Impact of fine sediment and nutrient input on the hyporheic functionality: A case study in Northern Mongolia

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"Impact of fine sediment and nutrient input on the hyporheic functionality: A case study in Northern Mongolia"

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stay close to nature.
It will never fail you."

Frank Lloyd Wright

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Contents

List of Publications

The manuscript of this cumulative thesis consists of an integrative chapter of synthesis and four articles with each of them building one chapter. The first two of them were already published by a journal at the time of submission of the thesis. One another article was already submitted and the other is in preparation for submission to a journal.

Chapter 2: **Hartwig, M.**, Theuring, P., Rode, M., and Borchardt, D. (2012). Suspended sediments in the Kharaa River catchment (Mongolia) and its impact on hyporheic zone functions. *Environmental Earth Sciences*, 65(5), 1535-1546. DOI: 10.1007/s12665-011-1198-2

Chapter 3: **Hartwig, M.**, and Borchardt, D. (2014). Alteration of key hyporheic functions through biological and physical clogging along a nutrient and fine-sediment gradient. *Ecohydrology*, DOI: 10.1002/eco.1571

Chapter 4: **Hartwig, M.**, and Borchardt, D. (in prep.). Boundaries of hyporheic functionality under physical and biological clogging. in preparation

Chapter 5: **Hartwig, M.**, Schäffer, M., Theuring, P., Avlyush, S., Rode, M., and Borchardt, D. (accepted). 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). *Environmental Earth Sciences*

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Abstract / Zusammenfassung

The hyporheic interstitial was recognized as an integral zone within the aquatic ecosystem bearing important functions for both adjacent compartments, surface and ground water, about 50 years ago. Since then, rather disciplinary works gained knowledge on the organismic community of this ecotone, it's spatial extent, the role of distinct parameters such as hydrology and morphology, temporal characteristics, process dynamics, the role for stream or groundwater quality and restoration measures. However, a systematic study on the risks to the hyporheic functions was missing to date.

This thesis combined existing methods in order to gather an integrated set of information allowing for the assessment of the ecotonal status. This approach was applied to investigate the functional behavior towards stressors like increasing nutrient and fine sediment input into a rather pristine environment. An interdisciplinary risk assessment and the establishment of adapted measures was called for as land-use scenarios for the studied catchment area indicated progressive onland erosion.

Therefore firstly, an integrated monitoring scheme was drawn up and conducted at three sites along a river that underlay a stressor gradient such as mentioned before. Secondly, the data sets were analysed in order to evaluate the status of the hyporheic funtions at the riffles. Thirdly, a coupled surface-subsurface modelling approach was set up to further study the impact of the stressors on the ecotonal integrity. And fourthly, an interdisciplinary consideration combined with studies on the catchment's sediment budget and the river's ecological status was applied to identify measures for the restoration and protection of the aquatic ecosystem.

The analysis of the data gathered with the help of the established monitoring scheme revealed that elevated nutrient or fine sediment input lead to biological or physical clogging, respectively, with consequences for the hyporheic zone functions. The surface - ground water connectivity was either lowered in summer months, when biofilm growth was highest, or permanently, as fine sediment particles infiltrated into the interstices of the riverbed sediment. Scouring did not seem to take place as high amounts of fine particles were found in the matrix after discharge events of snowmelt and summer precipitation. With respect to the biogeochemical regulation function, biofilm material appeared to provide an autochthonous carbon source boosting microbial substance turnover. The sediment underneath the physical clogged layer was cut off from carbon and oxygen rich surface water and thus was not reactive. However, the enhanced surface area provided by the fine sediment within the topmost sediment layer seemed to support microbial processing. The inclusion of the results of a study concerning the ecological status at the investigated reaches lead to the deduction that biological clogging at the present degree was not affecting habitat quality. Whereas the physical clogging had tremendeous and lasting effects on the macroinvertebrate community which carries to the conclusion that sediment management within the studied catchment is of uttermost importance.

A scenario analysis reflecting distinct clogging degrees and types with a calibrated model of a studied riffle within a pristine reach proved the observed loss of hydrologic connectivity due to physical and biological clogging. Further, a treshold of oxygen consumption rates above which the reproduction of salmonid fish would be unsuccessful was identified for the settings of the middle reaches. In summer month with low discharge it seemed to be likely that this treshold might be reached. Following, a dynamic discharge may be decisive to protect the ecotonal integrity.

The integration with the outcome of an investigation regarding the sediment sources within the catchment allowed for two suggestions. On the one hand, river bank restoration and protection within the middle reaches need to be prioritised, and on the other hand, the conservation of the natural vegetation at the steep slopes within the mountaineous areas need to be undertaken in order to secure the pristine aquatic environment of this area.

Hyporheic zone research of the last decade was driven by testing hypotheses on the functional significance of distinct spatial and temporal configurations in the field and by new modelling approaches. However, data on the quantification of the ecological impact of clogging processes were lacking. The thesis contributed to the systemic understanding of the hyporheic zone being affected by physical and biological clogging and new field data within a degrading pristine environment were generated, accessible for further hyporheic research. The interdisciplinarity enabled comprehensive statements for the usage of an Integrated Water Resources Management plan.

Vor etwa 50 Jahren begann man das hyporheische Interstitial als integrale Zone innerhalb des aquatischen Ökosystems zu verstehen, welches wichtige Funktionen für beide angrenzenden Kompartimente - Oberflächengewässer und Grundwasser - inne hat. Seit dem haben eher disziplinisch angelegte Arbeiten das Wissen um die organismische Gemeinschaft dieses Ökotons, die räumliche Ausdehnung, die Rolle verschiedener Parameter wie Hydrology und Morphology, zeitliche Aspekte, Prozessdynamiken, die Bedeutung für die Fluss- und Grundwasserqualität sowie Sanierungsmaßnahmen erlangt. Jedoch fehlte es bislang an einer systematischen Untersuchung zu Gefährdungen für die hyporheischen Funktionen.

In der vorliegenden Dissertation wurde ein Messkonzept entwickelt, mittels dessen ein integriertes Set an Informationen erhoben und der ökotone Zustand beurteilt wurde. Dieses Vorgehen wurde angewandt, um das Verhalten der Funktionen eines natürlichen Systems gegenüber Stressoren wie erhöhtem Nähr- und Schwebstoffdargebots zu untersuchen. Landnutzungen, welche zur erhöhten Oberflächenerosion führen, erforderten eine interdisziplinäre Gefährdungsabschätzung und die Aufstellung eines Katalogs effizienter Maßnahmen.

Zu diesem Zweck wurde als erstes ein integriertes Erkundungsprogramm zusammengestellt und an drei Untersuchungsstandorten entlang eines Flusses, welcher dem eben erwähnten Stressgradienten unterlag, durchgeführt. Als zweites wurden die daraus resultierenden Datensätze im Hinblick auf die Bewertung des Zustands der hyporheischen

Funtionen an jedem Riffel analysiert. In einem dritten Schritt wurde ein gekoppeltes Oberflächen-Grundwassermodell aufgesetzt, um die Auswirkung der Stressoren auf die ökotone Integrität genauer zu untersuchen. Und als viertes wurde eine interdisziplinäre Betrachtung zusammen mit Arbeiten zum Sedimenthaushalt des Einzugsgebiets sowie zu dem ökologischen Zustand dargelegt, um Maßnahmen zur Sanierung und Erhalt des aquatischen Ökosystems zu identifizieren.

Die Analyse der Daten, welche mit dem Erkundungsprogramm gewonnen wurden, zeigte, dass erhöhte Nähr- bzw. Schwebstoffeinträge zu biologischem oder physikalischem Clogging mit Auswirkungen für die Funktionen der hyporheischen Zone führten. Die Konnektivität von Oberflächen- und Grundwasser verringerte sich in den Sommermonaten, wenn das Wachstum des benthischen Biofilms seinen höchsten Stand hatte, oder permanent, da sich Schwebstoffpatikel auf dem Flussbett ablagerten und sich in den Zwischenräumen des Flussbettsediments einlagerten. Eine Auswaschung schien nicht stattgefunden zu haben, da ein hoher Anteil an Feinsedimenten auch nach den Schneeschmelz- bzw. Sommerhochwasserabflüßen nachgewiesen wurde. Biofilmmaterial stellte eine autochtone Kohlenstoffquelle für die biogeochemische Regulationsfuntkion dar, welches mikrobielle Umsatzprozesse zu unterstützen schien. Das Sediment unterhalb dem physikalisch kolmatierten Bereich war von der Zufuhr kohlenstoff- und sauerstoffhaltigem Oberflächenwassers abgeschnitten und folglich nicht reaktiv. Allerdings stellten die Feinsedimente in dem obersten Sedimentabschnitt eine erhöhte Oberfläche dar, welche mikrobielle Umsätze begünstigte. Unter Hinzunahme der Ergebnisse einer anderen Studie über den ökologischen Zustand der untersuchten Flussabschnitte kann geschlussfolgert werden, dass das biologische Clogging in dem vorliegenden Grad keine negativen Auswirkungen auf die Habitatqualität hatte. Im Gegensatz dazu hatte das physikalische Clogging enorme und nachhaltige Konsequenzen für die Makroinvertebratengemeinschaft, was zu dem Schluss führt, dass das Sedimentmanagement in dem Untersuchungsgebiet von äußerster Wichtigkeit ist.

Die Anwendung verschieder Szenarien des Grades und Typus des Cloggings mit einem für den naturnahen Flussabschnitt kalibrierten Modell eines Riffels bestätigte den beobachteten Verlust der hydrologischen Konnektivität durch das physikalische oder biologische Clogging. Desweiteren wurde ein Grenzwert der Sauerstoffzehrung, der bei Überschreitung zu einer erfolglosen Reproduktion von Salmoniden führt, für die Gegebenheiten der mittleren Flussabschnitte ermittelt. In Sommermonaten mit geringem Abfluss könnte dieser Grenzwert durchaus erreicht werden. Folglich spielt die Abflussdynamik eine entscheidende Rolle beim Schutz des Ökotons.

Die Integration mit den Resultaten einer Untersuchung zu den Sedimentquellen im Einzugsgebiet ließ zwei Schlußfolgerungen zu: zum einen sind die Sanierung und der Schutz der Uferbänke in den mittleren Flussabschnitten zu priorisieren, und zum anderen, muss die natürliche Vegetation an den steilen Hängen der Gebirgsregion erhalten werden, um das aquatische Ökosystem jener Gebiete zu schützen.

Die Erforschung der hyporheischen Zone der letzten zehn Jahre war getrieben von der Hypothesentestung der ökologischen Bedeutung verschiedener räumlicher und zeitlicher Zustände durch Arbeiten im Feld und mittels neuer Modellansätze. Jedoch mangelt es an Datensätzen zur Quantifizierung der ökologischen Auswirkung von Clogging-Prozeßen.

Diese Dissertation trägt zum systemischen Verständnis der durch physikalischen und biologischen Clogging beeinträchtigten hyporheischen Funktionen bei und liefert, zugänglich für nachkommende Forschung, neue Felddaten von einem degradierenden natürlichen System. Die Interdisziplinarität ermöglichte umfassende Aussagen für die Anwendung innerhalb eines Vorhabens zum integrierten Wasserressourcenmanagement.

1. Synthesis

1.1. The hyporheic zone and the inherent functions

The hyporheic zone builds a spatially and temporally dynamic region where groundwater (GW) and surface water (SW) environments intermingle as for example at the bed sediment of a river or stream. This boundary zone is characterized by vertical and lateral gradients of physical and chemical parameters such as light, temperature, flow velocity, pH, redox potential and solutes like dissolved oxygen and carbon or species of nitrogen and phosphorus. It is an integral part of the aquatic ecosystem being a transition zone between SW and GW ecosystems resulting in gradients of species abundance of lower and higher organisms.

Due to the circumstances resulting from the interaction, this ecotone bears several functions. Firstly, it functions as a hydrological connector mediating the flow of water between the GW and SW. Secondly, it is a biogeochemical regulator in the form of a dynamic sink or source of matter for both GW and SW. And thirdly, it provides a permanent or temporal habitat for a vast number of organisms.

Each of the functions is controlled by a distinct set of parameters. The hydrological connectivity is determined by the discharge of the SW and recharge of the GW (Cardenas and Wilson, 2007a), the bed morphology (Cardenas and Wilson, 2007b), the sediment characteristics (Packman et al, 2004), invertebrate engineering (Mermillod-Blondin et al, 2003) and aquatic plants (Salehin et al, 2004). The biogeochemical regulation is governed by the availability of electron donors and acceptors, redox conditions (Jones et al, 1985; Fisher et al, 1998; Storey et al, 1999), temperature, sediment characteristics, microbial toxins (Feris et al, 2004), and grazing pressure. The habitat function is a matter of discharge, temperature, food and oxygen availability (Malard et al, 2003) as well as sediment characteristics (Brunke and Gonser, 1997).

As stated in Krause et al (2011), the functions may be easy to be looked at seperately by hydrologists, biogeochemists or ecologists. However, there are many intermingling factors and dependencies to be considered when trying to understand hyporheic functioning. Thus, the first objective of the thesis was the following:

How does an adequate monitoring scheme have to look like in order to gather a set of data characterising the ecotone functions?

The riffle scale (see Fig. 1.1) was chosen for this purpose as it represents the relevant scale for the functions effective radius. The hydromorphological structure of a riffle was selected as it represents a highly interactive zone (Harvey and Wagner, 2000) with down- and upwelling of SW or GW, respectively. The vertical boundaries were set from the interface with the surface water down to a maximum observation depth of 45 cm below the interface with the SW as restricted through the porewater sampling device. The investigation was related to midflow conditions that covered most of the time during the

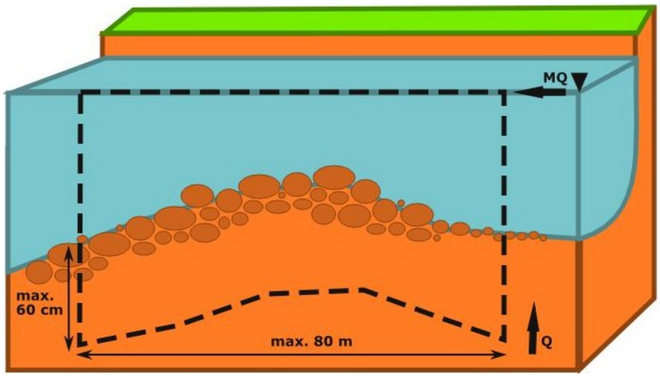

Fig. 1.1. – Spatial and temporal boundary conditions of the investigations.

ecological active period within the studied catchment.

According to this objective, an output of the thesis is an integrated monitoring scheme (see Fig. 1.2 and Tab. A.2, A.3, A.4) that helps characterising the status of the hyporheic zone at the riffle scale (see Chapter 2 & 3). It includes measurements of hydraulic, chemical and biological values in order to determine parameters describing the surface and subsurface compartment as well as their interactions.

Improvements are suggested in the following, insofar as they are feasible in terms of equipment and manpower. Several replications at similar boundary conditions are necessary in order to have a reasonable extrapolation of physical and chemical subsurface parameters that may uncover outliers. For example, multi-level water samplers could also be installed at a parallel longitudinal transect. Due to the complex regime of sedimentation and erosion at the river bottom it would be meaningful to increase the amount of sediment sampling points. In case of grain sizes smaller than 5 cm it would be feasible to switch from the laborious freeze core method to other techniques such as a sediment corer or falling head. On the one hand, high water exchange within the shallow sandy layers reduce the sampling volume sticking to the freeze corer, on the other hand, repetitions can be made much easier. More direct techniques are preferable with regard to

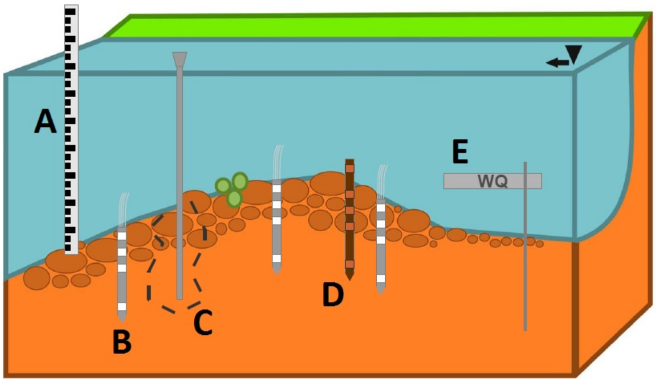

Fig. 1.2. – Scheme of the monitoring equipment: (A) meter, (B) multi-level sampler, (C) freeze corer, (D) multi-level temperature device, (E) multi-parameter water quality probe.

the determination of substance exchange and transport as other sinks and sources can be detected. Novel approaches are developed which allow for a combined performance of a conservative and reactive tracer test (e.g. Lemke et al, 2013). Compared to point measurements and their extrapolation, tracer tests also better reflect the reach scale.

1.2. Threats to the ecotone functioning

As the characteristic of the riverbed sediment is significant for hyporheic functioning, the physical or biological clogging of interstices may become of highly relevant. The impact of fine sediment blocking the pore spaces and therefore reducing hyporheic flux has been demonstrated in several experiments (Schälchli, 1992; Ryan and Packman, 2006). The effects for biogeochemical processes are more complex: the fine sediment may provide a carbon source and a larger colonizable surface area for microbes (Nogaro et al, 2010). This may favour only the uppermost part of the hyporheic zone as hyporheic exchange and solute transport is then restricted to the depth of clogging (Battin and Sengschmitt, 1999). Food availability may increase for biofilm grazing invertebrates, but habitat quality in terms of pore space and oxygen availability decreases at the same time (Wood and Armitage, 1997). The impact of (benthic and hyporheic) biofilm growth on sediment permeability was also recognized. On the one hand, hyporheic exchange is lowered (Ibisch et al, 2009) whilst on the other hand, biogeochemical processes may be fuelled by the decay of biofilm tissues or exudates (Battin and Sengschmitt, 1999). Both clogging phenomena are controlled by the discharge dynamic, hydromorphology as well as inputs of fine sediment and nutrients. All of these factors may be altered by human use of the SW, GW and adjacent land. Land-uses like cropland, pasture, mining and clear-cut logging were demonstrated to affect hyporheic functions through the displayed processes (Moring, 1982; Boulton et al, 1997).

The hyporheic's functionality as filter and buffer system can become important for the adjacent hydrological compartments and their inherent ecosystem (Smith, 2005). The ecotone may protect GW quality as well as improve the SW quality (Triska et al, 1993; Lefebvre et al, 2004; Pinay et al, 2009). Thereby, the significance of the hyporheic zone to SW or GW is a function of the activity and extent of the connection (Boulton et al, 1998; Findlay, 1995). The functionality was found to be increased in systems with dynamic and highly heterogeneous hydrologic and biogeochemical processes (Bencala, 2000). However, the relative importance of physical and biological disturbances to the functions of the hyporheic zone as well as their effect on the significance to the SW quality remain unclear (Boulton et al, 1998; Rode et al, 2010). Besides, field data on clogging effects for biogeochemial cycling are scarse (Nogaro et al, 2010). Hence, the second objective of the thesis was as follows:

How do the ecotone functions behave given the stressor gradient of increasing nutrient and fine sediment input?

The Kharaa River in Northern Mongolia was of special interest for this kind of investigations. In general, the Kharaa River has a large width to depth ratio and so it can be assumed that hyporheic zone processes are relevant for the entire river. Further, the impact on the aquatic system could be contributed to nutrient and fine sediment input only which made it easy to analyse the cause and effect regime. And, the state of the river was in a transition from pristine to affected conditions (see Tab. A.1) what made it possible to select an unaffected, a biologically clogged and a physically clogged sampling site within one river system. The integrated monitoring scheme was applied at three sites along this gradient of stressors to meet this objective. The data set gathered was analysed statistically and numerically (Chapter 3).

The data analysis revealed that elevated nutrient and fine sediment inputs at the two downstream reaches caused biological and physical clogging respectively. Thereby, biological clogging only affected the functions of hydrologic connectivity, biogeochemical regulation and habitat within the last summer month (Tab. 1.1). Biofilm activity, the carbon supply through biofilm mineralization and the biofilm as food source for higher organisms even lead to positive feedbacks on the hyporheic functionality. The effects of physical clogging were permanent with negative consequences for the entirety of functions. When related to the ecological study of Hofmann et al (2011), habitat quality must have been affected so much that a shift in the functional composition within the macroinvertebrate community towards fine sediment colonisers was recognised.

This data analysis gave only ideas of this cause and effect regime. In order to better understand this complex system, a model of a riffle structure under pristine conditions was build. It allowed for a numerical analysis of the set of data and the quantification of the clogging impacts for hyporheic functioning (see Chapter 4). The underlying questions were:

In which way do the degree and type of clogging affect the hyporheic functioning? Are there tresholds being decisive for the ecotonal integrity?

The observations on the negative effect of physical and biological clogging for the hydrologic connectivity were proven. The scenario analysis showed that this function is direct dependent on the clogging degree. Especially, when horizontal conductivities drop below an order of magnitude, the connectivity decreases most rapidly. The clogging type is critical for the habitat of spawning fish. Under moderate clogging conditions eggs and larvae would not survive if the oxygen consumption rate exceeds $1.2*10^{-4}$ s^{-1}. This is likely to occur as the reproduction season of salmonid fishes of this region spans until July when biofilm growth can be high. The natural discharge regime with high peak flows might protect or improve the ecotonal integrity as it controls biofilm growth and the sediment dynamic.

With regard to the models reactive transport of dissolved oxygen, the availability of carbon and its simultaneous degradation could be added. A higher resolution of the riverbed morphology may also help to improve transport simulation. Data on the distribution of distinct groups of organisms as well as infiltrated fine sediment can be gathered in order to refine the model set up.

Tab. 1.1. – The impact of investigated processes of clogging on the hyporheic zone functions compared to pristine conditions.

function		**clogging process**	
	physical clogging	**biological clogging**	**no clogging**
connectivity	low	moderate	high
	permanently decreased to top 5 cm	decreased in summer months	decreased below 40 cm depth
regulation	moderate	good	good
	restricted to uppermost sediment layer	fueled by organic tissue	dependent on nutrient input
habitat	moderate	good	good
	decreased quality and quantity	biofilms as food source	high habitat diversity

1.3. The role in water management and conservation

From an ecological point of view, the management of the water resources need to consider both, water quantity and quality. Thus, actions may address the modification and pollution of the water body and their adjacent catchment area. Given the importance of the ecotone functionalities for the aquatic ecosystem, stressors affecting the hyporheic zone need to be considered as well. Three possible impacts need to be considered for the Kharaa catchment: the load of toxic material such as heavy metals, the high load of nutrients and fine sediment load (Tab. 1.2). Ecological studies on the fish biocoenosis (Krätz, 2009) and the composition of the macroinvertebrate community (Hofmann et al, 2011) revealed habitat losses especially for the middle reaches. This impact was assumed to be caused by enhanced fine sediment load. Effects through the release of heavy metals from mining areas, the hydromorphological degradation or saprobic pressure could be excluded. In accordance with these findings, the fourth objective of this thesis was formulated as follows:

What kind of measures at which places are necessary in order to protect aquatic life?

As demonstrated before, the effects of physical clogging were permanent with negative consequences for all of the functions. Thus, measures considering the fine sediment inputs were prioritised. Consequently, establishing adapted measures protecting the aquatic ecosystems at risk or possibly at risk with regard to fine sediment input needed the integration of the findings of this thesis as well as the outcome of the research concerning the sources of fine sediment (Theuring et al, 2013) and upon the effects on the ecological status of the Kharaa River (Hofmann et al, 2011) (see Chapter 5). All three studies were part of the ”‘IWRM Model Region Mongolia”’ project (Grant-No. 033L003A, German Federal Ministry for Education and Research) focusing on the Kharaa River catchment (see Fig. 1.3).The DPSIR framework (EEA, 1995) represents a helpful guide for such a complex task and an appropiate tool for the communication between the research disciplines involved.

Tab. 1.2. – Possible impacts affecting the functions of the hyporheic zone that need to be considered within the Kharaa catchment.

impact	cause
toxic load	mining release (SW, GW)
nutrient load	urban waste water livestock fecals decreased discharge
fine sediment load	deforestation overgrazing decreased discharge

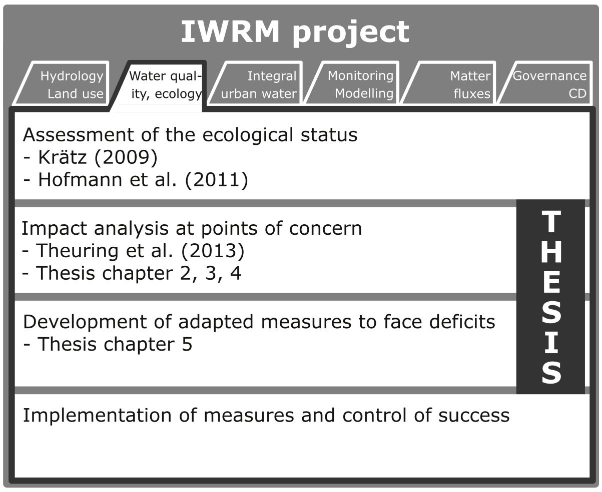

Fig. 1.3. – Overview on the working packages of the IWRM project and the placement of the thesis work within the project framework.

With the help of the demonstrated integrated approach it was proven that livestock grazing practices (Driver) enhance the destabilization of the river banks which leads to a high input of fine sediment (Pressure). This causes physical clogging of the riverbed sediment (State) which is responsible for a decrease of hyporheic functions (Impact) like the decline in habitat suitability for macroinvertebrates (see Chapter 5). Thus most acute, the riparian areas within the middle Kharaa need to be restored in order to protect the aquatic environment (see Tab. 1.3). Further, cropland expansion to steep slopes in the upper Kharaa (Priess et al, 2014) is also likely to drive the same process. Therefore, preventative measures are suggested within this area. Indicators for hyporheic health like the grain size distribution or the functional composition of the macroinvertabrate community are proposed in order to evaluate the effectiveness of applied measures. However, ongoing mining activities and plans of water infrastructure might increase the pressure on the aquatic ecosystems in the near future.

Tab. 1.3. – Conclusions for the further IWRM process - the implementation of adapted measures.

	upper Kharaa	**middle Kharaa**
status	good: hot spot biodiversity	moderate: affected ecosystem functions
risk	physical clogging deep sediment	biological and physical clogging
measure	conservation terrestrial vegetation	improvement grazing practices protected riparian areas
area	Bayangol subcatchment (Fig. **??**)	along middle Kharaa, lower Zagdelin Gol
indicator	grain size distribution riverbed	status riparian vegetation macroinvertebrates (functional composition)

1.4. Outline of the thesis

The goal of the thesis was to analyse the hyporheic ecotone and the inherent functionalities under different stress conditions in order to be able to suggest measures to manage the system. The scientific procedure is presented in the following chapters.

First of all, an adapted monitoring scheme integrating methods to obtain data for the assessment of the hydraulic regime, the sediment properties and the biogeochemistry within the surface and subsurface water compartment was elaborated. Representative sampling sites and sampling times were identified where and when to apply the scheme. Second, the data were analysed for the description of the status of the hyporheic zone and the impact on the ecotone functions at each site. Third, further numerical analyses were conducted which helped to understand under which circumstances the condition within the hyporheic zone becomes critical for aquatic ecosystem health. Fourth, adapted measures were deduced as part of the IWRM for the studied catchment. Therefore, the results of the impact study of this thesis were discussed together with the outcomes of two studies on the pressure to and status of the aquatic ecosystem.

References

Battin TJ, Sengschmitt D (1999) Linking sediment biofilms, hydrodynamics, and river bed clogging: Evidence from a large river. Microbial Ecology 37:185–196

Bencala E (2000) Hyporheic zone hydrological processes. Hydrological Processes 14:1085–1099

Boulton AJ, Scarsbrook MR, Quinn JM, Burrell GP (1997) Land-use effects on the hyporheic ecology of five small sstream near Hamilton, New Zealand. New Zealand Journal of Marine and Freshwater Research 31:609–622

Boulton AJ, Findlay S, Marmonier P, Stanley EH, Valett HM (1998) The functional significance of the hyporheic zone in streams and rivers. Annual Review of Ecology and Systematics 29:59–81

Brunke M, Gonser T (1997) The ecological significance of exchange processes between rivers and groundwater. Freshwater Biology 37:1–33

Cardenas BM, Wilson JL (2007a) Exchange across a sediment-water interface with ambient groundwater discharge. Journal of Hydrology 346:69–80

Cardenas BM, Wilson JL (2007b) Hydrodynamics of coupled flow above and below a sediment-water interface with triangular bedforms. Advances in Water Resources 30:301–313

EEA (1995) Europe's Environment: the Dobris Assessment. URL http://www.eea.europa.eu/publications/92-826-5409-5

Feris KP, Ramsey PW, Frazar C, Rillig M, Moore JN, Gannon JE, Holben WE (2004) Seasonal dynamics of shallow-hyporheic-zone microbial community structure along a heavy-metal contamination gradient. Applied and Environmental Microbiology 70(4):2323–2331

Findlay S (1995) Importance of surface-subsurface exchange in stream ecosystems: The hyporheic zone. Limnology and Oceanography 40(1):159–164

Fisher SG, Grimm NB, Marti E, Holmes RM, Jones JB (1998) Material spiraling in stream corridors: a telescoping ecosystem model. Ecosystems 1:19–34

Harvey JW, Wagner BJ (2000) Quantifying hydrologic interactions between streams and their subsurface hyporheic zones. In: Jones JB, Mulholland PJ (eds) Stream and Ground Waters, Academic, San Diego, Calif., pp 3–44

Hofmann J, Hürdler J, Ibisch R, Schäffer M, Borchardt D (2011) Analysis of Recent Nutrient Emission Pathways, Resulting Surface Water Quality and Ecological Impacts under Extreme Continental Climate: The Kharaa River Basin (Mongolia). International Review of Hydrobiology 96:484–519

Ibisch R, Seydell I, Borchardt D (2009) Influence of periphyton biomass dynamics on biological colmation processes in the hyporheic zone of a gravel bed river (River Lahn, Germany). Fundamental and Applied Limnology Advances in Limnology 61:87–104

Jones JG, Berner RA, Meadows PS, Durand B, Eglinton G (1985) Microbes and microbial processes in sediments. Philosophical Transactions of the Royal Society A 315:3–17

Krätz D (2009) Ökologie der Fischbestände in Fließgewässern des Khentii-Gebirges (Mongolei): Bestandsaufbau, Dynamik und Gefährdung durch den Gold-Tagebau. PhD thesis, Technische Universität Dresden

Krause S, Hannah DM, Fleckenstein JH, Heppell CM, Kaeser D, Pickup R, Pinay G, Robertson AL, Wood PJ (2011) Inter-disciplinary perspectives on processes in the hyporheic zone. Ecohydrology 4(4):481–499

Lefebvre S, Marmonier P, Pinay G (2004) Stream regulation and nitrogen dynamics in sediment interstices: comparison of natural and straightened sectors of a third-order stream. River Research and Applications 20(5):499–512

Lemke D, Liao Z, Wöhling T, Osenbrück K, Cirpka OA (2013) Concurrent conservative and reactive tracer tests in a stream undergoing hyporheic exchange. Water Resources Research 49(5):3024–3037

Malard F, Galassi D, Lafont M, Dolédec S, Ward J (2003) Longitudinal patterns of invertebrates in the hyporheic zone of a glacial river. Freshwater Biology 48(10):1709–1725

Mermillod-Blondin F, Gaudet JP, Gérino M, Desrosiers G, Creuzé Des Châtelliers M (2003) Influence of macroinvertebrates on physico-chemical and microbial processes in hyporheic sediments. Hydrological Processes 17:291–297

Moring JR (1982) Decrease in stream gravel permeability after clear-cut logging: An indication of intergravel conditions for developing salmonid eggs and alevin. Hydrobiologia 88:295–298

Nogaro G, Datry T, Mermillod-Blondin F, Descloux S, Montuelle B (2010) Influence of streambed sediment clogging on microbial processes in the hyporheic zone. Freshwater Biology 5:1288—-1302

Packman AI, Salehin M, Zaramella M (2004) Hyporheic exchange with gravel beds: Basic hydrodynamic interactions and bedform-induced advective flows. Journal of HHydraulic Engineering 130(7):647

Pinay G, O'Keefe TC, Edwards RT, Naiman RJ (2009) Nitrate removal in the hyporheic zone of a salmon river in alaska. River Research and Applications 25:367–375

Priess J, Schweitzer C, Batkhishig O, Koschitzki T, Wurbs D (2014) Impacts of agricultural land-use dynamics on erosion risks and options for land and water management in northern mongolia. Environmental Earth Sciences pp 1–12

Rode M, Arhonditsis G, Balin D, Kebede T, Krysanova V, van Griensven A, van der Zee, M SEAT (2010) New challenges in integrated water quality modelling. Hydrological Processes 24(24):3447–3461

Ryan RJ, Packman AI (2006) Changes in streambed sediment characteristics and solute transport in the headwaters of Valley Creek, an urbanizing watershed. Journal of Hydrology 323:74–91

Salehin M, Packman AI, Paradis M (2004) Hyporheic exchange with heterogeneous streambeds: Laboratory experiments and modeling. Water Resources Research 40:W11,504

Schälchli U (1992) The clogging of coarse gravel river beds by fine sediment. Hydrobiologia 235/236:189–197

Smith JWN (2005) Groundwater-surface water interactions in the hyporheic zone. Environmental Agency Science Report SC030155/SR1, Environmental Agency Bristol, UK

Storey RG, Fulthorpe RR, Williams DD (1999) Perspectives and predictions on the microbial ecology of the hyporheic zone. Freshwater Biology 41(1):119–130

Theuring P, Rode M, Behrens S, Kirchner G, Jha A (2013) Identification of fluvial sediment sources in the kharaa river catchment, northern mongolia. Hydrological Processes 27(6):845–856

Triska FJ, Duff JH, Avanzino (1993) The role of water exchange between a stream channel and its hyporheic zone in nitrogen cycling at the terrestrial-aquatic interface. Hydrobiologia 251:167–184

Wood PJ, Armitage PD (1997) Biological Effects of Fine Sediment in the Lotic Environment. Environmental Management 21(2):203–217

2. Monitoring concept

This chapter presents a monitoring scheme that helped to collect an integrated set of data in order to derive parameters for the description of the hyporheic zone properties, states and functions. The work was a part of an Integrated Water Resources Management (IWRM) project and closely linked to a study identifying the sources of suspended sediments within the catchment. These two studies were published together:

Hartwig, M., Theuring, P., Rode, M., and Borchardt, D. (2012). Suspended sediments in the Kharaa River catchment (Mongolia) and its impact on hyporheic zone functions. *Environmental Earth Sciences*, 65(5), 1535-1546. DOI: 10.1007/s12665-011-1198-2 .

The sections about the integrated monitoring scheme and analyses of the ecological implications for hyporheic functions ('2.3.3 Ecological functions', 2.4.4. Instream analyses' and 2.5.2. Ecological functions) as well as the general chapters ('Abstract', '2.1. Introduction', 2.2. 'Study site' and '2.6. Conclusions') were written by the author of this thesis.
Additional information on the sampling sites and on the monitoring devices is given within the appendix (A.1. and A.2.).

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

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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, river bank 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 modelling 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.

Keywords: suspended sediments · erosion · fingerprinting technique · hyporheic zone · clogging

3. Data analysis

Within this chapter, the data collected during the field campaigns gathered according to the monitoring concept displayed within the last chapter are analysed using different statistical and numerical methods. The results are integrated within a comprehensive discussion. This part of the research was submitted to a journal as the following article:

Hartwig, M., and Borchardt, D. (2014). Alteration of key hyporheic functions through biological and physical clogging along a nutrient and fine-sediment gradient. *Ecohydrology*, DOI: 10.1002/eco.1571 .

The article was completely written by the author of this thesis; the co-author gave assistance with the concept of the paper and the discussion of the results.

Alteration of key hyporheic functions through biological and physical clogging along a nutrient and fine-sediment gradient

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Abstract

The hyporheic zone bears key hydro-ecological functions like hydrological connectivity of surface and groundwater ecosystems and biogeochemical regulation of substance dynamics. These functions are controlled by the sediment permeability that in turn is affected by biological and physical clogging. A number of conceptual models have been developed on the interactions and feedbacks between these functionalities; surprisingly comprehensive field data are scarce. Thus, the aim of this study was to assess these functions and their vulnerability along a stressor gradient of nutrient and fine-sediment input at riffle scale. Three sampling sites along the Kharaa River (Northern Mongolia) were selected that represented conditions from being unaffected, affected by biological clogging and impaired by physical clogging. A significant impact on the hydrological connectivity was detected, as the vertical downward flux and the solute penetration depth decreased along the reaches. Simultaneously, the heterogeneity in biogeochemical patterns and the vertical extent of the oxygen gradients declined. Whilst biological clogging was apparently unstable and the biofilm supported the hyporheic organic carbon pool, it revealed to affect the two functions to a lesser extent when compared to physical clogging. In contrast, physical clogging seemed to be more permanent and restricted microbial metabolism to the uppermost centimeters, thus decreasing the active sediment depth. Moreover, fine-sediment particles enhanced the sediment surface area, thereby creating a high respiration potential that resulted in high values of community respiration and subsequent oxygen depletion. Concluding, the control of fine sediment emissions has to be a priority issue in river restoration and catchment management.

Keywords: hyporheic zone · hydro-ecological function · clogging · fine sediment

4. Numerical analysis

Within this chapter, a coupled surface-subsurface 2D modelling approach that is based on the data presented within the chapters before is described. It was applied in order to numerical analyse the impact of clogging degree and type on the hyporheic functions of the hydrologic connectivity and fish spawning habitat. This part of the research is in preparation for the submission to a journal as the following article:

Hartwig, M., and Borchardt, D. (in prep.). Boundaries of hyporheic functionality under physical and biological clogging. in preparation.

This chapter was completely written by the author of this thesis; the 'co-author' gave assistance with the concept of the 'paper' and the discussion of the results.

Boundaries of hyporheic functionality under physical and biological clogging

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Abstract

Clogging type and degree are decisive for the hyporheic functionalities such as the hydrologic connectivity being a control for water and matter fluxes from the catchment to the recieving water body as well as for the retention of nutrients or such as the fish spawning habitat where eggs and larvae develop. A numerical analysis of the impact of physical and biological clogging on the ecotonal integrity is presented. Therefore, the spatial decline and the oxygen patterns of the hydrologically connected hyporheic zone were studied for different scenarios of clogging degree and type. Field data from a pristine reach were collected in order to set up a coupled 2D surface-subsurface solute transport model at the riffle scale. Results indicated that firstly, the hydrologic connectivity is direct dependent on the clogging degree, with a decline of the hyporheic spatial extent from 75 to 49 % when clogging decreased the horizontal conductivity by two orders of magnitude. When conductivities declined by more than a decimal power, the loss in ecotonal area decreased more rapid. And secondly, the clogging type is critical for the habitat suitability as biological clogging favoured the consumption of oxygen within the uppermost layer leading to a decrease in oxygenated hyporheic areas from 13 to only 5 % under a moderate clogging and a treshold of 7 mg*l^{-1} as a minimum for spawn survival. Under these boundary conditions, a successful reproduction of salmonids would be endangered, if the oxygen degradation rate exceeded $1.2*10^{-4}$ s^{-1}. Concludingly, both clogging processes are relevant for the hyporheic functionality and thus, controls of clogging like a dynamic discharge is decisive for the status of the ecotone.

Keywords: hyporheic zone · clogging · ecotonal functions

4.1. Introduction

Stream ecosystems are under pressure by flow regulation, channelization as well as increased nutrient and sediment input affecting biological and physical clogging of the riverbed. As a consequence, the integrity of the inherent hyporheic zone may be altered in adverse ways, depending on the regional context.

Next to the connection of the ground- and surface water (GW/SW) ecosystems, the hyporheic zone bears the functions of being a three-dimensional fixed-bed reactor and habitat. GW or SW born substances are exchanged and transformed along gradients of physical and chemical conditions such as e.g. temperature and redox potential. At the same time, this ecotone is an important habitat for a broad spectrum of aquatic organisms having life-cycle stages associated to this zone. The GW/SW connectivity is dependent on hydrological, morphological and sedimentological circumstances. Hyporheic biogeochemical turnover is controlled by parameters such as the hyporheic exchange flux, redox gradients, the availability of organic matter and temperature (Fisher et al, 1998; Bardini et al, 2012). The hyporheic habitat suitability is determined by the sediment composition as well as the oxygen and food availability (Brunke and Gonser, 1997; Malard et al, 2003). As all of the functions are related to the structure or composition of the riverbed sediment or both of them, they are controlled by the clogging of the interstices with either mineral fine sediment or biofilm tissue. Thus, the hyporheic functionality is governed by the clogging type and intensity.

Ecologists were the first to understand the tremendeous effects of physical clogging for the habitat of the aquatic flora and fauna (reviewed by Ryan, 1991). For example, the reproduction of salmonids is endangered when the fine sediment fraction exceeds 8 % (?). Then, the process of physical clogging was examined within laboratory experiments and represented by (Schälchli, 1992; Packman and MacKay, 2003; Rehg et al, 2005; Cui et al, 2008). The derived theories of infiltration and declogging showed that next to sedimentological preconditions, the discharge regime controls the clogging process. Only few field studies have analysed the impact of physical clogging on hyporheic functions (Blaschke et al, 2003; Lefebvre et al, 2004; Kasahara and Hill, 2006; Nogaro et al, 2010) and even less is known for the process of biological clogging (Ibisch et al, 2009). They gave rather qualitative conclusion being specific for a distinct site and setting. Despite the importance of clogging, less attention is drawn to quantify this process within hyporheic zone research.

Therefore, the aim of this study was to take a model appraoch and to analyse the impact of physical and biological clogging on the SW/GW connectivity and the habitat funtion in a parameter space, that has been derived from real world conditions of hyporheic zone features. Two hypotheses were followed: (i) the loss of hyporheic functionality is not linearly dependent on the clogging degree and type with a mutual positive feedback of both and (ii) there are tresholds for the loss of the ecotonal integrity under clogging conditions. A quantitative conceptual model approach was taken to set up a calibrated numerical process model within pristine conditions and parameter spaces for scenarios of different clogging degrees and types were tested. Hereby,the subsurface transport of a conservative substance as well as the distribution and depletion of dissolved oxygen were used as indicator for the degree of SW/GW connectivity and habitat suitability.

4.2. Methodology

4.2.1. Study site and measurements

The setting of the Kharaa river offered a reference condition for this kind of model study. The river has a natural hydrology and undisturbed morphology and is not threatened by multiple stressors. However, the Kharaa catchment is characterized by an increase in land-use and urbanization from the rivers' spring to the outlet. As a consequence, pressures like grazing within the riparian zones, agriculture on steep slopes and the direct release of waste water from the settlements lead to enhanced fine sediment and nutrient input into the river system. In a previous study it could be demonstrated that the fine sediment and nutrient inputs affected biological and physical clogging of the hyporheic zone most significantly (Hartwig and Borchardt, 2014).

The most upstream sampling site was rather pristine and builds the object of investigation for this numerical clogging study. All data for model set up were gained during four monitoring campaigns each spring and summer in 2010 and 2011 at the Kharaa River in Northern Mongolia. The integrated monitoring scheme included measurements on the SW hydrology, hydromorphology, benthic algae, sediment composition, SW/GW quality and exchange flux. As all methods of measurements were presented in detail in Hartwig et al (2012) and Hartwig and Borchardt (2014), they are described only briefly. Riverbed and water level elevations were measured in June 2011 through digital leveling (Sprinter 100, Leica Geosystems, Switzerland) along 10 cross-sections. The samplers had a nested pipe design and were installed at the riffle head, crest and tail with each of them having a screen at the depth of 0.05, 0.15, 0.25 and 0.45 m underneath the SW/sediment interface. They either enabled to meter hydraulic heads or to extract water at the distinct depth in order to determine electrical conductiviy (EC) or the concentration of dissolved oxygen (O2). Altogether eight sediment freeze cores were taken in 2010 and 2011, splitted into layers representing the riverbed sediment depth from 0 to 0.2, 0.2 to 0.4 and 0.4 to 0.6 m which were then analysed for their sediment composition.

4.2.2. Modelling

Surface flow

A 1D hydrodynamic model was set up with HEC-RAS (Version 4.1.0, U.S. Army Corps of Engineers) in order to simulate the surface water flow for mid-flow conditions at the pristine reach. Steady water flow with a mixed flow regime (sub- and supercritical) were assumed and a uniform Manning's roughness coefficient of 0.03 was selected (after Chow, 1959). The channel elevations and the according water surface elevations along the longitundinal profile which contained multi-level samplers were exported as input for the subsurface model.

Subsurface flow

The groundwater flow model MODFLOW (Harbaugh, 2005) within the GMS user interface (by Aquaveo, LLC, U.S.) was used to simulate the 2D steady state subsurface flow within the riffle (longitudinal and vertical dimension). A grid with the longitudinal and vertical dimension of 37 by 1.0 m and a cell size of 0.1 by 0.02 m was set up. Thereby, the channel elevations of the HEC-RAS model were interpolated with the Natural Neighbor method (Fig. 4.1). The model was divided into three layers having a thickness of 0.2, 0.2 and 0.6 m from top (layer 1) to bottom (layer 3). An anisotropy (ratio of horizontal to vertical conductivity) of 10 was assumed in order to represent the layered structure of fluvial sediment (Freeze and Cherry, 1979). The boundary conditions at the model top (SW/sediment interface) were set as specified head derived from a linear interpolation of the water surface elevation of the HEC-RAS model (Fig. 4.1). The water surface elevations were also used for the up- and downstream boundary condition. As most of the precipitation is lost through evaporation and snowmelt water or summer precipitation

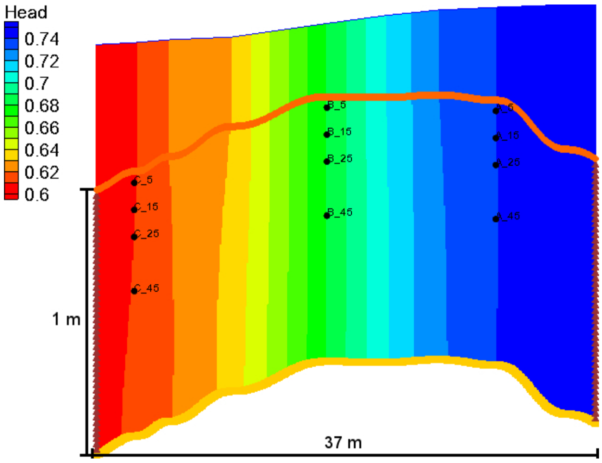

Fig. 4.1. – Setup of the subsurface model including (i) the riffle morphology, (ii) the boundary conditions on top, up-, downstream (heads of the surface flow model [m]) and bottom (GW flow) and (iii) positions of the multi-level samplers; for all model pictures the height is magnified 20 times.

drains as surface run-off (Hülsmann et al, 2015), a low upwelling of groundwater at the model bottom was assumed with 0.5 m*d^{-1}.

Solute transport and substance turnover

To simulate solute transport, the MT3DMS Package (Zheng and Wang, 1999) with the Hybrid Method of Characteristics (HMOC) solver (like Lautz and Siegel, 2006) was used. The species of EC and O2 were introduced with constant concentrations for SW and GW that were measured with 196 and 265 μS*cm^{-1} as well as 8.92 and 3.85 mg*l^{-1}. The conservative species 'HZ' was given 100 and 0 mg*l^{-1} at the top and bottom in order to gain the spatial extent of the hyporheic zone. Porosities of 0.25, 0.3 and 0.3 were entered for layer 1, 2 and 3 referring to the sediment analysis and standard literature (Freeze and Cherry, 1979). The longitudinal and vertical dispersivities were set to 0.1 and 0.001 m. An effective molecular diffusion coefficient of 5*10^{-11} m^2*s^{-1} was given for all species. The model was run at a 3600 s time interval for 1.5 days in order to get equilibrium.

Calibration and statistics

A calibration of the subsurface flow and transport was conducted in order to reproduce measured heads, EC (conservative) and oxygen (reactive) concentrations at the subsurface multi-level samplers. In accordance with the sediment analysis that revealed a coarse gravel with increasing finer fractions in the deeper layers, horizontal conductivities in a range of 0.005 to 0.5 m*s^{-1} were entered for each layer. Once flow and conservative transport was calibrated, subsurface oxygen reaction rates for a first order irreversible kinetic reaction (degradation) were fitted to meet measured oxygen concentrations.
The performance of the HEC-RAS model was evaluated refering to the coefficient of determination (R^2) that described the linear fit between modelled and measured water

levels. The quality of the MODFLOW and MT3DMS model was described using the correlation of observed versus predicted heads, EC and oxygen concentrations and the resulting root mean squared error (RMSE).

Parameter space to modelling experiments

In order to reflect different degrees of clogging, the horizontal conductivity was decreased stepwise by two orders of magnitude representing no clogged ($2.4*10^{-1}$ $m*s^{-1}$ as calibrated) and highly clogged ($2.4*10^{-3}$ $m*s^{-1}$) conditions. Only the topmost layer was considered assuming a preferred biofilm growth in more shallow sediments and an outer physical clogging, respectively. The simulation time was increased up to 3 days. As the SW/GW connectivity was related to the spatial extent of the hyporheic zone, the model space containing the cells with a minimum HZ concentration of 10 $mg*l^{-1}$ or 10 % as defined by Triska et al (1989) was determined for each scenario.

Different clogging types were represented through distinct oxygen consumption rates reflecting either restricted respiration under the physical clogged regime (mineral fine sediment) or unrestricted respiration under biological clogging (autochthonous carbon source). Therefor, the hydraulic conductivity of the topmost layer was set to $1.25*10^{-3}$ $m*s^{-1}$ (mid range clogging degree) and oxygen consumption rates were increased stepwise from $8*10^{-5}$ s^{-1} as calibrated to $2.4*10^{-4}$ s^{-1}. Again, only the topmost layer was considered assuming highest biofilm development at the region with high surface area and carbon availability. The simulation ran for 2.5 days in steps of 3 hours. The impact of the clogging type on the habitat function for fish spawning was evaluated by calculating the available area that contained more than either 6 $mg*l^{-1}$ of O2 after Lacroix (1985) or 7 $mg*l^{-1}$ after Davis (1975). Hereby, a maximum depth of 0.5 was evaluated as this is the maximum depth of salmonid redds (Devries, 1997).

4.3. Results

4.3.1. Model calibration and accuracy

The surface flow model showed a good performance with a R^2 of 0.97 between modelled and measured water level elevations. The calibration of the subsurface model resulted in a good model accuracy for subsurface flow and conservative substance transport (see Fig. 4.2). Hydraulic heads at the 12 locations of the multi-level samplers were reproduced with a RMSE of 0.02 m. In general, computed heads were slightly lower than the measured heads. This might be an artefact of the reduced dimensionality as lateral flow from both sides of the stream was not considered in the model. The EC's were predicted with an accuracy of RMSE = 6.6 $\mu S*cm^{-1}$. Especially the EC signal at the topmost sampling locations of the riffle tail (C05, C15) were underestimated by the model. This seemed to be caused by the downwelling of SW that was forced by the rugged SW/sediment interface. Thus, the model showed sensitivity towards the interpolation of the riverbed surface. The underlying horizontal conductivities of the calibrated model were $2.4*10^{-1}$, $1*10^{-1}$ and $8*10^{-2}$ $m*s^{-1}$ for layer 1, 2 and 3, respectively, which matched

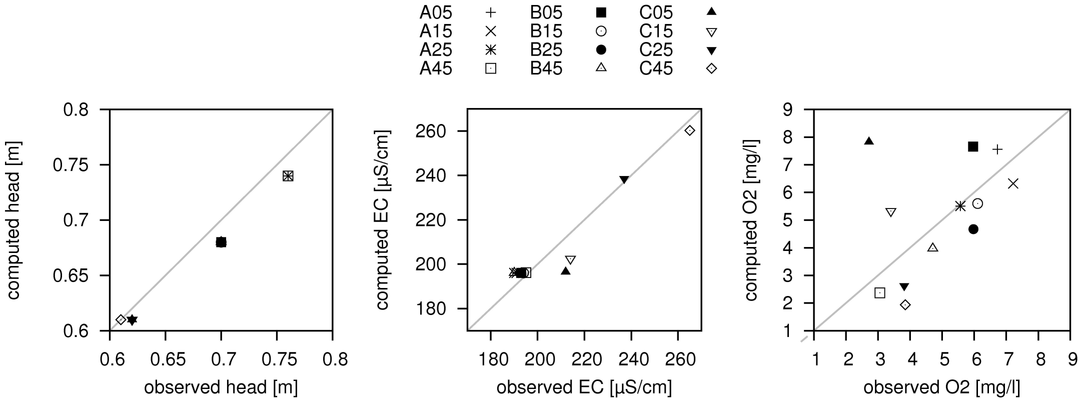

Fig. 4.2. – Computed versus observed subsurface heads (left) and EC signals (right) at the multi-level samplers.

well with the results of the sediment analyses.

The calibration of the reactive oxygen transport resulted in a moderate model accuracy with a RMSE of 1.9 mg*l^{-1} (Fig. 4.2). Again, at C05 and C15 the model showed the highest deviation from the measurements. As recognized before, downwelling of oxygen rich SW was simulated here which was an artefact of the interpolaion of the riverbed surface. The RMSE improved to 1.1 mg*l^{-1} when not considering these two sampling locations. The reaction rates which lead to the best fit of observed and computed oxygen concentrations were 8*10^{-5} s^{-1} for all three layers.

4.3.2. Scenario analyses

Different clogging degrees were simulated by varying the horizontal conductivities of the topmost layer from 2.4*10^{-1} as calibrated to 2.4*10^{-3} m*s^{-1}. The spatial extent of the hyporheic zone decreased from about 80 to only 50 % with increasing clogging degree (see Fig. 4.3). It showed an almost logarithmically drop with a more rapid decline of the spatial extent when conductivities were smaller than 2.4*10^{-2} m*s^{-1}.

In order to reflect different types of clogging, the horizontal conductivity of the topmost layer was decreased to 1.25*10^{-3} m*s^{-1} and the oxygen reaction rates within the topmost layer were increased from 8*10^{-5} s^{-1} as calibrated to 2.4*10^{-4} s^{-1}. Under these boundary conditions, a decrease of the spatial extent of the suitable habitat area within the model space from 27 to only 6 % was observed (see Fig. 4.4) for the 6 mg*l^{-1} treshold. A more tremendeous picture showed up for the 7 mg*l^{-1} treshold with a habitat area of maximum 13 % at the lowest simulated degradation rate and a rapid drop under 5% from rates higher than 1.6*10^{-4} s^{-1}. Here, already at a rate of 1.2*10^{-4} s^{-1} the 7 mg*l^{-1} treshold reached a maximum depth of 0.26 (see Tab. 4.1). Under pristine conditions, the suitable habitat area was about 10 % bigger for all oxygen degradation rates compared to the simulations with the treshold of 6 mg*l^{-1} as it reached greater depth along the whole riffle.

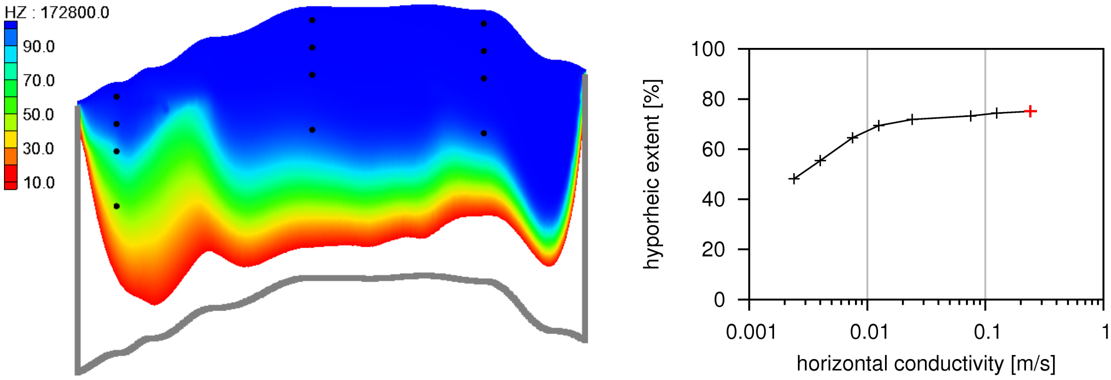

Fig. 4.3. – Subsurface transport of the HZ-species (in mg*l^{-1} introduced to identify the spatial extent of the hyporheic zone in dependency of the clogging degree represented by distinct horizontal conductivities: HZ transport for the no clogging scenario (left) and resulting indirect dependency of the hyporheic spatial extent and the clogging degree (right); the result of the model picture is marked red within the diagram.

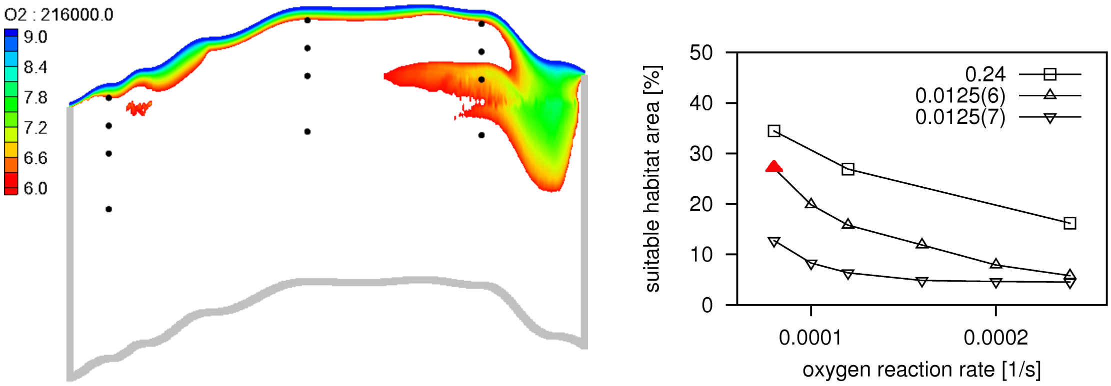

Fig. 4.4. – Reactive subsurface transport of oxygen with different reaction rates introduced to identify the areas with an oxygen content higher than 6 or 7 mg*l^{-1} in dependency of the clogging type represented by distinct oxygen reaction rates: oxygen concentrations for a moderate clogging degree and an oxygen reaction rate of 8*10^{-5} s^{-1} (left) and resulting indirect dependency of the suitable habitat area and the clogging type given for the pristine and moderate clogged condition (6 or 7 mg*l^{-1} treshold) (right); the result of the model picture is marked red within the diagram.

Tab. 4.1. – Maximum depth of the suitable habitat for the two tresholds of 6 and 7 mg*l^{-1} given for different oxygen consumtion rates under moderate clogging conditions.

Consumption rate [*10^{-5} s^{-1}]	**Depth for 6 mg*l^{-1} [m]**	**Depth for 7 mg*l^{-1} [m]**
8	0.48	0.36
10	0.46	0.28
12	0.42	0.26
16	0.32	0.06
20	0.28	0.04
24	0.20	0.04

4.4. Discussion

4.4.1. Model performance

For a modelling experiment testing parameter spaces for physical and biological clogging a coupled surface/subsurface flow and transport model was set up with HECRAS and MODFLOW/MT3DMS. Static hydraulic heads were considered only and the dimensionality of the subsurface was reduced to 2D assuming that the dominating processes were vertical exchange and longitudinal flow. Considering this, the calibrated SW/GW exchange model reproduced hydraulic heads and EC concentrations very well. For the given boundary conditions, the deviations for computed to observed heads and EC corresponded to 13 % and 9 % of the measured range for heads and EC, respectively. The discrepancy was larger, when calibrating the reactive transport of O2. The deviation of computed to observed concentrations correlated to 31% of the range of measurements. It showed that riverbed morphology needed to have a better resolution at this scale of interest. The discrepancy improved to 17 % not considering two out of twelve observation points that were situated at the riffle tail. This area was not of uttermost significance for the scenario analyses. The reactive model might be improved by the simultaneous simulation of carbon degradation as the availability of carbon controls oxygen respiration.

Based on that, different scenarios were applied in order to reflect the impact of clogging degree and type to the hyporheic extent and habitat suitability.

4.4.2. Impact of clogging degree

An increase in clogging caused by either mineral fine sediment or biofilm was shown to decrease the spatial hyporheic extent and thus affect the hydrologic connectivity of SW and GW. When the horizontal conductivity declined more than one order of magnitude, the deterioration became more rapid.

As revealed in Hartwig et al (2012), at the reaches of the Kharaa river affected by nutrient and fine sediment inputs benthic biofilm growth was strongly correlated to the nutrient concentration of the SW, the available light and the discharge regime. At the spring samplings, when the growth season began, solute penetration depth were recognized to be higher than in summer, when benthic growth was highest. Further downstream, suspended fine sediment was found to infiltrate into the riverbed sediment causing physical clogging and decreasing the active hyporheic zone to the topmost 0.05 m (Hartwig and Borchardt, 2014). These findings could be verified by the model outcome as the sampling settings like hydrology, morphology and sediment composition (excluding the fine sediment fraction) were comparable. Moreover it can be concluded that the discharge dynamic may be decisive as it controls the degree of biological clogging here.

Nevertheless, the model was built on several assumptions and may not completely describe the clogging processes. The even distribution of clogging in the topmost layer along the riffle may not be representative for all degrees of biological clogging. Clogging through benthic algae may be higher at the upwelling compared to downwelling areas (Wyatt et al, 2008). However, hyporheic biofilm biomass was recognized to be higher in downwelling areas Franken et al (2001). Fine sediment was also shown to preferably infiltrate at the downwelling zone (Seydell et al, 2009). Following, different clogging zones might be considered when building the model.

The effect of the clogging degree on the habitat suitability was not considered by the study. When the lithophilic fishes generate their spawning redds they decolmate part of the riffle for a certain space and time. Therefore, heterogenieties within the sediment composition and a transient modelling of the clogging process would be necessary.

4.4.3. Impact of clogging type

An increase of oxygen degradation caused by the respiration of growing biofilm was demonstrated to decrease the area with sufficient O2 for the development of salmonid egg and larvae thus affect the habitat function of the hyporheic zone. The negative effect was shown to be enhanced when the clogging degree increased.

This is realistic for conditions observed in 2011 at the Kharaa river when there were longer periods of low flow during the summer month. Exactly then, when the reproduction time by means of egg and larvae devolpment of the salmonid fishes of this region were found to take place (Krätz, 2009). Davis (1975) suggested the minimum of 7 mg*l^{-1} at a depth of 0.25 m for a successful reproduction of salmonids (Canadian species). Considering this, reproduction would fail when oxygen degradation rates exceed 1.2*10^{-4} s^{-1}. It would also fail if the spawning redds would not be placed right at the riffle head where advective downwelling of O2 rich SW water was fast enough to pass the layer with consumption.

4.5. Conclusions

In hyporheic research much qualitative knowledge about the ecological significance of clogging processes is available. However, attempts to quantify the impact of physical and biological clogging on the ecotonal functionalities and to understand the non-linear system behaviour with regard to ecological endpoints (hydrologic connectivity, habitat dimension, habitat functionalities) are lacking.

The approach of this study is a quantified conceptual model which has been tested for a parameter space referring to a gradient of enhanced nutrient and fine sediment inputs into a natural river system. A model of a riffle simulating the SW/GW flow and substance transport as observed at the pristine region was calibrated. Then, scenarios of different degrees and types of clogging represented through the variation of horizontal conductivities and oxygen degradation rates were analysed for their effect on the spatial extent of the hyporheic zone and the suitable habitat area for fish spawning.

The calibration of flow and conservative transport was reasonably. The reactive transport of oxygen might be improved through the application of a riverbed morphology with higher resolution and the consideration of the carbon availability.

The results of the scenario analyses reflect the observed functional loss for the hydrologic connectivity through an increase in the clogging degree. The loss was non linear and showed a treshold as a more rapid deterioration revealed for horizontal conductivities that were an order of magnitude smaller compared to the calibration. A functional loss for fish spawning habitat could be demonstrated as well. The reproduction of salmonids is endangered if under a moderate clogging degree oxygen degradation rates within the topmost layer would exceed a treshold of 1.2 10^{-4} s^{-1}. A positive feedback between clogging degree and type was shown. A dynamic discharge regime was recognised to control both clogging degree and type, thus protect or improve ecotonal integrity.

Acknowledgments

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References

Bardini L, Boano F, Cardenas M, Revelli R, Ridolfi L (2012) Nutrient cycling in bedform induced hyporheic zones. Geochimica et Cosmochimica Acta 84(0):47 – 61

Blaschke AP, Steiner KH, Schmalfuss R, Gutknecht D, Sengschmitt D (2003) Clogging processes in hyporheic interstices of an impounded river, the danube at vienna, austria. International Review of Hydrobiology 88(3-4):397–413

Brunke M, Gonser T (1997) The ecological significance of exchange processes between rivers and groundwater. Freshwater Biology 37:1–33

Chow VT (1959) Open-channel hydraulics. McGraw-Hill, New York

Cui Y, Wooster J, Baker P, Dusterhoff S, Sklar L, Dietrich W (2008) Theory of fine sediment infiltration into immobile gravel bed. Journal of Hydraulic Engineering 134(10):1421–1429

Davis JC (1975) Minimal dissolved oxygen requirements of aquatic life with emphasis on canadian species: a review. Journal of Fisheries Research Board of Canada 32(12):2295–2332

Devries P (1997) River salmon egg burial depth: a review of published data and implications for scour studies. Canadian Journal of Fisheries and Aquatic Sciences 54:1685–1698

Fisher SG, Grimm NB, Marti E, Holmes RM, Jones JB (1998) Material spiraling in stream corridors: a telescoping ecosystem model. Ecosystems 1:19–34

Franken RJM, Storey RG, Williams DD (2001) Biological, chemical and physical characteristics of dowwnwelling and upwelling zones in the hyporheic zone of a north-temperate stream. Hydrobiologia 444:183–195

Freeze RA, Cherry JA (1979) Groundwater. Prentice-Hall, Upper Saddle River, New Jersey

Harbaugh AW (2005) Modflow-2005, the u.s. geological survey modular ground-water model - the ground-water flow process. Tech. rep., U.S. Geological Survey Techniques and Methods 6-A16

Hartwig M, Borchardt D (2014) Alteration of key hyporheic functions through biological and physical clogging along a nutrient and fine-sediment gradient. Ecohydrology pp n/a–n/a

Hartwig M, Theuring P, Rode M, Borchardt D (2012) Suspended sediments in the kharaa river catchment (mongolia) and its impact on hyporheic zone functions. Environmental Earth Sciences 65(5):1535–1546

Hülsmann L, Geyer T, Schweitzer C, Priess J, Karthe D (2015) The effect of subartic conditions on water resources: initial results and limitations of the SWAT model applied to the Kharaa River Basin in Norhtern Mongolia. Environmental Earth Sciences 73(2):581–592

Ibisch R, Seydell I, Borchardt D (2009) Influence of periphyton biomass dynamics on biological colmation processes in the hyporheic zone of a gravel bed river (River Lahn, Germany). Fundamental and Applied Limnology Advances in Limnology 61:87–104

Kasahara T, Hill AR (2006) Effects of riffle?step restoration on hyporheic zone chemistry in n-rich lowland streams. Canadian Journal of Fisheries and Aquatic Sciences 63(1):120–133

Krätz D (2009) Ökologie der Fischbestände in Fließgewässern des Khentii-Gebirges (Mongolei): Bestandsaufbau, Dynamik und Gefährdung durch den Gold-Tagebau. Doctoral thesis, University of Technology Dresden, Germany

Lacroix GL (1985) Survival of eggs and alevins of Atlantic salmon (Salmo salar L.) in relation to the chemistry of interstitial water in redds of some acidic streams of Atlantic Canada. Journal of Fisheries and Auqatic Science 42:292–299

Lautz LK, Siegel DI (2006) Modeling the surface and ground water mixing in the hyporheic zone using modflow and mt3d. Advances in Water Resources 29:1618–1633

Lefebvre S, Marmonier P, Pinay G (2004) Stream regulation and nitrogen dynamics in sediment interstices: comparison of natural and straightened sectors of a third-order stream. River Research and Applications 20(5):499–512

Malard F, Galassi D, Lafont M, Dolédec S, Ward J (2003) Longitudinal patterns of invertebrates in the hyporheic zone of a glacial river. Freshwater Biology 48(10):1709–1725

Nogaro G, Datry T, Mermillod-Blondin F, Descloux S, Montuelle B (2010) Influence of streambed sediment clogging on microbial processes in the hyporheic zone. Freshwater Biology 5:1288—-1302

Packman AI, MacKay JS (2003) Interplay of stream-subsurface exchange, clay particle deposition, and streambed evolution. Water Resources Research 39(4):n/a–n/a

Rehg KJ, Packman AI, Ren J (2005) Effects of suspended sediment characteristics and bed sediment transport on streambed clogging. Hydrological Processes 19(2):413–427

Ryan PA (1991) Environmental effects of sediment on New Zealand streams: a review. New Zealand Journal of Marine and Freshwater Research 25:207–221

Schälchli U (1992) The clogging of coarse gravel river beds by fine sediment. Hydrobiologia 235/236:189–197

Seydell I, Ibisch R, Zanke U (2009) Intrusion of suspended sediments into gravel riverbeds: influence of bed topography studied by means of field and laboratory experiments. Fundamental and Applied Limnology Advances in Limnology 61:67–85

Triska FJ, Kennedy VC, Avanzino RJ, Zellweger GW, Bencala KE (1989) Retention and Transport of Nutrients in a Third-Order Stream: Channel Processes. Ecology 70:1877–1892

Wyatt KH, Hauer FR, Pessoney GF (2008) Benthic algal response to hyporheic-surface water exchange in an alluvial river. Hydrobiologia 607:151–161

Zheng C, Wang PP (1999) MT3DMS: A modular three-dimensional multispecies model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems: documentation and user's guide. US Army Engineer Research and Devlopment Center, Vicksburg

5. IWRM context

Within this chapter, the results of the study are discussed within the context of the IWRM project. Finally, research based management options are formulated in order to tackle the problem of a degrading pristine aquatic ecosystem. The presented integrated approach imbedding the research of this thesis is accepted by the Journal *Environmental Earth Sciences*:

Hartwig, M., Schäffer, M., Theuring, P., Avlyush, S., Rode, M., and Borchardt, D. (accepted). 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). *Environmental Earth Sciences.*

The author of the thesis created the concept of the paper, wrote the sections ’Abstract’, ’5.2. Study site’, 5.3.2. Impact’, 5.4.2. Impact’, and ’5.6. Conclusions’, as well as contributed to the sections ’5.1. Introduction’, ’5.3.1. State’, ’5.4.1. State’, and ’5.5.2. Response’.

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)

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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 characterisation 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, 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 instream transport, and a strong connection of erosional behaviour with land-use. Amongst others, the protection of headwaters and the stabilization of the river bank erosion hotspots in the mid-stream sections of the Kharaa River are the priority measures to avoid further degradation of the aquatic ecosystem status and functions.

Keywords: DPSIR · Land-use change · Erosion · Ecosystem integrity · Management

A. Appendix

The appendix contains additional (not published) material with respect to the description of the sampling sites (A.1.) as well as the monitoring scheme and design of the equipment (A.2.).

A.1. Sampling sites

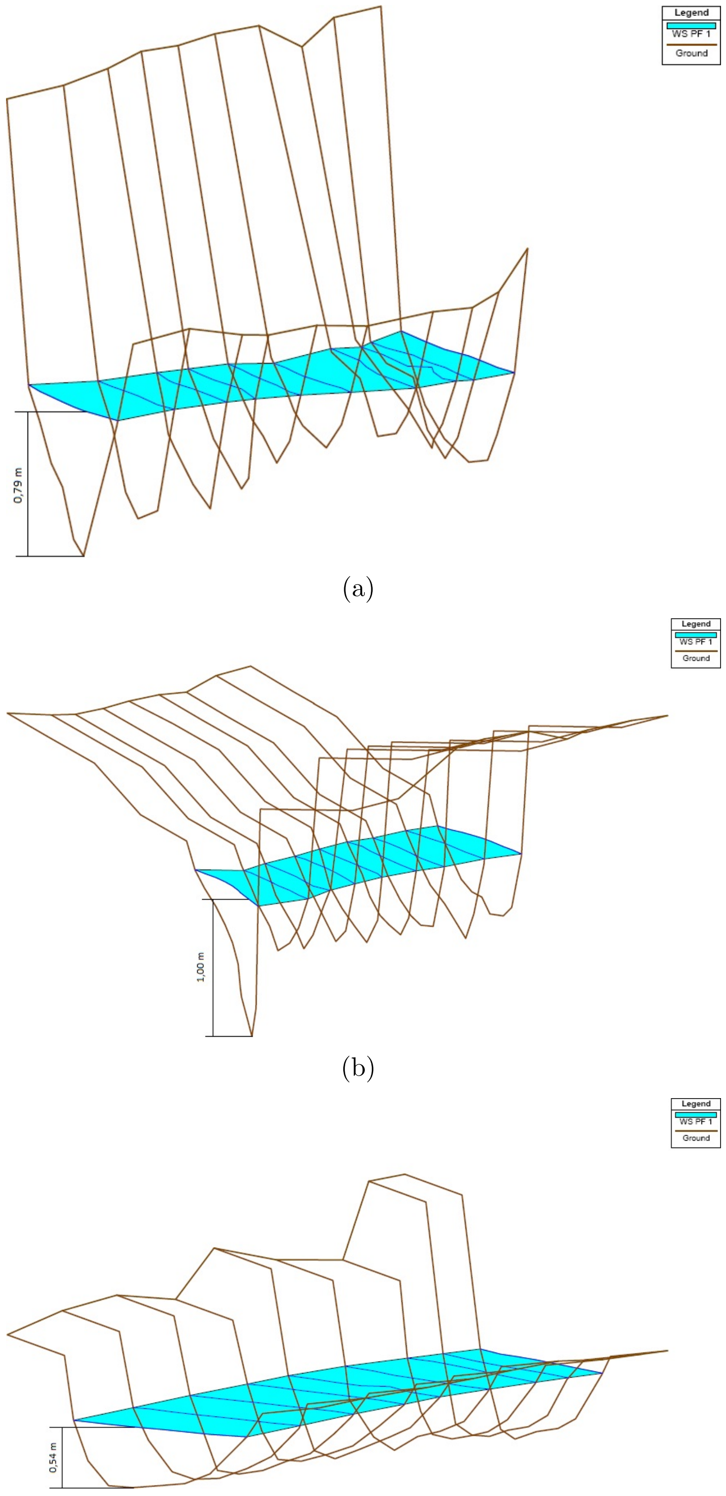
(a) 'UP' (b) 'MID'

(c) 'DOWN'

Fig. A.1. – Representative photographs of the sampling sites along the Kharaa River.

Tab. A.1. – A description of the sampling sites at the level of the river reach.

	UP	**MID**	**DOWN**
stream type	alluviated mountain valley	alluviated lowland	alluviated lowland
substrate	cobble	cobble - gravel	cobble - gravel
water appearance	clear	clear - light brown	light brown, turbid
biocoenotic type	hyporhithral	hyporhithral - epipotamal	hyporhithral - epipotamal
stream bank	active meandering	partially eroded	collapsed, eroded
riparian buffer	dense-patchy floodplain vegetation	partial floodplain vegetation	none
adjacent land uses	occasional grazing	grazing	massive grazing



(a)

(b)

(c)

Fig. A.2. – Morphologies at the sampling sites UP (a), MID (b) and DOWN (c) that were used to set up the steady flow hydrodynamic model; elevation to lateral width ratio of 25.

A.2. Monitoring scheme and equipment

Tab. A.2. – Comprehensive overview on the monitoring and the consequent laboratory or numerical analyses of hydraulic parameters, respectively.

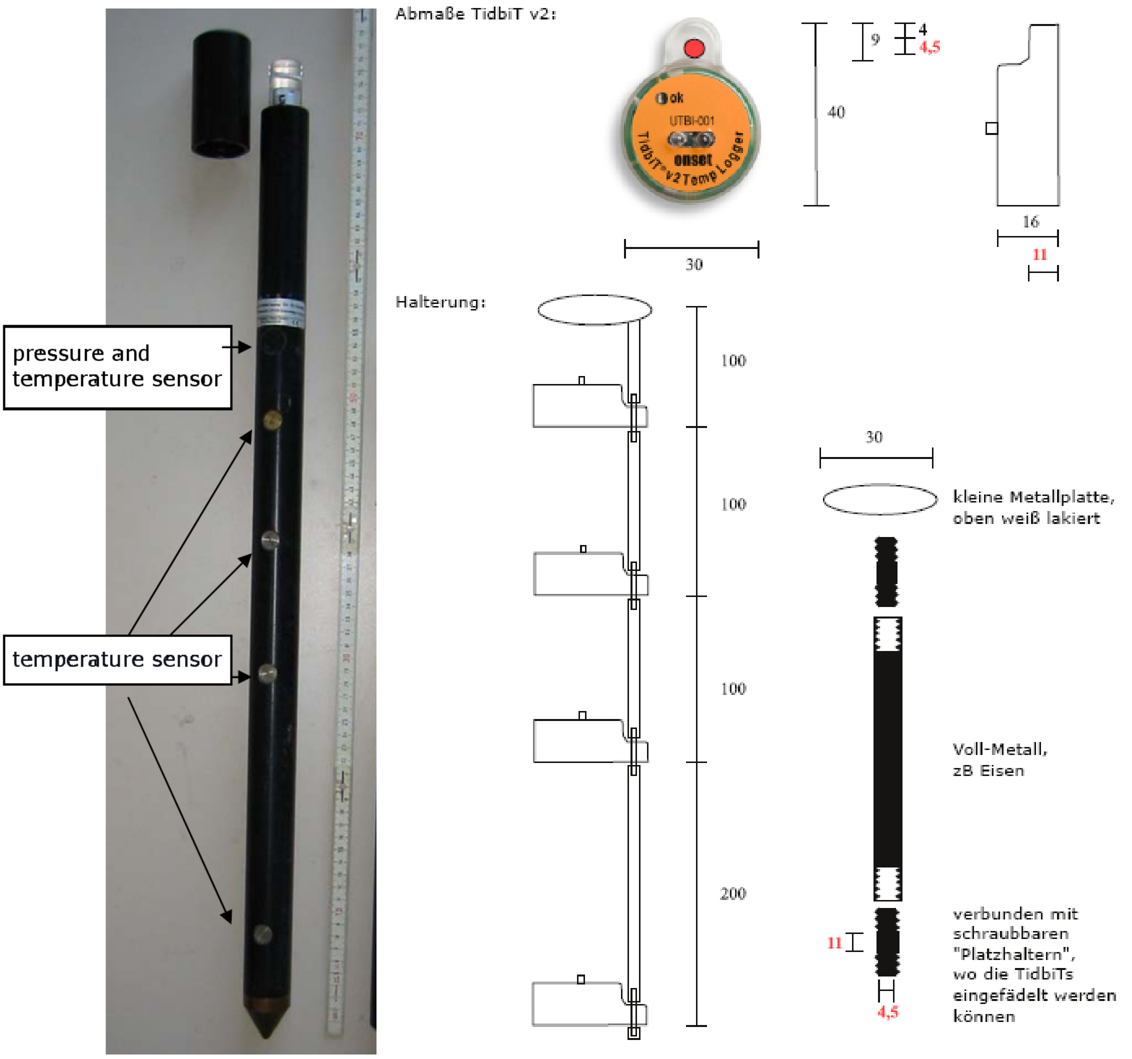
parameter	measurements	devices	analysis
discharge	river width water depth flow velocity water pressure	meter flow meter pressure logger	area-velocity approximation water level-discharge relationship
shear stress	pointwise x,y,z water level discharge	digital leveling	1D hydrodynamic model
total suspended solids	-	bottle filter hand-pump petri dishes oven fine balance	weighing
effecive grain size **medium grain size** **porosity**	grain size distribution	freeze core equipment hammer chisel meter oven sieves balance	weight per sieve fraction
vertical water flux across SW/GW interface	temperature SW, GW assumption physical, thermal properties of fluid and matrix	temperature sensor sensor holding device	1D analytical solution transient heat transport

Tab. A.3. – Comprehensive overview on the monitoring and the consequent laboratory or numerical analyses of physico-chemical parameters, respectively.

parameter	measurements	devices	analysis
electric conductivity pH (SW, GW)	-	bottle multi-level sampler multi-parameter instrument electrodes	potentiometric method
dissolved organic carbon (SW, GW)	-	glass bottle glass syringe filter multi-level sampler cooler	thermal catalytic oxidaton infrared spectroscopy
nitrate ammonium soluble reactive phosporous (SW, GW)	-	bottle syringe filter multi-level sampler cooler	continuous flow analyser photometric method
solute penetration depth (GW)	electric conductivity	(see above)	interpolation profile

Tab. A.4. – Comprehensive overview on the monitoring and the consequent laboratory or numerical analyses of biological parameters, respectively.

parameter	measurements	devices	analysis
dissolved oxygen **oxygen saturation**	-	bottle multi-level sampler multi-parameter instrument electrode	galvanic principle optical method
reaeration coefficient **gross primary production** **community respiration**	temperature electricl conductiity dissolved oxygen flow velocity water depth time of sunset, sunrise altitude	(see above)	single-station oxygen diel curve technique
hyporheic consumption of dissolved oxygen, organic carbon	electric conductivity dissolved oxygen dissolved organic carbon	(see above)	end-member mixing analysis
mineralizable fraction of hyporheic fine sediment	particulate organic carbon particulate nitrogen	freeze core equipment	combustion chromatographic separation thermal conductivity detector
benthic biofilm density	ash free dry mass per area	brush filter Hand-pump petri dishes cooler aluminium foil fine balance	stone scraping aluminium foil – stone area method combustion weighing
autotrophic fraction of benthic biofilm	chlorophyll *a* mass per area	(see above)	high-performance liquid chromatography spectrophotometric method



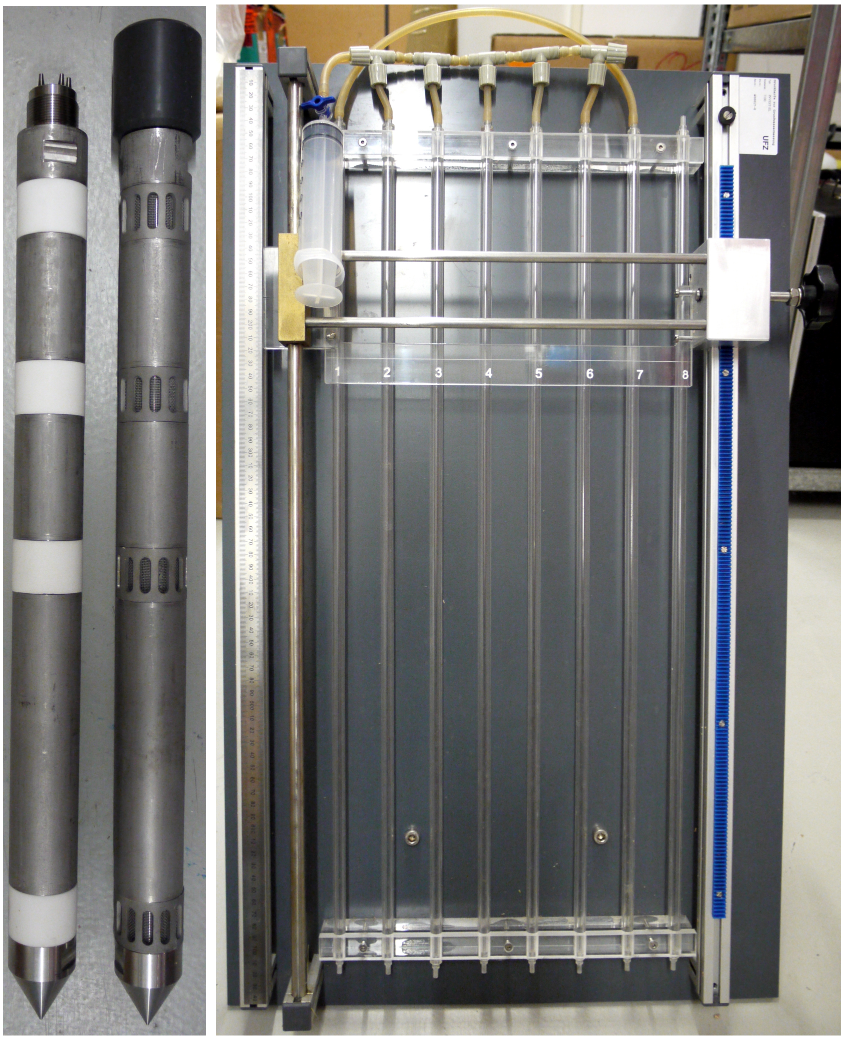
(a) (b)

Fig. A.3. – The two temperature probe designs for temperature logging within the riverbed sediment: (a) temperature loggers imbedded into a stick made from plastic (Driessen & Kern GmbH, Germany), (b) Tidbit temperature sensors and a system with placeholders for a complete integration into the sediment (self-production).

(a) (b)

(c) (d)

Fig. A.4. – Freeze coring method: (a) corer and installation equipment for hammering the corer into the sediment, (b) head of the corer for filling with liquid nitrogen, (c) tripod for pulling out the freeze core, (d) filling action.



(a) (b)

Fig. A.5. – Multi-level sampler (after Lenk et al. (1999)) (a); white plastic filter were used in order to prevent clogging of the pipes; a teflon tube was attached at each of the pipes that come out on top of the sampler. The tubes can either be connected to a syringe for sampling of the subsurface water or to a pressure-meter (b) in order to check the vertical hydraulic gradient at each sampling depth.