Institut für Erd- und Umweltwissenschaften
–Geoökologie–

Suspended Sediments in the Kharaa River, Sources and Impacts

Kumulative Dissertation
zur Erlangung des akademischen Grades
"doctor rerum naturalium"
(Dr. rer. nat.)
in der Wissenschaftsdisziplin "Geoökologie"

eingereicht an der
Mathematisch-Naturwissenschaftlichen Fakultät
der Universität Potsdam

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Potsdam, den 27.11. 2017

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Abstract

Anthropogenically amplified erosion leads to increased fine-grained sediment input into the fluvial system in the 15.000 km^2 Kharaa River catchment in northern Mongolia and constitutes a major stressing factor for the aquatic ecosystem. This study uniquely combines the application of intensive monitoring, source fingerprinting and catchment modelling techniques to allow for the comparison of the credibility and accuracy of each single method. High-resolution discharge data were used in combination with daily suspended solid measurements to calculate the suspended sediment budget and compare it with estimations of the sediment budget model SedNet. The comparison of both techniques showed that the development of an overall sediment budget with SedNet was possible, yielding results in the same order of magnitude (20.3 kt a^{-1} and 16.2 kt a^{-1}).

Radionuclide sediment tracing, using Be-7, Cs-137 and Pb-210 was applied to differentiate sediment sources for particles < 10µm from hillslope and riverbank erosion and showed that riverbank erosion generates 74.5% of the suspended sediment load, whereas surface erosion contributes 21.7% and gully erosion only 3.8%. The contribution of the single subcatchments of the Kharaa to the suspended sediment load was assessed based on their variation in geochemical composition (e.g. in Ti, Sn, Mo, Mn, As, Sr, B, U, Ca and Sb). These variations were used for sediment source discrimination with geochemical composite fingerprints based on Genetic Algorithm driven Discriminant Function Analysis, the Kruskal–Wallis H-test and Principal Component Analysis. The contributions of the individual sub-catchment varied from 6.4% to 36.2%, generally showing higher contributions from the sub-catchments in the middle, rather than the upstream portions of the study area.

The results indicate that river bank erosion generated by existing grazing practices of livestock is the main cause for elevated fine sediment input. Actions towards the protection of the headwaters and the stabilization of the river banks within the middle reaches were identified as the highest priority. Deforestation and by lodging and forest fires should be prevented to avoid increased hillslope erosion in the mountainous areas. Mining activities are of minor importance for the overall catchment sediment load but can constitute locally important point sources for particular heavy metals in the fluvial system.

Zusammenfassung

Durch Landnutzung erhöhte Erosion führt zu verstärktem Eintrag von Feinsedimenten im 15.000 km^2 großen Einzugsgebiet des Kharaa in der nördlichen Mongolei. Diese Einträge stellen einen starken Stressor für das aquatische Ökosystem dar.

Im Rahmen dieser Studie werden auf neuartige Weise verschiedene Ansätze zur Untersuchung der Feinsedimentdynamik im Einzugsgebiet kombiniert. Der Vergleich der Ergebnisse aus zeitlich hochaufgelösten Abfluss- und Schwebstoffanalysen, Sedimentbudgetmodellierung und „Sediment Source Fingerprinting“ Techniken erlaubt eine Bewertung der Genauigkeit und Anwendbarkeit jeder einzelnen Methodik im Untersuchungsgebiet. Das anhand von Abfluss- und Schwebstoffmessdaten berechnete Sedimentbudget am Gebietsauslass wurde mit dem mittels des Sedimentbudgetmodels SedNet berechneten Sedimentbudget verglichen. Die Ergebnisse von des aus Abfluss- und Schwebstoffmessdaten berechneten Sedimentbudgets (20,3 kt a^{-1}) und der mittels SedNet berechneten Werte (16,2 kt a^{-1}) zeigen eine befriedigende Übereinstimmung und bekräftigen die Anwendbarkeit des Models.

Zur Unterscheidung der Herkunft der Feinsedimente hinsichtlich des dominanten Erosionsprozesses wurde die Sedimentfraktion < 10µm hinsichtlich der Konzentrationen der Radioisotope Be-7, Cs-137 und Pb-210 analysiert. Die Ergebnisse zeigen, dass Gerinneerosion für 74.5% der Suspensionsfracht verantwortlich ist und Einträge durch Flächenerosion 21.7% und durch Gully-erosion nur 3.8% beitragen. Zur Untersuchung der Anteile der Teileinzugsgebiete an der Gesamtsuspensionsfracht am Gebietsauslass wurden die Sedimente der Teilgebiete hinsichtlich der Variation ihrer geochemischen Zusammensetzung untersucht (z.B. Ti, Sn, Mo, Mn, As, Sr, B, U, Ca und Sb). Anhand der Zusammensetzung wurde jeweils ein spezifischer “Fingerabdruck” für Sedimente aus spezifischen Teileinzugsgebieten definiert. Mittels Diskriminanzanalyse, Kruskal–Wallis H-test und Hauptkomponentenanalyse konnten die Beiträge der Teileinzugsgebiete an der Gesamtfracht mit einem Mischungsmodel berechnet werden. Generell trugen die oberläufigen Teileinzugsgebiete am geringsten, und die mittelläufigen am stärksten zur Sediment Fracht bei.

Die Ergebnisse der Studie zeigen, dass durch Überweidung begünstigte Ufererosion für den Hauptteil der Suspensionsfracht im Kharaa Fluss verantwortlich ist. Zur Verringerung des Schwebstoffeintrags in den Fluss werden Maßnahmen zur Uferbefestigung, insbesondere der Schutz und die Wiederherstellung der Ufervegetation als primäre Maßnahmen empfohlen.

1 Introduction

The basic processes of soil erosion, sediment transport, deposition and remobilization are in many areas of the world directly related to rainfall and runoff on the soil surface and discharge into the river system. A vast amount of studies in the last 80 years of geomorphological and hydrological research have described these processes and devised new methods for the measurement of these (Jain and Kothyari, 2000; Walling 1983; Walling 2005; Walling and Webb 1981; Walling et al., 2001). Especially for meso- and macroscale areas it is challenging to find a cost and time effective way of delineating diffuse sediment sources, as it is necessary to deliver this information to stakeholders to enable an integrated catchment management.

A range of remote sensing and modeling approaches exist to assess the erodibility and therefore potential sediment production areas. The most commonly applied modelling approach for soil erosion is the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978), or some of its derivates such as the (Revised Universal Soil Loss Equation (RUSLE) (Renard, 1997). However, while these are reliable tools to estimate upland erosion, they have two main limitations; i) they do not take into account other erosion forms such as gully erosion and riverbank erosion, which are hypothesized to be of a major importance, especially in the study area; ii) they are lacking discrimination of important processes of deposition and remobilization, e.g. the transport processes that are important to estimate how much of the sediment is reaching the fluvial system. The principle of using sediment geochemical or isotope properties as a signature fingerprint that can help detect its origin in the catchment area is a promising method to overcome the above mentioned obstacles in an elegant way. Although radionuclide isotope fingerprinting can help identifying the major contributing types of erosion, its use for the spatial delineation of sediment sources throughout large catchments is limited. The geochemical composition of sediment varies with geology, soil type distribution and landuse throughout different areas of a catchment. Using this information it is possible to develop an individual "fingerprint", i.e. a unique composition of elemental properties for sediment from potential source areas and calculate on the basis of statistical analysis and interpretation the percentage of contribution of these sources to the fluvial sediment load.

Fingerprinting studies based on the concentration of atmospheric fallout radionuclides have been developed and applied to analyze the erosion behavior in different regions and climatic conditions. Sediment source identification based on composite signatures of geochemical composition has proven to be a valuable method to identify sediment source areas especially in small and medium sized catchments (Collins and Walling 2002; Davis and Fox 2009; Hancock and Pietsch 2008; Hancock et al., 2014; Wilkinson et al., 2013). Using isotope fingerprinting techniques allows for the identification of the erosional process responsible for the sediment generation, whereas geochemical fingerprinting helps identify its source in a spatial distribution within a catchment. The combination of geochemical sediment properties with atmospheric fallout radionuclide concentrations as tracers can be used to generate information on the spatial distribution of sediment sources and the underlying erosion processes responsible for the sediment mobilization. Furthermore, the parallel use of these methods allows for an evaluation of their descriptive power for future applications. To date only few studies have been conducted that apply both these tracers in combination (Devereux et al. 2010; Motha et al. 2004; Mukundan et al. 2010; Russell et al. 2001; Walling et al. 1999; Walling et al. 2001; Walling et al. 2008; Wilkinson et al. 2013). However, most of these studies were conducted in small catchments and under different climatic conditions then the present study.

The relative contribution of a source area or a source type (i.e. erosion type) can be calculated with a multivariate mixing model. A range of different mathematical forms of mixing models have been developed and tested (Collins et al. 1997; Hughes et al., 2009; Motha et al. 2003; Slattery et al., 2000). By minimizing the errors, these mixing models determine the source component proportions in the suspended sediment samples. Prior statistical test like the Kruskal–Wallis H-test (KW), Principal Component Analysis (PCA) and genetic algorithm-driven Discriminant Function Analysis (GA-DFA) (Collins et al., 2012) as well as prior weighting, can increase the discriminatory power of these models by helping to identify statistically robust composite signatures.

Additional tools to discriminate sediment source areas in a catchment are sediment transport and budget models that use spatial data layers on land use, soil properties, precipitation and topography (DEM). Such models focus mainly on the spatial patterns of sediment generation and movement, rather than using temporal variable input data. Sediment budget models allow the evaluation of potential sediment source types and their spatial distribution within the catchment. The comparative application of sediment budget modeling with sediment tracing methods allows for the evaluation of both methods and higher accuracy results. A combination of sediment budget modeling with additional sediment tracing techniques and local suspended solid measurements has already been proven effective in large scale catchments (Rustomji et al., 2008). However, such studies are rare and to date it is not clear if they are applicable in large scale catchments in cold semi-arid regions like Central Asia.

Whereas many regions, especially in Europe and Australia are well investigated in terms of erosional and sediment transport behavior, little is known in semi-arid regions of Central Asia. Therefore this study is an important contribution to the state of the art applications and yields viable information for future studies in whole Central Asia.

In the last decades since the collapse of socialism in the 1990´s, Mongolia, as most Central Asian countries, has undergone massive political and socioeconomic transformation that lead to urbanization, increased industrialization, mining, husbandry and agricultural production that are main sources for water quantity and water quality impairment. Furthermore, this semi-arid region is impacted in many parts by decreased rainfall and increased sediment transport. Moreover, the presence of extreme rainfall events are associated with the impact of global climate change. In this water-scarce region, water resources are therefore increasingly contested between different user groups (e.g. mining, agriculture and hydro-power). Whereas a general understanding of the pollution and sediment sources and their impact on the fluvial system exists from previous studies, little is known about the actual dynamics and loads of sediments and pollutants as well as their effects on the receiving water bodies. Previous studies in the study area, investigating the habitat distribution of selected fish and macroinvertebrate species, (Avlyush et al., 2013; Hartwig and Borchardt 2015; Krätz et al., 2006) found that the ecological habitat functions in the downstream and midstream sections of the Kharaa are altered from their natural state and attributed this effect to fine sediment intrusion into the sediment pores of the hyporheic zone of the river. This zone constitutes the interface between surface and subsurface water in a river and plays a crucial role for water quality and the ecological functioning of a river (Borchardt and Pusch 2009). The intrusion of fine grained sediments into the riverbed can lead to colmation of the riverbed (Beyer and Banscher 1975; Schälchli 1992) that reduces the hydraulic connectivity and, therefore, the exchange of surface and subsurface water. This can lead to the impairment of the ecological habitat suitability for plant and animal species. This change of aquatic zone functions and habitat suitability can directly be linked to increased fine sediment input into a river system (Wood and Armitage 1997). This impact can differ considerably within different catchment regions, but is also highly influenced by seasonal variations in hydraulic conditions by high discharge events (Schälchli 1992). The investigation of the pressure of landuse on the aquatic ecosystem therefore asks for linked monitoring strategies investigating the sediment delivery system and its impact on the fluvial system (Hartwig et al. 2012). This includes an erosion risk assessment and the identification of ecological thresholds of influx for the improvement of management concepts.

The main challenge is to develop a clear conceptual framework that describes the cause–effect–response chain between landuse and riverbank degradation, the changes of the ecological status in the river and priority management measures in a qualitative and quantitative way. The grasslands of the semiarid steppe regions of Central Asia are heavily exploited by cattle farming, agriculture and mining of natural deposits (Moerlins et al. 2008; Rakhmatullaev et al. 2013; Karthe et al. 2015a).

To effectively implement mitigation measures it is crucial to identify those with the highest impact on the fluvial system. Pressures from anthropogenic activities can differ considerably in a spatial context. Whereas wide floodplains may be used as arable land, hilly slopes and riparian zones are more often influenced by livestock overgrazing, and mountainous areas receive more pressure from mining activities. An interdisciplinary investigation of the pressure–state–impact chain in the study region needs therefore to integrate the assessment of the ecological status along the river reach, the investigation of the spatial impact on the functionality of the benthic and hyporheic zone, the detection of the most relevant erosion sources, and the delineation of the most affected river reaches.

A major constraint for the development of an optimal and sustainable management of the water resources in the Kharaa River Basin is the need to take into account all the above mentioned socioeconomic conditions, key stakeholders' interests and hydrological and climate pressures. Furthermore, it is important to address the governance system of water management in the target region. Often, competencies for water management are fragmented spatially, because responsibility is often not related to the catchment area, but oriented on political divisions like the county administration.

This study is embedded into the Integrated Water Resource Management Project "Modelregion Mongolia" (IWRM-MoMo), which aims to develop sustainable strategies for the management of the water resources of the Kharaa River catchment (Karthe et al., 2015a; Karthe et al., 2015b; Karthe and Borchardt 2012; Priess et al., 2011). The project aims to establish a sustainable concept for water management at the catchment scale in a Model Region in northern Mongolia. The main objectives of the IWRM-MoMo project are: i) River Basin Management – The analysis and improvement of the legal, political and institutional framework of the water sector and its management.; ii) Water Technologies - Technical solutions and concepts related to drinking water supply and waste water management which are adapted to the environmental and socio-economic conditions; and iii) Monitoring of water quantity, quality and ecological status. The third objective focuses on the investigation of terrestrial/fluvial interactions that affect water quality and quantity and the development of innovative monitoring strategies and networks, suitable to the extreme climatic conditions in Mongolia.

It is important to evaluate the ecosystem functions of a river that can uphold a rivers self-cleaning capabilities, detect possible pressures to these systems, and develop strategies to effectively mitigate these. In case of the Kharaa River it is expected that diffuse sediment bound pollution is, besides a few local point sources, the main pressure influencing the water quality and the river ecosystem. Therefore this study is of vital importance for the whole IWRM-MoMo Project, since it helps to clearly pinpoint these pressures

The Kharaa River catchment in Northern Mongolia is a subcatchment of the Baikal Selenga catchment in Central Asia and drains a catchment area of approximately 15,000 km^2. The Kharaa River has a total length of 350 km. The elevation in the Kharaa catchment ranges from 655 m a.s.l. at the catchment outlet (northwest) to 2,665 m a.s.l. in the upstream areas (southeast). Geologically, the mountainous areas belong to the Hangay–Hentey granitoid complex in the south–east and the floodplain areas are located in the Orkhon–Selenge volcanic belt in the north–west (Batulzii et al. 2005). The geomorphology of the catchment is divided into the high mountain regions with v-shaped valleys between 1600 and 2665 m a.s.l., middle mountain ranges with u-shaped valleys from 1,200 to 1,600 m a.s.l., hilly regions with flat valleys and the lowest reaches from 655 to 950 a.s.l. that are dominated by strath shaped valleys with wide floodplains. The hydromorphology of the Kharaa River is unregulated except for three minor reservoirs in the subcatchments Zagdelin Gol and Boroo Gol. The Kharaa river has a heavily meandering, sometimes braided, structure with up to 2 m high river banks exhibiting erosion, especially bordering the floodplains which, in places, are 5 km wide (Chalov et al., 2014). Mountainous region soils from forested areas are dominated by Phaeozems, Leptosols, and Ferrasols, whereas the middle and downstream regions show a dominance of Castanozem soils, with Fluvisols on the floodplains (Dordschgotov, 1992; Iderjavkhlan, 2008). According to Priess et al. (2011) the major land use types are grasslands (60%), forests (26%) and croplands (11%). The main crop in the catchment is wheat and most of the grassland areas are used as pasture with high livestock grazing intensity with horses, cattle, sheep and goats (Priess et al. 2015). In Mongolia, fine grained sediment losses to surface waters is expected to increase rapidly, due to the overgrazing of pastured, amplifying the lack of riparian vegetation and leading to soil degradation and desertification and thus higher erosion susceptibility (Onda et al., 2007). In recent years, a trend towards increased irrigation and green houses that amplifies the pressure on the water resources is also evident (Schweitzer and Priess, 2009). The population in the catchment as of 2005 is approximately 147,000 with more than half of the inhabitants living in the city of Darkhan near the catchment outlet (Hofmann et al., 2011). The climate of the catchment area is characterized by its situation in a transition zone between boreal cold and arid steppe climate, featuring dry, very cold winters and warm to hot summers. This leads to temperatures between +30 °C in summer and -40 °C in the winter months when the river has continuous ice coverage. The total annual precipitation in general is low in the region, ranging from 250 to 350 mm but varies in intensity throughout the catchment (Menzel et al., 2011). Over recent decades the discharge has decreased significantly from 21.8 m^3/s during the period 1990–1995 to only 8.8 m^3/s for the years 1996–2002 (Hofmann et al., 2011; Batima et al., 2005). Future scenarios, although indicating an increase of precipitation, expect a further decrease in discharge due to the increase of evapotranspiration caused by higher temperatures (Menzel et al., 2008) and increased water abstraction for mining and irrigation purposes. The discharge hydrograph shows a distinctive peak around May that is associated with snowmelt. The highest discharges occur in the summer months between June and August and are induced by high intensity rainfall events.

1.1 Objectives and Research Questions

In cooperation with other research groups that measure the input of fine sediment in the hyporheic zone and studying its impact on the ecosystem (Hartwig et al., 2016), the main goal of this study is the detection of the fine sediment sources contributing to the fluvial suspended sediment load of the Kharaa.

The study combines state of the art techniques for sediment budget modelling, sediment source fingerprinting, in combination with short- and long-term monitoring data (Theuring et al., 2015) to answer the following research questions:

1. What are the dominant erosion types that produce and transfer fine grained sediments to the fluvial system in a cold semi-arid region?

2. What are the spatial patterns of diffuse sediment sources on a subcatchment level and which subbasins are most responsible for the fine grained sediment input?

3. What is the fluvial sediment load and sediment budget of the Kharaa River and how does it vary with season?

4. What methods are most efficient for the characterization of diffuse sediment sources and its transport in the Kharaa catchment, and how can they be used for future studies in similar climatic regions?
5. What management advice can be deduced from the results of this study by depicting the hotspot areas in the catchment and their contributing source types?

To achieve a detailed characterization of the sediment sources in the study region, a range of investigations were carried out.

1.2 Overview of Chapters

This section provides an overview of the different chapters of this cumulative dissertation, which are mainly constituted by research articles, and explains the main context of the chapters as part of the overall conception of this thesis.

1.2.1 Introduction

The introduction of this thesis describes the state of research in the field of fluvial sediment transport fingerprint analysis, as well as the impact of fine sediments in the riverbed and their ecological impact. It explains the role of this study within the IWRM project MoMo and describes the importance of its findings for river basin management practices in the Kharaa River catchment. Furthermore, this chapter describes the main objectives of this thesis and provides an overview of the structure of this study.

1.2.2 Identification of fluvial sediment source types

This chapter is based on the article: *Theuring, P., Rode, M., Behrens, S., Kirchner, G., Jha, A., 2013. Identification of fluvial sediment sources in the Kharaa River catchment, Northern Mongolia. Hydrol. Process.27, 845–856*. The main emphasis of this article is the identification of suspended sediment source contribution of different erosion types and the testing of a sediment budget Model using monitored discharge and TSS data. The chapter describes the monitoring approach, presents the data collected, the methodological approach, and the results.

The author was as the first author responsible for the work in this article, from data acquisition in the field, to analysis, and the presentation of the results.

1.2.3 The spatial distribution of fluvial sediment sources in the Kharaa River Catchment

This chapter is based on the article: *Theuring P, Collins AL, Rode M (2015) Source identification of fine-grained suspended sediment in the Kharaa River basin, northern Mongolia. Sci. Total Environ. 526: 77–87*. Following the identification of sediment source types in Chapter 2, this chapter investigates the spatial distribution of fine grained sediment sources within the Kharaa River catchment. It details the analysis of the geochemically analyzed soil samples and the calculation of the spatial distribution of fine grained sediment sources using a composite fingerprinting approach and a mixing model.

The author was as first author responsible for the work in this article, the data acquisition in the field, and the coordination of the analysis and the presentation of the results.

1.2.4 The impact of suspended sediments on hyporheic zone functions in the Kharaa River catchment

This chapter is based on the article: *Hartwig, M., Theuring, P., Rode, M., Borchardt, D., 2012. Suspended sediments in the Kharaa River catchment (Mongolia) and its impact on hyporheic zone functions. Environ. Earth Sci. 65, 1535–1546.* In order to utilize the findings of Chapter 2 and 3, this chapter analyses the source - receptor relationship between the erosional sources in the Kharaa catchments and their impact on the benthic system and presents the overall framework of the monitoring approach of this study.

The contribution of the author is in the development and implementation of the sediment source monitoring approach, all work on the “Sediment source side” of the article, as well as in the contribution to the overall concept of the paper and drawn conclusions.

1.2.5 Identification of management options based on the Cause–effect–response chains of suspended sediment input in the Kharaa River catchment

This chapter is based on the article: *Hartwig, M., Schäffer, M., Theuring, P., Avlyush, S., Rode, M., Borchardt, D., 2016 Cause–effect–response chains linking source identification of eroded sediments, loss of aquatic ecosystem integrity and management options in a steppe river catchment Kharaa, Mongolia). Environ. Earth Sci. 75 (10), art. 855*. It utilizes the findings from the previous chapters to describe the cause–effect–response chain from the sediment sources, to their impact on the fluvial system, to the loss of aquatic ecosystem integrity, and derives management options to mitigate these effects. As the last thematic chapter of this thesis it also provides an overview of the significance of the authors study for the greater framework of the IWRM-MoMo-Project. The contribution of the author is in the description of the pressures from sediment input and the development of mitigation strategies on the management of riverbanks and landuse in the catchment to decrease suspended sediment loads.

1.2.6 Discussion

This chapter discusses the choice of methodologies used for the identification of fluvial sediment sources and it´s impacts on the Kharaa River catchment. It describes the limitations of the methods used in this study and discusses the significance and uncertainties of the results. Lastly, this chapter reviews the innovation and value of the study for the development of scientific methodologies in the field of fluvial sediment source research, and the significance of the findings to implement a sustainable, integrated water resource management in the Kharaa River catchment.

2 Identification of fluvial sediment sources in the Kharaa River catchment, Northern Mongolia

2.1 Abstract

Fine-grained sediments constitute a major stressing factor for the aquatic ecosystem in the 15,000 km^2 Kharaa River catchment in Northern Mongolia. The objectives of this study were to identify the suspended sediment (SS) sources and quantify the sediment budget of the basin. Sediment sources were identified with the help of sediment tracing methods utilizing Be-7, Cs-137 and Pb-210 radionuclides. High resolution discharge data were used in combination with daily suspended solid measurements to calculate the SS budget. These calculations were compared with the monthly archive data on SS and discharge to investigate temporal load variations. In addition, the sediment budget model SedNet was used to estimate the SS budget and test its applicability in a cold semi-arid region. Results of the sediment tracing showed that riverbank erosion generates 74.5% of the suspended sediment load, whereas surface erosion contributes 21.7% and gully erosion only 3.8%. In the most intensely used agricultural tributary catchment Zagdelin Gol, upland erosion contributed only 12.7% to the total SS losses. The calculated mean annual sediment load for the years 1990-2002 was 20.3 kt·a^{-1}. The SedNet model computed SS export from the catchment in the same order of magnitude as measured data (16.2 kt·a^{-1}). The results help to identify effective management measures to reduce sediment loads and mitigate its impact on the aquatic environment.

2.2 Introduction

Soil erosion can create a multitude of problems in the terrestrial environment, in particular for human land use activities such as agriculture. This is especially true for semi-arid environments like Mongolia. However, it also has important and wide spread implications for fluvial systems (Hartwig et al., 2012). Therefore, knowledge of the specific sources and delivery pathways of fine-grained sediments into a river network is vital for understanding its associated impacts on aquatic ecosystems. In addition, fine sediments are considered to be a significant source for nutrient and heavy metal inputs into lake and river systems. Fine sediment intrusion has also been identified as a major factor contributing to significant ecosystem alterations, affecting the ecology of aquatic biota such as fish and macro invertebrates through congestion of the hyporheic interstices (Wood and Armitage, 1997*)*. Thus the need to identify and prevent these less obvious impacts on a river system is essential to help maintain basic ecosystem functioning in the face of inevitable river development.
Identifying the sources of fine sediments with specific regard to the main erosion processes is a difficult and challenging task for meso-scale catchments. Whereas it is comparably straightforward to investigate small scale areas and identify the main erosion drivers with the help of field plot experiments, comparable investigations can become increasingly labor intensive with catchment size. Therefore, often remote or indirect techniques are used to identify the sources of suspended sediments in a given river and understand the SS transport pathways. Remotely sensed data and information on soil and precipitation in combination with topographic information can be used to assess surface erosion susceptibility and to delineate areas with high erosion risk based on Universal Soil Loss Equation calculations (Jain and Kothyari, 2000). This technique however does not provide information concerning the proportion of surface eroded sediments, bank eroded sediments or sediments from other sources such as gullies on total loads. Sediment tracing techniques based on atmospheric fallout nuclides have proven to be a reliable method to distinguish suspended sediment sources. Sediment source tracing techniques are widely used on small scale catchments (Davis and Fox, 2009; Collins and Walling, 2002; Walling, 2005). In larger catchments it is more difficult to distinguish different sediment source types due to the often increased catchment complexity and heterogeneity (Caitcheon et al., 2012; Olley and Wasson, 2003). In addition, sediment sources and their contributions to the overall suspended sediment load of the river may change temporally within the catchment. Particularly, rainfall characteristics are often changing during the year and this may lead to varying sediment source contributions over time (compare Sogon et al., 1999; Smith, 2008).

Equipping meso-scale river systems of several thousand square kilometers with intensive monitoring systems is expensive and not easily implemented in central Asian regions. Therefore, long term data on discharge and sediments are often only available for very few gauge stations with low temporal resolution and inconsistent quality. Because rainfall and snowmelt induced erosion and subsequent sediment inputs underlie high temporal variations it is difficult to calculate consistent suspended sediment loads in such data sparse catchments. In meso-scale catchments high temporal resolution measurements e.g. turbidity measurements in combination with suspended sediment sampling are still needed at least for several years to calculate reliable sediment loads. In very large catchments, more infrequent sampling may lead to unacceptable deviations between calculated and true sediment loads (Rode and Suhr, 2007).

Many approaches have been applied to characterize catchment sediment delivery and calculate sediment budgets, although many of them as for example the sediment delivery ratio (SDR) put the focus on hillslope erosion processes. However, the SDR is a poorly-specified lumped descriptor and there is still debate about the concept and concern that there is no general or reliable basis to estimate its value (Walling, 1983; Parsons et al., 2006). Sediment production and routing within river basins involves the activation of multiple sediment sources through the operation of many different processes. These processes include hillslope sheet wash and rill erosion, gully erosion, mass movement, and river bank erosion. The main problem for understanding, quantifying and modelling the budgets of suspended sediments, especially in developing countries, is the lack of information about its origin, mobilization and transfer dynamics (Walling et al., 2001). Recently, attempts have been carried out to identify the sediment transport processes in data sparse meso-scale catchments by using simple sediment budget models. For example the SedNet model has been developed and implemented in Australian semi-arid environments with reasonable results (Bartley et al., 2004; *Prosser et al., 2001;* DeRose et al., 2003). Furthermore sediment budget modelling has already been proven effective in combination with additional sediment tracing techniques and local suspended solid measurements (Rustomji et al., 2008). The model allows evaluating different sediment source types and their spatial origin within the catchment. Up to now experiences with the model are restricted to semi-arid and warm climates, and it is unclear whether these model types are also applicable in cold semi-arid regions with contrasting environmental conditions.

The objectives of the study were to i) identify the main sources of suspended sediment and its seasonal variability (snowmelt and rainfall induced) by using Cs-137, Be-7 and Pb-210 radionuclides and to ii) calculate suspended sediment budgets for the Kharaa River (15,000km^2) and its tributaries in Northern Mongolia. This was achieved by combining long term infrequent suspended sediment sampling with short term temporal high resolution measurements and, for comparison, with the sediment budget model SedNet. The results help to identify effective management measures to reduce sediment loads and mitigate its impact on the aquatic environment.

2.3 Material and Methods

2.3.1 Study area and data

The study site is the Kharaa River catchment in northern Mongolia. The Kharaa River drains a catchment area of approximately 15,000 km2 and is one of the tributaries of the Orkhon River and later the Selenga River, which is the main tributary to Lake Baikal. The Kharaa River has a length of 350 km. The elevation in the Kharaa catchment ranges from 655 m a.s.l. at the catchment outlet (northwest) to 2,665 m above sea level in the upstream area (southeast). Geologically, the area is primarily situated in the Hangay–Hentey basin that is dominated by old, heavily eroded sedimentary rocks of marine origin like sandstone and schist's, sometimes ruptured by plutonic rocks like granite. Parts of the very southeast belong to the Hangay–Hentey granitoid complex consisting of plutonic and metamorphic rocks and small parts in the northwest to the Orhon-Selenga volcanic belt composed of basaltic rocks (Batulzii et al., 2005). The geomorphology of the catchment can be divided into the high mountain regions with v-shaped valleys between 1600 and 2665 m a.s.l., middle mountain ranges with u-shaped valleys from 1,200 to 1,600 m a.s.l., hilly regions with flat valleys and the lowest reaches from 655 to 950 a.s.l. that are dominated by strath shaped valleys with wide floodplains.

The hydromorphology of the Kharaa River is unregulated except for two minor reservoirs in the subcatchments Zagdelin Gol and Boroo Gol. Especially in the wide floodplains the river course is meandering and the river sometimes braided showing high levels of riverbank erosion, amplified by very little riverbank vegetation and livestock overgrazing. Mountainous region soils from forested areas are dominated by Phaeozems, Leptosols, and Ferrasols, whereas the middle and downstream regions show a dominance of Castanozem soils, with Fluvisols on the floodplains (Iderjavkhlan, 2008; Dordschgotov, 1992).

According to Priess et al., (2011) the major land use types are grasslands (60%), forests (26%) and croplands (11%). The main crop in the catchment is wheat and most of the grassland areas are used as pasture with high livestock grazing intensity. In Mongolia, fine-grained sediment losses to surface waters is expected to increase rapidly, due to the overgrazing of pastured land leading to soil degradation and desertification and thus higher erosion susceptibility (Onda et al., 2007). In recent years, a trend towards increased irrigation and green houses that amplifies the pressure on the water resources is also evident (Schweitzer and Priess, 2009). The population in the catchment as of 2005 is approximately 147,000 with more than half of the inhabitants living in the city of Darkhan near the catchment outlet (Hofmann et al., 2011).

The climate of the catchment area is characterized by its situation in a transition zone between boreal cold and arid steppe climate, featuring dry, very cold winters and warm to hot summers. This leads to temperatures between +30 °C in summer and -40 °C in the winter months when the river has continuous ice coverage. Precipitation in general is low in the region, ranging from 250 to 350 mm/a, but varies in intensity throughout the catchment (Menzel et al., 2011). The mean annual discharge at the catchment outlet gauging station at Buren Tolgoi (Kh_1) shows a significant decrease in the last decades with an average of 21.8 m3/s-1 during the period 1990-1995 to only 8.8 m3/s-1 for the years 1996-2002 (Hofmann et al., 2011). This decrease is primarily caused by a reduction in precipitation and an increase in evapotranspiration during that period (Batima et al., 2005, Menzel et al., 2008). Though intensified water use for irrigation purposes may have contributed as well. The discharge hydrograph shows a distinctive peak around May that is associated with snowmelt. The highest discharges occur in the summer months between June and August and are induced by high intensity rainfall events (Figure 2.1).

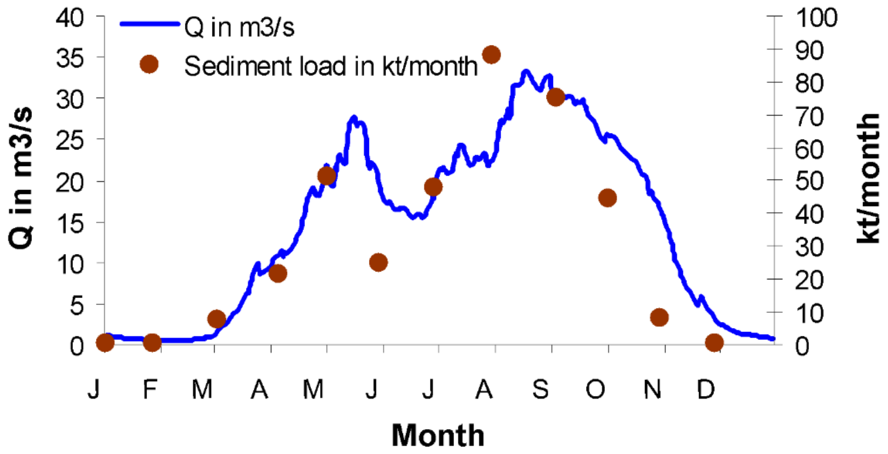

Figure 2.1: Average daily discharge and monthly suspended sediment load of the Kharaa River 1990-2002.

2.3.2 Fingerprinting methods

For the identification of suspended sediment sources and erosion types, radionuclide fingerprinting techniques can be used. In the Kharaa catchment three major erosion types can be distinguished: surface erosion, gully erosion and stream bank erosion. The anthropogenic occurring radionuclide Cs-137and the naturally occurring radionuclides Be-7 and Pb-210 are used to identify the erosion process responsible for the yield of suspended sediments. Be-7 and fallout Pb-210bex are naturally occurring nuclides in the atmosphere, whereas Cs-radionuclides originate from nuclear-weapons tests in the 1950s and 1960s (Poreba, 2006). All these radionuclides are deposited on the earth surface by wet and dry atmospheric deposition and are absorbed by the soil particles, especially, to fine grain particles. However, Pb-210 also occurs in situ in soils due to geological background radiation. In this study therefore all measured values refer to the total measured Pb-210, that is 210Pbex + insitu 210Pb. Due to their different half-lives (Be-7: 53.2 days, Cs-137: 30.1 years, Pb-210: 22.2 years) the radionuclides vary in their concentration in the soil profile changing with depth (Matisoff et al., 2002; Wallbrink et al., 2003; Hancock and Pietsch, 2008). Due to its fast decay rate Beryllium-7 is concentrated only in the uppermost 1 cm of the soil layer, whereas significant concentrations of Lead-210 and Caesium-137 also occur to depths of 10 cm. By comparing the different radionuclide concentrations and ratios in different soil depths with the radionuclide concentrations in suspended sediment it is possible to ascertain the previous location of the particles in the soil column. Ultimately, this knowledge allows conclusions about the way these sediments were eroded, namely via surface, gully or river bank erosion.

Four campaigns each in either spring or late summer 2010 and 2011 have been used to collect 12 topsoil samples comprising the uppermost 2 cm of soil of agricultural fields, 4 stream bank erosion samples from river undercuts, 4 samples from gully erosion sites and 4 samples of recently deposited river sediment (Figure 2.2). All sampling sites where chosen to resemble natural conditions of expected soil erosion. The sampling sites are spatially distributed throughout the catchment to pay tribute to possible spatial differences of radionuclides concentrations. For river bank erosion sampling sites highly erosive bank undercuts where chosen and mixed samples were taken from the full profile. For gully locations mixed samples were collected from the gully floors that have recently been deposited by gully erosion activity. Selected top soil erosion sites were distributed throughout the catchment. These arable and grassland sites differ in susceptibility to surface inter-rill and rill erosion and in slope angle. All samples were oven dried and sieved to 125 µm to remove major parts of roots and plant litter. All samples were analysed with gamma spectroscopy at the German Federal Office of Radiation Protection (BfS) with standardized analytical methods using a gamma ray spectrometer.

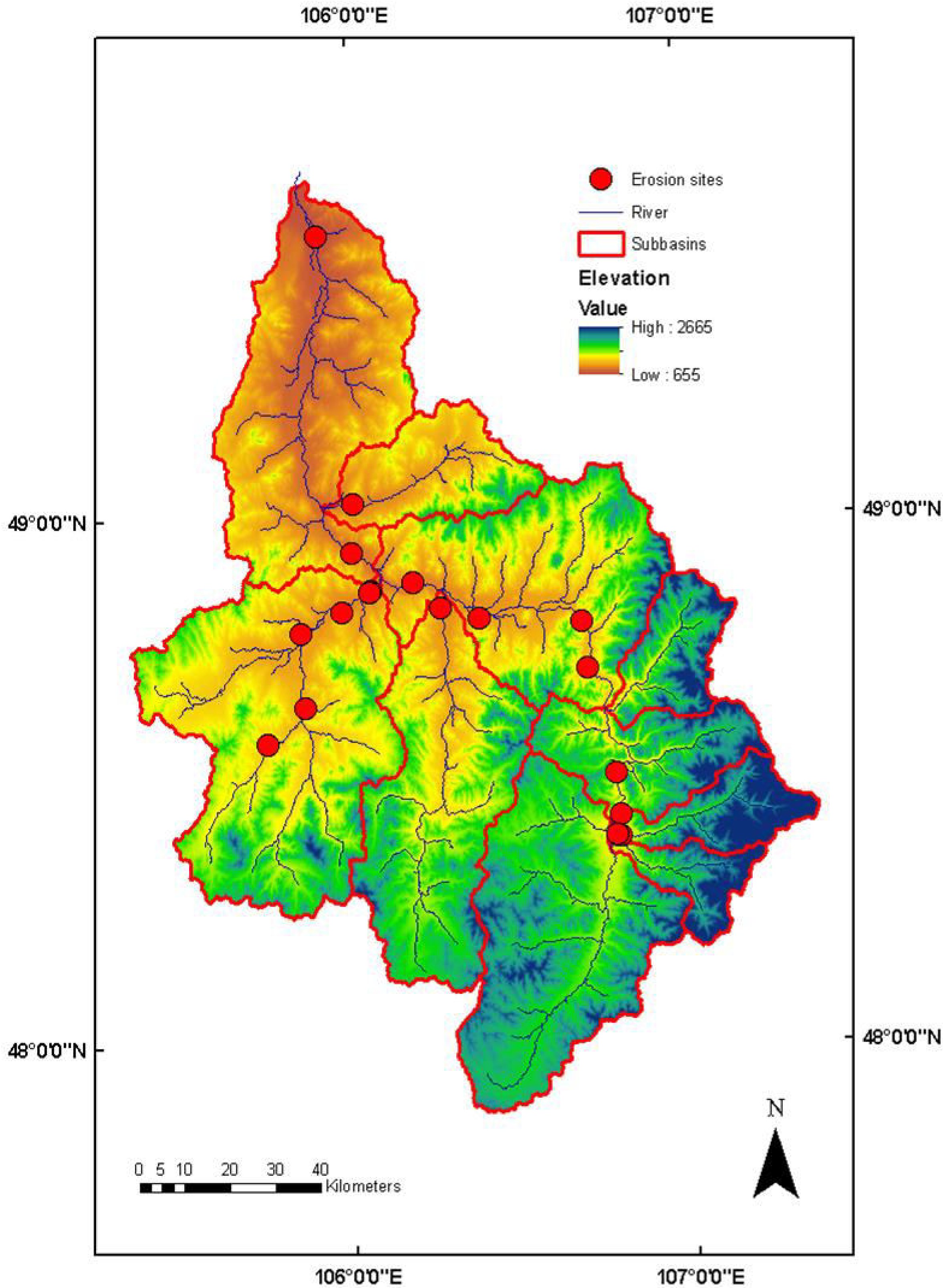

Figure 2.2: The Kharaa catchment with the sampling points for isotope analysis.

A major difficulty of the method is the mixed grain sizes of the suspended sediments and its selected transport and deposition behavior due to variable transport capacities of flowing water and flow duration. Since inputted sediment underlies deposition and re-suspension processes it has to be assumed that each sediment sample is not only composed from recently deposited suspended sediment. Coarser grain sized sediment might not actually originate from the last erosion inputs but remained in the system for a longer period of time (Walling and Moorehead, 1989). To minimize these effects, only the finest grain sizes that are easiest transported were analyzed. Therefore, all samples were wet-sieved to extract the <10 µm fraction of the samples. To assess if the distribution of grain sizes in the sampled deposited SS is representative for the distribution of the SS in the free flowing water we collected SS also from the water column. Grain size analysis were performed for the sediment size fractions of 63-20 µm, 20-10 µm and <10 µm. To collect a sufficient amount of SS of the water column for sediment size fractionation we installed 3 Phillip´s tubes (Phillips et al., 2000) that provided time integrated SS samples in different sections and depths across the river cross-section at Buren Tolgoi (Kh_1) during flood events in August 2010. Figure 2.3 shows that the grain size distribution is comparable to the sampled deposited SS with the <10 µm fraction accounting for 15-20 % of the total mass. This proves that it is possible to use freshly deposited SS samples as time integrated samples instead of filtering vast amounts of water to gain a necessary sample amount for isotope analyses. These findings were achieved at the catchment outlet where the SS concentrations and hence the differences between sampled deposited SS and SS in the water column can be expected to be smallest in the investigated river system. At the upstream sample locations it is likely that the SS concentrations and differences in grain size distribution between sampled deposited SS and SS in the water column are larger.

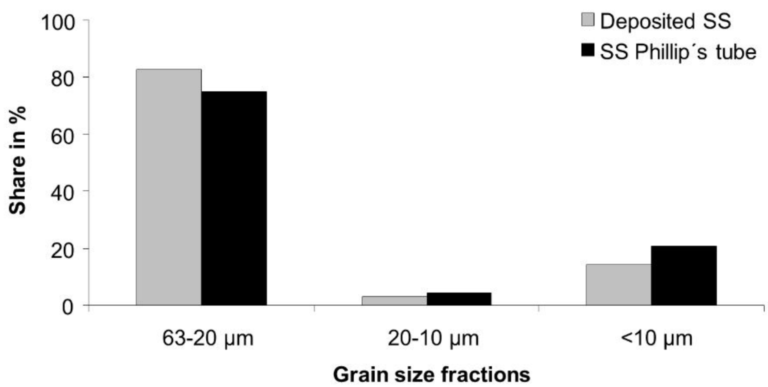

Figure 2.3: Distribution of grain sizes in deposited sediment in comparison with SS trapped in Phillip´s tubes at the station Kh_1 at the catchment outlet in 2010.

A major problem concerning the measurement of radionuclides activity in the SS is that for the measurements with a gamma ray spectrometer a certain amount of sample (usually around 30 cm^3) is needed in order to achieve exact results due to the detection limits of the spectrometer.

The extraction of an appropriate amount of material for the grain size (< 10 µm) can be achieved by dry and wet sieving each grab sample. This sample preparation is very time consuming. Thus it would take several weeks to complete all samples from each campaign (n= 20). In respect to the short half-life of Be-7 (53.2 days) this would lead to a decay of much of the Be-7 and therefore heavily impair the results. However, there is a distinctive relationship between the surface area of particles, sediment grain size and radionuclide adsorption of Be-7, Pb-210 and Cs-137 (He and Walling, 1996, Dyer and Olley, 1999). Therefore a grain sizes analysis of three samples from surface eroding reference sites was performed and the radiometric activity has been determined for each fraction of 125 µm, 63-20 µm, 20-10 µm and <10 µm (Figure 2.4). The radiometric activity showed a very strong relationship to the grain size with determination coefficients r^2 close to 1 for the power functions of the different radionuclides. Using this relationship all samples have been analyzed for the 125 µm fraction. Using this procedure, Be-7 measurements at the BfS in Berlin could be carried out between 20 and 30 days after sampling at the study site. After the radionuclides measurement grain size analysis was performed for each sample the activity in the < 10 µm fraction was calculated according to the grain size – radiometric activity gradient. The contribution of potential sediment sources to the sampled suspended sediment was assessed using a mixing model approach as described in Collins et al., (1997) and Collins et al., (2010).

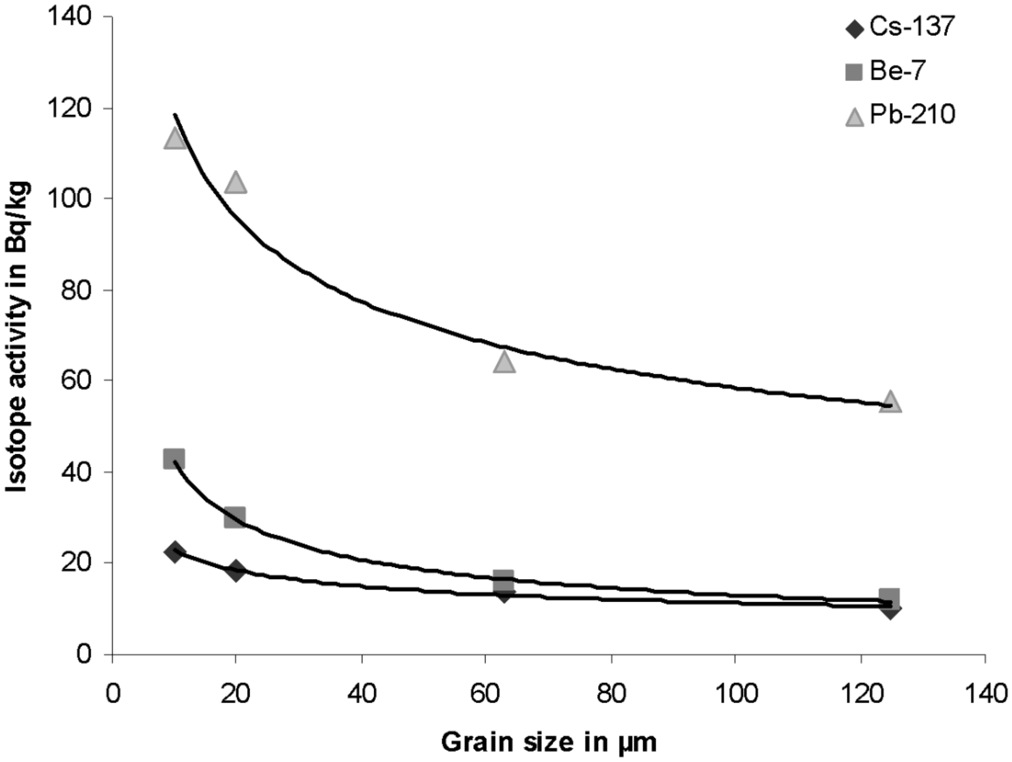

Figure 2.4: Mean radiometric activity of Be-7, Pb-210 and Cs-137 in different grain size fractions from surface erosion reference sites as power function.

2.3.3 Sediment data, measurements and load calculations

Sediment rating curves were calculated based on daily discharge and monthly SSC data from the gauging station Buren Tolgoi for the period between 1990 and 2002 (expect 1993). The correlation between discharge and SS concentration is r^2= 0.26 (n = 243). The SSC at the gauge station Buren Tolgoi show a strong correlation with SSC measurements at a second gauge station 10 km upstream of Darkhan (r^2 = 0.9; n = 243) underlining the reliability of the SSC data (Behrens, 2011). For the period 2009-2011 continuous water level data were measured at gauge station Buren Tolgoi with a pressure transducer water stage sensor (Schlumberger Micro Diver). Discharge was calculated via the velocity–area method using additional cross-sectional flow velocity profiles (n = 6) measured by an electromagnetic velocity sensor (Marsh-McBirney Flo-Mate, Hach Company, U.S.) and biweekly discharge calculations based on depth measurements from a gauging station (n = 68). The correlation between continuous water level measurements and manual controls was high (r^2 = 0,87;

n = 74). This allowed a direct calculation of the discharge based on the continuous water stage measurements.

Furthermore, an infrared backscatter turbidity sensor (LogTrans6-GPRS, UIT) was installed providing hourly turbidity data for the summer periods of 2010 and 2011. Turbidity measurements have been calibrated with total suspended sediment (TSS) concentration of 1 l grab samples filtered with 45 µm pre-weighed GC filters from summer months 2010 and 2011 (n = 275). The annual sediment budget for 2010 and 2011 was then calculated by applying the calculated correlation of TSS and discharge to the hourly measured discharge data.

For the years 1990 to 2002 the annual load was calculated based on the regression from daily discharge data and monthly SSC data using the SRC in Formula 1 (WALLING AND WEBB, 1981).

$$Load = K\sum_{i=1}^{n}\left(\frac{C_iQ_i}{n}\right) \qquad (1)$$

With: K = conversion factor to take account of period of record; Ci = instantaneous concentration associated with individual samples; Qi = instantaneous discharge at time of sampling; n = number of samples.

2.3.4 Sediment budget model

The sediment budget model SedNet has been developed and applied on large scale catchments in Australia (Prosser et al., 2001; Wilkinson et al., 2004; Wilkinson et al., 2005). Up to now only very few applications were conducted outside of Australia (Ding and Richards, 2009). The model uses spatial data layers on land use, soil properties, precipitation and topography (DEM), focusing on the spatial patterns in sediment generation and movement, rather than using temporal variable input data. SedNet allows the user to choose a daily or annual time step, depending on the input data. In SedNet the DEM derived stream network is divided with the help of linked stream node points and the catchment is divided into sub-catchments and river reaches. Each link extends between adjacent stream junctions or nodes, and has a sub-catchment that drains into the link between its upper and lower nodes. This allows the construction of the sediment budget for each section of the river network by calculating sediment delivery, transport and floodplain deposition. For this purpose SedNet calculates surface and bank erosion, as well as floodplain deposition with separate sub-models. The model calculates the sediment delivery following a load by source approach, calculating contributions from surface- riverbank and gully-erosion as separate sources (Rustomji et al., 2010). The sediment load output at each stream junction node is calculated by taking the difference between the supply of sediment from the internal sub catchment and tributary streams and the loss of sediment by deposition on the floodplain and in the channel. Surface erosion sediment supply is calculated based on RUSLE soil loss estimation (Renard, 1997). Floodplain deposition is calculated as the proportion of sediment deposited during average flooding (Bartley et al., 2004).

2.3.5 Model set up

We calculated the annual budget for the outlet gauging station Buren Tolgoi. As input data served a SRTM-DEM of the study area with 90 m x 90 m resolution, a soil map (150 x 150 m) (Dordschgotov, 1992), a land use map (1 km x 1 km) (Priess et al. 2011) and an interpolated annual rainfall distribution map (Wimmer et al., 2009). Daily precipitation and climate data from 3 climate measurement stations for the years 1986-2006 were available for the catchment. These data were used to calculate the input by surface erosion using the Revised Universal Soil Loss Equation (RUSLE). As only a fraction of all sediment eroded from hillsides reaches the stream, a hillslope sediment delivery ratio (HSDR) of typically 5 % was used to account for deposition of the generally coarser particle size fractions on hillslopes. Consequently, erosion from hillslopes is assumed to contribute mainly suspended load to river links. Since no significant lakes exist in the catchment, the only in-stream depositional processes are bed load deposition within the channel and suspended sediment deposition on the floodplain during flood events.

The sediment transport equations used in SedNet require a number of hydrological variables (mean annual flow and flow variability) which are derived by catchment wide regionalization of daily rainfall runoff records as described by Wilkinson et al., (2004). The average percent of riparian cover was calculated within a 40 m buffer on either side of the river from the land use map. The floodplain width used for the calculation was 50 m on each riverside. Since no information on the rates of bank erosion is available for the study area, these were estimated with a scaling coefficient of 0.0002, which is the default value used in SedNet (Wilkinson et al., 2004). Standard values where used to calculate gully erosion, since no definite information on gully density is available for the catchment.

2.4 Results

2.4.1 Radionuclide fingerprinting

Samples from surface erosion sites, prone to surface erosion showed variations depending on the single location with log-normal standard deviations of 16.3% for Cs-137, 4.5% for Be-7 and 1.7% for Pb-210 (Table 2.1). However, they showed higher radionuclide concentrations compared to the other measured erosion sources. This was expected as these sites have previously been exposed to atmospheric fallout. The analysis of the concentration of fallout radionuclides at reference sites revealed significant differences in the radionuclide concentrations of Pb-210 and Be-7 between spring and autumn, generally showing higher values in autumn. Differences in Cs-137 concentrations tended to be smaller (compare Table 2.1), since only small amounts of Cs-137 are currently deposited from the atmosphere. The differences of radionuclide concentrations at the sampling sites can be explained by seasonal differences in atmospheric deposition behavior. Dry deposition is the main source of radionuclides during the long winter period whereas more radionuclides are deposited due to higher values of wet deposition during summer by rainfall. More detailed information on radionuclide deposition behavior can be found in Hu et al., 2006 and Baeza et al., 2001. Samples from the gully floor showed similar behavior as hillslope samples with higher Be-7 concentration in autumn than in spring. Riverbank erosion sites showed only significant Pb-210 activity of an average of 72.9 Bq·kg-1 (±15.5, Bq·kg-1) very little Cs-137 (3.4 Bq·kg-1 (±0.6 Bq·kg-1)) concentrations and no Be-7 radionuclides within the detection limit. This is due to the behavior that riverbank erosion laterally erodes mainly deep soil horizons that are not exposed to atmospheric fallout (Figure 2.5).

Table 2.1: Average isotope concentrations in surface erosion reference sites 2010-2011 with error being the measurement accuracy ± in Bq/kg, and the standard deviation in % based on a Log-normal distribution.

Season	*n*	**Cs-137** Bq/kg	**Error**	**STD**	**Be-7** Bq/kg	**Error**	**STD**	**Pb-210** Bq/kg	**Error**	**STD**
Autumn	17	16.4	0.9	13.3	85.5	4	2.1	133.1	11.8	1.1
Spring	12	10.7	0.8	20.9	26.5	3.6	9.2	76.1	9	2.5
Total	29	13.7	0.8	16.3	55.4	3.7	4.5	105.6	9.9	1.7

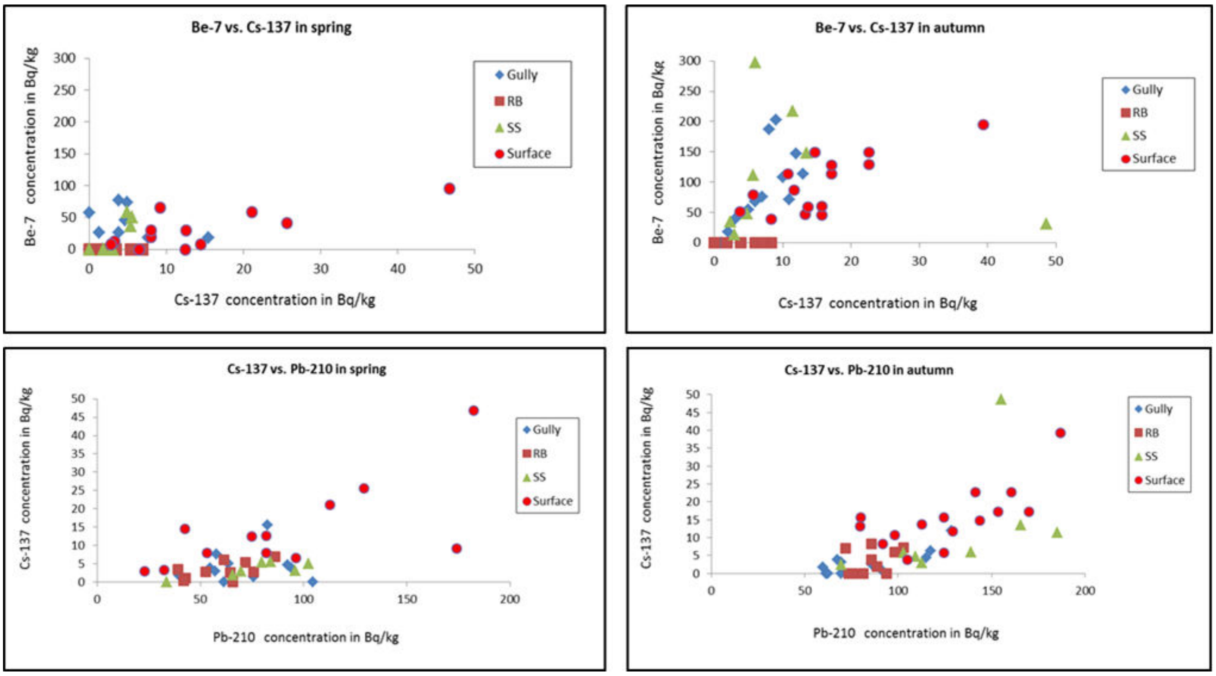

Figure 2.5: Isotope concentrations of different source groups and deposited sediments in spring and autumn.

Average radionuclide concentrations for all suspended sediment samples differed most clearly between spring and autumn. The spring samples average concentration of Pb-210 (75.9 Bq·kg-1 (±7.7 Bq·kg-1), Be-7 (below detection limit) and Cs-137 (3.4 Bq·kg-1 (±0.3 Bq·kg-1)) were low. The autumn sample concentrations of Be-7 and Cs-137 were 100.1 Bq·kg-1 (±8.4 Bq·kg-1) and 7.2 Bq·kg-1 (±0.7 Bq·kg-1), respectively. These differences can be explained by a generally increased amount of sediment input from topsoil surface erosion in summer compared to winter snowmelt erosion.

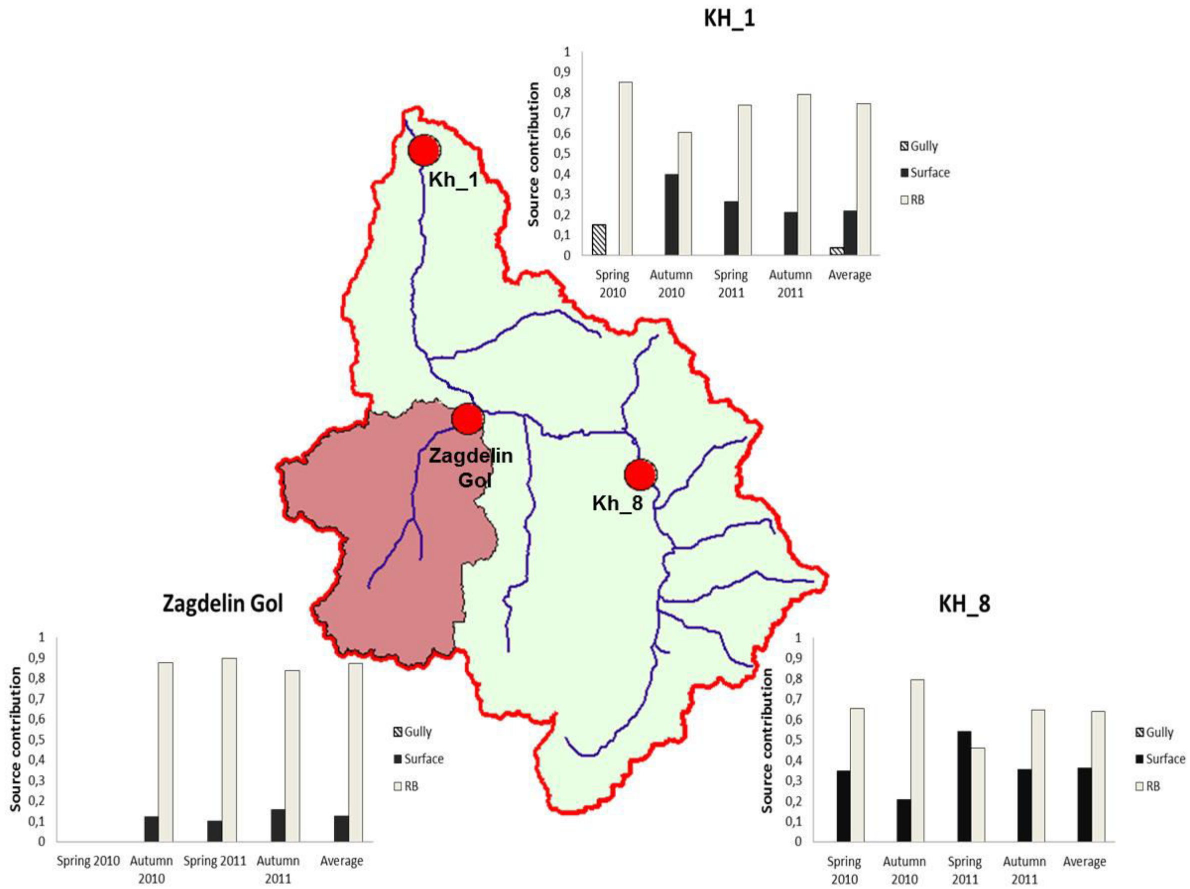

Figure 2.6: Sediment source contribution of different catchment regions as calculated with the Mixing Model for all sampling campaigns. The red catchment marks the subcatchment of tributary Zagdelin Gol, entering the main river in the lower midstream reaches.

The radionuclide concentrations of suspended sediments showed differences concerning their spatial origin within the catchment and also in respect to their seasonal behavior. In spring the mean radionuclide concentration of suspended sediments from the upstream location at Kh_8 was 91.1 Bq·kg-1 for Pb-210 (±9.5 Bq·kg-1), 47.4 Bq·kg-1 (±1.4 Bq·kg-1) for Be-7 and 5.2 Bq·kg-1 (±0.6 Bq·kg-1) for Cs-137 and in autumn for Pb-210 161.9 Bq·kg-1 (±9.5 Bq·kg-1); Be-7: 257.4 Bq·kg-1 (±6.2 Bq·kg-1); and Cs-137: 8.7 Bq·kg-1 (±0.6 Bq·kg-1). The analysis of the source contributions with help of the mixing model (Figure 2.6) showed that in the upper catchment at sampling point Kh_8 in average 63.8 % of the SS originated from riverbank erosion and 36.2 % from surface erosion. However, in spring 2011, when snowmelt occurred in combination with strong precipitation, surface erosion contributed with 53.9%. This indicates that an elevated contribution of suspended sediments from surface erosion to the sediment load was mainly associated with increased precipitation. At the catchment outlet sampling point (Kh_1) radionuclide values were 93.1 Bq·kg-1 (±9.5 Bq·kg-1) for Pb-210, 54.2 Bq·kg-1 (±0.9 Bq·kg-1) for Be-7 and 5.3 Bq·kg-1 (±0.4 Bq·kg-1) for Cs-137 in spring and of 106.1 Bq·kg-1(±7.5 Bq·kg-1) for Pb-210, 79.7 Bq·kg-1 (±3.1 Bq·kg-1) for Be-7 and 5.2 Bq·kg-1 (±0.4 Bq·kg-1) for Cs-137 in autumn. The identification of the contributing sources shows a domination of riverbank erosion to the total suspended sediment at the outlet. According to the mixing model analysis riverbank erosion contributed 74.5% to the total load, whereas only 21.7% originated from surface erosion and 3.8% from gully erosion. Since the SS at the catchment outlet is a mix of the SS from the upper sub catchments and the eroded sediment in the lower parts this indicates a strong dominance of riverbank erosion in the lower reaches.

Notable are the radionuclide concentrations in SS samples from the tributary Zagdelin Gol that showed concentrations of 65.5 Bq·kg-1 (±7.1 Bq·kg-1)for Pb-210, but no measurable Be-7 activity and only a concentration of 1.8 Bq·kg-1(±0.1 Bq·kg-1) for Cs-137. The mixing analysis confirms that on average only 12.7% of the SS originated from surface erosion. During the spring as well as during the autumn campaigns only low concentrations for Be-7 (24.0 Bq·kg-1 (±3.1 Bq·kg-1) and Cs-137 (2.7 Bq·kg-1) (±0.3 Bq·kg-1) were found in the sample from Zagdelin Gol, indicating riverbank and not surface erosion as the main SS source in 2011 for this sub catchment.

2.4.2 Discharge and Sediment transport

The total annual suspended sediment budget of the Kharaa River was calculated for the years 1990-2002 based on mean daily values of discharge and mean monthly values of suspended sediment concentration using sediment rating curves (Figure 2.7). The variability of the annual suspended load was high and varies between 3.4 kt·a^{-1} and 63.7 kt·a^{-1} (Figure 2.8). The calculated mean annual sediment load for the years 1990-2002 was 20.3 kt·a^{-1}. The winter months showed low discharges and SS transport. Hence, the months May to October constituted on average, 81.6% of the annual discharge and 89.6% of the annual SS transport. The analysis of the discharge during the summers of 2010 and 2011 clearly showed the influence of several rainfall events on the hydrograph (Figure 2.9). The discharge measurement station that was installed in 2009 showed that the daily variability of discharge is generally low, and the hydrograph peaks from single rainfall induced events were therefore also sufficiently well described in the daily measurements of the archive data used for long term calculations.

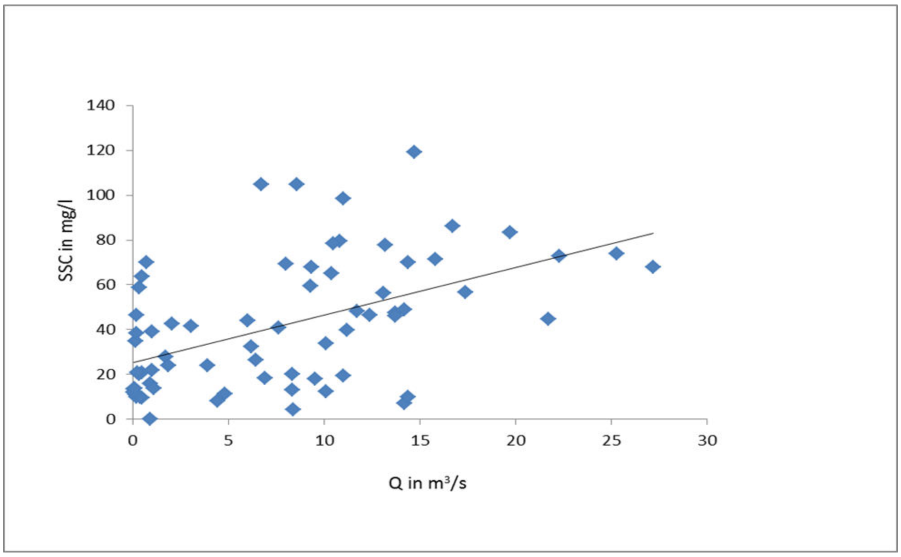

Figure 2.7: Monthly TSS concentration vs. discharge at the catchment outlet for the years 1990-2002. $y = 2.1235x + 25.32$; $R^2 = 0.2619$.

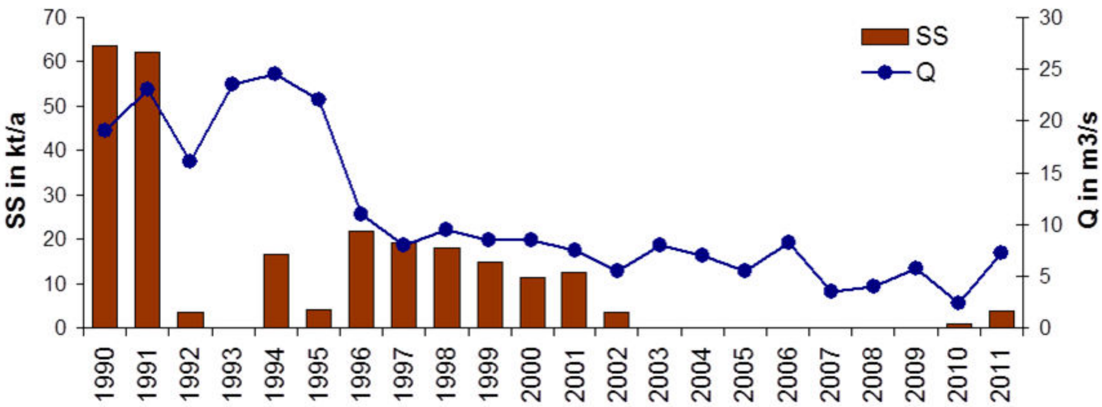

Figure 2.8: Suspended sediment load and mean annual discharge for the Kharaa 1990-2011. The sediment loads for the period 1990-2002 are based on monthly archive data, whereas the data for 2010-2011 are based on continuous and daily values. No SS load data is available for 2003-2009.

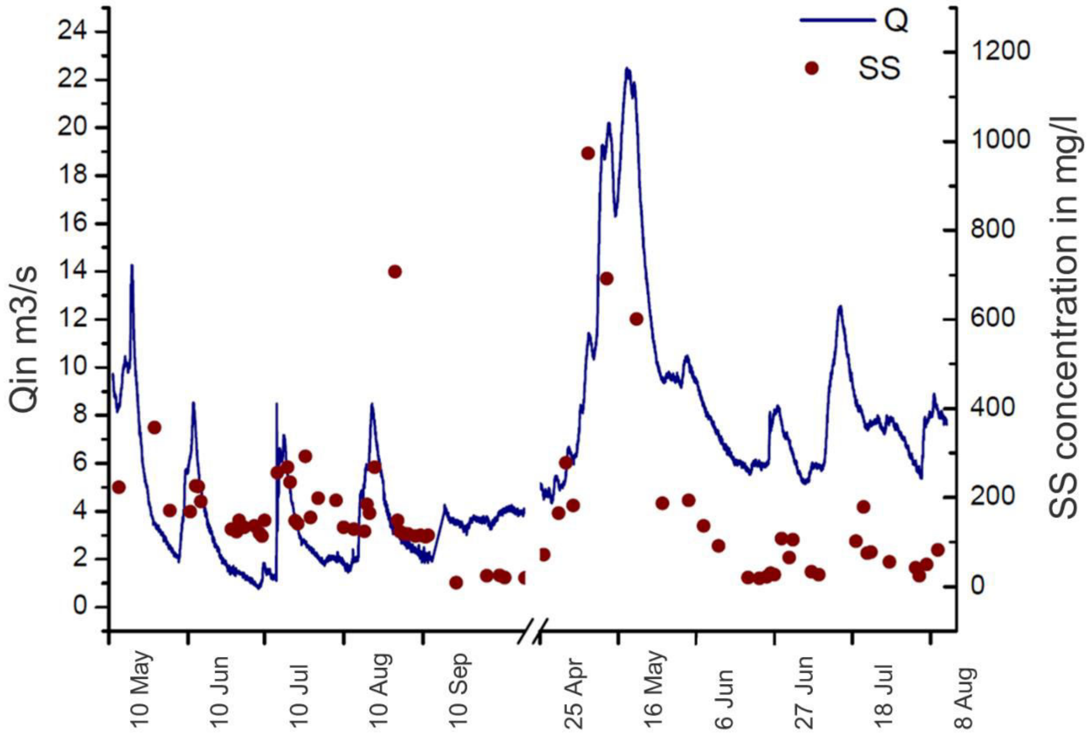

Figure 2.9: Discharge and TSS concentration of the Kharaa River at the catchment outlet for the summers 2010 – 2011 with break during the winter months.

Measurements during wintertime were not possible since the pressure transducer water stage sensor only operates at temperatures > 0°C and measurements are affected by the increased ice pressure during that time. Measurements of SS concentrations in 2010 revealed a clear influence of high discharge events on the sediment transport in the river with a mean concentration of 172 $mg \cdot l^{-1}$ and a maximum concentration of 1,140 $mg \cdot l^{-1}$. Mean daily SS load was 5.7 t with an average discharge of 3.7 $m^3 \cdot s^{-1}$ for the period from May to October 2010, and 22.1 t with an average discharge of 9.0 $m^3 \cdot s^{-1}$ during the period May to August 2011, amounting to a total SS load during these periods of 0.7 kt and 2.3 kt, respectively. Because 89.6 % of the annual load was transported from May to October the transported SS during the measured period amounts for most of the annual load during 2010/2011. The uncertainties of load calculations were assessed by comparing load calculations based on monthly and daily suspended sediment values for the years 2010 and 2011 at the catchment outlet station (Kh_1). The yielded budget of 0.7 kt (2010) and 20.6 kt (2011) during the period from May to October shows that the difference between monthly or daily based sediment budget calculations was small for the dry years in 2010 but significant for the wet year 2011.

2.4.3 Sediment budget modelling

The sediment budget was also calculated using the SedNet model for the period of 1990-2002. The catchment was subdivided into 344 subcatchments, for each of which the erosion rate of the surface areas and the SS supply to the according tributary was calculated (Figure 2.10). The calculated eroded sediment yields from surface erosion ranges from 0.0 $t \cdot ha^{-1} \cdot a^{-1}$ to 28.0 $t \cdot ha^{-1} \cdot a^{-1}$, with an average of 0.2 $t \cdot ha^{-1} \cdot a^{-1}$ throughout the catchment. Even in the more intensely agricultural areas in the subcatchment Zagdelin Gol the average sediment yield from surface erosion only amounted to 0.3 $t \cdot ha^{-1} \cdot a^{-1}$, though arable areas showed a much higher yield of 0.8 $t \cdot ha^{-1} \cdot a^{-1}$ (Table 2.2). However, the majority of these areas were not adjacent to the main river course. The majority of the total catchment area (92 %) contributed only in a range of 0.0 $t \cdot ha^{-1} \cdot a^{-1}$– 0.3 $t \cdot ha^{-1} \cdot a^{-1}$. The SS sediment supply from surface erosion to the river ranged between 0.03 $t \cdot ha^{-1} \cdot a^{-1}$– 0.09 $t \cdot ha^{-1} \cdot a^{-1}$. This corresponds well with field observations that lead to the assumption that only a very limited amount of surface eroded sediment reaches the channel, whereas most eroded sediments are deposited within the catchment. The calculation of the budget resulted in a suspended sediment export of 16.2 $kt \cdot a^{-1}$ for the whole Kharaa catchment.

Table 2.2: Soil erosion in the subcatchment Zagdelin Gol.

Landuse	Soil erosion in t/ha/a	Standard deviation	Max	Percent area
Settlement	0.01	0.03	0.09	0.1
Riparian	0.02	0.15	1.51	1.5
Forest	0.06	0.18	3.48	10.9
Potato	0.08	0.13	0.51	0.2
Open forest	0.20	0.42	9.74	4.4
Grassland	0.25	0.59	21.06	71.5
Wheat	0.79	1.27	21.06	11.4
Total	0.28	0.68	21.06	100.0

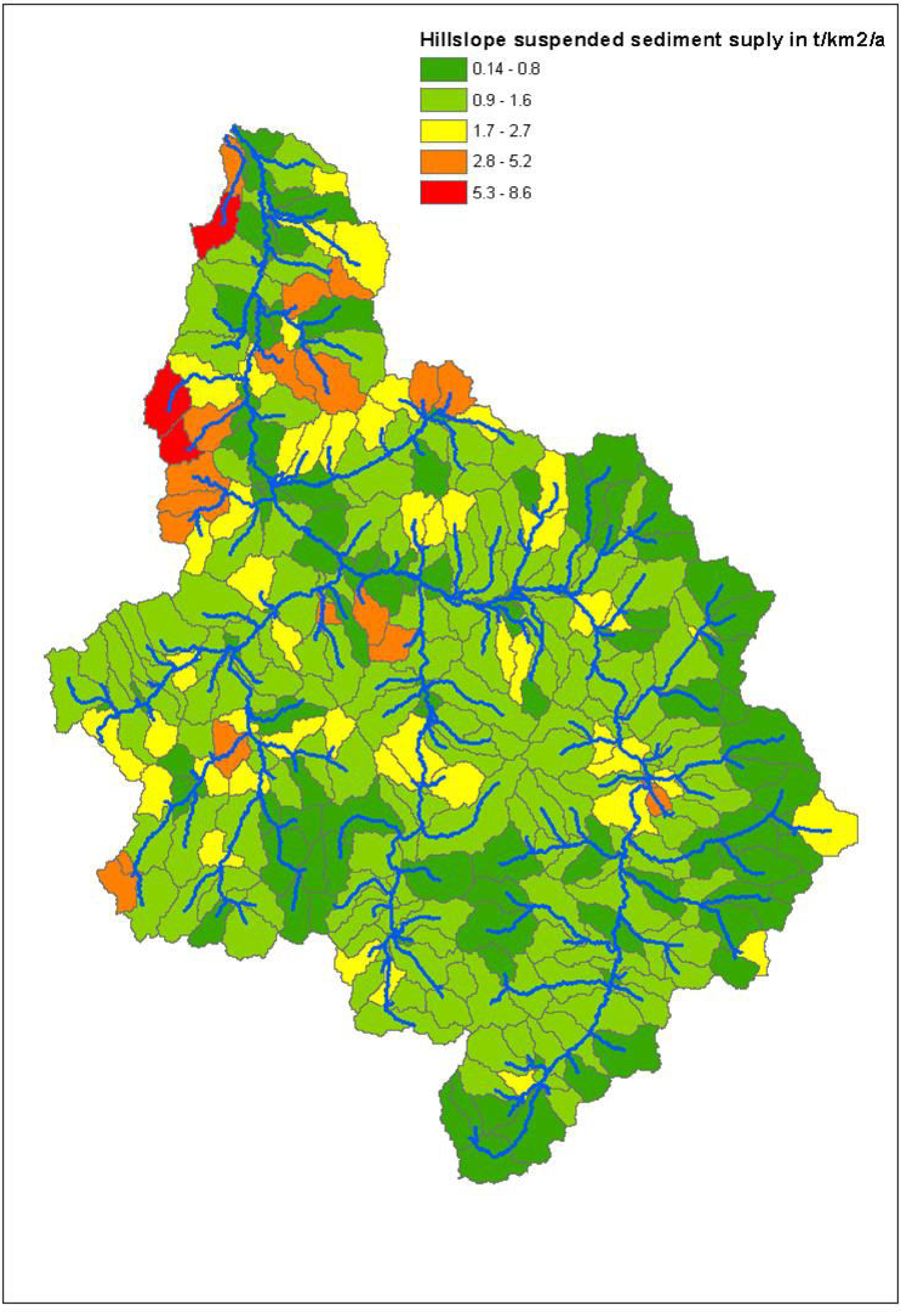

Figure 2.10: Calculated hillslope suspended sediment concentration with SedNet.

2.5 Discussion

The aim of the study was to identify the most important sources of suspended sediment in the Kharaa River catchment, as well as differences in their seasonal behavior and spatial distribution. Furthermore the sediment budget was calculated by measured discharge and sediment concentration data to assess the influence of temporal resolution of the measurements on budget calculations. Finally, the sediment budget was calculated with the SedNet model and its performance was compared with calculations based on field data.

Results from the radionuclide sediment source fingerprinting indicate that riverbank erosion is the most important sediment source in most catchment areas and that surface erosion only contributes significantly to the sediment load during rainfall induced high discharge events in summer especially in the upstream and midstream reaches. Gully erosion is of minor importance as suspended sediment load throughout the catchment and was only detected in the lower reaches in spring 2010. However, the samples represent only the conditions in 2010 and 2011 which were comparably dry years with mean discharges of only 3.7 m^3/s^{-1} respective 9.0 m^3/s^{-1} during the summer months. The erosional behavior during years with higher discharges might differ considerably. It was shown that most of the sediment from the tributary Zagdelin Gol originates not from surface erosion but riverbank erosion. This is particularly important because this subcatchment that constitutes 20 % of the total catchment is intensively used for agriculture and mining. However, the results show that the suspended sediments from this area show only very low concentrations of Be-7 (24.0 Bq·kg-1 (±3.1 Bq·kg-1)) and Cs-137 (2.7 Bq·kg-1 (±0.3 Bq·kg-1)). This indicates that the source of SS in this sub catchment is not surface erosion and agricultural land use is only of minor importance for total SS load. The same is true for downstream areas with arable land use. These areas are mostly disconnected from the fluvial system due to wide floodplains. These results have important implications for land use management and highlight the importance of riparian protection zones to reduce bank erosion. The calculated sediment budget based on daily and monthly archive values for the period 1990-2002 showed very high variations of 3.4 $kt \cdot a^{-1}$ to 63.7 $kt \cdot a^{-1}$ with a general decreasing trend. This is primarily due to the decreasing discharge during this time. The comparison of the results of the simulated average SS budget for the years 1990-2002 with the calculated long term budget from monitoring data showed that the model results of 16.2 $kt \cdot a^{-1}$ are in a similar range to the calculated long term budget of 22.3 $kt \cdot a^{-1}$. There are considerable uncertainties associated with the SS budget calculations as well as with the simulated load due to parameterization problems concerning the vegetation density, miscalculations of floodplain deposition and riverbank erosion. Also, the neglect of gullies as sediment source due to the lack of data is expected to have led to an underestimation of the delivery of subsurface sediment to the river network and affect the budget calculations. The high temporal resolution water level and SS load data from 2010/2011 showed the importance of short term high intensity rainfall events on discharge and SS load. The analysis of the daily SS concentrations in 2010 and 2011 showed that the variation of SS concentrations is very high during this time, with standard deviations between 83% and 175% of the monthly mean. This variation is not fully captured by the monthly long term archive data, which in turn may lead to an underestimation of the SS budgets for the time period 1990 – 2002. It needs to be stated that the use of only monthly data for rating the SSC – discharge relationship underlies high uncertainties and only allows for a rough estimate of the sediment budget. Sediment transport can be highly variable during short periods of increased discharge, and SSC does not always coincide with peak flow and can often be higher on the rising then the falling stage (Walling, 1977). The SSC – discharge relationship of meso-scale catchments can therefore only be described with limited accuracy by monthly measurements (Gao, 2008). The calculated SS loads from the years 2010 and 2011, which are calculated based on daily SS measurements (Figure 2.9), are not higher than calculated SS loads in earlier years with comparable yearly discharge, which have been calculated based on monthly sediment measurements (Compare Figure 2.8). This suggests that errors in SS load calculations based on monthly sediment measurements are likely to be smaller in years with comparably low discharge (years after 1995). The application of the SedNet model at a meso-scale, data scarce catchment delivered results in accordance with the budgets from measured data (20.3 kt·a-1). The comparison showed that SedNet tended to underestimate the SS output from the system (16.2 kt·a-1). This might be caused by the sensitivity of the model to several parameters that could be only provided with a certain degree of uncertainty and had to be estimated, namely floodplain width, vegetation density and riparian vegetation. Gully erosion, which is restricted to the central part of the catchment, could also not be incorporated in the model due to lack of data. For unknown parameters such as riverbank height, the model default values were applied, though river morphology differs throughout the catchment. This might lead to an underestimation of riverbank erosion in the calculations. Detailed information on the sensitivity of single input parameters and model restrictions can be found in Cogle et al., (2006). Improvements in input data quality and ground truthing for better parameterization is assumed to improve the model performance. The amount of sediment eroded by surface erosion in the catchment area calculated with SedNet was on average 0.2 t·ha-1·a-1. These values correspond to soil erosion measurements of Onda et al., 2007 and

Kato et al., 2010. They calculated erosion rates of 0.61-1.59 t·ha-1·a-1 in small experimental grassland catchments with steep slopes in Northern Mongolia. Findings of other studies on surface soil erosion in semi-arid rangelands vary largely depending on rainfall characteristics (compare e.g. Zhang et al., 2011; Creutzfeldt, 2006). Lowest values were found in cold semi-arid areas with low rainfall amounts and intensities (Wei et al., 2007). Our findings show that surface sediment erosion in the catchment can be regarded as comparatively small. A comparison of the SedNet results with the findings from nuclide fingerprinting investigations shows that the contribution from surface erosion is overestimated in our SedNet calculations. For example the contribution of sediment to the total SS load in the subcatchment Zagdelin Gol is calculated to originate to 47 % from surface erosion and 53 % from bank erosion, while the fingerprinting results show 12.7% of the SS from this catchment is originating from surface erosion. This discrepancy in the results may have its reasons in a possible underestimation of riverbank erosion in the SedNet calculations due to the use of the default values for river morphology that may not be representative for all parts of the catchment.

2.6 Conclusion

The combined sediment monitoring and modelling approach for the identification of the main drivers of SS input in the Kharaa River proved effective. Collecting data on water levels, suspended sediments and turbidity in combination with grab sampling sediment source fingerprinting analysis and the application of a large scale sediment budget model allowed to characterize sediment sources and sediment budget of the study catchment. The application of the SedNet model for the calculation of the sediment budget yielded promising results and proved its usability in the Central Asian region. The SedNet model calculated sediment yield of study catchment in the right order of magnitude. However, the model results showed differences between the prediction of the contribution of erosion sources to the fingerprinting and mixing model analysis. The results suggest that riverbank erosion is the most important process for the generation of SS in the Kharaa River and that hillslope sediment delivery was generally lower as previously expected in such a sparsely vegetated and agriculturally used semi-arid catchment. Measures to reduce suspended sediment concentration of the study river should therefore concentrate on the reestablishment of riparian vegetation to reduce riverbank erosion. Agricultural management practices for the reduction of soil erosion should be concentrated on small parts of the catchment with very high erosion risks.

3 The spatial distribution of fluvial Sediment sources

3.1 Abstract

Fine sediment inputs into river systems can be a major source of nutrients and heavy metals and have a strong impact on water quality and ecosystem functions of rivers and lakes, including those in semiarid regions. However, little is known to date about the spatial distribution of sediment sources in most large scale river basins in Central Asia. Accordingly, a sediment source fingerprinting technique was used to assess the spatial sources of fine-grained (<10 microns) sediment in the 15 000 km² Kharaa River basin in northern Mongolia. Variation in geochemical composition (e.g. in Ti, Sn, Mo, Mn, As, Sr, B, U, Ca and Sb) was used for sediment source discrimination with geochemical composite fingerprints based on Genetic Algorithm (GA)-driven Discriminant Function Analysis, the Kruskal–Wallis H-test and Principal Component Analysis. All composite fingerprints yielded a satisfactory GOF (<0.85) and were subsequently used for numerical mass balance modelling with uncertainty analysis. The contributions of the individual sub-catchment spatial sediment sources varied from 6.4% (the headwater sub-catchment of Sugnugur Gol) to 36.2% (the Kharaa II sub-catchment in the middle reaches of the study basin), generally showing higher contributions from the sub- catchments in the middle, rather than the upstream, portions of the study area. The importance of river bank erosion is shown to increase from upstream to midstream tributaries. The source tracing procedure provides results in reasonable accordance with previous findings in the study region and demonstrates the applicability and associated uncertainties of the approach for fine-grained sediment source investigation in large scale semi-arid catchments.

3.2 Introduction

Enhanced mobilization and delivery of fine-grained (<63 µm) sediment as a result of soil erosion can have a detrimental impact on water quality in rivers and lakes (Quinn and Stroud, 2002; Matthaei et al., 2010; Bilotta and Brazier, 2008; Rode et al., 2010; Collins et al., 2011). Fine sediment intrusion has also been identified as a major factor contributing to significant benthic ecosystem alterations, affecting aquatic biota such as fish and macro-invertebrates through congestion of the hyporheic interstices (Wood and Armitage, 1997; Collins et al., 2011; Kemp et al., 2011; Jones et al., 2012; Hartwig et al., 2012). Against this background a reliable understanding of the contributing sources and delivery pathways of fine-grained sediment into freshwater systems is of pivotal importance for sustainable River Basin Management Planning (RBMP) (Collins et al., 2011).

Whereas the investigation of fine-grained sediment sources in small catchments can rely on intensive measurement and monitoring procedures like erosion plot experiments, the use of profilometers or erosion pins (Collins and Walling, 2002), these techniques are impractical in large-scale catchments and become increasingly labor and resource intensive with catchment size. Equally, the information collected using erosion monitoring techniques needs to be converted into sediment source data on the basis of synthesis with additional lines of evidence including sediment transport and delivery pathways and ratios (Collins and Walling, 2004). The investigation of sediment sources in large-scale catchments has therefore frequently relied on indirect and remote investigation techniques. Remotely sensed data and information on soil, land use and climatic properties can be used to assess surface erosion. Universal Soil Loss Equation (USLE) calculations that include precipitation and topographic information have been used to delineate areas with high erosion risk (Jain and Kothyari, 2000; Lu et al., 2003). Alternatively, Theuring et al. (2013) estimated soil erosion, sediment transport and the sediment budget for the River Kharaa catchment, Mongolia, with the sediment budget model SedNet (Wilkinson et al., 2004). But, whereas these techniques help to assemble information on the potential for sediment inputs to streams from hillslope erosion, the sediment fluxes from river basins typically represent inputs from a variety of sources in addition to hillslopes, including eroding channel banks and road networks (De Rose et al., 2011; Wilkinson et al., 2005; Collins et al., 2010a)

A reliable approach to distinguishing the contribution of suspended sediment from different erosion processes in large scale catchments is the use of atmospheric fallout radionuclide (FRN) tracing techniques to estimate the proportion of surface eroded sediments, bank eroded sediments and sediments from other sources such as gullies (Zapata, 2002). By utilizing Be-7, Cs-137 and Pb-210, Theuring et al. (2013) have demonstrated that 13% and 54%, respectively, of the sampled suspended sediment originates from surface eroded sources in the Kharaa catchment, Mongolia. Spatial variations in these sediment source contributions depend on the location within the catchment (headwaters or downstream sections) and the principal causes of runoff generation (summer rainfall or snowmelt). The remaining sampled suspended sediment originates largely from river bank erosion and in some sub-catchment areas from gully erosion. The main challenge for understanding, quantifying and modelling catchment-scale fine-grained sediment budgets, especially in developing countries, is the lack of information on sediment origin, mobilization and transfer dynamics through the fluvial system (Collins et al., 2001; Walling et al., 2001).

Sediment source fingerprinting techniques have been increasingly used to assess the proportional contribution of erosion sources and to spatially delineate source areas in river catchments of varying scales and geographical locations (Owens et al.,1999; Bottrill et al., 2000; Owens et al., 2000; Russell et al., 2001; Collins and Walling, 2002; Carter et al., 2003; Motha et al., 2004; Walling et al., 2006, 2008; Foster et al., 2007; Minella et al., 2008; Hatfield et al., 2008; Hughes et al., 2009; Bird et al., 2010; Collins et al., 2013a,b). A review of the techniques and applications of sediment source fingerprinting techniques can be found for example in Walling, 2005, Davis and Fox, 2009 and Haddadchi et al., 2013. These techniques are based on identifying differences in the properties or 'fingerprints' of the potential sediment sources on the basis of statistical analysis and interpretation. A major prerequisite for this is need for a significant physico-chemical difference of the source areas (Smith and Blake, 2014). Since it was not possible to satisfactorily discriminate for example landuse, geological units or soils in the study catchment via geochemical composition, the discrimination was undertaken between subcatchments.

The key objectives of this study were therefore: i) to discriminate and apportion spatial fine-grained suspended sediment sources in the Kharaa River basin, northern Mongolia, on the basis of tributary sub-catchments, and; ii) to test the applicability of recent developments in the processing of sediment sourcing data collected for the study catchment using statistical analyses and numerical mass balance modelling with uncertainty analysis. Recent published work (Collins et al., 2010a,b, 2012, 2014) has outlined a revised source tracing procedure, that has now been applied in various forms in a number of contrasting environmental settings (e.g. Thompson et al., 2013; Stone et al. 2014). But it remains important to extend applying it also in different large drainage basins around the world to assess its utility more generally. Whilst the finite detail of sediment source tracing procedures does vary, one major attraction of the method applied here, is that it incorporates independent statistical tests to identify more than one composite signature and therefore provides a means of evaluating consistency in source predictions, using different combinations of tracers. To date, this revised statistical and numerical modelling procedure has not been applied in large drainage basins in semi-arid Asia.

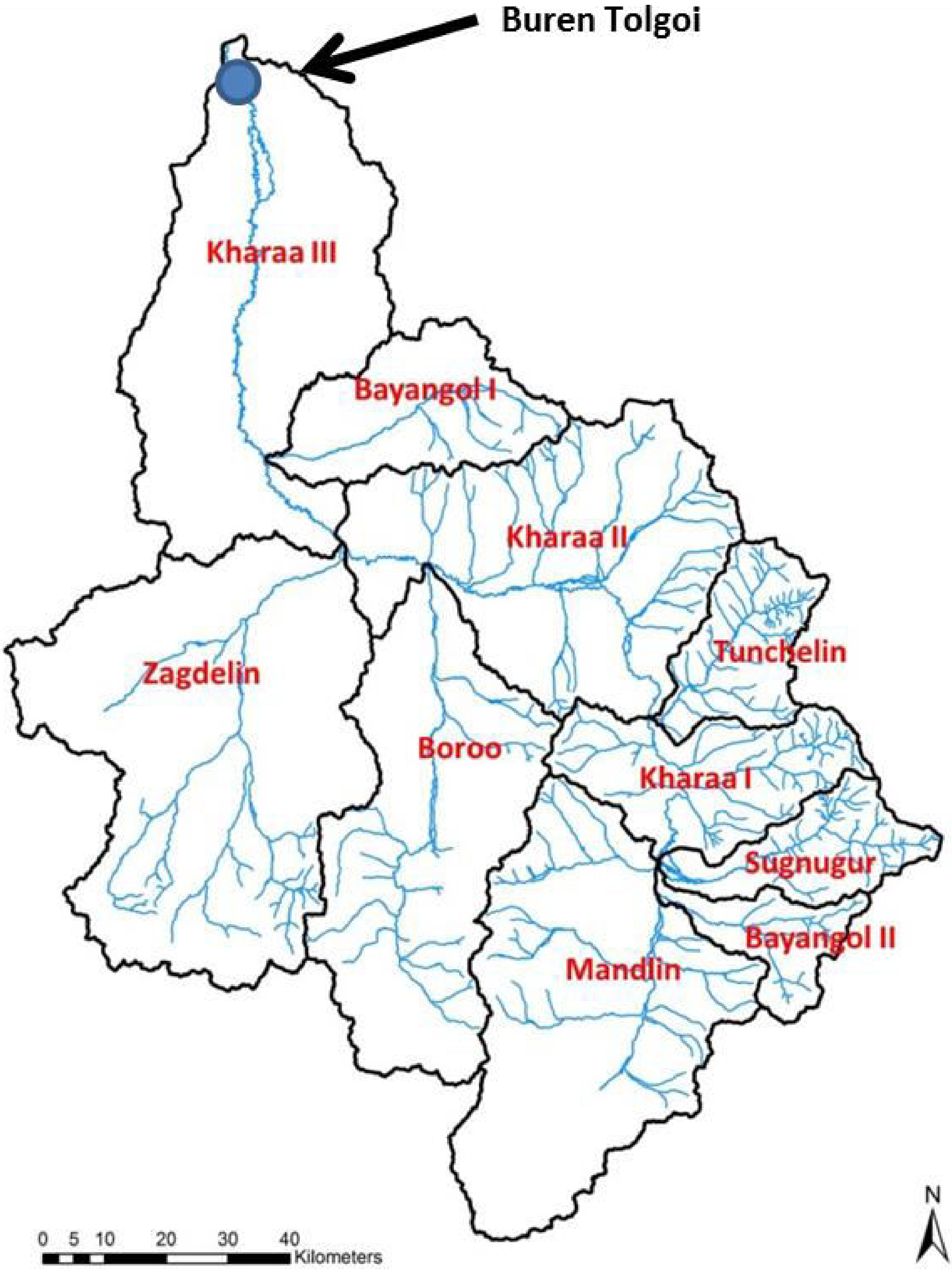

Figure 3.1: The channel network of the Kharaa River study basin, showing the sub-catchments used in the spatial sediment sourcing program.

Table 3.1: Land use (km^2) in the Kharaa River sub-catchments for 2010 based on SPOT and Landsat TM imagery. Numbers in brackets are percentage of surface area covered by the landuse type.

Sub-catchment	Urban	Water	Forest	Cropland	Grassland	Riparian	Total
Bayangol	0.8 (0)	0.0 (0)	323.8 (42)	112.5 (14)	308.2 (40)	31.2 (4)	779.7
Bayangol II	0.0 (0)	0.0 (0)	125.4 (37)	0.0 (0)	208.2 (62)	4.7 (1)	338.3
Boroo Gol	7.0 (0)	1.1 (0)	570.7 (29)	144.1 (7)	1194.0 (61)	51.7 (3)	1968.5
Kharaa I	1.2 (0)	0.0 (0)	300.5 (36)	0.0 (0)	510.6 (62)	12.6 (2)	825.0
Kharaa II	26.8 (1)	0.0 (0)	948.7 (45)	94.5 (5)	912.1 (43)	115.7 (6)	2097.8
Kharaa III	39.8 (2)	0.7 (0)	40.8 (2)	540.8 (22)	1708.3 (71)	78.0 (3)	2408.4
Mandlin Gol	10.9 (1)	0.1 (0)	342.1 (16)	40.9 (2)	1726.1 (80)	34.7 (2)	2155.1
Sugnugor Gol	0.4 (0)	0.0 (0)	300.1 (61)	2.0 (0)	143.3 (29)	48.4 (10)	494.2
Tunchelin Gol	0.0 (0)	0.0 (0)	354.3 (68)	0.0 (0)	155.4 (30)	13.7 (3)	523.4
Zagdelin Gol	10.1 (0)	1.1 (0)	806.2 (27)	527.1 (18)	1529.4 (52)	70.1 (2)	2944.0

3.3 The Kharaa River study basin

The study focused on the Kharaa River basin in northern Mongolia (Figure 3.1). The Kharaa River drains a total catchment area of approximately 15,000 km² and is one of the tributaries of the Selenga River which is the main tributary to Lake Baikal in Russia. The flow length of the main channel is 350 km. The catchment has an altitude range of 655 m a.s.l. at the catchment outlet (northwest) to 2,665 m a.s.l in the upstream reaches (southeast). Geologically, the area is primarily situated in the Hangay–Hentey basin that is dominated by old, heavily eroded sedimentary rocks of marine origin like sandstone and schists, sometimes ruptured by plutonic rocks like granite. Parts of the very southeast of the study catchment belong to the Hangay–Hentey granitoid complex consisting of plutonic and metamorphic rocks and small parts in the northwest to the Orhon-Selenga volcanic belt composed of basaltic rocks (Batulzii et al., 2005). Geomorphologically, the study catchment is divided into the high mountain regions with v-shaped valleys between 1600 and 2665 m a.s.l., the middle mountain ranges with u-shaped valleys from 1,200 to 1,600 m a.s.l., hilly regions with flat valleys and the lowland areas from 655 to 950 a.s.l. that are dominated by strath shaped valleys with wide floodplains. In terms of hydromorphology, the Kharaa River is unregulated, except for 3 minor reservoirs in the Zagdelin Gol, Bayangol and Boroo Gol sub-catchments (Figure 3.1). The study river has a heavily meandering and, sometimes braided, structure with up to 2 m high river banks exhibiting erosion, especially bordering the well-developed floodplains which, in places, are 5 km wide (Chalov et al., 2014). River bank erosion along the study river is further amplified by the lack of riparian vegetation and by the trampling and degradation resulting from livestock overgrazing and watering. In terms of soils, the mainly forested mountainous regions are dominated by shallow, little developed Phaeozems, Leptosols, and Ferrasols, whereas in the middle and downstream regions, Castanozem soils, and in floodplains Fluvisols, are the main soil types (Dordschgotov, 1992; Iderjavkhlan, 2008). Land use in the study area is dominated by grassland (60%), with forest in the mountainous regions (26%) and arable crops mainly in the lower reaches (11%) (Priess et al., 2011). The main crops include wheat and potatoes without artificial fertilization. Most of the grassland areas are used as pasture with high livestock grazing intensity especially on the floodplains (Priess et al., 2014).). According to Mongolian government Development Plans, a significant expansion of the agricultural area is planned for the study catchment (Dolgosuren et al., 2012) and, in recent years, a trend towards the increased livestock and the use of irrigation and greenhouses has also been evident (e.g. Schweitzer and Priess, 2009).

Table 3.2: Average elevation, steepness, drainage area, river network density and precipitation for the Kharaa River sub-catchments. The runoff rate and total runoff from the whole catchment is based on hydrological model estimates from Menzel et al. (2011).

	Elevation in m.a.s.l.	Slope angle	Catchment size in km^2	Network Density in m/km^2	Precipitation 2006 in mm/a	Runoff rate in l/s/km^2	Runoff in m^3/s
Bayangol I	1027.9	6.4	780	132	385	1.0	0.8
Bayangol II	1583.4	10.9	338	306	391	2.5	0.8
Boroo	1221.1	7.8	1969	95	379	0.6	1.1
Kharaa I	1398.8	11.7	825	318	400	0.9	0.7
Kharaa II	1126.3	8.3	2098	135	389	0.7	1.4
Kharaa III	866.3	4.1	2408	66	362	0.8	2.0
Mandlin	1402.3	7.9	2155	130	386	1.3	2.9
Sugnugur	1671.7	12.5	494	337	396	2.2	1.1
Tunchelin	1482.9	12.8	523	283	404	1.0	0.5
Zagdelin	1118	6.2	2944	87	369	0.9	2.6

The population in the study catchment is ~ 147,000, with more than half of the inhabitants in the city of Darkhan, near the study catchment outlet (Hofmann et al., 2011). The climate of the catchment is characterized by its situation in a transition zone between boreal cold and arid steppe climate, featuring dry, very cold winters and warm to hot summers. This leads to temperatures between +30 °C in summer and -40 °C in the winter months. During the months November – April, the river is covered by up to 1 m thick ice and thus, discharge and sediment transport is limited to a minimum. Precipitation in general is low in the region, ranging from 250 to 400 mm a-1, but varies in intensity throughout the catchment (Menzel et al., 2011; Table 3.2). The long term mean annual discharge is 12 m³/s at the Buren Tolgoi (Kh_1) catchment outlet gauging station.

Table 3.3: Average hillslope sediment supply in the Kharaa River sub-catchments based on RUSLE calculations.

	Hillslope sediment supply in t/ha/a	Total sediment supply in kt/a	Contribution to total budget in %
Bayangol	0.33	25.6	11
Bayangol II	0.16	5.3	2
Boroo Gol	0.25	49.5	21
Kharaa I	0.22	17.8	8
Kharaa II	0.24	50.6	21
Sugnugor Gol	0.15	7.5	3
Tunchelin Gol	0.17	8.9	4
Zagdelin Gol	0.24	70.6	30

In order to help interpret the estimated sediment contributions from the individual sub-catchments of the Kharaa River (Figure 3.1), information was collected on a range of factors including land use, the occurrence or absence of riparian vegetation, soil types, hillslope sediment generation by erosion, precipitation regime, channel network density and contribution to the total runoff from the study area as an entirety (Tables 3.1 – 3.3).

3.3.1 Field sampling

Five field sampling campaigns in late summer 2009, and spring and late summer in both 2010 and 2011, were conducted directly after high water flows, to collect an overall total of 900 sediment samples. These samples consisted of recently suspended solids transported in the water during runoff events, that where deposited on the riverbank as the high water-stage receded. Representative samples were obtained from three locations near the confluence of each major tributary of the Kharaa River (Figure 3.2): i) from the main channel upstream of the confluence, ii) from the tributary channel near the confluence, and iii) from the main channel downstream of the confluence. To ensure that sediment mixing had taken place, the downstream sample at each confluence was taken at least 1 km from the confluence itself. To assess the variation of sediment properties and the uncertainty due to sampling related errors, all samples were taken as quintuplicates, except during the first trial sampling campaign in

September 2009. It was assumed that the samples of deposited sediment provided a means of establishing the signatures of the individual tributary sub-catchments (cf. Walling et al., 1999; Collins et al., 2010c).

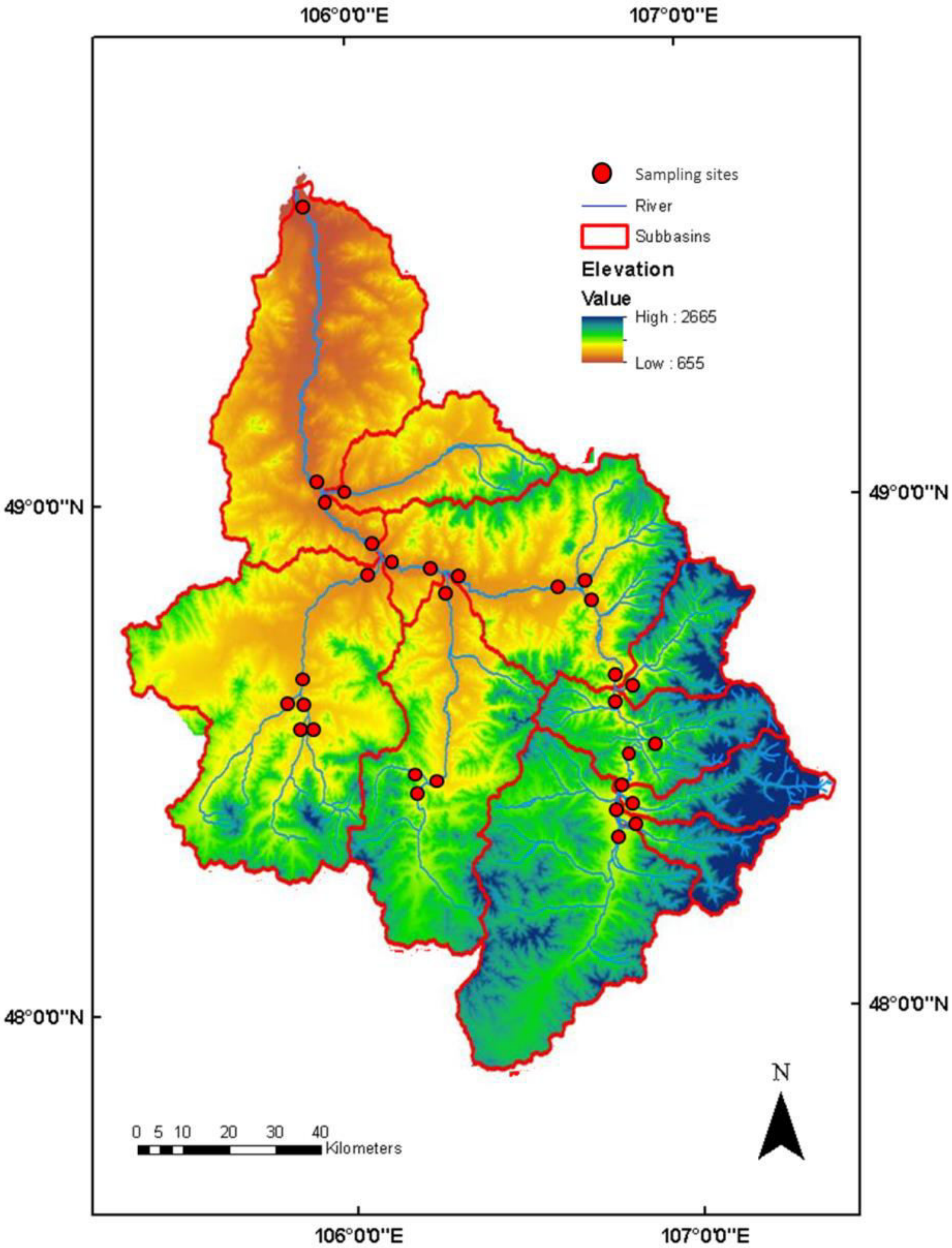

Figure 3.2: Distribution of sampling points.

3.3.2 Laboratory analyses

All samples where oven dried at 75 °C and dry sieved to extract the <63 µm fraction. Thereafter, the <10 µm fraction was extracted using wet sieving. The wet sieved sub-samples were centrifuged and oven dried at 75 °C. Only the <10 µm fraction was used for further laboratory analysis to minimize particle size contrasts between the samples and the associated need for a particle size correction factor (Wallbrink et al., 2003; Wilkinson et al., 2013), as well as the effects of connectivity and sediment cascades (Koiter et al., 2013). Theuring et al. (2013) recently showed that the grain size distribution of suspended sediment is similar to that measured for the sampled deposited material. The <10 µm fraction accounted for 15–20% of the total sample mass in both cases. Similarities between the particle size of samples used in sediment fingerprinting studies, albeit in those cases, soil and sediment samples, rather than the latter alone, have been reported by other studies (e.g. Evrard et al., 2011, 2013). All <10 µm sub-samples were microwave digested using nitric and hydrochloric acid (Allen, 1989) and subsequently analyzed for the elements Ag, Al, As, B, Ba, Be, Cd, Co, Cr, Cu, Fe, Hg, Li, Mn, Mo, Ni, Pb, Rb, Sb, Se, Sn, Sr, Ti, Tl, U, V, W, and Zn using an Inductively Coupled Plasma Mass Spectrometer (ICP-MS). It needs to be taken into account that using nitric and hydrochloric acid digestion may be not total and there might remain undissolved residues from the silicate phase that could be only digested with hydrofluoric acid. The concentration of single elements in the silicate fraction varies from one sample to the next and could in this case be underestimated. A summary of the results of the laboratory analyses for potential geochemical fingerprint properties is presented in Table 3.4.

3.4 Statistical discrimination of potential sub-catchment spatial sediment sources

The statistical procedure reported by Collins et al. (2012) was used to identify statistically robust composite signatures for discriminating the individual tributary sub-catchments of the Kharaa River (Figure 3.1). Prior to the selection of appropriate metrics for fingerprint property parameter location and scale, the Lilliefors test (Lilliefors, 1969) was applied to test for the normality of the fingerprint properties in the dataset (Table 3.5). The Lilliefors test is a two-sided goodness-of-fit procedure in situations where the fully specified null population for each fingerprint property is unknown, thereby requiring the estimation of its parameters using the significance of comparison at $p=\leq 0.05$.

Table 3.4: Average element concentrations in mg/kg, at the sampling points for all five sampling campaigns (n for each sub-catchment = 26).

	Catchment outlet		Kharaa I		Sugnugur		Bayangol II		Bayangol		Zagdelin Gol		Boroo Gol		Kharaa II		Tunchelin Gol	
	Mean	Coefficient of variation	Mean	Coefficient of variation	Mean	Coefficient of variation	Mean	Coefficient of variation	Mean	Coefficient of variation	Mean	Coefficient of variation	Mean	Coefficient of variation	Mean	Coefficient of variation	Mean	Coefficient of variation
Al	51,868.3	0.12	46,133.3	0.09	45,213.3	0.18	43,380.0	0.01	57,453.3	0.15	47,293.3	0.04	49,440.0	0.13	49,293.3	0.17	47,180.0	0.11
As	13.5	0.02	23.6	0.45	21.1	0.49	20.4	0.73	10.6	0.10	11.7	0.33	16.4	0.13	13.3	0.13	20.9	0.17
B	26.5	0.27	10.8		22.0	0.64	13.7	0.03	28.4	0.43	35.1	0.28	35.3	0.19	7.8		28.1	0.20
Ba	335.9	0.13	289.1	0.14	210.4	0.15	315.7	0.25	324.3	0.05	289.6	0.15	280.1	0.05	280.4	0.11	313.5	0.14
Ca	23,061.5	0.09	11,687.2	0.02	10,408.9	0.47	46,974.3	0.69	31,304.0	0.40	42,917.3	0.35	41,418.8	0.54	30,636.9	0.18	9462.3	0.26
Cd	0.6	0.16	0.5	0.10	0.7	0.31	0.5	0.20	0.6	0.13	0.5	0.03	0.5	0.09	0.5	0.26	0.7	0.32
Co	18.9	0.06	13.6	0.00	11.6	0.11	12.7	0.00	20.3	0.01	17.3	0.08	16.8	0.04	21.6	0.17	17.8	0.09
Cr	81.7	0.23	56.7	0.15	52.2	0.37	49.3	0.11	86.9	0.15	74.5	0.05	77.3	0.13	84.0	0.26	70.7	0.19
Cu	44.6	0.15	46.4	0.07	38.2	0.19	30.8	0.03	44.7	0.08	42.0	0.18	39.8	0.02	53.4	0.17	49.1	0.05
Fe	49,085.0	0.08	37,140.0	0.08	39,630.0	0.01	36,930.0	0.16	53,990.0	0.01	47,780.0	0.12	43,810.0	0.07	47,850.0	0.02	46,090.0	0.00
K	11,939.1	0.10	10,744.4	0.15	9898.9	0.11	11,659.5	0.15	11,967.1	0.08	11,530.1	0.09	11,458.5	0.17	10,485.9	0.11	10,585.7	0.33
Li	47.4	0.17	46.0	0.00	62.5	0.17	42.8	0.22	52.2	0.10	48.2	0.11	48.4	0.08	42.6	0.18	45.4	0.11
Mg	13,705.7	0.02	10,233.1	0.06	9130.0	0.13	11,314.1	0.13	15,204.5	0.02	14,536.0	0.11	13,385.1	0.14	14,354.1	0.03	11,195.5	0.18
Mn	1793.0	0.42	1123.5	0.14	1120.7	0.04	1444.7	0.14	1026.8	0.31	909.4	0.11	1252.8	0.67	1592.7	0.22	1740.0	0.32
Mo	0.9	0.13	0.9	0.14	1.6	0.40	0.7	0.30	0.7	0.14	1.2	0.11	0.7	0.43	0.6	0.23	0.9	0.24
Na	599.3	0.02	382.5	0.04	415.4	0.07	382.1	0.01	540.4	0.09	333.0		522.1	0.27	453.6	0.10	393.2	0.18
Ni	43.8	0.14	30.2	0.08	25.0	0.31	27.0	0.13	49.0	0.06	43.2	0.16	40.8	0.01	49.1	0.19	38.6	0.12
Pb	20.8	0.11	16.2	0.08	15.7	0.08	16.9	0.04	19.1	0.20	24.5	0.38	17.7	0.23	22.2	0.17	24.0	0.09
Rb	85.2	0.15	72.6	0.13	93.2	0.36	69.8	0.16	100.6	0.29	71.2	0.03	89.9	0.22	78.1	0.14	75.5	0.13
Sb	0.5	0.87	0.4	0.94	0.5	0.89	0.8	0.08	0.4	0.88	0.9	0.10	0.7	0.10	1.0	0.46	1.5	0.36
Sn	3.2	0.16	2.9	0.00	4.0	0.11	2.7	0.41	3.0	0.03	1.8	0.88	2.5	0.16	2.8	0.17	2.6	0.15
Sr	183.3	0.08	162.9	0.12	108.1	0.39	387.5	0.49	166.3	0.33	255.1	0.35	229.0	0.29	137.0	0.04	204.1	0.51
Ti	3469.7	0.16	4062.0	0.05	3436.0	0.17	2400.9	0.51	3248.7	0.24	3172.7	0.17	3123.3	0.07	3738.7	0.15	3408.0	0.53
U	3.8	0.24	8.0	0.13	27.9	0.39	6.8	1.04	5.2	0.21	6.5	0.25	3.9	0.07	2.3	0.14	4.5	0.45
V	112.7	0.17	104.9	0.16	97.2	0.29	83.7	0.11	125.4	0.20	101.8	0.09	107.8	0.16	122.9	0.23	130.5	0.33
Zn	135.9	0.08	125.3	0.20	136.5	0.27	111.4	0.09	138.5	0.06	124.7	0.07	129.1	0.17	126.4	0.11	131.8	0.04

For the statistical verification of composite signatures for discriminating the sub-catchment spatial sediment sources, we used a combination of the Kruskal–Wallis H-test (KW), Principal Component Analysis (PCA) and genetic algorithm-driven Discriminant Function Analysis (GA-DFA) (Collins et al., 2012). The Kruskal–Wallis H-test (Gibbons, 1985) was applied to examine the ability of individual geochemical elements to distinguish the overbank sediment samples, collected to characterize the eight individual sub-catchments (Table 3.6). Alternatively, PCA was also applied to the individual fingerprint properties (Table 3.7). This test converts observations of potentially correlated variables into uncorrelated principal components, using orthogonal transformation (Jolliffe, 2002). By ranking the Chi-square and p-values associated with each individual property passing either the Kruskal–Wallis H-test or the PCA (Tables 3.6 and 3.7), optimal composite fingerprints were devised on the basis of these independent statistical tests. The highest ranked properties identified, using either the Kruskal-Wallis H-test or PCA were passed through the GA-DFA to assess the discriminatory power of individual properties and the composite signatures (Table 3.8).

Table 3.5: The results of the Lilliefors test for Normality, using all elements above detection limit.

Property	P value	Property	P value
Ba	0.500	Co	0.072
Li	0.161	Cu	0.413
Rb	0.001*	Cr	0.003*
Sr	0.001*	Fe	0.070
U	0.001*	Mn	0.001*
Ca	0.001*	Ni	0.027*
K	0.500	Pb	0.004*
Mg	0.001*	Sn	0.003*
Na	0.006*	Zn	0.001*
B	0.021*	Mo	0.001*
Al	0.114	Ti	0.005*
As	0.001*	V	0.402
Cd	0.002*		

Table 3.6: The results of the Kruskal-Wallis-H-test.

Property	H- value	P-value	Property	H- value	P-value
Rb	27.6	0	Cu	79	0
K	32.4	0	Pb	82.2	0
B	34.4	0	Cr	91.6	0
Al	47.2	0	Co	106.5	0
Ti	49.1	0	As	112.7	0
Cd	51.3	0	Mn	112.9	0
Zn	52.8	0	Ca	114	0
Ba	53.5	0	Mo	116.7	0
Li	59.8	0	Fe	117.7	0
Sn	60.5	0	Ni	119.7	0
V	67.2	0	U	120	0
Sr	77.6	0	Mg	124.1	0
Na	78.8	0			

Table 3.7: Highest ranked property loadings using PCA.

Property	PC[a]	Property	PC[b]
Ca	0.994	Fe	0.764
Mg	0.074	Al	0.607
Fe	0.070	Mg	0.201
K	0.027	K	0.075
Ti	0.014	Ca	0.042
Al	0.009	Ti	0.006
Mn	0.005	Na	0.005
Sr	0.003	Ba	0.003
Na	0.002	Mn	0.002
Ba	0.001	Sr	0.002
As	0.000	V	0.001
Cu	0.000	Cr	0.001
Li	0.000	Ni	0.001
Rb	0.000	Rb	0.001
U	0.000	As	0.000
Zn	0.000	U	0.000
B	0.000	Zn	0.000
V	0.000	Cu	0.000
Ni	0.000	Pb	0.000
Cr	0.000	Co	0.000
Sn	0.000	B	0.000
Pb	0.000	Li	0.000
Mo	0.000	Sn	0.000
Co	0.000	Mo	0.000
Cd	0.000	Cd	0.000
VE%	81.0	VE%	12.1

VE% variance explained.

a Principal component 1.

b Principal component 2.

Table 3.8: The final composite signatures selected using the KW-H test and PCA.

KW H-test			PCA		
Property	%[1]	TDW[2]	Property	%[1]	TDW[2]
As	36	1.56	Al	24	1.19
Ca	34	1.46	As	36	1.77
Cd	23	1.00	Ba	23	1.14
Co	32	1.37	Ca	34	1.65
Cu	35	1.49	Fe	33	1.60
Fe	33	1.41	K	20	1.00
Li	26	1.13	Mg	41	2.00
Mg	41	1.77	Mn	35	1.73
Mn	35	1.52	Na	25	1.24
Mo	35	1.52	Sr	39	1.93
Ni	37	1.59	Ti	24	1.19
Pb	24	1.05	V	27	1.33
U	50	2.16	Total[3]	86	
Total[3]	96				

a % Spatial sediment source samples classified correctly by individual properties.

b Tracer discriminatory weighting used in the mass balance modelling.

c % Spatial sediment source samples classified correctly by composite signature.

Table 3.9: The results of the GA-DFA.

GA-DFA 1			GA-DFA 2			GA-DFA 3		
Property	%[1]	TDW[2]	Property	%[1]	TDW[2]	Property	%[1]	TDW[2]
As	36	1.76	Al	24	1.19	As	36	1.76
B	26	1.27	B	26	1.27	B	26	1.27
Ba	23	1.14	Ba	23	1.14	Cd	23	1.13
Cd	23	1.13	Ca	34	1.64	Cr	32	1.54
Cr	32	1.54	Cd	23	1.13	Cu	35	1.68
Cu	35	1.68	Cr	32	1.54	Fe	33	1.59
Fe	33	1.59	Cu	35	1.68	Mg	41	1.99
Mg	41	1.99	Fe	33	1.59	Mn	35	1.72
Mn	35	1.72	Mn	35	1.72	Mo	35	1.71
Mo	35	1.71	Mo	35	1.71	Na	25	1.23
Rb	21	1.00	Ni	37	1.79	Rb	21	1.00
U	50	2.44	Rb	21	1.00	Sr	39	1.92
Zn	22	1.07	Zn	22	1.07	U	50	2.44
Total[3]	98		Total[3]	98		Zn	22	1.07
						Total[3]	98	

1 % Spatial sediment source samples classified correctly by individual properties.

2 Tracer discriminatory weighting used in the mass balance modelling.

3 % Spatial sediment source samples classified correctly by composite signature.

The GA-DFA was performed with 200 repeat iterations, using the minimization of Wilks' lambda as a stepwise selection algorithm and a probability value for parameter entry of 0.05 (Collins et al., 2012). Three optimum composite signatures were identified using the GA-DFA (Table 3.9). Each of the three GA-DFA-based composite signatures (Table 3.9) classified 98% of the tributary sub-catchment spatial sediment source samples correctly, compared with classificatory efficiencies of 96% (KW-H) and 86% (PCA) for the other independent statistical tests see (Table 3.8).

The relative frequency-weighted average median (Collins et al., 2012) source contributions generated, using the five signatures, were averaged in conjunction with a weighting combining the discriminatory power of the composite fingerprints and their corresponding goodness-of-fit (GOF). This approach generated the final estimates of the overall relative frequency-weighted average median source contributions. The Monte Carlo framework comprised both local and global (genetic algorithm; GA) optimization of the repeat solutions generated using the un-mixing model (Collins et al., 2010b, 2012).

3.5 Numerical mass balance modelling for apportioning sub-catchment spatial sediment source contributions

The relative contributions of the eight tributary sub-catchments of the Kharaa River to the sampled suspended sediment load at the overall catchment outlet at Buren Tolgoi (Figure 3.1) were quantified using the mass balance mixing model described by Collins et al. (2010a,b). The model uses a set of linear equations for each composite signature by minimizing the sum of squares of the weighted relative errors:

$$\sum_{i=1}^{n}\left\{\left(\left(c_i-\left(\sum_{s=1}^{m}P_s S_{si} SVsi\right)\right)/c_i\right\}^2 W_i$$

where: Ci = deviate median concentration of fingerprint property (i) in deposited sediment sample; Ps = the optimised percentage contribution from source category (s); Ssi = deviate median concentration of fingerprint property (i) in spatial sediment source category (s); SVsi = weighting representing the within-source variation of fingerprint property (i) in spatial source category (s); Wi = tracer discriminatory weighting; n = number of fingerprint properties comprising the optimum composite fingerprint; m = number of tributary sub-catchment spatial sediment source categories.

Table 3.10: The average coefficient of variation of all elements for each sub-catchment in comparison with sub-catchment size.

	Catchment outlet	Zagdelin Gol	Kharaa II	Boroo Gol	Kharaa I	Bayangol	Tunchelin Gol	Sugnugur	Bayangol II
Average Variation	0.17	0.18	0.16	0.18	0.14	0.18	0.22	0.27	0.24
Catchment size (km^2)	14534	2944	2098	1969	825	780	523	494	338

Within-source variation weighting is incorporated in the mixing model to ensure that those properties with smaller variance exert more influence on the mathematical solutions generated. Since the inverse of the standard deviation generated disproportionately large weightings for some tracers, the inverse of the coefficient of variation was used as an alternative basis for the calculations. The tracer discriminatory power weighting is based on the relative outputs of the KW-H, PCA and GA-DFA, for the individual properties comprising each composite fingerprint (Collins et al., 2010a). Following this approach, the discriminatory power of the tracer providing the lowest discrimination of the sediment source samples was assigned a weighting of 1.0. The weighting of the other tracers was then calculated using the ratio of their discriminatory efficiency to that of the weakest property in any specific composite signature. Where weightings differ greatly in magnitude, the data can be normalized.

The uncertainties in characterizing the input spatial sediment source median tracer values for the mixing model on the basis of relatively few deposited sediment samples were quantified, explicitly using the scaling of the parameter distributions based on Qn (Rousseeuw and Croux, 1993) and a Monte Carlo approach. Stratified repeat (n = 5000) mixing model iterations using Latin Hypercube Sampling generated deviate predicted median relative contributions from each individual tributary sub-catchment spatial sediment source. The pdfs generated on this basis comprised feasible model solutions which were used to estimate relative frequency-weighted average median inputs (R) from the individual spatial sediment sources, viz.:

$$R = \sum_{i=1}^{n} v_i F_i$$

where n is the number of intervals for the predicted deviate relative contribution, scaled between 0 and 1; and v and F are the mid-value and the relative frequency for the ith interval, respectively (cf. Collins et al., 2012).

The use of the frequency-weighted approach provided a convenient means of summarizing the average median spatial sediment source contributions on the basis of a single number, whilst still taking into account the full range of the predicted feasible solutions generated using the Monte Carlo analysis. The convergence of the mixing model solutions and their reproducibility was interrogated by calculating 95% confidence limits about the average median inputs, using 10 sets of 5000 repeat iterations. The Monte Carlo framework included both local and global genetic algorithm (GA) optimization of the mixing model repeat solutions (Collins et al., 2010b, 2012, 2013b). Genetic algorithms evolve a population of candidate solutions using iterative application of the evolutionary processes of selection, crossover and mutation (Goldberg, 1989; Savic et al., 2011). Repeat mixing model iteration creates a generation of individual solutions that, on average, are fitter than the previous ones, as measured by the minimization of the objective function. GA-driven mass balance modelling was initiated with the output from the non-GA (local) optimization as the starting point (Collins et al., 2010b).

To assess the results of the numerical mass balance modelling of spatial sediment source contributions, we compared the results with the calculated surface erosion sediment supply and sediment delivery in the Kharaa River basin estimated using the sediment budget model SedNet (Theuring et al., 2013). The SedNet model uses spatial data layers on land use, soil properties, precipitation and topography (DEM), focusing on the spatial patterns in sediment generation and movement rather than using temporally variable input data (Prosser et al., 2001; Wilkinson et al., 2004; Wilkinson et al., 2005; Cogle et al., 2006). Surface erosion sediment supply is calculated on the basis of the RUSLE soil loss estimation (Renard, 1997). Floodplain deposition is calculated as the proportion of sediment deposited during average flooding (Bartley et al., 2004). The model calculates sediment delivery following a load by source approach, calculating contributions from surface, river bank and gully erosion as separate sources (Rustomji et al., 2008, 2010). The sediment load output at each stream junction node is calculated by taking the difference between the supply of sediment from the internal sub-catchment and tributary streams and the loss of sediment by deposition on the floodplain and in the river channel.

3.6 Results and discussion

To assess the range of concentrations of each property, the coefficient of variation was calculated (Table 3.4). The average coefficient of variation of the property concentrations per sub-catchment ranged from 0 to 1.04 and the overall average was 0.2. This suggests that the variability in source characteristics was generally low, reflecting the fact that the deposited samples collected to characterize each sub-catchment spatial sediment source would be expected to be well-mixed and representative of the average concentrations of sediment-associated elements, as a result of natural sediment delivery processes (cf. Walling et al., 1999). A comparison of the overall coefficient of variation with sub-catchment size (Table 3.10) suggests that the average variability of elements within the deposited sediment samples is higher for smaller sub-catchments. Again, this most likely reflects the fact that the ‘averaging’ of chemical constituents by intermediate storage and remobilization processes is likely to be more pronounced at larger, rather than smaller, scales (cf. Klages and Hsieh, 1975; Johnsson and Meade, 1990; Collins et al., 1998). The elements with the highest average variation are Ti, Sn, Mo, Mn, As, Sr, B, U, Ca and Sb (Figure 3.3). No distinction was made in this study concerning the conservancy of the elements, and all elements were used for statistical analysis.

Table 3.11 presents the GOF of the mixing model Monte Carlo analysis using each of the five composite signatures. The relative frequency-weighted average median spatial sediment source contributions generated using the five signatures (Table 3.12) were averaged in conjunction with a weighting (Collins et al., 2014) combining the discriminatory power of the fingerprints (Tables 3.8 and 3.9) and their corresponding goodness-of-fit (GOF) (Table 3.11) to calculate the final estimates of the median spatial source contributions (Table 3.12). None of the composite signatures yielded an unsatisfactory GOF (<0.85) (Table 3.11) and therefore no signature had to be excluded from the final calculations of median spatial source contributions (Table 3.12). The GOF and median absolute fit calculated as the median objective function value generated by the Monte Carlo mixing model iterations for each composite signature were strongly correlated ($r^2 = 0.96$). It is important to consider both performance indicators when using mixing models, since high GOF values are not necessarily indicative of satisfactory absolute fits, especially since the latter are influenced by the structure of the objective function. In this study, the median absolute fits were ~0.8.

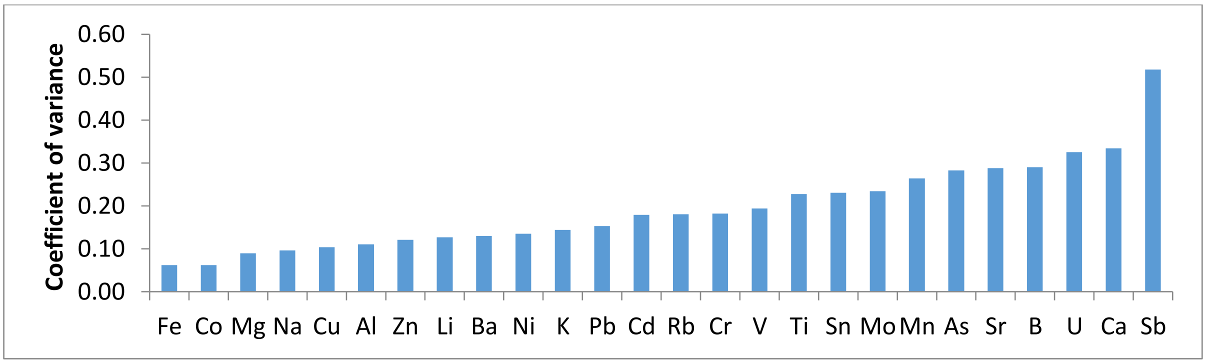

Figure 3.3: Estimates of the average coefficient of variation for individual fingerprint properties for all sub-catchments of the Kharaa River.

The median spatial sediment source contributions, based on the different composite signatures (Table 3.12), ranged between 6 % and 36%. Table 3.13 presents a summary of the full uncertainty ranges for the mixing model predictions. These uncertainties ranged from 0 - 100% depending on the sub-catchment and the composite signature in question. Interestingly, the highest uncertainties were associated with the downstream sub-catchments, which are also identified as the main contributors of fine-grained sediment. When interpreting the data in Tables 3.12 and 3.13, it is instructive to recognize that a high relative contribution may not necessarily reflect a high input in terms of the mass of sediment, in circumstances where the typical annual sediment load is low. The full uncertainty ranges in Table 3.13 underscore the need to use relative frequency-weighted estimates of source contributions to help make the mixing model outputs easier to interpret by catchment stakeholders and managers (cf. Collins et al., 2014). The spatial sediment source contributions vary from 6% in the case of the headwater sub-catchment of Sugnugur Gol to 36% from the Kharaa II sub-catchment in the midstream portions of the study basin. Generally speaking, the relative contributions are higher from sub-catchments in the middle rather than the upper reaches of the Kharaa River basin.

Table 3.11: The GOF using each optimum composite fingerprint in the mass balance mixing model to predict the measured values in the sampled deposited sediment collected from the overall study outlet of the Kharaa River catchment.

Signature	Goodness-of-fit
KW-H	0.971
PCA	0.981
GA-DFA 1	0.972
GA-DFA 2	0.983
GA-DFA 3	0.971

The findings suggest that the more intensively farmed sub-catchments in the midstream regions are the major sources of fine-grained (<10 micron) sediment. There is an agreement between the estimated relative contributions from the individual sub-catchments and corresponding estimated hillslope sediment supply based on the RUSLE calculations (Figure 3.4). Main exceptions are the Zagdelin Gol and Boroo Gol sub-catchments which, although exhibiting high hillslope sediment supply, are not among the main suspended sediment sources in the catchment. The reasons for this lie in the specific characteristics of these subcatchments, discussed below. In combination, the Bayangol (22%) and Kharaa II (36%) sub-catchments are estimated to generate 58% of the total deposited sediment sampled at the outlet of the Kharaa River. Whereas land use in the Kharaa II sub-catchment is dominated by intensive grazing and in addition this sub-catchment contains the second largest city of the study area (Zuunkharaa), sediment generation in the Bayangol sub-catchment is strongly impacted by intensive coal mining in its upstream area. However, no distinct increase in concentrations of heavy metals and elements that could be expected from coal mining activities (As, Cd, Cu, Pb, Hg and others) could be detected for the exported suspended sediment from this catchment (compare Table 3.4). The upstream sub-catchments are characterized by densely forested headwaters from which relative sediment efflux could be expected to be lower due to improved protection of surface soils by the tree canopy. Although these forested areas dominate the total runoff of the Kharaa River they are estimated to contribute little to the deposited sediment sampled at the outlet of the Kharaa River; (Kharaa I (7.6%), Bayangol II (7.8%) and Sugnugur Gol (6.4%). Because these catchments are mainly forested, hillslope erosion is low. Furthermore the riparian vegetation in these areas is dense which limits sediment mobilization from river bank erosion. Rather surprisingly, the mountainous Tunchelin Gol sub-catchment was estimated to contribute 18% of the sampled deposited sediment. Although most of this sub-catchment has similar characteristics to the other forested upstream sub-catchments, an important exception is the settlement of Tunchel close to the sub-catchment outlet which is the regional center for logging. Furthermore, recent studies have shown that forest fires strongly impact natural forest vegetation cover in this sub-catchment (Schweitzer and Pries, 2010). The incremental combination of forest fires and logging (cf. Silins et al., 2009) is therefore most likely to be responsible for the high sediment contribution from the Tunchelin Gol tributary sub-catchment. The relative contributions from the Zagdelin Gol (11.6%) and Boroo Gol (8.4%) sub-catchments are unexpectedly low for rivers draining the middle parts of the study basin, especially in comparison with the RUSLE estimated hillslope generated sediment supply in these areas (70.6 kt/a and 49.5 kt/a, respectively, Figure 3.4). In case of the Boroo Gol sub-catchment, a reservoir approximately 10 km upstream of the outlet acts as an effective sediment trap. The low sediment contribution from the sub-catchment Zagdelin Gol most likely reflects the special geological setting. Most of the very broad floodplain in the middle reach of the river in this particular sub-catchment consists of a very porous aquifer, which leads to complete infiltration of stream runoff during most periods of the year. Suspended sediment from upstream reaches is therefore trapped, with only a portion transported through the whole channel network of this sub-catchment. Downstream of the infiltration site discharge surfaces from the aquifer again and generates a channel of a length of 20 km up to the confluence with Kharaa River. Furthermore both the Boroo Gol, and the Zagdelin Gol sub-catchments are characterized by a low channel network density of only 95 and 87 m km-^{2}, and a low runoff rate of 0.6 and 0.9 l s-1 km-^{2}, respectively. This strongly reduces the probability of eroded soil from the uplands being transported to the river networks. Overall, the results of the sediment source apportionment are in accordance with earlier findings reported by Theuring et al. (2013).

Although the sediment contributions from the individual sub-catchments are strongly influenced by hillslope erosion, river bank erosion generates 74.5% of the total fine-grained sediment load (Theuring et al., 2013).

River bank erosion also occurs in the most downstream reaches of the Kharaa River below the most downstream sampled tributary (Figure 3.1). This section between the most downstream sampled tributary and the overall study outlet is approximately 50 km long and is characterized by wide floodplains, intensive livestock grazing, sparse riparian vegetation and erodible unprotected river banks. The effects of sediment generation from bank erosion along the lowest reaches of the main river channel are, however, not quantified as a separate fine-grained sediment source in this study, although it is highly unlikely that bank-derived sediment inputs from these lower reaches would outweigh those from the sampled major tributaries upstream (Figure 3.1). This potential limitation should, nonetheless, be kept in mind when interpreting the findings of this work (cf. Stone et al., 2014).

Table 3.12: Estimated relative-frequency weighted median spatial sediment source contributions using the different composite signatures and the final estimated contribution (- i.e. the average relative-frequency weighted median spatial sediment source contributions to the total sampled deposited sediment load collected at the overall outlet of the Kharaa.

	Kharaa I	Sugnugur	Bayangol II	Bayangol	Zagdelin Gol	Boroo Gol	Kharaa II	Tunchelin Gol
KW	0.05	0.04	0.06	0.23	0.1	0.07	0.45	0.23
PCA	0.07	0.09	0.07	0.32	0.11	0.04	0.3	0.17
GA-DFA 1	0.05	0.03	0.06	0.19	0.14	0.11	0.42	0.12
GA-DFA 2	0.17	0.12	0.15	0.17	0.09	0.08	0.21	0.28
GA-DFA 3	0.04	0.04	0.05	0.18	0.14	0.12	0.43	0.11
Final Contribution	**0.08**	**0.06**	**0.08**	**0.22**	**0.12**	**0.08**	**0.36**	**0.18**

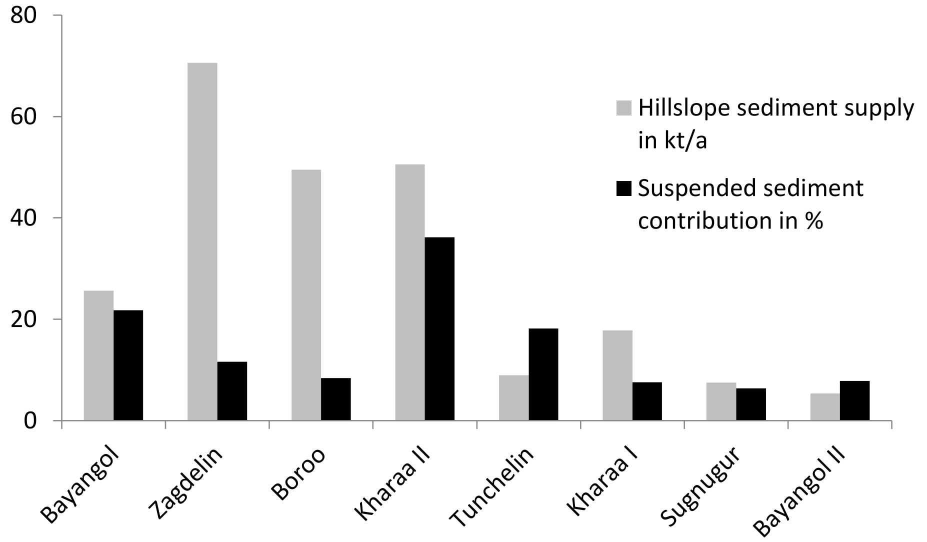

Figure 3.4: A comparison of the final estimated relative-frequency weighted median spatial sediment source contributions to the total sampled deposited sediment load collected at the overall outlet of the Kharaa River, with the hillslope sediment supply estimated using RUSLE calculations.

Table 3.13: Full uncertainty ranges for the mixing model predictions of median spatial source contributions using each composite fingerprint.

Signature	Statistics	Kharaa I	Sugnugur	Bayangol II	Bayangol	Zagdelin	Boroo	Kharaa II	Tunchelin
KW	Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	0.49	0.47	0.70	0.94	0.78	0.78	1.00	0.91
PCA	Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	0.67	0.67	0.54	0.94	0.72	0.45	0.95	0.81
GA-DFA 1	Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	0.67	0.72	0.74	0.96	0.74	0.99	1.00	0.96
GA-DFA 2	Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	0.94	0.94	0.79	0.93	0.81	0.92	0.98	0.88
GA-DFA 3	Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	0.55	0.44	0.54	0.89	0.78	0.95	1.00	0.77

3.7 Conclusion

A geochemical composite fingerprinting procedure has been successfully used to apportion the relative contributions of fine-grained (<10 µm) sediment from tributary sub-catchment spatial sediment sources of the Kharaa River in northern Mongolia. By combining KW-H, PCA and GA-DFA as independent statistical tests, the methodology provides a basis for identifying different statistically robust composite signatures for use in the numerical modelling framework. The use of a combination of independent statistical tests helps to take account of potential uncertainties in source estimates, associated with the use of a single composite signature.

The results suggest that the main contributors of fine-grained sediment are the intensively farmed sub-catchments of the middle Kharaa River drainage basin. These are impacted by the compound effects of livestock herding, arable land use for mainly wheat and potatoes, as well as mining, logging and forest fires. In two of the study sub-catchments, land use was of no importance for fine sediment release because either a reservoir served as a sediment trap (Boroo Gol sub-catchment), or because surface runoff across most of the sub-catchment infiltrates, at least partly, into the aquifer and therefore does not deliver suspended sediment from the total drainage area to the sub-catchment outlet (Zagdelin Gol sub-catchment). Furthermore river network density and runoff rate may control the net loss of eroded soil to the stream network. The pristine forested headwater sub-catchments were not identified by the sediment source fingerprinting to be contributing significantly to the downstream sediment samples, collected at the overall study outlet of the Kharaa River. In combination, the above findings suggest that livestock farming and herding close to river channels, mining and logging are the key drivers behind suspended sediment inputs to the Kharaa River channel system. This study demonstrates the general applicability of the sourcing procedure for large cold climate semi-arid Asian river basins. The sample size (n=25) proved sufficient to limit inter sample variation. Especially in data scarce areas like they can be found in Central Asia, this procedure can provide a cost effective way to characterize sediment sources in vast areas. Future studies using this approach in other catchments are recommended to utilize also different fingerprinting properties, like organic (P, C, N), physical (particle size, color) and Magnetic (χ, ARM, SIRM). In our study geological variations were small and impact of landuse on the concentration of nutrients due to the absence of fertilizer use not visible. This may be different in other areas. Of course, quantification is not possible with the technique on such a scale and much more detailed studies would be needed for this.

The composite fingerprinting procedure yielded results which are in good agreement with findings reported by previous studies using modelling methods for the identification of suspended sediment sources in the study catchment. The combined application of source fingerprinting and catchment modelling approaches can be used to assess whether tracing estimates are credible and in combination such approaches provide a basis for making sediment source apportionment more compelling to catchment stakeholders and managers.

4 Suspended sediments in the Kharaa River catchment (Mongolia) and its impact on hyporheic zone functions

4.1 Abstract

A previous study investigating the ecological status of the Kharaa River in Northern Mongolia reported fine-grained sediments as being a major stress factor causing adverse impacts on the benthic ecology. However, the source of these sediments within the catchment as well as the specific impact on hyporheic zone functions in the Kharaa River remained unclear. Therefore, the objective of the current study was to investigate the underlying source– receptor system and implement an integrated monitoring approach. Suspended sediment sources within the Kharaa catchment were identified by using extensive spatially distributed sediment sampling and geochemical and isotope fingerprinting methods. On the receptor side, the ecological implications across a gradient of fine-grained sediment influx were analyzed using a distinct hyporheic zone monitoring scheme at three representative river reaches along the Kharaa River. Results of suspended sediment source monitoring show that during snowmelt runoff,

riverbank and gully erosion were the dominant sources. During the summer period, upland erosion contributed a substantial share of suspended sediment. Fine-grained sediment influx proved to be the cause of habitat loss in the hyporheic zone and benthic oxygen production limitation. This combined catchment and in-stream monitoring approach will allow for a better understanding and spatially explicit analysis of the interactions of suspended sediment transport and hyporheic zone functioning. This information has built the basis for a coupled modeling framework that will help to develop efficient management measures within the Kharaa River basin with special emphasis on rapidly changing land-use and climatic conditions.

4.2 Introduction

Understanding terrestrial erosion behavior, its sources and delivery pathways of fine-grained sediments into the river systems is essential for understanding the associated impacts such as clogging of the hyporheic interstices on river ecosystem functions. In Mongolia, fine-grained sediment input is expected to increase rapidly, due to the overgrazing of pastured land leading to soil degradation and desertification and thus higher erosion susceptibility (Onda et al. 2007). Soil erosion is also highly dependent on climatic conditions and is most vulnerable during high precipitation and peak discharge events. Therefore, high resolution discharge and climate data are essential to understand soil erosion processes. According to field observations the main erosion types in the catchment are assumed to be surface-, riverbank- and gully erosion. Little is known, however, about their actual contribution to the river system, its delivery pathways, and its in-stream transport behavior. Assessing the sediment transport in a mesoscale catchment faces the problem of data constraints and requires the implementation of innovative, time and cost-effective monitoring and modeling approaches.

The hyporheic zone is the interface between surface and subsurface water (Orghidan 1959), which comprises a unique environment for bio-/geochemical reactions and ecological processes. Therefore, the hyporheic zone may play a crucial role in the ecological functioning of a river and the water quality that is in turn dependent on the zone's connectivity and activity (Borchardt and Pusch 2009). Fine-grained sediment input, e.g., caused by agricultural land use are a key constraint for this ecotone. The so called ''colmation of the riverbed'' as described in Beyer and Banscher (1975) and Schälchli (1992), reduces the hydraulic connectivity and, therefore, the exchange of surface and subsurface water. This process decreases the dynamics and transformations of solute and particulate matter as well as the habitat suitability (Brunke and Gonser 1997; Wood and Armitage 1997; Greig et al. 2007). Thus, river catchments susceptible to erosion and water stress are sensitive to impairments of aquatic functions from pressures on the rivers hyporheic zone.

In order to cope with these issues, it is crucial to establish adapted and linked monitoring strategies as a pressure-impact system analysis is complex and it needs to provide all necessary information for coupled numerical analyses. This is indispensable for supporting an erosion risk assessment and identifying ecological thresholds of influx for the improvement of management concepts. The study site of the Kharaa catchment in Mongolia offers a rare opportunity, as the considered pressure on the water resource is not masked by other anthropogenic factors such as organic or nutrient pollution.

The aim of this study is to understand the underlying mechanisms of soil erosion, suspended sediment transport and its aquatic impairment in order to analyze the causal relationship of land use and in-stream fate and behavior at the catchment scale. Within this paper, an integrative monitoring approach is presented, addressing the following issues: (1) tracing and quantifying the spatial sources of suspended sediments, (2) the importance of different erosion processes, and (3) the ecological implications for hyporheic zone functioning. Investigations on the runoff and suspended sediment transport behavior in combination with different sediment source fingerprinting techniques conducted for the entire catchment are presented. Furthermore, investigations on the riverbed sediment composition, the oxygen balance and the subsurface solute distribution are used to indicate ecological integrity and functioning of the hyporheic zone at three representative reaches along the Kharaa River.

The study is part of the International Water Science Alliance Saxony (IWAS) research program that aims to develop strategies, concepts, measures and technologies for a sustainable water management in order to meet the arising water stress in hydrologic sensitive regions (Kalbus et al. 2011). One of the focus region is Central Asia (Mongolia and Inner Mongolia), where project partners are focusing among others on environmental simulation (Vetter et al. 2011), socio-economic aspects (Sigel et al. 2011) and IWRM implementation (Horlemann and Dombrowsky 2011).

4.3 Study site

The study was carried out in the Kharaa River catchment in Northern Mongolia (Figure 4.1).

The Kharaa discharges together with the Orhon River into the Selenge River together forming the major inflow into Lake Baikal. The catchment covers an area of approximately 15,000 km² and its elevation ranges from 2,665 m above sea level upstream (southeast) to 655 m a.s.l. in the downstream part (northwest). The very southeast belongs to the Hangay–Hentey granitoid complex dominated by plutonic and metamorphic rocks, the very northwest belongs to the Orhon-Selenge volcanic belt with mainly basaltic rocks. In between, the catchment lies mostly in the Hangay–Hentey basin that is dominated by old, well eroded sedimentary rocks of marine origin, such as sandstone and schists ruptured by plutonic rocks like granite (Batulzii et al. 2005).

A geomorphological categorization into four classes can be made according to the altitude that is also reflecting the geological conditions. The first class spans the altitudes from 1600 to 2665 m a.s.l. showing the character of a mountain range with deep V-shaped valleys, the second class from 1,200 to 1,600 m a.s.l. is a mountain range having u-shaped valleys, the third class from 950 to 1,200 m a.s.l. shows more flat valleys, and the fourth class from 655 to 950 m a.s.l. is dominated by the floodplain with a strath valley form.

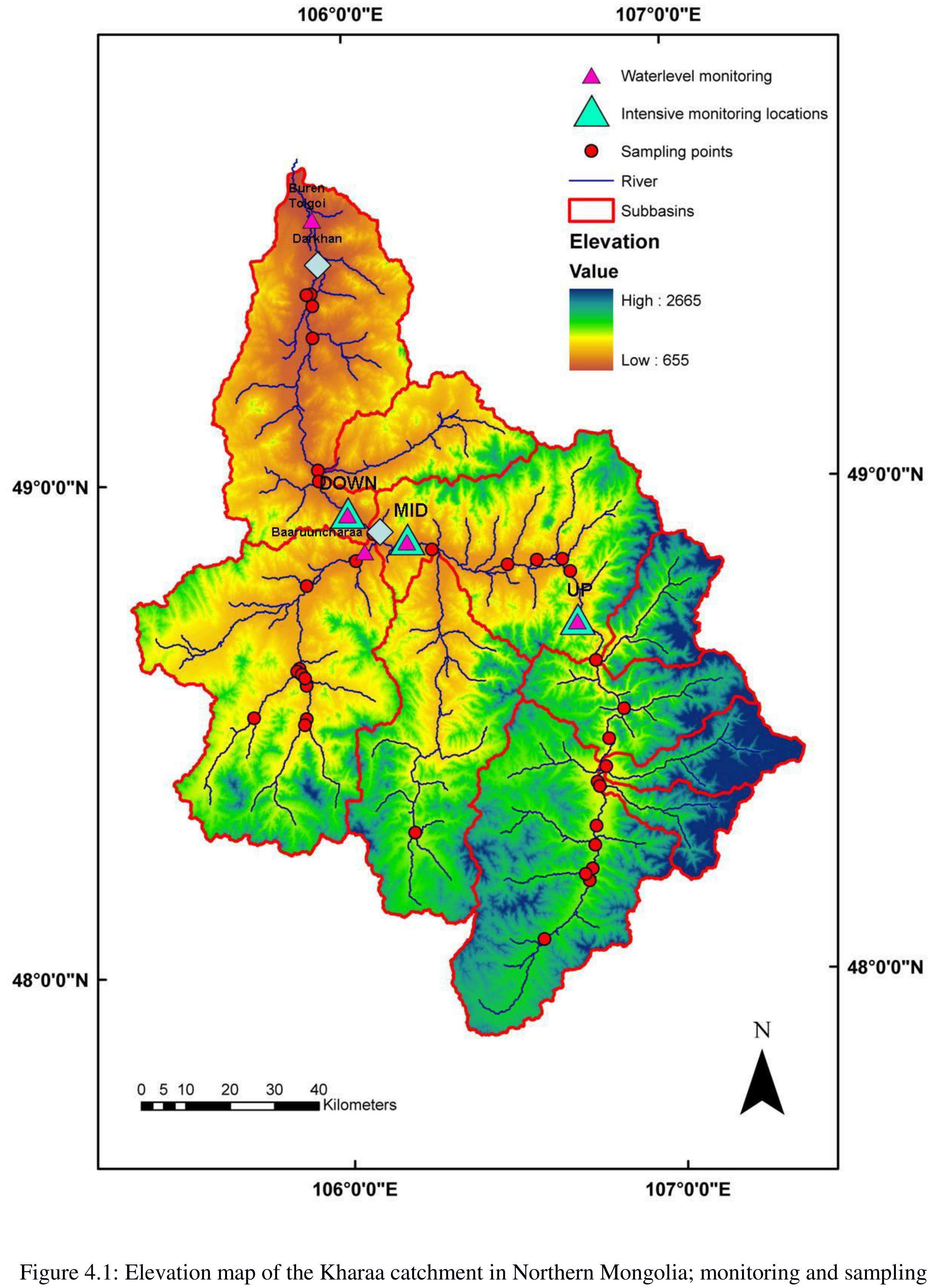

Figure 4.1: Elevation map of the Kharaa catchment in Northern Mongolia; monitoring and sampling points are highlighted.

Mountain soils are little developed and forested at the hillslopes and are affected by fires and deforestation. From the midstream part towards the floodplain areas downstream the dominance of castenozem soils that can also be found in the tributaries like the Zagdelin River increases (Iderjavkhlan 2008). These areas inhabit most of the extensive grazing and intensive agricultures. According to Priess et al. (2011) the major land use types are grasslands (60%), forests (26%) and croplands (11%). In recent years, a trend towards increased irrigation and greenhouses is also evident. A few kilometres upstream from the river outlet the expanding city of Darkhan is located. It is Mongolia's second largest city with a population of over 100,000 inhabitants.

The climate is continental with dry winters and hot summers, and extreme temperature ranges from -40 to +30°C. The intense winters last from October to April and are characterized by a persistent snow coverage. Average annual precipitation varies between 250 and 350 mm with seasonal peaks in summer. The mean annual discharge is 12 m^3/s at the outlet of the Kharaa catchment with two distinct runoff peaks after snow melt in spring and the maximum peak occurring after summer rain fall events.

The hydromorphology in terms of longitudinal or crosssectional profiles is undisturbed and meandering, only controlled by the geomorphological settings. Critical concerns arise due to the structure of the riverbanks where significant erosion has taken place, due to riparian vegetation existing on only approximately 20% of the riverbank at the mid and downstream reaches as a result of overgrazing practices. The assessment of the benthic invertebrate community appear in good ecological condition in the upstream reaches while the lower section of the middle reaches is deficient within the invertebrate community (data unpub., M. Schaeffer, Helmholtz-Centre for Environmental Research, Germany). Parallel studies of heavy metal concentrations have excluded pollution as a cause of this invertebrate deficiency which is probably mediated by poor habitat quality. Within this river section the tributary Zagdelin (second largest subcatchment) is likely to contribute considerable amounts of suspended sediments to the Kharaa River. Stream water nutrient concentrations are low with about 0.1 to 0.8 mg/l for nitrate-nitrogen, 0.01 to 0.04 mg/l for ammonium-nitrogen, 0 to 0.01 mg/l for nitrite-nitrogen and 0.01 to 0.1 mg/l for total phosphorous.

Observations showed a decrease in precipitation for this catchment (Batima et al. 2005), particularly between 1996 and 2002 when discharge was remarkably low. Future scenarios indicate increasing water stress: On the one hand, socio-economic drivers such as the intensification of mining and especially agriculture are expected to result in overexploitation of water resources (Priess et al. 2011). On the other hand, climate change scenarios indicate an increase in precipitation but also for evapotranspiration by increasing air temperatures (Menzel et al. 2008).

4.4 Methods

4.4.1 Suspended sediments

Understanding sediment inputs into a river system and the subsequent modeling of these transfers requires a prerequisite information on climate, land use, discharge and sediment transport. The main components of our investigation were, therefore, operative monitoring schemes within the catchment in order to provide discharge and suspended sediment information and the identification of the source locations of the sediment with fingerprinting techniques. Climate data comprise seven stations with daily mean values on precipitation, temperature, soil temperature, relative humidity and wind velocity for the Kharaa catchment. These data have been spatially interpolated for the catchment area in order to create input data for the hydrological model (Menzel et al. 2008). Daily discharge measurements were available for the catchment outlet at Buren Tolgoi for the period from 1990 to 2002 and for the station Baruunkharaa in the midstream region for the period from 1951 to 2001. At both stations the hydrogeometrical conditions were mostly stable in respect to riverbank structure and the adjacent floodplain. Data on suspended sediment concentrations exist for the station Buren Tolgoi for the period from 1986 to 2007 on a monthly basis. Because suspended sediments are transported in rivers during short periods of high discharge this data allowed only uncertain calculations of sediment budgets (Gao 2008). In order to improve the data basis, four pressure transducer water stage sensors (Schlumberger Micro Diver) were installed at selected cross sections of the Kharaa River system covering upstream, midstream and downstream reaches. For these stations, 30-min time step water level data were available since May 2009. This water level data were used in combination with cross-sectional flow velocity measured by an electromagnetic velocity sensor (Marsh-McBirney Flo-Mate, Hach Company, U.S.) in order to calculate the discharges via the velocity–area method. Furthermore, an infrared backscatter turbidity sensor (LogTrans6-GPRS, UIT) was installed at discharge gauge station Buren Tolgoi in May 2009. Due to technical problems 30 minute time step data were only available since May 2010. Turbidity measurements have been calibrated with daily measured total suspended sediment (TSS) concentration of 1 l grab samples filtered with 45 µm preweighed GC filters from May 2010 to September 2010 (n = 105).

In order to investigate the actual sediment sources in the catchment, geochemical and isotope sediment source fingerprinting techniques were applied. Geochemical sediment fingerprinting is based on the fact that sediments from different areas of the catchment differ in their chemical composition due to underlying geology, soil types and land use. By identifying the distinctive element composition of each contributing area a geochemical fingerprint can be created that can then be compared to the composition of sediments in the main channel (Collins and Walling 1998; Collins et al. 1998). Three grab sampling campaigns in September 2009, May 2010 and September 2010 have been undertaken. A total of 600 samples of deposited suspended sediments from previous high water stages after snowmelt and the summer rainfall season from the riverbank at the outlets of 22 subcatchments have been collected. At each outlet samples were taken from the main channel before the inflow of the tributary, the tributary itself and from the main channel after the inflow of the tributary. The sediment samples were oven-dried at 55°C and the <10 µm fraction extracted with the help of wet sieving in the laboratory. It has to be noted that only the <10 µm fraction was analyzed. Due to the size of the catchment, only the smallest fraction of suspended sediments can be assumed to be directly delivered to the catchment outlet, whereas the transport of coarser material is more heavily affected by sedimentation and resuspension processes (Walling and Moorehead 1989). The extracted material was digested and analyzed in an ICP-OES spectrometer for its concentration of 35 trace elements (Li, B, Al, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Rb, Sr, Mo, Cd, Sn, Sb, Ba, Au, Hg, Pb, Bi, U, W, Tl, Ag, Se, Be).

Besides the spatial identification of the suspended sediment sources, isotope fingerprinting techniques have been used for the identification of the contribution of different erosion types. In the Kharaa catchment three major erosion types can be distinguished: Upland erosion, gully erosion and streambank erosion. Both anthropogenic and natural occurring radioisotopes Cs-137, Be-7 and Pb-210 are used to identify the source type of the suspended sediments. Whereas Be-7 and Pb-210 are naturally occurring in the atmosphere, Cs- isotopes originate from atmospheric nuclear-weapons tests in the 1950s and 1960s. All three isotopes are evenly deposited on the earth surface by wet and dry atmospheric deposition and are absorbed by the soil particles, especially strong to fine grain particles. Due to their different half-lives (Be-7: 53.2 days, Cs-137: 30.1 years, Pb-210: 22.2 years) their concentration in the soil profile changes with depth (Matisoff et al. 2002; Wallbrink et al. 2003; Hancock and Pietsch 2008).

Beryllium isotopes can be found only in the uppermost 1 cm of the soil, whereas the lead and caesium can also be found in depths of 5 and 10 cm, respectively. Therefore, the isotope distribution in suspended sediments can be used as an indicator for the origin of the sediment from surface, gully or streambank erosion. In this study, grab sampling were conducted two times in 2010. Samples were taken in spring and late summer 2009/2010 from reference sites of each erosion type: 12 topsoil samples comprising the uppermost 2 cm of soil of agricultural fields, 4 streambank erosion samples from river undercuts 4 samples from gully erosion sites and 4 samples of recently deposited river sediment. All samples were analyzed with gamma spectroscopy at the German Federal Office of Radiation Protection with standardized analytical methods. The detected isotope concentration was then compared with the concentration of isotopes in the collected deposited suspended sediment from the river.

4.4.2 Ecological functions

An intensive monitoring program was developed with emphasis on appropriate spatial and temporal resolutions in order to investigate the impairment of fine-grained sediment inputs on ecological functions at the hyporheic zone, such as regulation, production, and habitat features. It was driven by the delivery of all essential information to perform a system analysis for a two-compartment river water quality model. Therefore, measurable parameters were identified and evaluated for their monitoring methods considering the applicability and feasibility.

Three sampling sites at the Kharaa River ‘UP’, ‘MID’ and ‘DOWN’ (see Figure 4.1) were chosen across a gradient of fine sediment impact for measurements at the riffle scale. The monitoring campaigns were undertaken at one riffle-like structure per site (about 30 to 80 m), whereas at UP the measurements were made at a side arm with about 30% of throughflow. A half year before sampling multi-level probes (Lenk et al. 1999) were installed in the stream bed at each riffle head (probe ‘A’), riffle crest (probe ‘B’) and tail (probe ‘C’). The sampling campaigns were considered to be carried out at two distinct hydrological conditions at the end of a low flow period in spring and after high water levels of the summer rainy season, respectively.

Hydromorphological parameters included measurements on the longitudinal river bed geometry and the slope using digital levelling (Sprinter 100, Leica Geosystems, Switzerland) as well as the river width at a representative profile (tapeline). Distinct river features were inspected for the channel, substrate, flow, and riverbank characteristics. The streamflow velocities were measured by an electromagnetic velocity sensor (Marsh-McBirney Flo-Mate, Hach Company, US) and discharge was calculated via the velocity– area method. For laboratory determination of TSS, the surface water was sampled and concentrated on pre-weighed GC filter (45 µm) in duplicate. The diurnal oxygen concentration profiles were recorded for 24 h (YSI 600 XLM, YSI Hydrodata, Letchworth, England) and corrected with parallel point measurements (WTW 350i, CellOx 325, Weilheim, Germany). For the analyses of the properties of the hyporheic zone, the freeze core technique (Bretschko and Klemens 1986, modified) was employed. The freeze cores were split into different levels (0–20, 20–40 and 40–60 cm) for separate grain size analyses after drying in the oven at 80°C. Here, grain size fractions greater than 50 mm were excluded (Adams and Beschta 1980). Due to restrictions in liquid nitrogen availability only two frozen cores per site and expedition were manageable (n = 4). The hydraulic conditions of the subsurface by means of the vertical flow component was measured using the multilevel probe metering the hydraulic heads in 5, 15, 25 and 45 cm depth. The vertical hydraulic gradient (VHG) equals the quotient dh/dl with the height of the heads (h) and the piezometer length (l). The multi-level probe was also used for hyporheic water extraction for water quality measurements of oxygen concentration and conductivity (WTW 350 i, CellOx 325, SenTix 41, TetraCon 325, WTW GmbH and Co., Weilheim, Germany). The biological assessment included measurements of the chlorophyll a content of benthic biofilms. Here, every 3 weeks material was completely scratched off from five stones at each site, homogenized in a standard volume of filtered water, and concentrated on filters that were kept at 4°C until laboratory analysis. According to Stich and Brinker (2005), chlorophyll a was determined without acidification. The stone area was calculated via the weight of aluminum foil that covered the part of the stones surface.

4.5 Results

4.5.1 Sediment fingerprinting

First results consider of the monitoring of the discharge and TSS concentrations for the years 2009 and 2010 at the catchment outlet and results from the first sediment grab sampling campaigns in spring and late summer 2009–2010. The correlation between continuous water level measurements and manual controls was highly significant ($r^2 = 0.98$; n = 4; $p<0.02$).

This allows a direct calculation of the discharge based on the continuous water stage measurements. This relationship was similar also at all four other monitoring locations.

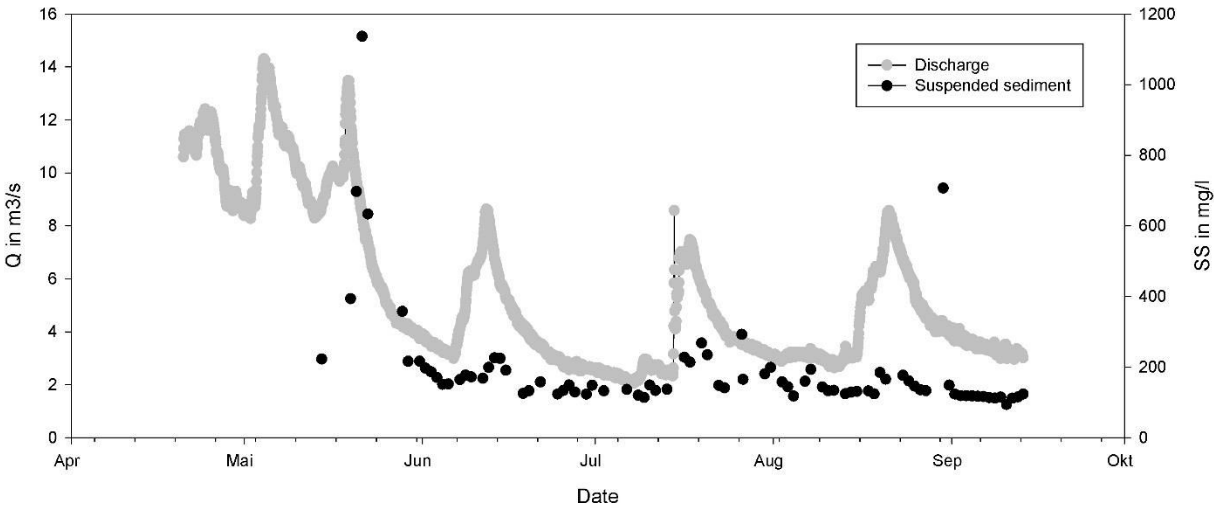

Figure 4.2: Discharge and total suspended sediment load at the catchment outlet in 2010.

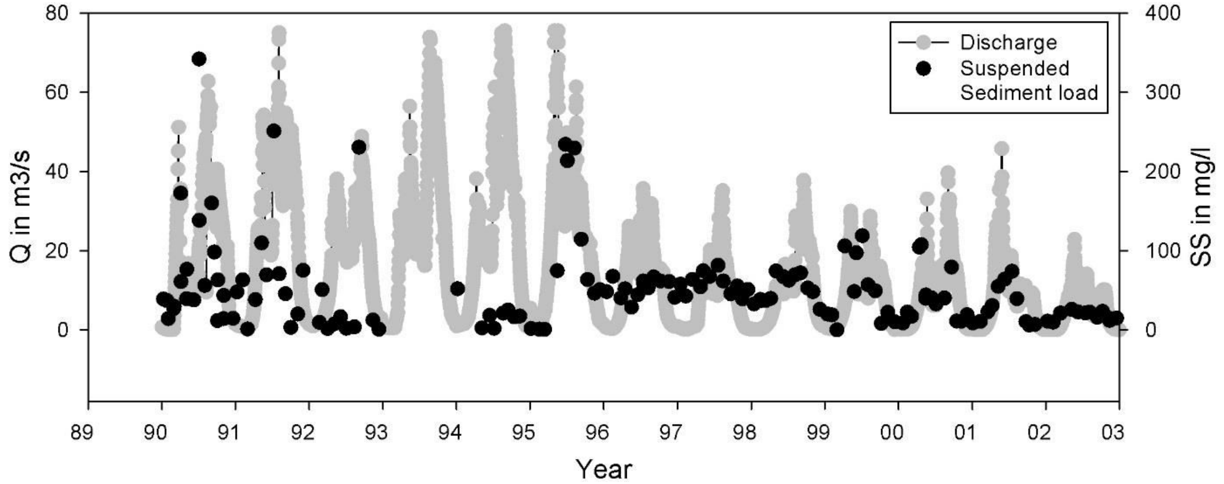

Figure 4.3: Discharge and total suspended sediment concentrations at the catchment outlet 1990–2002.

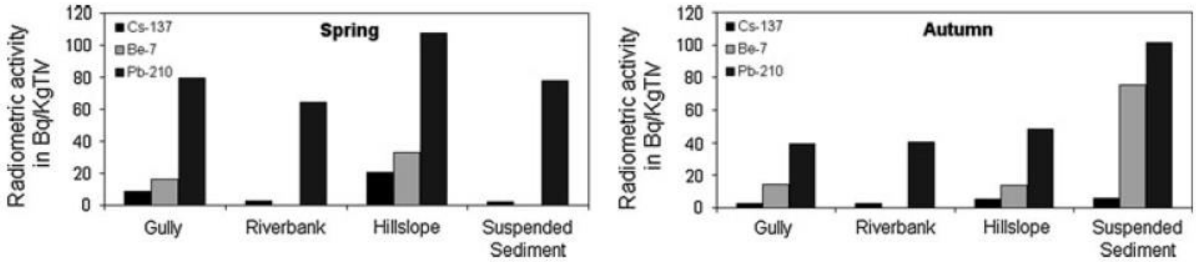

Figure 4.4: Concentration of Cs-137, Be-7 and Pb-210 in gully floor, riverbank, hillslope and suspended sediment samples in spring (left) and autumn (right) 2010.

The analysis of the discharge of summer 2010 clearly showed the influence of several rainfall events on the hydrograph (see Figure 4.2). Measurements during wintertime when the river is covered with ice were not possible. Measurements of TSS concentrations in 2010 revealed a clear influence of high discharge events on the sediment transport in the river with a mean concentration of 185 mg/l and a maximum concentration of 1,137 mg/l. Since the TSS concentration data consist only of daily measurements, it is difficult to calculate a clear regression relationship with the discharge. Further analysis of the data and comparisons with continuous turbidity measurements however will allow a more precise quantification of the actual transported sediment load.

The comparison of the recent high resolution discharge data with the daily long-term series archive data in Figure 4.3 shows that the decreasing trend of the annual discharge seems to continue. Total suspended sediment concentration, however, is considerably lower than during 2010 with a mean of only 51 mg/l and a maximum of 342 mg/l. However, it has to be noted that the monthly sampling frequency in this time series is unlikely to cover all short-term peak flow events.

The analyses of the concentration of fallout isotopes (see Figure 4.4) reveal that there are differences in the concentration between spring and autumn. Samples from surface erosion sites show no large variation and similar concentrations at both times, with high isotope concentration compared to the other sources. This can be expected since these sites are continuously exposed to atmospheric fallout. Riverbank erosion sites show only significant Pb-210, no Be-7 and very little Cs-137, and also riverbank erosion laterally erodes deep soil horizons that are not exposed to atmospheric fallout. Samples from the gully floor show a higher Pb-210 and, especially Cs-137 concentration in spring than in fall. The isotope concentrations in the suspended sediments differ most strikingly between spring and autumn. Whereas the spring samples only show concentrations of Pb-210 and very little Cs-137, the autumn samples show a significant amount of Be-7 which can be explained by input of topsoil from surface erosion.

A first screening with the help of the results from the geochemical analysis of the suspended sediment from the tributaries reveals significant differences in the geochemical composition of the sediments from the different subcatchments for a range of elements (Table 4.1). Especially B, As, Sr, Au, Pb and U show high RMSE (root mean square error) differences which allows the use of a mixing model analysis for the calculation of the percentage of contribution of the subcatchments to the total load.

Table 4.1: Differences in the element composition of the deposited suspended sediment samples from the grab sampling campaign in autumn 2009.

Element	Mean (µg/g)	RMSE in %
Li	51.63	23.14
B	31.98	44.65
Al	57,645.51	24.92
Ti	3955.56	26.39
V	146.62	26.87
Cr	88.06	20.44
Mn	1,672.15	34.84
Fe	44,968.34	21.66
Co	18.26	23.71
Ni	44.92	22.46
Cu	50.36	26.30
Zn	137.79	26.42
As	14.19	60.86
Rb	110.77	38.48
Sr	256.27	61.84
Mo	1.16	36.15
Cd	0.72	27.23
Sn	3.04	20.55
Sb	0.84	37.86
Ba	335.88	37.59
Au	2.54	66.16
Hg	1.55	13.69
Pb	20.21	45.21
Bi	0.77	25.66
U	5.61	84.10

Table 4.2: Hydromorphological features of the sampling sites during the spring and late summer expeditions; values in bracket refer to whole stream measurements at this site.

Parameter	DOWN	MID	UP
Distance from spring (km)	133	125	84
Water width (m)	26	17	9 (25)
	23	21	11 (21)
Discharge (m^3/s)	5.2	4.5	0.8 (2.9)
	4.3	4.9	1.1 (2.8)
TSS (mg/l)	22.6	9.6 ± 3.4	0.2 ± 0.0
	7.7 ± 0.7	1.7 ± 0.6	1.8 ± 0.1

4.5.2 In-stream analyses

The results on in-stream conditions originate from the spring and late summer expedition in 2010. The UP site belongs to the upstream part at the foothills of the Hentey Mountains where the U-shaped valleys are narrow and an average slope of 3 ‰ Here, features were similar to the headwaters with cobble substrate, rippled flow, point and mid-channel bars, natural banks and semi-continuous riparian vegetation. The sites MID and DOWN are more alike mid-reaches where the valley is flat and merges into the wider floodplain. Here, the slope is less with average values between 1 to 2 ‰; the substrate is gravel to cobble sized, the flow more smooth and point bars occur. Both sites were completely exposed to the sunlight with very little riparian vegetation.

In Table 4.2 the general site descriptions are summarized. The discharge during both expeditions was comparably low. With increasing distance from the headwater the concentration of TSS increased significantly. Especially the DOWN site showed higher concentrations than the nearby MID site confirming the visual impression of highly turbid water and a muddy layer covering the stones. Here, the Zagdelin Gol is contributing considerable suspended solid concentrations.

Selected grain size parameters are shown in Figure 4.5 demonstrating the matrix fraction of the hyporheic zone as well as its fine sediment content.

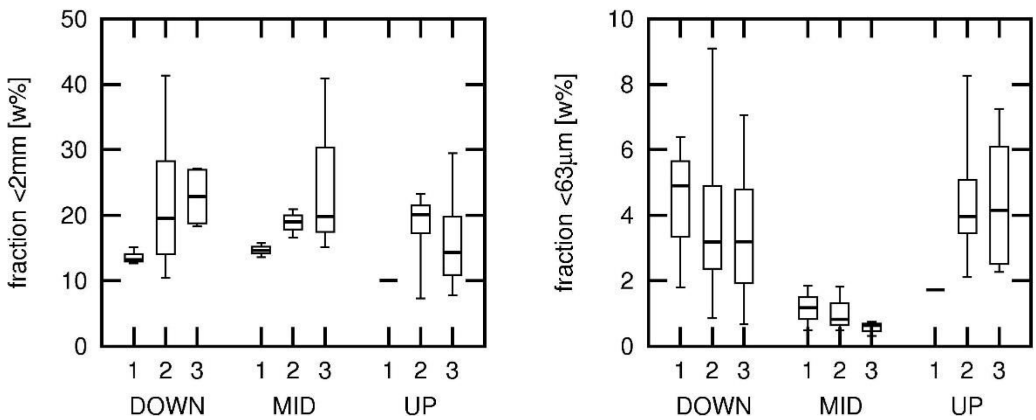

Figure 4.5: Sediment compartment characteristics: matrix fractions (left) and fine-grained sediment content (right) of this fraction; calculated for distinct horizons (1 0–20, 2 20–40 and 3 40–60 cm) and combined data of the two expeditions.

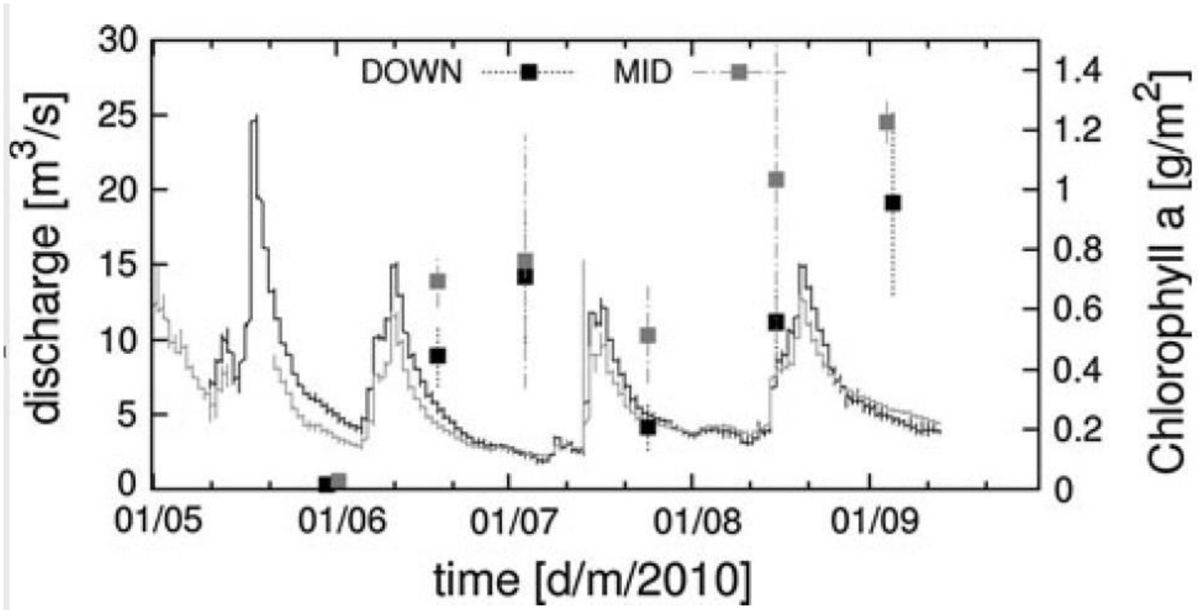

Figure 4.6: Discharge and chlorophyll a measurements throughout the summer season at the three sampling sites.

The matrix fraction of sediments was lowest at UP with the smallest sediment content in the uppermost horizon. At MID and DOWN the matrix fraction showed similar values and the same increase of the sediment content with increasing depth. The fine-grained sediment fraction within the matrix showed a different behavior. Here, the lowest fine-grained sediment content was observed for the MID site. At UP, this fraction was also low in the first horizon, but elevated levels were found at the two deeper sediment layers. At DOWN, the fine-grained sediment content was high for the whole sediment compartment with highest values observed for the uppermost horizon. When comparing the nearby sites MID and DOWN it revealed that although the matrix fractions of each distinct horizon were similar, the content of fine-grained sediments was four times higher at DOWN.

Throughout the season, chlorophyll a measurements were done at MID and DOWN sites (see Figure 4.6). It appears that the density of benthic algae was dependent on the hydrologic regime for the two midstream sites. After the high peak discharge in May the density decreased to a minimum. Besides that, the densities at MID were always higher than at DOWN.

In Figure 4.7a the 24-h records of surface water oxygen concentrations are given. The sinus shaped oxygen records reflected the diurnal primary production with oversaturated conditions in all cases. At the UP site, the oxygen curve showed the lowest amplitude and seemed to be limited during the production phase. The dissolved oxygen at MID and DOWN showed high levels with also a limitation in production at the latter. The baseline oxygen concentrations declined to a normal level at night times and showed an increase with increasing flow length. There were no significant differences in oxygen concentration between the spring and autumn survey. Figure 4.7b, c and d provides a comprehensive overview on the VHG and solute substance behavior with electrical conductivity as a conservative tracer and oxygen concentration as a reactive component. The patterns of the VHG's (see Figure 4.7b) showed significant spatial differences. Negative values or in other words downwelling could be observed at riffle heads and crests (probes A and B) at UP and positive VHG's or upwelling occurred at the riffle tail. Small negative VHG's were also found at the riffle head and crest at MID in spring. In summer a reverse direction of the VHG's was observed. For the downstream site DOWN a positive VHG was found for both surveys. As studies at UP were made at a sidearm with possibly different hydraulic settings, a second riffle in the main course was equipped for upcoming measurements.

In general, the electrical conductivities (Figure 4.7c) of surface waters increased with increasing longitudinal flow length. The electrical conductivity in the hyporheic zone at UP did not change at the riffle head and crest compared to the electrical conductivity of the water body. A steady increase of subsurface electrical conductance was observed with increasing depth at the riffle tail. Considering subsurface water being solute rich, and therefore, having a higher electrical conductivity, the conductivity profile suited the exchange patterns revealed from VHG measurements. This indicates that surface water downwelling reached down the entire sampled depth. A less pronounced increase of electrical conductivity was also observed, although less distinctively, at MID in spring. All profiles measured at MID in late summer and at DOWN (both expeditions) showed similar patterns. Below a 5 cm depth the electrical conductivity did not change within the hyporheic zone. These findings were similar to the observed upwelling signals of the VHG at MID in summer and DOWN in spring and summer. Furthermore, the upper horizon at both sites seemed to be in exchange with possibly lateral inflow of surface water. So, it seems that the transport of conservative solutes was coupled to the VHG.

The distribution of oxygen in the subsurface of a riffle structure (Figure 4.7d) showed a decrease in heterogeneity from UP to DOWN. At UP and to some extent also at MID, oxygen levels showed higher variation with distinct aerobic and close to anaerobic patches. The drop in oxygen levels at the downwelling areas at UP could possibly be explained with enhanced aerobic transformation processes, taking place at those locations. At MID the difference between the two oxygen profiles was higher in spring when downwelling occurred. Whereas at DOWN there was a uniform oxygen distribution in a longitudinal as well as a vertical direction with the gradient only occurring in the upper few centimeters. The small penetration depth of oxygen was likely caused by the positive VHG as seen for the electrical conductivity. Due to the given hydraulic settings it was not possible to compare the fine-grained sediment impact on subsurface solute transport between the three sites.

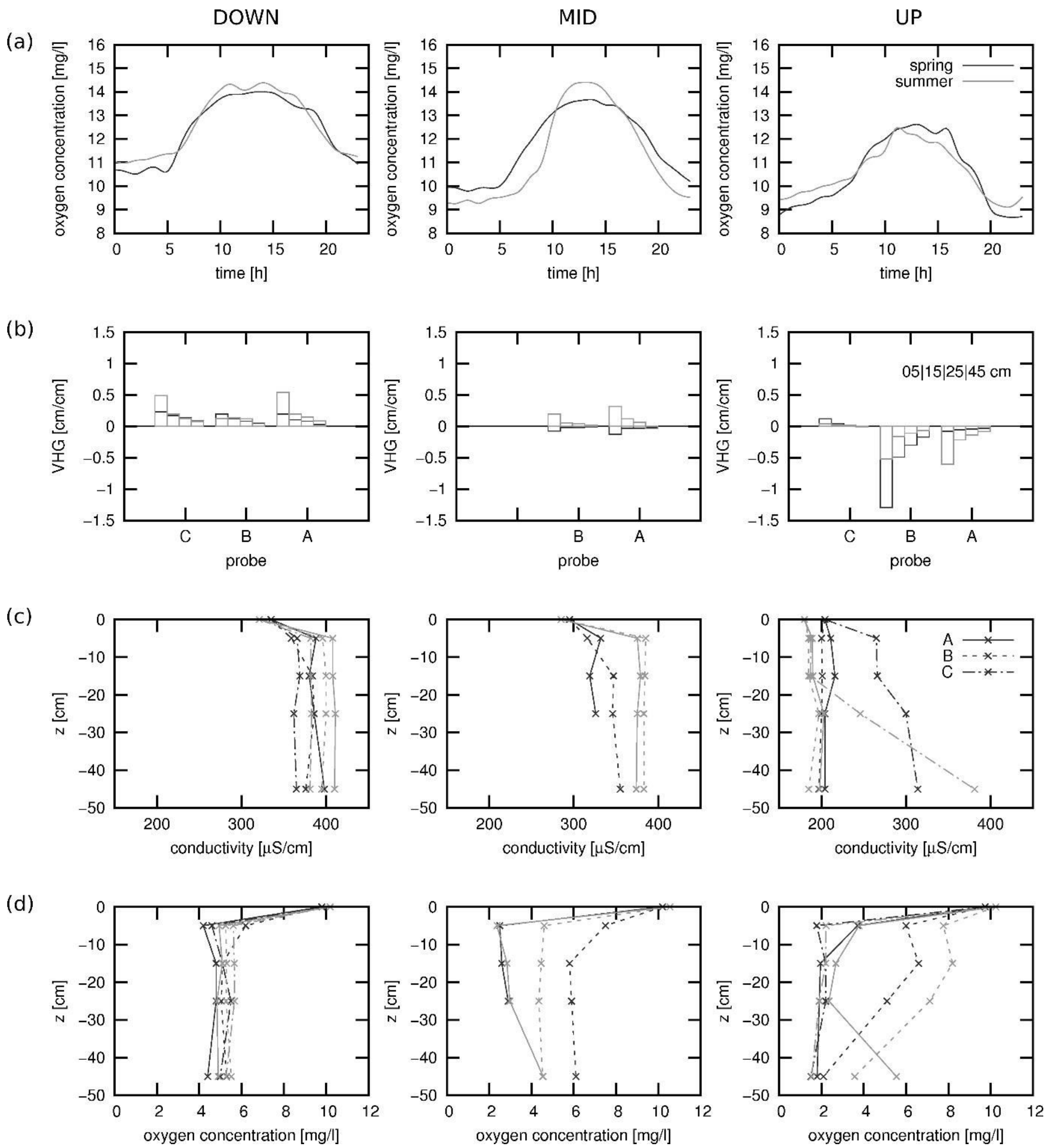

Figure 4.7: Surface and subsurface measurements at the three sites: diurnal oxygen concentration profiles (a), vertical hydraulic gradients at the three multi-level probes (b), electrical conductivity (c) and oxygen concentration (d); displayed for spring (dark grey) and late summer (light grey) expedition

4.6 Discussion

The aim of the study was to analyze suspended sediment transport and identify the sources of erosion as well as to diagnose the implications of elevated fine-grained sediment influx on the ecological integrity of the hyporheic zone of the Kharaa River.

4.6.1 Erosion transport

The five installed discharge monitoring stations greatly improved the previously limited database of the Kharaa River and provided new insights that helps characterizing the discharge regime throughout the catchment. However, the measurements do not deliver reliable information during winter time when the sensors are frozen or ice on the water surface does not allow to define a clear relationship between water level and discharge. Measurements of suspended sediment concentrations are only available for the catchment outlet on a daily basis. They reveal a clear relationship between discharge and sediment load. Newly installed turbidity monitoring sensors at the outlet allow for a more precise calculation of suspended sediment concentrations and hence sediment load calculations at the catchment outlet. Furthermore, these new data provides all necessary information for a coupled hydrologic and sediment transport modelling approach. Extending the turbidity measurements to other stations will increase the information on the subcatchment level.

Results from the isotope sediment source fingerprinting indicate that riverbank erosion is the most important sediment source during snowmelt and that surface erosion only contributes significantly to the sediment load during rainfall induced high discharge events in summer.

The geochemical analysis of the sediment shows significant differences in the sediments from the different subcatchments that will allow calculations of composite fingerprints of each subcatchment. Although geochemical sediment source fingerprinting methods are usually used in small-scale investigations and have rarely been used for catchments on a scale of several thousand square kilometers, first findings suggest a successful application of this method in the Kharaa catchment. However, further statistical and mixing model analysis is required to estimate contribution of the subcatchments and erosion types to the suspended sediment in the river.

4.6.2 Ecological implications

According to the hydromorphological features as well as the matrix fraction of the riverbed sediment, it is evident that the two downstream sites are comparable and the upstream site is useful as reference. It could be shown that in contrast to the MID site, the nearby DOWN site had elevated fine sediment content in the hyporheic zone, especially in the upper horizon. This is obviously caused by high suspended solid concentrations in the surface water supplied by the Zagdelin tributary. These findings support the hypothesis that poor habitat quality through clogged interstices of the hyporheic zone significantly impacts the macrozoobenthic communities (data unpub., M. Schaeffer, Helmholtz-Centre for Environmental Research, Germany).

The data on diel oxygen concentrations and chlorophyll a densities showed that the production function was also impaired by fine-grained sediment at the DOWN site due to light limitation through turbid water or the observed muddy covering of the benthic surface. The production at UP is not comparable in this context.

Conservative and reactive solute distribution combined with the vertical hydraulic gradients gave insights into subsurface settings. So, the typical riffle regime (Thibodeaux and Boyle 1987) was found at the upstream site, with downwelling and surface water inflow at riffle head and crest leading to a high oxygen turnover. At the riffle tail subsurface water was to some extent upwelling leading to a higher proportion of groundwater and less oxygen concentration. This was also observed at the MID site in spring when downwelling occurred. Under upwelling conditions, the connectivity seemed to be due to lateral inflow within the uppermost centimeters. However, the oxygen distribution as reactive signal gives evidence for higher biogeochemical turnover at MID, even in summer. Processes like nitrogen turnover are more likely to occur here, as anaerobic and aerobic patches may occur close together (Triska et al. 1993). So, concerning the impact on the regulation function of the hyporheic zone in terms of subsurface solute transport and biogeochemical conversion, further measurements are needed, especially at downwelling settings. Here, tracer studies are planned for understanding exchange and residence times and numerical analysis with a river water quality model according to Borchardt and Reichert (2001). In order to identify the temporal dynamics of the clogging process, it is essential to conduct these measurements under a range of hydrological conditions (Schälchli 1992). Especially, campaigns after a flooding events are of great interest in order to gain insights in terms of system regeneration. This knowledge is necessary for a quantitative understanding and process based numerical studies across gradients of controlling factors (cf. Ingendahl et al. 2009).

4.7 Conclusions

The approach of a small and cost effective monitoring program consisting of water level, suspended sediment and turbidity measurements in combination with grab sampling sediment source fingerprinting analysis showed promising results on the spatial explicit and catchment wide determination of sediment erosion. The in-stream monitoring is expected to allow for an effective modeling of the hydrology and sediment transport with a conceptual hydrological and nutrient transport model such as HYPE (Lindström et al. 2010) and a regional catchment scale sediment budget model such as SedNet (Wilkinson et al. 2004; Rustomji et al. 2008).

The Kharaa River represents a study site with a single stressor of fine-grained sediment input. It has been shown that the fine-grained sediments affect ecological functions of the hyporheic zone like habitat and production. The alteration of processes regulation and the recovery periods after sediment erosion events needs further consideration. The developed operative monitoring program offers an integrated set of data that will allow a process based river system analysis and provide a sound basis for subsequent numerical analyses.

For the purpose of the numerical coupling of the distinct hydrological compartments, the IWAS-ToolBox (Kalbacher et al. 2011) provides a sound basis.

5 Cause–effect–response chains linking source identification of eroded sediments, loss of aquatic ecosystem integrity and management options in a steppe river catchment (Kharaa, Mongolia)

5.1 Abstract

Although sparsely populated, the progressive degradation of Mongolia's rivers, lakes and groundwater, driven by land-use changes, poses a key challenge for the future sustainable development of the country. This paper deciphers the cause–effect–response chain between river bank degradation, changes of the ecological status, declines of ecosystem functions and priority measures with the case of the Kharaa River in Northern Mongolia. The underlying research approach comprised: (1) hydromorphological characterization of the Kharaa River, (2) water quality assessments, (3) determination of the riverbed composition including hyporheic zone properties, (4) the analysis of riverine biota (macroinvertebrates and primary producers) and (5) the identification of the sources of suspended and settled sediments. The assessment revealed a gradient of spatially heterogeneous river bank erosion due to the degradation of the riparian vegetation caused by overgrazing and wood utilization. As the most prominent ecological response, the biomass of benthic algae decreased and macrozoobenthic community metrics changed continuously along the pressure gradient, accompanied by shifts of habitat related functional traits. At the same time, the hyporheic zone dimensions and functioning were affected by suspended and infiltrated sediments in multiple ways (restricted spatial extent, lowered hydraulic connectivity, lower metabolism, and ecologically critical quality of pore water). Geochemical and radionuclide fallout isotope fingerprinting has identified riverbank erosion as the main source of the suspended sediments in the Kharaa River, when compared to gully and land surface erosion. Erosion susceptibility calculations in combination with suspended sediment observations showed a strong seasonal and annual variability of sediment input and in-stream transport, and a strong connection of erosional behavior with land-use. Amongst others, the protection of headwaters and the stabilization of the river bank erosion hotspots in the midstream sections of the Kharaa River are the priority measures to avoid further degradation of the aquatic ecosystem status and functions.

5.2 Introduction

Globally, aquatic ecosystems are increasingly threatened by anthropogenic land-use in their catchments (WWAP 2015). The effects of intensified agricultural practices on water resources are manifold. Besides decreased water availability caused by increased water demand for irrigation purposes, agricultural practices have also impacted significantly on water quality (UN Water 2011). Increased nutrient input into the river system due to the application of mineral fertilizers and manure causes eutrophication problems in many rivers in cultivated catchments. Furthermore, suspended matter inputs from erosion of upland topsoil and riverbanks affect the ecological integrity of freshwater systems. Central Asian landscapes are heavily exploited (Moerlins et al. 2008; Rakhmatullaev et al. 2013). Many of the areas in these regions are rich in deposits of coal, copper, gold, iron, oil and gas and have vast areas that are used for agriculture, including cash crops (Karthe et al. 2015a). Above all, these countries are the most important grassland regions of the world, with Mongolia and Kazakhstan being among the top ten countries of the world in terms of grassland area (White et al. 2000). The amount of livestock in Mongolia increased dramatically after the socio-economic changes in the 1990s (National Statistical Office of Mongolia 2009) which has led to severe degradation of grasslands in Mongolia (Janzen 2003; Javzandulam et al. 2005). Consequently, overgrazing has been identified as having a large-scale impact on the aquatic ecosystems of, for example, the Selenga River (UNEP 2002; Hayford and Gelhaus 2010; Maasri and Gelhaus 2011). Increased fine sediment loads in river systems can have significant impact on water quality and aquatic ecosystem functions, due to increased turbidity in the water column and the infiltration of fine particles in the riverbed (Wood and Armitage 1997). A range of studies in semiarid regions showed that the susceptibility to upland erosion strongly increased with a shift of naturally vegetated areas to agricultural land. This is especially the case during intense rainfall. Increased livestock density can also enhance soil erosion and sediment transport. Livestock located in the vicinity of rivers augment the problem of riverbank erosion due to reduced riparian vegetation during the summer months as shown by Scrimgeour and Kendall (2003). Riverbank stability is weakened by trampling bank material into the river, and more indirectly, by diminishing the riparian vegetation. Although single site effects of landuse on sediment transport in semi-arid regions is well known, studies exploring the linkage between land-use and ecological integrity of whole river networks are rare. The study presented in this paper develops a conceptual framework for analyzing and examining the cause–effect chain between fluvial sediment transport and the impairment of the aquatic ecosystem. This interdisciplinary approach integrates: (1) the assessment of the ecological status along the study river, (2) the investigation of the spatial impact on the functionality of the benthic and hyporheic zone, (3) the detection of the most relevant erosion sources and (4) the delineation of the most affected river reaches and analysis of the associated pressures. Finally, possible responses in terms of protection measures were derived for a science based dialog with relevant stakeholders. This concept was applied in order to give adequate management advices within the IWRM efforts for the Kharaa River Basin (KRB), which is also a model region for the situation found in many Central Asian water basins (Karthe et al. 2015b).

5.3 Study site

The KRB (Figure 5.1) is situated in Northern Mongolia and drains an area of about 15,000 km². Elevation ranges from 2672 to 658 m a.s.l., with mountainous areas belonging to the Hangay–Hentey granitoid complex in the south–east and floodplain areas located in the Orkhon–Selenge volcanic belt in the north–west (Batulzii et al. 2005). The climate is continental and features short summers and extreme annual temperature variations from -40 to +40 °C. The annual precipitation amounts 300 mm on average with most of rainfall occurring in the summer months and within the mountain areas of the headwaters (Menzel et al. 2011).
The KRB belongs to the drainage system of Lake Baikal, and has a mean annual discharge of 12 $m^3\ s^{-1}$ at the outlet where the Kharaa River discharges into the Orkhon River. Over recent decades the discharge has decreased remarkably (Batima et al. 2005) and future scenarios, though indicating an increase of precipitation, expect a further decrease in discharge due to the increase of evapotranspiration caused by higher temperatures (Menzel et al. 2008). The mountain slopes have marginal developed soils and are covered to some extent by forest. Castenozem soil dominates the floodplain areas, where intensive agriculture (vegetable crops) and livestock grazing (horses, cattle, sheep, goat) takes place (Priess et al. 2015). Livestock numbers increased drastically in the recently and the Mongolian government intends to increase the agricultural area especially within this catchment (Deems 2012; Priess et al. 2015). The river network including information about major tributaries and further catchment

characteristics are described in detail by Hofmann et al. (2013), Karthe et al. (2015b) and Theuring et al. (2015).

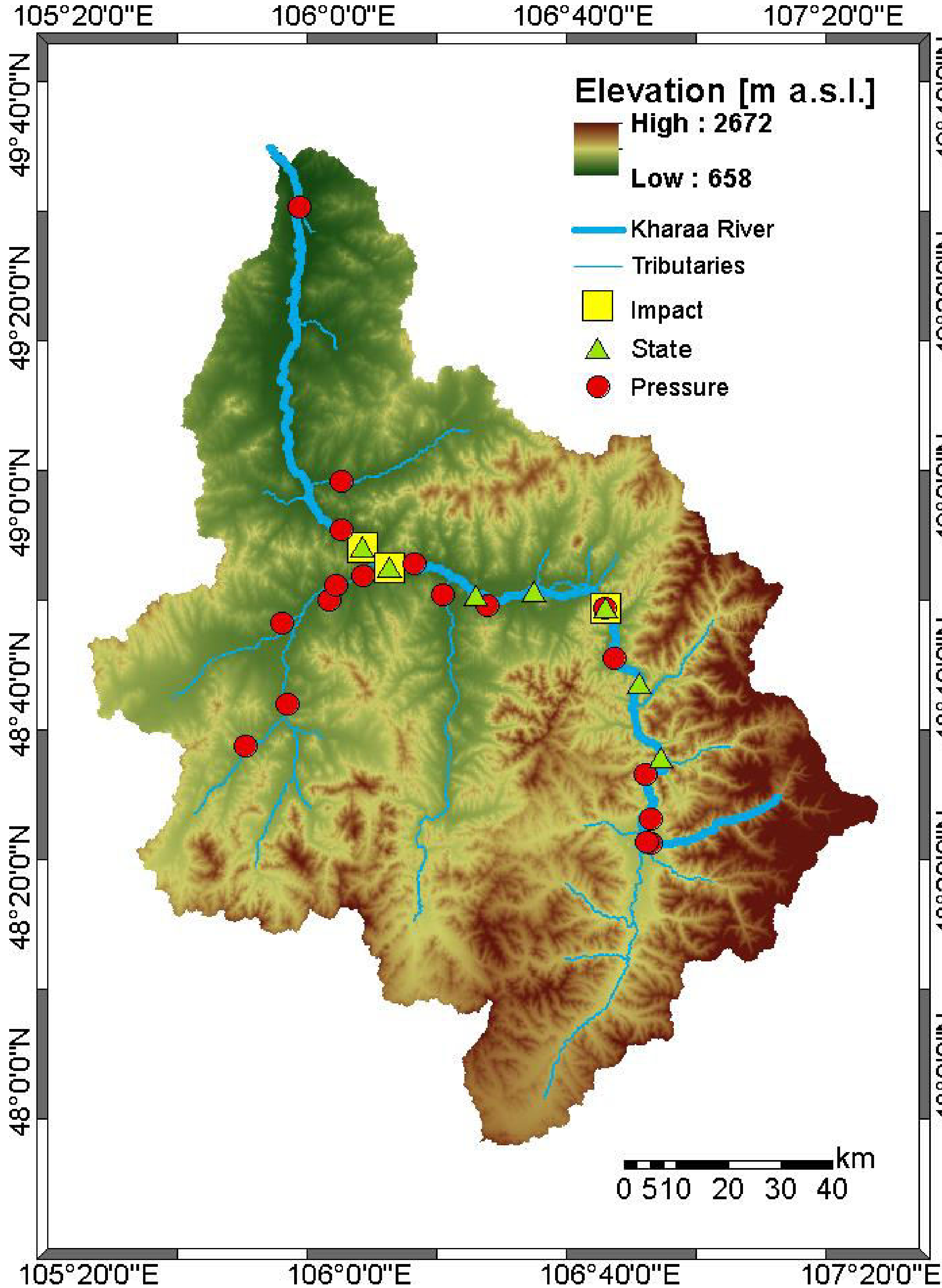

Figure 5.1: Map of the Kharaa River Basin in Northern Mongolia showing the sampling sites referring to the pressures, states, impacts. DEM from Karthe et al. (2015b).

5.4 Methodology

Given the rapid economic development of Mongolia as a governing driver (National Statistical Office of Mongolia 2009), the research approach comprehensively integrates investigations on a set of indicators that characterize anthropogenic pressures originating from land-use changes, the resulting ecosystem states, and impacts such as changes of ecosystem functions along a longitudinal gradient in the KRB. These assessments were structured according to the pressure, state and impact categories of the DPSIR framework (EEA 1995). The methods employed for the determination of these parameters (Figure 5.2) are described in the following section.

Figure 5.2: Overview of the pressures–state–impact chain and parameters used in the study.

5.4.1 Pressures

Increased sediment mobilization caused by upland erosion is strongly connected to land-use change, particularly by reallocation of vast areas in the catchment to agricultural use. Socioeconomic development scenarios in the region predict an increase in cattle density in coming years, but little is known about the resulting sediment transport behavior in the study area. A study by Theuring et al. (2013) investigated the influence of upland, riverbank and gully erosion for riverine suspended sediment contribution, based on isotope sediment source fingerprinting techniques. The study used 137Cs, 7Be and 210Pb isotopes to assess the qualitative contribution of each source type to the fine sediment load in the river. During four field campaigns in 2010 and 2011 samples were collected from 12 topsoil eroding reference sites, four gully erosion sites and four riverbank undercut sites throughout the catchment (see Figure 5.1). The contribution of each source type to the suspended sediment at three locations of the catchment was calculated based on their isotope concentration with the help of a mixing model (Collins et al. 1997). This understanding of the dominant sources is essential for the development of most effective measures for sediment input reduction. Depending on a predominance of upland or riverbank erosion as a sediment source, either management measures for reducing surface erosion on agricultural lands or riverbank protection measures might be needed in different areas of the catchment. Furthermore, it is crucial to investigate the spatial distribution of sediment sources, i.e. the sub-catchments of the reach that are the strongest contributors to the sediment load in the river. Theuring et al. (2015) used sediment source fingerprinting techniques based on the geochemical composition of sediments to investigate the qualitative contribution of each tributary from one of the eight main sub-catchments and to identify the location of hotspots of sediment input in the KRB.

5.4.2 State

The status of the aquatic ecosystem was assessed by hydrological, hydromorphological, physicochemical as well as biological parameters. The discharge, as a crucial parameter for the understanding of the hydrological regime, was recorded using continuous ambient water pressures and flow velocity profile measurements. The data set allowed the determination of water level to discharge relationships (Hartwig et al. 2012). Discharge time series for the years 2009–2012 were than created at four monitoring stations (Figure 5.1): in the upper reach, in the middle reach upstream and after the confluence of the tributary Zagdelin Gol which originates from the second largest sub-catchment (Zagdelin Gol), and at the catchment outlet. The hydromorphology was characterized at 11 sites along the river continuum (Figure 5.1) with a set of parameters adapted from the German on-site River Habitat Survey (LAWA 2000) and with additional components in order to characterize the river bank conditions in more detail. The characteristics comprise channel geometry, substrates, erosion/deposition, flow conditions, the river banks (structure, vegetation type and coverage) and the adjacent land (land-use types). The key physicochemical water quality parameters (temperature, electrical conductivity, pH, dissolved oxygen, turbidity, total suspended solids) and solute constituents (nitrate, ammonium, nitrite, soluble reactive phosphorus) were measured at appointed dates defined by cut off flow conditions in spring and late summer of 2009–2011 (Hartwig and Borchardt 2015) at medium flow conditions after floods caused by the snow melt and summer rainfall events. These sampling campaigns covered the river course from the mountainous transition zone, the middle reach and the stream reach up and down-stream of the confluence with the Zagdelin Gol as substantial amounts of suspended sediments were observed there (Figure 5.1). At the same sites, benthic algae, which dominate primary production in the upper and middle reaches, was sampled over one hydrological summer period in 2010 in order to determine the biomass and chlorophyll a content (Hartwig et al. 2012). Benthic macroinvertebrates communities were sampled using the multi-habitat sampling approach of Haase et al. (2004) during the vegetation periods from 2006 to 2010 with different intensities (Avlyush et al. 2013). Seven sites along the middle region of the Kharaa River were chosen to investigate the spatial and seasonal differences in macroinvertebrate community characteristics, resulting in the evaluation of the ecological status (Figure 5.1). During the sampling procedure all microhabitats were mapped at these sites to characterize the ecological features of the river bottom surface. Macroinvertebrate communities were analyzed for different structural, functional and diversity metrics (Hartwig et al. 2012).

5.4.3 Impacts

Based on the significant disturbances of the benthic and hyporheic habitat revealed by the assessment of the ecological status, further investigations on the impact on the zone's functionalities were conducted. The investigative monitoring included the hydrological connectivity between the surface and subsurface water compartments, the hyporheic regulation potential with respect to aerobic matter turnover and respiration, the benthic primary production as well as the habitat conditions of the benthic and hyporheic zone (Ingendahl et al. 2009; Hartwig and Borchardt 2015). These investigations were carried out at three reaches representing a gradient of impact on the ecological status (Figure 5.1) that were observed after flood events that occurred in June and September of 2010 and 2011. To determine the hydrological connectivity, temperature profiles spanning from the surface water to 45 cm sediment depth were recorded at the inflows of the three riffles (Figure 5.1). The vertical flux was computed using a 1 D heat model after Keery et al. (2007) implemented in the Matlab code assembled by Swanson and Cardenas (2011). For the detection of the hyporheic regulation potential, vertical profiles of water quality parameters (electrical conductivity, dissolved oxygen, dissolved organic carbon) were measured at the infiltration and exfiltration zones of the riffles. The data set facilitated the estimation of the surface water penetration depth which is important for spatial extent of the hyporheic zone and the biogeochemical turnover. Gains and losses of dissolved oxygen and organic carbon within the hyporheic zone were examined using an end-member mixing analysis (Battin et al. 2003). Gross primary production and respiration was calculated according to the single station approach, using diurnal profiles of the oxygen concentration (Odum 1956; Owens et al. 1964; Ingendahl et al. 2009). Finally, the benthic and hyporheic habitat suitability were assessed with regard to suspended sediment concentration, fine sediment infiltration into the river bed and sediment composition. The fine sediment infiltration rate into the upper layer of the river bottom was estimated using sediment matrix traps (Borchardt and Pusch 2009) installed during two intervals (summer and winter) over a 1 year period from 2009 to 2010 at three sites in the middle region of the Kharaa River (Figure 5.1). The fine sediment infiltration rate was calculated by dividing the mass of sediment smaller than 250 µm settled into the interstices of the sediment matrix trap by the volume of the trap and time. Furthermore, sediment samples were extracted using the freeze core technique (Bretschko and Klemens 1986, modified) and the grain size distributions were determined.

5.5 Results

5.5.1 Pressures

The analysis of the discharge and suspended sediment concentrations at the catchment outlet showed the relevance of peak discharge events for sediment transport with a maximum concentration of 1140 mg l^{-1} compared to a mean concentration of 172 mg l^{-1}. From May to October 2010, the mean daily suspended sediment load was 5.7 t with an average discharge of 3.7 m³ s^{-1}. During the period between May and August 2011, suspended sediment load amounted 22.1 t day^{-1}, with an average discharge of 9.0 m³ s^{-1}, amounting to a total load during these periods of 0.7 and 2.3 kt, respectively (Theuring et al. 2013;Hofmann et al. 2011). The RUSLE-based estimations of hillslope suspended sediment supply revealed a strong influence of agricultural land-use on surface erosion, especially in the intensely used mid- and downstream sections of the Kharaa River (Table 5.1) (Behrens 2011; Theuring et al. 2015). The sub-catchment Zagdelin Gol contributes 30 % to the total budget of average hillslope sediment supply of the Kharaa catchment (Theuring et al. 2015).

However, the analysis of fine sediment erosion sources with isotope sediment source fingerprinting (Theuring et al. 2013) revealed that on average 74.5 % of the total suspended sediment load originated from riverbank erosion, whereas 21.7 % were contributed by surface erosion and only 3.8 % by gully erosion. In the most intensely used agricultural sub-catchment Zagdelin Gol, upland erosion contributed only 12.7 % to the total suspended sediment losses (Figure 5.5).

Table 5.1: Selected characteristics of the sampling sites in the middle region of the Kharaa River from upstream to downstream.

Distance to outlet (km)	297	277	252	227	214	181	170
Degradation of wooden bank vegetation	±	±	±	+	++	+	++
Channel erosion	+	±	+	+	++	+	++
Suspended sediment load	+	−	±	±	+	+	++

− low, ± moderate, + enhanced, ++ high

Throughout the Kharaa catchment a significant shift in erosional behavior from the upstream to the downstream area could be observed. In the forested pristine headwater areas with high slope angles and high annual precipitation both hillslope and riverbank erosion contributed significantly to the suspended sediment load. However, in the lower parts of the catchment, and especially in the intensively agriculturally used sub-catchment Zagdelin Gol, the majority of fine sediment input was generated not by hillslope upland erosion, but by riverbank erosion. This is unexpected because agricultural areas often show high hillslope erosion rates. Due to the low precipitation, low river network density and low slope angles in this area, however, surface runoff transport capacity is obviously too low to transport eroded sediment directly into the river system. The importance of river bank erosion is shown to increase from upstream to midstream tributaries (Theuring et al. 2015). The increased contributions of riverbank erosion to the sediment load are associated with the widely degraded riparian vegetation in most regions of the mid and downstream Kharaa River. The long term high livestock densities damaged the riparian vegetation severely. At present only 25 % of the rivers in the mid and downstream sub-catchments are protected from riverbank erosion by vegetation.

Studies on the spatial distribution of total fine sediment contributions based on geochemical signature sediment source fingerprinting indicate that more than 76 % of the total sediment load a the catchment outlet is generated in the three sub-catchments of Tunchelin Gol, Kharaa II and Bayangol (Figure 5.1). Generally speaking, the relative contributions are higher from sub-catchments in the middle rather than the upper reaches of the Kharaa River Basin. Areas affected by riparian vegetation loss due to livestock grazing and wood utilization therefore are the most important sources of suspended sediments in the Kharaa catchment, whereas agriculture appears to be only of limited importance as source of fine sediment inputs in the river system.

5.5.2 State

The discharge regime of the Kharaa is characterized by low flows over winter from October to April with a subsequent high peak phase due to snow melt in May (see Hartwig et al. 2012). The summer period shows low to medium flow phases that were interrupted by peak discharges due to rainfall events from June to early September. Within the middle reaches the discharge remains almost constant with only small contributions from groundwater or tributaries. The highest in-put originates from the Zagdelin Gol subcatchment at the downstream end of the middle reach augmenting the discharge by about 10 %. During the hydromorphological surveys most of the investigated sites were characterized by high morphological diversity and natural channel structure richness due to the unregulated nature of the river network. Nevertheless, deficits in bank structure and coverage could be observed at most of the sites within the middle region (Table 5.2). Approximately 80 % of the mapped river stretches showed missing bank or riparian vegetation and about 70 % have shown evidence for increased channel erosion. Point measurements of suspended sediments and turbidity during low and mid flow conditions indicated increased fine sediment loads especially in the downstream part of the middle region (Table 5.2). These observations coincided with intensive grazing areas in the floodplains characterized by almost diminished riparian vegetation. Furthermore, observations revealed trampling damage caused by livestock that affected the river bank stability.

The characterization of the substrate surface according to the Wentworth scale (Wentworth 1922) showed a continuous longitudinal change in the dominating grain size from blocks and boulders at the most upstream to cobbles and coarse pebbles at the most downstream site of the Kharaa middle region, and could be interpreted as natural river continuum changes. Caused by lowered gradients and changes in transport kinetics along the river, larger sediment fractions were replaced step-by-step with smaller ones. Additionally, the channel substrate composition was recognized to become altered after the confluence of the tributary Zagdelin Gol at the downstream part of the middle reach. Fine particular substrate types were slightly increased to an average of 14 % coverage compared to an average of 10 % coverage in all upstream sites. Related to the microhabitat mapping (Haase et al. 2004) fine sediments and sand (<2 mm grain size) were not discriminated, because these substrate types were often associated with each other and represent similar habitat characteristics for macroinvertebrates. High concentrations of suspended and deposited fine sediments were observed during different sampling campaigns

Table 5.2: Soil erosion in the sub-catchment Zagdelin Gol showing the average erosion rate for different land-use classes and their overall contribution to the catchment area.

Landuse	Soil erosion in t ha^{-1} a^{-1}	Maximum erosion rate in t ha^{-1} a^{-1}	Area of catchment in %
Settlement	0.01	0.09	0.1
Riparian	0.02	1.51	1.5
Forest	0.06	3.48	10.9
Potato	0.08	0.51	0.2
Open forest	0.20	9.74	4.4
Grassland	0.25	21.06	71.5
Wheat	0.79	21.06	11.4
Total	0.28	21.06	100.0

at the most downstream site and verified by sediment matrix trapping. According to Mongolian water quality standards the assessed reaches spanned from very good to good conditions within the spectrum of analyzed parameters (MNCSM 2005). The levels of total suspended solids, nitrate and phosphorus increased significantly at the downstream end of the middle reach, which has also been observed by Hofmann et al. (2015) and Hartwig and Borchardt (2015). Measurements of the biomass and chlorophyll a of epilithic algae revealed increased areal densities at the middle reaches compared to upstream reaches, and a drop after the confluence with the Zagdelin Gol (Hartwig et al. 2012). Macroinvertebrate communities in the middle region of the Kharaa River were characterized by high diversity and high individual numbers in general (Hofmann et al. 2011). Deficits in several structural and functional metrics could be observed at the most downstream site (Figure 5.3) indicating environmental stress for aquatic key macroinvertebrate organism groups. Linear regression analyses between macroinvertebrate community metrics and turbidity measurements identified a negative impact of fine sediments on macroinvertebrate biodiversity and important macroinvertebrate community components, esp. EPT taxa (Ephemeroptera, Plecoptera, Trichoptera). Furthermore, support for the hypothesis of fine sediment being the most important environmental factor shaping macroinvertebrate communities in the Kharaa middle region was derived from functional trait analyses. The biomass proportion of the hard substrate colonizers were decreased at the most downstream sampling station compared to the most upstream one following the longitudinal turbidity gradient, whereas biomass proportions of chironomids and oligochaetes that typically colonize fine substrate habitats were increased. This site was situated in the Kharaa lower middle region downstream of a township and additionally downstream of the Zagdelin Gol confluence. This tributary was observed carrying higher loads of fine suspended solids regularly.

5.5.3 Impact

The assessment of the ecological status along the Kharaa River indicated deficits in water quality as well as in benthic and hyporheic biota communities, especially after the confluence with the Zagdelin Gol. The subsequent investigation of the impact on ecosystem functions revealed various direct and indirect effects of suspended and infiltrated sediment (Figure 5.4) (Hartwig and Borchardt 2015).

The vertical hydrological connectivity between the surface and subsurface water compartments, as well as the penetration depth for solutes was comparably very low at the site after the confluence with the Zagdelin Gol. Consequently, the advective exchange, and thus the hydrological connection between the two compartments must have been small, with consequences for the hyporheic regulation potential (Figure 5.5). This is noticeable, as the vertical extent of the physicochemical gradients declined and the subsurface oxygen and carbon depletion with depth was found to be lowest here. In terms of productivity, this reach showed a heterotrophic signal with lowered gross primary production values compared to the reach upstream of the confluence. With respect to habitat function, it can be concluded that the habitat conditions for epilithic algae were affected directly by settled particles on the physical

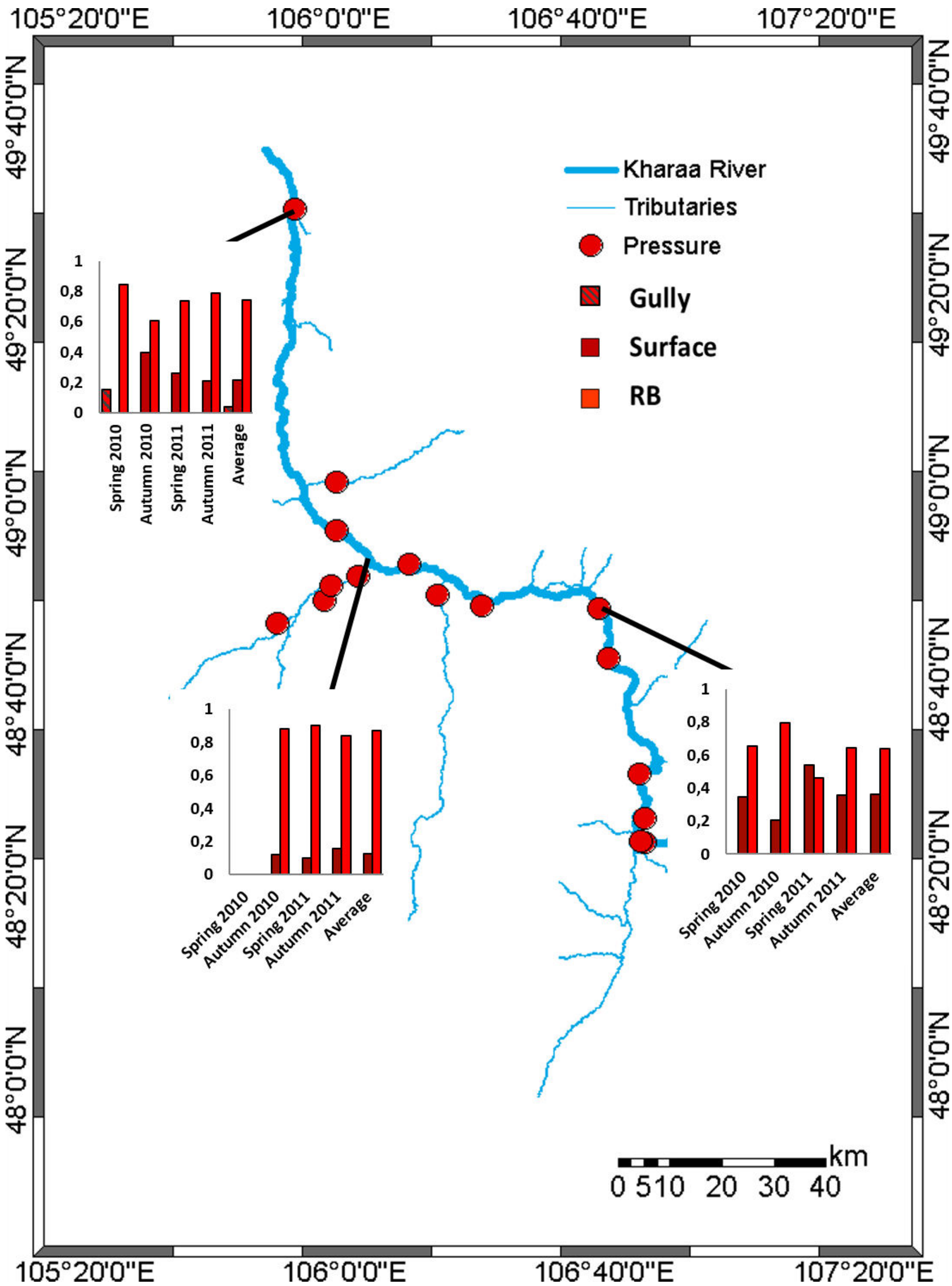

Figure 5.3: Sediment source contribution in different catchment regions as calculated with the mixing model for all sampling campaigns.

microhabitat, but also indirectly by shading caused by high suspended sediment loads in the water column. The habitat conditions for macroinvertebrates were altered by a high fraction of fine sediment that remained within the interstices of the riverbed. These increased inputs of fine sediment were associated with a reduced supply of oxygen, which decreased the depth of the suitable habitat for macroinvertebrates. This impact on the habitat function seemed to have acted for a longer time span, as indicated by the functional shift of the macroinvertebrate community composed of higher portions of fine sediment colonizers. Physical clogging and lowered vertical connectivity were also observed at deeper sediment layers at the reach within the mountain transition zone (Hartwig and Borchardt 2015), but without alteration of the ecosystem functions.

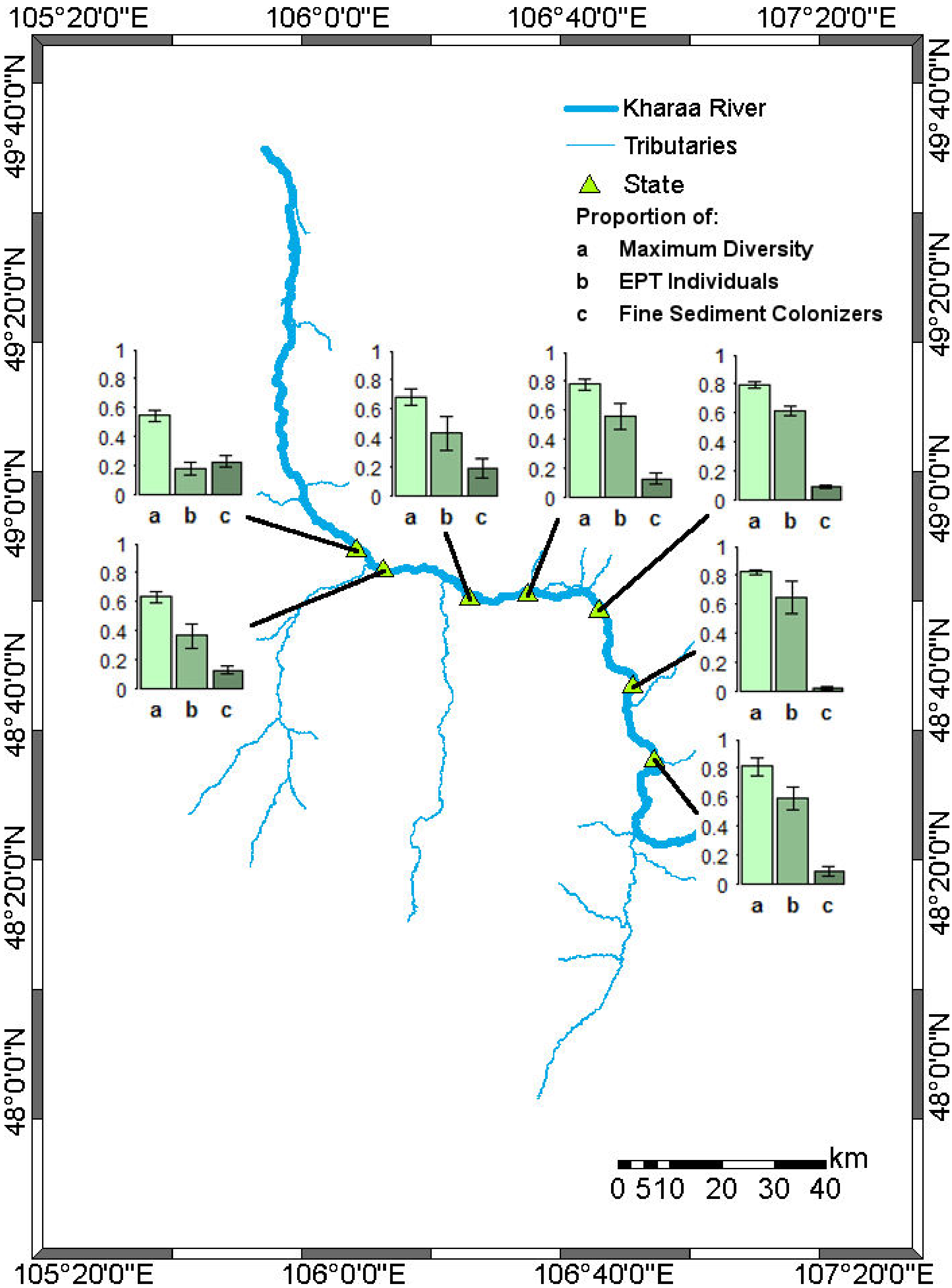

Figure 5.4: Structural and functional metrics of macroinvertebrate communities at the sampling sites in the middle region of the Kharaa River. EPT abbreviation for the insect orders Ephemeroptera, Plecoptera and Trichoptera.

5.6 Discussion

5.6.1 Pressure–state–impact chain

The results clearly showed that anthropogenically intensified river bank erosion has a significant and discernible impact on the aquatic biota and ecological functioning in the Kharaa River Basin. The determination of this causal relationship was possible, because the fine sediment loading acted as a single pressure within the investigated river reaches of the Kharaa River and other significant anthropogenic alterations typical in agricultural catchments were missing (e.g. river construction works and maintenance, flow regulations, drainage, pesticides, nutrients). Nutrient levels in the middle part of the Kharaa River are relatively low and have mean values of total N of 0.53 mg N l^{-1} and of soluble reactive phosphorus (SRP) of 0.022 mg P l^{-1} (Hofmann et al. 2011). Heavy metal contamination of the Kharaa River sediments is linked to mining activities within the catchment (Farrington 2000), but soluble heavy metal concentrations were below the maximum tolerable concentration in drinking water for all sample locations (Hofmann et al. 2010). Sparse riparian vegetation is an important reason for pronounced river bank erosion in the Kharaa River and high livestock densities accelerate these losses of riparian vegetation. Compared to other Mongolian river basins, the livestock density is highest in the Kharaa catchment with 196 head of sheep per 100 ha, although these numbers remain comparable with those of the other Mongolian catchments like the Selenga, Tuul and Khanui River (Schweitzer and Priess 2009). The general increase in livestock between 1990 and 2010 was 28.2 %, especially in regard to small animals like goats, which increased 2.7 fold (Demeusy 2012), enhanced the pressure on natural riparian vegetation and may have intensified river bank erosion. Goats have a stronger impact on soil degradation than any other species of livestock, caused by their natural grazing behavior which includes both climbing trees to feed on bark, branches, leaves and uprooting vegetation. The ongoing agricultural intensification might also result in enhanced upland erosion processes, sedimentation and associated unfavorable changes in river ecosystems. These problems are not restricted to the Kharaa study catchment and may also be important for other intensively used Mongolian catchments like the Selenga, Khanui, Tuul, Orkhon and Eroo river basins (Janchivdorj 2011). Scenario analyses on the impact of future arable land-use and intensification of grazing may help to assess their effect on suspended sediment concentration and sedimentation in river systems (Priess et al. 2011, 2015). The innovative large scale isotope sediment source fingerprinting technique applied in this study offers an excellent tool to identify the most relevant sediment sources within large river basins. In addition, erosion modelling and riparian vegetation surveys may allow the localization of hotspots of sediment sources in other comparable catchments.

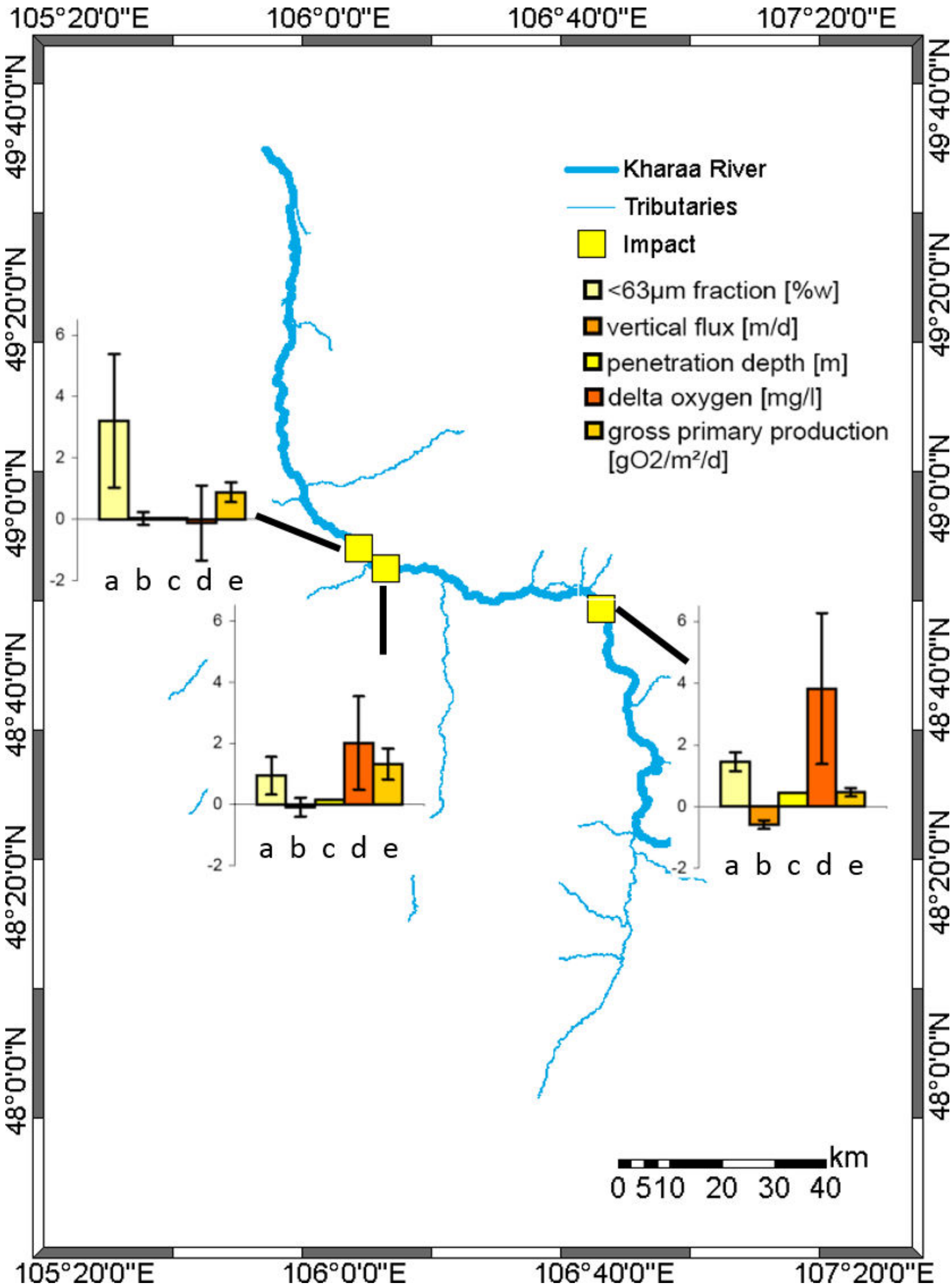

Figure 5.5: Parameters describing the fine sediment impact on the aquatic ecosystem of the Kharaa River: a clogging effective fine sediment content in the sediment matrix (0–20 cm depth); b vertical flux between surface water and 15 cm sediment depth within the riffle head (negative values indicate downwelling); c estimated solute penetration depth into the riverbed; d behaviour of subsurface dissolved oxygen (positive values indicate oxygen depletion); e gross primary production.

Within these reaches that are at risk of degradation, macroinvertebrate community analyses provided an indication of the ecological integrity of the river section. Hence, the research approach of this study helps to develop effective monitoring of aquatic ecosystem deterioration due to changing land-use conditions.

5.6.2 Response

Effective management via the application of multiply measures is urgently required to mitigate the fine sediment input in the Kharaa River system to conserve the integrity of the aquatic ecosystem and maintain the sustainable provision of water services for anthropogenic uses. Measures have to address the protection of the least impacted headwaters and tributaries, shore stabilization through restoration of riparian vegetation and the control of the currently unrestricted access of cattle to the riparian zone. Furthermore the monitoring of land-use types related to erosion processes, e.g. grazing or mining, as well as operational monitoring of the water quality has to be conducted. Efforts have to be made and last but not least raising the general public awareness and participation in maintaining and improving the ecological status of the Kharaa river system.

5.6.3 Protection of headwaters and source populations

The aquatic ecosystem is almost untouched in the Kharaa River headwater regions, but showed clear signs of degradation, declining biodiversity and loss of ecosystem functionality in their lower stretches. In particular, the riparian zones and the water quality display remarkable regional differences and significant anthropogenic degradation from upstream headwaters to downstream reaches (Hofmann et al. 2010, 2011; Hartwig et al. 2012). Like in other river networks in the region, the headwater macroinvertebrate communities were characterized by a remarkable high biodiversity (Narangarvuu et al. 2013) with distinct adaptations to the extreme continental climate through life cycles changes (Avlyush et al. 2013). Although the colonization patterns of macroinvertebrates in rivers are highly diverse among principal directions (Mackay 1992) the most dominant recovery process is by downstream drift (Waters 1972). The longitudinal fish zonation shows distinct patterns, with regional fish migration for spawning or between winter and summer habitats is pronounced for key species such as Lenok (Brachymystax lenok; Pallas 1776 and Baikal Grayling (Thymallus baicalensis; Dybowski 1874); in the reference erroneously named as Th. arcticus)

(Krätz et al. 2006). Furthermore, the Kharaa River is located within in the natural habitat range of the largest salmonid in the world, the Taimen (Hucho taimen; Pallas 1776). Its population in the Kharaa seems to be close to extinction, although there are healthy populations in adjoining catchments (e.g. Eroo River), which could still serve as source populations for the recovery in the Kharaa River system. Therefore, the consequent management of land and resource uses in the headwaters of the Kharaa River should be integral elements given the highest priority in an IWRM based management of the sediment pollution and their adverse effects on the aquatic ecosystems biodiversity and functions.

5.6.4 River bank stabilization

It could be clearly shown from the isotope signatures that bank erosion was the major source of in-stream fine sediment loadings. Consequently, measures need to be taken with high priority to further reduce the progressive erosion and loading with fine sediments. On the one hand, lateral channel dynamics are natural processes and may be a source for gravel transport (Calow and Petts 1994), but in the Kharaa, the bank erosion is significantly increased (Hartwig et al. 2012) caused by highly degraded riparian vegetation and subsequent loss of their bank stabilization function. Moreover, livestock (horses, sheep, cattle and goats) have unrestricted access to the riparian zone and further destroy the vulnerable residuals of the riparian vegetation or overgraze the sparse secondary grass vegetation. Therefore, an effective strategy for a sustainable management requires efforts to rehabilitate the riparian vegetation by increasing the natural dispersal or by reforest the autochthonous riparian vegetation in the most vulnerable river reaches. In the case of the Kharaa River, such measures are especially suggested for degraded areas in the lower middle region and the lower Zagdelin Gol. Essential complementary measures have to focus on providing alternatives for riparian firewood to the nomadic people and for watering places to control the access for livestock to the river along the riparian corridor. Especially goats are known to cause particular threats for higher riparian vegetation because of their selective feeding behavior, and should therefore be treated with special care.

5.6.5 Land-use management

After two decades of decreasing agricultural activities, in 2008 the Mongolian government started the ''Third Campaign of Reclaiming Virgin Lands'', aiming at a massive expansion and intensification of the agricultural sector (Priess et al. 2011). Furthermore, not only the extent of the land-use has been increased, but also the types of agriculture and the nomadic life styles including their traditional rules are going to change much more rapidly when compared to previous decades (Janzen 2003). With regard to land-use, Priess et al. (2015) could show in a scenario-based analysis that in the upper Kharaa catchment it is the combination of higher rainfalls on croplands combined with the expansion of agricultural land-use to steeper slopes that could cause a significant increase of water born soil erosion and subsequent fine sediment loadings into the whole Kharaa River system. Therefore, a targeted spatial allocation of the land-use and its developments in the agricultural sector is needed to minimize the potential soil erosion on catchment wide scales. A second significant source of fine sediments in the entire Tuul–Selenge–Baikal system is the mining sector, in particular gold mining (Tsengelmaa 2005; Torslund et al. 2012). Mongolia's first large scale hard rock gold mine is located in the Boroo River tributary of the River Kharaa (Hofmann et al. 2011) and there are further gold deposits expected in the catchment which might be explored in the future. In this case, a ban of these operations in the highly vulnerable headwaters might be necessary and in less sensitive exploitation areas efficient controls of the water use, sediment washout and pollution have to be implemented as integral elements of the management efforts of the Kharaa river system.

5.6.6 Monitoring

Monitoring is a core element and prerequisite for the implementation of an effective IWRM (Borchardt and Ibisch 2013). The intensity and scope of the monitoring concepts may be divided into surveillance, operational and investigative monitoring. For the entire Kharaa catchment the available data for land-use, water quantity and water quality are sparse both with respect to time series and monitoring locations (Hofmann et al. 2010, 2013). Therefore, efforts have to be taken to improve the knowledge base needed for a more effective land-use and water management and for improving the information regarding the state of the environment including trends and their drivers. The MoMo-project has developed a nested monitoring approach that would provide the required information with robust techniques and that take into account the logistic challenges of lacking infrastructures or the harsh climate (Karthe et al. 2015b). Efforts should also be made to integrate regional monitoring into larger networks, especially with regard to Lake Baikal, to create a reliable data base that would allow for the quantification of amounts and trends of sediment and contaminant loads to this unique freshwater lake (Torslund et al. 2012; Karthe et al. 2015a). Innovations could be made to involve the public more directly into the monitoring schemes, e.g. by proving cheap and robust smartphone photocells for turbidity measurements, which would apart from the direct involvement make use of the dispersal of the nomadic people across the catchment and their permanent contact with water.

5.6.7 Public awareness and participation

It is widely accepted that public awareness and public participation are needed for the sustainable implementation of wise water uses. In the MoMo-project, successful efforts have been made with stakeholder involvement in strategic sanitation planning in the city of Darkhan (Sigel et al. 2012) and in incorporating the household needs and demands for improved water supply and sanitation in peri-urban ger areas (Sigel et al. 2014). These experiences could be used and transferred to the efforts needed for a community-based management of bank erosion and riparian zones and the change of agricultural practices aiming at the minimization of soil erosion in the catchment and fine sediment inputs into the River Kharaa.

5.7 Conclusions

A system-related research approach on the analysis and examination of the cause–effect–response chain between fluvial sediment transport, the impairment of the aquatic ecosystem and effective management measures was developed. With regard to the DPSIR framework, the analysis integrated the detection of the catchments' relevant erosion sources, the assessment of the rivers' ecological status, the investigation of the impact on streambeds' functionality and the identification of abatement or mitigation measures. This scheme was implemented for the Kharaa River Basin which, for a number of characteristics, is representative for many Central Asian water basins. Serious deficits of the status of this pristine and biological rich aquatic environment could be detected with regard to the integrity of the macroinvertebrate and fish habitats which were ultimately caused by elevated fine sediment inputs. River bank erosion generated by existing grazing practices of livestock was shown to be the main cause for elevated fine sediment input. The temporal and spatial resolution of the investigations supported the explicit identification of effective measures for the protection and restoration of the aquatic ecosystem. Actions towards the protection of the headwaters and the stabilization of the river banks within the middle reaches were identified as the highest priority.

6 Discussion

In this study we developed a novel toolset for the characterization of sediment transport in semiarid regions. Radionuclide fallout fingerprinting analysis and geochemical composite fingerprinting was applied to determine the contribution of different erosional types of different catchment areas to the total suspended sediment load of the Kharaa River. To compare the quality and applicability of these methods for the study area, an additional sediment budget model was applied that allowed the calculation of erosion and sediment transport on the sub-catchment scale. Finally, these methods were complemented by a four year long continuous monitoring on discharge, sediment load, and water quality at selected points of the river reach. The results of the different methods show that:

High intensity rainfall events are of outmost importance for the discharge and suspended sediment load in the Kharaa River. The analysis of the daily SS concentrations in 2010 and 2011 show standard deviations between 83% and 175% of the monthly mean. Therefore high frequency monitoring is crucial for accurate sediment budget calculations.

The calculated sediment budget of the study catchment with the SedNet model is slightly underestimated in comparison with the budget calculated from the monitoring data (16.2 $kt \cdot a^{-1}$ compared to 20.3 $kt \cdot a^{-1}$), but both calculations are in good accordance.

Results from the radionuclide sediment source fingerprinting indicate that riverbank erosion is the most important sediment source for most catchment areas. Surface erosion only contributes significantly to the sediment load during rainfall induced high discharge events in summer, especially in the upstream and midstream reaches.

The results from the geochemical fingerprinting suggest that the main contributors of fine-grained sediment are the intensively farmed sub-catchments of the middle Kharaa catchment. These areas are impacted by the compound effects of livestock herding close to the river channels, arable land use for mainly wheat and potatoes, as well as mining, logging, and forest fires.

Anthropogenically intensified riverbank erosion linked to increasing livestock densities has a significant impact on the aquatic biota and ecological functioning in the Kharaa River.

6.1 Methods and their limitations

Each of the methods used in this study has certain advantages, but ultimately also limitations. Hence, the application of the different methods allow a comparison of the results and an assessment of the most reliable and effective method for the characterization of sediment transport and its sources in mesoscale catchment under central Asian climatic conditions.

6.1.1 Monitoring

The most accurate characterization of the suspended sediment fluxes in terms of quantity and quality is certainly the measurement of the sediment load in-situ with the help of either long term grab sampling and measurement of the suspended and dissolved load - or automated monitoring of water level, turbidity, and related water quality parameters. While these in situ measurements depict (if done properly) the situation well in small sized and experimental catchments, the implementation of a network of direct measurements in an area as large as the Kharaa River Basin allows for either a very crude network, or is inappropriately expensive. The measurement points in this study where therefore carefully chosen using the means available. The measurement of the daily suspended sediment load at the catchment outlet gives a good indication of the summarized fluvial sediment dynamic of the catchment, and is a helpful indicator for comparing the results of the other applied methods. However, this is still only an integral measurement of the total catchment and not suitable to explain the erosion and sediment transport inside the catchment area.

The installation of continuous measurements for water quality with a 15 minute resolution allows for the investigation of the seasonal and daily variation of sediment loads and conclusions of its impact on fluvial biological activity. The stations deliver information on the status of dissolved oxygen, pH, temperature, turbidity, chlorophyll a and electrical conductivity in the three most significantly differing river sections. The results are presented in a separate article co-authored by the author of this thesis (Hofmann et al. 2013) that does not constitute a part of this thesis. All other direct measurements and grab samplings were performed once or repeatedly during the study period. The longitudinal stream surveys give a good overview of the spatial distribution and difference of the dissolved concentrations of heavy metals, nutrients, and other pollutants, especially in the context of point source contributions to the fluvial system. This is clearly helpful in explaining the relationship between point and diffuse sources and their impact on dissolved or particulate inputs. The representativity of each sample point for a soil group, subcatchment or landuse class can be highly influenced by non-representative local factors. These include the sampling location of recently deposited sediments at the riverbank that can be influenced by the morphological river structure and should therefore be located at straight sections of the river channel. Sampling locations should be sufficiently far located downstream of river confluences to assure a complete mixing of the sediments after the confluence. To avoid these influences, the internal sampling variety for each sampling point was assessed by sampling five repetitive samples for each sampling point and time within the catchment.

Another limitation of the accuracy of this study is the ratio between the catchment size of the investigated study region and the number of sampling and measurement points. The Kharaa catchment covers a rather large area of 15,000 km^2. The sub catchments that were analyzed with help of the lumped samples at the sub catchment outlets range in size between 500 -2500 km^2. The accuracy to which such few samples can represent such large areas is limited and can be influenced by a wide range of factors. Therefore, a higher density of sampling points is suggested to further increase the sampling representativeness in future studies. The in situ monitoring and data sampling describe only the situation during the sampling campaigns, and at best for the few years of active monitoring. Long term changes in discharge patterns due to climatic or land use changes cannot be analyzed.

6.1.2 Sediment budget modelling

The calculation of the sediment budget and the sediment delivery pathways is based on empirical models. These models combine the calculation of erosional hillslope sediment mobilization and sediment transport to and within the fluvial system to the catchment outlet. This delivers valuable information for the characterization of the catchment, especially in data scarce areas like the study area. However, its accuracy is impaired by three main aspects

1. The usability and validity of the model parameters and coefficients used for calculation under the current climatic and erosional conditions of the study region impair the accuracy of the study. Since to date no model is available that can be developed based on process studies

in the Central Asian steppe regions, the SedNet model was chosen in this study. This model was developed in Australia for regions under similar conditions (semiarid climate, similar landuse with steppe grasslands, agriculturally used regions with few forested regions, large catchment size) (Prosser et al., 2001, Wilkinson et al., 2004; Wilkinson et al., 2005). Although the application catchment is similar in many ways, it needs to be kept in mind that it is not proven that all parameters developed in Australia can be applied for the study region. Further detailed process studies in the region are required to evaluate the natural conditions in the Kharaa catchment and help to adjust the model parameters to local specific conditions. However, the calculation of the sediment transport processes and deposition of sediments in the floodplains allows an estimation with this model for the Kharaa River catchment. Still, these estimates are associated with high uncertainties due to a lacing local parameterization of the model.

2. The accuracy of the model, as of any other model, is to a high degree determined by the quality and spatial resolution of its input data like the DEM, the spatial layers for, soil, landuse, as well as precipitation data. This also holds true for the boundary conditions applied in the model. Because in many cases, like this one, no sufficient data on these parameters exist, the definition of the parameters of the catchment properties (e.g. riverbank height and soil composition) depends highly on the expert knowledge of the user.

3. The temporal variability of erosion and sediment transport processes in the catchment can impair the accuracy of this study. Erosion and deposition pattern is highly dependent on surface cover and rainfall intensity during the different seasons of a year. High intensity rainfall events during periods with little developed vegetation cover in spring can lead to increased sediment mobilization and transport. However, the model applied in this study uses lumped sums for annual rainfall and vegetation cover on an annual basis. Data with higher temporal resolution on a monthly or weekly basis can therefore increase accuracy of the model application.

The study showed that the development of an overall sediment budget was possible using the sediment budget model SedNet. However, the obtained high resolution monitoring data showed that the fluvial sediment load is highly influenced by short term, high intensity rainfall events that cannot be described sufficiently by the model and can lead to an underestimation of the calculated budget.

6.1.3 Sediment source fingerprinting

Sediment source tracing techniques using geochemical and radionuclide properties have been widely used especially on small scale catchments (Collins and Walling, 2002; Walling, 2005; Davis and Fox, 2009). In larger catchments it becomes increasingly more difficult to distinguish different sediment source types due to increased catchment complexity and heterogeneity (Olley and Wasson, 2003; Caitcheon et al., 2012). The contribution from hillslope erosion, riverbank erosion and point sources (e.g. mining to the overall suspended sediment load of the river) may change temporally within the catchment in correlation with the annual rainfall characteristics and soil cover.

Depending on the heterogeneity in geochemical composition it is possible to differentiate the spatial distribution of sediment sources within a catchment, as well as the different source types. This does, however, depends on how distinctly source types differ in their chemical composition.

Whereas other studies (e.g. with croplands) show high Calcium concentrations, no significant difference was found in this study. Other indicators like N, or P, that helped distinguish agricultural areas from e.g. riverbank erosion in other studies, were not analyzed in this study and could not be applied. In this study we therefore compared both geochemical composition and radionuclide fallout isotope concentration of the sediments in the Kharaa catchment as suitable properties for a sediment source fingerprinting analysis. Since no single sediment source fingerprinting method delivered information on both the contribution of different erosion types to the sediment load, or a clear indication of the spatial distribution within the catchment, we utilized isotope fingerprinting techniques for the first and geochemical sediment fingerprinting for the later.

The results of the radionuclide sediment source fingerprinting in this study resulted in a very clear distinction between sediment from hillslope and sediment from riverbank erosion. The anthropogenically released radionuclide Cs-137, the naturally occurring radionuclides Be-7, and Pb-210 were used to identify the erosion process responsible for the fluvial suspended sediment yield. Since the atmospheric fallout of these radionuclides is nearly homogeneous throughout large areas, (asides from the difference in dry and wet deposition due to different precipitation quantities) it was possible to apply this method for this large study area. The differentiation between riverbank erosion and hillslope erosion worked especially well in our study. It is important to perform investigations during different years and under different rainfall and erosion patterns, since e.g. hillslope erosion is much more prominent during years with high precipitation events, and also differs greatly during the periods of summer rainfall and snowmelt induced discharge events. The method has two major obstacles to overcome.

Because of our large study catchment only the smallest particles (grain size fraction >10µm) of the eroded sediment can be assumed to be transported into and through the whole fluvial system during one rainfall event. The transport behavior of larger sediment grain size classes through the catchment is generally similar when comparing the long term behavior, but differs in terms of transit time. However, due to the higher kinetic energy necessary for the transport of larger particles, these particles underlie deposition and remobilization processes. In essence, larger particle classes are transported more slowly from their point of erosion to the catchment outlet, depending on their size. In this study no definite statement can be made on the mobilization and transport speed of these grain size classes. Therefore they cannot be used for the isotope sediment source fingerprinting, since this method is based on the decay time on isotopes. The use of only the smallest particle class renders the sample preparation very labor intensive and requires large amounts of samples to extract around 30 cm^3 of sampling material needed for gamma-spectrometric analysis within the 30 day window between sampling and analysis of the short-lived Be-7 isotopes. For future studies we therefore advocate the use of mobile centrifugation units to acquire samples directly from the suspension in water at each sampling point. Although his method is time and labor intensive in the field, it will require smaller sampling amounts and deliver only sampling material of smaller grain size classes.

The applicability of the geochemical fingerprinting method is highly dependent on the different elemental composition of the eroded sediment in areas of different landuse or geological composition throughout the catchments. This means, the more heterogeneous the catchment is in terms of geochemical sediment composition, the more effective is the differentiation between the sediment from the source areas. This also means that the method cannot be applied in study regions that show too low heterogeneity in geochemical composition. In this study there was no significant statistical difference found between the composition of samples in different landuse and soil classes nor between samples from areas of different geology, since the catchment is geologically too homogenous. Significant composite fingerprints could only be found within the subcatchments of the Kharaa. The contributions of single subcatchments could be separated. In future studies in the Kharaa and similar catchments it might also be possible to apply the method to differentiate between areas of different land use. However, this asks for the utilization of additional fingerprinting properties based on e.g. nutrients (P, C, N), physical characteristics (particle size, color), and magnetic properties (χ, ARM, SIRM) to increase the discriminatory powers of the method. This, in combination with an increased density of sampling points in future studies, can help to differentiate sediment source areas on a smaller scale. Furthermore, we advise future studies to aim for an evenly distribution of surface sampling points throughout the catchment.

6.2 The choice of the best method

While all methods used in this study have been developed and applied in previous studies, their application in a semiarid central Asian river catchment is unique to this date - enabling the evaluation of the applicability of these methods. By combining and comparing the usefulness of different approaches to characterize the erosional sources by type and spatial distribution, this study developed a toolset of methods that can be used to characterize sediment erosion and transport patterns efficiently in similar catchments throughout Central Asia, and other physio-geographically similar regions.

Depending on the resources and timeframe of a study, sediment budget models like the applied SedNet model can, in combination with basic monitoring or archive data, to a satisfactory degree depict the overall sediment budget of a catchment, and give an indication of areas which might be affected by erosion and therefore may be potential sources. Models like SedNet, however, often lack the ability to take into account the deposition and redistribution processes that occur along this path. The much more labor intensive geochemical sediment source fingerprinting technique applied in this study is therefore significantly more precise in delineating the actual source areas of the suspended sediments by directly linking them to the catchment outlet. The last missing important information, identifying the underlying processes responsible for the sediment input (in our case riverbank erosion, point sources and hillslope erosion), can be derived with the help of radionuclides. In this study Radionuclide based fingerprinting analysis therefore proved most valuable for the derivation of effective management advice. Each method used in this study is useful on itself, but only in combination is it possible to get a precise view of the full system.

The calculation of erosion susceptibility using remotely sensed data and information on soil and precipitation in combination with topographic information was used to delineate potential sediment source areas based on the Universal Soil Loss Equation in the SedNet model. The comparison of these results with the sediment source fingerprinting approach however, showed the superiority of this second method. However, sediment source fingerprinting is connected with much higher time efforts and costs. To which degree all these methods need to be applied in future studies will depend strongly on the information required. This study showed that river bank erosion generated by existing grazing practices of livestock was shown to be the main cause for elevated fine sediment input. Actions towards the protection of the headwaters and the stabilization of the river banks within the middle reaches were identified as the highest priority. Deforestation by lodging and forest fires should be prevented to avoid increased hillslope erosion in the mountainous areas. Although of limited importance for the total suspended sediment load in most of the catchment, mining activities should be monitored and well regulated by the authorities, as they can significantly contribute to the particular heavy metal concentration in the fluvial system as point sources.

6.3 Suggestions for further research

This study is an important step for the understanding of the sediment erosion and transport processes, its drivers, sources, and its impact on the fluvial ecosystem in the Kharaa river catchment. This chapter provides a list of suggestions for the improvement of the study approach and points out open questions for the focus of future research in the region.

This study greatly improved the database for continuous monitoring of discharge and suspended sediment transport in the Kharaa catchment. It is recommended that future studies continue developing these data series and supplement them by similar measurements on the subcatchment level.

The spatial resolution of the network of grab samples should be improved to allow for a more precise sediment source fingerprinting on a scale below the subcatchment level that was applied in this study.

For a better differentiation of the sediment sources in future studies we advocate the utilization of additional parameters like nutrients (P, C, N), physical characteristics (particle size, color) and magnetic properties (χ, ARM, SIRM) to increase the discriminatory powers of the method.

Instead of the sampling of recently suspended sediment from the riverbank after high water stages, it is recommended to use mobile centrifuges to extract large amounts of sediment directly out of the suspension in the water and avoid sorting effects during their deposition.

Future studies should apply the created dataset in different sediment budget and mixing models to compare the explanatory power of the models used in this study and to investigate the applicability of alternative models in this region.

The approach chosen proved useful for application in a Central Asian semi-arid cold climate basin and should be applied and tested in studies in similar conditions throughout the region.

Because the Kharaa catchment is a subcatchment of the Selenga-Baikal Basin, we recommend the application of this approach to this catchment.

The DPSIR framework applied in this study for the integrated analysis of the catchments' relevant erosion sources, the assessment of the rivers' ecological status, the investigation of the impact on streambeds' functionality, and the identification of abatement or mitigation options should be applied by future studies in the region. This will help to put the results of such sediment and erosion studies in a wider context.

Future studies should advocate the application of the management advice developed in this study and investigate the impact of best management practices on soil erosion, fluvial sediment transport, and its impact on the riparian ecosystem in the Kharaa.

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Acknowledgements

This study has been part of the research within the IWAS Initiative as well as the Integrated Water Resources Project Model Region Mongolia (MoMo), both funded by the Federal Ministry for Education and Research (Grant-No. 02WM1027, 033L003A). The author was additionally supported through the Helmholtz Impulse and Networking Fund through the Helmholtz Interdisciplinary Graduate School for Environmental Research (HIGRADE). The author thanks M. Schaeffer, S. Avlyush, B. Tsedendorj, N. Natsagnyam, and M. Hartwig for their help during the expeditions and S. Rossack, E. Maahs, M. Pfeifer, M. Raschewski, W. v. Tümpling, A. Hoff, and M. Hoffmeister for sample preparation and laboratory analysis. Further thanks go to all co-authors of the articles used in this thesis and to G. Aid for proofreading and structural analysis of this thesis

I am especially thankful to my supervisor Michael Rode for counselling, reviews, discussions, and guidance. This thesis would not have been possible without him. Further Thanks go to Axel Bronstert for his co-supervision of the thesis.

Finally, I would like to thank my wife, parents and friends for their constant motivation and support during the preparation of this work.

Eidesstattliche Erklärung

Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertation ohne fremde Hilfe angefertigt und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe. Alle Teile, die wörtlich oder sinngemäß einer Veröffentlichung entstammen, sind als solche erkennbar. Die Arbeit wurde noch nicht veröffentlicht und auch noch keiner anderen Prüfungsbehörde vorgelegt.

Kaufbeuren, den 15.11 2017

Philipp Theuring