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Land Use Policy 28 (2011) 4–10

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

The consequences of land-use change and water demands in Central Mongolia

Joerg A. Priess[a,b,*], Christian Schweitzer[a,b], Florian Wimmer[b], Ochirbat Batkhishig[c], Matthias Mimler[b]

[a] Helmholtz Centre for Environmental Research – UFZ, Department of Computational Landscape Ecology – CLE, Permoser Str. 15, D-04318 Leipzig, Saxony, Germany
[b] Center for Environmental Systems Research – CESR, University of Kassel Kurt-Wolters-Str. 3, D-34109 Kassel, Germany
[c] Soil Laboratory, Institute of Geography – Mongolian Academy of Science, P.O. Box 468, Ulaanbaatar 210349, Mongolia

ARTICLE INFO

Article history:
Received 17 July 2009
Received in revised form 1 March 2010
Accepted 8 March 2010

Keywords:
Hydrological model
Integrated water resources management (IWRM)
Land-use model
Mongolian agriculture
SITE framework
Socio-environmental system
Water use

ABSTRACT

After two decades of decreasing agricultural activities, in 2008 the Mongolian government started the "Third Campaign of Reclaiming Virgin Lands", aiming at massive expansion and intensification of the agricultural sector. This policy motivated the study presented here, for which we used an integrated modelling approach to investigate the feedbacks between land-use dynamics, agricultural management and biophysical conditions, with a strong focus on assessing availability of water for irrigation. Our simulation results clearly show that under the current extend of irrigated agriculture in several years water demands exceeded water availability, indicating an overexploitation of water resources, mainly in the period 1995–2006. Consequently, the targeted expansion of agricultural water use will either severely deplete water resources with potential negative effects on other users and the environment, or policies are needed to mitigate or avoid potential adverse effects. As simultaneously Mongolian authorities struggle to implement integrated water resources management (IWRM), the latter might provide monitoring concepts and regulations needed to minimise the potential gap between water demands and availability. In this context, integrated modelling could be a scientific tool to support future land and water management decisions, as researchers already started to integrate views and demands of Mongolian authorities into scenario and model development (identified during stakeholder workshops), and will continue to do so during the coming years of collaborative research.

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Introduction

Mongolia's transition towards a market economy is still on its way, and in the last two decades almost every economic sector has undergone reorganisation facing the chances and challenges of globalisation. Major changes have also been observed in the most land intensive sectors crop production, grazing and forestry. Increasing numbers of cattle and other livestock, and increasing sedentism mostly of wealthy herding families (Fernandez-Gimenez, 2004) are ongoing processes driven by incentives of living closer to attractive new markets, promising job and trade opportunities and the benefits of social and other services. The agricultural sector faced a period of abandonment of land after the communist period. Formerly state-managed farms were no longer profitable for private farmers and were partly given up. In Mongolia, the agricultural sector is constrained by short growing seasons, and strongly continental weather (very cold winters and hot summers), limited water availability and the lack of financial resources for the application of agro-chemicals including fertilizers. Furthermore, most farmers cannot afford neither to buy irrigation equipment, nor agricultural machinery. Recent national scale land-use policies are targeted towards a re-intensification of agricultural land use, aiming at the independence of food imports. In the "Third Campaign of Reclaiming Virgin Lands" (Bayar, 2008), which is supported by credits from Russia and the Asian Development Bank, it is planned to achieve the food self-sufficiency target via cheap loans for farmers and subsidies for irrigation equipment, machinery, fertilisers and a new composition of adapted crop varieties. Simultaneously in the (gold) mining sector, highly water demanding activities can be expected to increase, as mining generates the major fraction of the government budget (NSO, 2007) and world market prices for most mining products have been strongly falling since 2007/08. Furthermore, climate change is expected to bring higher temperatures resulting in increased evapotranspiration, and the same or slightly increased amounts of rain (Bates et al., 2008; Batima et al., 2005), and an overall increase in rainfall variability (IPCC, 2007). All of the policies, activities and processes mentioned above decrease water availability or increase water demands or both, resulting in challenging scientific, political and management tasks under the present and future semi-arid to arid climate conditions in Mongolia.

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[*] Corresponding author. Tel.: +49 341 235 1879; fax: +49 341 235 1879.
E-mail address: joerg.priess@ufz.de (J.A. Priess).

0264-8377/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.landusepol.2010.03.002

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An appropriate methodology to analyse and quantify dynamics, interactions and impacts of various components of socio-environmental systems, is provided by the development and application of integrated land-use models (GLP, 2005). Ideally, these models enable us to analyse the complex structure of linkages and feedbacks and to determine the impact of various driving forces (Heistermann et al., 2006). Land-use models are used to project how much land is used where and for which purpose under different boundary conditions or scenarios, and conduct simulation experiments testing our understanding, e.g. of the stability of socio-environmental systems (Veldkamp and Lambin, 2001) and quantitatively describing key processes (Lambin et al., 2000). In their review Schaldach and Priess (2008) point out that even recent approaches of integrated models of the land system represent the links and feedback mechanisms between human activities and the biophysical world, and the resulting socio-environmental impacts mostly in still very simple ways. In accordance with research priorities identified by the Global Land Project (GLP, 2005), they conclude that more research efforts are needed to improve existing and develop new integrated modelling approaches.

In this paper we study the potential consequences of recent land-use policies and policy goals in Mongolia, analysing and evaluating land use and land-cover dynamics and impacts on intensified agriculture focusing on water demand and water use. We demonstrate the advantages of coupling models representing land- and water use in a common framework to study land-use policies and their impacts. Furthermore, we discuss new insights generated, comparing coupled and uncoupled land use–water use simulations.

Materials and methods

Study region

This study was carried out within the project 'Integrated Water Resources Management in Central Asia: Model Region Mongolia' (MoMo), a joint Mongolian-German project aiming at the development of sustainable management strategies adapted to a river basin with typical water related problems (e.g. contamination, over use, potential water-use conflicts).

The Kharaa catchment (14,553 km^2) in which the study is conducted, is located north of the capital Ulaanbaatar (Fig. 1). Mean annual precipitation (1970–2000) is 250–320 mm, of which approximately 90% is lost via evapotranspiration. Elevation ranges from 600 to 2500 m.a.s.l. Mean annual air temperature is 0.4 °C. The major land-covers are grasslands (60%), forests (26%) and croplands (11%). Short vegetation periods and restricted water availability during the growing season are main factors limiting the productivity of Mongolian agriculture (and natural vegetation). It is noteworthy that a major fraction of Mongolian intensified agriculture is concentrated in the Kharaa catchment, although it covers only a small fraction of the Mongolian territory.

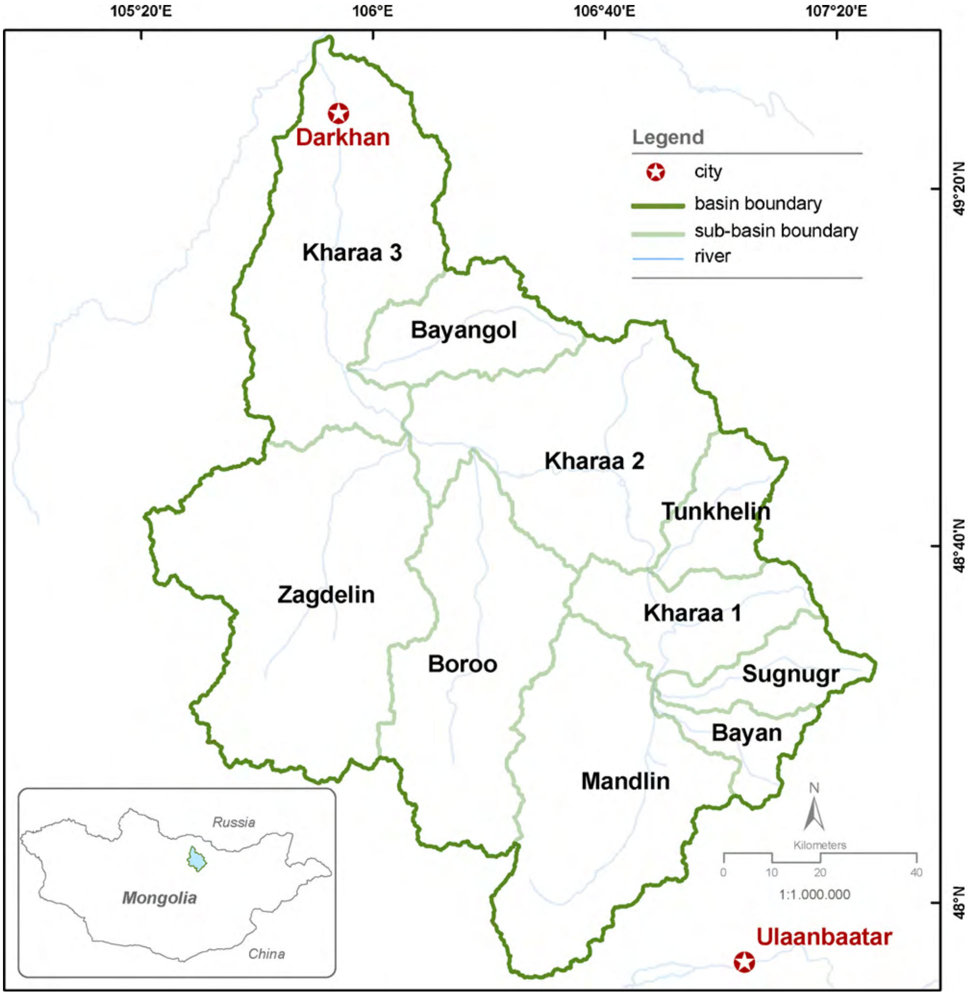

Fig. 1. The Kharaa catchment and its sub-catchments in Mongolia.

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The SITE framework—a software tool for spatially explicit modelling of land- and water use

The SITE (*SI*mulation of *T*errestrial *E*nvironments) modelling framework has been developed over the last years as a tool to simulate regional land-use dynamics and their impacts on environmental and socio-economic parameters. SITE has been applied in several studies in Europe, Central, South and South-East Asia (Das et al., 2010; Mimler and Priess, 2008; Priess et al., 2007a,b; Schweitzer and Priess, 2009).

The software design of SITE follows a modular component-based approach to reduce software complexity and to facilitate further development of the software, as well as the adaptation to new research questions and/or regions. The main SITE-components in this case study are:

- the MoMo land-model to simulate land use and land-cover dynamics, including a process-based biophysical component to simulate the growth of crops and natural vegetation, and
- the MoMo hydro-model to simulate vertical water fluxes and water redistribution.

SITE model structure and framework components are presented in the following paragraphs and in more detail in electronic supplement of this paper.

Land-model

The MoMo land-model is being developed to study regional dynamics and future scenarios with a strong focus on water resources and water use. In this case study, the biophysical environment is represented by a regular 1 km × 1 km grid. The model employs a rule-based approach, integrating spatial and statistical data from various sources, as well as knowledge and information provided by experts (Priess et al., 2007a; Erasmi and Priess, 2007).

Land-use decisions are simulated once a year in three steps. The first step consists of a multi-criteria analysis based on biophysical and socio-economic parameters (e.g. slope, distances to roads and settlements, rainfall, soil fertility, crop yield), carried out for each land-use category and each pixel individually. Outcomes are dynamic suitability maps, which are updated every time step. Throughout the suitability assessment normalized values are calculated to enable direct comparison and competition between different land-use types. In the second step, land-use types are allocated (i) driven by the regional demand for commodities such as space for housing, manufacturing or agricultural products, and (ii) based on their relative suitability in a given pixel (see Priess et al., 2007b). Finally, for the calculation of crop yields and plant biomass, the well established ecosystem model DayCent is used, simulating plant growth in daily time steps (Parton et al., 1998, 2001). DayCent was developed to simulate soil and vegetation dynamics at the field or ecosystem scale, but has successfully been applied from regional to global scales (Del Grosso et al., 2006; Lu et al., 2001; Stehfest et al., 2007). In the SITE framework DayCent in its version 4.5 was employed, including enhanced subroutines to simulate the nitrogen cycle (Stehfest, 2005). DayCent provides the possibility to simulate irrigation events. Options are (i) to apply a certain amount of water at a specific point in time or (ii) automatic mode, which is triggered by the fraction of plant-available soil water and kept above a predefined threshold value. We decided to trigger the irrigation events using the latter mode which is linked to the soil water deficit. In our study we simulated the common practice of irrigation for a 2-month period per growing season. The auto-mode eliminates the soil water deficit if it reaches the critical state of 50% below field capacity. The first irrigation event starts in late April, early May, to reduce salt accumulation during the pre-sawing phase. The second irrigation event was scheduled July 1st, approximately in the middle of the growing period. The simulated scheduling reflects current irrigation practise reported by farmers. Details about DayCent input data, parameterisation of crops and agricultural management are provided in the electronic supplement.

Hydrological model

The main task of the MoMo hydro-model is rainfall-runoff modelling, including the simulation of vertical water fluxes using the TRAIN model (Menzel, 1996, 1997). The subsequent routing of lateral water fluxes was implemented in the SITE framework. The model estimates potential water withdrawals for irrigation from surface waters based on simulated river discharge. The latter allows setting up an innovative model coupling with the MoMo land-model, dynamically linking biophysical conditions and land management.

The simulation of regional hydrology follows a step-wise procedure.

First, TRAIN computes the vertical water fluxes (e.g. evapotranspiration, surface runoff and percolation rate) for all grid cells driven by meteorological data. Second, surface runoff and percolation of all cells in the watershed of individual channel reaches are aggregated. In a final step, discharge (Q) in each channel reach is calculated using a cascade of reservoirs with linear storage–discharge relationship (e.g. Maniak, 2005). Third, during the growing season (May to August) irrigation of crop cells in a sub-basin is simulated if $Q > Q_{30}$, with Q_{30} defined as mean daily discharge exceeded in 30% of events. The actual withdrawal of irrigation water is limited to 2500 $m^3\,d^{-1}$ per irrigated crop cell (1 km^2). Withdrawals are multiplied by an efficiency factor of 0.46 (Kulkarni et al., 2006) lumping together water losses of the irrigation system. The resulting available irrigation water is accumulated and applied in two irrigation events following the same schedule as implemented in DayCent (see “Land model” section).

Linking land and water related processes

Fig. 2 shows a simplified schematic diagram of the coupled modelling approach linking land and hydrological components. The amount of water available for irrigation is calculated by the MoMo hydro-model and provided to the irrigated crop cells. This information is used by the vegetation model DayCent to simulate plant biomass and crop yields. Vice versa the hydrological model receives dynamic maps of land use and land-cover, as well as cells suitable for irrigation. Therefore the coupled system enables the representation of changes in catchment hydrology and dynamically calculated irrigation water availability and application.

Average cultivated area is approximately 59,000 ha of which approximately 6000 ha are irrigated. Fallows sum up to 93,000 ha. Note that the transition from socialist to market-oriented agriculture caused a considerable decrease in land-use intensity and spatial extend of agriculture during the period 1990–2006. The described trend is strongly reversed by current policies aiming at (re-)expansion and (re-)intensification of agriculture (see Chapters 1 and 4).

The models used are driven by spatially explicit data. Both, the MoMo-hydro and the MoMo land-model use spatially interpolated meteorological data provided by the Institute of Meteorology and Hydrology, Ulan Bator (Dr. G. Davaa, pers. comm., 2007). Elevation, slope and drainage direction of the grid cells were derived from the HydroSHEDS dataset (Lehner et al., 2006). Soil properties were derived from a refined soil map of the Kharaa catchment based on a large scale soil map of Mongolia (Dorjgotov, 2003) updated with results from soil campains in 2008 and 2009 conducted by one of the authors (O.B.). Reported data of texture and organic content

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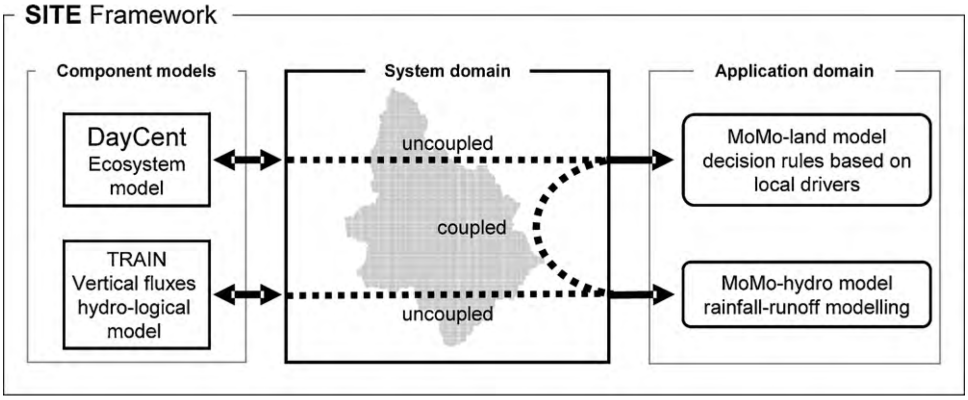

Fig. 2. The SITE modelling framework. Flow of information in the coupled version including the MoMo hydro-model, and the uncoupled version.

from soil profiles were used to estimate bulk density, hydraulic permeability and volumetric soil water content at saturation, field capacity, and permanent wilting point (AG Boden, 1994).

Results

Agricultural yields

Yields of the main crops spring wheat and potato were reported and simulated for the period 1989–2006. Yields and cropped areas decreased after the end of the socialist period, during which agricultural production was strongly subsidised. Starting in 1991, decreasing fertiliser inputs were reflected in lower yield levels and production with high interannual variabilities, the latter mainly due to a strong variation in summer rains. Table 1 presents an overview of reported and simulated yields grown under rainfed conditions, which were comparable to yields in neighbouring districts (data not shown here).

Agricultural land under production decreased considerably between 1990 and 2006. In the period 2003–2006 reported here, approximately 3/4 of the 135,000 ha of agricultural land were under fallow, while only ~35,000 ha were cultivated, mostly located in the floodplains around villages and cities (see Fig. 3). In the simulations on average, 5600 ha were irrigated, the spatial extent in dry years increasing up to ~14,000 ha. In Fig. 3 all grid cells irrigated at least once during the simulated period 1989–2006 are

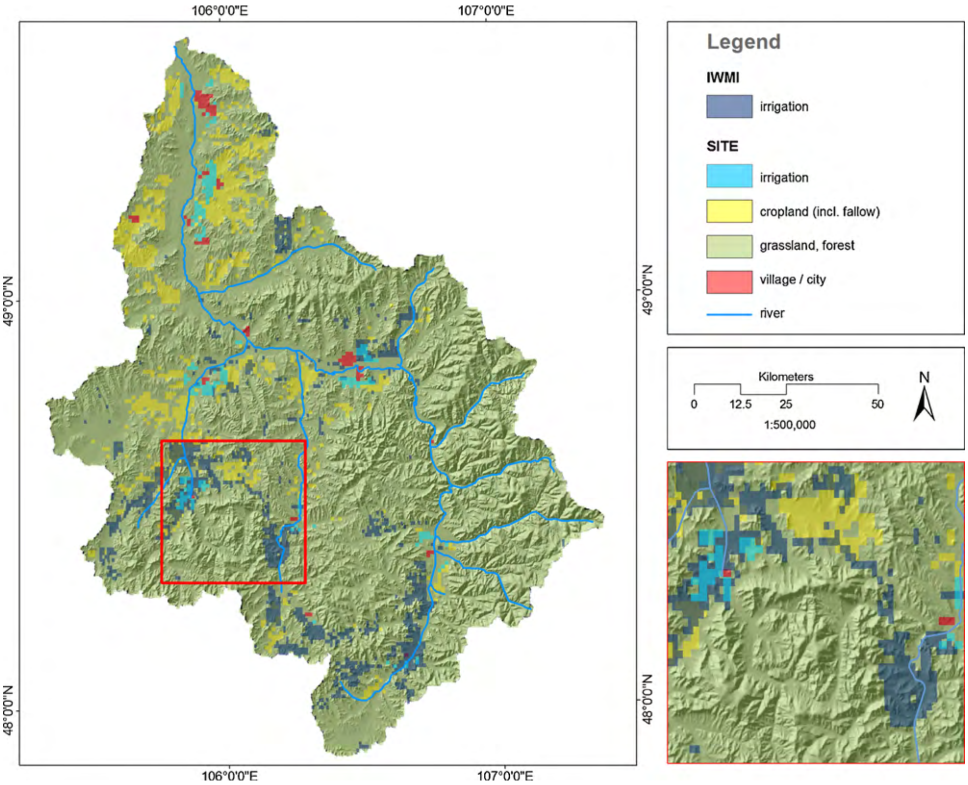

Fig. 3. Land use and irrigated areas. Land use and land-cover simulated for the year 2006 have been aggregated to the classes cropland (yellow: including fallow land), grassland and forest (green) and built up land (red: urban and rural settlements). Simulated irrigated cropland (light blue: comprising all grid cells irrigated at least once during the simulation period 1989–2006) and irrigated cropland from the Global Irrigated Area Map (GIAM v 2.0) by IWMI (dark blue). Note that considerable fractions of the GIAM-estimates are located on slopes and ridges (see map details on the right side). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

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Table 1
Rainfed crop yields in the Kharaa catchment 1989–2006 (Mg/ha).

Period	Wheat yields		Potato yields	
	Reported	Simulated	Reported	Simulated
1989–1991	1.2	1.1	11.9	10.9
1992–1994	1.1	1.2	8.8	10.3
1995–1997	0.8	0.8	9.4	7.9
1998–2000	0.7	1.0	8.7	8.5
2001–2003	0.6	0.6	7.5	6.5
2004–2006	0.9	0.8	8.7	8.7

More details about crop yields and model calibration are provided in electronic supplement. Values have been recalculated for the Kharaa catchment from district (Aimag) statistics.

presented (light blue). Validation and plausibility tests of simulated cropland and irrigated land using GLOBCover (ESA, 2009) and IWMI (Thenkabail et al., 2008) global data products, are presented in electronic supplement.

Sustainable and unsustainable irrigation

In order to analyse the potential new insights generated by the coupled modelling system, average crop yields were calculated in coupled (irrigation limited by water availability) and uncoupled (unlimited irrigation) simulation runs and compared on sub-basin scale. Fig. 4 shows the overestimation of wheat and potato yields by the uncoupled version in comparison to the coupled as reference. In the more intensively used agricultural areas (e.g. Mandalin, Zagdelin, Kharaa 2) yields achieved with unlimited irrigation were up to 9% higher for wheat and up to 15% for potato. This can be explained by the low discharge within these river tributaries. Contrastingly, in downstream areas (Khaaraa3, Bayangol) river discharge accumulates. Hence the gap between simulated water availability and demand is almost closed, which is mirrored in low calculated crop yield differences with and without water limitation. Due to the absence of irrigated areas in the eastern sub-basins (Bayan, Sugnugr, Kharaa 1, Tunkhelin), where runoff rates are high, no increase in yield levels was observed.

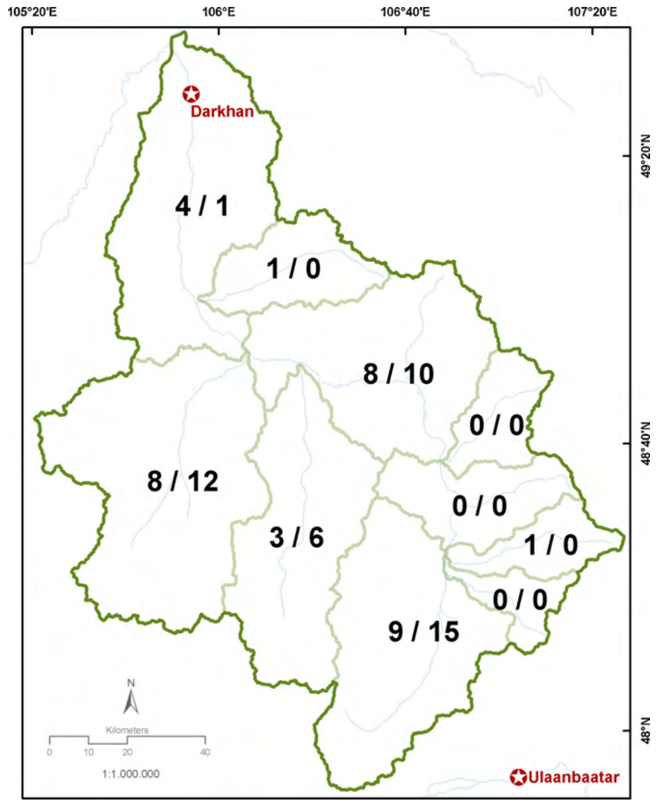

Fig. 4. Simulated crop yields under water limited and unconstrained conditions. Sustainable (water limited) production is used as reference. First number: overestimation of wheat yields; second number: overestimation of potato yields in percent.

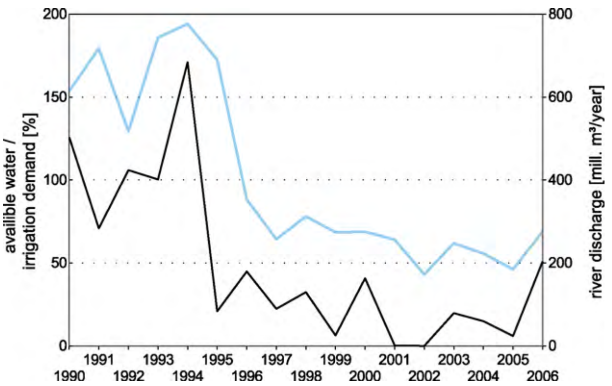

Fig. 5. Ratio of water available for irrigation to irrigation demand and measured river discharge. Narrow line, left axis: ratio of availability and demand (relevant for the coupled = water limited simulation); wide line, right axis: river discharge.

In Fig. 4 the level of crop yields simulated without water limitation (uncoupled) is compared to yields of the water limited (coupled) runs. Yields were averaged over the entire period 1990–2006. Not only clear spatial patterns, but also clear temporal patterns could be observed. In Fig. 5 water demand versus availability is presented. In the years 1990, 1992, 1993 and 1994 demands for irrigation water could be satisfied. In fact, availability clearly exceeded agricultural demands. Apparently related to a strong decline in measured river discharge starting in 1995, less than 50% of the simulated demand could be fulfilled during the second half of the period (without depleting water resources). This can be explained by an increase in potential evapotranspiration due to higher summer temperatures and lower air humidity. Additionally, even though total annual precipitation does not show a significant trend, winter snowfall tended to increase, while rainfall in summer decreased. These changes in precipitation pattern lead to higher evaporation rates from snow and therefore to less runoff generation (results not presented here).

Fig. 5 shows the ratio of water available for irrigation to irrigation demand, simulated by the MoMo hydro-model. For illustration, measured river discharge is presented. If crop yields are among other factors limited by the availability of water, the agricultural area needed to produce the same amount of crop is larger under water limited conditions. In our simulation study the known amount of crops produced in the period 1990–2006 was simulated both in the coupled (water limited) and uncoupled runs. The demand for agricultural area was on average 10% (∼6000 ha) higher in the coupled (often water limited) version, corresponding to the differences in yield levels shown in Fig. 4.

Discussion

Recently, the third campaign of land reclamation was launched in Mongolia, aiming to decrease food imports via (re-)intensification of agricultural land use (Badrakh, 2008; Bayar, 2008). This policy has two major consequences. Firstly, since 2008 agricultural areas were increased by 50,000 ha (for the whole country), converting and ploughing natural vegetation (mainly grasslands) and given up land or fallows to agricultural lands (Bulgamaa,

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2008). Secondly, the agricultural sector will severely increase the use of already scarce water resources, motivated by subsidised water fees, irrigation equipment and cheap loans (Hantulga, 2009). Consequently, the competition for water, e.g. between water users of different sectors such as households, industry, mining and agriculture is increasing. Comparable developments have been reported from other parts of Asia and Africa, although the importance of economic sectors as water users varies considerably between regions (Batchelor et al., 2003; Kluge et al., 2008; Ngigi et al., 2007). Land- and water use dynamics and the policy process described above motivated the assessment of spatial and temporal variations and seasonal dynamics of water demand and availability, which are presented in this paper. The set of models coupled in the SITE framework enabled us to assess the potentials and limits of irrigated agriculture via simulating the feedback mechanisms between hydrology (i.e. water availability) and land use (spatial extend, management and crop yields of irrigated crops).

Our results clearly demonstrate the need for and the advantages of approaches, which are sensitive to the regional hydrological variability and allow more realistic estimates of sustainably attainable crop yields. The term sustainable in this context is referring to a management strategy taking limitations in water availability into account, thus avoiding overexploiting water resources (other aspects of sustainability such as social or economic factors are not considered here). Contrastingly, the uncoupled model version only takes into account the irrigation water needed to keep soil moisture above a certain level to maximise plant production, assuming unlimited availability of surface and/or groundwater resources. The latter is representing the present situation in Mongolia. Currently two competing policies are on the way, severely affecting land- and water use, namely agricultural expansion and intensification and implementation of integrated water resources management (IWRM). Firstly, based on the “Third Campaign of Reclaiming Virgin Lands” (Bayar, 2008), which is supported by a 300 Mio. US$ credit from Russia (Hantulga, 2009), the Mongolian government started in 2008 to convert additional 50,000 ha to agricultural land. To a great extend, suitable land to be converted is located in the research area, the Kharaa basin and the neighbouring Selenge and Tuul basin. As a consequence, the agricultural area will increase approximately 50–100% (depending on whether fallows are included in the calculation or not). We have shown that even under the current extend of agricultural land use, water demands may considerably exceed availability. Thus, even if (subsidised) more efficient irrigation technologies are installed, the demand for water is expected to drastically increase from 2009 onwards. Our results clearly indicate that in the short term it is possible to produce more crops at the cost of depleting (ground-) water resources and/or reducing water availability for downstream users. The effects described above have repeatedly been reported from locations around the globe, and are expected to aggravate in many arid and semi-arid regions due to Climate Change (Bates et al., 2008). It has been argued that comprehensive policies combining land-use planning and integrated water resources management should be able to avoid or solve these problems (e.g. Mitchell, 2005). Thus, to assess whether water demands exceed availability, and to ensure long-term resource availability without negative ecological and economic impacts, appropriate monitoring and governance structures are urgently needed. To date, neither the monitoring concepts nor the governance structures, nor rules or regulations are in place to adequately manage water use. However, the Mongolian government currently undertakes multiple efforts to establish regulations and administrative units for a catchment-based integrated water management (the second policy affecting land- and water use). These efforts are involving ministries, the National Water Agency and national research institutions as well as various international partners (Badrakh, 2008, Water Authority and R. Mijidorj, 2008, National Academy of Science, pers. comm.).

Simultaneously, recent government assessments of the National water resources documented multiple reductions or complete disappearances of wells and creeks within the last years. Whether the observed changes are caused by climatic factors or human use or a combination of both remains unresolved (Batsukh et al., 2008). Based on historical and current water use and technology, it is obvious from our results that water availability in the catchment might limit sustainable water supply of the targeted additional 50,000 ha of agricultural land (Bulgamaa, 2008), even if we conservatively assume that the fraction of irrigated land remains at the current level of approximately 10%. The current often almost open access like situation provides little incentives for behavioural changes or the introduction of (costly) water saving technologies. As actual water consumption in agriculture, mining and households faces little or no control at all. Neither the ratio of surface to groundwater use, nor the volume of groundwater available in the catchment is known, and therefore it is currently impossible to predict the immediate and long-term negative consequences of overexploiting the water resources. Besides estimates of current and potential water use, clear rules are needed how water resources can be used, including mechanisms of control and enforcement, a task of the River Basin Organizations (RBOs), which are currently being established. RBO-establishment is considered an important step in the implementation of integrated river basin management (IRBM), as a tool of IWRM. In addition, incentives for water saving behaviour and technologies could help minimise the potential gap between water demands and availability, not only in the agricultural sector discussed in this paper, but just as well in the mining sector, in industries, households and other relevant sectors.

The integrated modelling approach presented in this paper clearly resembles the benefits of the SITE framework’s flexible and open IT design. From the viewpoint of integrated modelling, the obvious discrepancy between water demand and availability occurring already in several years before the 2008 agricultural expansion, demonstrates the added value of a framework facilitating the coupling and simulation of important feedbacks of land systems, providing scientific insights as well as information relevant for practitioners such as RBOs at the catchment scale, or the Water Authority at the national scale.

The threshold value to determine water availability (Q_{30} in this case study) is strongly related to management strategies and legal regulations of surface water abstraction. The lower the threshold value is, the higher is the potential risk of unsustainable water withdrawals. A potential future application of the modelling approach is to assess adequate threshold values as a trade off between ecological and economical needs, based on policy goals, or regulations of the Mongolian water authority or RBOs.

The advantage of a coupled approach, as presented here is that it attempts to provide dynamically linked estimation of water availability. The authors as part of a larger team, already started to integrate views and demands of Mongolian authorities into scenario and model development (identified during stakeholder workshops), and will continue to do so during the coming years of collaborative research. Hence, the modelling framework could be a scientific tool to support future land and water management decisions based on the analysis and comparison of alternative policy scenarios.

Acknowledgements

The authors are grateful to various donors for providing grants to the authors of this study: (i) the German Research Foundation

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(DFG) for funding the development of several SITE-components in the collaborative research centre SFB552 (STORMA) and (ii) the Federal Ministry for Education and Research (BMBF) for funding CS and FW. The authors like to thank Dr. G. Davaa of the Institute of Meteorology and Hydrology, Ulan Bator for providing the meteorological data. The authors like to thank Lucas Menzel, University of Heidelberg – Germany for providing the TRAIN model for adaptation to the SITE framework and to Jennifer Koch, University of Kassel – Germany, Martin Volk, UFZ Leipzig – Germany, and the anonymous reviewers for valuable comments on earlier drafts of the manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.landusepol.2010.03.002.

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