Recent developments in river water quality in a typical Mongolian river basin, the Kharaa case study

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Abstract The objective of this study is to evaluate current water quality conditions in the Kharaa River basin in northern Mongolia. Based on surveillance data from the Mongolian environmental authorities and our complementary monitoring scheme, we evaluated nutrient and sediment bound heavy metal contamination on a sub-basin scale. Although the headwaters of the Kharaa represent natural background conditions (total nitrogen (TN) 0.46–0.58 mg N L^{-1}, total phosphorus (TP) 0.011 to 0.018 mg P L^{-1}) and population densities within the catchment are very low (<10 inhabitants km^{-2}), the river basin is facing relatively high anthropogenic pressure on water quality in the middle and especially in the lower reaches (total nitrogen 1.50–1.52 mg N L^{-1}, total phosphorus 0.18–0.26 mg P L^{-1}). The main contributors to these nutrient emissions are urban settlements with a high proportion of households without connection to wastewater treatment plants and, to a lesser extent, agricultural land use. The nutrient levels have a significant eutrophication potential in the Kharaa River. Heavy metal concentrations in river sediments show a high variability within the river system. Especially elevated concentrations of As, Pb and U can be related to the impact of mining activities in parts of the basin. The drinking water abstraction through bank filtration showed initial alterations of raw water quality indicated by slightly increasing concentrations of heavy metals and pollution indicators like chloride and boron. The results of the Kharaa River basin case study are related to water quality conditions in other Mongolian river basins.

Key words nutrients; heavy metals; water quality monitoring; rivers; Mongolia

1 INTRODUCTION

Mongolia is facing a tremendous change in climate and land-use intensification due to expansions in the agricultural sector, an increase of cattle and livestock and a growth of urban settlements due to migration of the rural population to the cities. It is expected that this may lead to unfavourable changes in surface water quality. A key challenge of water resources management is the identification of the main anthropogenic pollution sources and the assessment of their downstream ecological and socio-economic impacts. This knowledge is needed to identify mitigation and rehabilitation measures for downstream recipients. With the current study we aim to quantify the net impact of nutrient and heavy metal transport in a sparsely monitored region (Karthe *et al*., 2012).

2 SITE DESCRIPTION

With a total catchment area of 14 534 km^2 the Kharaa River basin is located north of the capital Ulaanbaatar, between latitudes 47°53′ and 49°38′N, and longitudes 105°19′ and 107°22′E. The Kharaa River originates in the Khentii Mountains in northern Mongolia and flows north to north-westwards into the Orkhon River, thus being part of the Selenga River basin, which is the main source region of Lake Baikal. In around 60% of the basin area the elevation ranges between 900 and 1300 m a.s.l., and the average altitude of the whole catchment is 1167 m. From its headwaters to the outlet, the river basin was divided into 10 hydrological sub-basins (Fig. 1):

– the upper reaches comprising the sub-basins 1 to 5 in Fig. 1 are characterized by mid- to high mountain ranges of the Khentii Mountains, and have the highest specific runoff rates of the entire river basin;
– in the middle reaches, sub-basins 6 to 8 in Fig. 1, the relief is dominated by broad valleys with significant terrace levels and hilly uplands with gentle slopes; and

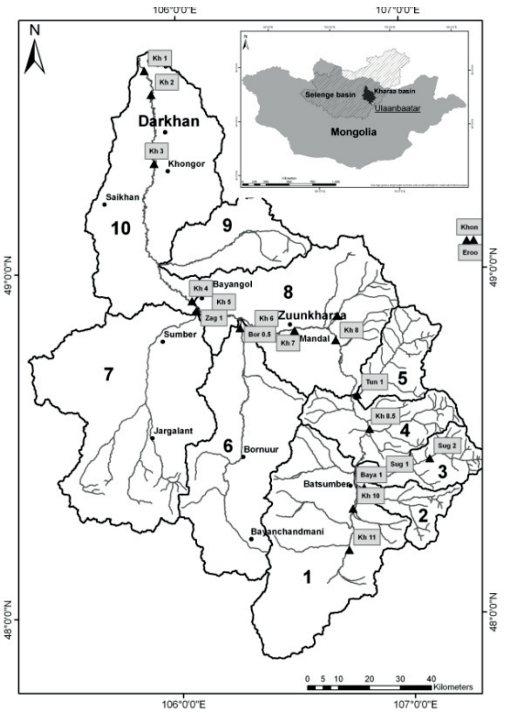

Fig. 1 Location of Kharaa River basin in northern Mongolia (see inset upper right). Numbers indicate the individual sub-basins. The river network is marked with grey lines (Hofmann *et al*., 2011).

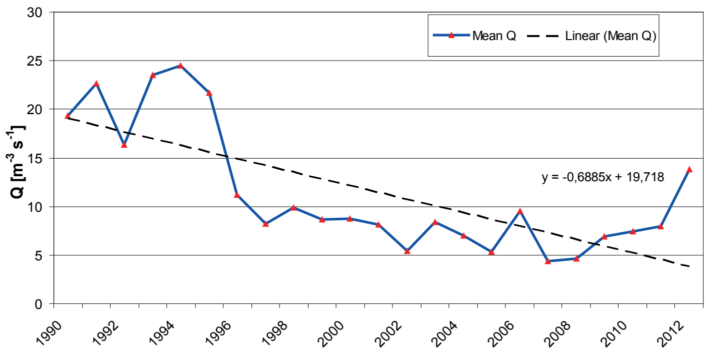

Fig. 2 Observed discharge from 1990 to 2012 at the river basin outlet of Kharaa River (gauge station Buren Tolgoi, data source: weather and forecast monitoring department Darkhan).

– the lower reaches comprising sub-basins 9 and 10 in Fig. 1 are typical for open steppe and lowland landscapes with features of peneplain formation processes.

The long-term (1990–2012) monitored average discharge of Khraa Gol is about 11.5 $m^3 s^{-1}$ at the outlet of the Kharaa River basin (Fig. 2; gauge station Buren Tolgoi, 49°35.485′N, 105°51.547′E), equivalent to a mean specific runoff of 0.83 L s^{-1} km^{-2}. The maximum discharge was approx. 62 m^3 s^{-1}, as in August 1994.

The climate of the area is semi-arid and belongs to the transition zone between the boreal climate with cold and very dry winters and the cold, semi-arid steppe climate. The winters are typically very cold, long and dry, and mean monthly temperatures in January range between –20 and –25°C (with minimum temperatures dropping to –40 °C). In contrast, the short summers are warm to hot (with an average July temperature exceeding 15°C), and the majority of the scarce precipitation falls between June and August.

Most of the river basin is covered by grassland (59%) and forest (26%) while the portion of arable land is only 11% (Schweitzer & Priess, 2009). The entire population of the Kharaa River basin is about 150 000 (mean population density about 10 inhabitants km^{-2}) with most of the inhabitants living in the city of Darkhan (about 75 000 inhabitants) near the river basin outlet.

Agricultural production on arable land is managed as a crop rotation system with predominantly wheat, and to a lesser extent with potatoes as cash crops. Livestock grazing has been a predominant land use over the last decades. However, since the collapse of the former socialist system in 1990/1991 the de-regulation of pastoralism has led to increased herd sizes and a concentration of grazing near cities and the river floodplains. Despite severe livestock losses due to a series of dry summers followed by winters with heavy snowfall (Mongolian *Dzud*) in the period 1997 to 2003 and 2009/2010, the overall stocking rate of grazing animals has increased dramatically from 25 million (1990) to recent record levels close to 40 million animals. The livestock numbers in the Kharaa River basin are estimated to be around 1 million animals.

Another important driver of land-use changes is the mining sector. Due to the geological situation in the Transmongolian lineament gold-mining is especially well developed in the middle reaches of Kharaa River basin, with most production in the Boroo and Gatsuurt gold mining areas. Currently more than 20 mines operate within the Kharaa region.

3 METHODS OF DATA COLLECTION AND ANALYSIS

To improve the existing database of monitoring by the Mongolian authorities (long time-series since 1986 for two measuring points up- and downstream of Darkhan city) we carried out detailed longitudinal stream surveys in spring, summer and autumn during the period 2006 to 2012 by sampling different water bodies (river water, groundwater, wastewater). The chosen water quality parameters included nutrients (total nitrogen, ammonium, nitrate, nitrite, orhto-phosphate, total phosphorus). As pollution indicators 11 heavy metals (Al, As, Cd, Cr, Cu, Fe, Mn, Hg, Ni, Pb, Zn) as well as chloride and boron, were selected. Reactive parameters such as nutrients were determined after filtration by photometry and standard cuvette tests (Hach-Lange) with standard solutions as blind tests. Other parameters like heavy metals, chloride and boron were analysed in German laboratories (Berlin and Magdeburg) according to the national standards for quality assurance of water analyses. To assess the seasonal pattern of suspended sediment load we used manual daily filtered suspended sediment samples from the catchment outlet for 2011 as described in Theuring *et al.* (2012). Furthermore, three water quality measurement stations were installed at different locations in the catchment in spring 2012 to monitor the behaviour of a range of water quality parameters: (a) Station Buren Tolgoi close to the catchment outlet approximately 15 km south of the city of Darkhan (sub-basin 10 in Fig. 1); (b) Station Baruunkharaa in the middle reaches of the catchment, adjacent to the intense agricultural and mining areas (sub-basin 8 in Fig. 1); (c) Station Sugnugur in one of the pristine headwaters in the Khentii Mountains (sub-basin 3 in Fig. 1). All three stations are equipped with optical YSI 6820 V2 probes that measure dissolved oxygen, pH, temperature, turbidity, chlorophyll and electrical conductivity at 15 minute time steps during the ice-free months. All data have been imported to a database and, following an outlier separation, statistically analysed and compared. For the evaluation of results and determination of water quality classes we used the Mongolian surface water classification 143/a/352 (Joint order of Mongolian Ministry of Nature and Environment and Ministry of Health, 1997), the WHO health risk based guideline value and also the Mongolian drinking water standard MNS 900: 2005 (Mongolian National Center of Standardizations & Meteorology, 2005) as comparisons, because the river water is also used as drinking water in rural areas.

During a campaign in May 2010, grab samples of freshly deposited suspended sediment were collected from all major tributaries close to their confluences with the main channel, and analysed for trace and heavy metals to investigate the contribution of the subcatchments to the sediment bound heavy metal load.

4 RESULTS

4.1 Water quality

As shown in Fig. 2 our monitoring observations started in a period of comparatively low discharge (2006–2009) while in the period 2010 to 2012 the discharge significantly increases again. In general, the water quality of the headwaters in the Khentii Mountains e.g. sub-basin 2 and 3 in Fig. 1 is characterized by very low nutrient, chloride, boron and heavy metal concentrations representing natural background conditions. For the middle and lower reaches the elevated levels, especially of nutrients, show increasing impacts of anthropogenic activities. At the river basin outlet this can be shown by a long-term comparison (2007 to 2012) of the resulting observed loads of total nitrogen (Fig. 3). The remarkable increase from 240 to 470 t TN yr^{-1} is an indication for the increasing nutrient release to Kharaa River by diffuse sources, mainly urban areas without connection to treatment plants (Hofmann *et al.*, 2011). Another important pathway is the direct nutrient input by manure from livestock during watering of animals. On a monthly scale the nutrient concentrations and loads show high variations according to the seasonality of the runoff regime. The resulting monthly TN loads show a typical seasonal pattern with a first peak in spring time in the melting period, known as "yellow water" event ("*shar uus*" in the Mongolian language). The second peak follows in autumn with again increased TN loads. With respect to the composition of the nutrients, NO_3^- and SRP were the dominant forms of dissolved N and P, respectively. The observed recent nutrient levels (2009 to 2012) show a very similar spatial pattern to those studied in detail by Hofmann *et al*. (2011) for the period 2006 to 2009. Although Zagdalin Gol and Darkhan City were found to be a source of total nitrogen, generally the nutrient levels have been rising.

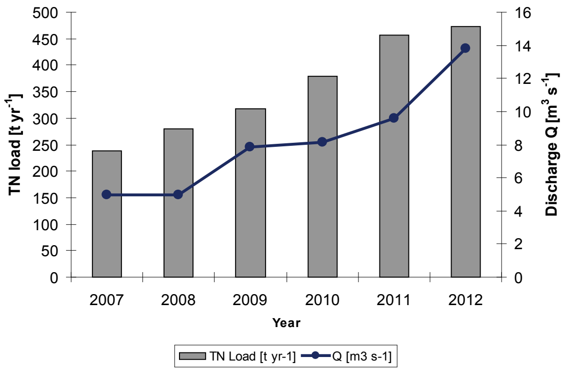

Fig. 3 Observed discharge (m^{-3} s^{-1}) and loads of total nitrogen TN (t^{-1} $year^{-1}$) at the outlet of Kharaa River basin (Buren Tolgoi) for the period 2007 to 2012. (Data source: discharge data of Buren Tolgoi station from Mongolian Weather and Forecast Monitoring Department; data of chemical analysis for total nitrogen by own monitoring.)

The evaluation of concentrations based on Mongolian Surface Water Guidelines resulted for TP and SRP in "moderate" or "poor" status in the downstream Kharaa River (sub-basin 10) and in Zagdalin Gol (sub-basin 7). Ammonium levels indicated "moderate" conditions in Boroo Gol and Zagdalin Gol while "poor" conditions (0.1–0.3 mg NH_4^+-N/L) occurred in sub-basin 1. TN was "moderate" in sub-basins 2, 3 6, 8 and "poor" conditions (average concentrations 1–2 mg N L^{-1}) in sub-basins 7 and 10. In general the anthropogenic impacts can be seen in the elevated concentrations levels for chloride, boron and sulphate at the tributaries Mandalin Gol (sub-basin 1), Boroo Gol (sub-basin 6) and Zagdalin Gol (sub-basin 7).

The dissolved concentrations of arsenic during four monitoring campaigns in May (spring time after ice melt with the first flood peak) and September (fading phase of second flood peak) in 2011 and 2012 are shown in Fig. 4. The measurements from the stations Buren Tolgoi, Baruunkharaa and Sugnugur show a clear gradient of many parameters between the upstream and downstream areas of the catchment. The average water temperatures show strong daily amplitudes

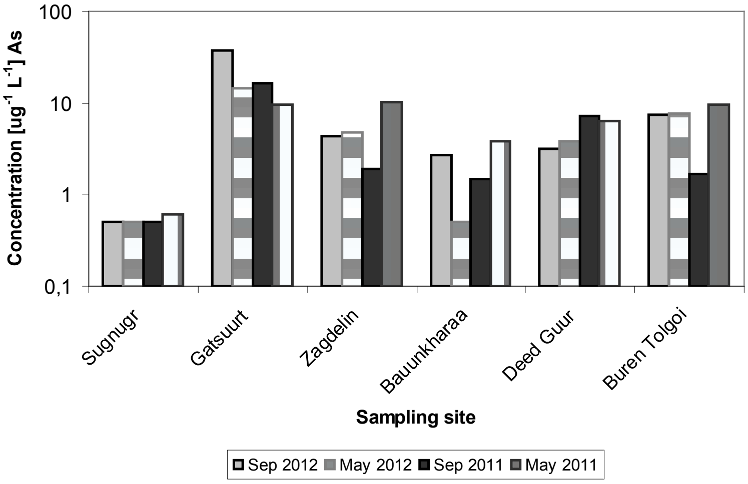

Fig. 4 Concentrations (dissolved) of Arsenic [μg^{-1} L^{-1}] at six different monitoring points along the Kharaa River from upstream (Sugnugr = sub-basin 3 in Khentii Mts) to downstream (Baruunkharaa = sub-basin 8, Deed Guur = sub-basin 10 and Buren Tolgoi River basin outlet) and selected tributaries (Gatsuurt brook = sub-basin 4, downstream of Gatsuurt goldmine, Zagdelin Gol =sub-basin 7 with mainly agricultural land use and small scale artisanal goldmines).

and range from 14.9°C at the outlet at Buren Tolgoi to 12.9°C in the midstream at Baruunkharaa and 7.2 at Sugnugur. Whereas the average conductivity in the upstream region at Sugnugur is very low, 41.7 μS/cm, the down- and midstream stations at Buren Tolgoi and Baruunkharaa show much higher values with averages of 251.0 μS/cm (maximum 453 μS/cm) and 250.7 μS/cm (maximum 481 μS/cm) for the respective stations. This implies much higher concentrations of TDS due to an increased matter input in these regions that is related to inputs from agriculture, settlements and mining activities.

The measurements of dissolved oxygen saturation (Fig. 5) as well as the chlorophyll-a content indicate an increased development of algae and macrophytes, especially during the months of May/June and during September, which is strongest in the mid- and downstream regions at Baruunkharaa and Buren Tolgoi. In a naturally nutrient limited river like the Kharaa, this is a strong signal for land-use induced eutrophication.

All dissolved arsenic concentrations show a clear spatial pattern with very low concentrations in the Khentii Mts (sub-basin 3) as natural background. In sub-basin 4 the Gatsuurt goldmine is located in the upper course of tributary Gatsuurt (sub-basin 4) releasing heavy metals from tailing deposits. Here the arsenic concentrations peak up to 38 μg L^{-1}. Also in sub-basin 6, the large Boroo goldmine contributes to the arsenic loads. Downstream of this tributary the level of arsenic concentrations in Kharaa River can reach up to 10 μg L^{-1}, close to the WHO health risk-based guideline value. In sub-basin 6 and 7 (Zagdalin Gol) wastewater from artisanal small-scale mining has also influenced the water quality. However, pronounced effects of seasonality could not be detected in the monitoring campaigns.

4.2 Seasonality of suspended sediment loads

Suspended sediment transport in the catchment shows a strong seasonal pattern with the months from May to October constituting on average 81.6% of the annual discharge and 89.6% of the annual SS transport. The analysis of the discharge during the summers of 2010 and 2011 clearly showed the influence of several rainfall events on the hydrograph (Theuring *et al.*, 2012).

Measurements of SS concentrations in 2010 revealed a clear influence of high discharge events on sediment transport in the river with a mean concentration of 172 mg/L and a maximum concentration of 1140 mg/L.

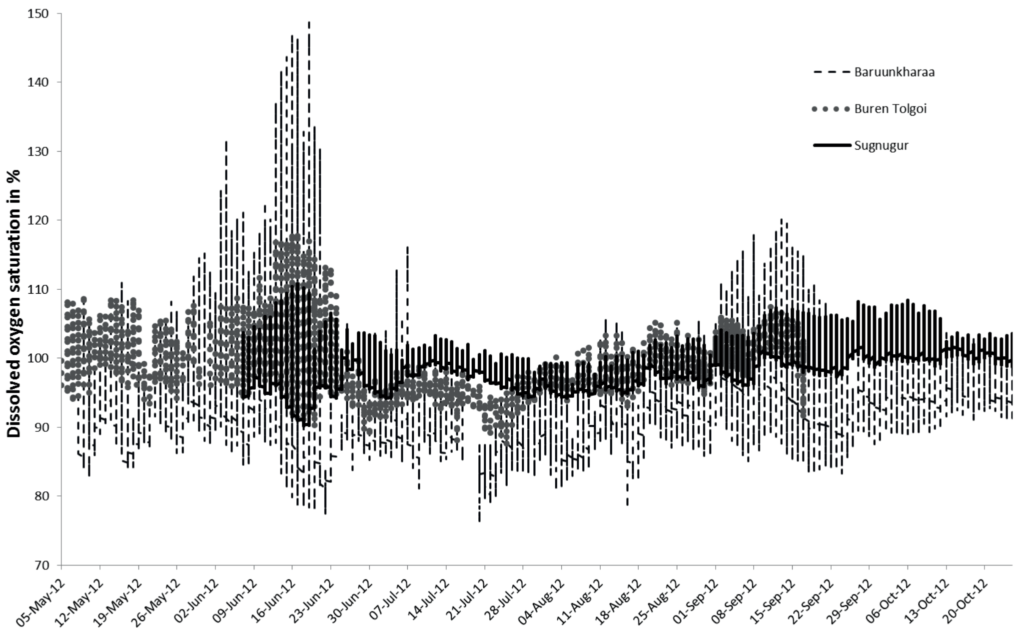

Fig. 5 Dissolved oxygen saturation in % during the summer months of 2012.

The analysis of the heavy metal concentrations in Table 1 shows a clear increase, especially at the Gatsuurt site, for most elements. Increased levels of arsenic are further recognizable in the subcatchments of Boroo Gol and Tunkhelin Gol, and are an indicator of mining activity in these subcatchments, whereas the highest lead concentrations occur in Zagdelin Gol. The by-far highest concentrations of uranium are found in samples from Mandalin Gol, and are assumed to be geologic in nature.

Table 1 Heavy metal concentrations (µg kg^{-1}) in the river sediment from the main tributaries in the catchment in May 2010 (maximum values in bold type, and minimum in italics).

Stream	U	Al	As	Cu	Cr	Fe	Mn	Pb	Zn
Buren Tolgoi	4.8	51.2	12.9	37.1	65.9	47.8	1300	22.8	136
Bayangol	4.6	49.6	*10.3*	40.6	73.2	46.1	913	21.7	129
Zagdalin Gol	5.6	52.9	16.3	40.7	64.4	**55.4**	1170	**26.0**	141
Boroo Gol	4.2	44.5	32.3	40.2	72.3	40.4	*766*	21.7	119
Shivertyn Gol	*2.2*	47.9	14.3	50.1	**81.6**	50.5	**1520**	21.2	136
Gatsuurt	4.8	**53.2**	32.7	**50.3**	76.4	51.7	1400	23.0	137
Tunkhelin Gol	9.2	48.4	**36.0**	48.1	67.2	43.3	992	*17.0*	121
Mandalin Gol	**17.3**	44.0	25.7	43.1	*54.6*	41.6	1070	17.1	**178**
Sugnugur Gol	2.5	*43.9*	17.0	*30.9*	54.9	*36.1*	1450	17.7	*101*

4.3 Mass flows

To investigate the mass flows of heavy metals and pollution indicators (chloride and boron) we concentrated our sampling activities in spring and autumn of 2011 and 2012 to consider the effects of different hydrological conditions. As shown in Fig. 6 the data set comprises four monitoring campaigns in May (spring time after ice melt with the first flood peak at 17.5.2011 (Q = 27 m^3 s^{-1}) and at 18.5.2012 (Q = 5.1 m^3 s^{-1}) and September (second flood peak at 6.9.2011 (Q = 6.2 m^3 s^{-1}) and 9.9.2012 (Q = 20.9 m^3 s^{-1}). The mass flows were calculated as products of local concentrations and discharge by applying the equations proposed by Thorslund *et al.* (2012: 2782). To facilitate accurate mass flow estimations, pollutant concentrations and discharge values were measured on

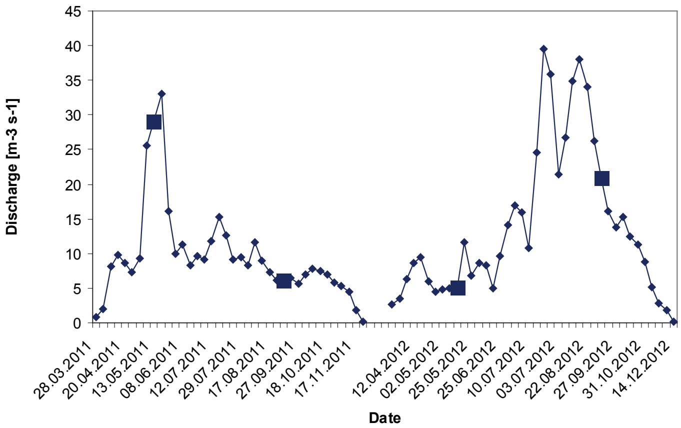

Fig. 6 Kharaa River discharge of at Buren Tolgoi (river basin outlet) for the observation periods in 2011 and 2012. The bold rectangles indicate the days of sampling for heavy metals, chloride and boron in May and September. The ice cover lasted from mid November 2011 until beginning of April 2012. (Data source: weather and forecast monitoring department Darkhan).

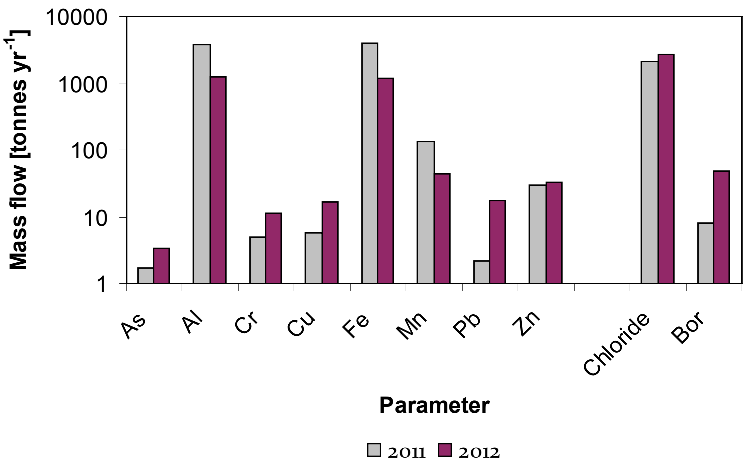

Fig. 7 Estimated mass flows [tonnes^{-1} year^{-1}] for heavy metals and pollution indicators (chloride and boron) in Kharaa River at the gauge station Buren Tolgoi (river basin outlet) based on monitored samplings in May and September 2011 and 2012. The relevant discharge data are shown as bold rectangles in Fig. 6 (data source: own monitoring and chemical analysis).

the same day, or with a time difference of less than 2 days. The bars in Fig. 7 show the dissolved mass flows of heavy metals and pollution indicators (chloride and boron) at the river basin outlet (station Buren Tolgoi) for 2011 and 2012, respectively. In terms of dissolved mass, Fe, Al and to a lesser extent also Mn, are the most relevant heavy metals. Comparison with the heavy metal concentrations of the river sediments (Table 1) shows a similar pattern. The mass flows of dissolved metals are substantially higher during flood events relative to normal or low flow conditions. However, the estimation of suspended transport and its contribution to the total mass flows needs further evaluation of total heavy metal concentrations in the river water. In accordance with the published data of Thorslund *et al.* (2012) on gold mining impacts in the upper Lake Baikal basin, we can suggest increasing mass flows for As, Cr, Cu, Pb and Zn. Special attention is given to arsenic since long-term exposure from drinking water may cause harmful effects to human health (USEPA, 1998, 2010). Groundwater recharge is mainly fed by bank infiltration from the Kharaa River. As most of the drinking water extraction sites of the city of Darkhan are situated in the river floodplain, the groundwater quality is already affected by increasing arsenic levels. From our groundwater and drinking water monitoring we can assume that the population of Darkhan is exposed long-term to a level of 3–5 µg L^{-1} arsenic in drinking water. This is still below the maximum tolerable concentrations of 10 µg L^{-1}, but the increasing trends are also influenced by the release of arsenic from ash deposits, remnants of coal combustion processes at the Darkhan Thermal power plant.

5 DISCUSSION

Livestock grazing near water bodies significantly altered nutrient inputs to the Kharaa River through multiple mechanisms, including reduction of vegetative cover and compaction of soils, leading to increased erosion and runoff, and increased animal waste near to the water's edge. These results support the findings of Shinnemann *et al*. (2009b) who describe increased eutrophication of 65 lakes in western Mongolia, primarily due to changing herding practices after 1991. Eutrophication does not occur to the same extent in the river system. However, our continuous oxygen and chlorophyll-a concentration results suggest that the middle and lower parts of the Kharaa River are more heavily impacted by eutrophication. Significant differences in the nutrient export to surface waters have been shown between moderately intense and high-intensity grazing areas (Shineemann, 2009a). Besides increased livestock, untreated wastewater was also responsible for higher nutrient levels in the middle and lower part of the Kharaa River. Similar findings were also reported by Kelderman & Batima (2006) in the Tuul River; especially in the lower parts of the river with elevated diffuse inputs from urban areas, deteriorating trends in water quality were found over recent years. Such clear spatial differences of pollution levels, with low levels in montane rivers and elevated nutrient levels in the middle or lower parts of these rivers were also reported by Zhu *et al*. (2011) in northwest parts of China.

We found a clear relationship between elevated dissolved and sediment heavy metal concentrations and mining activities in the Kharaa River. Mining impact on heavy metal and arsenic concentrations in sediments of surface water were also found by Inam *et al*. (2011) in the Boroo gold mine area. These findings support the results of Thorslund *et al*. (2012) who suggest that local to regional transformation and enrichment processes, in combination with suspended sediment transport from numerous upstream mining areas, contribute to high concentrations of dissolved heavy metals in downstream parts of the Selenga River. They stated that the Selenga River basin, which drains into Lake Baikal, should be recognised as one of the world's most impacted areas with regard to heavy metal loads.

These recent changes in water quality may accelerate the impact of climate change on water quality due to predicted warmer and more arid climate in these central Asia regions (Shinnemann *et al*., 2009a).

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