

What drives the water quality changes in the Selenga Basin: climate change or socio-economic development?

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Received: 30 June 2015 / Accepted: 6 June 2016 / Published online: 24 June 2016
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Abstract Lake Baikal is the largest near-surface global freshwater source and of high interest for water quality alterations, as deterioration of water quality is a main global and an increasing issue in the Selenga River Basin. Here, the Selenga River Basin as main contributor to the inflow of Lake Baikal is extremely important. Pressure on ecosystems and water resources increased due to population growth, rapid urbanization and rising industrial activities, particularly in the mining sector. In this study, the large-scale water resources model WaterGAP3 is applied to calculate loadings of conservative substances (total dissolved solids) and non-conservative substances (faecal coliform bacteria and biological oxygen demand) in a spatially explicit way as well as in in-stream concentrations to get an insight into the state of water quality under current and future scenario conditions. The results show a strong increase in loadings in the scenario period and consequently increasing concentration levels. Comparing the sectoral contributions of the loadings, domestic and industrial sectors are by far the main contributors today and expected to be in the future. Furthermore, for all modelled substances and time periods, water quality thresholds are

exceeded posing a potential risk to aquatic ecosystems and human health.

Keywords Selenga River Basin · Lake Baikal · Large-scale modelling · Water quality · WaterGAP3

Introduction

Deficient water quality induced by water pollution is one of the main global issues, as it is causing risk to human health, biodiversity, and food security. Generally, freshwater ecosystems are facing “increasing and multiple threats, including overgrazing, dams and irrigation systems, growing urbanization, mining and gravel extraction, impact of climate change and lack of water management policies and institutional framework” (FAO 2012). Lake Baikal, as the world’s largest freshwater reservoir, and its corresponding catchments are already affected by global changes, and sensitive regarding alterations in water quality. The mostly semi-arid environment is highly vulnerable and influenced by climate change as observed by an increasing temperature trend during the last decades (Batimaa 2006; Malsy et al. 2012; Törnqvist et al. 2014) accompanied by increasing water temperatures causing chlorophyll a and zooplankton grazers intensification (Hampton et al. 2008). The Selenga River Basin contributes more than 60 % to the total inflow of Lake Baikal (Törnqvist et al. 2014), meaning that changes in the Selenga River system in terms of water quantity and quality are of high importance concerning potential impacts on Lake Baikal. Mining increased strongly during the last decades accounting for about 25 % of the total national Gross Domestic Product (GDP) in 2014 (compared to ~10 % at the beginning of the twenty-first century, Mongolian Statistical Information

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Service 2015) as well as the highest share of total nationwide water use (cf. Batsukh et al. 2008; Malsy et al. 2013). Here, washing processes for mining from both licensed and unlicensed mining activities have severe impacts on surface water quality (Farrington 2005; Bolormaa et al. 2006; Krätz et al. 2010; Thorslund et al. 2012). During the last years, particularly in the Mongolian part of the Selenga River Basin, an expansion of agriculture and land use intensification took place (Hofmann et al. 2011; Sorokovikova et al. 2013). Furthermore, increasing industrial activities accompanied by a rapid urbanization trend put additional pressure on water resources. Low connection rates to wastewater treatment plants, malfunctioning wastewater treatment plants, and use of cyanide and arsenic in gold mining are of high concern and can lead to water quality deterioration (Hofmann et al. 2011; Sorokovikova et al. 2013). Studies focusing on the Kharaa River sub-basin showed high heavy metal concentrations in the surface water as well as high levels of boron, chloride, and electrical conductivity in the groundwater (Hofmann et al. 2010, 2015).

In the Selenga River Basin, water quality studies have so far been focusing on a sub-basin level (e.g. Hofmann et al. 2011, 2013; Karthe et al. 2013; Sorokovikova et al. 2013; Hofmann et al. 2015), while water quantity-related topics were addressed by sub-basin and large-scale studies (Stubblefield et al. 2005; Batimaa 2006; Malsy et al. 2012; Malsy et al. 2013; Törnqvist et al. 2014; Chalov et al. 2015; Nadmitov et al. 2015). A comprehensive spatially explicit water quality assessment covering the entire Selenga River Basin has, to our knowledge, not yet been carried out. Therefore, this study applies the large-scale modelling framework WaterGAP3 to simulate current and future scenario loadings and in-stream concentrations of conservative (total dissolved solids—TDS) and non-conservative substances (biological oxygen demand—BOD, faecal coliform bacteria—FC) in the Selenga River Basin to gain insight into the sectoral (agricultural, industrial, and domestic) contributions as well as spatial patterns of potential water pollution. These substances were chosen as they represent different kinds of pollution and indicate potential risks for human health (FC) and aquatic ecosystems (BOD, TDS). In general, Mongolia is not only a water-scarce region but also scarce in terms of environmental data (Karthe et al. 2015) which require a comprehensive water quality modelling study.

Materials and methods

The WaterGAP3 modelling framework

The global integrated water resource model WaterGAP3 (see Fig. 1) operates on a five arc minutes spatial resolution

and consists of three main components: (a) a water balance model to simulate the terrestrial water cycle with the aim to estimate the available water resources (Verzano et al. 2009; Schneider et al. 2011; Müller Schmied et al. 2014), (b) the water use sub-models to estimate anthropogenic water abstractions (withdrawal and consumption) for the sectors such as agriculture (irrigation, livestock), industry (manufacturing processes, thermal electricity production), and domestic households and small businesses (aus der Beek et al. 2010; Flörke et al. 2012, 2013), and (c) a water quality model (WorldQual) to calculate loadings and in-stream concentrations of conservative (e.g. TDS) and non-conservative (e.g. BOD) substances (Voß et al. 2012; Williams et al. 2012; Reder et al. 2015).

Climate data on precipitation, air temperature, and radiation from the WATCH forcing data (WFD, Weedon et al. 2011) were used to calculate the daily water balance for each grid cell for the time period 1971–2000, taking into account physiographic characteristics like soil type, slope, and vegetation. Runoff generated on the grid cell is routed to the basin outlet based on a global drainage map (Lehner et al. 2008). The routing approach considers the influence of lakes, wetlands, reservoirs, and dams (Döll et al. 2009). For the scenario period 2071–2100, bias-corrected climate input developed within the WATCH project (Piani et al. 2010; Hagemann et al. 2011) was used as a basis to derive representative conditions for a wet, dry, and average year to cover the whole range of future projections.

Based on the results of the hydrological and water use modelling, simulations with the water quality module WorldQual of TDS, BOD, and FC were conducted following the methodology described in Voß et al. (2012), Williams et al. (2012), and Reder et al. (2015). For this study, effects of water use in mining were also considered as described in Malsy et al. (2013). Pollutant loadings are calculated for point and diffuse sources separately (see Fig. 2) where point sources include domestic sewage, wastewater from industries and mining, and urban surface runoff. Diffuse sources comprise agricultural inputs such as manure (livestock), industrial fertilizer, and natural background emissions. Additionally, domestic—non-sewered—sources are considered as point (e.g. hanging latrines) and diffuse (e.g. open defecation) sources depending on the type of disposal.

Diffuse loadings from manure application are calculated by multiplying the substance-specific loading in livestock manure with a substance-specific release rate and the respective surface runoff. Domestic—non-sewered—sources cover loadings from population not connected to wastewater treatment plants (WWTPs). In this context, three different classes of sanitary waste disposal were distinguished:

- (a) Settlements with some type of private onsite disposal, such as septic tanks or pit toilets, etc.:

Fig. 1 WaterGAP modelling framework (Verzano 2009, modified)

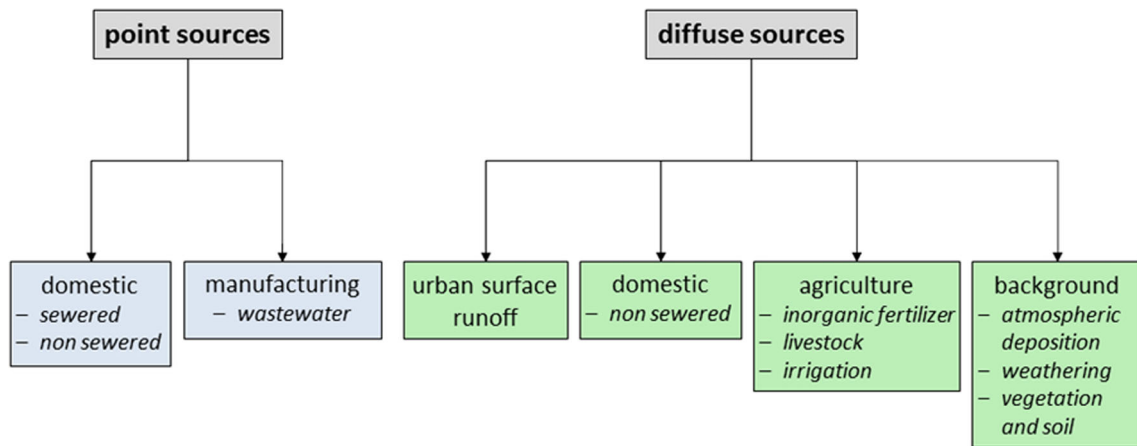
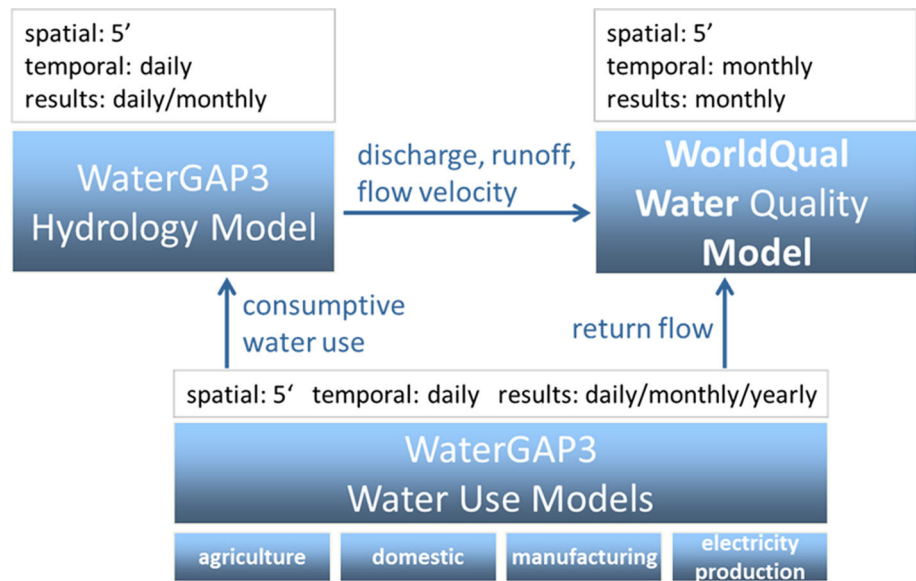


Fig. 2 Pollutant loading sectors represented in WorldQual categorized as either point sources or diffuse sources (Reder et al. 2015, modified)

calculated by multiplying the connected population with a per-capita emission factor. To achieve the final loadings inflowing into the stream a reduction factor is used.

- (b) Settlements with open defecation: calculated analogously to loadings from manure application by multiplying the load of a pollutant in human faeces by a substance-specific release rate and the respective surface runoff.
- (c) Settlements with hanging latrines: calculated by multiplying the per-capita load by a per-capita emission factor.

The domestic loadings from sewage are calculated by multiplying a per-capita emission factor by the urban and rural population connected to wastewater treatment plants. Loadings reaching WWTPs are reduced depending on the

treatment level, i.e. primary, secondary, and tertiary treatment. Loadings from urban surface runoff are calculated by multiplying a typical event mean concentration with the urban surface runoff. The loadings resulting from industries are estimated by multiplying the average raw effluent concentration by the return flow from industries. An overview of the input assumptions used for Mongolia is given in Table 1.

The estimated cell-specific pollutant loadings are divided by the river discharge of each grid cell to calculate the in-stream concentration. In addition, the model simulates substance-specific sedimentation and decay processes depending on temperature and/or solar radiation that reduce the in-stream concentration.

In this study, atmospheric deposition, background concentration from vegetation and loadings from inorganic fertilizers are not considered. Furthermore, background

concentration from soil and rock is only used for TDS calculations.

The simulations in this study concentrate on the Mongolian part of the Selenga River Basin because the socio-economic projections and information on mining water use were only available for this particular part of the basin. Further, no information was available on the future development of connection rates and treatment levels, and therefore, baseline values were kept constant in the scenario period.

Study region

The Selenga River Basin (see Fig. 3) accounts for over 60 % of the total inflow and contains 80 % of the total drainage basin of Lake Baikal (Törnqvist et al. 2014). Hereby, around two-thirds of the Selenga River Basin area is located in Mongolia, and one-third is in Russia. In Mongolia, increasing impacts due to mining activities, urbanization, and land use changes have already been observed and further growth is expected (Hofmann et al. 2011; Priess et al. 2011; Sorokovikova et al. 2013; Priess et al. 2015). The Strahler stream number for the Selenga River Basin network based on the model stream net is of order six, which is comparable to, e.g. the Colorado River in the USA (Strahler 1957; Pierson et al. 2008; see Fig. 3). The climate is continental with cold, dry winters and short

mild summers, while most of the precipitation occurs in summer (Batimaa et al. 2006). The basin is underlaid by mountain and arid land permafrost (Gruber 2012; Kopp et al. 2014; Törnqvist et al. 2014). During the last decades, air temperature has been increasing with a warming rate almost twice as high as the global average, especially during the winter period (+3.6°K between 1940 and 2001), whereas no clear trend could be detected for the summer season (Batimaa et al. 2005; Malsy et al. 2012; Törnqvist et al. 2014). Runoff showed a slight decrease in the mid-1990s but without a long-term trend, although precipitation as well as evapotranspiration has been increasing (Törnqvist et al. 2014). Projections, on the other side, show a further increase in temperature as well as in precipitation until the end of the twenty-first century (Malsy et al. 2012; Törnqvist et al. 2014). The dry, wet, and average conditions as derived from various GCM outputs and used in this study are characterized by a high temperature increase of more than 5°K and a precipitation increase of 2.3 mm (dry) to 96.3 mm (wet) for the entire basin compared to the baseline period (cf. Table 2). The socio-economic scenario applied in this study is marked by an increasing trend in population growth, urbanization, and industrial development and based on the assumptions given in Table 3. According to the assumptions, an ongoing trend of rising water abstractions is very likely. However, the quantification of the scenario resulted in an increase in water

Table 1 Input data assumptions for Mongolia

Input variable	Spatial resolution	Temporal resolution	Assumptions for Mongolia
Connection rate [%]	Country	Annual	21
Treatment level [%]	Country	Annual	0; 15; 0; 6
Primary; secondary; tertiary; untreated but collected			
Treatment efficiency [%]	Global	Static	BOD 50; 90; 90 FC 43; 97; 99 TDS 1; 1; 1
Primary; secondary; tertiary			
WWTP not working properly [%]	Country	Static	59
Effluent concentration (manufacturing; irrigation; mining)	Country	Static	BOD (400; 0; 0) FC (0.0004; 0; 0) TDS (3000; 165–3500; 3000)
BOD [mg/l]; TDS [mg/l]; FC [10^{10} cfu/L]			
Human emission factor	Country	Static	BOD 40 FC 1.9 TDS 100
BOD [g/cap*d]; TDS [g/cap*d]			
FC [10^{10} cfu/cap*d]			
Event mean concentration (urban surface runoff)	Country	Static	BOD 105 FC 105000 TDS 246
BOD/TDS [mg/l]; FC [cfu/100 ml]			
Emission from livestock (excretion of one livestock unit)	FAO Region	Static	BOD 0.31 FC 16.79 TDS 0.17
BOD/TDS [t/a*livestock unit (lsu)]; FC [10^{10} cfu/a*lsu]*			

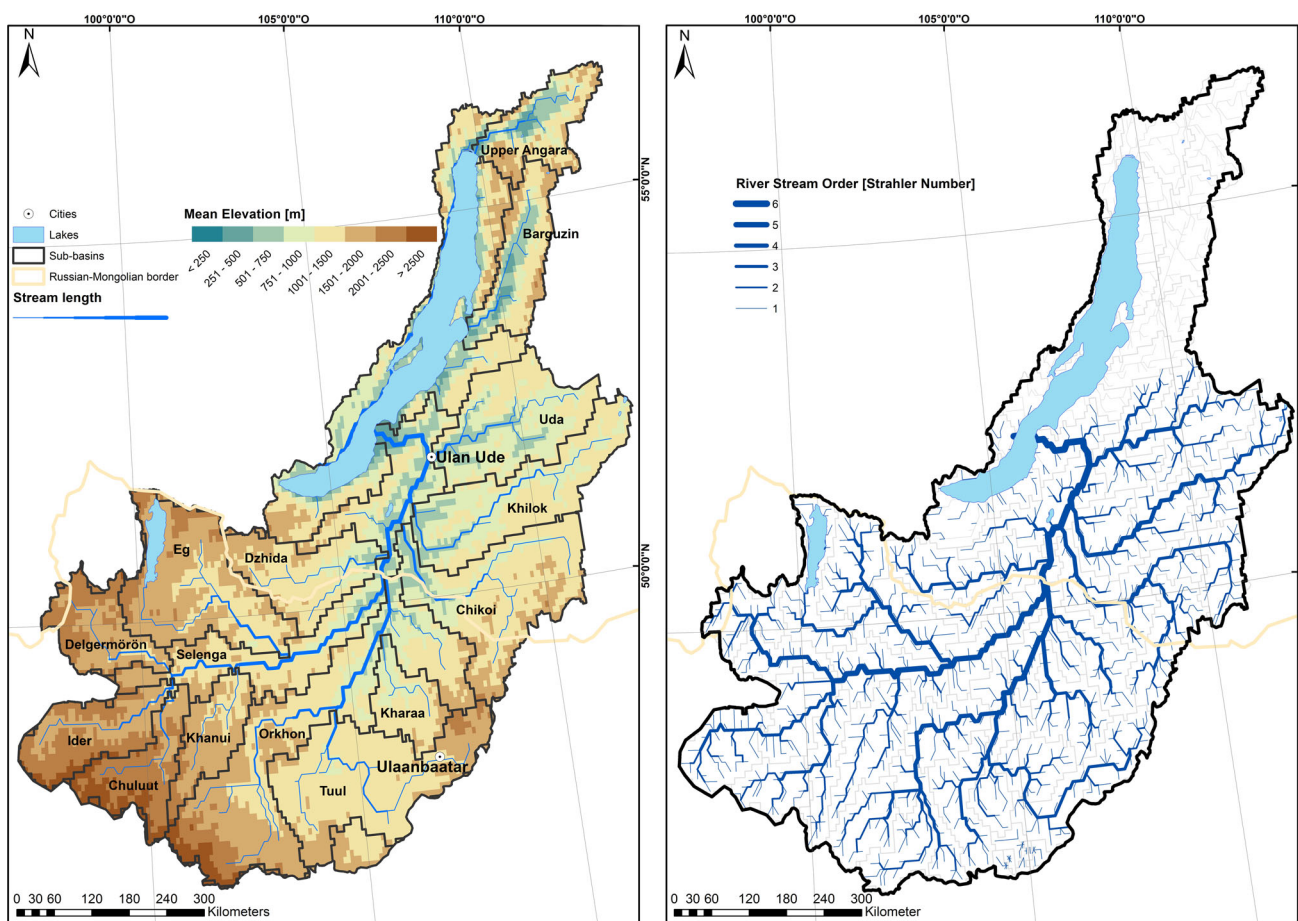


Fig. 3 *Left* Overview of the study region including the sub-basins contributing to the Selenge–Lake Baikal River system; *right* Strahler stream order number for the Selenge River Basin

Table 2 Changes of temperature and precipitation comparing the baseline period (1971–2000) and the wet, dry, and average scenario

	Scenario		
	Wet	Dry	Average
Temperature (°K)	5.27	5.05	5.29
Precipitation (mm)	96.29	2.32	43.70

abstractions, particularly in the domestic (from 82 to 367 mill m³) and mining (from 81 to 343 mill m³) sectors. The water abstractions for thermal electricity production is expected to rapidly decrease due to a change from one-through cooling to tower cooling systems in the future as assumed under the given scenario (Vassolo and Döll 2005; Malsy et al. 2013).

Model validation

As already mentioned, Mongolia can be described as a data-scarce region (cf. Törnros and Menzel 2010; Malsy et al. 2013; Karthe et al. 2015) and only few measurements

Table 3 Key drivers of the socio-economic scenario for Mongolia taken from Malsy et al. (2013)

Indicators/driving forces	Urban	Rural
Population development	+++	+
Growing rate	+++	+
Household size	-	0
Population density	+++	+
GDP/capita	+++	
Gross value added (GVA)	+++	
Access to water	+	+
Land use management	++ (in terms of forest -)	
Technological change	+	

are available to validate the water quality model. The validation of the hydrological model is described in Malsy et al. (2012) and Malsy et al. (2015). In this study, BOD and TDS measurements at Tuul River in Ulaanbaatar for the time period 1996–2000 were used (Altansukh 2008),

but no values for FC validation could be found. The model results (see Fig. 4) show a peak overestimation for BOD during the winter period, while the overall dynamics and the level of simulated concentrations are in a good agreement with the observed data. In contrary to BOD, for TDS, the higher concentrations during winter could not be reproduced by the model, while the concentration levels during summer match with the observed data quite well. During winter, the water availability is in general very low in Mongolia and leads therefore to larger deviations, i.e. higher uncertainties, in the modelled results. Because of missing information on measured surface water quality data, particularly consistent time series, a validation of model results could not be carried out for wide regions.

Results and discussion

The simulation results for the Mongolian part of the Selenga River Basin (cf. Table 4) show a strong increase in BOD, FC, and TDS loadings in the future. TDS loadings are expected to be 4.5 times higher in the scenario period compared to the baseline conditions, while BOD loadings may increase by a factor 3.4 and FC by 1.5, respectively. Overall, the climate change effect represented by dry, wet, and average climatic conditions in the scenario runs on the

calculation of future loadings is negligible compared to the effect of socio-economic development. However, to our knowledge no information is available on recent BOD, TDS, and FC loadings for the entire catchment or a sub-catchment for model testing. Nevertheless, Hofmann et al. (2013) report a nearly doubling in total nitrogen loadings in the Kharaa River Basin for the time period 2007–2012.

Looking at the main sources contributing to the annual loadings (cf. Table 5) for biological oxygen demand, domestic—sewered—sources (41.5 %) and industry (39.8 %) are the main sources in the baseline period followed by domestic—non-sewered—sources (12.7 %) and livestock (5.3 %). Urban surface runoff has little to no effect on the loadings of the different substances for the baseline and scenario periods, and its share remains below one per cent of the total loadings. For the scenario period, industry has by far the highest share (74.6 %) followed by domestic—sewered—sources (16.2 %), domestic—non-sewered—sources (7.1 %), and livestock (2.0 %). For FC, domestic (sewered and non-sewered) source is clearly the dominant source in the baseline as well as in the scenario period. Here, the share of domestic—sewered—source decreases from 73.7 % in the baseline to around 63 % in the scenario period, but persists as dominant source followed by domestic—non-sewered—source with about 29 %. This is caused by a population increase which is not

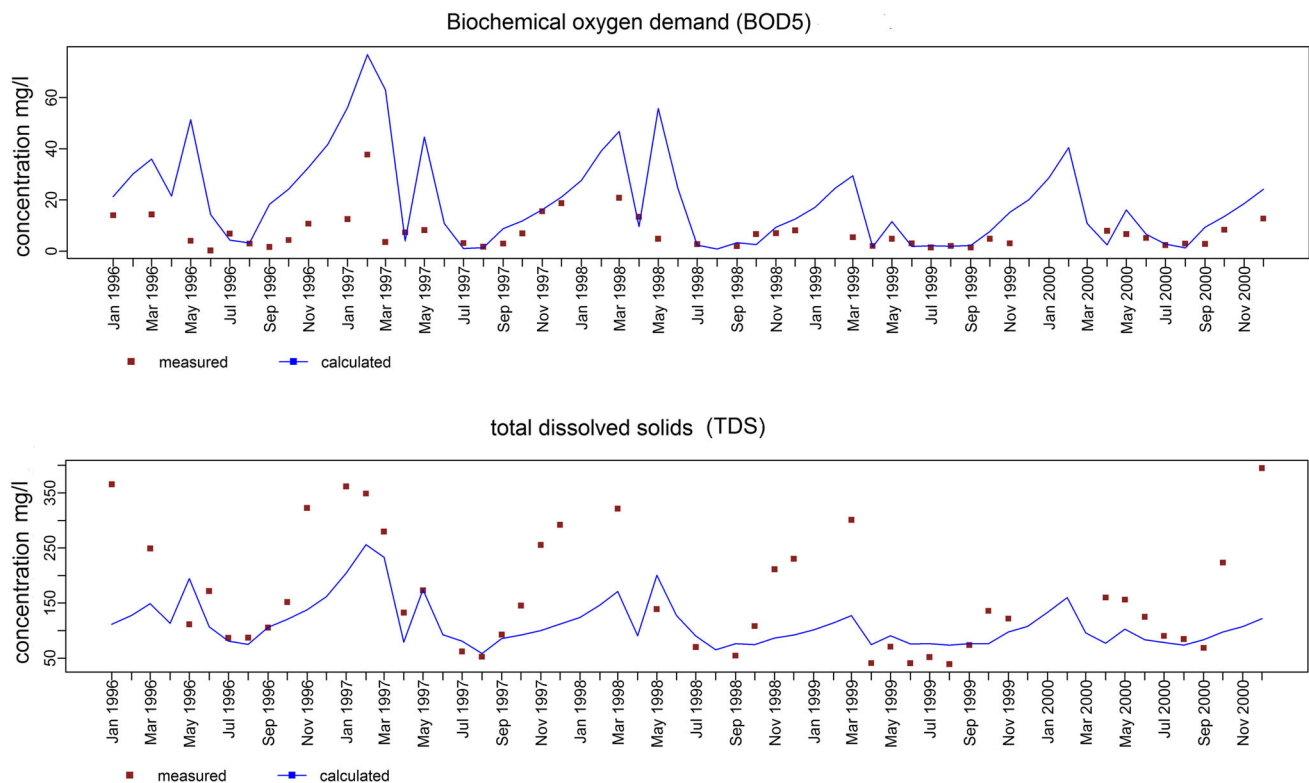


Fig. 4 Validation of simulated BOD5 (*top*) and TDS (*bottom*) in-stream concentration at Ulaanbaatar for the time period 1996–2000

Table 4 Annual loading per parameter in the Mongolian Part of the Selenga River Basin for the baseline (water use base year 2000) and scenario time period (water use base year 2085)

Parameter	Loadings BOD, TDS [t/a], FC [10^{10} cfu/a]			
	Baseline	Scenario—average	Scenario—dry	Scenario—wet
BOD	9832	33,537	33,328	33,616
FC	265,535,194	391,406,316	388,859,560	392,848,370
TDS	96,433	449,532	446,450	450,062

For TDS only the anthropogenic loadings (without natural background) are shown

Table 5 Sectoral contribution to total annual loading for the baseline and scenario period; values are given in per cent

Parameter—time period	Domestic sources—sewered	Industry	Domestic sources—non-sewered	Livestock	Irrigation	Urban surface runoff
BOD baseline	41.5	39.8	12.7	5.3	–	0.7
BOD scenario—average	16.2	74.6	7.1	2.0	–	0.2
BOD scenario—dry	16.2	74.6	7.1	2.0	–	0.2
BOD scenario—wet	16.2	74.5	7.1	2.0	–	0.3
FC baseline	73.7	0.5	23.0	2.5	–	0.3
FC scenario—average	63.2	5.2	29.0	2.5	–	0.2
FC scenario—dry	63.2	5.2	29.2	2.3	–	0.1
FC scenario—wet	63.0	5.1	28.9	2.6	–	0.3
TDS baseline	15.1	62.2	3.2	1.4	17.9	0.2
TDS scenario—average	4.8	87.8	1.3	0.4	5.7	0.1
TDS scenario—dry	4.7	87.8	1.3	0.4	5.6	0.1
TDS scenario—wet	4.8	87.8	1.3	0.4	5.6	0.1

accompanied by enhanced connection rates or wastewater treatment. Share of industry increases from 0.5 to above 5 %, while the shares of livestock and urban surface runoff stay on the same low level as in the baseline period.

In terms of TDS, industry is in the baseline period as well as in the scenario period the biggest contributor with 62.2 and 87.8 %, respectively. domestic—sewered—sources and irrigation shares drop from 15.1 and 17.9 to 5.6 and 4.8 % in the scenario period. Furthermore, livestock, domestic—non-sewered—sources, and urban surface runoff are a minor contributor in both time periods. The industry sector dominates the generation of TDS loadings as it contains both manufacturing and mining processes. These are already the major water users (Batsukh et al. 2008) and are expected to increase in the future (cf. Hofmann et al. 2010; Malsy et al. 2013) which in turn poses a risk to surface water quality.

Looking at spatial patterns of simulated loadings (see Fig. 5), hot spots of FC loadings are next to bigger settlements, and in the Tuul River around the capital Ulaanbaatar. Comparing the baseline and scenario periods, FC loadings increase in the south-western part of the Selenga River Basin. In general, FC loadings are spread throughout

the Selenga River Basin, while BOD loadings are spottier distributed mainly along the Tuul, Orkhon, and Kharaa rivers. In the scenario period, increasing loadings can be found particularly in the urbanized areas of Ulaanbaatar, Darkhan, Sukhbaatar and Erdenet as increasing urbanization, and population growth lead to rising pollution loadings. TDS loading hot spots are at Ulaanbaatar, in the Orkhon River Basin as well as in the Kharaa River Basin, which is the main region of irrigation and gold mining in Mongolia (cf. Hofmann et al. 2010; Krätz et al. 2010; Karthe et al. 2013).

Concentrations for BOD, FC, and TDS (see Fig. 6) are shown for May, as this month shows on the one hand effects of snowmelt (i.e. increased dilution capacity) and on the other hand of increasing precipitation during spring (i.e. increased wash-off capability) and is therefore particularly sensitive to potential climatic and socio-economic changes. High BOD values can be found around and downstream of the cities Ulaanbaatar and Erdenet, but also in the Kharaa River Basin. The dry and wet scenarios show very similar spatial patterns of simulated concentrations compared to the baseline period, but with increasing maximum values, while the average scenario results in

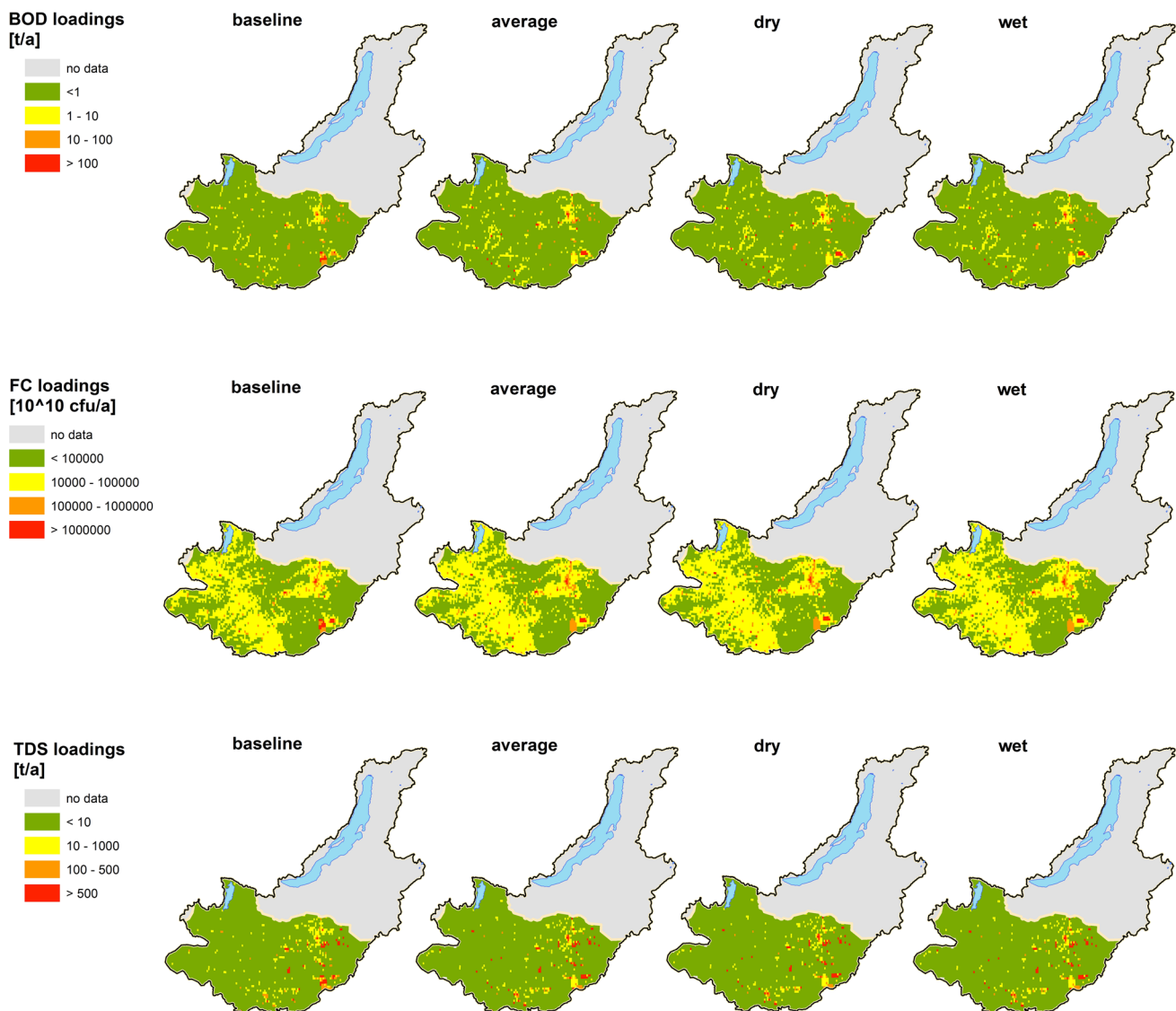


Fig. 5 Spatial patterns for BOD (*top*), FC (*middle*), and TDS (*bottom*) loadings for the baseline and scenario period. For TDS background loadings are not show in this figure

lower concentrations, particularly in the Tuul River. High FC concentrations are more widely spread throughout the basin with hot spot areas around Ulaanbaatar and Darkhan in the baseline period. Increasing concentrations can be found in the south-western part of the basin for the average and dry scenarios, while concentrations decrease under the wet scenario conditions. The decrease is induced by the high dependency of FC concentrations on loadings from domestic sources (cf. Table 5) and the higher dilution capacity in the wet scenario. The hot spot areas in the Tuul and Kharaa River remain in all scenarios analysed in this study. For TDS, values exceeding the water quality guidelines can be found in the Tuul River Basin, particularly in the dry scenario period. Furthermore, river stretches downstream of Erdenet, and in the Tuul and Kharaa

River Basin feature increasing TDS concentrations. Beside spatial alterations, maximum values differ clearly between the scenarios and are up to seven times higher in the dry scenario compared to the baseline period.

To gain further insight in the development of concentrations, for May cumulative distribution functions (see Fig. 7) of simulated BOD, TDS, and FC concentration were compared. For FC, the limit for primary contact and irrigation of 1000 cfu/100 ml (WHO 2000; Britz et al. 2013) was used as a threshold to describe the impact of future changes on water quality. Compared to the baseline period, the wet scenario results in fewer values exceeding the threshold and is generally characterized by more “low values” due to a higher dilution capacity. The dry scenario is indicated by a similar gradient and behaviour as the

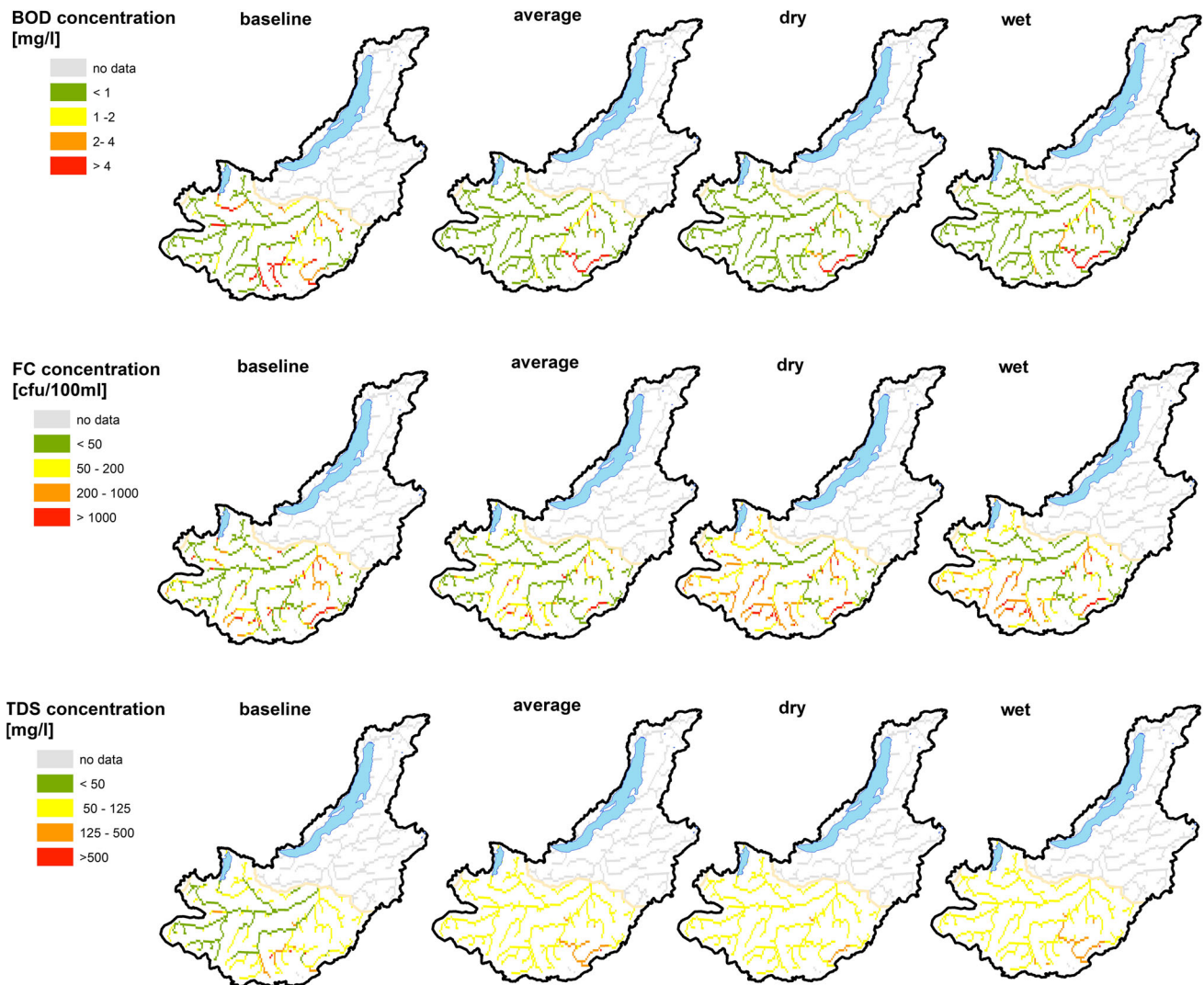


Fig. 6 Spatial patterns for BOD (*top*), FC (*middle*), and TDS (*bottom*) in-stream concentration in May for the baseline and scenario period

baseline period, while the average scenario builds a flatter curve with one-sixth of the grid cells exceeding the threshold. A threshold of 4 mg/l was set for BOD as a concentration threshold in surface waters as guidelines consider this level as moderately polluted with increasing impact on freshwater, fisheries, and water supply (PCD 2004; Ministry of the Environment 2012). BOD shows similar cumulative distribution functions across the baseline and scenario periods as well as within the different scenario projections. Generally, BOD is characterized by lower concentration levels with spatially sparse loadings (cf. Fig. 5), which leads to the similarity of curves and median concentrations. BOD concentrations reach high levels in densely populated areas with industrial production like Ulaanbaatar. For TDS, 500 mg/l was used as a threshold as restrictions for drinking water, freshwater, and irrigation water use are unlikely below this level (FAO

1985; El Bouraie et al. 2011; Ministry of the Environment 2012). In general, the cumulative distribution functions of the baseline and scenario period are similar, with a sharper increase in TDS values and more values exceeding the threshold of the scenario curves.

As Mongolia is a data-scarce region, particularly in the western sub-basins of the Selenge River Basin, water quality studies conducted in the study region focused mainly on one sub-basin like Kharaa River (see MoMo Consortium 2009; Hofmann et al. 2010; Inam et al. 2011; Hofmann et al. 2013) or Tuul River (Byambaa and Todo 2011; Thorslund et al. 2012). Nevertheless, high pollution loadings are reported in these studies focussing on heavy metals, nutrients, or sediment loads, especially downstream of mining areas. According to Nadmitov et al. (2015), heavy metal concentrations are high in the Selenge River Basin, in particular in the Tuul, Kharaa, and Orkhon River.

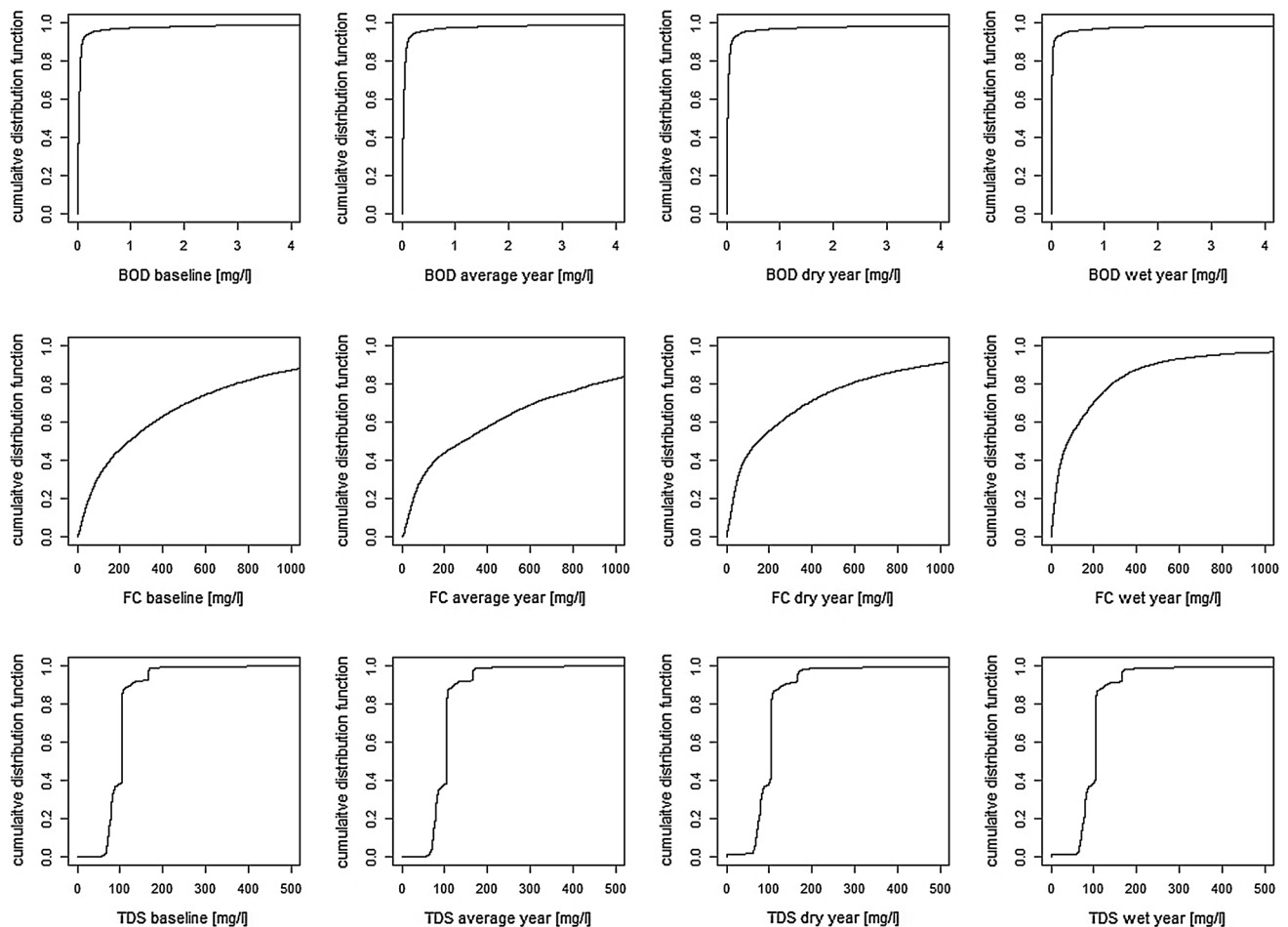


Fig. 7 Cumulative distribution function for FC (*top*), BOD (*middle*), and TDS (*bottom*) for the baseline and the scenario period

Batsukh et al. (2008) stated a high sediment load in the Yeroo River, a high pollution level in the Orkhon River, while the Khangal River is highly affected by mining. Aquatic ecosystems can not only be harmed by large mines (e.g. Erdenet mine), but also by small mining sites and placer mining, i.e. the mining of stream bed deposits, which are used in the study region, and are leading to an increasing polluton (Krätz et al. 2010). Stubblefield et al. (2005) reported a salinity range between 21 mg/l (Yeroo River Basin) and 171 mg/l (Sharyn Gol) for August 2001, and long-term mean annual concentrations of total dissolved solids are between 129 mg/l in the Yeroo River and 282 mg/l in the Kharaa River (UNESCO 2013), but exceed thresholds, e.g. for drinking water and irrigation, occasionally (cf. KEI 2006). According to Kelderman and Batimaa (2006), high TDS concentrations mainly occur after snowmelt and during rainstorms, but no correlation between TDS and river discharge could be detected. As high chloride concentrations are toxic for fishes, TDS concentrations, as proxy, can be useful for the identification of river stretches where water quality deterioration is a

potential threat to fish species. Even if species are not directly affected by TDS concentrations, habitat alteration may be a greater threat to aquatic ecosystems (Dunlop et al. 2005). Kaus et al. (this issue) detected the accumulation of heavy metals in fish tissue. Here, endemic red list species, e.g. *Hucho taimen*, are of high importance.

From the literature, only little is known about FC in Mongolia. Considering a number of livestock units of about 40 million in Mongolia (Hofmann et al. 2013) and low connection and treatment rates, coliform bacteria should be monitored, with priority in densely populated areas. Sorokovikova et al. (2013) reported FC pollution with 227–6600 cfu/100 ml for the Naushki settlement located at the Selenga River at the Russian–Mongolian border, which exceeds the thresholds of international standards for primary contact and drinking water (e.g. DWA 1996; WHO 2000). However, according to our model results, FC concentrations are an issue in the Selenga River Basin affecting surface water quality. As shown for Ulaanbaatar, simulated and measured BOD values can reach high levels of pollution and can be used as

an indicator for WWTPs effectivity and organic water pollution. For instance, Hofmann et al. (2010) stated that the WWTP of Darkhan is not working properly and MEGD (2012) reported that 67 % of Mongolian wastewater treatment plants are in a poor condition.

Conclusions

In this study, loadings and concentrations of BOD, FC and TDS were modelled to assess current and future water quality in the Mongolian part of the Selenga River. So far no comprehensive study exists analysing all Mongolian sub-basins of the Selenga River Basin, and therefore, a large-scale modelling approach was applied. Further, we used cumulative distribution functions to analyse the change in concentrations between current and future conditions. The key findings of this study are as follows:

Overall, our model results show a strong increase in loadings for the scenario period (average, dry, and wet) likely leading to rising pressure on freshwater resources. Connection rates and treatment levels are low, treatment plants often do not work properly, and large urban areas are initial loading hot spots. Hence, pollution prevention becomes important to reduce the impacts of urbanization, population growth, and increasing manufacturing and mining activities on the wastewater generated and discharged into surface waters.

High BOD loadings are generated by the domestic (23–55 %) and industrial (40–75 %) sectors, and hot spots can be found in the Tuul and Kharaa sub-basins where densely populated areas and/or areas with industrial activities are major areas of concern. Depending on the dilution capacity, BOD concentrations exceed a threshold of 4 mg/l in the Tuul and Kharaa rivers and therefore may pose a risk to aquatic ecosystems.

A major source of FC loadings is the domestic sector (>90 %), and hot spots are the big settlements, especially Ulaanbaatar and Darkhan. In comparison, FC loadings originating from livestock (about 3 %) are lower but spread over large areas in the south-western part of the Selenga River Basin. High TDS loadings are produced by industries (62–88 %), in particular mining, with some contribution from the domestic (6–18 %) and agricultural (6–19 %) sectors. Hot spots can be found in the Tuul, Kharaa, and Orkhon sub-basins, indicating the areas where industrial activities are high. Overall, TDS concentrations are on a moderate level; however, high concentration spots are located in the Tuul River and downstream Erdenet mine.

High BOD, FC, and TDS in-stream concentrations are a result of high loadings entering surface waters with low dilution capacity. Törnros and Menzel (2010) and

Törnqvist et al. (2014) stated that an increasing temperature and in turn increasing evapotranspiration will lead to a decrease in runoff in the study area in the future. Therefore, rising concentrations can be expected in surface waters in the future due to reduced river discharge and increased point source pollution.

It can be expected that the above-mentioned key findings will lead to major changes in water quality of the Selenga River and consequently affect the Lake Baikal, which is the world's biggest freshwater source. In addition, Mongolia is planning several major projects in the basin, which will have huge effects on water resources and water quality, in particular the Orkhon-Gobi canal and the Shuren Hydropower project (Sorokovikova et al. 2013; Ministry of Energy 2014; Withanachchi et al. 2014). Nevertheless, as consistent, reliable, and sufficient environmental data are not available for large parts of the study region (Karthé et al. 2015), the presented results include uncertainties in regard to input data and therefore calculated emissions and in-stream concentration. This study is the first comprehensive water quality modelling study in this region leading to potential hot spots of insufficient water quality and shows the need of a consistent monitoring programme in Mongolia to get further insight of water quality in the Selenga River Basin.

Acknowledgments The authors gratefully acknowledge the IWRM-MoMo project and Boldbaatar Sosorburam for the provision of data for model calibration; Kristina Gruber & Alejandra Matovelle for additional data acquisition and processing; Sergey Chalov for the provision of current mining and exploration sites; Klara Reder for the support and data concerning FC modelling. This paper is part of the work conducted within the United Nations Environment Programme report “The world's water quality: A pre-study for a worldwide assessment”.

References

- Altansukh O (2008) Surface water quality assessment and modelling: a case study in the Tuul River, Ulaanbaatar City, Mongolia. Master thesis, University of Twente, The Netherlands, p 105
- Aus der Beek T, Flörke M, Lapola DM, Schaldach R, Voß F, Teichert E (2010) Modelling historical and current irrigation water demand on the continental scale: Europe. *Adv Geosci* 27:79–85. doi:10.5194/adgeo-27-79-2010
- Batimaa P (2006) Climate change vulnerability and adaptation in the livestock sector of Mongolia. A final report submitted to assessments of impacts and adaptations to climate change (AIACC), Project no. AS 06, Washington. <https://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKewiome2ykc3KAhXF-A4KHezjAVsQFggkMAA&url=http%3A%2F%2Fstart.org%2Fdownload%2Fpublications%2FAIACCfullreport.pdf&usq=AFQjCNHrR2baEl2rfNjt9vWckXTDtbngGQ>. Accessed 11 Jan 2016
- Batimaa P, Natsagdorj L, Gombluudev P, Erdenetsetseg B (2005) Observed climate change in Mongolia. AIACC Working paper no. 12. http://www.start.org/Projects/AIACC_Project/working_papers/Working%20Papers/AIACC_WP_No001.pdf. Accessed 15 Jan 2016

- Batsukh N, Dorjsuren D, Batsaikhan G (2008) The water resources, use and conservation in Mongolia. First National Report, Ulaanbaatar
- Bolormaa O, Baasansuren J, Kawasaki K, Watanabe M, Hattori T (2006) PIXE analysis of heavy metals in water samples from a mining area in Mongolia. *Nucl Instrum Methods Phys Res Sect B Beam Interact Mater Atoms* 243(1):161–166. doi:10.1016/j.nimb.2005.07.190
- Britz TJ, Sigge GO, Huisamen N, Kikine T, Ackermann A, Lötter M, Lamprecht C, Kidd M (2013) Fluctuations of indicator and index microbes as indication of pollution over 3 years in the Plankenburg and Erste Rivers, Western Cape, South Africa. *Water SA* 39(4):357–366. doi:10.4314/wsa.v39i4.3
- Byambaa B, Todo Y (2011) Technological impact of placer gold mine on water quality: case of Tuul river valley in the Zaamar Goldfield, Mongolia. *World Acad Sci Eng Technol* 75:167–175
- Chalov SR, Jarsjö J, Kasimov N, Romanchenko A, Pietron J, Thorslund J, Belozerova E (2015) Spatio-temporal variation of sediment transport in the Selenga River Basin, Mongolia and Russia. *Environ Earth Sci* 72(2):663–680. doi:10.1007/s12665-014-3106-z
- Döll P, Fiedler K, Zhang J (2009) Global-scale analysis of river flow alterations due to water withdrawals and reservoirs. *Hydrol Earth Syst Sci* 13:2413–2432
- Dunlop J, McGregor G, Horrigan N (2005) Potential impacts of salinity and turbidity in riverine ecosystems. Characterisation of impacts and a discussion of regional target setting for riverine ecosystems in Queensland. The State of Queensland, Australia. <https://www.ehp.qld.gov.au/water/pdf/potential-impacts-sal-tur.pdf> Accessed 15 June 2015
- DWA Department of Water Affairs and Forestry (1996) South African water quality guidelines, Vol 1. Domestic use. Pretoria, South Africa, p 190. https://www.dwa.gov.za/iwqs/wq_guide/Pol_saWQguideFRESH_vol1_Domesticuse.PDF. Accessed 16 Jan 2016
- El Bouraie MM, Motawea EA, Mohamed GG, Yehia MM (2011) Water quality of Rosetta branch in Nile delta, Egypt. *Suouseura* 62(1):31–37
- FAO Food and Agricultural Organization of the United Nations (1985) Water quality for agriculture. FAO Irrigation and drainage paper 29 Rev. 1, Rome. <http://www.fao.org/DOCR/P/003/T0234e/T0234e00.htm>. Accessed 16 June 2015
- FAO Food and Agricultural Organization of the United Nations (2012) Irrigation in Southern and Eastern Asia in figures. AQUASTAT Survey—2011. FAO Water Reports 37, Rome. <http://www.fao.org/docrep/016/i2809e/i2809e.pdf>. Accessed 10 June 2015
- Farrington JD (2005) The impact of mining activities on Mongolia's protected areas: a status report with policy recommendations. *Integr Environ Assess Manag* 1:283–289. doi:10.1897/2004-008R.1
- Flörke M, Kynast E, Bärlund I (2012) Will climate change affect the electricity production sector? A European study. *J Water Clim Change* 3(1):44–54. doi:10.2166/wcc.2012.066
- Flörke M, Kynast E, Bärlund I, Eisner S, Wimmer F, Alcamo J (2013) Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: a global simulation study. *Glob Environ Change* 23:144–156. doi:10.1016/j.gloenvcha.2012.10.018
- Gruber S (2012) Derivation and analysis of a high-resolution estimate of global permafrost zonation. *Cryosphere* 6:221–233. doi:10.5194/tc-6-221-2012
- Hagemann S, Chen C, Haerter JO, Heinke J, Gerten D, Piani C (2011) Impact of a statistical bias correction on the projected hydrological changes obtained from three GCMs and two hydrology models. *J Hydrometeorol* 12:556–578. doi:10.1175/2011JHM1336.1
- Hampton S, Izmet'eva LR, Moore MV, Katz SL, Dennis B, Silow EA (2008) Sixty years of environmental change in the world's largest freshwater lake—lake Baikal, Siberia. *Glob Change Biol* 14:1–12. doi:10.1111/j.1365-2486.2008.01616.x
- Hofmann J, Venohr M, Behrendt H, Opitz D (2010) Integrated water resources management in Central Asia: nutrient and heavy metal emissions and their relevance for the Kharaa River Basin, Mongolia. *Water Sci Technol* 62(2):353–363. doi:10.2166/wst.2010.262
- Hofmann J, Hurdler J, Ibisch R, Schaeffer 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). *Int Rev Hydrobiol* 96(5):484–519. doi:10.1002/iroh.201111294
- Hofmann J, Rode M, Theuring P (2013) Recent developments in river water quality in a typical Mongolian river basin, the Kharaa case study understanding freshwater quality problems in a changing world. In: Proceedings of H04, IAHS-IAPSO-IASPEI Assembly, Gothenburg, Sweden, July 2013 (IAHS Publ. 361)
- Hofmann J, Watson V, Scharaw B (2015) Groundwater quality under stress: contaminants in the Kharaa River Basin (Mongolia). *Environ Earth Sci* 73(2):629–648. doi:10.1007/s12665-014-3148-2
- Inam E, Khantotong S, Kim KW, Tumendemberel B, Erdenetsetseg S, Puntsag T (2011) Geochemical distribution of trace element concentrations in the vicinity of the Boroo gold mine, Selenge Province, Mongolia. *Environ Geochem Health* 33:57–69. doi:10.1007/s10653-010-9347-1
- Kaus A, Schäffer M, Karthe D, Büttner O, von Tümpling W, Borchardt D (this issue) Regional patterns of heavy metal contamination in river water, sediment and locally consumed fish species of the Kharaa River basin, Mongolia. *Reg Environ Change*
- Karthe D, Malsy M, Kopp B, Minderlein S, Hülsmann L (2013) Assessing water availability and drivers in the context of an integrated water resources management (IWRM): a case study from the Kharaa River Basin, Mongolia. *Geo-Öko* 34(1–2):5–26
- Karthe D, Hofmann J, Ibisch R, Heldt S, Westphal K, Menzel L, Avlyush S, Malsy M (2015) Science-based IWRM implementation in a data-scarce Central Asian region: experiences from a research and development project in the Kharaa River Basin, Mongolia. *Water* 7(7):3486–3514. doi:10.3390/w7073486
- KEI Korea Environment Institute (2006) Joint research between Korea and Mongolia on water quality and contamination of transboundary watershed in Northern Mongolia. Seoul, Korea
- Kelderman P, Batima P (2006) Water quality assessment of rivers in Mongolia. *Water Sci Technol* 53(10):111–119. doi:10.2166/wst.2006.304
- Kopp B, Menzel L, Minderlein S (2014) Soil moisture dynamics in a mountainous headwater area in the discontinuous permafrost zone of northern Mongolia. *Arct Antarct Alp Res* 46(2):459–470. doi:10.1657/1938-4246-46.2.459
- Krätz DA, Ibisch RB, Avlyush S, Enkhbayar G, Nergui S, Borchardt D (2010) Impacts of open placer gold mining on aquatic communities in rivers of the Khentii Mountains, North-East Mongolia. *Mong J Biol Sci* 8(1):41–50
- Lehner B, Verdin K, Jaarvis A (2008) New global hydrography derived from spaceborne elevation data. *EOS Trans Am Geophys Union* 89(10):93–94. doi:10.1029/2008EO100001
- Malsy M, aus der Beek T, Eisner S, Flörke M (2012) Climate change impacts on Central Asian water resources. *Adv Geosci* 32:77–83. doi:10.5194/adgeo-32-77-2012
- Malsy M, Heinen M, aus der Beek T, Flörke M (2013) Water resources and socio-economic development in a water scarce region on the example of Mongolia. *Geo-Öko* 34(1–2):27–49
- Malsy M, aus der Beek T, Flörke M (2015) Evaluation of large-scale precipitation data sets for water resources modelling in Central

- Asia. *Environ Earth Sci* 73(2):787–799. doi:10.1007/s12665-014-3107-y
- MEGD Ministry of Environment and Green Development (2012) Integrated water management national assessment report, vol II. Ulaanbaatar, Mongolia
- Ministry of Energy (2014) Terms of reference for environmental and social impact assessment of ‘Shuren Hydropower Plant’ project. Ulaanbaatar. http://www.minis.mn/file/files/Shuren_TOR_for_EIA_EN_2014.12_08_.pdf. Accessed 17 June 2015
- Ministry of the Environment (2012) Conama resolutions, Brasilia, Brazil, p 916. <http://www.mma.gov.br/port/conama/processos/61AA3835/CONAMA-ingles.pdf>. Accessed 08 June 2015
- MoMo-Consortium (2009) MoMo—IWRM in Central Asia—Model Region Mongolia (MoMo): case study in the Kharaa River Basin. Final Project Report
- Mongolian Statistical Information Service (2015) GROSS DOMESTIC PRODUCT, by divisions. <http://www.1212.mn>. Accessed 12 June 2015
- Müller Schmied H, Eisner S, Franz D, Wattenbach M, Portmann FT, Flörke M, Döll P (2014) Sensitivity of simulated global-scale freshwater fluxes and storages to input data, hydrological model structure, human water use and calibration. *Hydrol Earth Syst Sci* 18:3511–3538. doi:10.5194/hess-18-3511-2014
- PCD Pollution Control Department (2004) Water quality standards. Ministry of Natural Resources and Environment, Thailand. http://www.pcd.go.th/info_serv/en_reg_std_water.html. Accessed 02 June 2015
- Nadmitov B, Hong S, In Kang S, Chu JM, Gomboev B, Janchivdorj L, Lee C-H, Khim JS (2015) Large-scale monitoring and assessment of metal contamination in surface water of the Selenga River Basin (2007–2009). *Environ Sci Pollut Res* 22:2856–2867. doi:10.1007/s11356-014-3564-6
- Piani C, Weedon GP, Best M, Gomes SM, Viterbo P, Hagemann S, Haerter JO (2010) Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models. *J Hydrol* 395:199–215. doi:10.1016/j.jhydrol.2010.10.024
- Pierson SM, Rosenbaum BJ, McKay LD, Dewald TG (2008) Strahler stream order and Strahler calculator values in NHDPLUS. SOSC technical paper, September 30, 2008. ftp.horizon-systems.com/NHDPlus/NHDPlusV21/Documentation/TechnicalDocs/SOSC_technical_paper.pdf. Accessed 13 Jan 2016
- Priess JA, Schweitzer C, Wimmer F, Batkhishig O, Mimmler M (2011) The consequences of land-use change and water demands in Central Mongolia—an assessment based on regional land-use policies. *Land Use Policy* 28(1):4–10. doi:10.1016/j.landusepol.2010.03.002
- Priess JA, Schweitzer C, Batkhishig O, Koschitzki T, Wurbs D (2015) Impacts of agricultural land-use dynamics on erosion risks and options for land and water management in Northern Mongolia. *Environ Earth Sci* 73(2):697–708. doi:10.1007/s12665-014-3380-9
- Reder K, Flörke M, Alcamo J (2015) Modeling historical fecal coliform loadings to large European rivers and resulting in-stream concentrations. *Environ Model Softw* 63:251–263. doi:10.1016/j.envsoft.2014.10.001
- Schneider C, Flörke M, Eisner S, Voss F (2011) Large scale modelling of bankfull flow: an example for Europe. *J Hydrol* 408:235–245. doi:10.1016/j.jhydrol.2011.08.004
- Sorokovikova LM, Popovskaya GI, Tomberg IV, Sinyukovich VN, Kravchenko OS, Marinaite II, Bashenkhaeva NV, Khodzher TV (2013) The Selenga River water quality on the border with Mongolia at the beginning of the twenty-first Century. *Russ Meteorol Hydrol* 38(2):126–133. doi:10.3103/S1068373913020106
- Strahler AN (1957) Quantitative analysis of watershed geomorphology. *Trans Am Geophys Union* 38(6):913–920. doi:10.1029/TR038i006p00913
- Stubblefield A, Chandra S, Eagan S, Tuvshinjargal D, Davaadorzh G, Gilroy D, Sampson J, Thorne J, Allen B, Zeb Hogan (2005) Impacts of gold mining and land use alterations on the water quality of central Mongolian rivers. *Integr Environ Assess Manag* 1(4):365–373. doi:10.1897/1551-3793(2005)1
- Thorslund J, Jarsjö J, Chalov S, Belozeroeva EV (2012) Gold mining impact on riverine heavy metal transport in a sparsely monitored region: the upper Lake Baikal Basin case. *J Environ Monit* 14:2780–2792. doi:10.1039/C2EM30643C
- Törnqvist R, Jarsjö J, Pietron J, Bring A, Rogberg P, Asokan SM (2014) Evolution of the hydro-climate system in the Lake Baikal Basin. *J Hydrol* 519:1953–1962. doi:10.1016/j.jhydrol.2014.09.074
- Törnros T, Menzel L (2010) Heading for knowledge in a data scarce river basin: Kharaa, Mongolia. In: Herrman A, Schumann S (eds) Status and perspectives of hydrology in Small Basins (Proceedings of the Workshop held at Goslar-Hahnenklee, Germany, 30 March– 2 April 2009). IAHS Publ. 336:270–275
- UNESCO United Nations Educational, Scientific and Cultural Organization (2013) Water quality of the Kharaa River Basin, Mongolia: Pollution threats and hotspots assessment. Ulaanbaatar, p 76. <http://unesdoc.unesco.org/images/0023/002312/231293e.pdf>. Accessed 16 Jan 2016
- Vassolo S, Döll P (2005) Global-scale gridded estimates of thermoelectric power and manufacturing water use. *Water Resour Res* 41(4):W04010. doi:10.1029/2004WR003360
- Verzano K (2009) Climate change impacts on flood related hydrological processes: further development and application of a global scale hydrological model, reports on earth system science, 71–2009, dissertation, Max Planck Institute for Meteorology, Hamburg, Germany, p 166. http://www.mpimet.mpg.de/fileadmin/publikationen/Reports/WEB_BzE_71_verzano.pdf. Accessed 28 Jan 2016
- Voß A, Alcamo J, Bärlund I, Voß F, Kynast E, Williams R, Malve O (2012) Continental scale modelling of in-stream river water quality: a report on methodology, test runs, and scenario application. *Hydrol Process* 26(16):2370–2384. doi:10.1002/hyp.9445
- Weedon GP, Gomes S, Viterbo P, Shuttleworth WJ, Blyth E, Österle H, Adam JC, Bellouin N, Boucher O, Best M (2011) Creation of the WATCH forcing data and its use to assess global and regional reference crop evaporation over land during the twentieth century. *J Hydrometeorol* 12:823–848. doi:10.1175/2011JHM1369.1
- WHO World Health Organization (2000) Monitoring bathing waters—a practical guide to the design and implementation of assessments and monitoring programmes. London, New York. http://www.who.int/water_sanitation_health/bathing/monbathwat.pdf. Accessed 14 Jan 2016
- Williams R, Keller V, Voß A, Bärlund I, Malve O, Riihimäki J, Tattari S, Alcamo J (2012) Assessment of current water pollution loads in Europe: estimation of gridded loads for use in global water quality models. *Hydrol Process* 26(16):2395–2410. doi:10.1002/hyp.9427
- Withanachchi SS, Houdret A, Nergui S, Gonzalez EE, Tsogtbayar A, Ploeger A (2014) (Re)configuration of water resources management in Mongolia: a critical geopolitical analysis. The International Center for Development and Decent Work, ICDD Working Papers 13, Kassel, Germany. https://www.die-gdi.de/uploads/media/IWRM_Mongolia_2014.pdf Accessed 20 Nov 2015