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Assessment of Runoff, Water and Sediment Quality in the Selenga River Basin Aided by a Web-Based Geoservice[1]

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Abstract—The Selenga River is the main artery feeding Lake Baikal. It has a catchment of ~450000 km² in the boundary region between Northern Mongolia and Southern Siberia. Climate, land use and dynamic socioeconomic changes go along with rising water abstractions and contaminant loads originating from mining sites and urban wastewater. In the future, these pressures might have negative impacts on the ecosystems of Lake Baikal and the Selenga River Delta, which is an important wetland region in itself and forms the last geobiochemical barrier before the Selenga drains into Lake Baikal. The following study aims to assess current trends in hydrology and water quality in the Selenga-Baikal basin, identify their drivers and to set up models (WaterGAP3 framework and ECOMAG) for the prediction of future changes. Of particular relevance for hydrological and water quality changes in the recent past were climate and land use trends as well as contaminant influx from mining areas and urban settlements. In the near future, additional hydrological modifications due to the construction of dams and abstractions/water diversions from the Selenga's Mongolian tributaries could lead to additional alterations.

Keywords: Selenga river system, Lake Baikal, water quality assessment, transboundary rivers, geodatabase

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INTRODUCTION

Lake Baikal's most important tributary is the Selenga River, which contributes about 50 to 60% of the surface water influx [10, 51, 72]. North of the Buryatian capital Ulan Ude, the Selenga River branches into the largest freshwater inland delta in the world [40]. The associated wetland constitutes a unique ecosystem [19] and acts as the final geobiochemical barrier before the Selenga discharges into Lake Baikal. Because of its sheer size and unique ecological characteristics, Lake Baikal and the Selenga river system form an ecoregion of global relevance that is being exposed to numerous anthropogenic stressors [7, 28]. The Selenga river system, which drains a 447060 km² watershed or 82% of the Lake Baikal Basin [50] plays a key role in this regard:

Various mining activities are found in the Selenga River Basin, including the exploitation of coal, gold, copper, molybdenum and wolfram [62, 71]. As a consequence, elevated levels of heavy metals and other mining-related pollutants (cyanides, phosphorus) have been detected in the water and sediments of the Selenga and its tributaries, as well as floodplain soils and groundwater [8, 10, 26, 50, 53, 55, 68, 71]. Even though contaminant transport towards the Selenga delta does take place [10, 36, 35, 71], it should be noted that contaminations so far have the largest effects in local hot spots [25, 26, 55]. Currently, there are different views regarding their impacts on Lake Baikal [12, 53]. However, bioaccumulation and toxicological effects observed in aquatic biota ranging from insects to fish already indicate that water quality deterioration in the Selenga river system does have an ecological impact [3, 34, 37].

A considerable part of the Selenga River Basin's population is concentrated in four cities. The three largest cities of Mongolia (Ulaanbaatar, Erdenet and Darkhan) as well as Ulan Ude, the capital of the Republic of Buryatia in Russia, are located on the Tuul, Orkhon, Kharaa and Selenga Rivers, respec-

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tively. These urban areas have multiple impacts on the region's water resources. Firstly, per capita water consumption in urban areas is considerably higher than in peri-urban or rural regions [63, 64]. Secondly, poor wastewater treatment infrastructures lead to nutrient inputs [24, 25, 30] and microbiological contamination of rivers [66]. Thirdly, urban areas in the Selenga River Basin are characterized by a concentration of pollutants originating from the combustion of fuels and various industries [13, 33, 52, 65], some of which enter the water cycle directly or via atmospheric deposition.

Land use change, which is currently more pronounced in the Mongolian than the Russian part of the Selenga River Basin, is primarily driven by mining and the expansion of agricultural land [49, 57]. The conversion of forests and natural grasslands into pastures and fields has implications for both hydrology [45] and water quality, particularly by stimulating erosion processes [56, 69, 70].

Present and expected hydrological changes in the Selenga River Basin are caused by three processes: land use changes [29, 45], the impacts of global climate change on precipitation and evaporation [22, 32, 42, 43, 72] and permafrost [46, 72], and increasing water withdrawals. The latter are related to the expansion of agriculture and rising irrigation needs in the context of global warming [43, 57] and in the future, potentially due to water diversions into mining areas in the South Gobi [66].

For many of the above mentioned developments, evidence on the ecological consequences does not only exist from the Selenga–Baikal Basin but from several other Central Asian river basins [27]. The protection of Lake Baikal depends to a considerable degree on developments and conservation measures in the Selenga River Basin as well as a good understanding of the current state and functioning of the delta's ecosystem and the geo- and biochemical processes taking place in it [11, 51].

MATERIAL AND METHODS

For the assessment of past and future changes in hydrology, water and sediment quality we have combined data and model-driven approaches. The aims of the paper include the following: (a) assembling all currently accessible data on river discharges, sediment and water quality in the Selenga River Basin in an online geodatabase; (b) characterizing contemporary changes in the hydrology and contaminant loads due to climatic and human impacts and (c) assessing different hydrological and water quality models (particularly WaterGAP3, SedNet and ECOMAG) with regard to their suitability to predict future trends in hydrology as well as water and sediment quality.

Data Compilation and Geodatabase Setup

We collected hydrological and water quality data from external sources and own projects carried out in the Selenga-Baikal Basin. While the discharge data are based on gauges operated by the hydrometeorological services of Mongolia and the Russian Federation and a few additional measurements performed by the project scientists, the situation is vastly different for water quality data for which there is no exhaustive database to this date. Therefore, we had to rely on (a) data published in scientific papers and (b) data collected by our own projects. Most of this data is from individual field campaigns rather than from regular monitoring, and therefore only available for limited periods of time. Table 1 provides an overview of published and own data used in the context of this study. Data were considered "usable" when they fulfilled at least the following characteristics: all sampling points had to be clearly described by geographic coordinates, and the methodology of data collection and laboratory analysis had to be documented.

To facilitate the systematization of all collected information and provide access to all project counterparts we set up a web-based geographical information system. We used the Geomixer.ru web GIS developed by Scanex company of Russia [www.geomixer.ru]. It allows for multi-user spatial data upload and demonstration on several base maps, such as physical maps, elevation models, administrative maps, or satellite imagery. Furthermore, the Geomixer.ru allows to export or access data via the WMS (web map service) functionality of desktop GIS products.

The uploaded data comprised:

- general information on the Selenga, its basin and tributaries (e.g. river courses, lakes, government monitoring stations locations);
- daily time series of air temperature, air humidity and precipitation;
- catchment parameters of the Selenga River and its tributaries (over 50 variables of topography (USGS Hydrosheds [39]), vegetation and soil cover properties, permafrost distribution, land use and land cover characteristics, population, climatic variables);
- water and sediment quality information from literature and sampling campaigns conducted by the authors and their research teams.

All of the working groups were provided with the access to the GIS system to upload the available data. Further applications of the system are described below.

Water Runoff Modelling

To assess the variability of water resources in the Selenga River Basin we used the ECOMAG model developed in the Water Problems Institute of the Russian Academy of Sciences [47, 48]. ECOMAG is a

Table 1. Data on water quality in the Selenga River Basin used for this study (TN = total nitrogen; TOC = total organic carbon; DOC = dissolved organic carbon; TP = total phosphorus; SPM – suspended particulate matter; SL – sediment loads; TDS – total dissolved solids)

Reference/ Author	No. of sampling points	Measured parameter	Date of measurement	Short description
GEMS Database	2	DO, pH, water temperature NH_3, BOD, Cl, SiO_2	1990–2003, 2010	Monthly data for basic water quality data
Altansukh et al. 2012	15	SS, DO, BOD5 Cations: Ca^{2+}, K^+ , Mg^{2+}, Na^+, $NH_4{}^+$ Anions: Cl^-, HCO_3^-, NO_2^-, NO_3^-, PO_4^{3-}, SO_4^{2-}	1998–2008	Investigation of spatial and temporal trends of water quality in the Tuul River
Brumbaugh et al. 2013	15	Ag, As, Ca, Cd, Cl, Co, Cr, Cu, Hg, K, Ni, Mn, Mo, Pb, Rb, Sb, Se, Sn, Sr, Ti, V	2010	Elemental analysis of streambed sediment and subsurface floodplain soil in the Tuul and Orkhon River Basin
KEI 2008	28 (16 Mongolia, 12 Russia)	DO, hardness, EC, mineralization, pH, SPM concentrations, TDS, turbidity, water temperature As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn Anions: CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}, NO_2^-, NO_3^- Cations: Na^++ K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Fe^{3+}, NH_4^+ Chlororganic pesticides: DDD, DDE, DDT, HCB, HCCH alipatic hydrocarbons, PCB; PAH; Phenols; POP	2007	Identification of distribution of pollution sources to estimate the degree of water pollution in the Selenga River Basin
KEI 2009	37 (23 Mongolia, 14 Russia)	DO, hardness, EC, mineralization, pH, SPM concentrations, TDS, turbidity, water temperature As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn Anions: CO_3^{2-}, Cl^-, HCO_3^-, NO_2^-, NO_3^-, SO_4^{2-} Cations: Ca^{2+}, Fe^{2+}, Fe^{3+}, K^+, Mg^{2+}, Na^+, NH_4^+ Chlororganic pesticides: DDD, DDE, DDT, HCB, HCCH PCB; PAH	2008	Identification of distribution of pollution sources to estimate the degree of water pollution in the Selenga River Basin
KEI 2010	30 (19 Mongolia, 11 Russia)	COD, DO, hardness, EC, mineralization, pH, SS, TDS, turbidity, water temperature As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn Anions: CO_3^{2-}, Cl^-, HCO_3^-, NO_2^-, NO_3^-, SO_4^{2-} Cations: Na^++ K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Fe^{3+}, NH_4^+ TN, TP, PO_4-P, NO_3-N, NO_2-N, NH_3-N	2009	Assessment of environmental state of Selenga River Basin as a prerequisite for IWRM planning
Inam et al. 2010	14 (groundwater)	pH, SS NO_3, SO_4, PO_4 Al, As, B, Ca, Cd, Cl, Cu, F, Fe, Mg, Mn, Ni, Pb, Se, U, Zn	2009	Environmental impact assessment of Boroo Gold Mine. No coordinates of sampling points

Table 1. (Contd.)

Reference/ Author	No. of sampling points	Measured parameter	Date of measurement	Short description
Mongolian Aquatic Insect Survey	30	DO, EC, turbidity, water temperature PO_4^{3-}, TN, NO_2^-, NO_3^-, NH_3	2006	Water quality investigation in the Selenga River; website is offline and data not published
Nadmitov et al. 2014	76	As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn	2007–2009	Assessment of metal pollution in river water in the Selenga River Basin. Based on the studies described in KEI 2008–2010
Nriagu et al. 2011	129	Al, As, Cd, Co, Mn, Pb, Se, U, Zn	2011	Assessment of groundwater quality in Ulaanbaatar. No coordinates of sampling points
Sorokovikova et al. 2013		Cations: Ca^{2+}, K^+, Mg^{2+}, Na^+ Anions: Cl^-, HCO_3^-, SO_4^{2-} TP, P_{inorg}, TN, TOC, NO_3^-–N, NH_4 PAH Total coliforms, enterococci	2010	Assessment of Selenga River water quality near the Russian-Mongolian border
Thorslund et al. 2014		Al, As, Cu, Fe, Mn, Pb, Zn		Data for water quality in the Tuul and Orkhon rivers, compiled from different data sources
Own Data				
UFZ Magdeburg, Germany	52	As	2011	As screening using the ArsoLux biosensor system (partially with ICP-MS controls) in the Kharaa, Eroo and Orkhon River Basins
UFZ Magdeburg, Germany	50	TP, TN, TOC Dissolved elements: Ag, Al, As, B, Ba, Be, Bi, Cd, Co, Cr, Cu, Fe, Hg, Li, Mn, Mo, Ni, Pb, Rb, Sr, Ti, Tl, U, V, Zn	2013	26 samples for water quality plus 24 samples for sediment quality, taken in the Tuul, Kharaa, Orkhon and Selenga River Basins
Batbayar 2012	47	As	2011–2012	As screening using the ArsoLux biosensor system (partially with ICP-MS controls) in the Tuul, Kharaa and Orkhon River Basins

Table 1. (Contd.)

Reference/ Author	No. of sampling points	Measured parameter	Date of measurement	Short description
UFZ Magdeburg, Germany (partly published in Batbayar et al. 2015)	94	TN, TP, TOC, DOC Ag, Al, As, B, Ba, Be, Bi, Cd, Co, Cr, Cu, Fe, Hg, Li, Mn, Mo, Ni, Pb, Rb, Sb, Sn, Sr, Ti, Tl, V, U, Zn Cations: Ca^{2+}, K^+, Mg^{2+} , Na^+ Anions: Cl^-, SO_4^{2-} Organic matter and nutrients: DOC, TOC, TN, TP	2014–2015	Assessment of water quality in the Mongolian part of the Selenga River Basin
Pfeiffer et al. 2015	309	As For some samples: Cl, Cr, Cu, Fe, K, Mn, Na, Sb, U; pH, EC, TDS	2007–2013	As survey along the Kharaa, Orkhon, Tuul, Sharyn and Eroo rivers in Mongolia
Moscow State University field campaigns: July–August 2011 June 2012 September 2013 August 2014 March 2015	 56 55 35 53 22	Cations: Ca^{2+}, K^+, Mg^{2+}, Na^+ Anions: Cl^-, HCO_3^-, SO_4^{2-} pH, DOC, POC Concentrations in bottom sediments and in suspended and dissolved loads: Li, Be, B, Na, Mg, Al, Si, Psum., S, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Rb, Sr, Y, Zr, Nb, Mo, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Re, Os, Iu, Pt, Au, Tl, Pb, Bi, Th, U TP, mineral P, Si SPM concentrations (g/m^3), SL(t/day), SPM in the certain classes	2011–2015	Tuul River, Orkhon River, Eg River, Eroo River, Khangal River, Selenga River, Kharaa River Dzhida, Temnik, Chikoy, Hilok, Orongoy,Uda, Itantsa, Kiran, Kudara, Zheltura, Udunga , Suhara, Tugnui, Menza , Buy, Bryanka, Ilka, Chelutay, Kurba, Kodun, Kizhinga, Ona

regional semi-distributed physical process-based hydrological model. The model accounts for watershed parameters taken from geodatabase, such as elevation, slope, aspect, land use, soil type, stream network and meteorological stations locations for weather variables distribution. The parameters are spatially distributed by partitioning the watershed into units called elementary basins. Each elementary basin accounts for different combinations of the parameters by computing the fraction of these combinations within it. In each elementary basin the processes of snow accumulation and melt, soil freezing and thawing, water infiltration into unfrozen and frozen soil, evapotranspiration, thermal and water regime of soil, overland, subsurface and channel flow are described. The water balance is computed in each elementary basin on a daily time step. The basin response is routed to the outflow point through a calculated river network.

The model is calibrated against streamflow measurements and, if available, measurements of the internal basin variables (snow characteristics, soil moisture, groundwater level, etc.). The ECOMAG model is driven by daily time series of surface air temperature, air humidity and precipitation. The model has been extensively tested in various types of catchments around the world (see [20, 47, 48]). The model was set up using the spatial data stored in the web-GIS, namely digital elevation model USGS HydroSheds [39], land cover database GLCC2000 [4] and soil type database from FAO HWSD [16], and river gauging stations locations.

For the initial parameters estimation, the ECOMAG model for the Selenga River Basin was driven by daily weather time-series from the ERA-Interim dataset [14] for the period of 1996–2005 on a 0.5° by 0.5° spatial grid and calibrated against the observed flow discharges from the most downstream gauge of Kabansk. The estimated Nash-Suttcliffe model efficiency criteria for daily discharges reached 0.85, which shows a good agreement between the modelled and the observed streamflow. The linear correlation coefficient between observed and simulated annual runoff volumes reached 0.72.

Sediment Load Modelling

Despite recent progress in setting up hydrodynamical models to predict sediment loads and in-channel processes at the level of single channel reaches (along the mined reaches of Tuul river by Pietron et al. [54]; and within reaches of almost 300 km of the Tuul and Orkon river by Chalov et al. [10]) there is still a need to link the sediment loads to the catchment characteristics. In this study we aimed at developing a basinwide sediment model for each particular hydrological season. Data for 50 sub-catchments was taken from the geodatabase for the periods of Moscow State University field campaigns: July–August 2011; June 2012; September 2013; August 2014; March 2015 (Table 1).

Each season was characterized by the set of variables which was linked with SSC, daily sediment load and SPM grain size compositions. We tested the full data bank to find correlations between sediment load and catchment parameters. A step-forward procedure was used. On the first stage simple linear correlations (Pearson's *r*) were computed to explore relationships among sediment loads/characteristics and catchment properties: $r_{xy} = C(x,y)/\sigma_x\sigma_y$. For those properties which yielded significant correlations ($|r_{xy}| > 0.5$, $r_{xy} = C(x,y)/(\sigma_x\sigma_y)$), mixed model analysis using STATISTICA V. 8.0 [67] was used. The linear regression model SelengaStatistic, based on multivariate analysis ($y_i = b_1x_1+b_2x_2+ \ldots + b_nx_n +b_0 + c_i$), was developed for each hydrological season.

In addition, the sediment budget model SedNet was used to estimate the SS budget in the main subcatchments (Fig. 1) of the Selenga River. The model applicability was tested in a cold semi-arid region before [70]. The model uses spatial data layers on land use, soil properties, precipitation and topography (DEM), focusing on the spatial patterns in sediment generation and movement. DEM derived stream network is divided with the help of linked stream node points, and the catchment is divided into sub-catchments and river reaches. Each link extends between adjacent stream junctions or nodes and has a subcatchment that drains into the link between its upper and lower nodes. This allows the construction of the sediment budget for each section of the river network by calculating sediment delivery, transport and floodplain deposition. For this purpose, SedNet calculates surface and bank erosion, as well as floodplain deposition with separate submodels [61]. The sediment load output at each stream junction node is calculated by taking the difference between the supply of sediment from the internal sub-catchment and tributary streams and the loss of sediment by deposition on the floodplain and in the channel. Surface erosion sediment supply is calculated on the basis of the revised universal soil loss equation (RUSLE) soil loss estimation [56, 60].

Water Quality Modelling

The trend in water quality in terms of organic pollution was calculated with the WaterGAP3 modelling framework for the entire river basin for the time period 1990–2010. The model framework operates on a 5 arc minute global grid and includes a large-scale hydrology model, five sectoral water use models and a water quality model (WorldQual). Based on time series of daily climatic data, the hydrology model calculates the daily water balance for each grid cell, taking into account physiographic characteristics like soil type, vegetation, slope, and aquifer type. Runoff generated

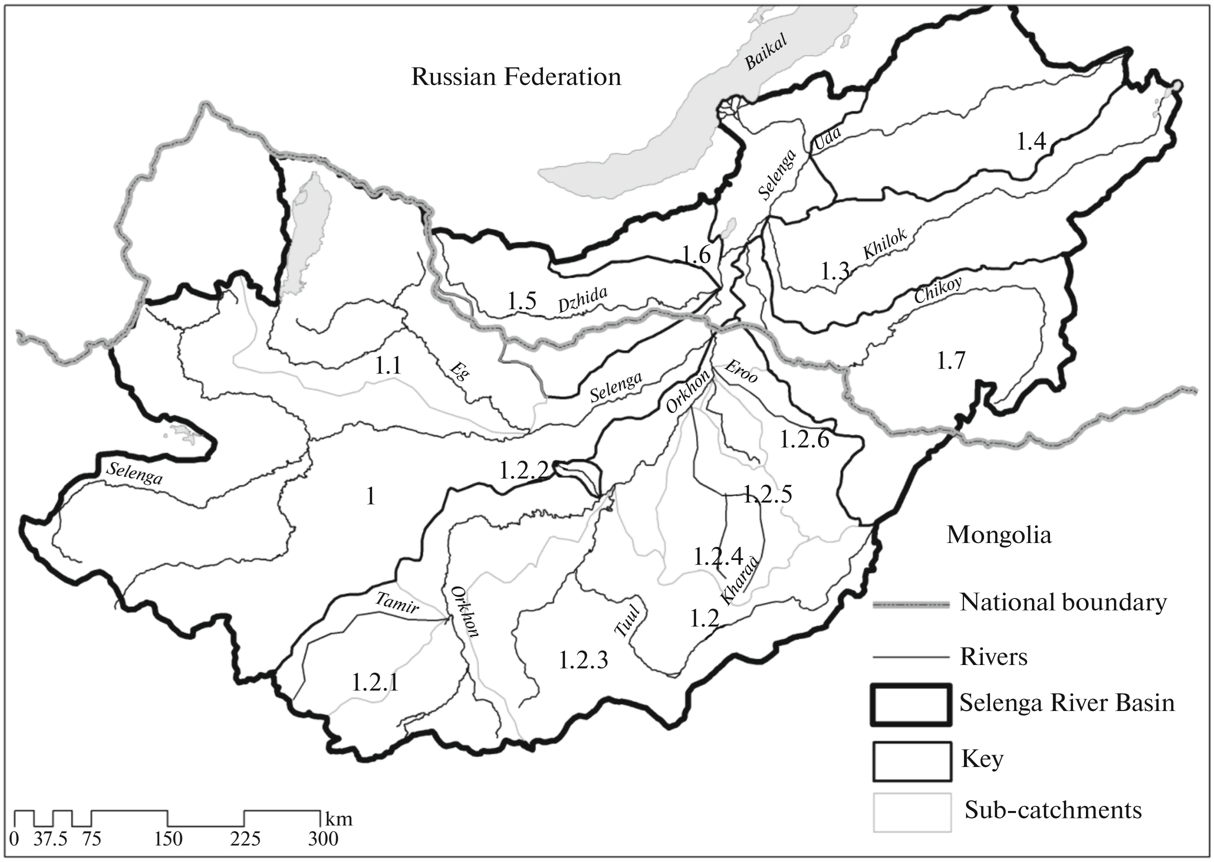

Fig. 1. Geographic overview of the Selenga River Basin and key sub-catchments recognized as a responsible for the in-catchment discrepancies of water and sediment flow.

on the grid cells is routed to the catchment outlet on the basis of a global drainage direction map [39], taking into account the extent and hydrological influence of lakes, reservoirs, dams, and wetlands. Spatially distributed sectoral water withdrawals and consumption are simulated for the five most important water use sectors: irrigation, livestock based agriculture, industry, thermal electricity production, and households and small businesses. Countrywide estimates of water use in the manufacturing and domestic sectors are calculated based on data from national statistics and reports and are then allocated to grid cells within the country based on the geo-referenced population density and urban population maps [18]. Irrigation and livestock water uses are calculated on the grid cells. As part of the model framework, the large-scale water quality model WorldQual calculates loadings to rivers on the basis of sectoral wastewater volumes and return flows as calculated by the water use models as well as the resulting in-stream concentrations based on the hydrological information simulated by WaterGAP3 following the standard equations of water quality dynamics. Up to now the model has been used to simulate biochemical oxygen demand (BOD_5), faecal coliform bacteria (FC), total phosphorus (TP), total nitrogen (TN) and total dissolved solids (TDS) [44, 58, 59, 73, 75]. All models are soft-linked and communicate through fluxes on a monthly temporal resolution.

The climate input for the hydrology and irrigation models consists of precipitation, air temperature and solar radiation. Here we make use of the WATCH data set (Water and Global Change) applied to ERA-Interim data (WFDEI) for the time period 1979–2010 [74]. The climate data have a temporal resolution of one day, and a spatial resolution of 0.5° by 0.5° (latitude and longitude, respectively) downscaled to the 5 arc minute grid cells.

Time series of domestic, manufacturing and cooling water use for the time period 1990–2010 were used from Flörke et al. [18], livestock water use was calculated according to the approach in Alcamo et al. [1] but with data on livestock numbers from FAO [17].

The WaterGAP3 modelling framework was used to estimate organic pollution loads generated within the river basin from different point and diffuse sources. Based on the pollution loads the in-stream concentrations are calculated for each grid cell and routed through the river network. Sectoral loadings considered in the modelling approach are domestic-sewered, domestic-non sewered, irrigation, animal wastes, urban surface runoff, fertilizer, and background concentration. Non-conservative substances are reduced by decay and decomposition, e.g. solar radiation, and sedimentation.

RESULTS AND DISCUSSION

Catchment Characterization

The Selenga River is the receiving water body for several tributaries from Mongolia and Russia that vary vastly with regard to their catchment size and characteristics. Based on GDB, the features of the key parameters are listed in the Table 2.

In Mongolia, the largest tributary is the Orkhon which itself is fed by several larger but also some much smaller rivers. The Tuul, Khangal and Kharaa pass by the cities of Ulaanbaatar, Erdenet and Darkhan respectively. These three cities concentrate almost half of the country's population and the major part of industrial activities. While the Tuul directly passes through large areas of gold mining, the Khangal is situated downstream of the copper-molybdenum mining complex of Erdenet. The Kharaa river basin is also home to several gold mines. Gold mining is also found on Eroo and Sharyn River. Moreover, the latter also flows through the coal mining town of Sharyngol. The Khangal and Sharyn are the two river basins with the largest share of land degraded by mining activities. The river basins of the Eg and the Eroo are characterized by a mountainous terrain and forest covers of more than 50%, whereas all other Mongolian subbasins of the Selenga are predominantly covered by grassland that is typically used as pasture and has locally been transformed into large plots of agricultural land. (Seasonal) permafrost is present only in the most upstream subbasins.

The basins of the Russian tributaries of the Selenga have a much higher degree of forest cover than their Mongolian counterparts, but are typically free from seasonal permafrost. They tend to receive a slightly higher precipitation. Major settlements in the Russian part of the Selenga River Basin include the Buryatian capital of Ulan Ude and the mining town of Zakamensk which is located on the Dzhida River.

Water Runoff Modelling and Projections

According to Törnqvist et al. [72], who compared projections of future climate changes in the Selenga River Basin using a number of CMIP5 carbon emission scenarios, this area is expected to experience a significant increase in both annual air temperature and precipitation amount. To assess the variability extent of the Selenga River annual runoff under changing conditions we conducted several ECOMAG model runs with the weather forcing altered by a possible change in air temperature and precipitation amount. This approach to assess the hydrological system response to altered climate is known as the "delta change" method [23]. The changes were applied to the same ERA-Interim reanalysis time-series as used for model calibration. The results are given in Table 3. The experiments showed that the significant increase of annual temperature by 3°C leads to changes in annual runoff by more than 20%, while the increase in precipitation amount by 10% may result in runoff increase almost by 30%. In case of a decrease in annual precipitation (which was not projected by any of the above mentioned scenarios), the runoff would also decrease.

Sediment Load Modelling

Surface runoff changes and land use impacts induced comprehensive response of the river system. There has been a substantial decline in sediment yield of Selenga River (from 5832 to 3015 t/day) and its main tributaries in the Russian part of the river basin since 1996 [10]. In the upper part of the basin where an absence of routine monitoring of sediment loads precludes statistical analyses of the sediment trends, the assessment of the sediment yield decrease was based on the comparison between SPM concentrations measured during the campaigns of 2011–2014 and historical field campaigns of 1934–1936 [10].

The calculated eroded sediment yields using SedNet model (Fig. 2) range from 5 to over 1000 t/year/km^2 with an 470 t/year/km^2 average throughout a catchment which is in line with large scale sediment budget modelling for Kharaa river system [70]. The calculation of the budget resulted in a suspended sediment export of 2.6 mln t/year for the whole Selenga River Basin, thus fitting well with recent estimates of 2.5 mln t/year which are based on the Selenga's outlet monitoring station [10]. The spatial distribution of the erosion potential based on RUSLE application follows mostly orographic drivers, with little relation to human impact. Anthropogenic pressure could be seen only within small impacted catchments. The highest annual SPM concentrations were predicted for the Khangal (139 t/year/km^2) and Modonkul Rivers (114 t/year/km^2), which corresponds to the observed increase of sediment and pollutants fluxes [10] below a large copper-molybdenum mine-mill complex and wolfram-molybdenum mining and processing factory, respectively. In certain catchments, an underestimation of the present anthropogenic conditions could be seen but not incorporated in the model at its present stage. This particularly includes the heavy pollution with sediments due to insufficient wastewater treatment in Ulaanbaatar which explains over 90% of the sediment yield in the Tuul downstream [54].

The mostly environmental drivers of the sediment loads formation are also evidenced by the basinwide

Table 2. Environmental characteristics of the Selenga River Basin and sub-catchments (based on GDB)

No.	Basin/Subbasin	(Sub-) Catchment size, km²	Average elevation, m	Forest cover, %	Degraded land from mining, km²/1000 km²	Seasonal Permafrost, km²	Average Precipitation, mm
1	Selenga	447.000	1406	37.5		9.5	314
1.1	Eg	42.412	1653	50.8	0.02	0	333
1.2	Orkhon	129.711	1422	14.08	0.92	36	285
1.2.1	Tamir	12.965	1966	12.36	0.01	85	322
1.2.2	Khangal	910	1220	22.8	36	0	129
1.2.3	Tuul	48.573	1375	5.05	0.75	34	243
1.2.4	Kharaa	16.310	1191	21.04	1.14	0	296
1.2.5	Eroo	11.555	1255	65.98	0.55	0	362
1.2.6	Sharyn	897	1639	28.85	3.32	0	299
1.3	Khilok	38.303	998	80.27	0.79	0	316
1.4	Uda	35.088	952	81.71	0.17	0	290
1.5	Dzhida	25.159	1292	71	0.6	0	327
1.6	Temnik	5.844	1222	54.2	1.92	0	262
1.7	Chikoy	44.914	1226	82.79	0.54	0	390

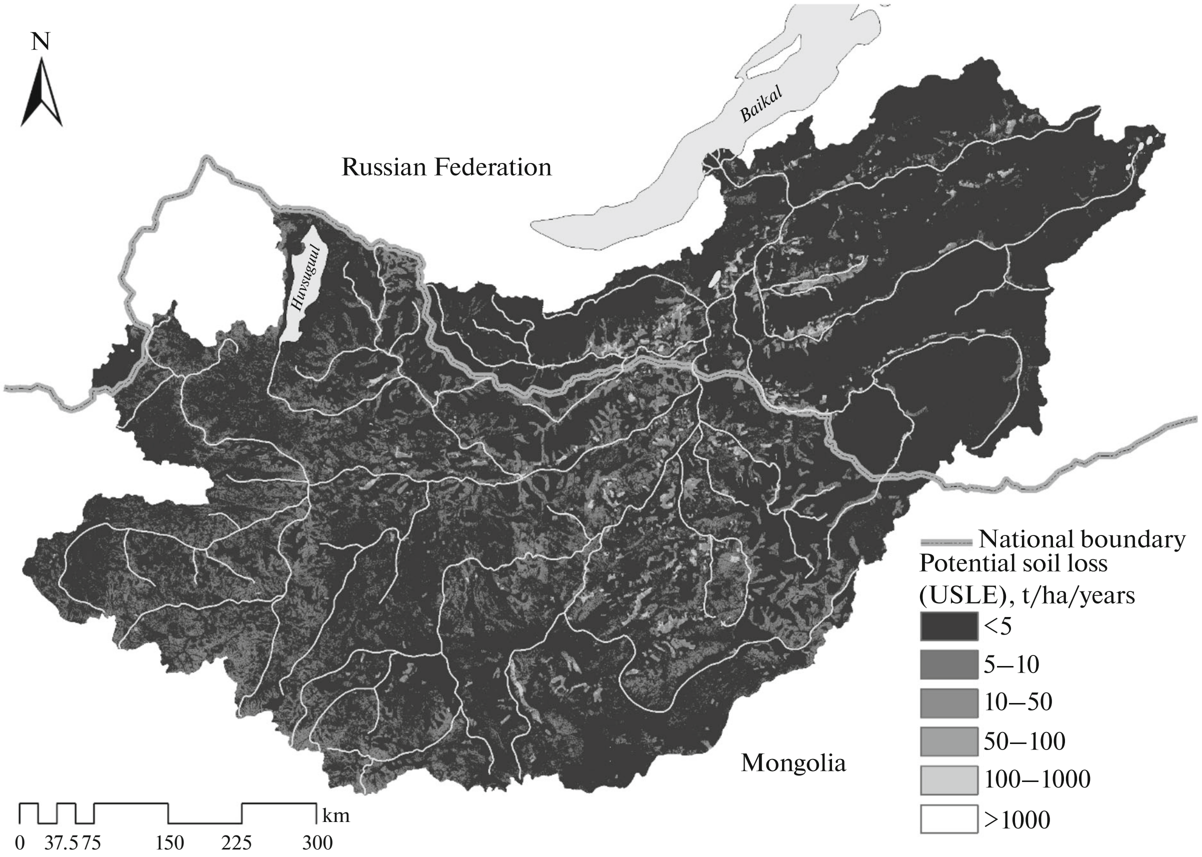

Fig. 2. Modeled eroded sediment yields (B) in the Selenga River, t/year km^2.

multivariate model SelengaStatistic. Among the monthly averages of SPM concentrations almost all were driven by catchment vegetation (T—tundra, % of the catchment area; MF—mountain forests, % of the catchment area; FS—flat steppes, % of the catchment area), permafrost (SP—seasonal permafrost, % of the catchment area; NP—areas with near-surface permafrost, % of the catchment area), glaciers (GL—glaciers, % of the catchment area) or topology (I—slope, DF—denudation plains % of the catchment area, ML—midlands, % of the catchment area). Grazing (GR—grazing lands % of the catchment area), population density (PD, people per sq. km of land area) and density of disturbed lands (DDL, per sq. km of land area) which were the only human drivers in the basin-wide model:

$$S(\text{July}) = 0.55SP + 0.44T - 0.12GL - 63.9,$$

$$S(\text{September}) = 0.68FS - 0.02MF + 0.22I - 0.51ML + 22.8,$$

$$S(\text{August}) = 0.46FS + 0.33GR + 0.17DF + 0.14F + 0.24DDL - 0.17I - 9.4,$$

$$S(\text{March}) = 1.2PD + 0.11I + 0.46MF + 0.36NP + 0.62GR - 55.2.$$

These results indicate that future hydroclimatic and associated environmental trends and variations will remain main drivers of sediment and contaminants fluxes within the river system. Taking into account the expected change in temperature and precipitation (Table 3), shifts in sediment transport patterns are particularly likely during extraordinary meteorological events. Among the main driving forces of the sediment transport during hydrological peaks flows within subbasins (happened in July and August) are permafrost thaw and shifts in soil temperature and moisture, which exert a strong control on soil aggregate stability, and thus on soil erosion intensity. Model structure for March and September represents homogenous conditions and significant drivers are related to longitudinal shift of terrestrial parameters (see Table 2).

Analysis of Trends in Organic Pollution

Between 1990 and 2000 a rapid decrease in total annual BOD loadings from 24573 t/a to 18623 t/a could be detected. This was followed by an increase to 22208 t/a in 2010 (Fig. 3). The first period (1990 to 2000) is clearly influenced by the collapse of the Soviet Union, while the second period (2000 to 2010) reflects

Table 3. Changes in Selenga's annual runoff volume under different climate forcings

Forcings		Changes in mean annual air temperature, °C				
		−1	0	+1	+2	+3
Changes in annual precipitation amount, %	−10	−12.6	−19.0	−25.4	−31.6	−37.7
	0	7.3	0	−7.4	−14.7	−21.9
	+5	17.7	10.0	2.0	−5.8	−13.5
	+10	28.3	20.3	11.8	3.4	−4.8

Mongolia's progress in the political and socioeconomic transformation to a market economy. Nevertheless, for all three time steps domestic wastewater is by far the most important contributor (65–80%), especially wastewater from sewered areas (≈55%). The importance of the manufacturing sector dropped by nearly two-thirds (64%) from 1990 to 2000, but subsequently doubled before 2010. Other contributors like animal wastes and urban surface runoff play only a minor role (2.5–4%).

The spatial distribution of BOD loadings (see Fig. 4) shows hotspots around the major settlements, especially Ulaanbaatar and Ulan-Ude. These two regions together accounted for more than 50% of the total loadings in 2010 and may therefore be considered regional loading hotspots. The years 1990 and 2000 show a very similar picture in terms of spatial pattern, but differ in the total amount of BOD loadings, in particular around urbanized areas.

According to international guidelines (e.g. [9, 15]) three classes of BOD concentration were used to categorize organic pollution in the Selenga-Baikal River Basin (low: <4 mg/L, moderate: 4–8 mg/L, and severe >8 mg/L). In some parts of the Selenga river system, in-stream concentrations rose from the low class in 1990 to the moderate class in 2010 ('increasing trend' category in Fig. 5). In other cases, the simulated in-stream concentration reached the severe class (>8 mg/L) in 2010, or remained in this class but further increased by 2010 ('increasing trend of particular concern' in Fig. 5). The strongest increases were observed in the Orkhon River Basin, with an increasing trend of particular concern in three of its subbasins (Kharaa, Eroo, Tuul) and near Ulan-Ude (Fig. 5). By contrast, in most of the western and northern part of the Selenga River Basin, no shift to higher classes could be observed even though in-stream concentrations increased in large areas (but without class change).

Further Water Quality Problems

Anthropogenic water quality impairments in the Selenga River Basin show spatial pattern that are to a large degree related to the location of urban and mining areas [6, 38]. They are of relevance both locally and in the context of contaminant transport towards the Selenga River Delta and Lake Baikal. In order to come to a comprehensive assessment of current water quality issues in the Selenga River Basin, we compiled data from literature and our own fieldwork. Table 4 provides a detailed overview about the currently known water (and sediment) quality problems in the subbasins of the Selenga. However, for the interpretation of the results it is important to keep in mind that environmental monitoring in the region has so far been quite limited [30], with very strong variations between different subbasins.

Despite the differences regarding the water and sediment quality parameters measured and methodol-

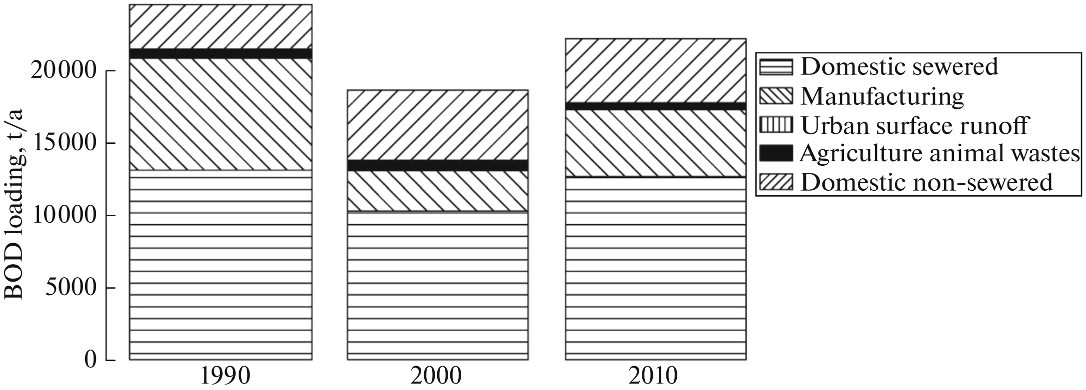

Fig. 3. Annual BOD loadings in the Selenga–Baikal River Basin between 1990 and 2010.

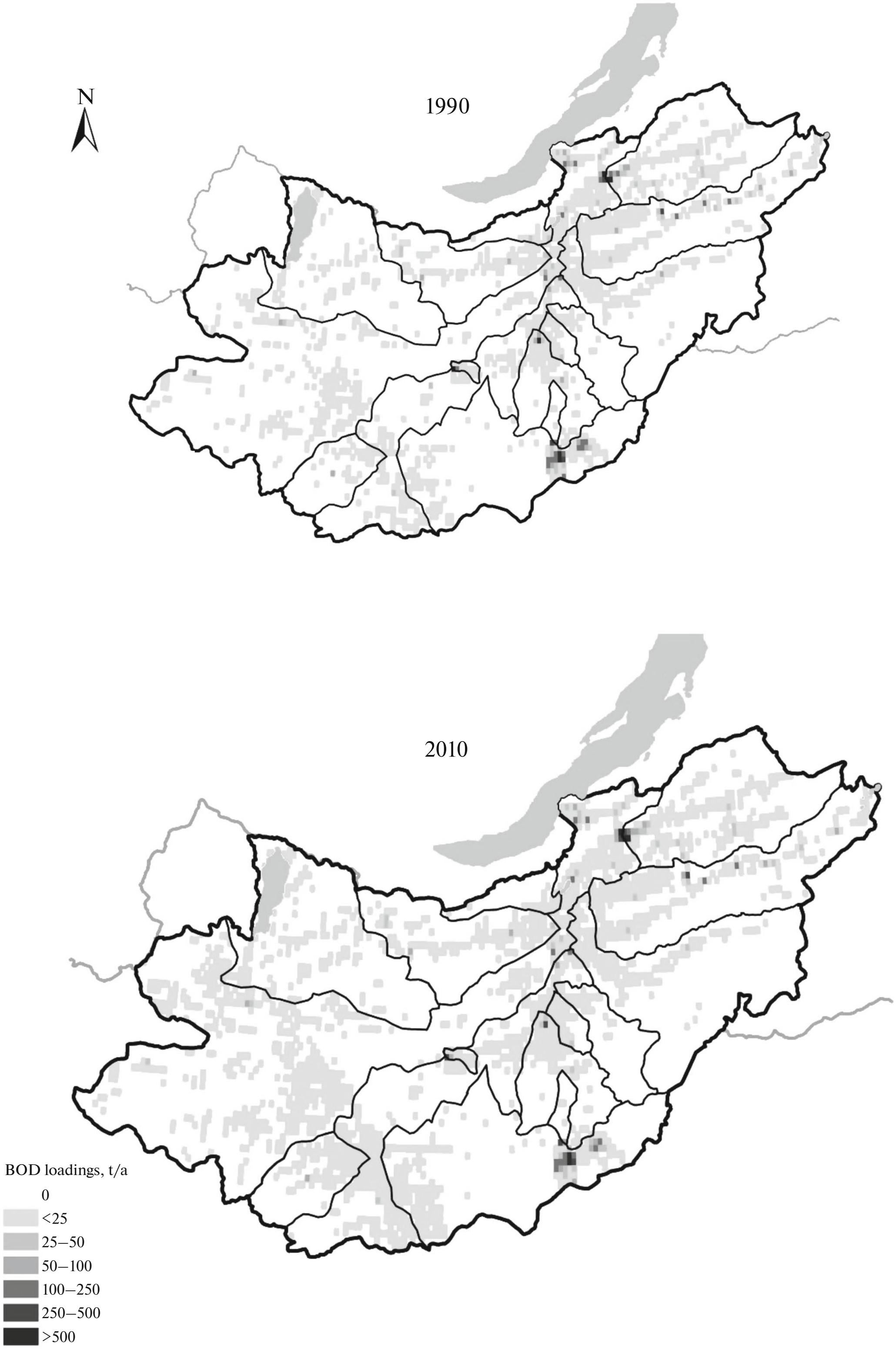

Fig. 4. Spatial distribution of annual BOD loadings in the Selenga–Baikal River Basin in 1990 and 2010.

ogies used in the studies included, their synopsis is an important step towards an integrated assessment of the current state of water quality in the Selenga River Basin. As shown by Table 4, a few tributaries that were investigated were found to be in a relatively pristine condition, including the Eg and Tamir rivers in Mon-

Fig. 5. Change of mean annual BOD concentrations between 1990s and 2010s.

golia and the Chikoy river in Russia. On the other hand, all rivers passing by urban and mining areas show clear and multiple signs of water contamination, including elevated levels of nutrients and mining-related metals. According to present knowledge, at least the following elements (for which an elevation beyond natural background levels was detected in at least one sampling location) are of potential concern for surface water quality in (parts of) the Selenga River Basin: Al, As, Be, Cd, Cr, Co, Cu, Fe, Hg, Mn, Mo, Ni, Pb, U, V, W, and Zn. Even though not all of these elements are enriched in the Selenga's water, elevated levels for the underlined elements have been found in the Selenga's main channel.

CONCLUSIONS

The Selenga-Baikal Basin is a very sparsely settled region by international standards, but is characterized by significant and globally relevant changes in hydrology and water quality. Firstly, this highly continental region is affected by strong climate change signals and currently faces major land use changes due to the conversion of forests and steppe into agricultural land and mining areas. Mining is not only an important backbone of the regional economy, but also a major water user and polluter. Urban areas are limited to a few centers, but also represent hotspots of water withdrawals and water contamination.

Even though the discharge of the Selenga and many of its tributaries has been below long-term averages for most years since 1995, climate change which is predicted to lead to rising temperatures but also increasing precipitation will most likely lead to an increase in surface water discharge in the Selenga River and its tributaries. However, rising abstractions and a planned water diversion project from the Orkhon River may in the future counteract this positive trend. In the recent past, lower mean discharge rates resulted in reduced total sediment loads. However, it is important to understand both long-term and seasonal sediment transport variations, which have important implications for contaminant transport regimes and the morphodynamics of the Selenga river delta, the final biogeochemical barrier before the Selenga drains into Lake Baikal.

Water quality in the Selenga river system is strongly linked to discharge, but also shows clear spatial pattern that are largely determined by mining sites and urban areas. One important consequence are significant differences in water quality in the Selenga River Basin. Through the discharge of poorly treated wastewater, urban areas constitute key sources of nutrients, BOD loadings and microbiological contamination. On the other hand, mining areas which exploit coal, Au, Cu, Mb and W resources are the sources of various heavy metal emissions. These are of localized concern when they affect drinking water resources or lead to bioaccu-

Table 4. Water pollution problems the Selenga River Basin and sub-catchments

No	River	Characterization of water quality	Sources
1	Selenga	Mongolian Part: elevated Fe and Pb concentrations (with Fe exceeding WHO drinking water guidelines); elevated concentrations of Al, As, Cu, Fe, Mn and Ni downstream of the outlet of the Orkhon river. Russian Part: recent increase in sulfate and nutrient concentrations near the Russian-Mongolian border; among the most polluted Russian rivers in its downstream section, with elevated concentrations of As, Cd, Cu, Fe, Mn, Zn (particularly near Ulan Ude); concentration factors of 1 to 2 times for As, Cr, V, U; 3 to 4 times for Co, Fe Mn, Ni, V, Zn; and 5 to 10 times for Cu and Pb below Ulan-Ude; PAHs occasionally exceed the maximum allowable concentrations for drinking and surface waters; microbial pollution (E. coli, enterococci) is problematic during low flow situations	Nadmitov et al. 2014 Sorokovikova et al. 2013, Thorslund et al. 2012; Own data
1.1	Eg	Close to natural background conditions	Own data
1.2	Orkhon	Elevated levels of Al, As, Ca, Cu, Fe, Mo, Mn, Mg, Ni, U as well as SO_4^{2-} and nutrients documented along the Orkhon; very high As concentrations (190 μg/L in one sample) just upstream of the confluence of Tuul and Orkhon; contaminant concentrations (Al, As, Cu, Fe, Mn, Pb and Zn) typically below the levels found in the Tuul; elevated Cu concentrations in sediments downstream the outlet of the Khangal river; high levels of metal contamination downstream of Darkhan city (frequently exceeding Mongolian surface water guidelines); elevated concentrations of As in surface and drinking water in various parts of the Orkhon river basin	Brumbaugh et al. 2013, Nadmitov et al. 2014, Thorslund et al. 2012; Own data
1.2.1	Tamir	Close to natural background conditions	Own data
1.2.2	Khangal	High concentrations of Cu in the upper part (near the Erdenet Cu-Mo mine); elevated nutrient concentrations; massively elevated levels of Ca^{2+}, K^+, Mg^{2+}, Na^+ and Cl^-, HCO_3^-, SO_4^{2-} (by two orders of magnitude vs. natural background conditions)	Brumbaugh et al. 2013; Own data
1.2.3	Tuul	Elevated concentrations of Al, As, Cu, Fe, Mn, Mo, Ni, Pb, U, V, Zn as well as Na^+, Cl^- and SO_4^{2-} documented along the Selbe river (tributary to the Tuul in Ulaanbaatar); elevated Pb, Zn and high nutrient levels; most polluted river in Mongolia (in terms of metals exceeding guidelines) near Ulaanbaatar; Al, Cu, Fe, Mn, Mo, V, Zn below Ulaanbaatar increase from 3 to 9 times at low water period and from 9 to 52 times at summer flood period; 50 to 100 times increase in nutrient levels levels below Ulan-Baatar during winter; highest concentrations of Fe, Mn and Zn near Ulaanbaatar and Zaamaar mining area; dissolved concentrations of Al, As, Cu, Fe, Mn, Pb and Zn typically increase below Zaamar; TP concentrations double to triple downstream of Zamaar; elevated U levels detected in groundwater, sometimes exceeding the WHO drinking water guidelines; As levels in the Tuul are close to the limits of WHO drinking water guideline	Brumbaugh et al. 2013 Nadmitov et al. 2014, Nriagu et al. 2011, Stubblefield et al. 2005, Thorslund et al. 2012; Own data
1.2.4	Kharaa	Elevated concentration of Al, As, Cd, Cu, Fe, Mn, Ni, Pb, U, Zn documented along the river; Al, As, Cu, Fe, Mn, Pb, U and Zn higher than the maximum allowable concentration in the monitoring and heap leach wells around Boroo gold mine; Boroo (tributary to the Kharaa): elevated As and Hg concentrations, with elevated levels of As in the Kharaa downstream of the Boroo confluence (90 μg/L in one sample); most polluted sections near Darkhan City, with high concentrations of As, Cd, Cu and Mn (frequently exceeding the MNS (1998) guidelines); increasing levels of N and P since 2000, with a clear longitudinal trend (highest concentrations downstream of Darkhan); elevated As concentrations downstream of mining sites, in the ash basin of Darkhan's thermal power station and in drinking water of Khongor Soum	Brumbaugh et al. 2013, Hofmann et al. 2010, Inam et al. 2011, Nadmitov et al. 2014; Own data
1.2.5	Eroo	Elevated levels of Al, Fe and nutrients (TN, TP) measured in the downstream section	Stubblefield et al. 2005; Own data

Table 4. (Contd.)

No	River	Characterization of water quality	Sources
1.2.6	Sharyn	Elevated concentrations of Al, As, Cd, Cu, Fe, Mn, Ni, U in the downstream section (partly exceeding the MNS (1998) guidelines); elevated nutrient levels in the downstream section	Nadmitov et al. 2014; Own data
1.3	Khilok	Elevated concentrations of As, Cd in suspended sediments	Nadmitov et al. 2014; Own data
1.4	Uda	High levels of Zn near Ulan Ude; elevated levels of suspended As, Cd, Mo, W in the downstream part	Nadmitov et al. 2014; Own data
1.5	Dzhida	Elevated concentrations of Cd, Mn, Pb in the upstream reaches, indicating an independent source of metals originating in Russia considerable heavy metal pollution around Zakamensk	Nadmitov et al. 2014; Own data
1.5.1	Modonkul	Total concentrations of Cd, Cu, Mn, Pb, Zn exceed permissible levels by one to two orders of magnitude; elevated levels of SPM in comparison with baseline values during low water season: Be (780×), Cd (650×), Cu (450×), Pb (100×), Zn (300×); elevated levels of dissolved Be (90×), Cd (450–650×), Zn (80×), Cu, Mo, W (10×)	Own data
1.6	Temnik	Zn concentration exceed water quality guidelines	Nadmitov et al. 2014; Own data
1.7	Chikoy	No reported water quality problems	Nadmitov et al. 2014; Own data

mulation in fish, but are similarly relevant for regions further downstream including the Selenga Delta (where they are largely removed from the water but accumulated in the delta sediments) and ultimately Lake Baikal.

A good understanding of hydrological trends and changes in water quality in the Selenga River and its tributaries is an important prerequisite for water management. Science-based environmental management concepts in the region are needed for at least three reasons: (1) to solve localized water-related challenges in the Selenga River Basin that show a strong spatial variation; (2) to ensure the protection of the Selenga delta's and Lake Baikal's unique ecosystems, and (3) to overcome disputes in transboundary water management between the riparian states, Mongolia and the Russian Federation.

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