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Assessing the impacts of global change on water quantity and quality: Large-scale modelling studies for Central Asia

DISSERTATION

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Erklärung des Promovenden:

Die Übereinstimmung dieses Exemplars mit dem Original der Dissertation zum Thema:

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Statement of the PhD Candidate:

I hereby confirm that this copy is identical with the original dissertation titled:

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List of Abbreviations

Aphrodite	Aphrodite's water resource – Asian Precipitation – Highly Resolved Observational Data Integration Towards Evaluation of the Water Resources
A1B	IPCC-SRES Scenario
A2	IPCC-SRES Scenario
B1	IPCC-SRES Scenario
BMBF	Bundesministerium für Bildung und Forschung (Federal Ministry of Education and Research)
BOD	Biological Oxygen Demand
CNRM-CM3	Model from the Centre National de Recherches Météorologiques, France
CRU	Climate Research Unit, University of East Anglia, U.K.
c.t.Q90	consumption to Q90 ratio – water stress indicator
DDM	Drainage Direction Map
E	Evapotranspiration
E_a	Actual Evapotranspiration
E_c	Canopy Evaporation
E_{pot}	Potential Evapotranspiration
ECHAM5	Model from the Max-Planck-Institute, Hamburg, Germany
ERA-40	re-analysis dataset from the European Centre for Medium-Range Weather Forecasts, Reading, U.K.
FC	faecal coliform bacteria
FONA	Forschung für Nachhaltige Entwicklung (Research for Sustainable Development)
GCM	General Circulation Model
GDP	Gross Domestic Product
GPCC	Global Precipitation Climatology Centre
GRACE	Satellite: "Gravity Recovery And Climate Experiment"
GRDC	Global Runoff Data Centre
GVA	Gross Value Added
IMHE	Institute of Meteorology, Hydrology and Environment,Ulaanbaatar, Mongolia
IPCC	Intergovernmental Panel on Climate Change

IPSL-CM4	Model from the Institute Pierre Simon Laplace, France
IWRM	Integrated Water Resources Management
JMP	Joint Monitoring Programme of WHO/UNESCO
M	million
MoMo	Project “Integrated Water Resources Management in Central Asia – Model Region Mongolia”
NSE	Nash-Sutcliffe-Efficiency
P	Precipitation
PCR-GLOBWB	Model: “PCRaster Global Water Balance”
Q_b	Groundwater Baseflow
R_g	Groundwater Recharge
R_l	Runoff generated on land
R_s	Surface Runoff
SRES	Special Report on Emission Scenarios (IPCC)
TDS	Total Dissolved Solids
UN	United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
VIC	Model: “Variable Infiltration Capacity”
WASMOD	Model: “Water and Substance Simulation Model”
WaterGAP	Model: “Water - Global Assessment and Prognosis”
WATCH	EU-FP6 project “WATer and Global Change”
WBM	Model: “Water Balance Model”
WDD	WATCH driving data – scenario projections
WFD	WATCH forcing data
WHO	World Health Organization
w.t.a.	water to availability ratio – water stress indicator
WWTP	Waste Water Treatment Plant
yr	Year

Chapter 1

1. Summary

1.1. Introduction

Water resources in the semi-arid to arid areas of Central Asia are often limited by low precipitation, and hence vulnerable to impacts of global change, i.e. socio-economic development and climate change. Both, socio-economic development and climate change are very likely causing significant changes as water resources are affected by two main effects: Firstly, growing population and industrial activities in the region raise the pressure on water resources due to increasing water abstractions. Secondly, air temperature in the region has been rising in the past far above global average and it is expected to increase further, which will lead to changes in runoff generation and therefore water availability. Increasing temperature as well as increasing water abstractions will affect water quantity and consequently water quality as a result of higher pollution intake or reduction in dilution capacity. Thus, it is of crucial importance to analyse and assess the state of current and future water resources to implement sustainable water management as the above mentioned effects very likely causing significant changes of water resources. Consequently, adaptation is required to “anticipate to adverse effects of climate change and taking appropriate action to prevent or minimise the damage they can cause (EC 2014).”

In general, Central Asia is likely to be severely affected by climate change and increasing water abstractions whereas the potential development of water resources is of crucial importance to develop sustainable water management strategies and an integrated water resources management system. To achieve a comprehensive assessment of current and future water resources also cultural adaptation and governance policy is important. At this, also data scarcity is a major problem as observed data is only sparsely available (Karthe et al. 2015) and therefore large-scale modelling is needed to get a comprehensive overview of the study region, to close knowledge gaps and assess future state and potential impacts.

Here, Mongolia is of high interest as current water availability is generally low and during last decades climate change induced temperature increase is nearly twice as much as the global average (Batimaa et al. 2011, Törnqvist et al. 2014). Already today, wide regions are characterized by low annual precipitation below 100 mm per year. Furthermore, due to a rapid urbanization, particularly around the capital of Ulaanbaatar, pressures on water resources are increasing. At this, infrastructure is often in a worse condition, e.g. around 50 % losses due to leakages in the sewage pipe system (Scharaw and Westerhoff 2011) or per capita water use in urbanized areas is ~230 l/d (Batsukh et al 2008; MEGD 2012). Therefore, improved infrastructure to prevail or reduce the overexploitation of water resources and water quality deterioration is needed. As the Selenga river is the main contributor (>60 % of the total inflow) to Lake Baikal, which is the world's largest freshwater source, special attention was given to evaluate the current and future state of water quality in the Selenga river basin.

Within the last years, the number of scientific research studies using large-scale models to simulate water availability and water use has increased substantially. Several new datasets from earth observations and new or improved models have been published (Werth et al. 2009; Werth and Güntner 2010; van Beek et al. 2011). Nevertheless, those studies focussed on water quantity and did not take into account impacts on water quality induced by global change although changes in water quality affecting aquatic ecosystems and species. Furthermore, spatially explicit large-scale modelling studies have not been carried out for Mongolia and Central Asia to get a comprehensive overview and assessment.

To address this research gap, the large-scale water resource modelling framework WaterGAP 3 was applied to Central Asia with a focus on Mongolia to simulate impacts on current and future water resources. WaterGAP 3 consists of hydrology, water use and water quality sub-models in order to simulate current and future water quantity and quality (cf. Chapter 1.2).

This thesis provides the first integrated-model-based assessment to simulate spatially explicit water quantity and quality alterations induced by global change in Central Asia, particularly in Mongolia. Hence, impacts of global change, i.e., socio-economic factors and climate change have been separated in order to quantify their specific effects on water resources and to simulate loadings and in-stream concentrations for conservative and non-conservative substances to gain insight into the sectoral (agriculture, industry, and domestic) contributions as well as spatial patterns of potential water pollution.

In detail, within this thesis four different studies have been carried out to assess the impact of global change on water resources using the large-scale water modelling framework WaterGAP 3: The first analysis (see Chapter 2) describes the application of the large-scale modelling framework to the study region Central Asia. The performance of model simulations was evaluated against measured data from different sources. The hydrological model was driven by different climate datasets in order to analyse the impact of climate change on water resources and accompanied uncertainties caused by different climate forcing. The second study (see Chapter 3) deals with the impact of climate change on water availability in Central Asia. Simulations were conducted with the WaterGAP 3 hydrology model in order to quantify the effects of climate change on water resources up to 2100. The third model experiment (see Chapter 4) refers to the development and application of socio-economic scenarios for Mongolia and the quantification of the impact of increasing water abstractions for domestic, industrial and agricultural purposes on water resources until 2100. In this study, for the first time mining was included as water use sector, because mining accounts for nearly 40 % of the water withdrawals and has the potential to affect water quality. The fourth study (see Chapter 5) combines the hydrology model and knowledge of the first three model experiments to implement a water quality sub-model for simulating water pollution in Mongolia, in particular in the Selenga River Basin. For this, loadings and in-stream concentrations of total dissolved solids (TDS), biological oxygen demand (BOD) and faecal coliform bacteria (FC) were simulated and –if possible- validated against observed data.

Finally, a conclusive discussion analyses the methods applied and results produced in this thesis. In addition, based on the newly gained knowledge, a comprehensive outlook discusses recommended further developments and shortcomings identified within this thesis.

1.2. Data & Methods

1.2.1 Water Resource Model WaterGAP 3

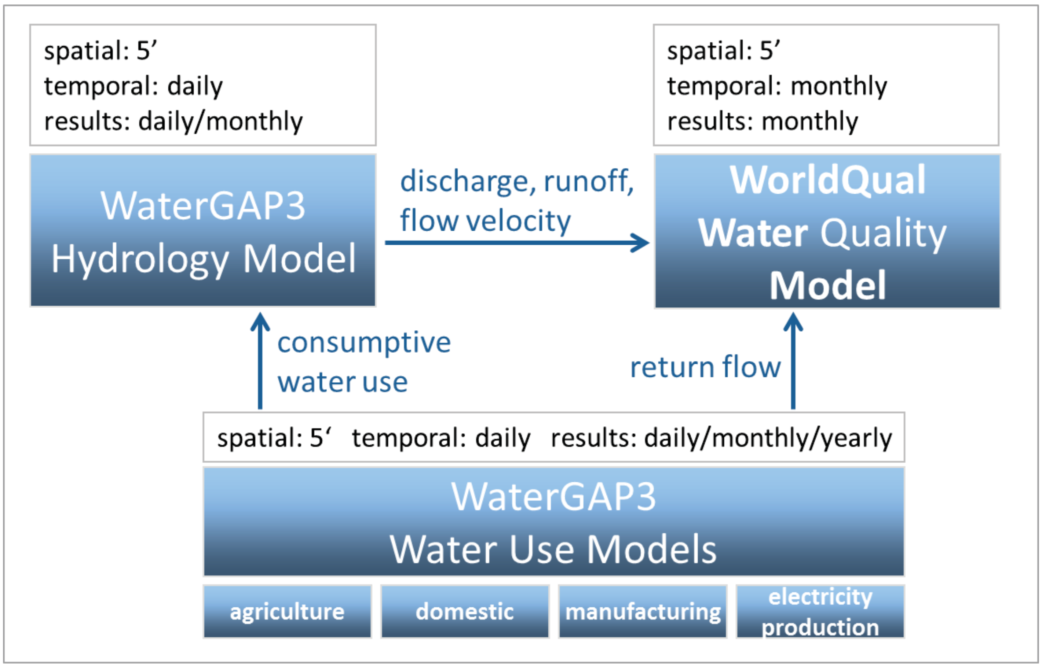

Figure 1: Overview of the WaterGAP 3 modelling framework (Verzano, 2009, modified)

Within this thesis, the large-scale water resources model WaterGAP 3 (Water – Global Assessment and Prognosis, see Figure 1) has been used as it is the most suitable tool to simulate large-scale water quantity and quality. Besides WaterGAP 3, several other large-scale models are available such as WBM (Vörösmarty et al. 2000), WASMOD (Widen-Nilson et al. 2007), PCR-GLOBWB (van Beek et al. 2011), and VIC (Andreaidis and Lettenmaier 2006). WaterGAP 3 is –next to PCR-GLOBWB- the only model which runs on a high spatial resolution of five arc minutes (~ 6x9 km in Central Asia) compared to thirty arc minutes (~50x50 km) or less of the other models. This allows not only global but also regional to mesoscale model studies (Verzano 2009). Furthermore, WaterGAP 3 is the only large-scale model featuring a water quality sub-model and includes also five sub-models for water use for the sectors irrigation (aus der Beek et al 2010), livestock (Alcamo et al. 2003), domestic and small businesses, manufacturing industries and thermal electricity production (Flörke et al. 2012, Flörke et al. 2013). Additionally, the model's water quality sub-model allows the simulation of biological oxygen demand, total dissolved solids and faecal coliform bacteria loading and in-stream concentration. The regional studies in this thesis (particularly Chapter 4 and 5) could not have been accomplished with a lower resolution model.

WaterGAP 3 calculates the daily water balance for each grid cell based on climatic time series and the physiogeography like slope, elevation, and soil type. The climate forcing includes precipitation, air temperature and solar radiation. The runoff is calculated for each grid cell and routed by a drainage direction map through the catchment until it reaches the outlet. The vertical water balances consist of (i) radiation budget and potential evapotranspiration, (ii) snow accumulation and melting, (iii) interception, (iv) soil water balance and (v) groundwater (see Figure 2). The lateral water balance routes surface runoff, subsurface runoff and baseflow first through lakes, wetlands and reservoirs, and finally to the river segment.

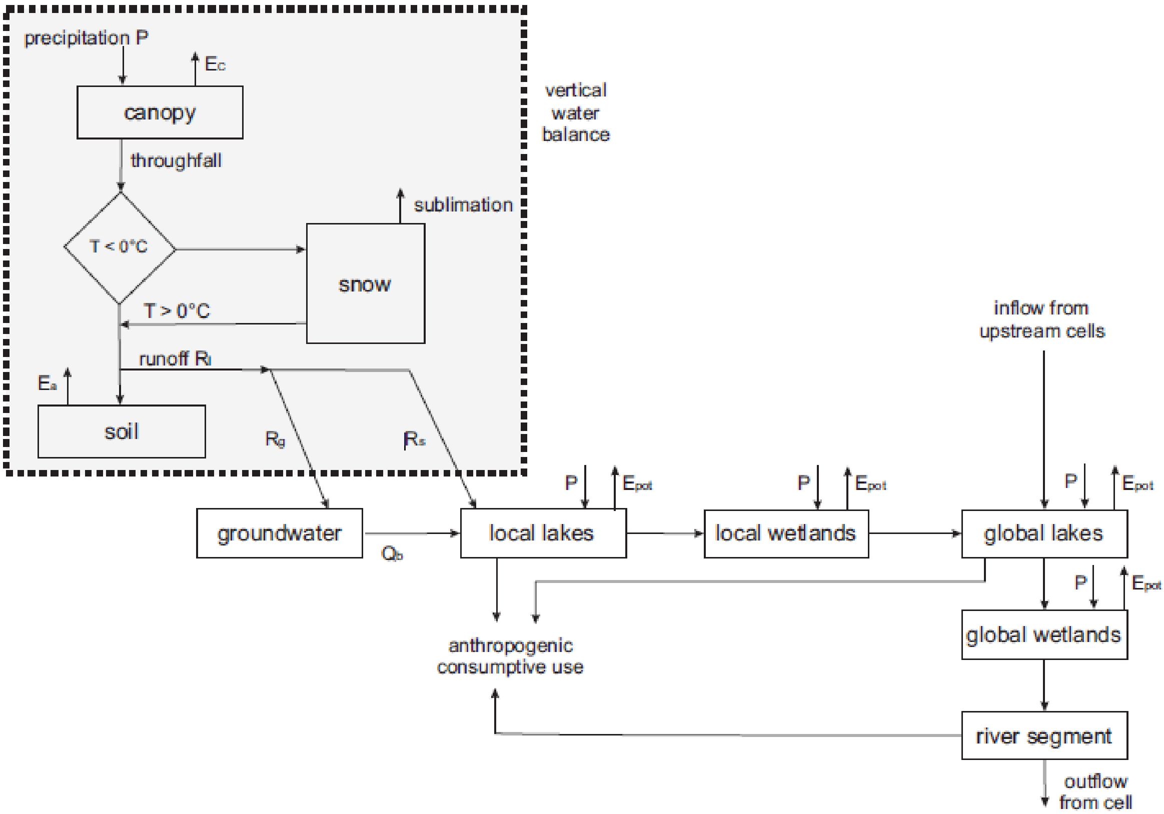

Figure 2: Schematic illustration of water fluxes considered in WaterGAP 3; R_g (groundwater recharge), R_s (surface runoff), R_l (runoff generated on land), E_{pot} (potential evapotranspiration), E_a (actual evapotranspiration), E_c (canopy evaporation) (Verzano, 2009)

The above mentioned water use models calculate the water abstractions for the industry (manufacturing, thermal electricity production), agriculture (livestock, irrigation) and domestic and small businesses sectors separately (aus der Beek et al. 2010, Flörke et al 2012, Flörke et al. 2013). The water balance calculated within the hydrology model is then reduced by the water consumption from the water use sub-models. Subsequently, the calculated water resources are fed in the water quality sub-model (WorldQual) to calculate in-stream concentrations. The water quality model (WorldQual, Voß et al. 2012, Williams et al. 2012, Reder et al. 2015) considers loadings from point and diffuse sources (see Figure 3) 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, loadings from domestic – non sewered 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: calculated by multiplying the connected population with a per-capita emission factor. To achieve the final loadings flowing 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 loading 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.

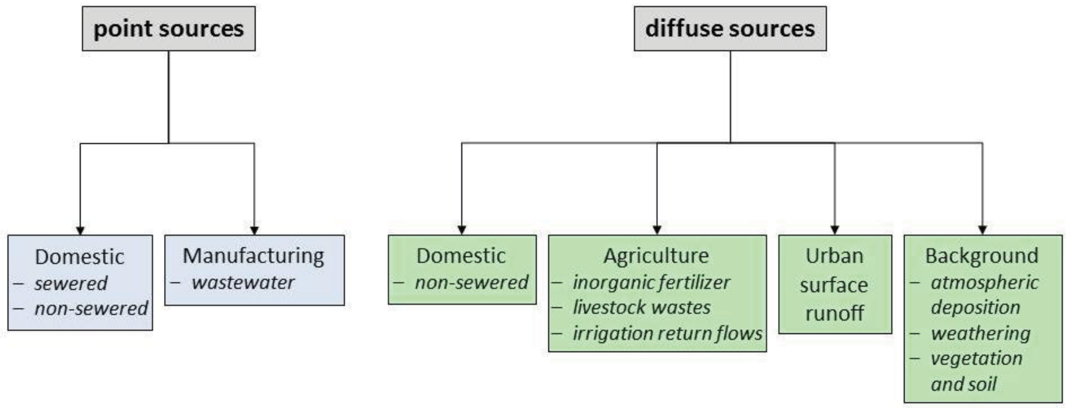

Figure 3: Pollutant loading sectors in WorldQual categorized as either point sources or diffuse sources (Reder et al. 2015, modified)

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 reducing the in-stream concentration.

1.2.2 Data assimilation

Simulation results depend highly on the quality and accuracy of the input data, particularly climate input data is one of the most sensitive drivers (see Chapter 2). For the standardized baseline model period (1971-2000), climate forcing from the EU-FP6 WATCH project was used (Chapter 3, 4, and 5). This so called WATCH forcing data (WFD, Weedon et al. 2010, 2011) has been incorporated into WaterGAP 3 and covers the time period from 1958-2001 in 0.5° resolution and daily (or aggregated monthly) time steps, providing parameters like precipitation, air temperature, and long- and shortwave radiation. The climate data has been rescaled to the five arc minutes WaterGAP 3 grid. As Chapter 2 compares the suitability of precipitation data for Central Asia it examines also the TS 3.2 datasets of the Climate Research Unit (CRU) (Harris et al. 2014), the Aphrodite's water resources dataset (Yatagai 2009, 2012), and the precipitation dataset version 6 from the Global Precipitation Climatology Centre (GPCC, Schneider et al. 2011). These datasets, as mentioned above, were also rescaled to the WaterGAP 3 spatial resolution. Based on observed river runoff from the Global Runoff Data Center (GRDC) and data from the Mongolian Institute for Meteorology, Hydrology and Environment (IMHE), the calibration and validation of the WaterGAP 3 hydrology model has been conducted for in total 158 gauging stations in Central Asia. Socio-economic data was taken from national datasets and gridded by the water use sub-models as described in aus der Beek et al. (2010) for irrigation, Flörke et al. (2012, 2013) for domestic and industry, and Alcamo et al. (2003) for livestock. Water Quality validation data for Mongolia was taken from Altansukh (2008) as it is the only source with continuous long-term time series for BOD and TDS in Mongolia for the baseline period. At this, input data assumptions were derived from global or national datasets, e.g., Joint Monitoring Programme (WHO/UNICEF (JMP 2013)), in terms of connection rates and treatment level or derived within an extensive literature recherché, e.g., effluent concentration, event mean concentration (urban surface runoff) or livestock excreta.

1.3. Results and Discussion

Four research studies and modelling experiments have been conducted to analyse and quantify impacts of global change on water quantity and quality in Central Asia with a focus on Mongolia. The first study (see Publication 1, Chapter 2) includes the evaluation of global and regional climate datasets, which are available for Central Asia. The second study (see Publication 2, Chapter 3) focuses on impacts of climate change on Central Asian water resources, whereas the third study (see Publication 3, Chapter 4) focuses on the impacts of socio-economic changes on water resources in Mongolia. Both (Publication 2 and 3) studies are combined with water stress indicators to highlight potentially impacted basins. The fourth study (see Publication 4, Chapter 5) deals with the impacts of changes implied in study 2 and 3 on water quality in the Selenge river basin in Mongolia.

1.3.1 Suitability of large-scale datasets for regional hydrological modelling in Central Asia

Focus of this study was the comparison of global and regional datasets to estimate the uncertainties in simulated water resources. The quality of hydrological model results strongly depends on input data (Ludwig et al. 2009, Kauffeldt et al. 2013). Particularly precipitation is a very sensitive parameter. Hence, the study focuses on the uncertainty of simulated runoff induced by precipitation input data. The study compares simulated and observed runoff at 142 gauging stations in Central Asia. Four different regional and global datasets have been applied. The CRU TS 3.2 dataset (Harris et al. 2014), the full data reanalysis of the Global Precipitation Climatology Centre (GPCC) in version 6 (Schneider et al. 2011), the WATCH forcing data (Weedon et al. 2010, 2011) and the Aphrodite’s water resources precipitation data (Yatagai et al. 2009, 2012). All datasets have been rescaled to the WaterGAP 3 resolution and applied for the baseline time period 1971-2000. The datasets show already big differences in the input data, particularly in the maximum precipitation per grid cell (822 mm to 1415 mm), and therefore also in the mean precipitation. Especially in the southern part of the study region (Tien-Shan, Pamir, and

Taklamakan desert), spatial patterns differ between the datasets. Nevertheless, the interannual behaviour shows a good accordance, but varies in the amount of precipitation.

As an indicator to examine the effects of low water availability and anthropogenic water abstractions, the withdrawal-to-availability ratio was applied to point out water stress at the basin level (Alcamo et al. 2007). Spatial distribution of water stress shows a high accordance between the datasets with a focus on south and south-western parts of the study region (Tarim River, Amu and Syr Darya). The magnitude of water stress between the datasets differs clearly and the robustness and goodness at each of the 142 gauging stations is evaluated. Overall, GPCC shows the best results on the whole study region, while WFD lead to more extreme values in the results and therefore to a higher standard deviation. Nevertheless, all datasets feature stations with lower or higher Nash-Sutcliffe-Efficiency (NSE, Nash and Sutcliffe 1970) compared to other datasets. For example, stations in northern part of Mongolia could only be modelled accurately with WFD or Aphrodite but not with the GPCC or CRU dataset. The station at Ulgii in Mongolia differs by twice as much precipitation induced by the CRU dataset and leads to inadequate overestimation of simulated runoff compared to the other datasets. This is in line with a study conducted by Fekete et al. (2003) in which they compared six precipitation datasets in their latitudinal profile and showed large (up to 100 %) differences in the datasets for arid regions, while the datasets are more consistent in wetter regions. This leads to the need for the improvement and more numerous precipitation sampling, particularly in dry regions.

In addition to the fact that only few runoff stations are available compared to the size of the study area, stations are also concentrated in the northern part of the study region while large regions are not represented by any station.

Furthermore, the study showed that WaterGAP 3 is capable to represent water resources in Central Asia realistically, but shortcomings could be identified as well. Unreported overexploitation of water resources can sometimes lead to an overestimation in simulated water availability though water use is considered in the model. This is due to a lack of information in the input data (e.g. industries or thermal power plants) and the disregard of land use change in this study. Global and regional datasets should be backed up by regional socio-economic data as studying water-human interactions becomes a rising issue.

1.3.2 Climate Change impacts on water availability in Central Asia

Large parts of Central Asia are dominated by low precipitation and consequently low water availability and are therefore vulnerable to climate change. Objective of this study is to simulate impacts of climate change on water resources and to point out regions, which are potentially most impacted by climate changes. At this, transient climate scenarios from three different GCMs are applied to simulate current and future water availability (1961-2100), based on daily internal time steps and a spatial resolution of five arc minutes (~ 6x9 km). At this, climate change is analysed solely and water use is not included in this study. Overall, more than 167,000 grid cells and 1,536 basins were included in this study taking into account spatially distributed information, e.g. slope, elevation, and land cover. The stream network is defined by a drainage direction map indicating the drainage direction of surface water (Lehner et al. 2008). To calculate baseline water resources, the WATCH forcing data was applied to the model region. For the scenario period, the WATCH driving data was applied for two IPCC-SRES scenarios A2 and B1 and three GCMs: CNRM-CM3 (Salas-Mélia et al. 2005), IPSL-CM4 (Marti et al. 2010), and ECHAM5 (Roeckner et al. 2003). The WATCH driving data provides transient bias-corrected scenarios on daily time steps. The data has been rescaled from 0.5° to five arc minutes and was validated against data from the Global Runoff Data Centre (GRDC). Not all stations covered the complete baseline time period 1971-2000, but were validated against the available time period. The results show low water availability especially in the wide arid regions with annual water availability below 10 mm. In contrast the mountainous areas show annual water availability up to more than 1200 mm. Simulation results show an increase of mean annual water availability to the end of the 21st century. At this, the differences between the GCMs are higher compared to the differences in the scenarios A2 and B1. For the baseline period only a small change from 64 mm to 63 mm between the time period 1961-1990 and 1971-2000 was detected. Although the WATCH driving data is bias-corrected, an offset between the WATCH forcing data for the baseline period and the scenario period exists. The IPSL-CM4 and CNRM-CM3 GCMs show a more or less constant increase of simulated water availability till 2100, while ECHAM5 shows a decrease by the middle of the century followed by an increase until 2100. Looking at spatial patterns, the Ob River basin and the Altai Mountains show high water availability in all GCM-scenario combinations, while the western part in the Aral-Caspian depression shows a decrease of simulated water availability. The trends are particularly robust in the south of the study region (Chinese Xinjiang), in the Mongolian Altai, the north of Mongolia, and at the Aral-Caspian depression. Inter-annual variations show an increase of simulated water availability in all GCM-scenario combinations during spring (March-April) and for some GCM-scenario combinations also in July.

1.3.3 Socio-economic development in a water scarce region and its impact on water resources

Socio-economic development in Mongolia may impact water resources and vice versa. Therefore, water abstractions and their potential change are of high importance. At this, socio-economic scenarios for Mongolia were developed to analyse the impacts of anthropogenic water use on water resources. Given the low natural water availability, special attention was paid to overexploitation of river basins and therefore, different water stress indicators were applied. Scenarios are based on development of socio-economic indicators like population and gross domestic product as well as technological change. Current water use in Mongolia is dominated by mining followed by livestock, domestic, and irrigation (Batsukh et al. 2008). Domestic water use differs completely between rural and urban areas. At this, rural areas use 5-10 l per person per day, while the daily water use in housing areas is around 230 l per person per day. This is often induced by high losses caused by old and broken water supply pipes (Batsukh et al. 2008, Scharaw and Westerhoff 2011). In terms of land cover, Mongolia is dominated by agricultural land with pasture as dominating land use type. Arable land accounts for less than 1 % of the total area, but mostly occurs in the Selenga Aimag. Here, cropland is mostly used for wheat, barley and oat production whereas irrigation is dominated by sprinkler technique (75 %). The WATCH forcing and driving data was applied to simulate water resources from 1971 to 2100 transiently. Two socio-economic scenarios were developed to quantify the effects of anthropogenic activities on water resources following the IPCC-SRES climate change scenarios A2 (economic growth) and B1 (sustainable development). At this, population density, household size, population growth, GDP per capita, and GVA (gross value added) are main drivers to quantify the potential abstractions of mining, manufacturing, electricity production, irrigation, and livestock sectors. Finally, two water stress indicators were applied to examine the current and future pressures on water resources as they include the long term effects of water use on water stress; the withdrawals-to-availability (w.t.a.) ratio and the consumption-to-Q90 ratio (c.t.Q90). At this, water withdrawal is defined as "the volume of water abstracted from either a surface water or groundwater source", while water consumption is "the share of water withdrawal that is evaporated, transpired, incorporated into products or crops, or consumed by humans (Flörke et al. 2013)." Q90 means "the monthly river discharge that occurs under dry conditions (monthly discharge is higher in 90 % of the time than the Q90-value (Alcamo et al. 2007)."

The first indicator focuses on the abstracted water in a river basin compared to the total available water and the second indicator focuses on long-term low-flow conditions (Alcamo et al. 2007). As Mongolia is a data scarce region (cf. Karthe et al. 2015), only 13 gauging stations were available to validate the model results. Looking at mean annual water balance, the model show very good results (NSE 0.96) while low flows are mostly overestimated (NSE 0.66). Sectoral water abstractions show a huge increase in manufacturing, domestic, and mining sector; in particular for the A2 scenario. Irrigation shows a slight increase, while thermal electricity production decreases rapidly. This is caused by an implied change from once-through to tower cooling, which lead to a huge reduction of water withdrawals. In total, water withdrawals increase in the economic growth scenario about 63 % and in the sustainable development scenario 9 % till 2100. While w.t.a. focuses on water abstractions and shows the highest ratio in the Tuul and Orkhon river basin, the c.t.Q90 is more sensitive to low flows and shows therefore higher ratios in the southern parts of Mongolia with low water availability. Looking at future changes of w.t.a., an increasing trend was found for both IPCC-SRES scenarios in the Tuul river basin and for the business-as-usual scenario (A2) in the Orkhon river basin. The southern region mostly feature low water consumption, but are highly vulnerable to increasing water consumption, e.g., for industrial purposes.

1.3.4 Water quality alterations in Mongolia induced by global change

The above mentioned studies focussed on water quantity and showed that the large-scale water resources model WaterGAP 3 is able to represent water fluxes in Central Asia in a realistic way. Based on these scenarios, water quality alterations by conservative (total dissolved solids) and non-conservative (biological oxygen demand and faecal coliform bacteria) substances are examined. For this purpose, a large-scale approach was applied to model comprehensive and spatially explicit water quality patterns in the Selenge river basin to get an insight in current and potential future water quality. Time series data for BOD and TDS in the Tuul River at Ulaanbaatar with monthly data covering the period (1996-2000) was used for model validation. At this, summer in-stream concentrations could be reproduced well by the model, while concentration levels during winter were overestimated. Simulation results show a strong increase in BOD, FC, and TDS loadings in the scenario period 2071-2100, while the differences between the representative dry, wet, and average scenario conditions are quite low. Main contributing sectors are generally the domestic and industry sectors. Particularly, FC is dominated by loadings from domestic–sewered and domestic-non sewered. Urban surface runoff and livestock play a minor role in sectoral contribution to total loadings. TDS is dominated by industrial activities like manufacturing and mining as they are already major water users and are expected to increase in the future. Hotspots, especially for the non-conservative substances, are found around bigger settlements like in the Tuul river basin at Ulaanbaatar. In the scenario period loadings are concentrated around the urbanized areas of Ulaanbaatar, Darkhan, Sukhbaatar, and Erdenet. High concentrations of TDS are found mainly in the Orkhon river basin, Kharaa river basin and around Ulaanbaatar, which is the main region of irrigation and mining in Mongolia. BOD concentrations are highest downstream of Erdenet and Ulaanbaatar but also in the Kharaa river basin. FC is more spread across the basins but river stretches with higher concentration are located downstream of Ulaanbaatar and Darkhan. TDS concentrations exceed the guideline limit in the Tuul River. Furthermore, other research studies showed high pollution loadings for heavy metals, nutrients or sediment loads (e.g. Batsukh et al. 2008, Hofmann et al. 2011, Nadmitov et al. 2015) or FC concentrations at Naushki settlement in 2010 (227 to 6600 cfu/100 ml, Sorokovikova et al. 2013), which is far above the guidelines for bathing and drinking water. FC concentrations are mainly driven by the domestic sector, but connection and treatment rates are on a low level in Mongolia and wastewater treatment plants (~67 %) are often malfunctioning or in a poor condition. Nevertheless, only little information is available in the literature about FC in Mongolia. Considering the simulation results FC should be measured and monitored more extensive as it poses a risk to human health. Generally, urban areas are initial loading hotspots and pollution prevention becomes important, to reduce initial pollution discharged into surface waters.

1.4 Conclusion

Within this thesis the WaterGAP 3 modelling framework has been adapted, improved, and validated in order to model water quantity (in terms of water availability and water use) and water quality in Central Asia. The model was tested against observed data. The model approach has been applied to analyse and assess large-scale hydrological and water quality patterns. Climate change and socio-economic impacts on Central Asia's water resources have been investigated and the WorldQual model has been applied to Mongolia to calculate, for the first time, in a comprehensive manner loadings and in-stream concentrations. The major findings of this thesis can be summarized as follows:

- The WaterGAP 3 hydrology model was successfully applied and validated for Central Asia. Available global and regional datasets differ significantly in parts of the region and, consequently, introduce large uncertainties to hydrological modelling results. The improvement and adaptation of WaterGAP 3 to reflect regional characteristics has led to a better reproduction of observed runoff.

- Climate projections following different emission pathways show a high temperature increase throughout the region for the entire 21st century. Although changing precipitation patterns differ regionally, precipitation is expected to generally slightly-moderate increase until the end of the 21st century.

- Simulated water availability as calculated on the basis of daily time series of various bias-corrected climate data sets shows large spatial variability with an overall increasing mean annual water availability until the end of the 21st century.

- A trend of increasing water use as a result of socio-economic development has strong impacts on water availability, particularly the industrial and domestic sector. Urbanization likely lead to higher water withdrawals as a result of leakages in the public water supply system and higher consumption of drinking water compared to nomadic lifestyle.

- Water stress indicators, though initially on a lower level, are expected to increase in Mongolia, in particular in the Tuul, Orkhon, and Kharaa River basins.

- The first comprehensive water quality study was carried out for the Selenga river basin in Mongolia. Here, the newly developed water quality model WorldQual, which was applied and validated for Selenga river basin, was used to identify hotspots of conservative (TDS) and non-conservative substances (BOD, FC). Loadings of TDS, BOD, and FC were found to increase strongly during the scenario period. Hotspots of water quality deterioration became obvious mainly in the Kharaa, Tuul and Orkhon river basins.

- Despite uncertainties in climatic forcing datasets from different underlying GCMs, the major uncertainty for water quality modelling results from a lack of information on the condition and operability of sewage systems and treatment levels as well as observed water quality data for model calibration and validation (ground truthing).

- Overall, it is concluded that the further improved WaterGAP 3 modelling framework has the ability to reproduce past and current water fluxes as well as the potential to project water availability and water use across Central Asia. Moreover, the model skill in simulating water quality patterns of pollution loadings and in-stream concentrations was tested and improved in Mongolia. However, these skills ensure an improved evaluation of global change impacts.

1.5 Outlook

The state-of-the-art integrated modelling framework WaterGAP 3, consisting of hydrology, water use and water quality models, has been successfully applied, tested and validated to reproduce the state of water resources in terms of water quantity and water quality in Central Asia. First encouraging water quality results show the possibility and need of comprehensive modelling studies, particularly in data scarce regions like Mongolia.

This thesis has shown that socio-economic development is a main driver of change in Mongolia and therefore anthropogenic overexploitation of river basins might be a key issue in the future. In this context spatially explicit information on the location of water abstraction points and industrial activities would improve the model results. Currently, global or national datasets are used as input and are allocated over the study region according to generic rules.

Nevertheless, the assessment of water quality in Mongolia shows a need for monitoring and field campaigns to generate continuous long-term time series data for improving the model (calibration and validation) and to assess current and future state of water resources. Furthermore, the model requires several assumptions as input data, e.g., per capita emission factors are not available for Mongolia. Information on such parameters would greatly help to improve and verify the model results. At this, better data would be needed also to provide an enhanced picture of the state of water resources, to estimate impacts on water resources, aquatic ecosystems and human health, and to develop strategies and solutions to adapt to global change impacts.

Moreover, better data would provide the basis to implement an integrated water resources management (IWRM) in the region and to achieve the targets set by the sustainable development goals. For this purpose an assessment of current situation is required to "ensure availability and sustainable management of water and sanitation for all (UN 2015)."

In addition, several major water infrastructure projects are planned in Mongolia like a channel from the Orkhon River to the Gobi desert or the Shuren Hydropower project. Studies on the effects of these large projects on water availability and water quality should be performed as these interventions will definitely severely change the catchment hydrology. At this, also transboundary cooperation is needed as the Selenga flows into Lake Baikal in Russia and people as well as ecosystems are affected in both countries.

Furthermore, pipe leakages and malfunctioning of wastewater treatment plants are widely reported. Thus, a study should be carried out to analyse population growth and urbanization on wastewater generation as well as the impacts of connection rates and treatment levels on water quality. In a next step a “wastewater scenario study” should then be executed, because increasing connection rates without any improvement in treatment can be expected to even worsen water quality. Hence, local data would help to verify and potentially improve the model results.

However, as consistent and reliable environmental data is not available for large parts of the study region (Karthe et al. 2015), the presented model results include uncertainties in regard to input data, and therefore estimated impacts like pollution loadings and in-stream concentrations. Nevertheless, this study is the first comprehensive water quality modelling study in this region identifying potential hotspots of water quality deterioration and shows the need of a consistent monitoring programme in Mongolia to get further insight on water quality.

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Chapter 2

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2. Evaluation of large-scale precipitation data sets for water resources modelling in Central Asia

2.1. Abstract

Central Asia features an extreme continental climate with mostly arid to semi-arid conditions. Due to low precipitation and therefore low water availability, water is a scarce resource and often the limiting factor for socio-economic development. The aim of this model study was to compare the uncertainties of hydrological modelling induced by global and regional climate data sets and to calculate the impacts on estimates of renewable water resources. Within this integrated model study the hydrological and water use model Water Global Assessment and Prognosis 3 (WaterGAP 3) is being applied to all river basins located in Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, and Mongolia in five arc minutes spatial resolution (~6x9 km/grid cell). The model was driven by different global and regional climate data sets to estimate their impact on modelled water resources in Central Asia. In detail, these are the global TS data set of the Climate Research Unit (CRU), the WATCH forcing data (WFD) developed within the EU–FP6 Project ‘‘WATer and global Change’’, the Global Precipitation Climatology Centre (GPCC) Reanalysis product v6, and the regional Aphrodite’s Water Resources data set (Aphrodite). The performance of the model is then being evaluated by comparing modelled and observed river discharge for the time period 1971–2000. Finally, the uncertainties in modelled water availability induced by the different data sets are quantified to point out the consequences for water management. Over the entire region, mean and maximum annual precipitations given by the various data sets differ by 13 % and up to 42 %, respectively. In addition, considerable deviation of temporal dynamics is found in some locations, where a pair wise comparison showed poor agreement between CRU and GPCC/WFD (Nash–Sutcliffe efficiency 0.27/0.23). Thus, also modelled discharge shows high temporal and spatial variations which leads to differences in median model efficiency of 0.11 between the data sets.

2.2. Introduction

During the last decade sustainable water management has emerged as a widely recognised method to solve water related problems (MoMo-Consortium 2009). Previously, environmental problems have often been solved with technical solutions such as dams, reservoirs, and dikes solely (MEA 2005), whereas Integrated Water Resources Management (IWRM) concepts are now being considered the more sustainable pathway for managing Central Asian water resources (e.g. Wouters et al. 2004; Dukhovny and Sokolov 2009; MoMo-Consortium 2009). Especially, in regions where high pressures on water resources persist, it becomes more important to set up an integrated and sustainable water resources management system (Jakeman et al. 2006). This enables not only a holistic assessment of current available water resources but also, even more important, an analysis of anthropogenic water abstractions, which often are the reasons for water scarcity (e.g. Alcamo and Henrichs 2002; Alcamo et al. 2007; Aus der Beek et al. 2011; Malsy et al. 2013). Furthermore, cultural adaptation and governance policy are important issues to develop a concept for sustainable water use (MEA 2005; Pahl-Wostl et al. 2008). Central Asia features an extreme continental climate with mostly arid to semi-arid conditions and high interannual variability. In detail, due to low precipitation and therefore low water availability, water is a scarce resource and often a limiting factor for socio-economic development. For example, the ‘‘Dzud’’ events in Mongolia mark unusual extreme cold–dry weather conditions which result in livestock death over wide regions (IPCC 2012). According to Unger-Shayesteh et al. (2013) in the most studies performed since the 1970s a warming trend in air temperature was detected, but with a disagreement in terms of seasonal changes. Furthermore, the glacierized area in Tian Shan and Pamir Mountains decreased, which applies as well for the trend in snow depth and snow cover duration. At this, changes in runoff show no clear trend. The collapse of the Soviet Union caused a depression during the 1990s and a change to market economy. During the last decade, Gross Domestic Product (GDP) increased in all Central Asian countries, in particular in Kazakhstan and Turkmenistan. Also in Mongolia GDP per capita doubled between 2009 and 2011 (The World Bank 2013). Agriculture still plays a dominant economic role as it generated 27 % of Tajikistan’s, 19 % of Uzbekistan’s and Kyrgyzstan’s, 17 % of Mongolia’s, and 15 % of

Turkmenistan's GDP in 2012. Only in Kazakhstan it is less important with 6 % of the GDP in 2011 (The World Bank 2013). Irrigated area tripled throughout the 20th Century (Sattarov et al. 2006) and groundwater resources are increasingly used for irrigation and livestock purposes (Rakhmatullaev et al. 2010). Especially in Mongolia, Russia, and China up to 36 % of groundwater resources are used for irrigation, while in Kazakhstan, Uzbekistan, Tajikistan, Kyrgyzstan, and Turkmenistan it is currently below 10 % (Siebert et al. 2010). In the Amu Darya river basin, farmers started to use groundwater resources for irrigation at the end of the 1990s, as surface waters were often polluted by salts and pesticides. Due to pollution of surface water, sustainable water management is becoming more important (Rakhmatullaev et al. 2010). In this study, the hydrological conditions in Central Asia are being assessed using the large-scale hydrology model WaterGAP 3, which provides a geographically explicit overview of Central Asian water resources. However, it needs to be noticed that the quality of hydrologic model results strongly depends on the quality of the input data driving the model (Ludwig et al. 2009; Kauffeldt et al. 2013). Here, especially climate as well as river runoff data have proven to be very sensitive input parameters. Therefore, the aim of this model study is to compare the uncertainties of hydrological modelling induced by global and regional climate data sets and to calculate the impacts on estimates of local water resources. As precipitation is the most important driver of hydrological cycle (Yu et al. 2003), this study focuses on the uncertainties of modelled water fluxes induced by different precipitation data sets. Modelled water fluxes, i.e., river runoff, are being compared to observed data in order to evaluate the performance of WaterGAP 3, which also enables to assess the reliability and robustness of the model results in the real world.

2.3. Data and Methods

2.3.1. Study Region

This study focuses on Central Asia whereas this region is not defined by political borders but through the extent of river basins. Therefore, the term Central Asia contains the countries Kazakhstan, Kyrgyzstan, Mongolia, Tajikistan, Turkmenistan, and Uzbekistan entirely as well as parts of Russia and China (cf. Cowan 2007) (see Figure 4). The largest water bodies in the study region are the rivers Ob with its tributaries Irtysh and Tobol, as well as Ural, Amu Darya, Syr Darya, Tarim and the lakes Balkhash, Issyk Kul, and Aral Sea. Elevation ranges from -152 m in the Turpan Depression up to 7,500 m in the Pamir and Tian Shan Mountains, whereby downstream arid lowlands are highly reliant on water provision from the mountainous regions (Hagg et al. 2007). The extreme continental climate is mainly arid to semi-arid with a wide temperature amplitude (up to +40 °C in summer and –40 °C in winter) (Worden and Savada 1991; Curtis 1997; Kottek et al. 2006; for a more detailed description of the study region see Malsy et al. 2012). Mountainous regions play a major role for runoff generation in Central Asia and the majority of hydrographs are mainly shaped by meltwater components (Savoskul and Smakhtin 2013). The meltwater component of runoff generation is very important for rivers flowing into arid areas or into warm and dry climate conditions (at least seasonal). For instance, 79 % of the precipitation in the Aral Sea basin runs off as delayed meltwater with decreasing importance from higher to lower altitudes (Kaser et al. 2010). In the Amu and Syr Darya Basin, hydrographs at upstream stations like Zerafshan, Vaksh, or Naryn feature a more or less equal contribution of seasonal snow melt, glacier melt, and groundwater to runoff generation. The area covered by glaciers and snow as well as the meltwater component of river discharge decreased in the Amu and Syr Darya basin comparing 1961–1990 to 2001–2010. In particular snow melt decreased in the Syr Darya river basin, but still ''meltwater plays a dominating role in the hydrological regime of Amu and Syr Darya'' (Savoskul and Smakhtin 2013). For the Alay mountain range, which is located between Pamir and Tian Shan Mountains, snow melt decreases from West to East. Hagg et al. (2013) found a decreasing glacier area for Tian Shan, and Konovalov (2007) reports a slight decrease in glacier runoff for the Zerafshan river basin, which originates in the Pamir Mountains. Streamflow variations of the Aksu River, which drains the Tian Shan Mountains, show stronger dependency on precipitation in its less glacierized subcatchment compared to its more glacierized sub-catchment (Kundzewicz et al. 2014). According to Kriegel et al. (2013), a prolongation of the melting season causes increasing discharge during early spring and winter, though absolute discharge in winter is low. Although population density is in general low, especially in Mongolia (1.8 pop/km^2) and Kazakhstan (5.7 pop/km^2), some regions, such as the Aral Sea basin, feature high population densities and/or high pressures on scarce water resources, which is heavily influenced by human activities altering hydrological fluxes in large areal extents (Aus der Beek et al. 2011). Furthermore, basins surrounding the capitals are often widely overused, due to urbanisation; therefore, water abstractions for domestic and industry purposes are high. Generally, water abstractions for agricultural, domestic, and industrial purposes play a major role, as water use increased, e.g., in Mongolia from 434 M. m^3/year (2005) to 551 M. m^3/year (2008). Also, immense water losses due to leakages are often caused by old and broken water supply pipes (Scharaw and Westerhoff 2011). Due to former Soviet infrastructure planning, transboundary reservoir management is important as new upstream reservoirs are planned (Rakhmatullaev et al. 2013), and inequalities in the access to water reservoirs for irrigation or hydropower between upstream and downstream countries have been a source of conflict (UNEP 2005). In total, data from 158 gauging stations from the Global Runoff Data Centre (GRDC) and the Mongolian Institute of Meteorology, Hydrology and Environment (IMHE) are available for the study region. As some stations feature a short or discontinuous time series, just 142 stations could be applied within this study. The gauging stations show a concentration in the northern parts of the study region in the river basins of Ob, Tobol, Irtysh, Selenga, plus in the Amu and Syr Darya catchments (see Figure 4), while for large areas no observed discharge data is available.

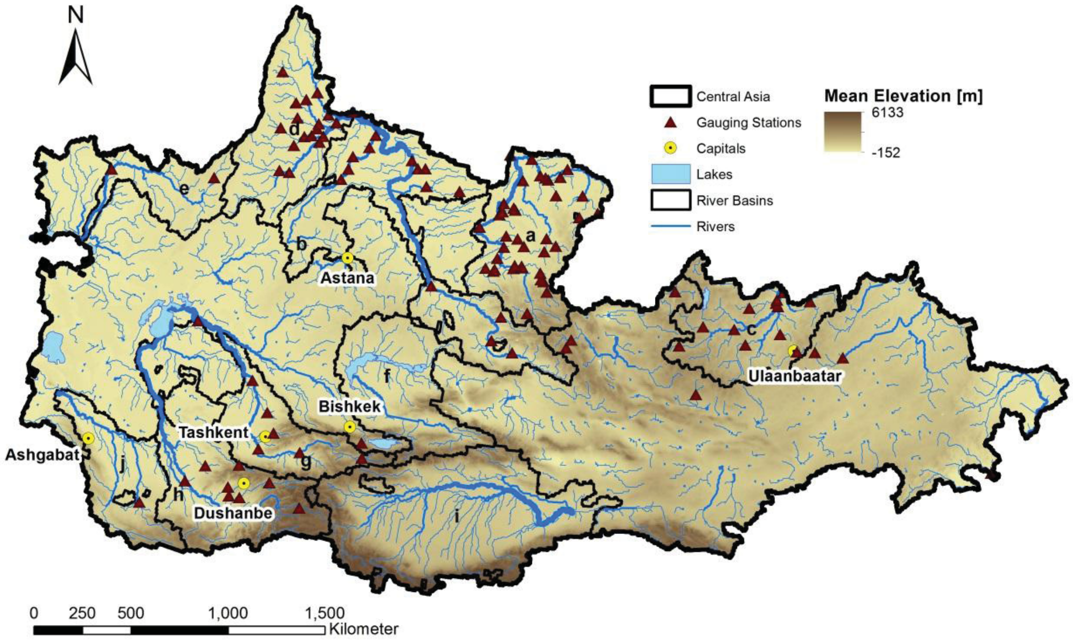

Figure 4: Study region with most important river basins [a Ob, b Irtysh, c Selenga, d Tobol, e Ural, f Ili River (Lake Balkhash), g Syr Darya, h Amu Darya, i Tarim, j Morghab (Karakum Canal)]; river line width depending on river length; mean elevation per grid cell based on SRTM30 data (Farr and Kobrick 2000)

2.3.2. Data and models

The simulations of Central Asian water resources have been conducted with the large-scale hydrology and water use model WaterGAP 3 (Water—Global Assessment and Prognosis) (Verzano 2009, online electronic supplement). WaterGAP 3 is a further development of WaterGAP 2 (Alcamo et al. 2003; Döll et al. 2003) and operates on a five arc minute grid (~6x9 km^2) in daily internal time steps (Verzano 2009). Although WaterGAP 3 can operate on a global scale, an adapted land mask derived from river basins in Central Asian has been applied in this study. The water use model contains five sub models for irrigation, domestic, manufacturing, electricity production, and livestock water uses (Aus der Beek et al. 2010; Flörke et al. 2013). In this study, only irrigation water use differs within each model application, as it is the only climate dependent water use sector. The other water use sectors remain constant. Water abstractions from all sectors are being computed and then fed as time series into the hydrological module of Water- GAP 3 on the same grid scale in order to simulate human impacts on natural river discharge. In addition, WaterGAP 3 needs to be calibrated to each climate data set by taking into account observed runoff data (next to water abstractions). The calibration and validation routine is described in detail by Alcamo et al. 2003. However, as shown in Figure 4, discharge data are scarce in Central Asia and not equally distributed throughout the region. For river basins without gauging stations, calibration parameters are being transferred by regionalisation from neighbouring basins. In total, four different global and regional climate data sets have been applied, which all are based on observed data. In particular, these are the data sets of the Climate Research Unit (CRU) TS 3.2 (Harris et al. 2013), Full Data Reanalysis from the Global Precipitation Climatology Centre (GPCC) in version 6 (Schneider et al. 2011), the forcing data of the WATCH project (WATCH forcing data, WFD) (Piani et al. 2010; Weedon et al. 2011, 2012), as well as the Aphrodite's water resources precipitation data (Yatagai et al. 2009, 2012, see Table 1).

Table 1: Characteristics of the applied climate data sets

Climate Dataset	Spatial resolution	Temporal resolution	Time period
Climate Research Unit TS 3.2 (CRU)	0.5°	Monthly	1901-2011
Global Precipitation Climatology Centre version 6 (GPCC)	0.5°	Monthly	1901-2010
WATCH forcing data (WFD)	0.5°	Daily	1958-2001 (ERA 40) / 1979-2009 (ERA Interim)
Aphrodite´s water resources (Aphrodite)	0.25° / 0.5°	Daily	1951-2007

However, spatial and temporal resolution as well as available time period differs significantly. Thus, all data sets have been rescaled to the five arc minute spatial resolution of WaterGAP 3. The daily values of the WFD and Aphrodite record were aggregated to monthly values, as baseline time period 1971–2000 was chosen. It also needs to be mentioned that the WFD is already bias corrected. Based on the ERA-40 or ERA-Interim reanalysis data, precipitation of WFD is adjusted with data of the Global Precipitation Climatology Centre (Weedon et al. 2011, 2012). As GPCC and Aphrodite only provide precipitation data, air temperature and radiation data were taken from the CRU data set and remain the same for all model runs. The precipitation input and number of rain days were replaced with the data of each climate record (GPCC, WFD, and Aphrodite). In the next step, a separate calibration of the WaterGAP model for each climate data set was processed in order to calculate the climate specific terrestrial water fluxes and irrigation demand of each Central Asian grid cell. Thereafter, WaterGAP was set up for each climate data input to simulate the water fluxes, such as runoff and evapotranspiration, in Central Asia for the time period 1971–2000. These model runs were conducted with and without consideration of anthropogenic water uses to analyse impacts of precipitation input data and human water abstractions solely. As precipitation data of GPCC and Aphrodite records are inserted into the CRU data, the interplay of parameters, e.g., temperature and precipitation, might not match. Finally, modelled river runoff was validated with 142 stations of the GRDC and the IMHE. It needs to be mentioned that stations with a negative Nash– Sutcliffe efficiency (NSE) in all data sets were not examined at all, as these stations are expected to be strongly influenced by anthropogenic activities, as for example flow regulation by dams. Therefore, affected river basins, such as the Amu Darya River basin, need to be modelled with additional input data and expert knowledge (see Aus der Beek et al. 2011). The reassessment of runoff stations resulted in about 102 GRDC stations which could be used to validate the modelled runoff. As mentioned above one problem in the study region is the lack of validation data in dry regions, because of the few numbers of gauging stations and the often short or discontinuous time period of discharge data which is available. The input data of the four climate data sets vary highly in terms of precipitation quantity (cf. Table 2) as well as in spatial distribution (see Figure 5a). GPCC shows a much higher maximum annual precipitation (1,415 mm) compared to the other data sets (CRU 822 mm, Aphrodite 998 mm, and WFD 1,036 mm). In terms of mean annual precipitation Aphrodite is dryer than the other data sets (237 mm) followed by GPCC (260 mm), WFD (271 mm), and CRU (272 mm).

Table 2: Mean annual precipitation input data for baseline time period (mm)

	Aphrodite	CRU	GPCC	WFD
Minimum	30	0	0	7
Mean	237	272	260	271
Maximum	998	822	1415	1036

Concerning minimum values, CRU and GPCC show the lowest values with no precipitation, while WFD features 7 mm, and Aphrodite 30 mm. In terms of spatial distribution the lowest values can be found in the South of the study region at Gobi and Taklamakan deserts. Here, large areas have a mean annual precipitation below 100 mm. The highest mean annual precipitation occurs at Ob river basin and Pamir Mountains. Here, CRU is much dryer than other data sets. On the other hand, CRU is not as dry compared to the other data sets at Tarim basin. In general, GPCC features the highest global station density with 10,700 up to more than 47,000 depending on the year and month (Schneider et al. 2011). Aphrodite consists of 5,000–12,000 stations for Asia (Yatagai et al. 2009), while CRU includes up to 19,000 stations globally (Harris et al. 2013). As WFD is in terms of precipitation derived from GPCC (version 4 and 5) (Weedon et al. 2010, 2012; Rudolf et al. 2011; Schneider et al. 2011), it relies on the same database. For Asia, Aphrodite has the highest station density compared to GPCC and CRU (cf. Yatagai et al. 2012; Harris et al. 2013) and should lead to more precise results.

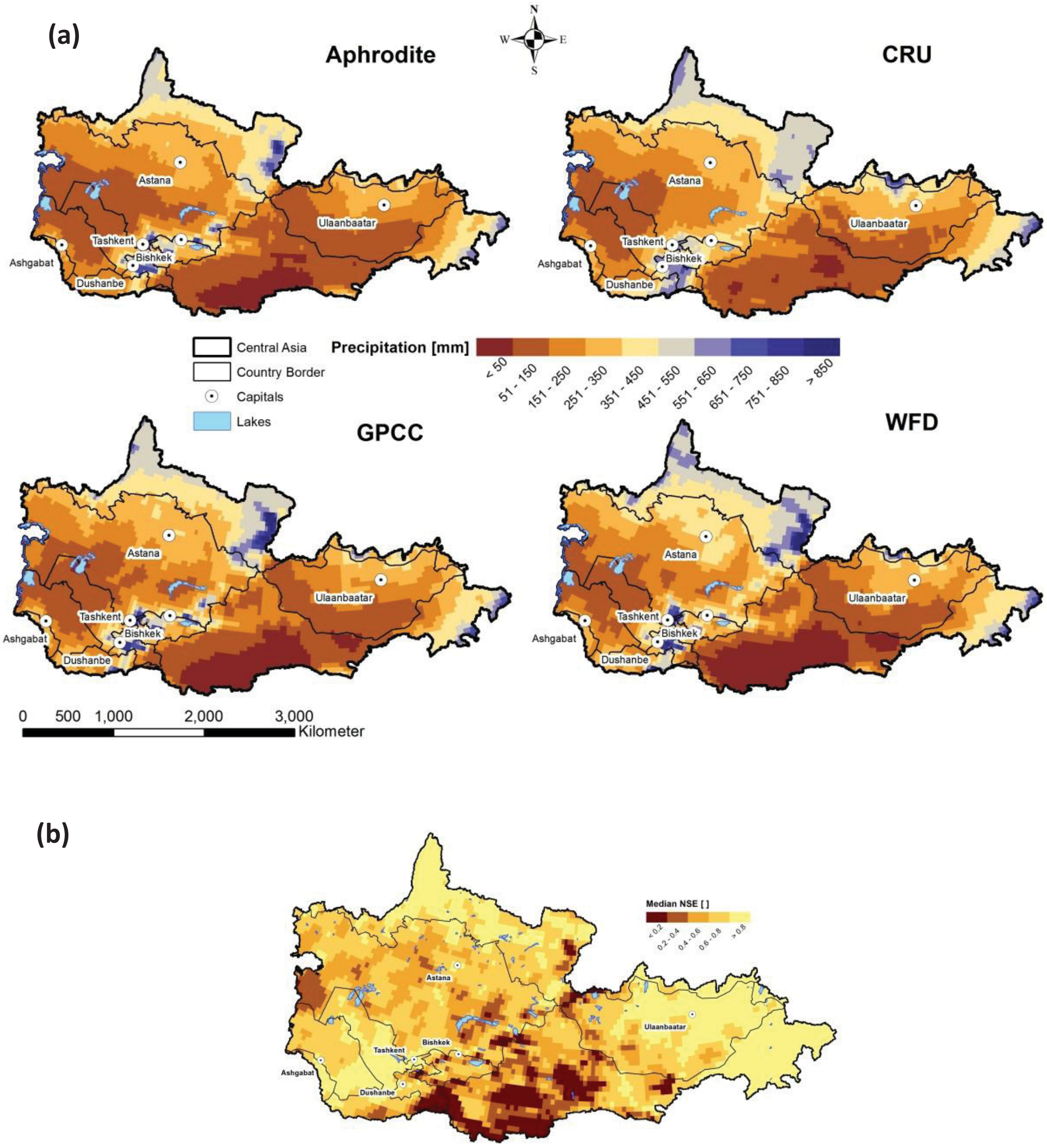

Figure 5: a) Spatial distribution of mean annual precipitation in Central Asia for the time period 1971–2000, b) spatial accordance of precipitation data sets expressed by a median Nash–Sutcliffe Efficiency (NSE) per grid cell for baseline time series

To evaluate the spatial accordance of the four precipitation data sets, all data sets were compared pair wise to each other and the median NSE over all combination was calculated in each grid cell for the baseline time series (see Figure 5b). Hereby, it can be found that the data sets agree very well in northern and eastern Mongolia, in southern Russia (Tobol) as well as in eastern Turkmenistan, and Uzbekistan. The highest deviations are obvious in the Pamir Mountains, Kunlun Shan, and Taklamakan Desert. At this, it is obvious that CRU and

GPCC/WFD show the least accordance and therefore highest deviations. Aphrodite and GPCC show the highest agreement both for mean and median NSE (cf. Table 3). Continuing to seasonal differences in precipitation input (see Figure 6) illustrates the mean monthly precipitation for each data set for the time period 1971–2000. At this, it becomes clear that WFD is considerably wetter during the first half of the hydrological year. In contrast Aphrodite features the lowest precipitation values during summer especially in July. CRU and GPCC show a very similar behaviour throughout the year as well as in terms of monthly values. Hereby, CRU is slightly wetter than GPCC with the highest deviation from March till May.

Table 3: Pair comparison of mean and median NSE for each data set combination and monthly time series (01.1971–12.2000)

	Aphrodite – CRU	Aphrodite – GPCC	Aphrodite – WFD	CRU – GPCC	CRU – WFD	GPCC - WFD
Median NSE	0.71	0.87	0.69	0.69	0.68	0.81
Mean NSE	0.62	0.82	0.61	0.27	0.23	0.71

2.4.Results and Discussion

In the following, simulated water availability results are shown in order to compare the different data sets and to evaluate their impact on modelled water resources in Central Asia. Furthermore, the spatial and temporal distribution is analysed by hydrographs and maps. To validate the modelled results, river discharge has to be compared with observed values of gauging stations. Hereby, the water availability depends on the amount of river discharge. The evaluation of the goodness of the modelled river runoff is performed with different efficiency criteria. In this study, the coefficient of determination (R^2) and the NSE are applied (Nash and Sutcliffe 1970). For both, NSE and R^2, it needs to be mentioned that they are very sensitive to peak flow under- and overestimations; in addition, NSE tends to underestimate low flows and overestimate peak flows. As R^2 only quantifies the dispersion of the values it is not sensitive for systematic over- or underestimation (Krause et al. 2005).

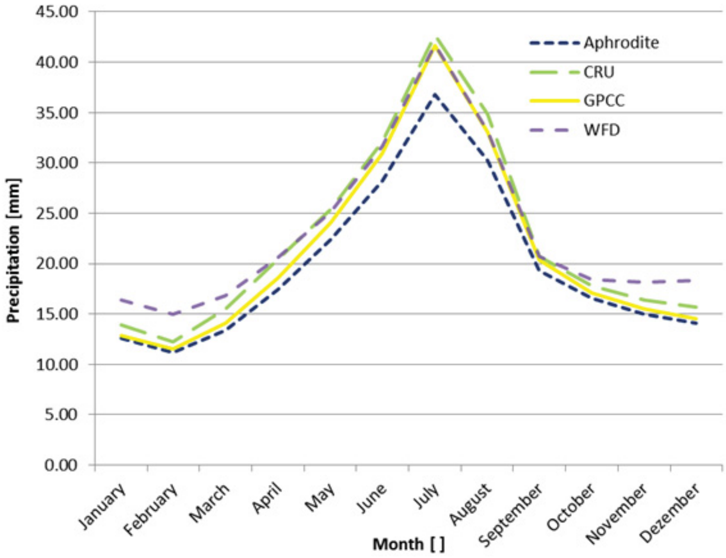

Figure 6: Mean monthly precipitation in Central Asia for the time period 1971-2000

The global and regional data sets differ considerable in amount and spatial distribution of mean annual water availability (see Figure 7). Three sub-regions feature very low water availability; the first one is Southern Mongolia and Northern China which is affected by the Gobi desert. The second one is in the middle and west of Kazakhstan, Uzbekistan and Turkmenistan which contains the Karakum and Kyzyl Kum deserts. The third one is the Taklamakan Desert which is located in north-western China at the border to Tajikistan and Kyrgyzstan. In these regions the mean modelled yearly water availability is <10 mm. In particular, WFD induces a large and very dry area in southeast Mongolia and Inner Mongolia. In contrast to the other data sets, CRU shows high water availability at Tarim catchment, whereas all other data sets tend to very dry conditions. Further on, WFD does not reproduce the very dry part at the Kazakh-Russian border northwest of the capital Astana.

The highest water availability can be found for GPCC (1,336 mm), WFD (1,305 mm), and Aphrodite (1,012 mm) in the Ob River basin, whereas CRU (925 mm) has the maximum in Pamir-Alay Mountains in Tajikistan. In general, the wettest parts can be found in the mountainous regions of Alay, Pamir, Tian Shan, and Altai. For the baseline 1971–2000, mean annual simulated water availability is 64 mm (CRU), 61 mm (GPCC), and 60 mm

(Aphrodite, WFD). In terms of water use, irrigation is the only sector which depends on climate. At this, WFD features highest mean and maximum annual irrigation water withdrawal with 0.84 and 29.46 km^3, respectively (see Table 4), while CRU, GPCC, and Aphrodite are on an equal level at 0.78 and ~27 km^3.

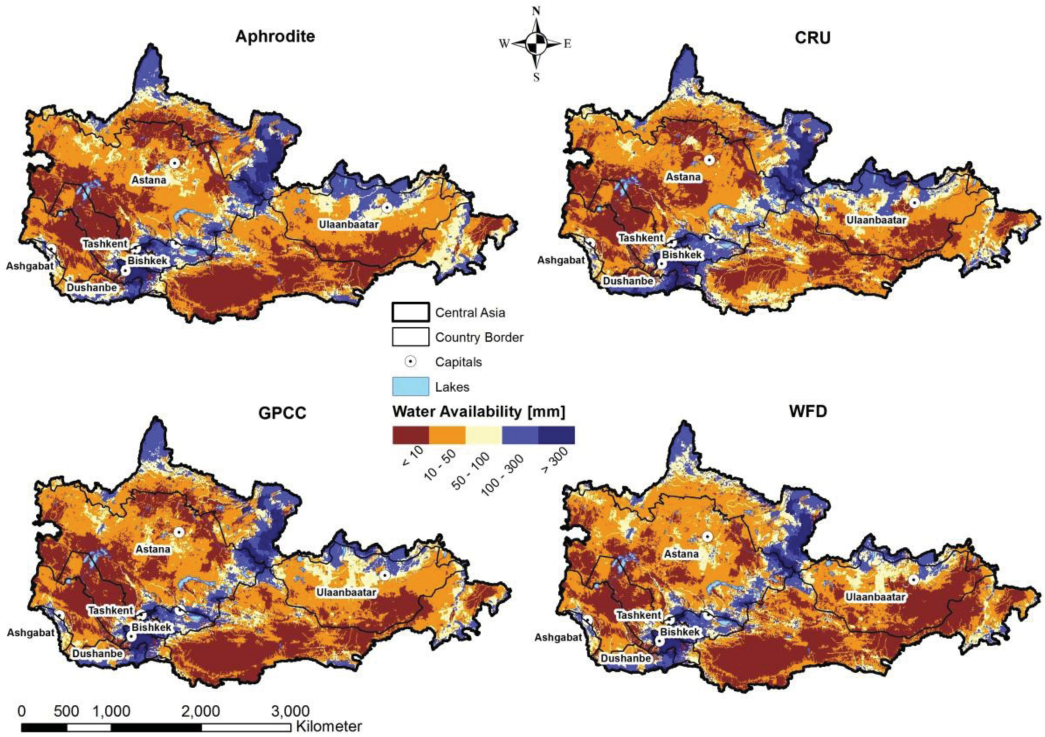

Figure 7: Simulated mean annual water availability (time period 1971–2000)

Compared to other water use sectors irrigation is by far the biggest contributor, as summed water abstractions of other sectors are considerably lower (0.029 km^3 mean, and 5.51 km^3 maximum). Highly influenced by abstractions for irrigation purposes are Syr Darya and Amur Darya river basins as well as Tarim River basin. However, not only high abstractions for irrigation are present in the river basins but also low precipitation and therefore low water availability persist. As indicator to examine these effects the water withdrawal to availability ratio (w.t.a.) is used, which points out the water stress level in river basins (Alcamo et al. 2007). No water stress is assumed, if the ratio is below 0.2, which means that <20% of the available water is withdrawn. The range between 0.2 and 0.4 is defined as medium water stress, whereas over 0.4 severe water stress occurs. In general, the data sets show high agreement concerning spatial distribution of water stress (cf. Figure 8), as all data sets show severe water stress in the southern and south-western study region (e.g. Tarim River, Amu Darya and Syr Darya). Furthermore, Ural River at the Russian- Kazakh border as well as in the very East severe water stress can be found. Medium water stress is present in the centre surrounding Lake Balkash (e.g. Ili River), while in most parts of Mongolia as well as in north and mid-west region no water stress can be found. This might be surprising as Mongolia is well known for its arid to semi-arid climatic conditions. However, due to its sparsely populated area, anthropogenic pressure and thus water stress, is low. Nevertheless, a recently published scenario study (Malsy et al. 2013) shows an increase in water stress for the Tuul river basin, which is the single water source for the rapidly increasing population of the Mongolian capital Ulaanbaatar. Even if the spatial distribution of water stress is similar, absolute values differ clearly, but lead not to changes into a higher w.t.a category (e.g. Tuul River: Aphrodite 0.06, CRU 0.15, GPCC 0.07, and WFD 0.19), or induce with all data sets severe water stress (e.g. Tarim River: Aphrodite 5.4, CRU 0.98, GPCC 4.97, and WFD 9.20). Following the water stress analysis for Central Asia, we evaluated the goodness and robustness of the WaterGAP 3 model results.

Table 4: Mean simulated annual irrigation water withdrawals per basin (1971–2000)

	Aphrodite	CRU	GPCC	WFD
Minimum [km³]	0	0	0	0
Maximum [km³]	27.30	26.97	27.18	29.46
Mean [km³]	0.078	0.078	0.078	0.084

The analysis of the spatial distribution of NSEs shows that various patterns dominate (cf. Figure 9). Firstly, stations agglomerate in the northern part. Secondly, stations in Amu and Syr Darya basin show low NSEs while basins at Ob, Irtysh and Tobol rivers feature generally good NSEs. At this, one exception surrounding Vasyugan Mire in the middle north is obvious. Further on in the east, Mongolia is characterised by low station density and varying NSEs. For large parts especially in arid regions such as southern Mongolia, northwest China, west and middle Kazakhstan, not a single station is available. In addition, various effects concerning the model results have to be mentioned. Some stations in particular in arid regions as well as regions with impounding soil layer could not be modelled accurately, which is on one hand the result of heavy anthropogenic water abstractions and on the other hand of insufficient represented processes in the model, as evaporation is modelled with Priestley-Taylor equation (see Priestley and Taylor 1972), which was used due to lack of input data.

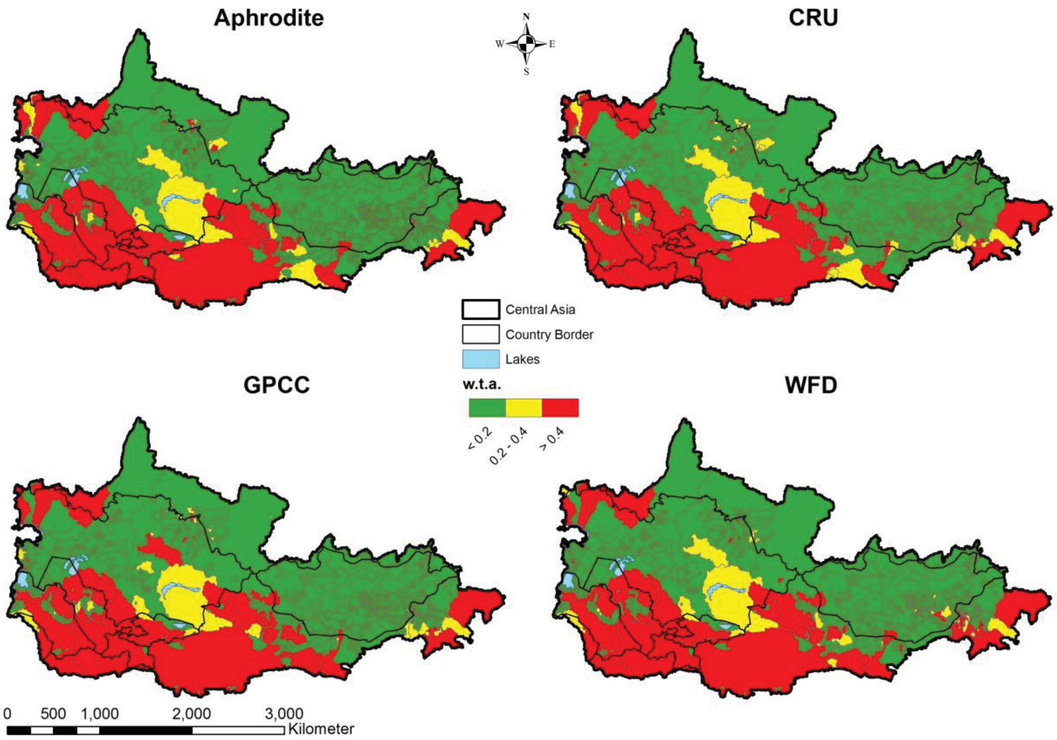

Figure 8: Comparison of water stress (w.t.a.) (Climate period 1971–2000; water use base year 2005)

In terms of anthropogenic influence, the Aral Sea basin with Amu Darya and Syr Darya Rivers has to be mentioned. Huge water abstractions for irrigation in conjunction with large canals lead to a complete modification of the natural hydrological cycle. Here, Aus der Beek et al. (2011) has shown that the performance of WaterGAP 3 can drastically be improved when taking into account local data sets and infrastructure, such as the Karakum Canal, as well as dynamic land use maps. Furthermore, stations influenced by swamp and inundation areas could not be modelled accurately as far as WaterGAP only consists of one soil layer which is derived from soil texture and land cover (Alcamo et al. 2003). At this, soil retention capacity is probably underestimated and leads to simulated discharge ahead of time. Also, interflow processes are not included in the model, which would as well slow down discharge generation. As example in the Vasyugan Mire, between of Irtysh and Ob River, peak discharges are overestimated in the simulation results, which lead to a low NSE. Beside this, at some stations rather large disagreements between the data sets persist, as some stations, e.g., in Mongolia, could only be modelled accurately with WFD or Aphrodite, but not with GPCC or CRU. However, no standard is evident, as all data sets feature stations with high or low NSE compared to the other data sets. Comparing NSE and R^2 (Figure 10, left) the study region was modelled best with GPCC (Median 0.59) followed by Aphrodite (0.56), CRU (0.51) and WFD (0.48). This is probably attributable to the fact of availability and distance to precipitation stations in that region, as precipitation distribution strongly influences runoff generation, and thus NSE. Generally, WFD tends to more extreme results and therefore higher standard deviation.

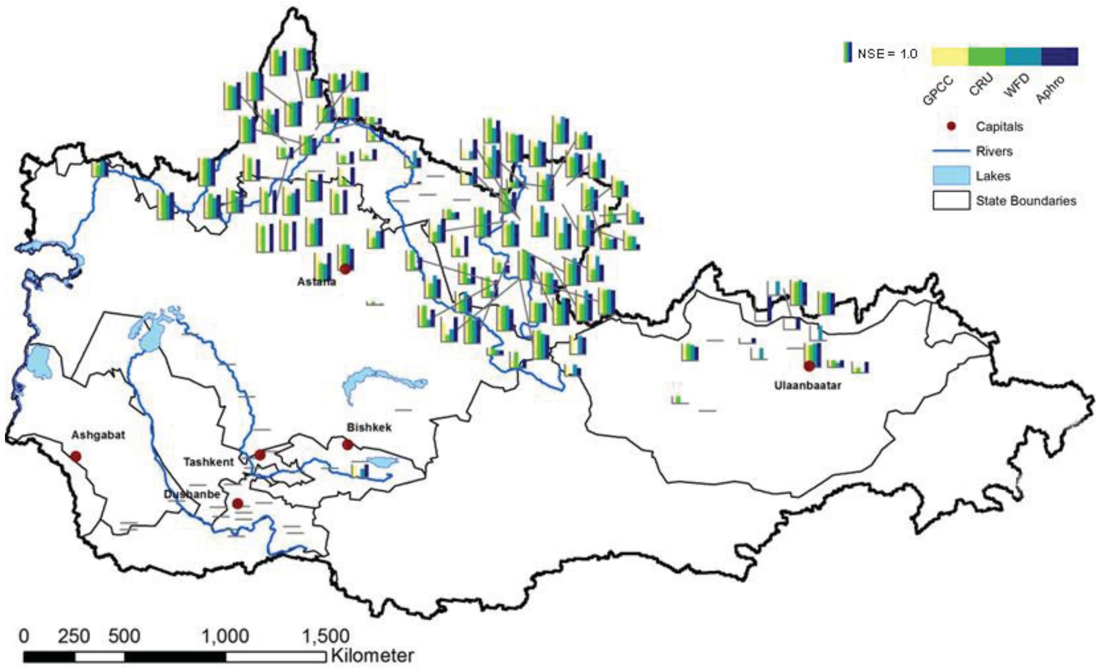

Figure 9: Spatial distribution of NSE efficiency at gauging stations

The NSE box plot also points out this behaviour. Here, GPCC shows more clustered results, while WFD is more scattered. CRU and Aphrodite take a central position in between these two data sets. The reasons for these patterns are unknown as the raw input data for these gridded data sets are not available; also, different interpolation and gridding techniques may have been applied to produce these data sets.

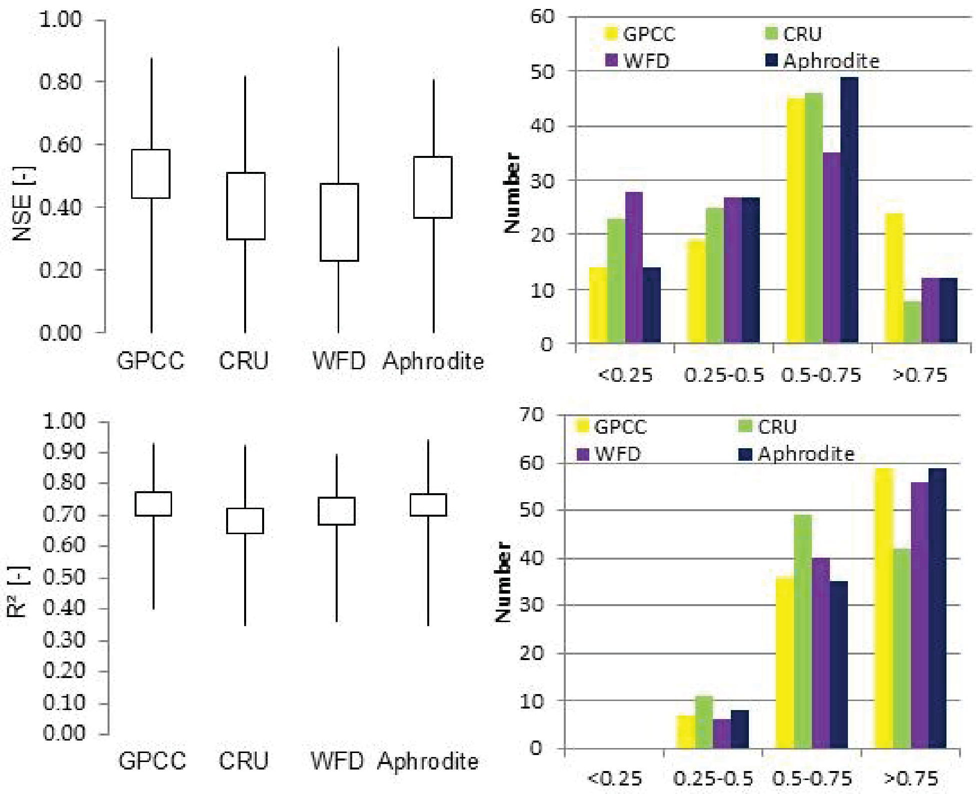

Figure 10: Box plot (left) and histogram (right) of NSE (top) and R^2 (bottom)

The histogram underlines this as WFD shows more stations in the lowest class (NSE<0.25), whereas GPCC has by far the largest amount of stations in the highest class (NSE>0.75). In terms of R^2 the differences between the data sets are lower. Here, Aphrodite and GPCC show a median of 0.77, WFD of 0.76, and 0.72 for CRU. The histogram (Figure 10, right) shows a concentration of all data sets in the middle NSE classes (classes 0.25–0.50 and 0.50–0.75) and in the highest classes for R^2 (classes 0.50–0.75 and >0.75). In the following, two hydrographs are discussed to highlight the differences in simulated results of the four applied climate data sets in Central Asia. These hydrographs were selected because they exemplary show the varieties and similarities which are induced at a station by climate data input. One is located in the Tuul River, a tributary to Selenga River at Ulaanbaatar in Mongolia with a catchment size of 6,900 km^2; the second one is located at Khovd River at Ulgii in western Mongolia with a catchment area of 22,057 km^2 (see Figure 11). For the station at Ulaanbaatar overall agreement between the data sets is very high and all data sets show a considerable good NSE (GPCC 0. 66, CRU 0.61, WFD 0.67, and Aphrodite 0.68).

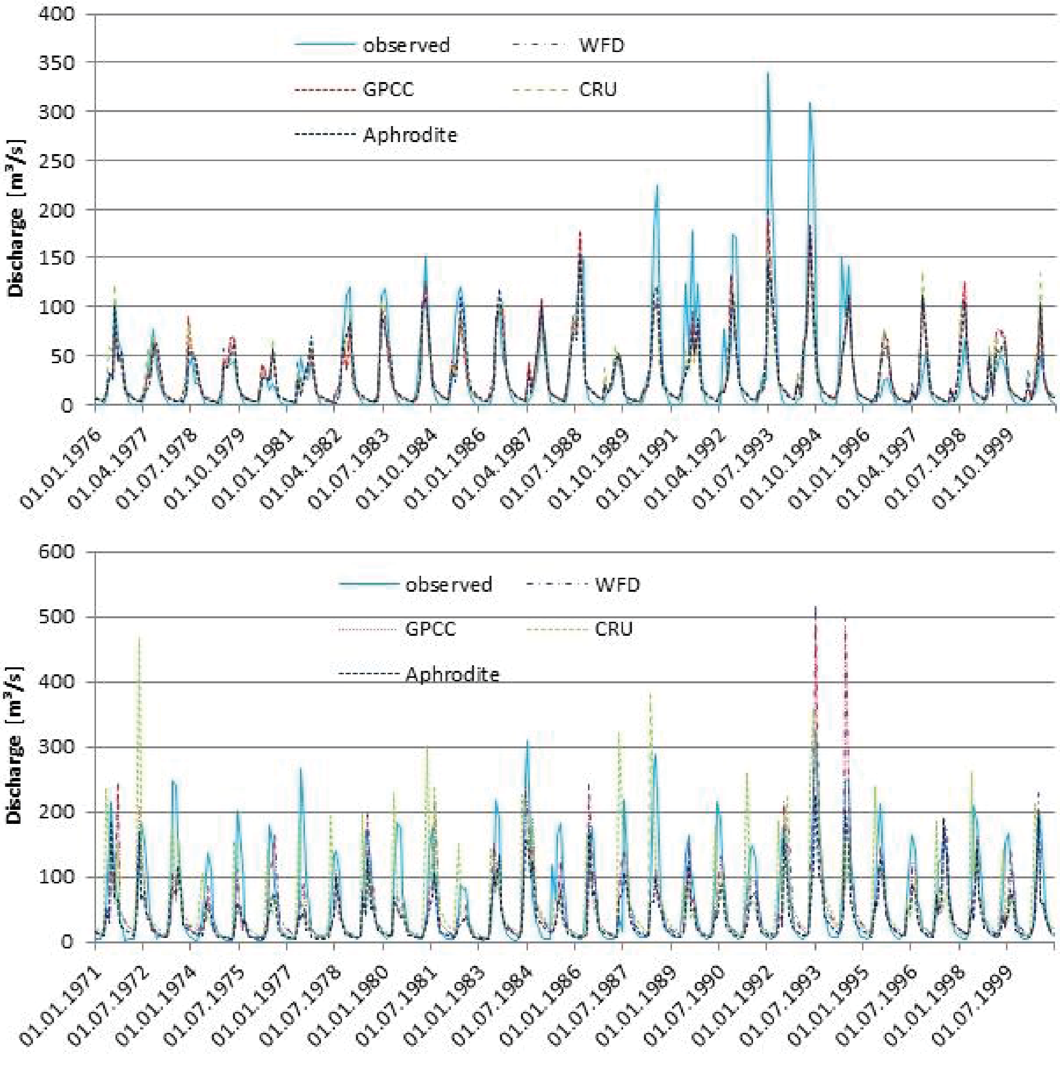

Figure 11: Hydrograph of Station Ulaanbaatar at Tuul River (top) and Station Ulgii at Khovd River (bottom)

The observed discharge features a high increase during the early 1990s, due to increasing precipitation. During mid-late 1990s discharge decreased rapidly, which leads to overestimated runoff peaks with all climate data sets, but matches regarding runoff dynamics and variability. A complete different picture appears when analysing station Ulgii; here, the four data sets lead to large differences in runoff simulation, especially regarding high peaks. CRU tends to overestimate the peaks during the entire time period except for two very high peaks in 1993 and 1994. On opposite, GPCC and WFD overestimate these two peaks, while Aphrodite tends to underestimate them. Furthermore, CRU induces the first peak earlier in spring as the other data sets and the observed data. This is mirrored in the NSE: while Aphrodite (0.47), GPCC (0.52), and WFD (0.52) are on a similar level, CRU features a low NSE of 0.02 at Ulgii. These patterns correspond to precipitation sums and distribution in headwater region (see Table 5).

Table 5: Precipitation input data at headwater of station Ulaanbaatar and Ulgii (time period 1971–2000)

	Aphrodite		CRU		GPCC		WFD	
	Ulaan-baatar	Ulgii	Ulaan-baatar	Ulgii	Ulaan-baatar	Ulgii	Ulaan-baatar	Ulgii
Minimum [mm]	263	92	289	232	279	120	254	117
Maximum [mm]	309	159	362	358	311	168	294	171
Mean [mm]	290	120	330	284	292	132	265	131
Minimum [%/100, compared with CRU]	0.91	0.40	1.00	1.00	0.97	0.52	0.88	0.50
Maximum [%/100, compared with CRU]	0.85	0.44	1.00	1.00	0.86	0.47	0.81	0.48
Mean [%/100, compared with CRU]	0.88	0.42	1.00	1.00	0.89	0.47	0.80	0.46

Comparing the precipitation input data at headwater region of gauging station Ulgii and Ulaanbaatar, huge differences between the data sets at station Ulgii occur. Here, CRU features twice as much precipitation in terms of minimum, mean, and maximum precipitation than the other data sets (cf. Table 5). As in particular WFD and GPCC but also Aphrodite, show similar precipitation, data mismatch of CRU at Ulgii station is apparent. At station Ulaanbaatar, all data sets feature more homogenous input data, which consequently leads to NSE at a similar level. As shown in this study data reliability is a problem in regions with scarce data. Fekete et al. (2003) showed for six precipitation data sets differences in the latitudinal profile for mean annual precipitation. At this, the relative range differences are high in dry regions (up to 100 %) and are more consistent in wet regions. Bosilovich et al. (2008) compared reanalysis data on a global scale among themselves and with satellite data and found huge regional differences. Overall the need for precipitation sampling improvements especially in dry regions is obvious (Fekete et al. 2003).

2.5. Conclusions and Outlook

This hydrological model study for Central Asia focussed on two topics. First, an uncertainty analysis concerning precipitation input data and their effect on water availability and model performance. Here, it could be shown that large regional differences persist between the four data sets, which can have enormous consequences on modelled local water availability, and thus on model performance, too. The GPCC and Aphrodite data sets have shown to generally yield the best hydrological results and can thus be considered as the most suitable data sets for Central Asia.

However, it is unknown if the same results would be reproducible with a different hydrological model (see Schewe et al. 2013; Haddeland et al. 2011). The validation of the goodness of the modelled water availability is difficult, because only a few runoff stations are available compared to the size of the study area. Also, due to the fact that the stations are concentrated in the northern part, some larger regions, such as southern Mongolia, do not contain a single station. Secondly, this study focussed on a first assessment of Central Asian water resources in a geographically explicit manner. The results show large differences between the arid deserts in the South with less than 10 mm water availability per year and humid mountainous regions in the north and middle of Central Asia with more than 300 mm/year. At this, validation and regionalisation are difficult in particular for arid regions as gauging station density is very low. This is not only the case regarding gauging stations but also holds true for meteorological stations which are the basis for climatological data sets. This is reflected in the geographical differences in climate input data as well as in depending model results. Furthermore, catchment size seems not to be an important factor in this study as smaller basins (around 5,000 km^2) were modelled accurately as well. From a scientific point of view, this study has shown that WaterGAP 3 is capable of a realistic representation of Central Asian water resources. However, two shortcomings have been identified. First, overexploitation of regional water resources can sometimes lead to overestimation of water availability even though WaterGAP 3 models include water use from five different sectors and also features a reservoir algorithm for dams. Moreover, ‘‘non-climatic stresses are likely to increase regional vulnerability to climate change and reduce adaptive capacity (Lioubimtseva and Henebry 2009).’’ Therefore, it is according to Lioubimtseva et al. (2005) of high importance for Central Asia to consider land use changes in future modelling experiments, especially for regions with high human impacts. Aus der Beek et al. (2011) has shown for the Aral Sea in a WaterGAP 3 study that regional dynamic data sets, e.g., on land use, need to be included to better represent anthropogenic effects on local water resources, as climate change only accounts for 14 % of the Aral Sea inflow reduction, whereas the remaining 86 % can be assigned to anthropogenic overexploitation of local water resources. This study has also shown that the global data sets are not able to represent local and sub-national water use patterns, and need to be backed up by regional data. Therefore, future studies of water resources in Central Asia should not only include regional climate data sets but also regional socio-economic data input, as studies of human–water interactions (socio-hydrology) become a rising issue (cf. Sivapalan et al. 2012; Savenije et al. 2013). Second, several processes have been identified, which need to be further investigated in order to improve the model performance in Central Asia. For example, this study has shown that the reliability of the model decreased in wetlands as well as in arid regions. This may originate from the historical development of WaterGAP starting in the mid-1990s, where it was planned as a global water balance tool. Since the development of the high-resolution WaterGAP 3 model (Verzano 2009), regional hydrological aspects came into focus, and more sophisticated hydrological processes have been integrated.

2.6. Acknowledgements

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Chapter 3

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3. Climate Change Impacts on Central Asian Water Resources

3.1. Abstract

Central Asia is in large parts dominated by low precipitation and, consequentially, by low water availability. Therefore, changes of natural water resources induced by climate change are of high interest. The aim of this study is to analyse the potential impact of climate change on Central Asian water resources until the end of the 21st century and to point out the main affected regions. Thus, simulations with the large-scale hydrology model WaterGAP 3 for the baseline and scenario periods were performed with outputs from three General Circulation Models (GCMs: ECHAM5, IPSL-CM4, and CNRM-CM3) and two IPCC-SRES emission scenarios (A2 and B1). The results show that mean modelled annual water availability increases for all scenarios and GCMs while CNRM-CM3 induces the wettest water situation for the 2085s and ECHAM5 the lowest water availability. Furthermore, robust trends to wetter or dryer conditions could be found for many basins. A seasonal shift of mean modelled water availability could be derived for ECHAM5 which does not show a second peak during summer. The application of daily input data showed no improvement of modelled monthly river discharges for most Central Asian basins compared to monthly input data.

3.2. Introduction

Large parts of Central Asia feature arid to semi-arid conditions and are therefore of high interest for hydrological studies, as water scarcity often limits the development of human, ecological, and industrial resources. However, not only climate change induced water problems, such as permafrost and glacier melting (Marchenko et al., 2007) and increased evapotranspiration (Yu et al., 2003) prevail in Central Asia, but also overexploitation of existing water resources (aus der Beek et al., 2011; Bucknall et al., 2003), transboundary water conflicts (ICG, 2002), failure of post-soviet water management strategies (O'Hara, 2000), and many more (EDB, 2009; Lioubimtseva and Henebry, 2009). Within this integrated model study the hydrological and water use model WaterGAP 3 (Water – Global Assessment and Prognosis) is applied to all river basins located in Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, Southern Russia, North-Western China, and Mongolia in five arc minutes spatial resolution (6×9 km per grid cell). Furthermore, an overview of the Central Asian water resources of the last three decades is given. To verify the plausibility of the model results, simulated river discharge is compared to observed river discharge. At this point, the impact of daily climate input data compared to monthly climate input data on modelled monthly river discharge is examined. Following the successful validation of the model results, transient bias-corrected climate change projections are being applied to estimate their impact on the water resources of Central Asia. Monthly fields of precipitation, radiation and air temperature output from the Global Circulation Models (GCMs) CNRM-CM3, ECHAM5, and IPSL-CM4 for the SRES-IPCC scenarios A2 and B1 (IPCC, 2000) are used to drive WaterGAP 3 to calculate potential changes in future local water resources. Thus, the model results also provide further insight into the range and uncertainty of climate change impacts when applying opposing climate models and scenarios. Menzel et al. (2008) analysed precipitation trends in a study for Mongolia. Even if water availability was not the focus of this study, but runoff generation, it is of high interest. They found an increase with ECHAM5 in the Middle and East of Mongolia with up to 20% more precipitation while the other parts mostly show small changes in the B1 scenario. For the A1B scenario the western and southern parts of Mongolia showed a decrease in runoff generation.

3.3. Methods and Study Region

3.3.1. Study Region

This study focuses on the region of Central Asia whereas this region is not defined by political borders but through the extent of river basins. Therefore, the term Central Asia contains the countries of Kazakhstan, Kyrgyzstan, Mongolia, Tajikistan, Turkmenistan and Uzbekistan entirely as well as parts of Russia and China (cf. Cowan, 2007) (see Figure 12).

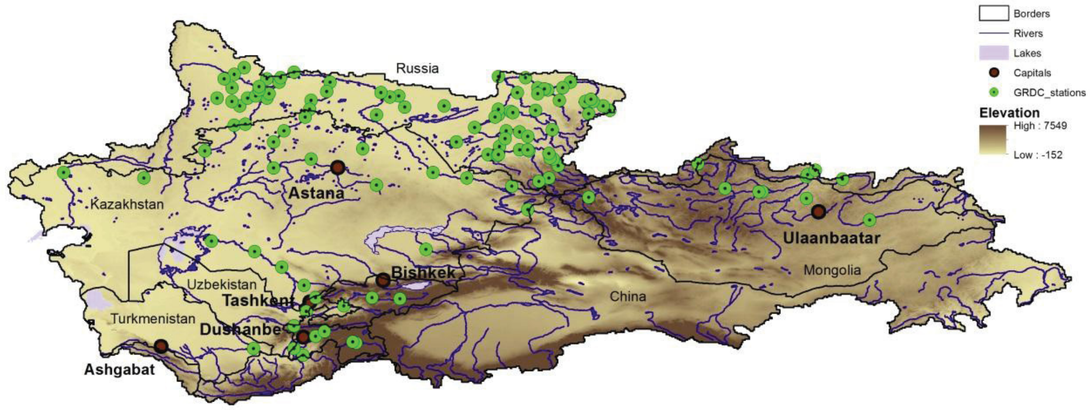

Figure 12: Study Region of Central Asia with GRDC (Global Runoff Data Center) stations

The study region is confined in the South (-West) by the mountains of Kopet Dag and Pamir, and with the Caspian Sea as western border. Moving on eastwards from the Pamir, the southern border is determined by the Kunlun Shan and Altun Shan mountains. Next to this mountain chain the Tarim basin with the desert of Taklamakan followed by Mongol Shan and Gobi desert can be found. The northern boundary is determined by the south Siberian lowlands with its large plain areas. The middle parts in the West (Kazakhstan) and East (Mongolia) are dominated by the Eurasian Steppe. The driest part of the study region is located in the desert regions of Gobi, Taklamakan, Karakum and Kyzyl Kum while the mountainous regions of Pamir, Altai, Alatau as well as south Siberia have the highest annual precipitation amounts. Especially, the downstream arid lowlands are highly reliant on water provision from the mountainous regions (Hagg et al., 2007). The biggest water bodies in the study region are the rivers Ob (North-Northeast Kazakhstan) with its tributaries Irtysh and Tobol, as well as Ural (West-Northwest Kazakhstan), Amu Darya (Fountain head in Pamir Mountains, then runs Turkmenistan and Uzbekistan to the Aral Sea), Syr Darya (Origin in Tien-Shan Mountains, then runs through Kyrgyzstan, Uzbekistan and Kazakhstan to the Aral Sea), Tarim (Northwest-China) as well as the lakes Balkhash (East-Kazakhstan), Issyk Kul (Kyrgyzstan) and Aral Sea (Border of Kazakhstan and Uzbekistan). In summary, the study region is topographically dominated by the Eurasian Steppe and additionally by mountains and deserts (Worden and Savada, 1991; Curtis, 1997). Overall, the study region features a spatial extent of 10 million km^2 with an elevation range from below sea level in the Turpan

Depression (−152 m) and (−135 m) in the Aral-Caspian Depression up to 7,500 m in the high mountainous regions of Pamir and Tien-Shan. Due to the continental and mainly arid to semi-arid climate the study region has a high temperature amplitude from −45°C in winter up to 40°C during the summer. Although the study region is sparsely populated in the most parts, some regions – such as the Aral Sea basin – are heavily influenced by anthropogenic water uses (e.g. water abstractions for agriculture).

3.3.2. Data and methods

Within this study the large-scale hydrology and water use model WaterGAP 3 has been applied, which is a further development of the global model WaterGAP 2 (Alcamo et al., 2003; Döll et al., 2003). WaterGAP 3 still can operate on the global scale, whereas in this study a Central Asian landmask derived from river basins has been applied. In addition to the increase in spatial resolution from 0.5° (~50 km × 50 km) to 5' (~6 km × 9 km) (Verzano, 2009) also some hydrological process descriptions have been improved in WaterGAP 3, such as snow related processes (Verzano and Menzel, 2009), flow velocity (Schulze et al., 2005), and water use (aus der Beek et al., 2010; Flörke et al., 2012). However, as this study focuses on the impact of climate change on available water resources, water use will not further be considered herein, but will follow in a future study. Monthly water fluxes for each of the 167,600 Central Asian grid cells forming 1,536 basins were calculated taking into account spatially distributed physiographic information on elevation, slope, hydrogeology, land cover and soil properties, as well as location and extent of lakes, wetlands, and reservoirs. It has to be mentioned that many of the small basins are closed depressions. The upstream/downstream relationship among the grid cells is defined by a global drainage direction map (DDM) which indicates the drainage direction of surface water (Lehner et al., 2008). If only monthly climate input is available WaterGAP 3 internally calculates the water balance of each grid cell on daily time steps. Therefore, all climate input, except precipitation, is interpolated with cubic splines to daily values. In terms of precipitation the model computes pseudo-daily time series from the number of rain days using a Markov chain algorithm (Geng et al., 1986). As climate input data for the baseline period 1971 to 2000 the WATCH forcing data (WFD), generated within the European Union-Framework Six (EU-FP6) – WATer and global CHange Project (WATCH), was used. This half degree global climate dataset was derived from ERA-40 reanalysis data and is available in daily time steps for the time period 1958 to 2001. For detailed information on the WATCH forcing data see Weedon et al. (2010, 2011). As radiation input shortwave derived from CRU data was used. Malsy et al. (2011) have shown that the WATCH forcing dataset is suitable for application in Central Asia. The climate change projections for the 21st century were extracted from the WATCH driving data. This dataset is available for two IPCC-SRES scenarios (A2 and B1) and for three GCMs; IPSL-CM4 (Institute Pierre Simon Laplace, France), ECHAM5 (Max Planck Institute for Meteorology, Germany) and CNRM-CM3 (Centre National de Recherchés Météorologiques, France). The WATCH driving data provides transient bias-corrected scenarios and is available with a daily temporal and a half-degree spatial resolution from 1960 to 2100. For further information on the WATCH driving dataset and the statistical bias correction see Hagemann et al. (2011) and Piani et al. (2010). All climate datasets have been rescaled from half-degree to five arc minute spatial resolution. The transient and bias-corrected climate scenarios have been divided into 30-yr time slices, i.e. 2011–2040, 2021–2050, ..., 2071–2100, for a better comparison to the 1971–2000 baseline results. The baseline time period has been simulated with daily and monthly climate data input to explore the impact of daily input data on the simulated monthly water fluxes. For this reason the daily WFD data was aggregated to monthly values. The performance of the model results was evaluated by comparing modelled to observed river discharge for 73 valid stations in Central Asia available from the Global Runoff Data Center (GRDC) database. Since some GRDC stations records do not cover the entire baseline period, only parts of the baseline could be validated. The location of the GRDC gauging stations shows a concentration in the northern part of the study region at the Russian border. Especially, the arid parts lack gauging station data, which is shown in Fig. 1. In this region only a few runoff stations with often short time series observations are available for model calibration and validation. Also, climate data is less reliable in these regions, which leads to interpolation inconsistencies, as often only few climate stations are available. For the scenario period the influence of climate change on the water fluxes, e.g. water availability has been examined. First, the decadal trend of mean annual water availability in comparison to the baseline results has been analysed.

Furthermore, modelled water availability for 2071–2100 (2085s) has been compared with the baseline water availability on river basin level to assess spatial changes. Here, the robustness of trends in water availability – three GCMS pointing into the same direction of change – has been analysed. The threshold for relative changes has been set to ±5 % and for absolute changes to ±5 mm. Finally, changes not only in mean annual water availability but also seasonal variability are of high interest. On this account, the monthly variability for three GCMs and two IPCC-SRES scenarios (2071–2100) have been simulated and compared with the baseline period (1971–2000).

3.4. Results and discussion

3.4.1. Modelling current water resources in Central Asia

Central Asia features large areas with low precipitation and therefore limited water resources, which can be observed in the modelled annual water availability for the time period 1971–2000 (cf. Figure 13).

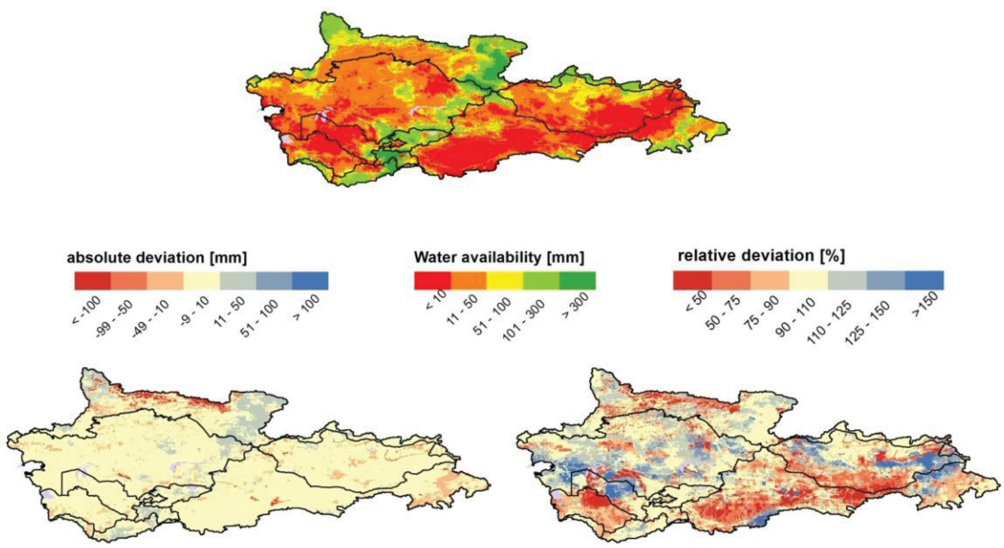

Figure 13: Modelled annual water availability based on monthly input data (top); alongside absolute and relative deviation between monthly and daily data input (baseline period 1971–2000)

The big desert regions, i.e., Gobi, Karakum, and Taklamakan, show mean annual water availability below 10 mm. Predominant westerly winds, lee side effects and orographic precipitation patterns are the reasons for this low precipitation (e.g. Taklamakan desert). In contrast, there are mountainous regions, e.g., the Pamir and Altai mountains, with high precipitation and mean annual water availability of more than 1200 mm. The mean water availability in the study region is 63 mm and 66 mm as modelled with monthly and daily data input, respectively. Here, the predominant patterns of modelled annual water availability are very similar for monthly and daily data input. The highest deviations for absolute values between daily and monthly data input are in the mountainous regions of Central Asia, i.e., Pamir, Dzungarian Alatau, and Altai, as well as southern Siberia (Figure 13). On the one hand, model results with monthly input data result in wetter conditions in the mountain regions.

On the other hand, model results with daily input data show higher water availability in the North of the study region (Siberia). In contrast, the examination of relative differences leads to different spatial patterns. The reason for these differences can be found in the input data; daily input data result in wetter conditions in the southern desert parts, i.e., Gobi, Taklamakan, and Karakum, as well as again at the Siberian border in the North. Monthly data is wetter around the Aral Sea and in eastern part of Mongolia. Whereas the mean modelled annual water availability slightly differs between daily and monthly input, more effects can be found in the modelled hydrographs of river discharge and its model efficiency evaluation. The Nash- Sutcliffe Efficiency (NSE) and coefficient of determination (R^2) for modelled monthly river discharge show higher, and thus better values with monthly (NSE 0.45, R^2 0.65) than daily (NSE 0.39, R^2 0.56) input data. Generally, the model application is suitable for the entire study region with a mean NSE of 0.45. Not only the level of the efficiency criteria is higher with monthly data input, also more stations were modelled validly (73 to 60). Mostly, the river runoff peaks are overestimated with daily input data, which leads to overestimated runoff generation and, hence, to lower efficiency criteria (Krause et al., 2005). Further, the base flow appears higher for daily input data. In many cases, this is caused by rather small peaks in autumn, which lead to a slower transition from peak to low flow. It has to be mentioned that some regions and rivers which are heavily influenced by anthropogenic water abstractions such as Amu Darya and Syr

Darya cannot be simulated accurately because the model setup within this study simulates the water fluxes only with natural conditions (i.e., water abstraction is not considered). Beside this, also the observed runoff data may include uncertainties – for example measurement errors. As shown above, daily data input does not improve the results for modelled monthly river discharge. One reason for this could be that the model structure and the representation of evapotranspiration processes was developed for monthly data input. Hence, further adaptation of the model to daily input data might improve the results.

3.4.2. Potential future development of Central Asian water resources

The simulation of the potential future development of Central Asian water resources has been carried out with the WATCH driving data (see Sect. 2.2). While for the baseline a small decrease between the time periods 1961–1990 and 1971– 2000 (64 mm to 63 mm) was noticed, an increase of mean annual water availability for each scenario and GCM until 2100 compared to the baseline was found. For both scenarios, A2 and B1, CNRM-CM3 shows the highest increase in water availability and ECHAM5 the lowest. It has to be mentioned that the baseline values were computed with the ERA-40 corrected WFD and not with the respective GCM baseline. This was necessary to calibrate WaterGAP 3 accurately, because the GCM baselines are too wet and lead to overestimated calibration parameters. For a detailed description of the calibration method of WaterGAP see Alcamo et al. (2003). Thus, even though WATCH forcing (until 2001) and driving (scenarios) data are supposed to be transient and bias-corrected, an offset between the observed WFD data (time period 1971–2000) and the first scenario period 2001–2030 (see Figure 14) exists.

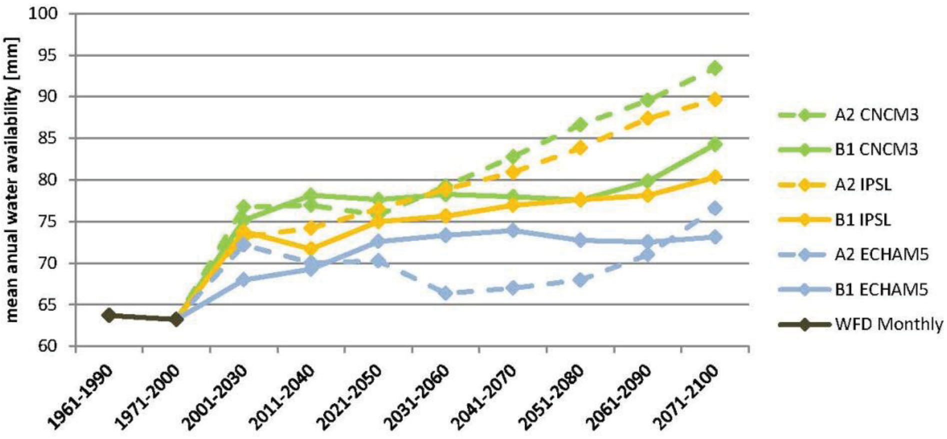

Figure 14: Modelled decadal mean annual water availability from 1971 to 2100 (Baseline period 1971–2000 with WFD, scenario period 2001–2100 with three GCMs and two scenarios)

While CNRM-CM3 and IPSL-CM4 show a constant increase in mean water availability for the study region, ECHAM5 causes firstly a decrease which turns from the 2045s to an increase until the end of the 21st century (scenario A2). This is induced by an increasing precipitation input in the scenario data during the 21st century, as precipitation is the main driver of the water cycle. In general, it can be determined that the differences between the IPCC-SRES scenarios (up to 9 mm in 2071–2100) is smaller than between the GCMs (up to 17 mm in 2071–2100). Furthermore, the impact of the A2 scenario is stronger than of B1 except for the ECHAM5 driven simulations. Here, the B1 scenario results are well above the A2 outcomes until the last phase (2071–2100). This is in agreement with Zwolsman et al. (2011) who detected also stronger impacts under the A2 than the B1 scenario.

Looking at the spatial distribution of mean modelled water availability the following picture emerges (Figure 15). Compared with the baseline the Ob river basin and the Altai Mountains river basins remain with high water availability in all GCM/scenario combinations. For the Tobol river basin in the north western part of Central Asia the A2 scenario leads to an increase of water availability with ECHAM5 as well as CNRM-CM3. This trend cannot be found for IPSL-CM4 and for the B1 scenario. In the western part in the Aral-Caspian depression water availability stays in dry conditions with all GCM/scenario combinations. In contrast to the Karakum and Gobi Desert, where all three GCMs and scenarios project ongoing dry conditions, the Tarim basin within the Taklamakan desert gets wetter with the IPSl-CM4 and CNRM-CM3 and less wet with ECHAM5. In the Amu Darya and Syr Darya basins only ECHAM5 shows a decrease in water availability. Generally, in relation to the baseline (1971–2000) the middle and middle-eastern parts of the study region are mostly affected by increasing natural water availability (e.g. Tarim basin, Selenga basin). In contrast, the biggest change to dryer conditions can be found in the Aral Caspian Depression within all models and scenario combinations. Also, parts of the Gobi Desert in Southeast Mongolia, Dzungaria and middle southern Turkmenistan show decreasing trends, particularly with ECHAM5. IPSL-CM4 shows for nearly entire Mongolia an increasing trend and CNRM-CM3 for the North and West. ECHAM5 leads to a decrease in water availability in the Southeast (Gobi Desert) and to an increase in the Altai Mountains. In comparison, Ragab and Prudhomme (2002) projected for the Aral Sea basin an increasing precipitation by 5–20 % in summer and winter, and also Batimaa et al. (2011) expected a sharp increase of winter precipitation for Mongolia which leads in combination with increasing air temperature to changes in evapotranspiration and water availability.

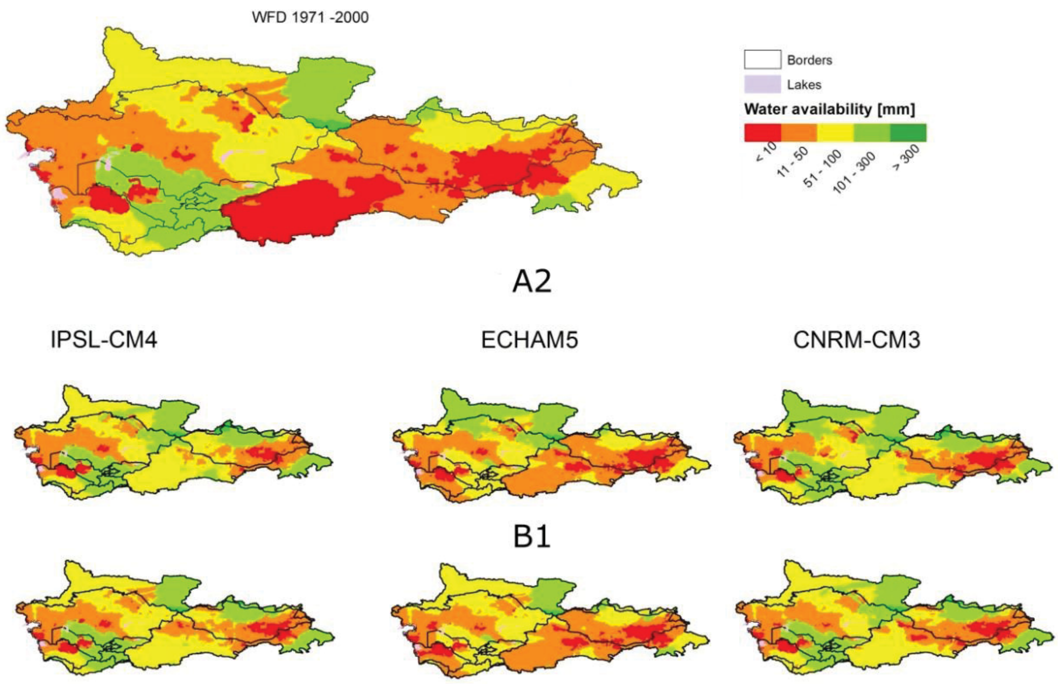

Figure 15: Modelled annual average water availability on river basin level for the baseline period 1971–2000 and for the scenario time period 2071–2100, separately shown for each GCM/emission scenario combination

The robustness of trends (Figure 16) confirms the above named changes in water availability. Modelled water availability (absolute values) shows an increasing trend for both scenarios in the south of the study region (Chinese Xinjiang region), for the north of Mongolia and the Mongolian Altai, and in the A2 scenario also for the Tobol and Ural basin. A decreasing trend can be found in the Aral Caspian Depression, North-Northwest and Southwest of the Aral Sea. For relative values the same patterns can be found, whereas an increasing trend also in Russian Altai and the Ob river basin can be observed. Ragab and Prudhomme (2002) expected a change in water availability due to alterations in precipitation and high interannual variability in semi-arid and arid regions.

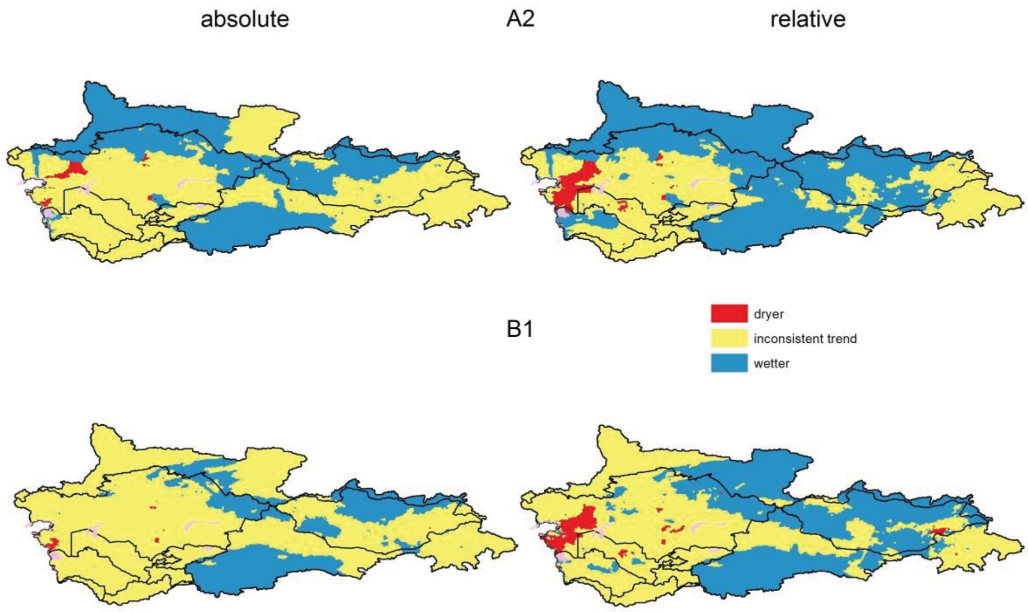

Figure 16: Robustness of trends (all GCMs show the same direction of change; threshold of 5 % for the relative trends and 5 mm for absolute trends) in modelled water availability for the scenario period 2071–2100 and the two emission scenarios A2 and B1

The seasonal variability in the study region (cp. Figure 17) shows two peaks in water availability during the year, a high spring peak which is caused by snow melting and a minor peak in summer. For example in Mongolia the highest precipitation rates are during the summer months. In this study no shift in the seasonal variability of modelled water availability could be found, except ECHAM5 which does not show the second peak during July. The spring peak increases for all scenarios and GCMs until 2100, but with an earlier and sharper rise. In the case of IPSL-CM4 and CNRM-CM3 also the second peak during the summer increases.

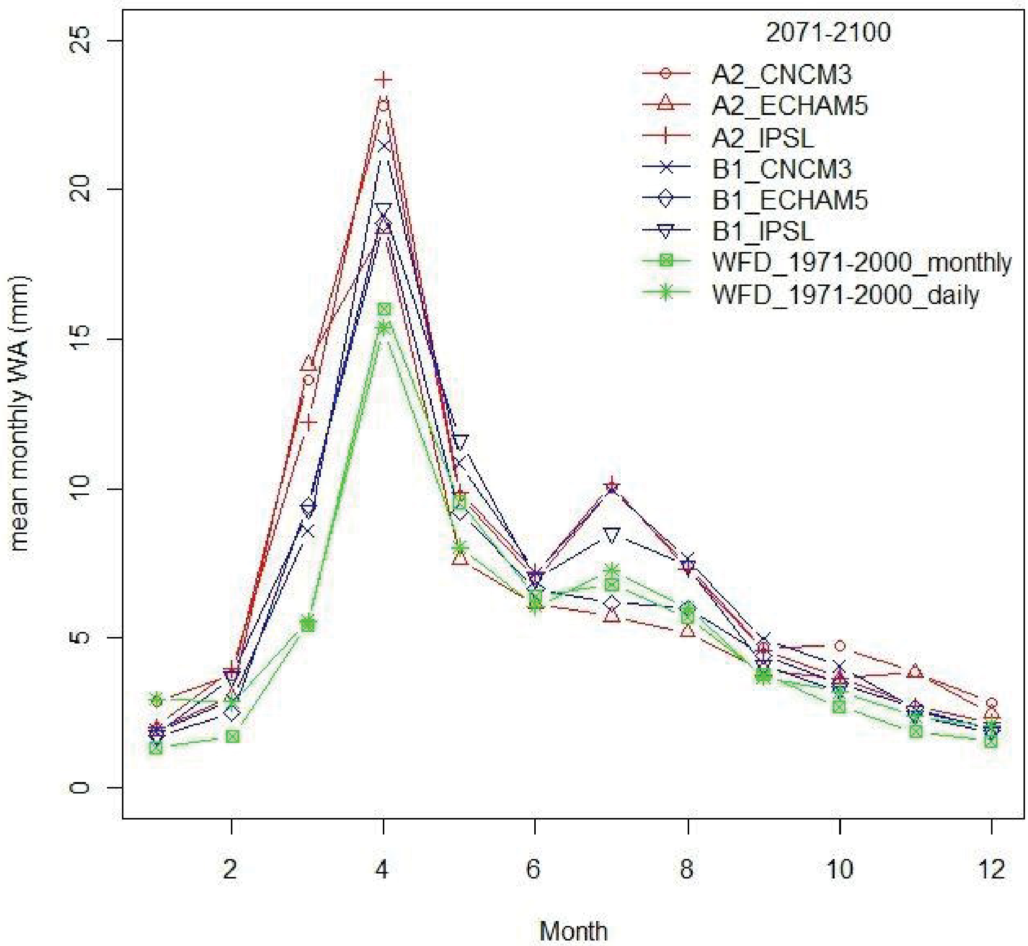

Figure 17: Seasonal variability of modelled monthly water availability (WA) for time period 2071–2100 in comparison to baseline time period (1971–2000)

3.5. Conclusions

In this study the hydrology model WaterGAP 3 has successfully been applied in order to analyse the water resources of Central Asia, driven by daily and monthly WATCH forcing and driving data. Generally, an increase in mean annual water availability was found in the scenario analyses. This increase might be overestimated – especially for the trends to wetter conditions- because the baseline was simulated with observed data and not with the GCM baselines. Also, an offset between observed baseline and modelled scenario climate data has been evident. Not only today's wetter regions in Central Asia, such as the Pamir and Tien Shan Mountain ranges feature this increase in water availability but also arid regions, e.g. Taklamakan, show an increasing trend. In contrary, the Aral Caspian Depression has a robust trend to dryer climate conditions until 2100. In case of the three applied GCMs CNRM-CM3 shows the highest increase in water availability for both scenarios A2 and B1, whereas ECHAM5 leads to the driest conditions. Our results for the study region also show that the range between the different GCMs is larger than between the emission scenarios A2 and B1. Seasonal changes in runoff characteristics could be encountered only for ECHAM5 during the summer. Also, according to this study the spring and summer runoff peaks are expected to significantly increase, especially for the CNRM-CM3 model output. Further work needs to be done to verify the results obtained for the scenario period. In detail, the results should be analysed in the context of regional climate classifications e.g. Köppen-Geiger, or elevation. Also, future changes of major hydrological events, such as droughts and floods, with their frequency, duration and occurrence, are important for the study region and should be examined. Furthermore, the impacts of land-use change and water uses on the water resources and future conditions in Central Asia are of high importance, in particular for the regions with growing population density and/or anthropogenic water abstractions.

3.6. Acknowledgements

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Chapter 4

This chapter has been already published as:

Water resources and socio-economic development in a water scarce region on the example of Mongolia. **Geo-Öko,34, pp. 27-49.**

Authors: Marcus Malsy, Monika Heinen, Tim aus der Beek, Martina Flörke

4. Water resources and socio-economic development in a water scarce region on the example of Mongolia

4.1. Abstract

Mongolia is characterized by a highly continental semi-arid to arid climate, characterised by low precipitation and therefore low water availability. The limited water resources may impede socio-economic development of the country. Consequently, climate change impacts as well as anthropogenic water use and its potential change are of crucial importance. In combination with IPCC-SRES climate change scenarios, socio-economic scenarios were developed in order to analyse the impact of changes in anthropogenic water uses on Mongolian water resources. Induced by low natural water availability, special attention was paid to overexploitation of river basins. For this purpose, different water stress indicators were applied to point out water stressed basins. As drivers for calculating the impacts on water resources and water use sectors, socio-economic parameters (e.g. population development, and Gross Domestic Product) as well as technological and land use changes were used. The results show a strong increase of anthropogenic water uses until end of the 21st century, and hence, increasing pressure on Mongolian water resources. Intensification of water stress was strongest in the river basins surrounding the capital Ulaanbaatar.

4.2. Introduction

For hundreds of years mankind influenced natural processes through changes in land use and land cover. The ability to gain and exploit natural resources increased rapidly during the centuries (RAMANKUTTY ET AL. 2006). At this, change can be for example an intensified use or change in land cover (MEYER & TURNER II 1994). Water availability and water demand is strongly influenced by land use changes due to, for instance, changes of socio-economic activities such as irrigation (NUNES & AUGE 1999, GIAMBELLUCA 2005).

Subsequently, the hydrological cycle is affected in terms of e.g. evaporation, runoff, or soil moisture (GIAMBELLUCA 2005, GIERTZ ET AL. 2010), but impact level depends on vegetation type, climate conditions, and soil properties (CHABBRA & GEIST 2006). Worldwide, water abstraction for irrigation purposes (66 %) is the main water user (GIAMBELLUCA 2005). These current and future anthropogenic as well as natural water demands are highly correlated to climate, which especially holds true for the continental Mongolian climatic conditions. The climate of Mongolia is characterized by high daily and annual fluctuations. The mean annual air temperature ranges from -7.8 °C in the Darkhad depression to +8.5 °C in the Gobi desert and south Altai; the nationwide average annual air temperature is +0.7 °C. Mean annual precipitation spans from 50 mm to 400 mm. In detail, the Gobi desert features the lowest precipitation with 50-100 mm, followed by 100-150 mm in the steppe-desert, and 150-250 mm in the steppe. The wettest region with 300-400 mm can be found in the mountainous regions of Khangai, Khentii, and Khuvsgul. On the basis of low annual precipitation, water availability is low as well, and overall the Mongolian climate can be characterized as arid to semi-arid (BATIMAA 2006). On this account, Mongolia is very vulnerable for Climate Change as well as for changes in anthropogenic water uses. ROST et al. (2007) have shown for Inner Mongolia the complex interactions and impacts of climate and anthropogenic changes on desertification. For these reasons the estimation of future water resources is very important to avoid their overexploitation. Further, water scarce regions and hotspots of anthropogenic water abstractions can be detected for the present and the future in order to set up a sustainable water management.

4.3. Study area and methods

4.3.1. Characteristics of Mongolia

Mongolia (see Figure 18) is a landlocked country which is dominated by opposing land characteristics of Siberian taiga, Central Asian steppe, Gobi deserts and Altai Mountains (MNETM 2001). The altitude ranges from 4,734 m in the far West at Huyten Orgil to 560 m in the eastern plain (WORDEN & SAVADA 1991). Even though plain steppe is dominating the landscape, 81 % of the territory lies above 1,000 m and 50 % above 1,500 m (DAMIRAN 2005). Rivers extensively exist in the North with the Selenge as main river basin. The Mongolian rivers drain in three directions: to the Arctic Ocean (North), to the Pacific (East) and to the deserts and depressions of Inner Asia (South) (WORDEN & SAVADA 1991). The water regime can be divided into four main seasons: Winter low-flow period from December to April, spring-runoff period due to snow melting from April to June, summer runoff period due to rainfall from June to September, and warm season low-water period, which usually follows the rainy season and lasts to the winter low-flow period (BATIMAA 2006). Dryness is one of the biggest issues in Mongolia as in 2003 of 5,565 rivers in total 683 dried out during the last years. Further on 1,484 springs of in total 9,600 and 760 lakes of in total 4,193 dried out as well. Additionally glaciers decreased by 30 % in Kharkhiraa, Turgen, Tsambagarav and Tavanbodg mountains between 1940 and 2002 (BATSUKH ET AL. 2008).

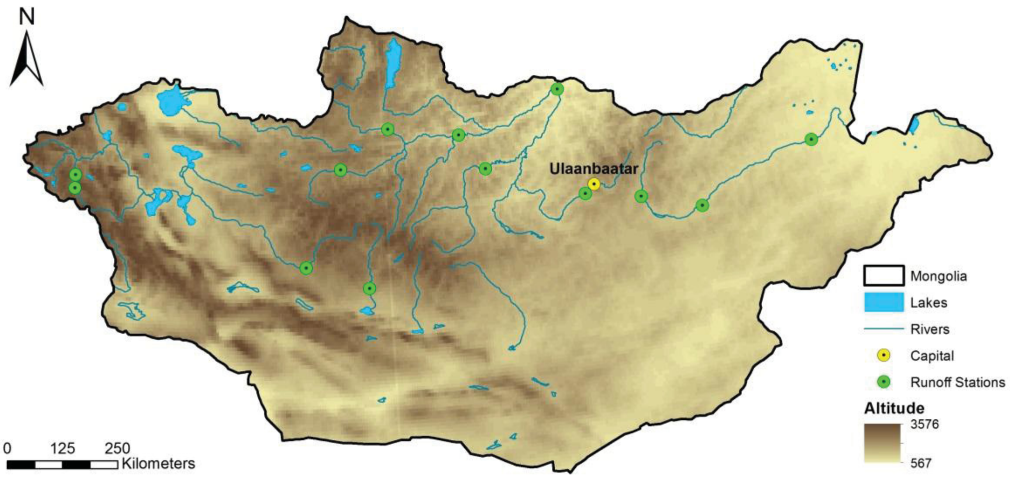

Figure 18: Study region of Mongolia with runoff stations (Altitude is mean value per grid cell)

In terms of climate Mongolia is characterized by a high continental semi-arid to arid climate with a high altitude in daily and annual temperature, long cold winter, dry and hot summer and low precipitation (BATIMAA 2006, NANDINTSETSEG ET AL. 2007). In general, Mongolia features a seasonal climate but with less distinctive spring and autumn. Large seasonal (up to 90 °C) and daily (up to 30 °C) fluctuations in air temperature are present. Annual precipitation is low but with a high intensity, whereat 50-60 % of total precipitation falls in July and August. During the last 60 years an increase in air temperature of 1.8 °C was determined, whereas for precipitation no statistically significant trends were detected. Furthermore, dust storms, summer droughts, blizzards, and harsh winter ("Dzud") are common (BATIMAA 2006, JAMIYANSHARAV ET AL. 2006). "Dzud" events strongly influence the well-being of livestock dependent Mongolian herders, because they occur with on-going reduced water and fodder availability, which leads to an increased livestock death rate (BATIMA 2006, IWASAKI 2006, and LIU ET AL. 2010). With a population of 2,800,114 and a land area of 1,564,100 km² Mongolia is a very sparsely populated country (1.79 people per km²), but with an annual population growing rate of 1.6 % (THE WORLD BANK 2012). Since the 1960s an urbanization trend can be determined which leads to an urban population rate of 68.5 % in 2011, while in 1960 just 35.7 % lived in urban settlements. As result, the capital Ulaanbaatar grew rapidly from 179,063 inhabitants in 1960 to 965,961 in 2010. The Gross Domestic Product (GDP) quintupled during the last ten years from 568 US$ (GDP/capita) in 2002 to 3,129 US$ in 2011 with "mining and quarrying" as the most important sector followed by "agriculture, forestry and fishing." The section "Other" consists mainly of "Net taxes on products", "Real estate activities" and "Information and communication" (see Figure 19) (MEF 2012, THE WORLD BANK 2012, NSO 2013).

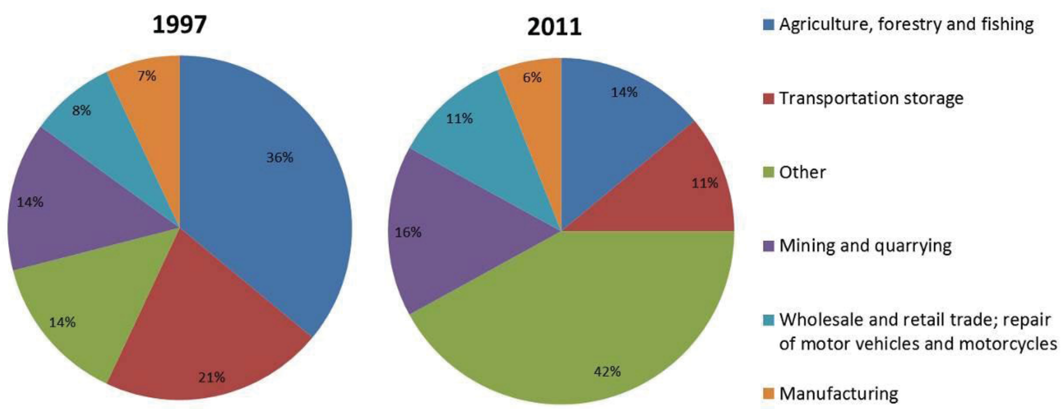

Figure 19: Change of important divisions of Mongolian Gross Domestic Product between 1997 and 2011 (source :MEF 2012, adjusted colours)

4.3.2. Land and water use in Mongolia

According to BATSUKH ET AL. 2008 water use is dominated by water abstractions for mining purposes (26.7 %) followed by domestic (20.3 %) and livestock (20.2 %). Irrigation (14.9 %) is the fourth biggest water user (see Figure 20 right) with a rapid increasing trend. Water uses for irrigation tripled between 2000 and 2005, but are still below the level of the late 1980s and early 1990s, where irrigation was organized by the Soviet occupation. During the last few years Mongolia has invested in new irrigation and agricultural technology in order to be independent of food imports (JAMIYANSHARAV ET AL. 2006, PRIESS ET AL. 2011), which was succeeded for the first time in 2011 (SDC 2011). The mining sector includes 182 mines (mainly gold, coal, copper, and construction materials) in 2005. Focus of the mining industry is on the Selenge Aimag in the North (BATSUKH ET AL. 2008), in addition, mining activities are increasing in the Gobi desert and in the Southwest. Domestic water use is characterized by a sharp disparity between rural and urban water use. While in cities and bigger settlements the daily water use is 230-250 l per person, for ger areas, rural herders, and most province towns just 5-10 l per person are used (BATSUKH ET AL. 2008), which is far below minimum requirements (GLEICK 1996). High domestic water use in cities can be explained by tremendous losses of up to 40 % (e.g. City of Darkhan) caused by old and broken water supply pipes (SCHARAW & WESTERHOFF 2011) and inefficient technology.

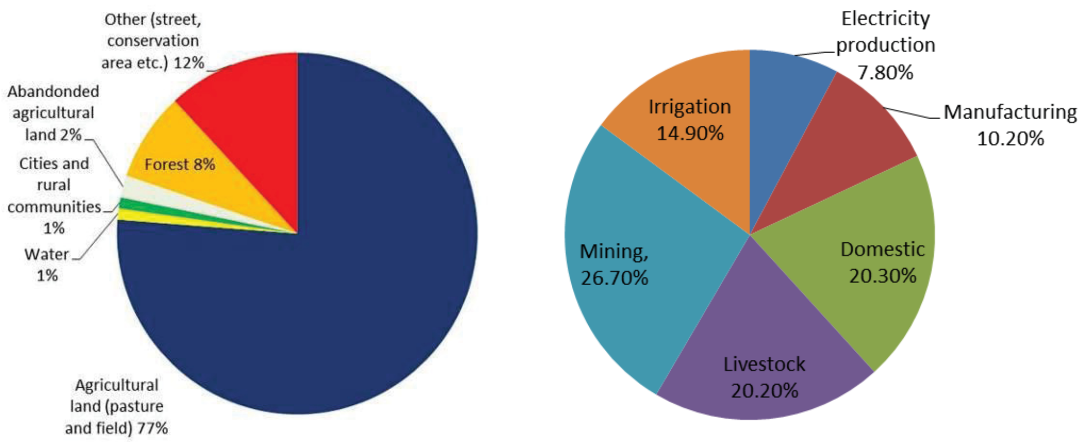

Figure 20: Sectoral land uses (2010, left) and water uses (2005/2006, right) in Mongolia

Consequently, 92 % of domestic water is abstracted for the apartments in the central area of the cities, whereas only 30 % are connected to the drinking water system in total. People without connection to the drinking water system receive their water mainly from water kiosks (~35 %), water trucks (~24 %), or wells and rivers (~9 %) (BATSUKH ET AL. 2008, BATIMAA ET AL. 2011). In 2005, the number of livestock was ten times higher (30.4 million) than human population with substantial fluctuations that greatly depend on the occurrence of “Dzuds”. These “Dzuds” have a big impact on number of livestock, due to the high dependence on access to grassland for grazing purposes. The reoccurring cold-dry “Dzud” events are often accompanied by a loss of many animals; for example, the “Dzud” of 2009-2010 affected over 50 % of the Mongolian herders, with 75,000 herders who lost all or more than half of their livestock (IPCC 2012). “Dzuds” can be also the reason for decreasing access to drinking water, because of reduced groundwater levels and drying out of wells and springs (BRUTSAERT & SUGITA 2008). In terms of land use Mongolia is dominated by agricultural land (see Figure 20 left). On this occasion, arable land accounts only for 0.8% of the agricultural land, while pasture is the dominating land use type (MNETM 2010). Livestock provides the main income for rural population and, therefore, the main element in the agricultural sector (UN 2002). After the political change in the early 1990s the number of livestock increased rapidly, because many Mongols, which became unemployed due to the economic change, started to work as herders (SAIZEN ET AL. 2010). Cropland septupled from 2000 (117,600 ha) to 2008 (835.700 ha) and is mainly used for wheat, barley, and oat production. However, only 17,637 ha (2005) are being irrigated, but tripled as well since 2000 (BATSUKH ET AL. 2008). Spatial focus of cropland is on the Selenge Aimag, because of advantageous climate conditions compared to other parts of Mongolia (MENZEL ET AL. 2010). Sprinkler technique is with 75 % the most common irrigation technique (FAO 1999, FAO 2012). Forest covers 8 % and is located predominantly in Northern Mongolia. The forests are mostly affected by wildfires, overgrazing, mining, illegal wood harvesting, and insect plagues (BATSUKH 2004, TSOGTBAATAR 2004, MNETM 2010, and YKHANBAI 2010).

4.4. Data and methods

The simulation of present and future water resources were conducted with the large-scale hydrology and water use model WaterGAP 3 (Water – Global Assessment and Prognosis) (VERZANO 2009). WaterGAP 3 is a further development of WaterGAP 2 (ALCAMO ET AL. 2003, DÖLL ET AL. 2003) and operates on a five arc minute grid (~7x8 km²) in daily internal time steps (VERZANO 2009). WaterGAP 3 still can operate on a global scale, whereas in this study a Mongolian landmask derived from river basins has been applied. In total, Mongolia features 403 basins; at this many basins especially in the South are closed depressions. The calibration and validation of the model was done with the global meteorological dataset WATCH forcing data (WFD). The WFD is based on a half degree grid in daily time steps (WEEDON ET AL. 2011). As baseline time period 1971-2000 was used.

The future projections were conducted with the WATCH driving data (WDD). This dataset provides transient bias-corrected scenarios on a half degree grid for two IPCC-SRES scenarios (A2, B1) (IPCC 2000) and three General Circulation Models (GCMs): IPSL-CM4 (Institute Pierre Simon Laplace, France), ECHAM5 (Max Planck Institute for Meteorology, Germany) and CNRM-CM3 (Centre National de Recherchés Météorologiques, France) (PIANI ET AL. 2010, HAGEMANN ET AL. 2011). Both input datasets were rescaled to the model resolution of five arc minutes. The water use model contains five sub models for irrigation, domestic, manufacturing, electricity production, and livestock water uses (AUS DER BEEK 2010, FLÖRKE 2013). For this study, additionally a mining sub model was included for the first time in an application of the WaterGAP model. The estimation of mining withdrawals bases on annual production statistics, target values for water use, and the location of mining districts (MINISTRY OF ENVIRONMENT 1995, USGS 2007, MINISTRY OF MINING 2007, BATSUKH ET AL. 2008,). In the next step mining water consumptions were assessed by the average ratio of consumption to withdrawal water use per mineral type according to QUAN 1988. As not all types of mines could be derived from literature, the water uses for mining purposes are probably underestimated. The distinction between water use, water withdrawals, and water consumption follows the definition in HUTSON ET AL. 2004. By analysing past and recent changes in Mongolia's socio-economy two scenarios were developed in order to quantify the effects of anthropogenic activities on future water resources. Based on global datasets also regional datasets –if available- were integrated. Basis for the development of socio-economic scenarios were population development, growing rate, household size, population density, GDP per capita, Gross Value Added (GVA) which are main drivers for quantification of water abstractions for mining, manufacturing, electricity production, irrigation, domestic, and livestock purpose. Anymore, access to water, land use management, and technological change was as well considered in the scenario development process. Following the IPCC-SRES scenarios A2 and B1 two socio-economic scenarios, A (economic growth) and B (sustainable development), were build (cp. Tab. 1). These qualitative changes were spatially explicit quantified and fed into the water use models of WaterGAP 3. Quantitative estimation bases on a trend matrix (Table 6), national and international statistics, and local newspaper articles. The general development trend, was calculated on basis of national statistics (NSO 2001-2010, NSO 2013), while the development of livestock bases on historic data with interruptions by „Dzud "events (IPCC 2012). Further development of population bases on the Global Environmental Outlook (GEO-4) report (UNEP 2007) as well as on national statistics (NSO 2001-2003, NSO 2013). The economic indicators bases on the World Development Indicators (THE WORLD BANK 2012) and the GEO-4 report (UNEP 2007). At this, beside historical data further planning such as new power plants (PADCO, 2005), new mines (THE WORLD BANK 2004) or agricultural land (PRIESS ET AL. 2011) was considered to estimate further development.

Table 6: Trend matrix for the development of socio-economic scenarios A and B

Indicators / driving forces	Scenario A (Economy)		Scenario B (Sustainability)	
	urban	rural	urban	rural
Population development	+++	+	+	+
Growing rate	+++	+	+	+
Household size	--	0	-	0
Population density	+++	+	++	+
GDP / capita	+++		++	
Gross value added (GVA)	+++		++	
Access to water	+	+	+++	++
Land use management	++ (in terms of forest -)		+	
Technological change	+		++	

In order to compensate natural inter-annual climate variability, irrigation water demand and water availability were computed for 30-year time slices (1971-2000 and 2071-2100) and subsequently aggregated to long-term annual averages. In a last step two water stress indicators were applied in order to examine the present and future pressure on water resources. As indicator the withdrawal to availability ratio (w.t.a.) and the consumption to Q90 ratio (c.t.Q90) were applied. While the first indictor (w.t.a) compares the total available water in a basin to the total abstracted water, the second indicator (c.t.Q90) focuses on long term low-flow conditions in a basin (ALCAMO ET AL. 2007). Correspondingly to the applied indicators for the baseline period 1971-2000, simulated and observed annual water availability as well as low-flow conditions (Q90) were compared to validate the model results (see Figure 21).

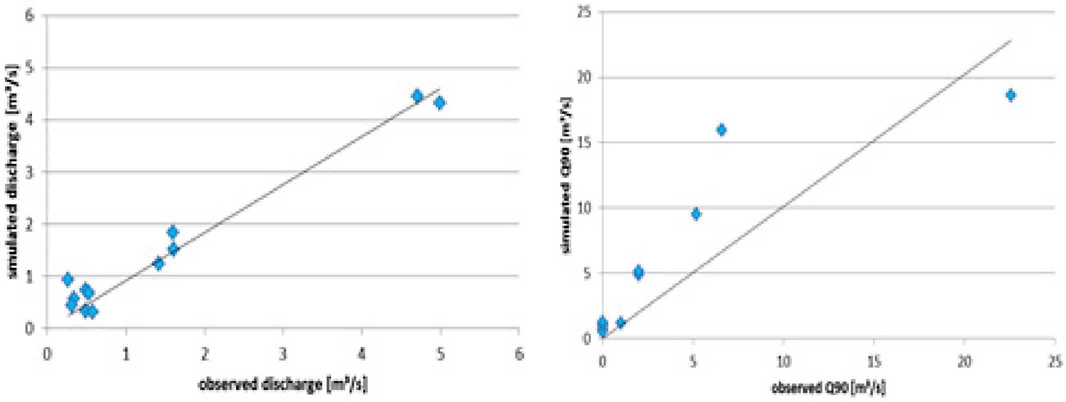

Figure 21: Comparison of mean simulated and observed annual water availability (left, R^2=0.96) as well as low flow conditions (right R^2=0.66)

However, it needs to be mentioned that Mongolia is a data scarce region where only 13 runoff stations with a long time period (>30 years) are available (see Figure 18). Regarding mean annual water balance, simulated and observed annual discharges show a very good agreement (R^2= 0.96). The correlation between simulated and observed low-flows is less reliable (R^2=0.66), whereas simulated low-flows are mostly overestimated (see Figure 21).

4.5. Results

This section provides the present and future modelled water uses and their impact on natural water resources. Future scenarios of modelled water availability show an increasing trend in northern and western Mongolia. At this, a bias between observed baseline (WFD) and GCM baseline was found. The smallest deviation exists between the observed data and ECHAM5, while IPSL and CNCM3 are distinctly wetter. On the whole, all GCMs tend to a baseline overestimation in terms of precipitation and probably lead to an overestimation of future water resources as well. For a detailed description of potential water availability changes see Malsy et al. 2012. Furthermore, two water stress indicators (water to availability ratio (w.t.a.) and consumption to availability ratio (c.t.Q90) are applied to clarify the impacts of water use on water resources and to avoid catchment overexploitation. At this, special attention is paid on the one hand to the total amount of water which is withdrawn from a basin (w.t.a) and on the other hand, if enough water for consumption needs is available during low flow periods (c.t.Q90).

4.5.1. Current and future water uses

Six sectoral water users were considered in the model setup (electricity production, manufacturing, irrigation, livestock, mining, and domestic) (see Figure 22). In the baseline period, electricity production (347 M m^3) is the biggest water user, due to water intensive once through cooling. The second biggest user is irrigation (235 Mio m^3) followed by domestic (82 M m^3), mining (81 M m^3), and livestock (71 M m^3). Manufacturing shows the least water withdrawals with 41 M m^3.

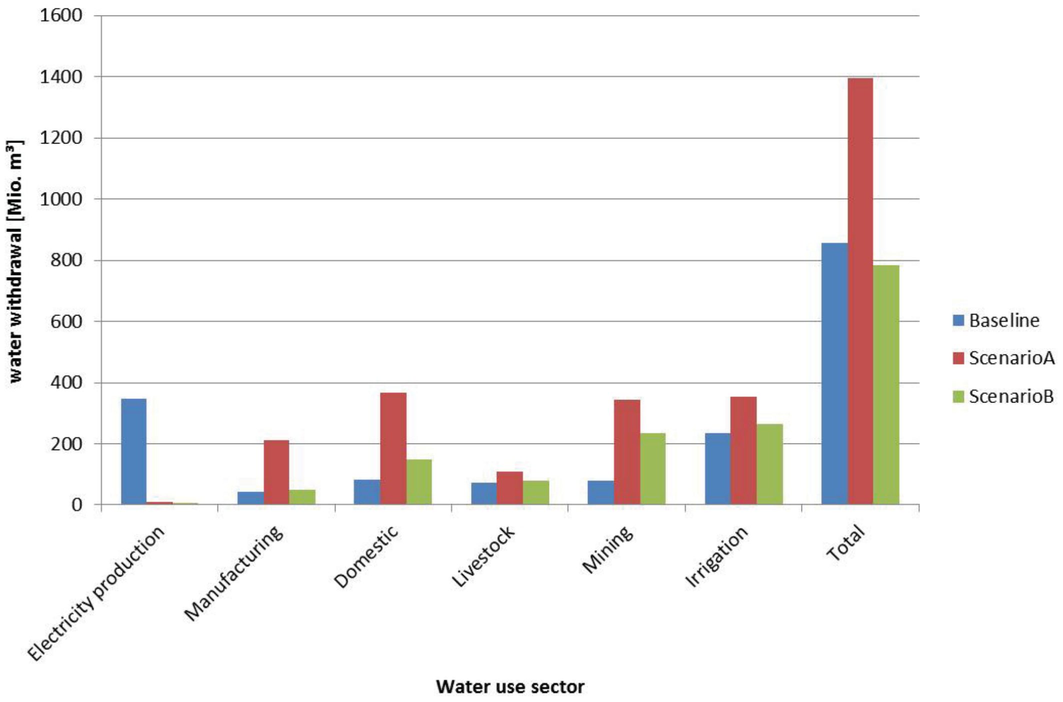

Figure 22: Sectoral water withdrawals for baseline and scenario period; for irrigation the GCM average is shown

Compared to water withdrawal data in BATSUKH ET AL. 2008 the sectors electricity production and irrigation are overestimated. One reason for the overestimation of the irrigation sector is the much larger irrigated area (59,178 ha) in WaterGAP compared to BATSUKH ET AL. 2008. Generally, irrigated area highly varies between different authors (see Table 7). Thus, in GANBAATAR 2003 irrigated area is in 1989 nearly twice as high compared to BATSUKH ET AL. 2008. In subsequent years the irrigated area decreased rapidly in GANBAATAR 2003 and BATSUKH ET AL. 2008, while FAO 1999 shows the highest value (57,300 ha) in 1993. In general, it can be noticed that after the political change irrigated area decreased, because of high operation costs, huge energy consumption, and a shortage of skilled manpower (GANBAATAR 2003). Since 2000 irrigated area has been increasing and tripled until 2006 (BATSUKH ET AL. 2008). As described, variation and uncertainty in the extent of irrigated area are apparent and lead likewise to varying annual water withdrawals (cf. Table 7).

Table 7: Comparison of irrigated area and irrigation water withdrawals

	1989	1990	1991	1992	1993	1996	1998	2005	2006
Irrigated Area [ha] GANBAATAR 2003	41,170					10,443	8,140		
Irrigated Area [ha] BATSUKH ET AL. 2008	22,178	39,342	27,347	17,435		11,393	5,331	17,637	17,200
Water Withdrawals [Mio. m³ / yr.] BATSUKH ET AL. 2008	59.8	106.5	74.9	46.9		31.3	14.0	52.3	50.7
Water withdrawal per ha for Batsukh et al. [m³]	2,696	2,707	2,739	2,690		2,747	2,626	2,965	2,948
Irrigated Area [ha] FAO 1999,2012,2013					57,300				
Water withdrawal / requirement [Mio. m³ / yr.] FAO 1999,2012,2013					108				94
Water withdrawal per ha for FAO [m³]					1,885				
Irrigated Area [ha] WaterGAP3 (constant for baseline)	59,178	59,178	59,178	59,178	59,178	59,178	59,178		
Water Withdrawals [M. m³ / yr.] WaterGAP3	294	234	220	238	182	223	288		
Water withdrawal per ha for WaterGAP3 [m³]	4,968	3,984	3,718	4,022	3,076	3,768	4,867		

It has to be concluded that the values for Mongolia ranges widely and substantially fluctuate during the years. BATSUKH ET AL. 2008 estimates water withdrawals for 2005 in the livestock and irrigation sector to 123.3 M m³ / yr., while 227 M m³ are mentioned in FAO 2012. With regard to electricity production it was assumed that all power plants in Mongolia use once-through cooling. This was necessary, because no data supporting the cooling type is available. For this reason all power plants are in the highest water use category and lead therefore to an overestimation of water withdrawals compared to BATSUKH ET AL. 2008. The two socio-economic scenarios lead in terms of Scenario-A (economic growth) to an increase (63 %) of total water withdrawals up to 1397 M m³, whereas Scenario-B (sustainable production) leads to a slight decrease (9 %) to 784 M m³. For both scenarios electricity production is decreasing sharply, because of technological change and a switch from once-through to tower cooling. With regard to once-through cooling abstracted water is returned immediately after it is cooled down, which leads to very low water consumption (0.36 % of water withdrawals). For tower cooling water withdrawals are 45 times smaller than for once-through systems, but water consumption is twice as high compared to once-through cooling, due to water flows in a closed loop (VASSOLO & DÖLL 2005). In Scenario-A the sectors manufacturing (514%), domestic (448 %) and mining (425 %), and in Scenario-B the sectors mining (289 %) and domestic (184 %) show the strongest increase. Whilst in Scenario-A the sectors domestic (367 Mio. m³), irrigation (355 M m³) and mining (343 M m³) become the biggest water users, in Scenario-B just irrigation (263 M m³) and mining (234 M m³) feature the biggest water withdrawals. The percentage shares of each sector for the baseline period and their changes in the socio-economic scenarios A and B are given in Figure 23. Key drivers for domestic water use are GDP, population density / distribution, and the technological change rate (FLÖRKE ET AL. 2013). At this, Scenario-A features a higher population growth rate and urbanization trend compared to Scenario-B. Due to higher per capita water demand in urban areas than in rural areas, domestic water uses increase rapidly. Scenario-B features additionally a smaller GDP increase and a more intense technological change, which reduces the potential water demands. Triggers for changes in the manufacturing sector are structural water intensity, the GVA, and the technological change rate (FLÖRKE ET AL. 2013). On this occasion, Scenario-A is characterized by stronger impacts on these key drivers, except the technological change rate. In terms of mining again the strong economic development leads to higher water withdrawals, due to initiation of new mines and intensified exploitation of the existing mines. Irrigation is the only sector, which depends on climate changes, whereat increasing temperature leads to increasing water demands, due to higher evaporation losses. Further on, irrigation efficiency is an important part, as upgraded irrigation technique (e.g. drip irrigation instead of sprinkler) leads to water savings and therefore reduced water demands (ROHWER ET AL. 2006). In terms of electricity production the location and number of power plants, the annual thermal electricity production and the intensity factor are the key drivers. Here as well, increasing technological change leads to reduced intensities (FLÖRKE ET AL. 2013). At this, the change from once-through to tower cooling leads to a sharp decrease in water abstractions for electricity production (VASSOLO & DÖLL 2005) and covers almost completely the effects of the other triggers for Mongolia.

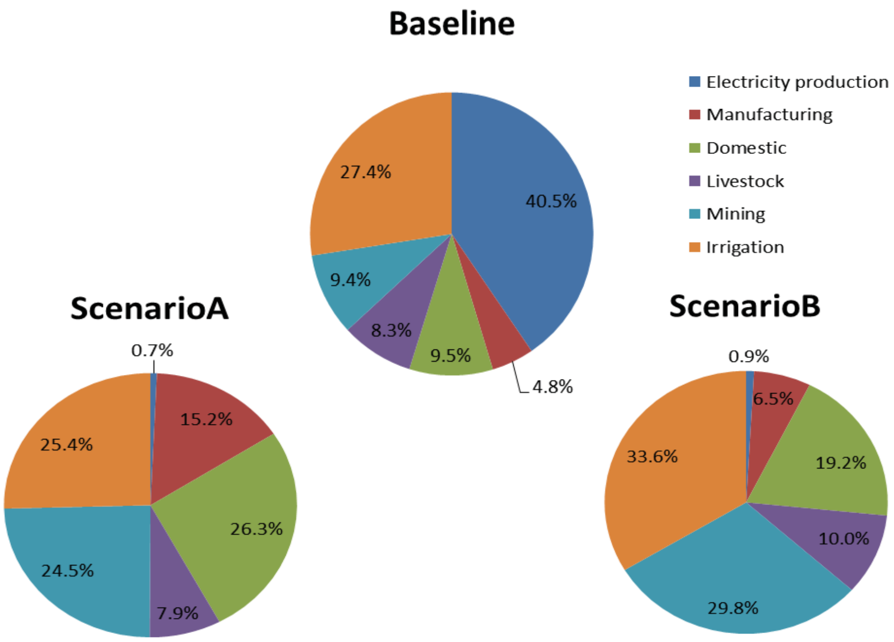

Figure 23: Percentage of current and future sectoral water uses

4.5.2. Water stress (w.t.a. indicator)

The withdrawal to availability ratio (w.t.a) examines pressure on water resources induced by external sources. At this, w.t.a. compares the sum of water withdrawals per basin to the natural water availability, whereat water stress is categorized in three divisions: low, medium, and severe water stress. Low water stress ranges from 0 to 20, medium water stress from 20-40, and in case of severe water stress more than 40 percent of the water availability is withdrawn (ALCAMO ET AL. 2003a, 2007). The results show for baseline time period severe water stress in a few basins in the South and Southwest (see Figure 24). This water stress is induced by very low water availability in these basins, where already small amounts of consumed water (e.g. livestock, domestic or irrigation), can trigger water stress.

Similar results for Mongolia can be found in ARNELL 1999 and 2004, who could not detect water stress in Mongolia. Due to different spatial resolutions (five arcminutes versus half degree) the water basins which are stressed in our results are probably too small and not separately examined in Arnell´s half degree model analyses. The results for Scenario-A (economic growth, 2071-2100) show an increasing water stress level, especially around the capital Ulaanbaatar (Tuul +13 %, Kharaa +15 %, and Orkhon +7 %), in the Gobi desert (+13,5 %, and + 6,5 %.), in the eastern steppe (+11 %), and in west Mongolia (+7 %). The increasing trend outside the basins around Ulaanbaatar is induced by increasing water withdrawals for mining purposes. In the Kharaa, Orkhon, and Tuul River water stress increase is mainly caused by growing domestic and mining sectors. On the other hand, a decreasing trend can be found in the water stressed basins of the baseline and additionally in basins in the Southeast, due to both, increasing water availability and decreasing water uses. For Scenario-B (sustainable production) similar spatial patterns can be found compared to Scenario-A, but less severe. In particular, in terms of an increasing trend Kharaa (+2 %) and Orkhon (+2 %) river basin show a much lower change compared to Scenario-A. For basins with decreasing trend in water stress no big contrast between the results of scenario A and B can be found.

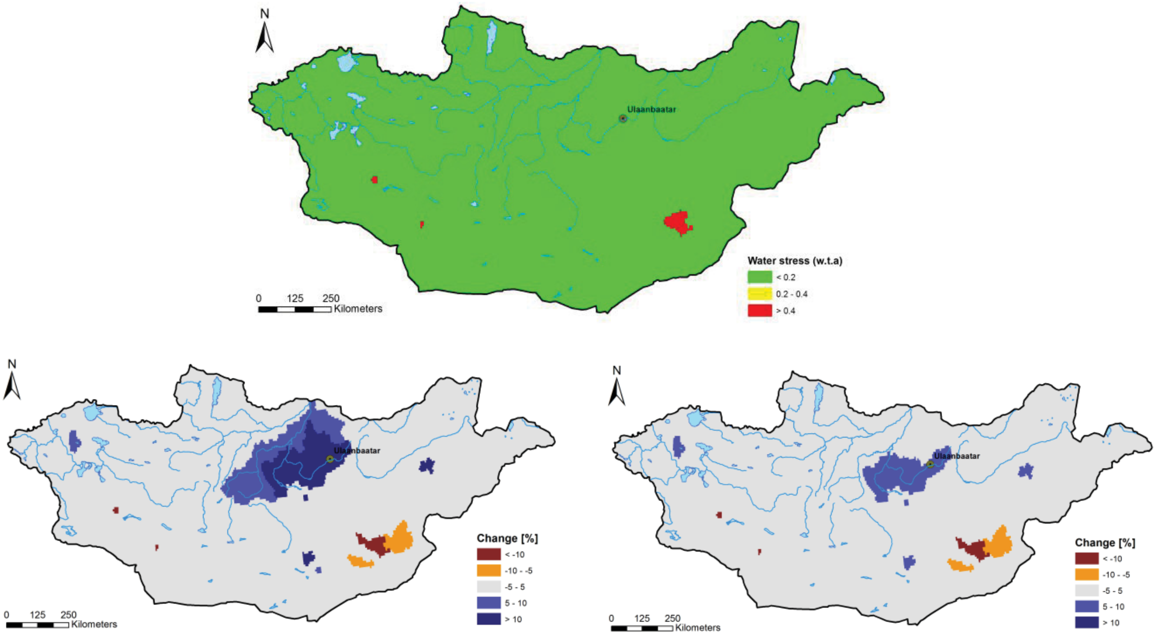

Figure 24: w.t.a. indicator for baseline (top) and scenario time period (bottom); scenario period is shown for ECHAM5 (Scenario-A, bottom-left, Scenario-B, bottom-right) as a baseline percentage difference

4.5.3. Water stress (c.t.Q90 indicator)

The consumption to Q90 indicator (c.t.Q90) is used to describe low-flow characteristics at river basin scale and incorporates long term effects. It is defined as the ratio of consumed water per river basin to Q90 low-flow, whereby Q90 means that the monthly discharge is higher than Q90 in 90 % of the time. The indicator is categorized in three divisions: low water stress 0-0.5, medium 0.5-1.0 and severe >1.0 (ALCAMO 2007). The c.t.Q90 provides a completely different picture compared to the w.t.a. indicator (see Figure 25). For the baseline, the most affected areas are located in the Southwest, South, and especially in the Southeast, while the northern part of Mongolia is nearly completely in the lowest category. The water stressed basins feature a very low precipitation and, therefore, small low-flows. Thus, water consumption surmounts the Q90 in the baseline period. For Scenario-A (economic growth) a clear decreasing trend in water stress can be found in the Southwest, while in the South, basins with increasing trend and decreasing trend are located next to each other. An increasing trend can be found in the Southeast of Ulaanbaatar and around the capital in the Tuul and Kharaa catchment. Scenario-B (sustainable production) leads to similar spatial patterns, but with a less severe trend. The biggest difference between both scenarios can be found around Ulaanbaatar, as Scenario-B does not show a water stress increase for the Kharaa and Tuul catchment. It has to be mentioned that the simulated low-flows are probably overrated, due to the overestimation of precipitation of the climate models and water stress is more severe than in the presented results.

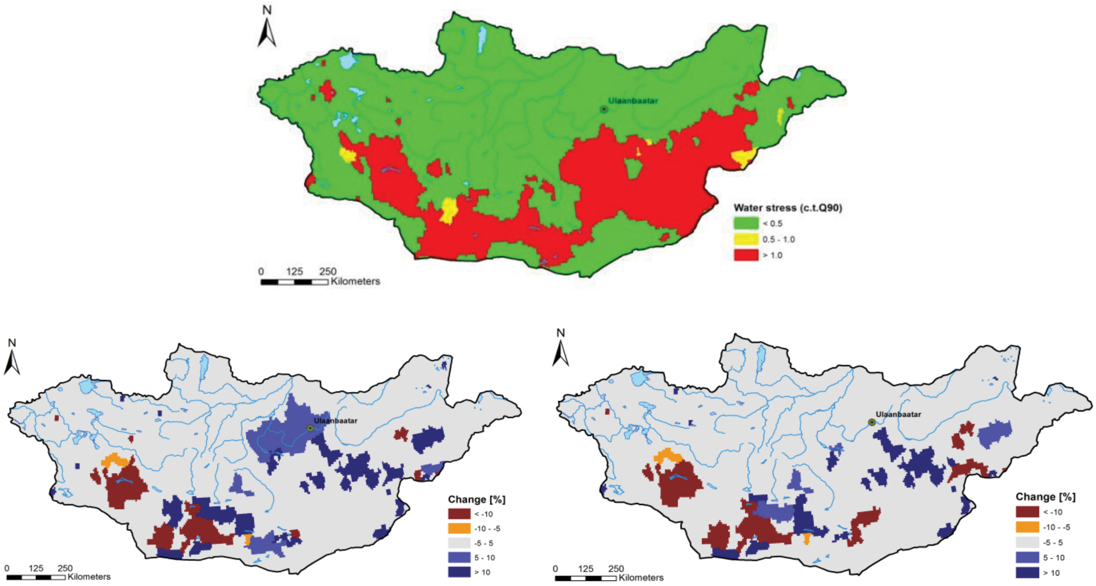

Figure 25: c.t.Q90 indicator for baseline (top) and scenario time period (bottom); scenario period is shown for ECHAM5 (Scenario-A, bottom-left, Scenario-B, bottom-right) as a baseline percentage difference

The results show, in terms of water stress, that Mongolia is divided into two parts. On the one hand, the northern part with higher water availability, but also higher water uses and on the other hand the southern part with low water availability and in general low water uses. Even though Mongolia is a very sparsely populated country, it features a growing population and an intense urbanisation trend. This will lead to rising water stress, especially in basins surrounding the capital Ulaanbaatar, as already nowadays 35 % of Mongolians live in Ulaanbaatar with an expected further increase (THE WORLD BANK 2012), although the water availability scenarios lead to increased water availability. In this connection, Tuul, Kharaa and Orkhon river basins are particularly affected. Furthermore, simulated future water availability is probably overestimated due to a bias between GCMs and observed WFD baseline. In this study, seasonality is not examined. At this point, even if no water stress was found on an annual basis, water stress can be an issue in several months of the year. It also needs to be mentioned that local water stress in sub-basins of a non-stressed river basin can occur, as the here applied method only looks at average water availability and use values of the entire river basin. Furthermore, the Tuul River basin may be affected by a planned multi-purpose dam to improve water supply of Ulaanbaatar (DAVAASUREN & BASANDORJ 2008). This leads to the conclusion that basins surrounding Ulaanbaatar need a water management strategy for a sustainable development and to avoid overexploitation of natural resources, and increasing water scarcity. As mentioned above Mongolia is a data scarce region and therefore a Monitoring network and long term measurement of water fluxes is essential. The southern part is characterised by very low precipitation and therefore low water availability and low-flows. Already nowadays many basins show water stress conditions due to higher water consumptions compared to Q90. Overexploitation of basins in the South in terms of withdrawal to availability ratio is induced by mining activities. In future it is planned to build canals from northern Mongolia to Gobi desert to supply mining activities. This will have a high impact on the water system of Mongolia and lead to increasing water stress in Kherlen and Orkhon river basin (see DAVAASUREN & BASANDORJ 2008, ENKHBAATAAR 2012). Also, water quality issues, which have not been tackled by this study, will become more important as they already are (HOFMANN ET AL. 2011) as the pressure on Mongolian water resources will increase. Additionally, environmental flow limits which ensure the survival of the riverine ecosystems need to be defined for each basin separately before additional industries and irrigation projects are planned in order to avoid the crossing of natural tipping points.

With regard to water uses a huge difference between global datasets and the national report (BATSUKH ET AL. 2008) has been found for the baseline in terms of irrigation and electricity production. All water use sectors rise rapidly for both socio-economic scenarios except electricity production. Irrigation is nowadays still mainly conducted with sprinkler technique, which leads to high evaporation losses and holds a big potential to reduce water abstractions due to more efficient irrigation techniques (e.g. drip irrigation). Also, a high daily amount for domestic water uses per capita was found in cities. At this, a high potential to water-saving measures (e.g. replacement of old technical equipment, use of water meters, raise of environmental awareness, introduction to water pricing) exists. For future research seasonal aspects and changes as well as trends in extreme events, especially droughts, should be examined to provide a better picture of the potential future changes and thus, for the basis for a sustainable water management.

4.6. Acknowledgements

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Chapter 5

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***What drives the water quality changes in the Selenga Basin: climate change or socio-economic development?* Regional Environmental Change, pp. 1-13.**

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

5.1. 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 WaterGAP 3 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-stream concentrations to get an insight into the state of water quality under current and future scenario conditions. The results show a strong increase of loadings in the scenario period and consequently increasing concentration levels. Comparing the sectoral contributions of the loadings, domestic and industry 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.

5.2. 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 21st century, Mongolian Statistical Information 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, mal-functioning 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; Hofmann et al. 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; Hofmann et al. 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 WaterGAP 3 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 (agriculture, industry, 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.

5.3. Materials and Methods

5.3.1. The WaterGAP 3 modelling framework

The global integrated water resource model WaterGAP 3 (see Figure 26) 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 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; Flörke et al. 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).

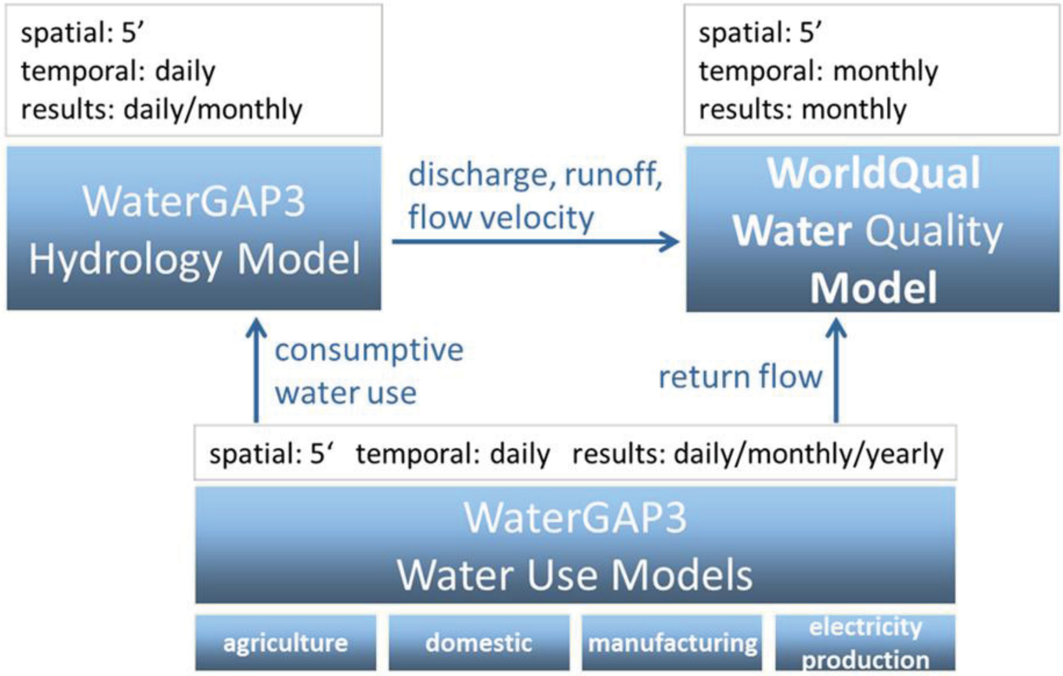

Figure 26: WaterGAP modelling framework (Verzano 2009, modified)

Climate data on precipitation, air temperature, and radiation from the WATCH forcing data (WFD, Weedon et al. 2011) was used to calculate the daily water balance for each grid cell for the time period 1971 to 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 to 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 Figure 27) 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 are considered as point (e.g. hanging latrines) and diffuse (e.g. open defecation) sources depending on the type of disposal.

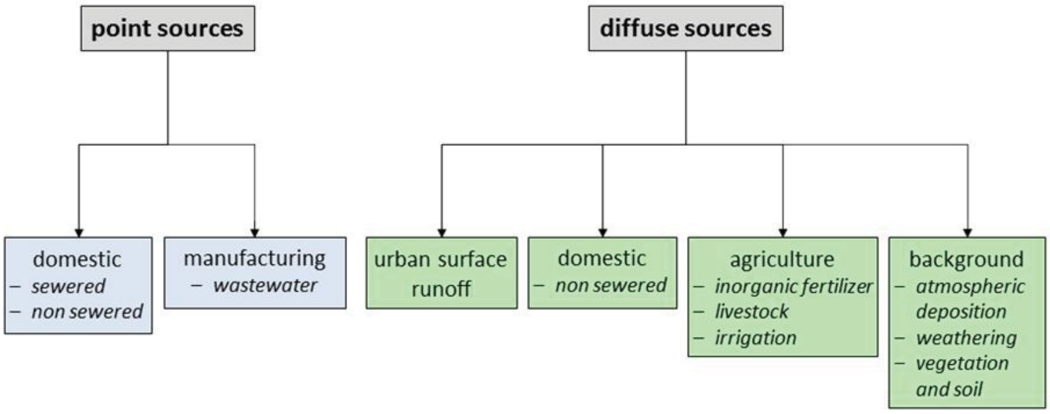

Figure 27: Pollutant loading sectors represented in WorldQual categorized as either point sources or diffuse sources (Reder et al. 2015, modified)

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.: 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 8.

Table 8: Input data assumptions for Mongolia

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

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.

5.3.2. Study region

The Selenga River basin (see Figure 28 left) 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, 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 Figure 28 right). 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 underlayed by mountain and arid-land permafrost (Gruber 2012; Kopp et al. 2014, and 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 1940-2001), whereas no clear trend could be detected for the summer season (Batimaa et al. 2005; Malsy et al. 2012; Törnqvist et al. 2014).

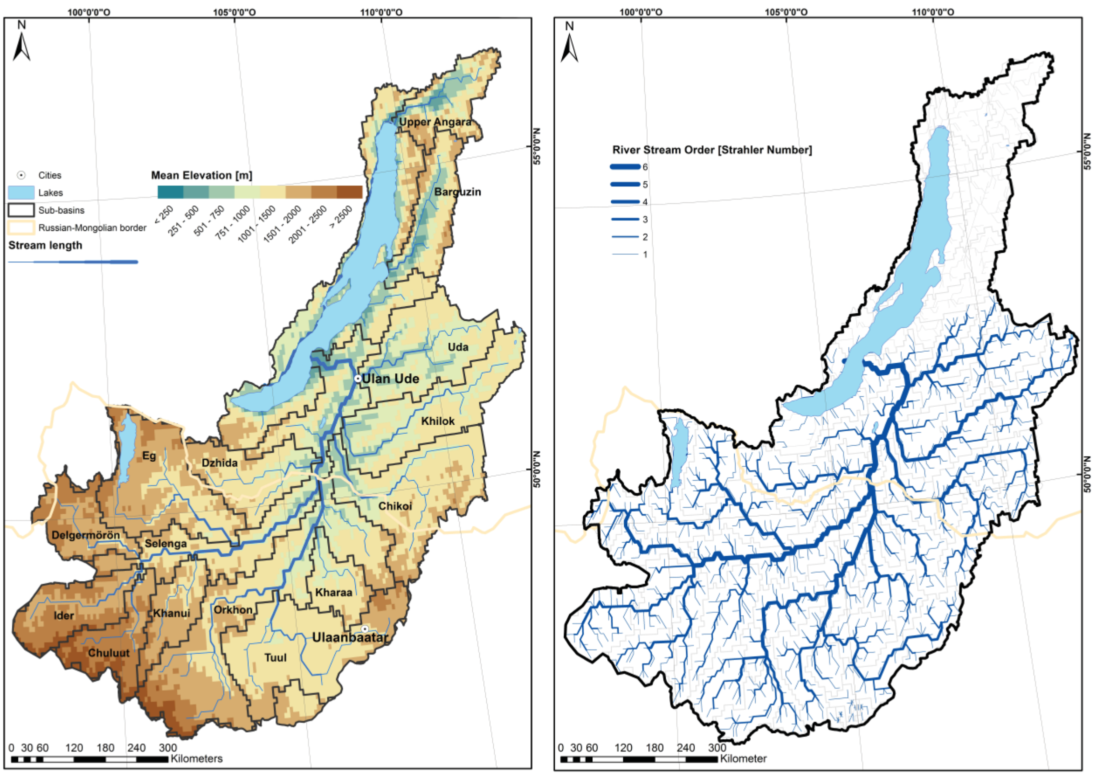

Figure 28: left: Overview of the study region including the sub-basins contributing to the Selenga-Lake Baikal River System; right: Strahler stream order number for the Selenga River Basin

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 21st 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 10). 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 9. 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 abstractions, particularly in the domestic (from 82 mill. m^3 to 367 mill m^3) and mining (from 81 mill. m^3 to 343 mill. m^3) 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).

Table 9: 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	+	

Table 10: 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

5.4. 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 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 Figure 29) 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.

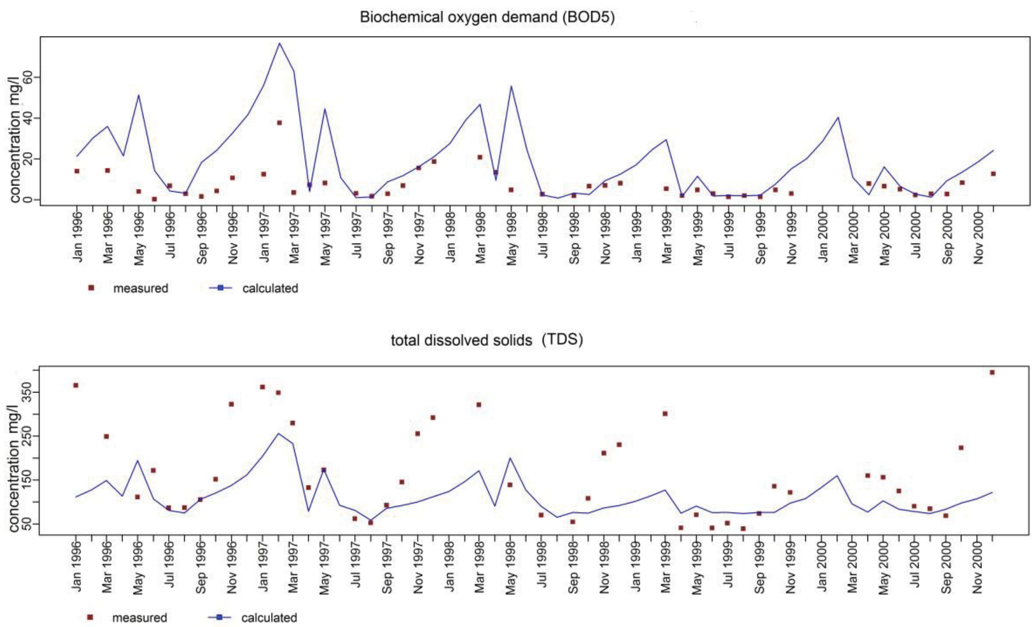

Figure 29: Validation of simulated BOD (top) and TDS (bottom) in-stream concentration at Ulaanbaatar for the time period 1996-2000

5.5. Results and Discussion

The simulation results for the Mongolian part of the Selenga River Basin (cf. Table 11) show a strong increase of 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 to 2012.

Looking at the main sources contributing to the annual loadings (cf. Table 12) for biological oxygen demand, Domestic - sewered (41.5 %) and Industry (39.8 %) are the main sources in the baseline period followed by Domestic - non-sewered (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 percent of the total loadings. For the scenario period, Industry has by far the highest share (74.6 %) followed by Domestic - sewered (16.2 %), Domestic non-sewered (7.1 %) and Livestock (2.0 %). For FC, Domestic (sewered and non-sewered) is clearly the dominant source in the baseline as well as in the scenario period. Here, the share of Domestic - sewered decreases from 73.7 % in the baseline to around 63 % in the scenario period, but persists as dominant source followed by Domestic - non sewered with about 29 %. This is caused by a population increase which is not accompanied by enhanced connection rates or wastewater treatment. 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.

Table 11: 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). For TDS only the anthropogenic loadings (without natural background) are shown

Parameter	Loadings BOD, TDS [t/a], FC [10^10 cfu/a]			
	Baseline	Scenario - average	Scenario - dry	Scenario - wet
BOD	9,832	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

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 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 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 as well as mining processes. These are already the major water user (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.

Table 12: Sectoral contribution to total annual loading for the baseline and scenario period; values are given in percent

Parameter - Time Period	Domestic - sewered	Industry	Domestic - 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

Looking at spatial patterns of simulated loadings (see Figure 30) 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 River. 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).

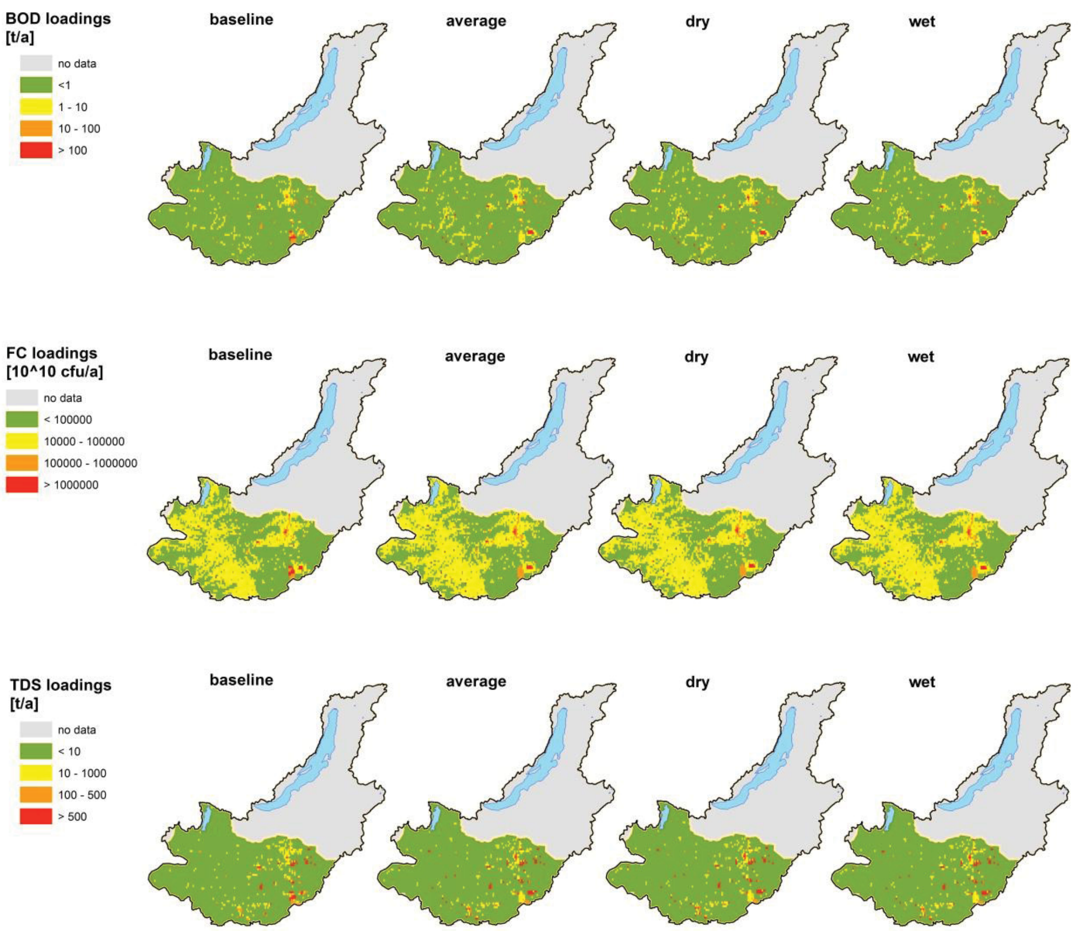

Figure 30: Spatial patterns for BOD (top), FC (middle) and TDS (bottom) loadings for the baseline and scenario period. For TDS background loadings are not show in this Figure

Concentrations for BOD, FC, and TDS (see Figure 31) are shown for May, as this month shows on the one hand effects of snow-melt (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 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 12) and the higher dilution capacity in the wet scenario. The hotspot 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.

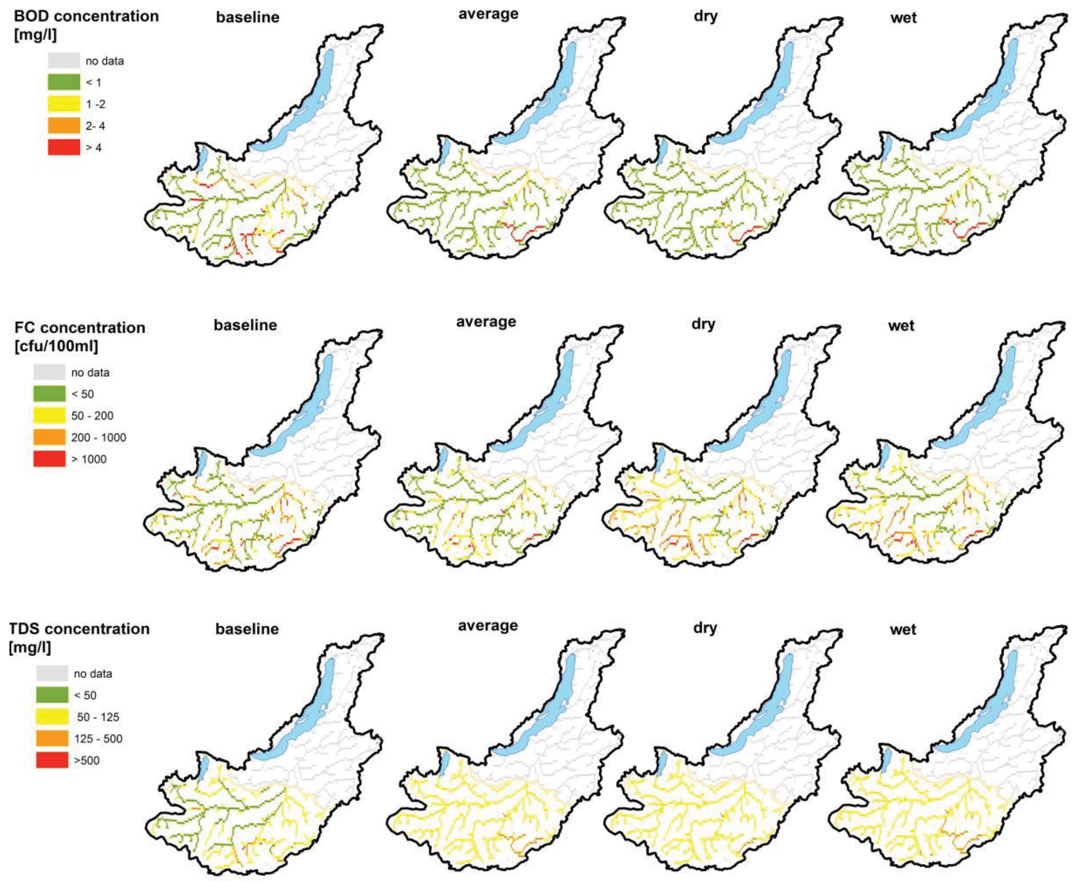

Figure 31: Spatial patterns for FC (top), BOD (middle) and TDS (bottom) in-stream concentration in May for the baseline and scenario period

To gain further insight in the development of concentrations, for May cumulative distribution functions (see Figure 32) 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 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. Figure 30), 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 Selenga 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 Selenga River Basin, in particular in the Tuul, Kharaa, and Orkhon River. 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 a lot of small mining sites are located and placer mining, i.e. the mining of stream bed deposits, is used in the study region, which leads to increasing pollution (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 snow melt 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.

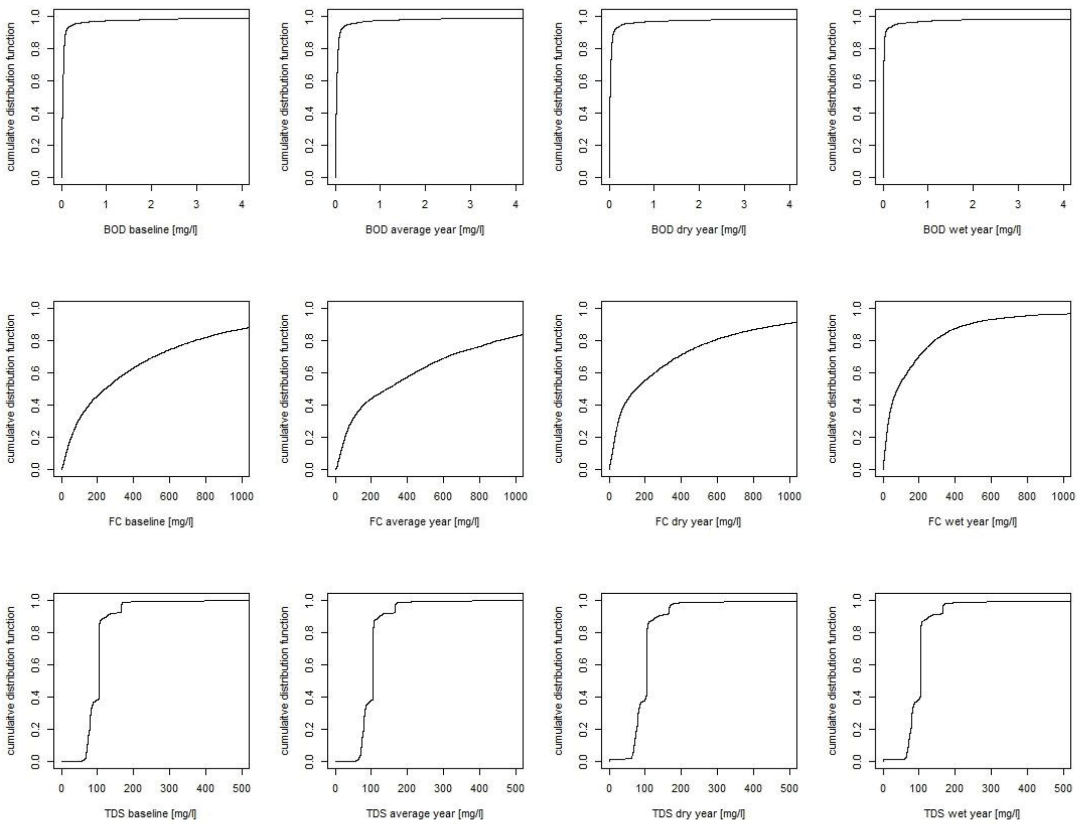

Figure 32: Cumulative distribution function for FC (top), BOD (middle), and TDS (bottom) for the baseline and the scenario period

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 to 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.

5.6. 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 hotspots. 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 industry (40 %-75 %) sectors and hotspots can be found in the Tuul and Kharaa sub-basins where densely populated areas and/or areas with industrial activities, e.g., mining, 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 hotspots 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. Hotspots 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 is not available for large parts of the study region (Karthe 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 hotspots 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.

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Appendix

References to own published articles used in the present thesis

Chapter 2 has been already published under the title:

Malsy M, aus der Beek T, Flörke M (2015). Evaluation of large-scale precipitation data sets for water resources modelling in Central Asia. Environmental Earth Sciences, 73, 2, 787-799.

The final publication is available at: http://link.springer.com/article/10.1007/s12665-014-3107-y

Chapter 3 has been already published under the title:

Malsy M, aus der Beek T, Eisner S, Flörke M (2012). Climate change impacts on Central Asian water resources. Advances in Geosciences, 32, 77-83.

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Chapter 4 has been already published under the title:

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, 27-49.

The Chapter differs from the final published article in the following respects: German Summary was removed.

The final publication is available at: https://www.uni-goettingen.de/de/2013/479170.html

Chapter 5 has been already published under the title:

Malsy M, Flörke M, Borchardt D (2016). What drives the water quality changes in the Selenga Basin: climate change or socio-economic development? Regional Environmental Change, 1-13.

The final publication is available at: http://link.springer.com/article/10.1007/s10113-016-1005-4

For all chapters the numbering (e.g. Figures and Tables) has been changed to a continuous numbering throughout the thesis.

Further Publications

During the preparation of this thesis I have been author or co-author of the following relevant publications, which are not part the thesis:

Karthe D, Chalov S, Moreydo V, Efimov V, Romanchenko A, Batbayar G, Kalugin A, Westphal K, Flörke M, Malsy M (submitted). Assessment of Runoff, Water and Sediment Quality in the Selenga River Basin aided by a Web-Based Geoservice. Water Resources.

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