Environ Earth Sci (2016) 75:855
DOI 10.1007/s12665-015-5092-1

THEMATIC ISSUE

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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Received: 11 March 2015 / Accepted: 10 December 2015 / Published online: 10 May 2016

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 midstream 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

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

This article is part of a Topical Collection in Environmental Earth Sciences on "Water in Central Asia", guest edited by Daniel Karthe, Iskandar Abdullaev, Bazartseren Boldgiv, Dietrich Borchardt, Sergey Chalov, Jerker Jarsjö, Lanhai Li and Jeff Nittrouer.

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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 land-use 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 analysing 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).

Study site

The KRB (see Fig. 1) is situated in Northern Mongolia and drains an area of about 15,000 km^2. 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

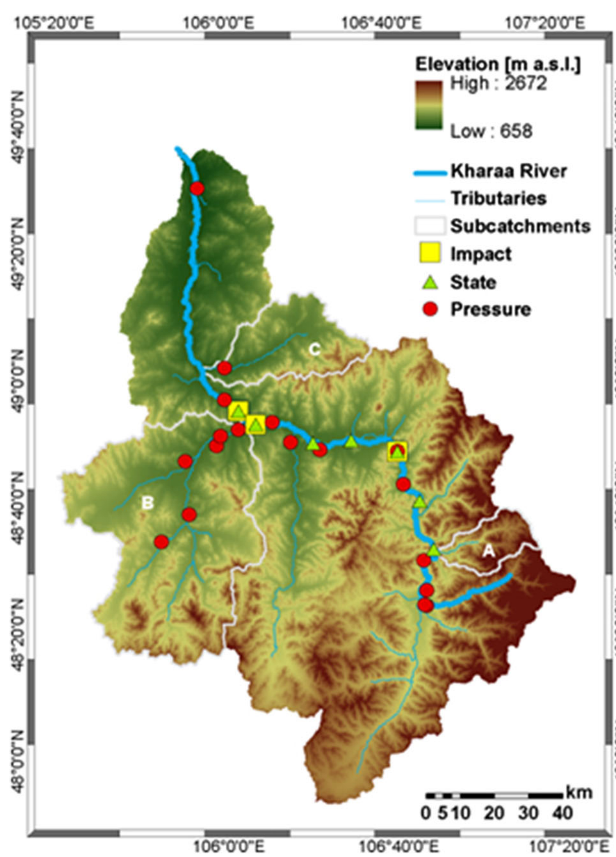

Fig. 1 Map of the Kharaa River Basin in Northern Mongolia showing the sampling sites referring to the pressures, states, impacts and the subcatchments Kharaa I (*A*), Zagdelin Gol (*B*) and Bayangol (*C*). DEM from Karthe et al. (2015b)

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 (Demeusy 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).

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 characterise 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 (see Fig. 2) are described in the following section.

Pressures

Increased sediment mobilisation 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 behaviour 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 Fig. 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.

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 (see Fig. 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 (see Fig. 1) with a set of parameters adapted from the German on-site River Habitat Survey (LAWA 2000) and with additional components in order to characterise the river bank conditions in more detail. The characteristics comprise channel geometry,

Fig. 2 Overview of the pressures–state–impact chain and parameters used in the study

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 (see Fig. 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 (see Fig. 1). During the sampling procedure all microhabitats were mapped at these sites to characterise the ecological features of the river bottom surface. Macroinvertebrate communities were analysed for different structural, functional and diversity metrics (Hartwig et al. 2012).

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 (see Fig. 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 (Fig. 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 (Fig. 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.

Results

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 m^3 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 m^3 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

Table 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

sections of the Kharaa River (Table 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 (Fig. 5).

Throughout the Kharaa catchment a significant shift in erosional behaviour 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 (see Fig. 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.

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 sub-catchment at the downstream end of the middle reach augmenting the discharge by about 10 %. During the hydromorphological surveys most of the investigated sites were characterised 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 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 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 characterisation 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

Table 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 (t ha^{-1} a^{-1})	Maximum erosion rate (t ha^{-1} a^{-1})	Area of catchment (%)
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

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 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 analysed 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 characterised 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 (see Fig. 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 Zagdalin Gol confluence. This tributary was observed carrying higher loads of fine suspended solids regularly.

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 (see Fig. 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 (Fig. 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 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

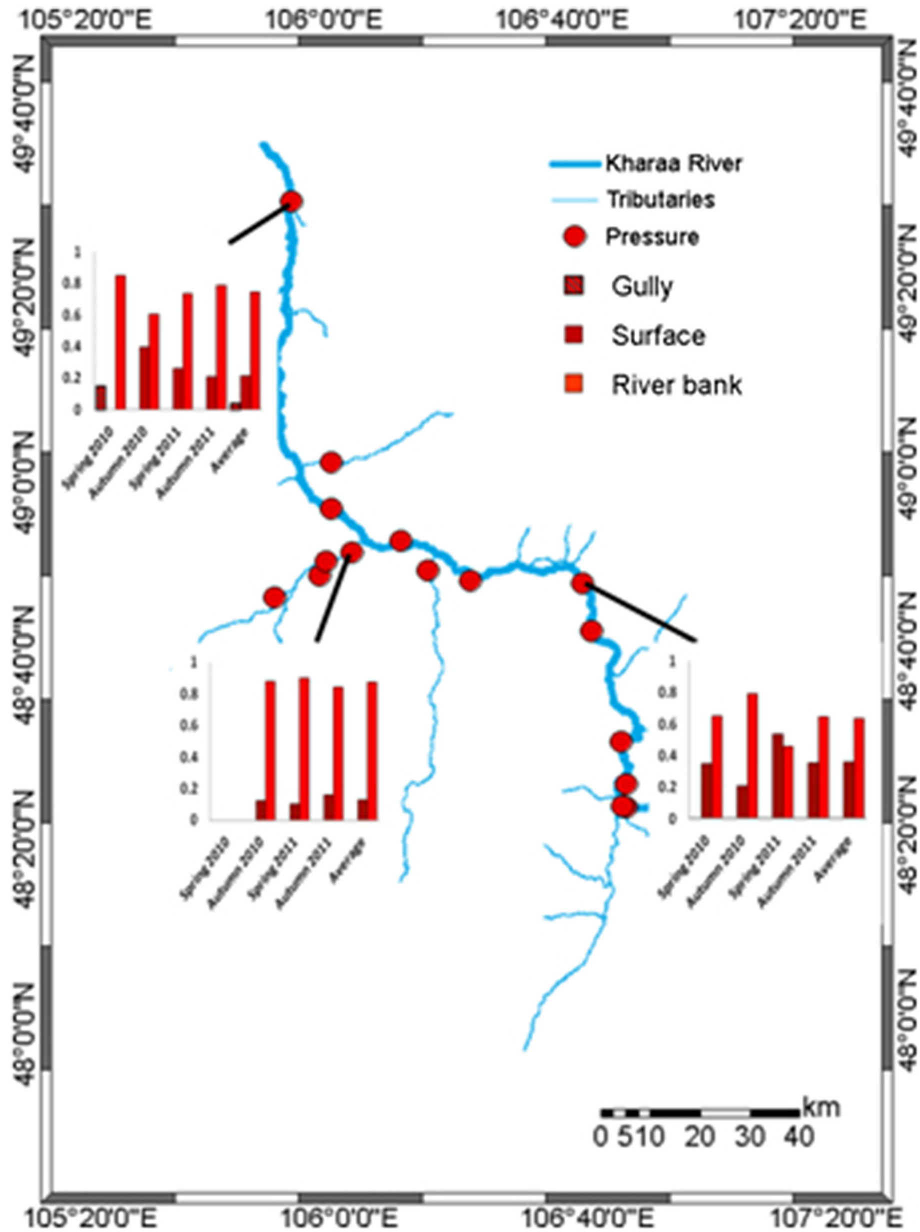

Fig. 3 Sediment source contribution in different catchment regions as calculated with the mixing model for all sampling campaigns

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.

Discussion

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

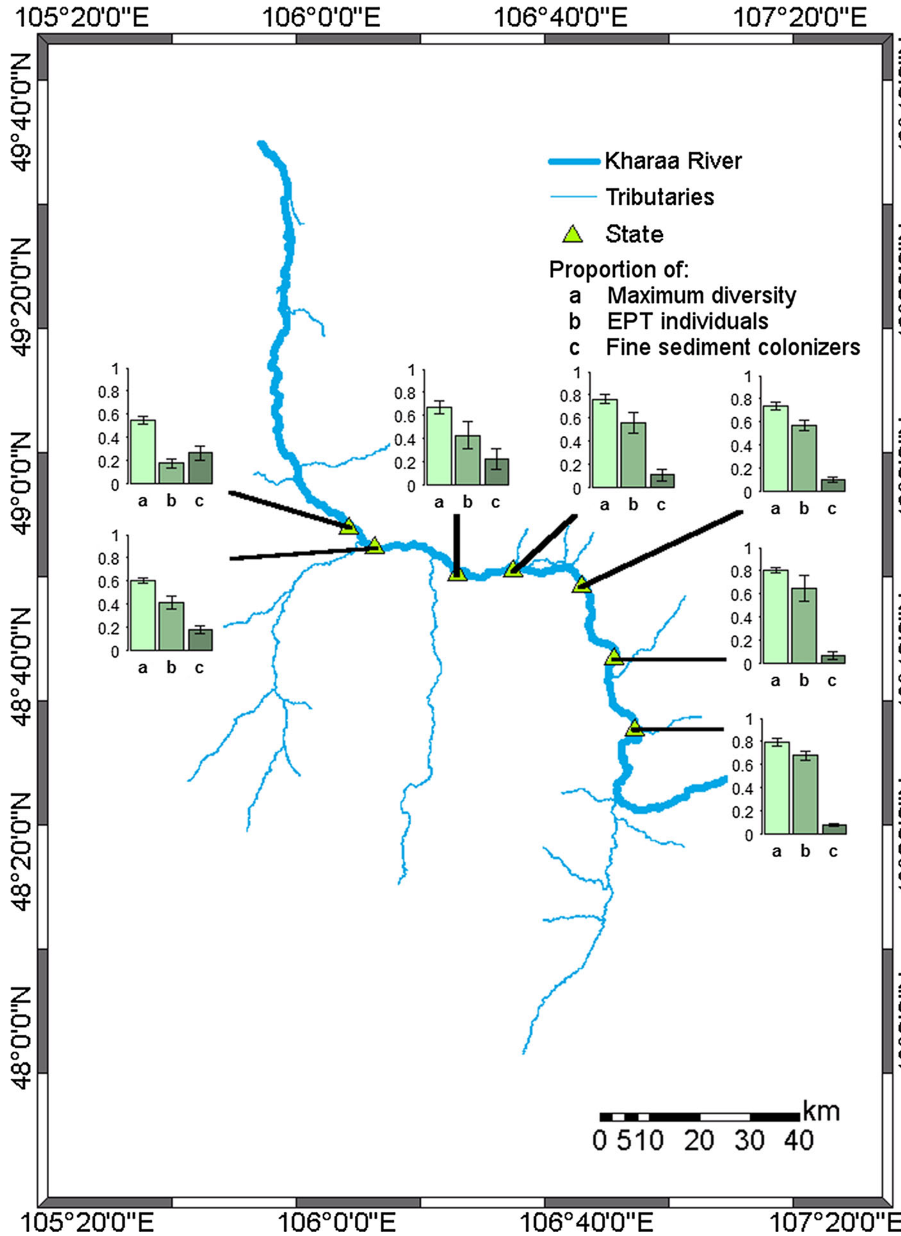

Fig. 4 Structural and functional metrics of macroinvertebrate communities at the sampling sites in the middle region of the Kharaa River. *EPT* abbreviation for the insect orders Ephemeroptera, Plecoptera and Trichoptera

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 behaviour 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 unfavourable 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

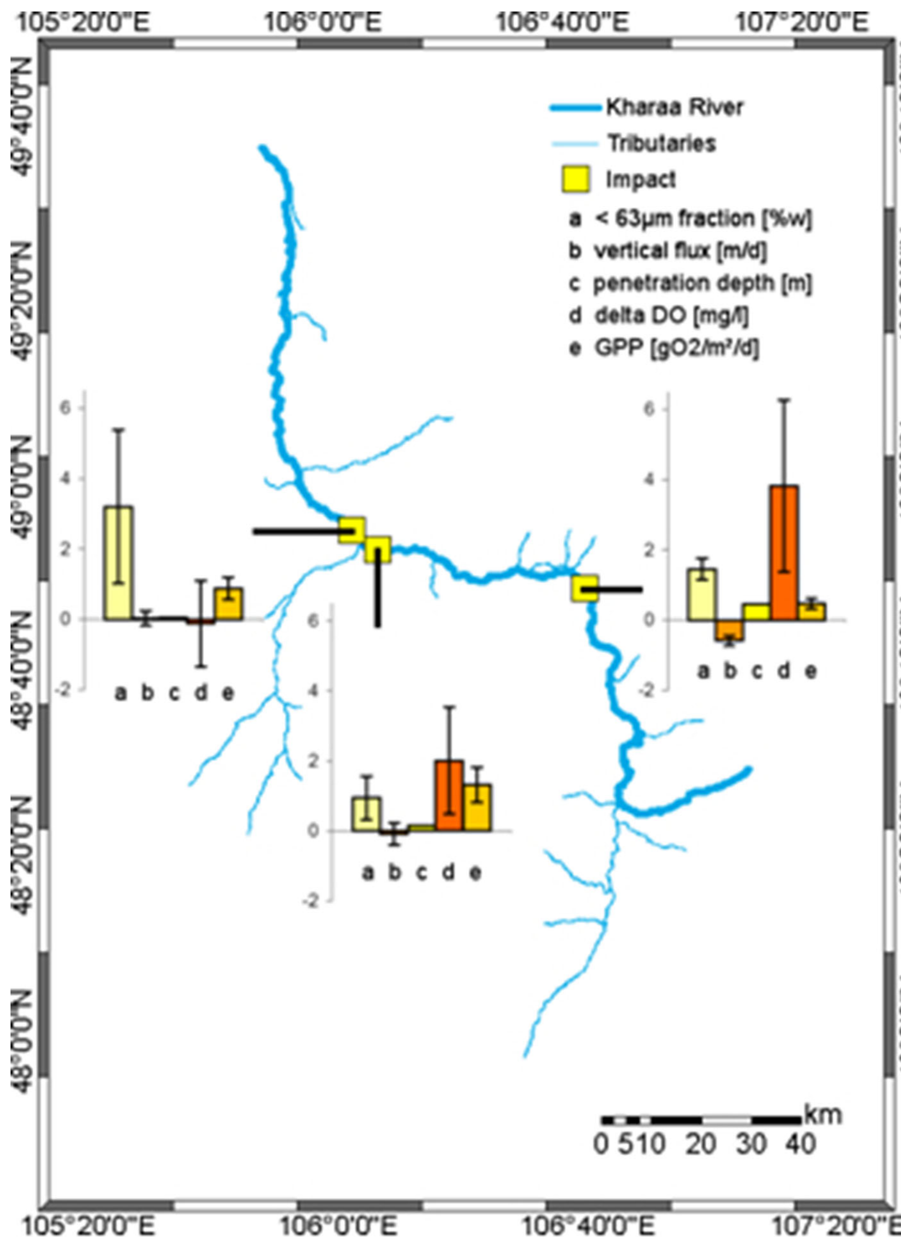

Fig. 5 Parameters describing the fine sediment impact on the aquatic ecosystem of the Kharaa River: **a** clogging effective fine sediment content in the sediment matrix (0–20 cm depth); **b** vertical flux between surface water and 15 cm sediment depth within the riffle head (*negative values* indicate downwelling); **c** estimated solute penetration depth into the riverbed; **d** behaviour of subsurface dissolved oxygen (*positive values* indicate oxygen depletion); **e** gross primary production

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. 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.

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.

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.

River bank stabilization

It could be clearly shown from the isotope signatures that bank erosion was the major source of instream 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 Zagdalin 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 behaviour, and should therefore be treated with special care.

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.

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.

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.

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.

Acknowledgments 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). P. Theuring and M. Hartwig were additionally supported through the Helmholtz Impulse and Networking Fund through the Helmholtz Interdisciplinary Graduate School for Environmental Research (HIGRADE). Andrew Kaus gave linguistic advice. All these supports are gratefully acknowledged.

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