model results further show a high contribution of the main flow events to the total sediment transport for the studied period at the control points and for the entire modeled reach (Fig. 9). In contrast, the total durations of the main flow events are relatively short (74 % of the transport occurs in 20 % of the modeled flow time). The sediment transport is

Fig. 9 Percentage of simulation time and modeled sediment transport of the base and event flow (main and minor events) for the entire model and four sampling points (Fig. 1)



high during the main events, but exhibits spatial variability along the model reach. The highest sediment transport rate during the main flow events is 80 %, at a cross-section upstream of the mining area (T5a). Not far downstream (at T5b) this rate decreases to 67 %. In the middle of the mining area (at T6), the rate rises to 76 %. The outlet rate (at T7) is the lowest of all analyzed locations 62 %. The different sediment transport rates from varying flow events depend mainly on (1) type and availability of the bed material, (2) channel slope and (3) upstream sediment supply of a location along the reach.

Discussion

In the considered extensive Selenga River Basin, the river sedimentation exhibit diverse patterns. The novel estimates for the Selenga River presented here specifically regard the total SPM transport and its characteristics and riverine delivery of natural and anthropogenic sediment-associated chemical constituents, resulting from natural processes and anthropogenic activities in the upstream part of the basin. From the presented results and the below discussion of sediment loads, sediment budgets and SPM structure, more specific conclusions are drawn in the next chapter, regarding (i) sediment load quantifications, (ii) erosion–deposition patterns along Selenga River main stem, (iii) SPM structure and relative element concentrations, and (iv) impacts of hydrological peak flow events.

Sediment loads

The results indicated that the highest sediment loads were associated with heavily disturbed channel reaches from present mining activities (in the Tuul River below the Zaamar Goldfield), as well as channel reaches draining undisturbed parts of the basin (the Orkhon River at O1, and the Kharaa River at Hr1-2). Consistent with the findings of other studies (Stubblefield et al. 2005; Lee et al. 2006; Pfeiffer et al. 2014), our observations suggest that placer mining activities might have contributed to increased levels of suspended solids at locations sampled further downstream. At the same time, these impacts were documented mostly for relatively short hydrological events as discussed in "Impacts of hydrological peak flow events".

The long-term decline in annual suspended sediment loads of the Selenga River is a result of a number of factors. For the downstream Selenga River within Russia, the obtained results could be explained by land use change and a long-lasting low water period (since around 1989; Bereznykh et al. 2012) that is reported for the Selenga River. It is most apparent towards the end of the 1990s, as seen in Fig. 2. The runoff record for the downstream Selenga shows a statistically significant downward trend from 903 (for the period 1941–1982) to 888 m^3/s (for the period 1983–2011). The correlation factor between runoff and SSC was 0.52 in the earlier period and 0.16 in the later period. However, the main part of the estimated decline within the Russian part of the basin can almost certainly be ascribed to the crisis in the agricultural sector of the Russian economy in the end of the twentieth century, that led to the abandonment of cultivated lands.

The intensity of activities causing erosion in the basin has decreased. Hence, sediment load has also decreased. The reported significant change in the annual fluxes of suspended sediments for the Selenga River (totally from about 2.2 to about 1.1 Mt) is smaller than in the adjacent main tributaries of Lake Baikal. The basins of the tributaries used to be more intensively used for pastures than the lands of the Selenga basin. The reported (Potemkina 2011) declines of annual fluxes in Barguzin, Verhnaya, and Angara have been between 60 and 80 % since 1982. This is a little bit confusing. Maybe, at the same time, the decreasing trend of annual fluxes for the Selenga River is consistent with decreases reported in many river basins worldwide (down to 50 %). Changes of sediment load of the major US rivers (Missouri, Ohio Rivers) and the Danube River (Walling and Fang 2003) were related to the construction of numerous dams, and other engineering structures are regarded to have the most important influence on annual fluxes. In the mentioned cases, there were no statistically significant trends in the runoff records.

An opposite trend of land use change is currently observed in Mongolia. Overgrazing of pasture, leading to soil degradation and desertification and thus higher erosion susceptibility (Onda et al. 2007), is the primary anthropogenic driver of sediment formation within Mongolia. According to Ogureeva et al. (2012), pasture degradation within Mongolia reached 1.2 million km^2, and occurs particularly within the mountain steppe zone. An absence of routine monitoring of sediment loads precludes statistical analyses of the sediment trends. However, despite overgrazing, and with only one exception (upstream Orkhon river at O-1, near Kharkhorin Village), the studied rivers within Mongolia had lower SPM concentrations and carried lower suspended sediment loads during the campaigns of 2011 and 2012 than during previous field campaigns. At the midstream of the Selenga River, upstream of the Eg River (S1), SSC varied between 1.2 (20th February) and 1,193 mg/l (8th August) in 1934 (Kuznetsov 1955), whereas in 2001 it was 11.5 mg/l (18th–24th August). During our field campaigns SSC varied from 9.51 (16th June 2012) to 114 mg/l (2nd August 2011). At the confluence of Orkhon and Tuul, a 65-fold increase of SSC was observed during summer floods for the Tuul River (T-9) (from 11 mg/l on the 19th October 1934 to 716 mg/l on the 26th August 1934) and 43-fold for the Orkhon River (O-6) (from 23.3 mg/l on the 17th June 2012 to 1,000 mg/l on the 7th May 1934).

This result implies that other drivers, probably including hydrometeorological ones, must have a significant impact on the annual sediment fluxes. The mean annual discharge at some gauging stations within the Mongolian part of the basin (Buren Tolgoi, the Kharaa River) shows a significant decrease during the last decades, from an average of 21.8 m^3/s during the period 1990–1995 to only 8.8 m^3/s for the period 1996–2002 (Hofmann et al. 2011). This decrease is primarily caused by decreased precipitation and increased evapotranspiration during that period (Batimaa et al. 2011; Menzel et al. 2011; Malsy et al. 2014). However, an intensified water use for irrigation purposes may have contributed as well.

Sediment budgets

The mentioned contrasting conditions of sediment formation in the upstream and downstream parts of the Selenga River Basin have significant influence on the sediment budget along the river reaches. The present results provide some important evidence on the spatial variability of sedimentation patterns within the river basin. The study shows that the main part of the river-borne suspended matter in the Selenga River (up to 90 %) is deposited in the downstream reach within a distance of 200 km from the Selenga River Delta during the flood season. During the base flow period (June 2012), the net loss from suspended sediment load was negligibly small. This is consistent with the model results of the Tuul River case study, which showed that high deposition of the material most often occurs during the falling limb of a hydrological event.

Two possible processes can explain this storage: channel storage or loss to overbank flow. However, since no significant overbank flow was observed during the period of summer floods 2011, channel storage must be the main contributing process to the suspended load retention. Similar rates of suspended matter deposition as in the downstream main stream of the river (more than 50 %, including particulate organic carbon) were reported for the Selenga River Delta area (Khazheeva et al. 2004). The influence of the downstream part of the main stream of the Selenga River on the total delivery to the recipient enables a comparison of the sediment storage rates for the downstream reaches of Selenga River (upstream form the delta) with sediment load stored in the deltaic estuaries of other large rivers whose sediment budget has been quantified. For instance, channel/overbank storage and exit loss suggest that only 19 % of the annual total suspended sediment load of the Mississippi River reaches deep water outside of its delta (Allison et al. 2012). For the Amazon River, Mertes et al. (1996) concluded that about one-third of the total suspended load of this relatively unaltered river was stored in the deltaic estuaries. It indicates that in the piedmont environment area the river system can act as a fluvial sediment trap, similar to deltaic estuaries. It is due to loss of gradient and valley expansion which characterize such environments. Hence, not only the Selenga River Delta but also the downstream reach of the river plays a crucial role in decreasing the inflow of the total sediment loads to Lake Baikal. This can also refer to attenuation of inflow of pollutants to the lake.

The next important contribution following from above discussion is the understanding of the behavior of stored material in the downstream Selenga River. We assumed that the observed patterns of sediment storage in the downstream reaches of Selenga River during flood season could be related to bed load transport. Coupling the results of suspended sediment and bed load measurements to observed channel storage rates during the summer flood season ($\Delta W_{\mathrm{R}} = -2{,}445$ t/day) and taking into account negligibly small rates of bed load transport in the upper parts of the river system, we conclude that the bedform sand transport was of sufficient magnitude to entirely account for the annual channel bed storage. These assumptions are also supported by the fact that bed load transport usually is significant only at high discharges (Bagnold 1977; Alexeevsky et al. 2008), meaning that the observed suspended sediment fluxes for the flood season are comparable to the annual average bed load fluxes. This generally suggests that large amounts of sand in the channel are transported as bed load during high discharges, a phenomenon recently described using the C-M image technique in an alluvial channel of the Mekong River (Bravard et al. 2013).

The contributions of the channel bed storage to bedform sand transport were of similar magnitude as the results of Allison et al. (2012) for the Mississippi–Atchafalaya River. This emphasizes the importance of bed load for large rivers (Alexeevsky et al. 2013) which could play a significantly larger role that has been commonly accepted (Walling and Fang 2003). We concluded that the annual total sediment flux (suspended and bed load) delivered to the Selenga delta is 2.51 Mt/year.

SPM structure

Sediment storage and entrainment are closely connected with changes in SPM structure. Our results demonstrated unexpectedly low fractions of organic content in the suspended load. Even in comparison with forested streams (e.g., Walling and Kane 1982), where POM concentrations were reported to reach 80 % of the suspended matter, the obtained results in our study were below these values, even though intensive grazing is associated with a delivery of mostly organic fractions.

Low levels of POM might reflect the significant role of sediments originating from mining areas and in-channel sources. The maximum value of POM (16.3 %) was found at the Khangol River (H3, 4, 5), which contains wastewater copper–molybdenum mining and processing plant “Erdenet” and at the same time is regarded with a very high levels of grazing pressure. Extraction of placer gold in the Tuul River (T5–T7) and Boroo River (B2) basins were associated with lack of organic matter in suspended sediment loads in the reaches influenced by mining. Through hydraulic and sediment transport modeling, we could investigate the erosion–deposition patterns along the Tuul River, including the immediate vicinity of the Zaamar mining site. Notably, using a model setup that allowed quantification of erosion and deposition patterns under natural conditions, sediment transport contributions without the influence of anthropogenic mining activities could be investigated.

Results showed that relatively steep channel slopes at the mining site must contribute considerably to sediment erosion under natural conditions. This points to a high transport potential of metal-rich geological material in the

Zaamar region, even without human disturbance. Natural processes can amplify effects of mining-related disturbances such as the additional release of erodible and metal-containing sediments from placer mining. This contributes to explaining the previously mentioned observations of very low fractions of organic content in the suspended load of the region.

According to our results, sediments play a key role in the transport of certain chemical constituents. The investigated high concentration of Al, Fe, Cu and Mn can often be found at mining sites (e.g., Hudson-Edwards 2003), in some cases at concentrations that are above health risk-based guideline values (WHO 2006). Other metals that are usually associated with mining include As, Mo, and Hg. However, in the Selenga basin Hg has not been reported to exceed detection limits in most studies (Lee et al. 2006; AATA 2008; Thorslund et al. 2012), since it in the Zaamar case is not used in the extraction process. Cu–Mo mineralization is on the other hand important, with the Erdenet mine alone producing around 354,000 t of Cu and 3,500 t of Mo annually (Lee et al. 2006).

The relative differences in estimated $r_{s\text{–}d}$ ratios between individual sediment-associated chemical constituents tend to generally agree with average patterns from other major rivers of the world, for instance showing high ratios (indicating largely dominating suspended-phase transport) for Al and Fe, and relatively low ratios for Cu (indicating a higher importance of dissolved-phase transport). Furthermore, Thorslund (2013) considers the Tuul river system and shows that dissolved-phase transport is important for both As and Mo (in addition to Cu), which is consistent with the fact that these metals more generally are preferentially found as dissolved constituents rather than in suspension.

The high pH (average of 9 during the 2012-campaign) of the Tuul river can limit the transfer of heavy metals from the suspended phase into the water phase (e.g., Thorslund et al. 2012). This is consistent with field observations under high pH conditions elsewhere (Tarras-Wahlberg et al. 2001; Zak et al. 2009). As a consequence, absolute concentrations of the water phase (dissolved phase) were relatively low in the considered Tuul river and exceeded WHO's health risk-based guideline values (WHO 2006) only for As (Thorslund 2013) of the considered seven key heavy metals (Al, Fe, Cu, Mn, As, Mo, and Hg).

The heavy metal transport with suspended sediments accounted in the present case for 98 % of total transport on average (in some cases 99.8 %), which is even higher than the estimate of Martin and Meybeck (1979), yielding that sediment-associated transport accounts for about 90 % (in some cases more) of the total river-borne flux of elements such as P, Ni, Mn, Cr, Pb, Fe and Al. Notably, the bioavailability of heavy metals (which largely governs the risk for adverse impacts on ecosystems in recipients) is generally much lower if the metals are attached to the suspended phase, than if they are dissolved in the water phase. However, as discussed in for instance Thorslund et al. (2012), sediment-bound heavy metals are at risk of becoming bioavailable if they along their transport pathways become subject to regions of lower pH, that for instance exist in the downstream Selenga River Delta area (Khazheeva et al. 2004; Plyusnin et al. 2008; Chebykin et al. 2010, 2012), changes in dissolved organic matter, or digestion by organisms.

Impacts of hydrological peak flow events

Snapshot measurement data from current field campaign clearly showed very large influence of a single hydrological event on sediment transport (peaking at a 100-fold increase in suspended load). Hydraulic modeling of transport dynamics throughout a full hydrological year, as well as independent application of an empirical sediment rating curve, indicated more generally contributions of a series of peak flow events occurring during the spring and summer season. It was assumed that peak flow events determine the main part (between 74 and 80 %) of the annual sediment load, while their total duration was only between 0.5 and 2 months (depending on definition).

Application of the 2011 hydrograph sediment rating curve for Ulan Bator gauging station ($S = 1.2\exp^{0.06Q}$) revealed that 80 % of the sediment transport occurred during 16 days characterized by flows peaking over 50 m^3/s (during three of the main flow events). The total sediment yield of the Tuul River in Ulan Bator was found to be around 10,900 t/year, while only 220 t/year (2 %) were transported during the days of base flow ($Q < 20$ m^3/s). Hence, present measurement and modeling results converge on showing that individual hydrological events have large influence on total mass transport in terms of the delivery of natural and anthropogenic sediment-associated chemical constituents to the downstream recipients.

Reported values on relative event flow contributions are higher than corresponding values for rivers intensively regulated by reservoirs for hydropower and irrigation purposes. For instance, in the Po River Basin (Tesi et al. 2013) event-dominated transport accounts only for one-third of the annual particulate export to the Mediterranean Sea.

Impacts of hydrological peak flow events on the SPM size and their influence on metal partitioning between dissolved and particulate phases generally confirm recent findings by Roussiez et al. (2013) who reported dilution of the particulate phase by coarser and less-contaminated particles from river bottom and banks. Whereas an increase of the coarse material concentration is typically associated with in-channel sources of sediment, resulting from bed erosion during floods, slope wash usually causes delivery of finer sediments into rivers. Since all the studied sites here are located in basins that are disturbed by mining works, the latter could also have an impact on sediments loads. The delivery of fine material from open-cast mining sites are typically associated with flooding due to breaches thin strips of land separating dredge pits from river channels (Robert and Church 1986). During the flood peak, concentration of the fine particles (with diameter < 0.001 mm) increased from 5 to 20 % in the Orkhon river (O1), from 0.5 to 2 % in the Tuul river (T2), and from 2.3 to 4.6 % in the Kharaa river (Hr2).

These changes were reported mostly during relatively short hydrological events, during which intensified slope wash near floodplain mining activities (as in the Tuul River) could cause large amounts of turbid water to flush into the river. At the same time, large sediment loads were also reported for the unmined rivers, showing that both natural processes and anthropogenic activities are main drivers of the observed spatial sediment transport variability. Considering the combined effects of the increases in SSC and discharge in response to these high water levels, it is possible that relatively large portions of the sediment-associated pollutants can occur within limited periods of time.

Conclusion

Related to the aims (1–4) of the paper, the following conclusions are drawn:

1. The results indicate that suspended sediment transport dominates in the upstream part of the Selenga River Basin, whereas bed load transport is considerable in the downstream part (up to 50 % of total transport). High sediment loads were reported both for mined and unmined rivers. Mining impacts on sediment loads were seen mostly during relatively short hydrological events, during which an intensified slope wash near floodplain mining activities could flush large amounts of turbid water into the river. The annual total sediment load (suspended and bed load) delivered to the Selenga River Delta at Lake Baikal is about 2.5 Mt/year. Reported multi-decadal declines in sediment loads in the downstream part of Selenga River can be attributed to the abandonment of cultivated lands and changing hydroclimatic factors, such as in particular climate-driven decrease of water flows and intensified water use for irrigation purposes.
2. Channel storage was shown to be important for sediment transport to Lake Baikal. Due to loss of gradient and valley expansion in the downstream Selenga River Basin, the river system acts as a fluvial sediment trap just as in deltaic estuaries. The observed suspended sediment flux during the flood season is comparable in magnitude to the annual average bed load flux. Our results suggest that the large amounts of sand present in the channel are transported as bed load during high discharge events.
3. Snapshot measurement data, hydraulic modeling, and empirical sediment rating curves converge on showing that a series of peak flow events during spring and summer contribute to the main part (70–80 %) of the annual sediment and pollution loads, whereas their total duration was only on the order of 1 month. Seasonal changes in SPM size are probably related to the intensive slope wash during rainfall events that dominate the flood period. They may furthermore be related to seasonal changes of vegetation coverage and properties, temperatures (that influence the concentration of suspended matter), colloids, and organisms.
4. Field data-driven modeling results show that even without human disturbance, there is high potential for transport of metal-rich geological material in one of the basin's largest mining regions (Zaamar Goldfields), e.g., due to steep channel slopes. This provides evidence that natural processes can amplify effects of mining-related disturbances. The significant role of sediments originating from mining areas and in-channel sources is reflected in relatively small POM values. An example from the Tuul River demonstrates that the observed high pH values in the upstream parts of the Mongolian basin can limit the transfer of heavy metals from the suspended phase into the water phase. This is consistent with observed high contributions (around 98 %) of suspended-phase transport, relative to total sediment transport in the upstream region.

The present novel study of sediment transport in this economically fast growing region has given new perspectives on hydrological research and its implications. An important conclusion is that the noted longitudinal inequalities in sediment balances could increase after the planned construction of dams, reservoirs, and other engineering structures in the upper parts of the Selenga River. If dams are constructed along the main stream of the lower Orkhon–Selenga Rivers, they will alter the equilibrium of sediment transport. Monitoring strategies may need to be adapted, considering on-going and projected future trends of hydroclimatic change.

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