Model based decision support system for land use changes and socio-economic assessments Postprint

Authors: YU, Yang, CHEN, Xi, HUTTNER, Philipp, HINNENTHAL, Marie, BRIEDEN, Andreas, SUN, Lingxiao, DSE, ISMarkus, YU, Yang

Date: 2018-02-28T00:00:00+00:00

Abstract

Hydrological models are often linked with other models in cognate sciences to understand the interactions among climate, earth, water, ecosystem, and human society. This paper presents the development and implementation of a decision support system (DSS) that links the outputs of hydrological models with real-time decision making on social-economic assessments and land use management. Discharge and glacier geometry changes were simulated with hydrological model, water availability in semi-arid environments. Irrigation and ecological water were simulated by a new commercial software MIKE HYDRO. Groundwater was simulated by MODFLOW. All the outputs of theses hydrological models were taken as inputs into the DSS in three types of links: regression equations, stationary data inputs, or dynamic data inputs as the models running parallel in the simulation periods. The DSS integrates the hydrological data, geographic data, social and economic statistical data, and establishes the relationships with equations, conditional statements and fuzzy logics. The programming is realized in C++. The DSS has four remarkable features: (1) editable land use maps to assist decision-making; (2) conjunctive use of surface and groundwater resources; (3) interactions among water, earth, ecosystem, and humans; and (4) links with hydrological models. The overall goal of the DSS is to combine the outputs of scientific models, knowledge of experts, and perspectives of stakeholders, into a computer-based system, which allows sustainability impact assessment within regional planning; and to understand ecosystem services and integrate them into land and water management.

Full Text

Preamble

Model-based decision support system for land use changes and socio-economic assessments

YANG Yu[1]*, CHEN Xi[1], Philipp HUTTNER[2], Marie HINNENTHAL[3], Andreas BRIEDEN[3], SUN Lingxiao[1], Markus DISSE[2]

[1] Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
[2] Chair of Hydrology and River Basin Management, Technical University of Munich, Munich 80333, Germany
[3] Chair of Statistics and Risk Management, Universitaet der Bundeswehr Muenchen, Neubiberg D-85577, Germany

Abstract: Hydrological models are often linked with other models in cognate sciences to understand the interactions among climate, earth, water, ecosystem, and human society. This paper presents the development and implementation of a decision support system (DSS) that links the outputs of hydrological models with real-time decision making on socio-economic assessments and land use management. Discharge and glacier geometry changes were simulated with the hydrological model WASA (Water Availability in Semi-Arid Environments). Irrigation and ecological water use were simulated by the commercial software MIKE HYDRO. Groundwater was simulated by MODFLOW. All outputs from these hydrological models were taken as inputs into the DSS through three types of links: regression equations, stationary data inputs, or dynamic data inputs as the models run parallel during simulation periods. The DSS integrates hydrological data, geographic data, and socio-economic statistical data, and establishes relationships using equations, conditional statements, and fuzzy logic. The programming is realized in C++. The DSS has four remarkable features: (1) editable land use maps to assist decision-making; (2) conjunctive use of surface and groundwater resources; (3) interactions among water, earth, ecosystem, and humans; and (4) links with hydrological models. The overall goal of the DSS is to combine the outputs of scientific models, knowledge of experts, and perspectives of stakeholders into a computer-based system that allows sustainability impact assessment within regional planning, and to understand ecosystem services and integrate them into land and water management.

Keywords: decision support system; hydrological modeling; ecosystem services; land management; socio-economic indicator; Tarim River Basin

1 Introduction

The debate over the effectiveness of integrated water resources management (IWRM) in practice has lasted for years [?, ?, ?, ?]. As the complexity and scope of IWRM increases, the difficulties of hydrological modeling are shifting from the model itself to the links with other cognate sciences and to understanding the interactions among water, earth, ecosystem, and humans. This paper presents the development and implementation of a decision support system (DSS) that links the outputs of hydrological models with real-time decision making on socio-economic assessments and land use management. The DSS assists decision-making in a qualitative manner based on the outputs of hydrological models and knowledge of experts in cross-disciplinary fields.

There are currently many DSS models with economic assessments [?, ?, ?, ?], focusing on single topics (e.g., climate change, land use, agriculture, water accounting), and many socio-economic models [?, ?, ?, ?] without simulation of hydrological processes. Few models are capable of integrating meteorological, geographical, ecological, social, and economic factors based on the simulation of hydrological models. Little research has been done to show the interactions of so many cross-disciplinary studies on IWRM to understand ecosystem services (ESS) and integrate them into land and water management. Due to model complexity issues, many DSS models have to consider fewer issues within a specific research framework [?, ?]. However, the model complexity of DSS is worth the effort [?, ?] to increase model accuracy for comprehensive analysis in IWRM.

Since the last decade, the Chinese government has been promoting the development of western China. Demographic development and socio-economic change have led to rapid changes in land use systems in the Tarim River Basin, which is the habitat for more than 80% of *Populus euphratica* trees in China, and has substantially affected the quantity and quality of arable soil, surface water, and groundwater [?, ?, ?]. These changes in soil and water have large impacts on crop production and natural vegetation [?, ?], such as the *P. euphratica* trees.

Since 2011, the German Ministry of Science and Education (Bundesministerium für Bildung und Forschung, BMBF) established the Sino-German SuMaRiO (www.sumario.de) project for sustainable management of river oases along the Tarim River. A cross-disciplinary consortium of 11 German and 9 Chinese universities and research institutes joined together for research on SuMaRiO and the DSS. Project SuMaRiO focuses on realizable management strategies, considering social, economic, and ecological criteria. This will have positive effects for nearly 10^6 inhabitants of different ethnic groups. The DSS is the main outcome of SuMaRiO. The overall goal of the DSS is to integrate all crucial research results of SuMaRiO, including stakeholder perspectives, into a model-based decision support system that allows sustainability impact assessment within regional planning on land and water management in the Tarim River Basin, to understand ESS and interactions with water, earth, and humans. The DSS is an indicator-based tool that enables stakeholders and decision-makers to evaluate the consequences of their intended actions, which helps implement sustainable land and water management measures in upcoming development plans [?].

2.1 Study Area

This research is conducted in the Tarim River Basin. With a mainstream length of 1321 km and located at the northern edge of the Taklimakan Desert, the Tarim River is the longest inland river in China. The Tarim Basin is known worldwide for its natural resources, extreme arid climate, and vulnerable ecosystem. In this region, agricultural water consumption and allocation management are crucial to address conflicts among irrigation water users from upstream to downstream [**?**], which cause severe water scarcity problems for the ecosystem [**?**] and sustainable land management [**?**, **?**].

This research focused on the mainstream of the Tarim River, starting from Aral to Taitema Lake. With a mean annual precipitation of around 40 mm and more than 3000 mm potential evapotranspiration per year, the region is extremely arid with a vulnerable ecosystem. Water in the mainstream of the Tarim River is mainly provided by high mountain glacier melting, which feeds the Tarim River through its tributaries. Water resources and ecosystem stability are the most obvious and sensitive issues in this hyper-arid region.

The oases along the Tarim River are covered by riparian forest, grassland, reed, shrubs, and farmlands. The main crop of the irrigated fields is cotton, which is also a major income source for the local people. The Tarim River Basin has a global reputation for producing high-quality cotton, which provides more than half of the cotton production in China.

2.2 Research Fields

The interdisciplinary research challenges are clustered in five interrelated work blocks, WB 1–WB 5 (Fig. 1 [Figure 1: see original paper]), with WB 1 on organization with stakeholders and management issues, WB 2 on regional climate change and discharge of the Tarim River tributaries, WB 3 on sustainable water and land use management, WB 4 on ecosystem services (ESS) and ecosystem functions (ESF), and WB 5 on multi-level socio-economic assessment of ecosystem services and implementation tools. The DSS will identify realizable management strategies, considering social, economic, and ecological criteria.

Research content of the DSS covers the following aspects in the Tarim River Basin: water resources, climate, biodiversity, demographics, energy consumption and production, poverty and health, economic development, land management, and scenario management. A number of these research fields involve more than one WB, and thus need expert knowledge from interdisciplinary cooperation.

2.3 Indicators of DSS

Under scenario assumptions, possible actions and their impacts are estimated in a quantitative way with the help of sustainability indicators (Table 1). Climate indicators, socio-economic indicators, and management indicators are input indicators, while ESS indicators are output indicators. Input indicators give users opportunities to change the scenario on the baseline or perspective in the planning years, and output indicators demonstrate the simulation results caused by management alternatives.

Users can define the inputs of the DSS according to reference values, possible ranges, and certain rules. Simulation years can be chosen from 2012 to 2050. The climate projections were based on three emission scenarios, nine global climate models, and two additional regional climate models. Four types of climate scenarios, CCLM RCP 2.6, CCLM RCP 4.5, CCLM RCP 8.5, and REMO A1B, are included in the DSS. For socio-economic indicators and management indicators, users can change the reference values for management alternatives in the planning years. The results of their actions will be demonstrated by the output indicators.

2.4 Logics of DSS

Equations, conditional statements, and fuzzy logic constitute the three logical relationships that connect the parameters in the DSS.

2.4.1 Equations

Equations are formed by expert knowledge, theorems, empirical equations, and literature findings to build relationships among the parameters in the DSS. In total, 115 equations were established in the DSS. Two examples are given in the following text.

Due to the absence of industry in the region, water consumption in the catchment is comprised of domestic use, flooding of natural vegetation, irrigation water use, and water losses (Eq. 1). Inflow of the first sub-catchment is given by a model of water availability in semi-arid environments (WASA) depending on the climate scenarios. Because no bifurcation exists in the mainstream of the Tarim River, inflows into the sub-catchments are calculated in a simple way each month.

$$Q(n+1) = Q(n) - Q(n) \times P(\text{domestic}) - Q(n) \times P(\text{flood}) \times k - IW \times 0.964$$

where $Q(n+1)$ is the inflow into the next sub-catchment (m^3), $Q(n)$ is the inflow of the current sub-catchment (m^3), $P(\text{domestic})$ is the interpolated value of domestic water use (%), $P(\text{flood})$ is the interpolated value of flooding of natural vegetation (%), k is the flood distribution over the month (%), and IW is the irrigation water demand of the current sub-catchment (m^3), which is multiplied with a loss factor of 0.964.

Cotton production is calculated cell-by-cell, then aggregated in sum for the DSS output (Eq. 2).

$$Y_c = \sum \left[Y_m \times \left(1 - \frac{ET_c - ET_a}{ET_c} \times K_y \right) \times \frac{m}{100} \right]$$

where Y_c is the cotton production (t) in each cell, ET_c is derived from the Penman-Monteith method and influenced by crop factors, ET_a is calculated by MIKE HYDRO, which identifies the actual rate of crop evapotranspiration under the effects of soil water stress, Y_m is the maximum harvest yield (kg), m is the cotton production distribution over months (%), and K_y is the yield response factor representing the effect of reduction in evapotranspiration on yield loss. K_y values were obtained from FAO Irrigation and Drainage Paper No. 33 [?].

2.4.2 Conditional Statements

The knowledge of experts is also used to formulate ‘if-then’ rules to solve modeling problems. Such conditional constructs perform different computations depending on whether a condition is evaluated as true or false. Conditional statements are a convenient method when the rules are clear and homogeneous.

Three examples are given as follows:

1. For a grassland cell, if groundwater level < -5 m in 9 months each year and this continues for 7 years, then the land use type of the cell will become unused land in the 8th year.
2. For a high-density riparian forest cell, if groundwater level < -10 m in 9 months each year and this continues for 7 years, then the grid cell will become riparian forest with low density in the 8th year.
3. For a low-density riparian forest cell, if groundwater level < -10 m in 9 months each year and this continues for 7 years, then the grid cell will become unused land in the 8th year.

2.4.3 Fuzzy Logic

In the DSS, some relationships cannot be precisely expressed as equations or conditional statements, and a useful method under such circumstances is called fuzzy logic. Fuzzy logic is a logical approach to deal with uncertainty management [?]. Elements have degrees of membership in the fuzzy set. Membership functions represent the degrees of truth in vaguely defined sets. Unlike possibilities or conditions, the truth values of variables may be any real number between 0 and 1.

Examples of tree height, crown area, and drifting dust control by riparian forest are demonstrated in Tables 2–4.

2.5 Models Linked with DSS

Discharge and glacier geometry changes were simulated with the hydrological model WASA [?]. The calibration and evaluation of the model were conducted in the headwater catchments of the Tarim River. WASA provides daily discharge input into the DSS. Based on different temperature rise and precipitation change projections, four climate scenarios—A1B, RCP2.6, RCP4.5, and RCP8.5—could be selected by users [?].

For surface flow, the hydrological model MIKE HYDRO [?] provides inputs for the DSS at the catchment level. MIKE HYDRO is a comprehensive deterministic and physically based modeling tool for the simulation of water flow, water supply/demand, soil moisture, and crop growth. It has an integrated modular structure with basic computational modules for hydrology and hydrodynamics. The DSS and MIKE HYDRO have the same delineation of sub-catchments (SC): SC1 from Aral to Xinqiman, SC2 from Xinqiman to Yingbazar, SC3 from Yingbazar to Qiala, and SC4 from Qiala to Taitema Lake. The irrigation water demand, ecological water for natural vegetation, seepage losses, fruit production, and crop yields were calculated and summarized as inputs into the DSS.

For groundwater simulation, a MODFLOW model was computed with internal links to the DSS on a 500 m × 500 m cell level (Fig. 2 [Figure 2: see original paper]). MODFLOW runs parallel with the DSS during simulation. The daily water head of each cell is simulated in MODFLOW, which then updates the cells in the DSS. Groundwater recharge is considered via four different sources: river leakage, irrigation water seepage, infiltration during flood season, and ecological water percolation in the lower reaches.

It is a challenge to find links between the DSS and other models. The key issue is that the outputs of different models are not uniform for input into the DSS. The parameter sets and their relationships vary largely from model to model. The outputs of different models can either serve as stationary data inputs, regression equations, or dynamic data inputs into the DSS as the models run parallel during simulation periods.

As MIKE HYDRO is linked with the DSS at the sub-catchment level, data and equations bridge the two models. MIKE HYDRO provides simulation results of ecological water for natural vegetation in the upper and middle reaches to the DSS. Crop productions are linked by yield equations calculated from evapotranspiration. Seepage losses were calculated in MIKE HYDRO and aggregated into monthly values for the DSS. Irrigation water consumptions were distributed in MIKE HYDRO and integrated at the sub-catchment level in the DSS.

Particularly, MODFLOW has internal links with the DSS. With the same delineation at the cell level, both models run parallel during simulation periods. At the beginning of each year, water heads from MODFLOW results update the groundwater levels in the DSS. Groundwater plays a crucial role in the ecosystem and has large influence on a number of output indicators in the DSS.

2.6 Graphical User Interface of DSS

A user-friendly graphical user interface (GUI) was developed to assist decision-makers and common users, with Chinese and English versions currently available. Labels and instructions allow users to interact with the DSS more conveniently. The input indicators have default values acquired from databases, literature, and expert knowledge. Calculation years range from 2012 to 2050. The land use map is also editable in the baseline year to assist decision-making on land use changes. The GUI is designed to be user-friendly so that more stakeholders and scientists can be involved in using and improving the model. Implementation of the DSS bridges the gap between research and practice through interviews, workshops, and feedback.

3.1 Land Use Changes

Users can freely define input land use types by clicking cells in the GUI. In this trial, land use types remain as they were in the default map acquired from MODIS data. The baseline year is 2012, and all values of input indicators are kept as business-as-usual. The planning years are 2030 and 2050, which indicate land use changes in the near and far future (Fig. 3 [Figure 3: see original paper]).

Grassland, natural vegetation, and forest will suffer varying degrees of deterioration in the near and far future if the scenario remains business-as-usual. In the upper, middle, and lower reaches, the decay of green areas is obvious. Similar results were shown by recent findings [**?**, **?**]. Because of low precipitation and flow rate in dry seasons, vegetation is dependent on summer floods and groundwater. Additionally, riparian forests would gradually vanish in some regions by 2050, especially in the middle reaches. Since cotton and other agricultural fields are determined by anthropogenic activities, farmland areas remain unchanged throughout the simulation period. However, the consequences of farmland changes can be revealed by output indicators if a user changes the land use types initially. In the middle reaches, where riparian forest (mostly *P. euphratica*) mainly grows, forest degradation will be severe by 2050 (Fig. 4 [Figure 4: see original paper]).

Simulation results indicate that both forest area and density have been reduced to various degrees. In several hotspots, riparian forest areas have substantially dwindled or even faded away. These hotspots are all located north of the river. Population is one reason to identify a hotspot, where deforestation could be a major threat to the living conditions of local residents. Another reason is the vanishing points of forest in several regions, which would destroy the ecological balance in arid lands. Groundwater recession is the reason for forest decay in the model, as deforestation has been prohibited in the oases along the Tarim River. Continuous low groundwater level for more than 7 years is considered fatal to the forest. The correlations between groundwater and *P. euphratica* were also discussed by Thomas et al. [**?**], who made further discussions on the threats to these precious trees.

3.2 Downstream Outflow

The natural terminus of the Tarim River is Taitema Lake. However, due to long-term water interception downstream, the outflow of the Tarim River is studied at Daxihaizi Reservoir. The reservoir is located 358 km upstream from the river to Taitema Lake. The outflow of the Tarim River in future years is dependent on upstream discharge and water consumption along the oases, which were calculated from other hydrological models. Simulation results indicate an increasing trend of outflow in 2020, and decreasing trends in 2030 and 2040 (Fig. 5 [Figure 5: see original paper]).

Peak volumes of outflow appeared in July, with 7.3\$$\times 10^{\{8\}, 9.5\times 10}\{8\}, 6.9\times 10^{\{8\}, and 5.9\times 10}\{8\}$\$ m^3 in 2012, 2020, 2030, and 2040, respectively. From Figure 5, it is noticeable that summer floods last two months in July and August, and drop dramatically in September. These results agree with the outputs of the hydrological model [?]. The dry season occupies most of the year. In June, water deficits occurred in all simulation years. Particularly, nearly 4.0\$×10^{8}\$ m^3 of water shortage was predicted in June 2040. A noticeable water deficit also appeared in September 2040, which is the first time that outflow water is on shortage in September. Upstream reservoirs need to prepare adequate storage for the water crisis in the future.

3.3 Socio-economic Outputs

Cotton production, fruit production, biomass production, mean species of plants, farmer' s income, wind control, drifting dust control by riparian forest, drifting dust control by grassland, and sand mobilization control by grassland are shown as examples for socio-economic assessments (Fig. 6 [Figure 6: see original paper]). These indicators were calculated separately in the four sub-catchments of Aral to Xinqiman, Xinqiman to Yingbazar, Yingbazar to Qiala, and Qiala to Taitema Lake. The simulation period is from 2012 to 2050, and all inputs were kept as default values.

Cotton production shows an increasing trend in all sub-catchments. The largest cotton production region is within SC1, but the fastest production growth comes from SC4. This result complies with the study of Xu et al. [?], who warned that agricultural development in the lower reaches may cause water scarcity problems for the ecosystem. Fruit production also shows a rising trend and develops rapidly in the lower reaches. Biomass production experiences an increasing period until 2018, then drops in 2019 and remains steady afterwards. The reason for this sudden change may be that the rules in the DSS are not complex and smooth enough, and quantitative accumulations lead to a qualitative transformation in 2019.

The number of mean species of plants shows steady growth, similar to farmer' s income. Because of the development of economic crops, farmer' s income in the lower reaches has the largest growth among all sub-catchments. Due to a lack of clear policy and data for future years, changes in population and migration are not considered in the current version of the DSS. Wind control and drifting dust control by riparian forest remain stable, even though the forest area is shrinking. This is caused by the contribution of growing tree height and crown area. In comparison, drifting dust and sand mobilization control by grassland have declined to varying degrees until 2050.

One scenario was tested as an example for land use management and assessment (Fig. 7 [Figure 7: see original paper]). In the baseline year of 2012, 4\$$\times 100 cells(1\times 10$^{4}\$ hm^{2}) of cotton fields are changed into grassland in the first sub-catchment to investigate the consequences of this action in future years until 2030. The simulation results indicate the reduction of cotton production and farmer’ s income, and the increase of sand mobilization control by grassland after land use change. Cotton production provides the main income for local farmers. From a local decision-maker’ s point of view, if the losses of farmer’ s income are too large to bear, then this land use change scenario may not be accepted. However, if sand mobilization control is considered more important than the economic losses, the decision-maker may adopt this scenario and mitigate the farmer’ s losses in other ways. Additionally, the increased portion of sand control is shrinking in future years. This phenomenon indicates that either the groundwater level is too low in the fields, or groundwater salinity is too high for grass to grow.

3.4 Uncertainties and Further Developments

In the DSS, the delineation of regions is relatively homogeneous across multiple criteria, including hydrological, meteorological, geographical, ecological, socio-economic, and political aspects. Therefore, the complexity of management practices cannot be completely reproduced. Equations, conditional statements, and fuzzy logic all have limitations in delineating parameter relationships, and thus cause uncertainties through temporal and spatial changes on specific matters. Socio-economic and management indicators (e.g., cotton price, farmland area, and drip irrigation coverage) are often sensitive to changes in government policies and water authority regulations, which could cause large uncertainties in future planning years.

Although the hydrological models were calibrated and validated to increase the possibility of more reliable results, the DSS has not been calibrated so far. However, comprehensive model calibration requires feedback from local stakeholders, more statistical data, and a better understanding of the DSS itself. Since the DSS involves knowledge on varying aspects, no individual developer is able to master all criteria. Interdisciplinary cooperation is as important in the implementation and optimization phase as it was in the system development phase.

It is difficult to say which scenario has the most robustness, or whether one scenario is more preferable than another. Based on a number of trials and comparisons with real data, most outputs of the DSS were reasonable and comply with the knowledge and perceptions of local stakeholders. However, the sensitivity of soil salinization change is lower than expected. Because winter irrigation uses extra water to wash down salt, salinization on the surface soil should change obviously in winter. The process of winter irrigation is not included in the simulation of the DSS at the moment and can be considered as a special stress to increase system reliability in future improvements.

4 Conclusions

A model-based DSS was developed to assist stakeholders with decision-making on sustainable land management and socio-economic assessments in the oases along the Tarim River. The development and implementation of the DSS involves knowledge from experts in interdisciplinary research aspects, as well as experiences and feedback from a large number of local stakeholders. The DSS has notable features in several research aspects:

1. Editable land use maps in the GUI were developed to assist stakeholders in decision-making on land use management. The clicking and drawing on the land use map provide stakeholders an intuitive approach for examining land management alternatives. If the scenario remains business-as-usual in the simulation, natural vegetation, riparian forest, and grassland would suffer varying degrees of deterioration in the near and far future. In the upper, middle, and lower reaches, the decay of natural vegetation is obvious.

2. The conjunctive use of surface and subsurface water resources provides more accuracy for the system. The DSS integrates hydrological data, geographic data, and socio-economic statistical data, and establishes relationships using equations, conditional statements, and fuzzy logic. Under scenario assumptions, possible actions and their impacts are estimated in a semi-quantitative way with the help of climate indicators, socio-economic indicators, management indicators, and ESS indicators. Socio-economic outputs illustrate increased crop production and farmer’ s income, but weaker sand mobilization and drifting dust control in the future.

3. The integration of expert knowledge from interdisciplinary studies provides specific insights on the interactions among water, earth, ecosystem, and human activities. The system not only considers direct impacts but also side effects among different matters. For instance, increased irrigation water may raise crop production, but it can also cause less water for winter flooding, thereby aggravating salinization in the field and leading to lower yields in the end.

4. Links with hydrological models help reduce system complexity and increase model accuracy of the DSS. MODFLOW runs parallel with the DSS during simulation periods. WASA provides discharge inputs, and MIKE HYDRO simulates irrigation and ecological water consumption. All outputs from these hydrological models were taken as inputs into the DSS. After the calculations of water balance in the DSS, simulation results indi-

cate an increasing trend of outflow in 2020 and a decreasing trend in 2030 and 2040.

Although much expert knowledge and stakeholder feedback were considered during the development phase, the DSS should not be recognized as an end product. Many estimations and uncertainties still remain in the system, which requires further research and development. The GUI was designed to be user-friendly so that more common stakeholders can use and improve the system, and make steps toward bridging the gap between research and IWRM practice.

Acknowledgements: This study was supported by the German-Sino bilateral collaboration research project SuMaRiO funded by the German Federal Ministry of Education and Research. We are grateful for the support of the NSFC-UNEP Project (41361140361): Ecological Responses to Climatic Change and Land-cover Change in Arid and Semiarid Central Asia during the Past 500 Years. This work is the outcome of interdisciplinary cooperation research among 11 German and 9 Chinese universities and research institutes. Many further researches and projects can learn from the algorithms and methodologies of the DSS, which is applicable to other regions. The DSS is freely available on request. Comments and further discussions are welcome.

References

Arnell N W, Lloyd-Hughes B. 2014. The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios. *Climatic Change*, 122(1–2): 127–140.

Basso B, Ritchie J T. 2015. Simulating crop growth and biogeochemical fluxes in response to land management using the SALUS model. In: Hamilton S K, Doll J E, Robertson G P. *The Ecology of Agricultural Landscapes: Long-term Research on the Path to Sustainability*. New York: Oxford University Press, 252–274.

Biswas A K. 2008. Integrated water resources management: is it working? *International Journal of Water Resources Development*, 24(1): 5–22.

Chen Y N, Li W H, Xu C C, et al. 2015. Desert riparian vegetation and groundwater in the lower reaches of the Tarim River basin. *Environmental Earth Sciences*, 73(2): 547–558.

Chenoweth T, Dowling K L, St. Louis R D. 2004. Convincing DSS users that complex models are worth the effort. *Decision Support Systems*, 37(1): 71–82.

Disse M. 2016. Sustainable land and water management of River Oases along the Tarim River. *Proceedings of the International Association of Hydrological Sciences*, 373: 25–29.

Doorenbos J, Kassam A H. 1979. *Yield Response to Water*. Rome: FAO, 257.

Duethmann D, Menz C, Jiang T, et al. 2016. Projections for headwater catchments of the Tarim River reveal glacier retreat and decreasing surface water availability but uncertainties are large. *Environmental Research Letters*, 11(5): 054024.

Feng Q, Endo K N, Cheng G D. 2001. Towards sustainable development of the environmentally degraded arid rivers of China –a case study from Tarim River. *Environmental Geology*, 41(1-2): 229-238.

Flörke M, Kynast E, Bärlund I, et al. 2013. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: a global simulation study. *Global Environmental Change*, 23(1): 144-156.

Giordano M, Shah T. 2014. From IWRM back to integrated water resources management. *International Journal of Water Resources Development*, 30(3): 364-376.

Güntner A, Bronstert A. 2004. Representation of landscape variability and lateral redistribution processes for large-scale hydrological modelling in semi-arid areas. *Journal of Hydrology*, 297(1-4): 136-161.

Herrero M, Thornton P K, Bernués A, et al. 2014. Exploring future changes in smallholder farming systems by linking socio-economic scenarios with regional and household models. *Global Environmental Change*, 24: 165-182.

Jeffrey P, Gearey M. 2006. Integrated water resources management: lost on the road from ambition to realisation? *Water Science & Technology*, 53(1): 1-8.

Liu G L, Yin G, Kurban A, et al. 2016. Spatiotemporal dynamics of land cover and their impacts on potential dust source regions in the Tarim Basin, NW China. *Environmental Earth Sciences*, 75(23): 1477.

Liu X P, Meng M. 2011. Sustainable land use and the coupling relation of ecological economic harmonious development: a case study of Tarim River Basin. *Arid Land Geography*, 34(1): 173-178. (in Chinese)

Liu Y B, Chen Y N. 2006. Impact of population growth and land-use change on water resources and ecosystems of the arid Tarim River Basin in Western China. *The International Journal of Sustainable Development & World Ecology*, 13(4): 295-305.

Lv X, Liu X P, Li Z B. 2016. Coupling of ecological economic system in Tarim River Watershed. In: Qu F T, Sun R M, Guo Z X, et al. *Ecological Economics and Harmonious Society*. Singapore: Springer, 197-208.

McCown R L. 2002. Locating agricultural decision support systems in the troubled past and socio-technical complexity of ‘models for management’ . *Agricultural Systems*, 74(1): 11-25.

Pedro-Monzonís M, Jiménez-Fernández P, Solera A, et al. 2016. The use of AQUATOOL DSS applied to the System of Environmental-Economic Accounting for Water (SEEAW). *Journal of Hydrology*, 533: 1-14.

Power D J, Sharda R, Burstein F. 2015. Decision support systems. Volume 7. Management information systems. In: Cooper C L. *Wiley Encyclopedia of Management*. New York: John Wiley & Sons, Ltd, 1-11.

Quevauviller P. 2010. Is IWRM achievable in practice? Attempts to break disciplinary and sectoral walls through a science-policy interfacing framework in the context of the EU Water Framework Directive. *Irrigation and Drainage Systems*, 24(3-4): 177-197.

Rumbaur C, Thevs N, Disse M, et al. 2015. Sustainable management of river oases along the Tarim River (SuMaRiO) in Northwest China under conditions of climate change. *Earth System Dynamics*, 6(1): 83-107.

Thomas F M, Jeschke M, Zhang X M, et al. 2017. Stand structure and productivity of *Populus euphratica* along a gradient of groundwater distances at the Tarim River (NW China). *Journal of Plant Ecology*, 10(5): 753-764.

Visconti P, Bakkenes M, Smith R J, et al. 2015. Socio-economic and ecological impacts of global protected area expansion plans. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 370(1681): 20140284.

Wenkel K O, Berg M, Mirschel W, et al. 2013. LandCaRe DSS-An interactive decision support system for climate change impact assessment and the analysis of potential agricultural land use adaptation strategies. *Journal of Environmental Management*, 127(Suppl.): S168-S183.

West G G, Turner J A. 2014. MyLand: a web-based and meta-model decision support system framework for spatial and temporal evaluation of integrated land use. *Scandinavian Journal of Forest Research*, 29(Suppl.): 108-120.

Xu H L, Ye M, Li J M. 2008. The water transfer effects on agricultural development in the lower Tarim River, Xinjiang of China. *Agricultural Water Management*, 95(1): 59-68.

Yu Y, Disse M, Yu R D, et al. 2015. Large-scale hydrological modeling and decision-making for agricultural water consumption and allocation in the main stem Tarim River, China. *Water*, 7(6): 2821-2839.

Yue H L, Zhu Y P, Xue Y, et al. 2014. Study on counties agricultural economic intelligent decision-making support system (IDSS) based on GIS and knowledge. *Advanced Materials Research*, 889-890: 1319-1322.

Zadeh L A. 1983. The role of fuzzy logic in the management of uncertainty in expert systems. *Fuzzy Sets and Systems*, 11(1-3): 199-227.

Zhang Q, Sun P, Li J F, et al. 2015. Assessment of drought vulnerability of the Tarim River basin, Xinjiang, China. *Theoretical and Applied Climatology*, 121(1-2): 337-347.

Zhang Z, Hu H, Tian F, et al. 2014. Groundwater dynamics under water-saving irrigation and implications for sustainable water management in an oasis: Tarim

River basin of western China. *Hydrology and Earth System Sciences*, 18(10): 3951-3967.

Zhao R F, Chen Y N, Li W H, et al. 2009. Land cover change and landscape pattern in the mainstream of the Tarim River. *Acta Geographica Sinica*, 64(1): 95-106. (in Chinese)

Note: Figure translations are in progress. See original paper for figures.