Sediment transport from source to sink in the Lake Baikal basin
Impacts of hydroclimatic change and mining

Jan Pietroń

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Abstract
Different magnitude, intensity and timing of precipitation can impact runoff, hillslope erosion and transport of sediment along river channels. Human activities, such as dam construction and surface mining can also considerably influence transport of sediment and sediment-bound contaminants. Many river basins of the world are currently subject to changes in climate at the same time as pressures from other human activities increase. However, because there are often complex interactions between such multiple drivers of change, it is challenging to understand and quantify contributions of individual drivers, which is needed in predictive modelling of future sediment and contaminant flows. This thesis considers sediment transport in the Lake Baikal basin, which is hydrologically dominated by the transboundary Selenga River of Russia and Mongolia. The Selenga River basin is, for instance, subject to climate change and increasing pressures from mining, but process complexity is reduced by the fact that the river basin is one of few large basins in the world that still is essentially undammed and unregulated. A combination of field measurement campaigns and modelling methods are used in this thesis, with the aim to: (i) identify historical hydroclimatic trends and their possible causes, (ii) analyse the spatial variability of riverine sediment loading in the mining affected areas, and (iii) investigate sediment transport and storage processes within river channels and in river deltas. Results show that, during the period 1938-2009, the annual maximum daily flow in the Selenga River basin has decreased, as well as the annual number of high flow events, whereas the annual minimum daily flow has increased. These changes in discharge characteristics are consistent with expected impacts of basin-scale permafrost thaw. Both field observations and modelling results show that changes in magnitude and number of high-flow events can considerably influence the transport of bed sediment. In addition, the average discharge has decreased in the past 20 years due to an extended drought. Under conditions of low flow, metal-enriched sediment from mining areas was observed to dominate the river water. If discharge will continue to decrease in the Selenga River (or other mining-impacted rivers of the world), further increases in riverine metal concentrations may hence be one of the consequences. Furthermore, under current conditions of extended drought, less sediment may have been distributed over the floodplain wetlands in the Selenga River delta. Present estimates, however, show that sediment can still be transported to, and deposited within, the banks and water bodies located in the backwater zone of the Selenga River delta. This can aid bank and levee stabilization, support the development of wetlands and foster net sedimentation.

Keywords: sediment transport, human impact, hydroclimatic change, surface mining, metal-enriched sediment, Lake Baikal, the Selenga River, the Selenga Delta.

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In memory of my grandparents
Teresa and Stanisław Litak
Abstract

Different magnitude, intensity and timing of precipitation can impact runoff, hillslope erosion and transport of sediment along river channels. Human activities, such as dam construction and surface mining can also considerably influence transport of sediment and sediment-bound contaminants. Many river basins of the world are currently subject to changes in climate at the same time as pressures from other human activities increase. However, because there are often complex interactions between such multiple drivers of change, it is challenging to understand and quantify contributions of individual drivers, which is needed in predictive modelling of future sediment and contaminant flows. This thesis considers sediment transport in the Lake Baikal basin, which is hydrologically dominated by the transboundary Selenga River of Russia and Mongolia. The Selenga River basin is, for instance, subject to climate change and increasing pressures from mining, but process complexity is reduced by the fact that the river basin is one of few large basins in the world that still is essentially undammed and unregulated. A combination of field measurement campaigns and modelling methods are used in this thesis, with the aim to: (i) identify historical hydroclimatic trends and their possible causes, (ii) analyse the spatial variability of riverine sediment loading in the mining affected areas, and (iii) investigate sediment transport and storage processes within river channels and in river deltas. Results show that, during the period 1938-2009, the annual maximum daily flow in the Selenga River basin has decreased, as well as the annual number of high flow events, whereas the annual minimum daily flow has increased. These changes in discharge characteristics are consistent with expected impacts of basin-scale permafrost thaw. Both field observations and modelling results show that changes in magnitude and number of high-flow events can considerably influence the transport of bed sediment. In addition, the average discharge has decreased in the past 20 years due to an extended drought. Under conditions of low flow, metal-enriched sediment from mining areas was observed to dominate the river water. If discharge will continue to decrease in the Selenga River (or other mining-impacted rivers of the world), further increases in riverine metal concentrations may hence be one of the consequences. Furthermore, under current conditions of extended drought, less sediment may have been distributed over the floodplain wetlands in the Selenga River delta. Present estimates, however, show that sediment can still be transported to, and deposited within, the banks and water bodies located in the backwater zone of the Selenga River delta. This can aid bank and levee stabilization, support the development of wetlands and foster net sedimentation.
Sammanfattning

Streszczenie

Wielkość, czas trwania oraz intensywność opadów atmosferycznych oddziałuje na charakter odpływu, erozję oraz transport osadów rzecznych. Również inergencja człowieka w środowisku – np. budowa zapór i zbiorników wodnych, czy górnictwo odkrywkowe – w różnym stopniu może wpływać na transport osadów oraz powiązanych z nimi zanieczyszczeń. Wiele dorzeczy na Ziemi, będących pod wpływem obecnych zmian klimatycznych, jest jednocześnie poddawanych narastającej antropopresji. W celu przewidywania przyszłych zmian w transporcie osadów i powiązanych z nimi zanieczyszczeń, potrzeba dogłębnego zrozumienia i oceny wpływu poszczególnych czynników powodujących te zmiany. Taka analiza jest jednak często utrudniona ze względu na złożone interakcje pomiędzy czynnikami powodującymi zmiany.

Niniejsza rozprawa doktorska przedstawia wyniki badań związanych z analizą transportu osadów rzecznych w zlewni jeziora Bajkał, zdominowanej hydrologicznie trasgraniczną rzeką Selenga, przepływającą przez tereny Rosji i Mongolii. Zlewnia rzeki Selengi podlega współczesnym zmianom klimatycznym oraz wzrastającej presji związanej z górnictwem. Złożoność procesów hydrologicznych jest jednak w tym wypadku ograniczona, ponieważ zlewnia Selengi jest jednym z nielicznych, względnie dużych dorzeczy na świecie, które przepływają – jak dotychczas – naturalne, nieuregulowane przez żadne zapory lub zbiorniki wodne. Dla poszczególnych celów: (i) identyfikacji historycznych trendów hydroklimatycznych i ich przyczyn, (ii) analizy przestrzennych zmian w transporcie osadów rzecznych w części zlewni dotkniętej górnictwem odkrywkowym oraz (iii) badania procesów transportu i magazynowania osadów w korycie i delcie rzeki; zostały w pracy zastosowane hydrometryczne dane pomiarowe, dane pochodzące z badań terenowych oraz metody modelowania. Wyniki badań wskazują na to, że w latach 1938-2009 zmalały roczne przepływy maksymalne oraz liczba wezbrań, podczas gdy w tym samym czasie wzrosły roczne przepływy minimalne. Powyższe zmiany są zgodne z oczekiwanym wpływem rozmarnania wiecznej zmarzliny na ustrój przepływów rzecznych. Analiza danych pomiarowych oraz wyników modelowania wskazują na to, że obecne zmiany dotyczące liczby oraz wielkości wezbrań mogą znacznie wpłynąć na transport osadów dennych w korytach rzek. Dodatkowo, w ciągu ostatnich 20 lat (1995-2014), średnie roczne przepływy znacznie spadły ze względu na przedłużający się okres suszy na terenie zlewni. Analiza danych terenowych pochodzących z obszarów górniczych wskazała, że podczas obniżonych przepływów, w zanieczyszczeniach zdominowanych przez metale, dominuje materiał pochodzący z działalności człowieka (około 80% transportowanych osadów). Należy zatem przewidywać, że jeśli obecne zmiany w ustroju przepływów w dorzeczu Selengi (lub w innych podobnych dorzeczenach na świecie) będą postępować, to ich następstwem może być dalszy wzrost koncentracji zanieczyszczeń (metali pochodzących z obszarów górniczych) rzek. Dodatkowo, w obecnym okresie obniżonych przepływów, na terenach zalewowych i jeziorach delty rzeki Selengi zatrzymuje się prawdopodobnie mniej osadów. Wyniki badań wskazują jednak na to, że osady rzeczne mogą być wciągane do brzegów oraz obszarów wodnych znajdujących się w strefie, w której stany wodne cieków delty Selengi są pod wpływem stanów wodnych jeziora Bajkału. Akumulacja materiału w tych częściach delty Selengi może pozytywnie wpływać na stabilizację naturalnych wałów oraz mokradeł i zwiększać sedymentację netto.
Dissertation content

This doctoral thesis consists of a summary text and four papers. The papers will be referred to by their Roman numbers (Papers I-IV) in the summary text. The published papers are reprinted by permission from the respective copyright holders.


Author contributions

The contributions from listed authors are divided as follows for each article:

I  TR led the writing with the help of all co-authors. JP acquired historical hydroclimatic data and spatial data. RS acquired projected climatic data. All co-authors contributed to the data analysis and the design of the study.

II JP led the writing, compiled the datasets and did the data analysis. The writing was assisted by all co-authors. The study and related methods were designed by JP with help of JJ. The field data were collected by: JP, JJ, SRC and AVA. JP acquired and analyzed spatial data. Long term hydrological data were provided by SRC.

III JP led the writing, compiled the datasets and did the data analysis. The writing was assisted by all co-authors. The study and related methods were designed by JP with help of JJ and SRC. All co-authors contributed to the field data collection. JP acquired and analyzed spatial data. Long term hydrological data were provided by SRC.

IV JP led the writing, compiled the datasets and did the data analysis. The writing was assisted by JJ, JAN, SRC and TD. The study and related methods were designed by JP with help of JJ and JAN. All co-authors contributed to the field data collection. Long term hydrological data were provided by SRC.
List of relevant co-authored papers, not included as part of this thesis


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<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\Delta S$</td>
<td>[LT$^{-1}$]</td>
<td>basin scale change in water storage</td>
</tr>
<tr>
<td>$\Delta SSL$</td>
<td>[LM$^{-1}$]</td>
<td>difference in suspended sediment load</td>
</tr>
<tr>
<td>$A_m, A_n, A_T$</td>
<td>[L$^2$]</td>
<td>mining, natural and total basin area</td>
</tr>
<tr>
<td>CV</td>
<td>[-]</td>
<td>coefficient of variation</td>
</tr>
<tr>
<td>CV$Q$</td>
<td>[-]</td>
<td>coefficient of variation of water discharge</td>
</tr>
<tr>
<td>$D_{10}, D_{50}, D_{90}$</td>
<td>[L]</td>
<td>sediment size coarser than 10%, 50% and 90% of the sediment grain size distribution</td>
</tr>
<tr>
<td>$D_{B10}, D_{B50}, D_{B90}$</td>
<td>[L]</td>
<td>$D_{10}, D_{50}, D_{90}$ of bed material (sediment $&gt; 63 \mu m$)</td>
</tr>
<tr>
<td>ET</td>
<td>[LT$^{-1}$]</td>
<td>evapotranspiration</td>
</tr>
<tr>
<td>P</td>
<td>[LT$^{-1}$]</td>
<td>precipitation</td>
</tr>
<tr>
<td>$P_{eff}$</td>
<td>[LT$^{-1}$]</td>
<td>effective precipitation</td>
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<tr>
<td>$P_n$</td>
<td>[-]</td>
<td>Rouse number</td>
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<td>Q</td>
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<td>water discharge</td>
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<td>$Q_{max}$</td>
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<td>[L$^3$T$^{-1}$]</td>
<td>minimal water discharge</td>
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<tr>
<td>R</td>
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<td>$SD_m, SD_n, SD$</td>
<td>[MT$^{-1}$]</td>
<td>sediment load contribution from $A_m, A_n, A_T$</td>
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<tr>
<td>$SLO_m, SLO_n, SLO$</td>
<td>[MT$^{-1}$L$^{-2}$]</td>
<td>soil loss from $A_m, A_n, A_T$</td>
</tr>
<tr>
<td>SSL</td>
<td>[MT$^{-1}$]</td>
<td>suspended sediment load</td>
</tr>
<tr>
<td>T</td>
<td>[$^\circ$C]</td>
<td>air temperature</td>
</tr>
<tr>
<td>TSL</td>
<td>[MT$^{-1}$]</td>
<td>total sediment load</td>
</tr>
<tr>
<td>U</td>
<td>[LT$^{-1}$]</td>
<td>depth-average flow velocity</td>
</tr>
<tr>
<td>$u_*$</td>
<td>[LT$^{-1}$]</td>
<td>shear stress velocity</td>
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<tr>
<td>$\tau_b$</td>
<td>[P]</td>
<td>boundary shear stress</td>
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CMIP5 | | the Coupled Model Intercomparison Project, Phase 5 |
1 Introduction

1.1 Introduction and problem description

The hydrological cycle drives sediment supply and transport in fluvial systems. For example, different magnitude, intensity and type of precipitation ($P$, mm) can impact runoff ($R$, mm), hillslope erosion (Planchon et al., 2000), and control transport of sediment along river channels (Peizhen et al., 2001; Berezhnykh et al., 2012; Li and Gao, 2015). Flood events can be exceptionally important in sediment transport, due to high water discharge ($Q$, m$^3$ s$^{-1}$) and large masses of conveyed material (Leenaers, 1989; Coppus and Imeson, 2002; Cánovas et al., 2008; Chalov et al., 2015a). In contrast, evapotranspiration ($ET$, mm) decreases discharge by removing water from the fluvial systems back to the atmosphere. Hence, depending on regional hydroclimatic conditions, sediment transport regimes may differ considerably, which for instance impacts the total sediment export from different river basins (Dedkov and Moszherin, 1992).

Recent changes in climate are associated with global alterations of air temperatures and water balance components ($P$, $ET$ and $R$), which can impact sediment transport in different ways (Poesen et al., 2003; Walling and Fang, 2003; Bring et al., 2015; Fischer et al., 2017). For example, changing air temperatures can impact evapotranspiration and vegetation growth, which in turn may influence sediment supply through changed soil stability and soil erosion (Pruski and Nearing, 2002). In cold environments, changed temperatures impact snow melt and related hillslope erosion (Chalov et al., 2017b) as well as permafrost distribution, which affects runoff and water discharge patterns in streams (Frampton et al., 2011).

Various human activities can also impact sediment transport considerably. Dam and reservoir constructions act as traps that reduce sediment delivery to downstream river sections causing channel incision (Kondolf, 1997; Walling and Fang, 2003). Water use, such as irrigation, can influence sediment transport (e.g., Gebrehiwot et al., 2015) via reduced river water discharge (Törnqvist and Jarsjö, 2012). Soil erosion and associated sediment delivery to stream networks can be impacted by changes in land-use or land-cover related to agricultural expansion, deforestation and surface mining activities (Walling, 2006; Jaramillo et al., 2015). Mining operations may also involve erratic discharge of turbid wastewater into nearby streams and altering of the natural river channels (Chalov, 2014). More effective mining methods (Hooke, 2000) and increasing demands from a growing population (Paull et al., 2006) have generally increased the mining impacts on sediment transport in the last century. However, many mining areas are located in remote and unmonitored regions, which complicates comprehensive assessments of environmental risks (Paull et al., 2006; Thorslund et al., 2012). Such risks may for instance be related to erosion of soils enriched with metals.
and metalloids (Jarsjö et al., 2017), which may harm downstream riparian and aquatic environments (Chalov et al., 2015a, 2016). The impacts may be long lasting, since contaminated sediment can be stored along the transport pathways (e.g. on the streambed and in floodplains) and act as new sources under certain transport conditions (Walling, 1988; Axtmann and Luoma, 1991).

Main possible downstream impacts include the growth and stability of river deltas, which depend on the amount and grain size distribution of the sediment delivered from their river basins (Orton and Reading, 1993). Changes in these drivers can affect sediment and contaminant retention functions and lead to net erosion in the deltaic channels, wetlands and plains (Svoboda et al., 2010; Edmonds and Slingerland, 2010). In turn, this can impact the export of sediment and associated contaminants from deltas to downstream seas and lakes. An notable example of the latter is Lake Baikal (Southern Siberia; Figure 1), which is the oldest and deepest freshwater lake on the earth (25 million years old and over 1,600m deep) and stores around 20% of the world's unfrozen freshwater (Brune et al., 2006). The lake and its surroundings host unique ecosystems and has been declared an UNESCO World Heritage Site (UNESCO, 1996).

![Figure 1. Location of the Lake Baikal basin, the specific case study areas from Papers I-IV and the relevant gauging stations (red points).](image-url)
Concerns about the water quality of Lake Baikal and status of its ecosystems have been raised (Henry and Nikanarov, 1988; Lindström-Seppä et al., 1998; Thorslund et al., 2012; Chalov et al., 2015a; Batsaikhan et al., 2017), for instance, due to increasing development of mining activities, and related sediment and metal contamination within the lake’s largest tributary, the transboundary Selenga River. The development of mining significantly contributes to the economic growth in the region (Malsy et al., 2016) and its impacts on water resources and landscape disturbances are therefore likely going to continue in the future (Malsy et al., 2013). Therefore, understanding of the hydrological flow regime, soil erosion and sediment transport processes of the mining affected, free-flowing (undammed) Selenga River, as well as their sensitivity to climate change, can aid in studies regarding the sediment transfer processes and its distribution among sinks (e.g. river channels and floodplains; Ciszewski, 2001). This includes large sinks, such as the Selenga River delta, named a “geochemical barrier” (Chalov et al., 2016) between the Selenga River basin and Lake Baikal.

Effects of changing climate on hydrological flow and sediment transport regimes can be challenging to recognize and predict, for instance because river basins of the world are commonly dammed, such that long-term cause-and-effect relations can be masked by direct human flow regulations (see Nilsson et al., 2005). Hence, case studies of large to medium free-flowing rivers such as the Selenga River basin, which are exceedingly rare, can aid in the general understanding of the climate changes effects and related consequences. Additionally, studying mining affected areas in such rivers can increase our knowledge of spreading and storage of sediment-bound contaminants under combined effects of climate change and mining disturbances.

1.2 Aims and scopes of the thesis

This thesis considers the unregulated Selenga River system of the Lake Baikal basin with an overall objective to determine relative contributions of mining activities and hydroclimatic change on sediment transport processes, from source zones in headwater areas and hillslope areas, via transport through river channels to net deposition areas, i.e. lakes and wetlands of the river delta. Specific aims of the thesis are to:

A. Identify historical hydroclimatic trends and their possible causes.

B. Investigate the spatial variability of riverine sediment loading in the mining affected areas.

C. Investigate the sediment transfer and storage processes within riverine channels as well as deltaic systems.

These aims are addressed in Papers I-IV, which focus on different areas (Figure 1), variables and processes of the Lake Baikal basin, according to the following:

I. Paper I considers the entire Selenga River basin (within the grey frame in Figure 1) to address aim A. It also considers projected (2010-2039 and 2070-2099) trends in air temperature and water balance components of the Selenga River basin, based on CMIP5 (the Coupled Model Intercomparison Project, Phase 5) ensemble mean of 22 individual climate models (Stocker et al., 2013).
II. Paper II considers the Tuul River basin (headwaters of Selenga River basin; black frame in Figure 1) to address aim B, using an observation based nested catchment approach combined with soil erosion modelling.

III. Paper III considers the downstream part of the Tuul River (green frame in Figure 1) to address aim C, using a field data based sediment transport model.

IV. Paper IV considers the Selenga River delta (red frame in Figure 1), to address aim C, using observational data on grain size distribution of deposited and suspended sediment combined with analytical methods to evaluate flow and transport dynamics in the delta.
2 Studied Area

The Lake Baikal basin is shared between Mongolia (63% of the river basin) and Southern Siberia, Russian Federation (37%; Figure 1). Direct precipitation on the lake surface accounts for approximately 13% of the water inflow to the lake. The same amount of water is lost to the atmosphere via the lake’s water surface evaporation. River flow is the main input to the lake’s water balance and accounts for 82% of the total input (4.5% is groundwater discharge directly into the lake, according to data from 1960; Colman, 1998). The main tributaries to Lake Baikal, which to date are free-flowing riversystems (undisturbed by dams or reservoirs), are the Barguzin River, the Upper Angara River and the Selenga River. The latter contributes with over 60% of the water discharge (Mun et al., 2008) and 82% of the sediment load into the lake (Potemkina and Potemkin, 2015). Long-term data show that all the tributaries exhibited significant decreases in suspended sediment load (SSL, kg s⁻¹). For instance, the annual SSL of the Selenga River decreased on average by 48% between the periods 1941-1982 and 1983-2008 (Potemkina and Potemkin, 2015; Figure 2b). Such decreases have been partly explained by a decrease in arable land and grazing intensity in the Selenga River basin since the 1970s (e.g. sheep population; Bazhenova and Kobylik, 2013). Climate change may also have contributed to the sediment load decreases. The most significant decreases in the average annual water discharge in the Selenga River occurred after the mid-1950s (Potemkina and Potemkin, 2015; Chalov et al., 2015a).

![Chart A: Average Annual Discharge](image)

![Chart B: Average Annual Suspended Sediment Load](image)

Figure 2. Average annual: (a) discharge (Q, m³ s⁻¹) and (b) suspended sediment load (SSL, kg s⁻¹) in the main rivers of Lake Baikal basin for periods: 1941-1982 and 1983-2008 for the Selenga River, 1943-1982 and 1983-2008 for the Barguzin River, 1946-1976 and 1977-2005 for the Upper Angara River (Potemkina and Potemkin, 2015).
The Selenga River basin accounts for over 82% of the area of Lake Baikal and its basin (576,500 km$^2$). Continental climate characterizes the Selenga River basin as well as the entire Lake Baikal basin. The average monthly temperatures of the Selenga River basin span from around -24 °C in January to 17 °C in July (CRU TS3.10/CRU TS3.10.01 climate data; Harris et al., 2014). The annual average precipitation within the Selenga River basin spans from 250 mm in the lower parts, up to over 600 mm in the mountainous parts. Around 80-90% of the annual precipitation occurs during May to September (Tulokhonov et al., 2015; Potemkina and Potemkin, 2015). Most of the high rainfall-runoff events naturally occur around this period (Chalov et al., 2015a).

The landscape of Selenga River basin comprises mainly of mountainous taiga and steppe types. The basin relief ranges from 456 m a.s.l. at the mouth of the Selenga River to 3,539 m a.s.l. in the Khangal Mountains (southeast part of the basin). Most of the basin area is underlain by permafrost that varies from isolated patches in the central parts to continuous in the highland parts of the basin (Brown et al., 1997; Figure 1 in Paper I). Studies have shown that the permafrost layers are thermally unstable and vulnerable to impacts of climate change (Zhao et al., 2010). A rapid growth of mining industries since the early 1990s (copper, molybdenum, gold and coal) has been a major cause of landscape disturbance and metal contamination of river waters within the Selenga River basin (Robinson et al., 2004; Thorslund et al., 2012; Batsaikhan et al., 2017). One of the largest placer (alluvial) mining area is the Zaamar Goldfield located in the Tuul River basin (headwaters of the Selenga River basin, Figure 3). The mining activities last approximately eight months a year, from mid-April to mid-December (Karpoff and Roscoe, 2005).

![Figure 3. Location of the Zaamar Goldfield mining area along the Tuul River (headwaters of the Selenga River basin). Locations related to Paper II: A – the Tuul River basin with the studied basin area (red border), the location of Ulaanbaatar/Ulan Bator gauging station; B – lower part of the studied basin (green area in A) (Figure 1 in Paper II: Pietroń et al., 2017).](image-url)
Many metals in the Selenga River basin are strongly associated with river sediment, since the prevailing mostly alkaline pH of the waters (Thorslund et al., 2012, 2016; Chalov et al., 2016; Lychagin et al., 2017; Batsakhlan et al., 2017) suppresses dissolution. According to Lychagin et al. (2017) most metals of the suspended sediment load (i.e. Fe, Co, Ni, As, Cr, V and Cd) occur in higher concentrations in fine sediment fractions (ranging from approximately clay to very fine silt), as compared to coarser fractions. However, there are still number of metals (i.e. Cu, Zn, Mn, Pb and U) that may be transported mainly with coarser fractions, such as very fine sand and fine sand. A part of the sediment and the metal load accumulates in the delta of the Selenga River at Lake Baikal (Chalov et al., 2016; Figure 4). The area of the delta is approximately 600 km². It is characterized by eight orders of natural distributary channels. The flow partitioning and physical parameters of the channels cause decreased transport capacity in the outer parts of the delta (Dong et al., 2016). Many of the channels are connected to wetlands that comprise a significant part of the delta’s area (Lane et al., 2015; Chalov et al., 2016).

Figure 4. A map of the Selenga River delta and location of the sampling points from Paper IV (Figure 1 in Paper IV; Pietroń et al., in review).
3 Methods

3.1 Analysis of long-term hydroclimatic data

To analyze historical changes in the hydroclimatic variables of the basin (Paper I), records of runoff \( (R, \text{ mm year}^{-1}) \), precipitation \( (P, \text{ mm year}^{-1}) \), and air temperature \( (T, ^\circ\text{C}) \) were considered. Area-average monthly \( P \) and \( T \) for period 1938-2009 were acquired from the CRU TS3.10/CRU TS3.10.01 datasets (Harris et al., 2014). The data covered the extent of the Selenga River basin, which was defined using a digital elevation model (Section 2.2 in Paper I). Later area-average annual \( P \) and \( T \) for the basin were estimated. The \( R \) data were calculated as average annual discharges \( (Q, \text{ m}^3\text{ s}^{-1}) \) divided by the area of the Selenga River basin (with an outlet at Mostovoy station, Russian Federation; Figure 1). Additionally, evapotranspiration \( (ET, \text{ mm year}^{-1}) \) data were estimated by closing the water balance \( ET = P - R - \Delta S \), where the long-term average change in water storage \( \Delta S \) (mm year\(^{-1}\)) is assumed to be zero. Additionally, \( T, P, R \) and \( ET \) results (historical and projected) of 22 individual CMIP5 climate models (Stocker et al., 2013) over the extent of the Selenga River basin were extracted to investigate their consistency with observed historical data and examine the characteristics of projected future trends of the basin’s hydroclimate (2010-2039 and 2070-2099; Section 2.2 in Paper I).

To identify major hydrological trends in the Selenga River basin, various analyses of daily discharge \( (Q, \text{ m}^3\text{ s}^{-1}) \) data were performed. First, analyses of intra-annual changes of the annual maximum and minimum \( Q \) at the downstream Mostovoy gauging station of Selenga River (Paper I) were carried out for the period 1938-2009. Additionally, data on the relative frequency of daily \( Q \) were compared between two periods: (1) before the recent change of average discharge at the Selenga River outlet (1975-1994; Chalov et al., 2015a) and (2) after this change (1995-2014). These analyses were also carried out for the Tuul River at Ulaanbaatar gauging station (Mongolia; Figure 1; data source: Paper II). Lastly, to investigate long-term intra-annual changes in daily discharge data variations within the Selenga River basin, annual coefficients of variation of daily discharges \( (CV_Q) \) were estimated for the Selenga River (Mostovoy, 1938-2014) and the Tuul River (Ulaanbaatar, 1945-2014).

3.2 Analysis of the impact of mining activities on riverine sediment load input

To investigate possible relations between riverine sediment load increases and the areal extent of mining regions of the Tuul River basin (Paper II), the basin area \( (A_T, \text{ km}^2) \); red border, Figure 3A) was divided into mining areas \( (A_m, \text{ km}^2) \)
and remaining natural areas \( (A_n = A_T - A_m; \text{ km}^2; \text{ Section 2.2 in Paper II} ) \). Two different approaches were used to study soil loss including impacts of human activities within both area classes: (1) an area-weighted nested catchment approach and (2) a spatially distributed soil erosion model. The former method was based on snapshot measurements of total sediment load \( (TSL, \text{ t day}^{-1}) \) at up to four locations along the Tuul River (green points in Figure 3) during three different sampling campaigns. In contrast to method (1) that captures impacts of anthropogenic disturbances, method (2) only accounts for rainfall-runoff erosion of soil. A comparison of the results between both methods is expected to provide a quantitative measure of the contribution of direct human activities to soil losses, such as the direct discharge of turbid wastewater to the streams.

The nested catchment approach is used to interpret snapshot \( TSL \) observations acquired during three field campaigns (June 2012, September 2013 and August 2014; Paper II), during different hydrometeorological conditions (Figure 4 in Paper II). The method divides the studied part of the Tuul River basin (red border, Figure 3A) into one upper, “reference” basin (including the river’s source, e.g. yellow basin area, Figure 5) and one lower, incremental “nested” basin (e.g. purple basin area, Figure 5). The areas of the basins were constrained by \( TSL \) measurement points (i.e. T5b, T6, T6a, T6b; Figure 3 and Figure 5). A detailed description of the methods can be found in Section 2.4 of Paper II. The nested catchment approach was used to estimate soil loss \( (SLO, \text{ t day}^{-1} \text{ km}^{-2}) \) from \( A_m \) and \( A_n \) for each studied period of observations. Additionally, sediment load contributions \( (SD, \text{ t day}^{-1}) \) from \( A_m \) and \( A_n \) were approximated according to:

\[
SD_n = A_n SLO_n \\
SD_m = A_m SLO_m
\]

The soil loss and sediment load contributions from rainfall-runoff soil erosion were also estimated using the empirical and spatially distributed model WATEM-SEDEM (Van Rompaey et al., 2001; Verstraeten et al., 2006; Paper II). The following data were used in the model development: soil types from field measurements, digital elevation model, satellite images and climate data (precipitation). The model was developed to simulate hydrometeorological conditions similar to those prevailing in the August 2014-field campaign. An effective rainfall contribution \( (P_{eff}, \text{ mm month}^{-1}) \) corresponding to the observed discharge at the time of the campaign was therefore used in the model instead of annual average precipitation values (Sections 2.2.2 in Paper II). The model was

![Figure 5. Two examples (A and B) of pairs of the upper “reference” and lower, incremental “nested” catchments (Figure 3 in Paper II: Pietroń et al., 2017).](image-url)
3.3 **Analysis of in-channel sediment transport and storage dynamics**

The natural, event-based dynamics of in-channel storage of the bed material load and its contribution to the evolution of hysteresis in sediment load concentration data were investigated (Paper III). The focus was on a 14 km river reach in a part of the Tuul River located just downstream the Zaamar placer mining region. For the analyses, a one-dimensional dynamic sediment transport model was developed in HEC-RAS 4.1 (Section 2.2 in Paper III). The modelled river reach extend up to 245 km from the Tuul River mouth in the upstream direction (see blue river reach in Figure 6b). A 14 km long focus reach (Figure 6c) is located approximately in the middle of the entire model extent. This allowed the model to simulate the sediment input to the focus reach based on the transport of bed material (that is also incorporated into the model) upstream it. The river and floodplain geometry was based on interpolation of measured cross-sectional data and the digital elevation model. To obtain reliable depth-average stream velocities in the model, the flow model was calibrated by adjusting Manning’s n-values for the channel using a set of measured flow profiles acquired in 2011 and 2012. The bed representation in the model was based on measured bed material during the 2011 and 2012 field campaigns. Two additional scenarios of the model were created to test model’s sensitivity to different bed-material initial boundary conditions. Daily discharge data of year 2011 ($Q$, m$^3$ s$^{-1}$) from the Ulaanbaatar station were used as flow input conditions. The flow events were separated from the base flow using local-minima method (Sloto and Couse, 1996). A more detailed description of the model development is given in Section 2.2 of Paper III. Furthermore, discharge data as well as SSL data from the Mostovoy and Kabansk gauging stations at the Selenga River were compared to analyze differences between these locations (data for period: 1981-2005). The Kabansk station is located about 20 km upstream the Selenga River delta’s apex and 80 km downstream the Mostovoy station (see Figure 1). The data used in the analysis were acquired as a part of a collaborative project (see Section 2.2 of Paper I).

3.4 **Analysis of grain size distribution of the deltaic sediment and sedimentation processes**

The grain size distribution of sediment found at various locations within the Selenga River delta (Figure 4) was studied in Paper IV. These considered locations were: marginal areas of confined channels or areas of subaqueous levees formation, for simplicity denoted submerged banks (18 samples); subaerial sand bars (4 samples) as well as various wetlands and water bodies characterized by different level of connectivity with the main channels (7 samples in total). The latter group involve floodplain lakes that receive water and sediment during high discharge conditions (3 samples), marshlands that are well connected with the main channels also under conditions of lower discharges (2 samples) and the...
newly formed subdelta front (2 samples). Additionally, the study in Paper IV investigated which flow conditions are needed in the delta channels to transport sediment outside of the channel margins. It was tested if bed material sediment (>63 μm) can be conveyed outside of the channel in suspended transport mode (see Section 3.2 of Paper IV) based on estimates of the dimensionless Rouse number ($P_n$). If the estimated $P_n$-values for the considered sediment particle size are lower than the critical Rouse number $P_n^* = 2.5$, it means that the sediment start to be transported with the suspended load (Middleton and Southard, 1984; Huston, 2014). If estimated $P_n$-values are higher than $P_n^*$, it indicates that the sediment is most likely transported with the bed load (Lynds et al., 2014). The tested bed material ranges were based on grain size statistics of the sampled locations. The considered flow characteristics were approximated from independently reported minimum, median and maximum boundary shear stress values ($\tau_b$, Pa) for bankfull flow conditions (Dong et al., 2016) and from measured discharges ($Q$, m s$^{-1}$) and depth-average flow velocities ($U$, m s$^{-1}$) at different channel cross-sections within the delta (see Table 2 in Paper IV).
4 Results

4.1 Hydroclimatic trends in the Selenga River basin

The results from the analysis of long-term hydroclimatic data show that the annual average $T$ of the Selenga River basin increased by 1.6 °C (0.022 °C year$^{-1}$ on average) over the studied period of 1938-2009 (Figure 7a). The temperature mostly increased gradually, however in the late 1980s to the mid-1990s $T$ increased more rapidly. The largest and smallest changes of seasonal $T$ between the periods 1961-1985 and 1986-2009 occur in winter (+1.32 °C) and autumn (+0.85 °C), respectively. The annual mean values of the water balance components ($P$, $ET$ and $R$) show relatively small temporal variability during the studied period (Figure 7b). For example, a comparison of the data between the two 20-year periods (1961-1980 and 1986-2005) shows that the annual mean $P$ increase by 7.8 mm and the annual mean $R$ decrease by 1.4 mm. The biggest decrease in seasonal $R$ occur during summers. An increased annual average $ET$ by 9.2 mm can have contributed to the above-described decrease in $R$. According to the water balance assessments, on average 85% of $P$ is lost through $ET$ during the entire studied period (1938-2009).

Additionally, a comparison with the historical observed and modelled $T$ data (Paper I; based on CMIP5 ensemble mean of 22 individual climate models; Stocker et al., 2013) show reasonable consistency. The ensemble mean of the projected future $T$ in the Selenga River basin shows continued warming of the climate. However, a comparison of the historical modelled and measured data of the water balance components ($P$, $R$ and $ET$) between the modelled and measured data show large differences. This decreases the reliability of the corresponding projections that show long-term increasing values of all the water balance components (see Figure 4 in Paper I).

The average observed $Q$ in the Selenga River basin (Mostovoy station) for the period 1938-2009 is 855 m$^3$ s$^{-1}$. A comparison of mean inter-annual daily discharges for three periods (1938-1961, 1962-1985 and 1986-2009) shows a recent decrease in discharges for the period between April and October (Figure 7c). The annual minimum daily discharge has increased, whereas the maximum daily discharge has decreased since 1938 (Figure 7d and 7e, respectively). A comparison of the daily $Q$ frequency between the periods 1975-1994 and 1995-2014 shows major changes in the Selenga River’s hydrological flow regime (Figure 8a). The average daily discharge, for instance decreased from 893 m$^3$ s$^{-1}$ to 725 m$^3$ s$^{-1}$. Moreover, during the last 20 years the frequency of moderate discharges ($Q = 750 - 1250$ m$^3$ s$^{-1}$) increased and high discharges ($Q > 1350$ m$^3$ s$^{-1}$) decreased, both by about 10 percentage points (Paper IV). Long-term daily discharge data show quite unchanged variability of flow during the period 1938-1994, with 10-year running average annual coefficients of variation of
daily discharges \((CV_Q)\) ranging between 0.88 and 0.95 (Figure 9a). After 1995, the \(CV_Q\) drops and the 10-year annual average \(CV_Q\) is 0.81 for the most recent decade (2005-2014).

Daily discharge frequencies in the Tuul River (Ulaanbaatar station) for the two different periods (1975-1994 and 1995-2014) are presented in Figure 8b. The average daily discharges decreased from 34 m\(^3\) s\(^{-1}\) to 16 m\(^3\) s\(^{-1}\) during the most recent 20 years. Low discharges (0.0-5.0 m\(^3\) s\(^{-1}\)) are most frequent, occurring 49% of the time (1995-2014) which corresponds to 177 days per year. The relative frequency of discharges between 0.0-35 m\(^3\) s\(^{-1}\) increased from 76% to 86% during the period of 1995-2014. The frequency of discharges greater than 35-55 m\(^3\) s\(^{-1}\) did not change between the periods, and are around 7.0%. The frequency of discharges greater than 55 m\(^3\) s\(^{-1}\) decreased from 18% to 6.6%. Long-term daily discharge data show changing variability of flow during the period 1938-1988, with 10-year running average annual coefficients of variation of daily discharges \((CV_Q)\) ranging between 1.4 and 2.0 (Figure 9b). After 1989, the 10-years running average \(CV_Q\) drops from to 1.4 and slightly increases to almost 1.5 in the most recent decade (2005-2014).
Figure 8. Comparison between frequencies of daily discharges for periods 1975-1994 (blue bars) and 1995-2014 (red bars) in: (a) the Selenga River (Mostovoy station, see Figure 1), the scale of the bar is 50 m$^3$ s$^{-1}$ (Figure 5 in Paper IV: Petrović et al., in review); and (b) the Tuul River (Ulaanbaatar station, see Figure 1), the scale of the bar is 5.0 m$^3$ s$^{-1}$, the relative frequency of the bar between 0.0-5.0 m$^3$ s$^{-1}$ reaches 45% and 49% for periods 1975-1994 and 1995-2014, respectively.
Figure 9. Annual coefficient of variation of daily discharge ($CV_Q$) for (a) the Selenga River (1938-2014, Mostcvo station, see Figure 1), and (b) the Tuul River (1945-2014, Ulaanbaatar station, see Figure 1).

### 4.2 Impact of surface mining on riverine sediment load inputs

The conditions captured in the field campaign of June 2012 are characterized by low $Q$ and $TSL$, whereas the conditions from September 2013 and August 2014 show higher $Q$ and $TSL$ (bankfull conditions Figure 4 in Paper II). The results of the nested catchment approach show that the soil loss from natural areas dominated by grasslands ($SLO_n$) range from 0.02 t month$^{-1}$ km$^{-2}$ to 0.28 t month$^{-1}$ km$^{-2}$ with $CV = 0.97$. The soil loss from mining areas ($SLO_m$), that covers only 0.12% of the studied basin areas ($A_f$), is significantly greater, from 7.7 t month$^{-1}$ km$^{-2}$ to 95.7 t month$^{-1}$ km$^{-2}$ with $CV = 0.12$. The latter, low $C_f$ suggests that the sediment contribution from the mining areas is relatively constant, regardless of the differences in hydrometeorological conditions between the measurement campaigns, whereas contributions from natural areas respond as expected when governed by water erosion, with much higher $CV$ that e.g. reflect low soil losses during drier periods (Paper II). The corresponding estimated sediment load contribution ($SD$) from $A_n$ and $A_m$ for the entire studied part of
Sediment transport from source to sink in the Lake Baikal basin

the Tuul River basin is 699 t day\(^{-1}\) for higher flow (August 2014) down to 255 t day\(^{-1}\) for the low flow conditions (June 2012). The contribution from mining areas \((SD_m)\) to those values range from 24\% to 82\%, respectively (Figure 10).

The results of the soil erosion model for August 2014 considering the lower part of the studied basin (green area, Figure 3A) show that on average the mining areas are characterized by larger net erosion than the natural areas (Figure 11). This result is mainly due to poor vegetation cover in the mining areas (see Figure 6 in Paper II). On the other hand, net deposition pools that are located close to the mining erosion hot spots limit transfer of a considerable part of the eroded sediment to the streams (Figure 11). According to the balance between net erosion and deposition, 18.2 t day\(^{-1}\) and 1.30 t day\(^{-1}\) of the sediment origi-
nate from natural and mining areas, respectively. A comparison of these results with the results of the observation-based approach (August 2014) shows that the sediment contributions from the natural areas of the lower part of the studied basin are similar (15.2 t day\(^{-1}\)) to the modelled ones. However, the observed contribution from the mining areas was 116 times higher (151 t day\(^{-1}\)) than the corresponding model result (see Figure 8 in Paper II). This suggests that a considerable part of the mining impact in the Zaamar Goldfield comes from direct human activities (that are not included in the soil erosion model), such as discharge of turbid waste waters, extensive channelization and destabilization of rivers’ banks (Paper II).

4.3 Transfer of sediment and role of in-channel storage

Five major flow events (the ones that doubled current base flow) and eleven minor events can be distinguished in the daily discharge data from 2011 (Figure 12). The results of the sediment transport model show that the overall change in the net storage of sediment within the 14 km long channel of the focus reach (Figure 6c) is -14 kt for the studied period. Additional scenarios show that the results of the model are sensitive to the initial bed material conditions. In particular, in case of initial abundance or scarcity of the finest bed material the same hydrograph (of the considered hydrological period) can yield negative
or positive net storage changes, respectively (see Supplementary Information of Paper III as well as Section 4 in Paper III). The finest considered grain size class 1 (0.062-0.25 mm) exhibit the largest dynamics with regard to net deposition and net erosion, whereas the other, coarser grain classes are characterized by net deposition. Snapshot measurements of suspended sediment load along the downstream Tuul River showed that the finest considered fraction in the model (grain size class 1) accounts for most of the sand particles in suspension (up to 100%) and up to 40% of the analyzed bed material.

Most of the estimated net erosion (83% of the total for the period) at the focus reach during the considered period (April-December 2011) occur during major flow events (E1-E5; Figure 15a). These events also stand for a considerable part of the total net deposition (56% of the total for the period, Figure 13d). Detailed analysis of the erosion and deposition patterns of the major flow events show that in-channel storage changes can contribute to the evolution of both clockwise and anti-clockwise sediment transport hysteresis (Figure 8 in Paper III). The results show also that the majority of sediment deposited during high flow events can be eroded during the same or subsequent events. Therefore, such areas as the focus reach in the Tuul River channel can act as local sources of sediment. Possibly, changes in the number and magnitude of the high-flow events can alter the downstream transfer of the bed sediment and associated pollutants.

Observed data (1981-2005) from the most downstream reach of the Selenga River (about 80 km; Figure 14) show that, SSL at the downstream station Kabansk is on average about 20 kg s⁻¹ (37%) larger than at the adjacent station Mostovoy. The largest observed difference is 109 kg s⁻¹ (73%, Figure 14a).
Figure 13. High flow events at the focus reach as: (a) percentage of the total magnitude of daily erosion, (b) percentage of time of estimated daily net erosion, (c) percentage of time of estimated daily net deposition, (d) percentage of the total magnitude of daily net deposition, (e) the magnitude of the daily net erosion and deposition in kilo tons (kt) (Figure 6 in Paper III: Pietroń et al., 2015).

A distinct period with great differences occurred between 1990 and 1994 (on average 67 kg s⁻¹; Figure 14a). The differences decreased after 1995 (on average 10 kg s⁻¹), with two years even showing higher SSL at the Mostovoy station. The difference between the suspended sediment load at Kabansk and Mostovoy (\( \Delta SSL = SSL_{Kabansk} - SSL_{Mostovoy} \)) is positively correlated with the annual maximum discharges \( (Q_{max}) \) at Mostovoy station \( (R^2 = 0.61) \) for the studied period (Figure 14c).

### 4.4 Sediment deposition on the Selenga River delta

The overall results show that most of the sampled deposited and suspended sediment is characterized by a large proportion of fine sediment (< 63 μm; Figure 3 in Paper IV). The average median grain size \( (D_{50}) \) of the sediment deposits at different locations within the Selenga River delta varies as follows: submerged banks \( (D_{50} = 37 \mu m) \), subaerial sand bars \( (D_{50} = 140 \mu m) \), floodplain lakes \( (D_{50} = 52 \mu m) \), marshlands \( (D_{50} = 23 \mu m) \) and the subcelia front \( (D_{50} = 98 \mu m) \). The \( D_{50} \) of the suspended sediment load is on average 32 μm. As shown in Section 4.1 the high discharges \( (Q > 1350 \text{ m}^3 \text{ s}^{-1}) \) decreased during the recent 20 years (Figure 8a). The reduced number of high discharges in the Selenga River can limit the hydrological connectivity and accumulation of sediment within floodplain lakes, that act as sinks of very fine sediment (82% of sediment < 16 μm; Figure 3b in Paper IV) and associated metals.

According to the results of the Ph analysis, a considerable fraction of bed material (mainly between 70-148 μm) can be transported with the suspended
load outside of the channels’ margins even during moderate flow conditions ($Q = 984-1191$ m$^3$ s$^{-1}$) with low shear velocities ($\nu_s$, m s$^{-1}$; Figure 15b). Such moderate flows have become more common ($Q = 750-1250$ m$^3$ s$^{-1}$; Figure 8a) likely due to climate change. This implies that the delta under these conditions can trap sediment within the submerged banks and marshlands located in the backwater zone (areas where stages of the streams are influenced by the water level of the Lake Baikal). Such sediment accumulation can aid banks and levees stabilization, support the development of wetlands and foster net sedimentation. Hence, numerous bank and wetland locations within the backwater zone can act as important sinks of metals. Moreover, these locations can aid in the storage of metals that commonly bond with coarser fractions (sand) in the Selenga River waters (Section 4 in Paper IV).
Figure 15. Rouse numbers (Pn) for different channel orders in the Selenga River delta for shear velocity values $u_*$ (m s$^{-1}$) representing: (a) bankfull flow conditions (based on $\tau_b$ data from Dong et al., 2016) and (b) in situ measurements of depth-average flow velocities ($U$, m s$^{-1}$). The presented $Pn$-values are for the average and extreme (whiskers) $D_{10}$, $D_{50}$ and $D_{90}$ of the sand-gravel material ($D_{B10}$, $D_{B50}$ and $D_{B90}$) of submerged bank samples within different channel orders (modified from Figure 7 in Paper IV: Pietroń et al., in review).
5 Discussion

5.1 Impact of changing hydroclimate

Results of the long-term discharge ($Q$) data analysis (Paper I) indicate that there are considerable trends in the hydrological regime of the Selenga River. In particular, during the period 1938-2009 the annual maximum daily flow decreased, whereas the annual minimum daily flow increased. This result is consistent with expected impacts of large-scale permafrost thaw (Frampton et al., 2011) within the basin. The thawing permafrost in the Lake Baikal basin is likely a result of changing climate that is depicted by the rate of increasing temperature $0.022 \, ^\circ C \, year^{-1}$, which is faster than the global average $0.012 \, ^\circ C \, year^{-1}$ (Stocker et al., 2013). The analysis of daily $Q$ presented in this thesis shows that the frequency of high $Q$ decreased and the frequency of moderate as well as low $Q$ increased both in the upstream and downstream parts of the Selenga River basin (Figure 8). The variation of daily $Q$ decreased in the most recent 20 years (1995-2014) too, as depicted by $CV_Q$ results in Figure 9. Therefore, despite the discussed effect of permafrost thaw on the stream flow patterns, additional factors might have contributed to these relatively large changes in the hydrological regime of the Selenga River basin. These include a drought that started in mid-1990s in the upper parts of the basin. Climate analyses of the last 400 years showed that such dry periods are usual for the semi-arid climate of the northern Mongolia (Davi et al., 2013). However, the ongoing drought is the warmest observed (tree-rings analysis) since over the last millennium (Pederson et al., 2014). Additionally, the effects of the dry conditions can be amplified by rapidly increasing water demands (for mining and irrigation, Priess et al., 2011; Davi et al., 2013; Malsy et al., 2016). Land-use changes in the Russian part of the Selenga River basin, such as afforestation (Bazhenova and Kobylkin, 2013) could also contribute to the changes in observed $Q$ (Hundecha and Bárđossy, 2004). Overall, except for this recent drought, there are no clear trends in the annual precipitation ($P$) over the last century in the Selenga River basin (Figure 7b).

The above-mentioned, recent $P$ decrease over the Selenga River basin could be linked with shifts in the summertime atmospheric circulation over East Asia (Berezhnykh et al., 2012). Parallel studies show that there are recent shifts in the rainfall patterns of northern Mongolia too. In particular, the number of long, low intensity rainfalls (up to 3 days of $\leq 2.5 \, mm \, hr^{-1}$) has decreased, whereas the frequency of short high intensity and patchy rain events has increased (couple of minutes of $> 7.6 \, mm \, hr^{-1}$; Marin, 2010; Goulden et al., 2016). Such changes can impact the generation of runoff and soil erosion patterns in semi-arid areas (Mohamadi and Kavian, 2015). High intensity patchy rainfalls can lead to rapid surface runoff generation and flash floods in small catchments (Cudennec et al., 2007). However, such precipitation patterns may not have the same impact on
generation of peak flow events in larger river basins due to the scattered and local character of these intense rainfall events (Bracken and Croke, 2007).

The results of this thesis show that the number and magnitude of high-flow events are important for the transfer and exchange patterns of a river’s fine bed sediment (0.062-0.25 mm; Paper III). Within a year, more than 80% of the net bed erosion happened during about 12% of the time, during the five highest flow events (E1-E5) of the year. The three first high flow events of the year (E1-E3; Figure 12) were important for remobilisation of the in-channel sediment. The latter two events, which were the highest in the studied period (E4-E5; Figure 12), did not remobilize similar amounts of sediment, partly because supply limited conditions emerged in the channel. Similar patterns have been observed in other rivers, e.g. in Mexico (Hudson, 2003) or upper Mississippi (Magilligan et al., 1998) were the first events in hydrological periods exhausted the in-channel sediment storage. Changes in magnitude and number of high flow events can theoretically alter the dynamics of the bed sediment transfer. In the Selenga River case, broader annual hydrographs with relatively lower peaks can make the inter-event character of sediment erosion more pronounced, and deposition less pronounced. Such replenishment of the bed sediment storage can occur even during time of lower discharges or flow events that according to the here discussed model account for more than 30% of the total net deposition in the studied period (Figure 13d).

A comparison of rating curves for the average annual suspended load (SSL) between the Mostovoy and the Kabansk gauging stations (approximately 80 km long river reach between the stations, Figure 1) in the most downstream Selenga River reach, shows significantly increased SSL in Kabansk (situated closer to the Selenga River delta) at conditions of greater annual average discharge (Figure 14b). A relatively clear relation between the annual maximum discharges ($Q_{max}$) and the difference in SSL between the stations ($\Delta SSL$; Figure 14c) indicates that the increased suspended load at the Kabansk station is linked to the magnitude of $Q_{max}$. Extreme events can also resuspend the sediment usually transported as bed load, and thus contribute to the observed differences in the SSL. An important role of flow events for the transfer of sediment and bed storage dynamics in the Selenga River system was previously seen also in its headwater parts through the model study of the Tuul River (Paper III). The reach between the Mostovoy and Kabansk stations can have similar storage functions and dynamics as the focus reach studied in Paper III.

The hydroclimatic changes discussed above are important for understanding (potential) changes in the sedimentation processes of the Selenga River delta. The delta is characterized by a considerably decreased stream power due to flow partitioning between up to eight orders of channels (Dong et al., 2016). This causes a non-linear deposition of sediment within the channel network, starting with the coarsest sediment load (gravel) in channels of low orders, eventually giving way to sand and silt in the terminal channels at the interface between the delta and Lake Baikal (Ilyicheva et al., 2015; Dong et al., 2016). The results of this thesis suggest that part of the bed material load can also be transported outside of the channels with suspended load even during moderate flow conditions (Figure 15; Paper IV), characterized by relatively low average shear velocities ($u_*$) in the distributary channels (Figure 8 in Paper IV). Eventually, the bed material (mainly between 70-148 μm; Paper IV) together with the wash load (silt and clay, < 63 μm) can be trapped in submerged banks and marshlands within
the backwater zone (∼9 km from the delta’s outlet, Dong et al., 2016). Such storage process in the wetlands and in bank areas can partly explain the observed decreases in sediment concentrations along channels of the Selenga River delta (Chalov et al., 2016, 2017b). On the other hand, the changed hydrological regime with lower median flows of the Selenga River (Figure 8a) is currently suppressing the connectivity between the main channel and floodplain water bodies that trap mainly silt and clay fractions.

5.2 Impact of human activities on transport patterns of sediment and contaminants

Results of this study (Paper II) suggest that mining impacts on sediment transport in the Tuul River originate mostly from direct inputs, such as input of sediment-loaded wastewaters to the streams or input from poorly maintained settling ponds, which lead to discharge of fine-grained material into the Tuul River (Farrington, 2000; Stubblefield et al., 2005). Destabilization of banks, mining too close to the river (Farrington, 2000) as well as dredging of the channels (Chalov et al., 2015a) can also contribute to the mining impact. The latter can furthermore lead to spreading of bed incision and channel degradation outside of the mined river reaches (Kondolf, 1997; Simon and Rinaldi, 2006). Identification of such key processes and assessment of their effects is important for establishing better management strategies (Rinaldi et al., 2005) to mitigate adverse impacts on downstream water systems (MEGD, 2012; Chalov et al., 2015a,b; Jarsjö et al., 2017). Due to the here identified high impact of wastewaters and ponds, it can be expected that better management solutions of the mining areas (e.g. Farrington, 2000) can aid in mitigation of their adverse impact on sediment transport in the Tuul River.

Present results also showed that the sediment input from mining areas are essentially independent of changing hydrometeorological conditions and rainfall-runoff soil erosion processes. Therefore, during dry conditions (\(Q \sim 12 \text{ m}^3 \text{s}^{-1}\)) the mining activities at the Zaamar Goldfield can contribute with as much as 80% of the TSL at the site. The highest considered discharges in the study were up to bankfull (∼60 \text{ m}^3 \text{s}^{-1}), which were close to the August average at the Ulaanbaatar station (Figure 2B in Paper II; \(Q \leq 60 \text{ m}^3 \text{s}^{-1}\) occurred on average for about 94% in the recent decades in the Tuul River, see Figure 8b). During such conditions around 24% of the TSL in the Tuul River can originate from the human activities (mostly the direct ones) at the mining areas (Figure 10). Mining areas frequently exhibit elevated concentrations of many metals in soils compared to non-mining areas (Jarsjö et al., 2017). These metals can hence enter the river through the mining activities and be transported with the sediment load as shown above. Thorslund et al. (2016) observed that concentrations of mining-related metals in suspended sediment increased during lower flow conditions in the Zaamar Goldfield area. The present results suggest that this may be an effect of increased relative sediment load contribution from mining sources during dry conditions (Figure 10). In this case, the metals are likely transported with fine-grained fractions (silt and clay, < 63 \(\mu\text{m}\)), which can be transported in suspension even during low discharge conditions (see Einstein et al., 1940). On the other hand, the concentration of some metals (i.e. Cu and Zn) were higher during periods of increased discharge (Thorslund et al., 2016). Since these metals were found to bond with coarser sediment fractions than silt and clay in the
Selenga River system (e.g. fine sands, ~63-250 μm; Lychagin et al., 2017), they likely are transported with bed material load. In that case, high flow events were shown to be important in mobilization and transient storage of associated sediment and sediment-bound metals (Paper III). Observations in rivers worldwide show that high discharge events are important in “flushing” of river channels from contaminated sediment in the human impacted areas (Davide et al., 2003). The sediment transported during such flows is likely redistributed between downstream sinks (floodplains and channel bed).

Paper IV of this study shows that sediment deposits and sediment loads in the Selenga River delta, the final sink of the sediment in the basin, are characterized by high cohesion. The median diameter of sediment in submerged banks and of suspended sediment were $D_{50} = 37$ μm and $D_{50} = 32$ μm, respectively (Paper IV). Potentially, the fine particles that reach the delta can be trapped in the wetlands and banks within the backwater zone (Paper IV). This is consistent with studies concluding that the Selenga River delta plays a prominent role in the storage of sediment and associated metals (Khazheeva et al., 2008; Chalov et al., 2016, 2017a). Furthermore, the gradual deposition of sediment on the channel beds is another process that can cause decreasing metal concentrations in the delta (Chalov et al., 2016). An effect of such a process would be that the grain size of the bed sediment should change with distance and degree of flow partitioning in the delta, which has been observed in the case of the Selenga delta (Dong et al., 2016). Although these sedimentation processes in the delta will decrease the amount of the potential metal pollution entering Lake Baikal with suspended material, they may impact biota of the delta itself (Plyusnin and Zhambalova, 2014) and may eventually also be further transported as dissolved constituents into Lake Baikal. Taken together, to quantify the impact of the mining on the large scale sediment transport, the distribution and delivery to the delta’s wetlands, future studies in the Selenga River basin should focus on identification and tracking of the mining sediment (e.g. via fingerprinting analyses). Such efforts can more generally aid in understanding the sediment associated metal contamination of the environment by mining (see Thorslund et al., 2012, 2016).
6 Conclusions

In this thesis, data analysis and modelling approaches are used to investigate how a changing climate and human activities alter transport of sediment within the Lake Baikal basin. The main conclusions are:

- During the period 1938-2009, the annual maximum daily flow in the Selenga River basin has decreased, as well as the annual number of high flow events, whereas the annual minimum daily flow has increased. These changes in discharge characteristics are consistent with expected impacts of basin-scale permafrost thaw.

- In the past 20 years, drought conditions that may be linked with shifts in the summertime atmospheric circulation over East Asia have caused considerable decreases in water and sediment discharges in the basin.

- Under high (bankfull) discharge conditions in mining-impacted hillslope areas of the Selenga River basin headwaters (the Tuul River basin, Mongolia), about 24% of the sediment input to the river originated from the placer mining areas that occupied roughly 0.12% of the considered hillslope areas ($57 \times 10^3$ km$^2$).

- The sediment input from the placer mining areas were observed to be constant regardless of hydrometeorological conditions, which under low discharge conditions lead to a dominance (82%) of sediment originating from the placer mining areas, most probably entering the river through wastewater discharge or malfunctioning settling ponds.

- Metal-enriched sediment from mining areas can hence dominate river waters under low flow conditions, which implies that if discharge will continue to decrease in the Tuul and Selenga rivers (and in other mining regions of the world) increased riverine metal concentrations may be one of the consequences.

- Regarding in-channel storage and transfer of the river bed-material (sediment with grain size $> 63$ μm), recorded data and modelling results showed that changes in magnitude and number of high-flow events can considerably influence the dynamics of bed sediment transfer. Given also the conclusive results regarding on-going changes in peak flow characteristics, it is likely that in-channel sediment transport characteristics may now be under conditions of considerable change.

- Under present conditions of extended drought, less sediment may have been distributed over the floodplain wetlands in the Selenga River delta. However, our field-data based modelling shows that, despite these changes
in ambient conditions, sediment can still be transported to, and trapped within, the banks and water bodies located in the backwater zone of the Selenga River delta. This can aid banks and levees stabilization, support the development of wetlands and foster net sedimentation.
7 Future Prospects

As shown in this thesis, ongoing climatic changes have likely contributed to shifts in hydrological characteristics and related sediment transport characteristics in the Selenga River system in recent decades (Sections 4.1 and 5.1). In the future, it is conceivable that the flow regime of the Selenga River will be affected by dam and reservoir construction, for instance due to plans of the Mongolian government to construct a cascade of hydropower dams in the region (see, e.g. Chu et al., 2010). The construction of dams and related flow changes can affect the sediment transport processes and the ecology of river systems in different ways and to various degrees (Ligon et al., 1995; Kondolf, 1997; Walling and Fang, 2003). Hence, an essential first step in taking well-informed management decisions regarding such large-scale flow regulation projects in the Selenga River would be to systematically investigate the potential impacts on sediment and contaminant transport along the river, all the way to the delta and the deltaic wetlands. Present results, including the here developed models and analysis methods, may provide a useful basis for some of the needed impact assessments.

The results showing that mining can have large impacts on the composition of transported sediment (in particular under low flow conditions; Section 4.2) call for more detailed investigations of the actual origin of sediment found along transport pathways in the Selenga River system. This should include refined assessment of contributions from multiple mining areas to downstream sediment loads and metal pollution. Methodologically, this can for instance be achieved by conditioning transport models such as HEC-RAS with information from fingerprinting analysis methods, including isotope analyses (Viparelli et al., 2013), geochemical assessments and composite approaches (Collins et al., 1997; Miller et al., 2015; Tiecher et al., 2016). Such efforts would also increase our knowledge regarding the role of the Selenga River delta in accumulation and storage of the mining-originating sediment and contaminants.

This thesis provided an example of how particle size can control where particle-bound metals can be sequestered in river deltas (Section 4.4). Although fine sediment fractions generally contain higher concentrations of most metals compared to coarse sediment fractions (de Groot et al., 1971), recent studies have shown that some metals in the Selenga River waters consistently bond preferentially with coarse sediment fractions (Lychagin et al., 2017). This may be for various reasons such as the specific mineral composition of the coarser sediment, or the close proximity of a sampled site to a source of metal contamination with particular characteristics (Whitney, 1975; Tessier et al., 1982; Singh et al., 1999). To better understand the ultimate fate of different sediment-bound metals, detailed studies are needed regarding the generality and predictive capabilities of metal-specific relations between particle size and metal concentrations.
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Sediment transport from source to sink in the Lake Baikal basin


