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Sustainable management of river oases along the Tarim River in North-Western China under conditions of climate change

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Abstract

The Tarim River Basin, located in Xinjiang, NW China, is the largest endorheic river basin of China and one of the largest in whole Central Asia. Due to the extremely arid climate with an annual precipitation of less than 100 mm, the water supply along the Aksu and Tarim River solely depends on river water. This applies for anthropogenic activities (e.g. agriculture) as well as for the natural ecosystems so that both compete for water. The on-going increase of water consumption by agriculture and other human activities in this region has been enhancing the competition for water between human needs and nature. Against this background, 11 German and 6 Chinese universities and research institutes formed the consortium SuMaRiO (www.sumario.de), which aims at gaining a holistic picture of the availability of water resources in the Tarim River Basin and the impacts on anthropogenic activities and natural ecosystems caused by the water distribution within the Tarim River Basin. The discharge of the Aksu River, which is the major tributary to the Tarim, has been increasing over the past 6 decades due to enhanced glacier melt. Alone from 1989 to 2011, the area under agriculture more than doubled. Thereby, cotton became the major crop and there was a shift from small-scale farming to large-scale intensive farming. The major natural ecosystems along the Aksu and Tarim River are riparian ecosystems: Riparian (Tugai) forests, shrub vegetation, reed beds, and other grassland. Within the SuMaRiO Cluster the focus was laid on the Tugai forests, with *Populus euphratica* as dominant tree, because the most productive and species-rich natural ecosystems can be found among those forests. On sites with groundwater distance of less than 7.5 m the annual increments correlated with river runoffs of the previous year. But, the further downstream along the Tarim River, the more the natural river dynamics ceased, which impacts on the recruitment of *Populus euphratica*. Household surveys revealed that there is a considerable willingness to pay for conservation of those riparian forests with the mitigation of dust and sandstorms considered as the most important ecosystem service. This interdisciplinary project will result in a decision support tool (DST), build on the participation of

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regional stakeholders and models based on results and field experiments. This DST finally shall assist stakeholders in balancing the water competition acknowledging the major external effects of any water allocation.

1 Introduction

The Tarim River Basin is located in Xinjiang, Northwest China. It is bordered by the mountain ranges Tian Shan in the north, Kunlun in the south, and Pamir in the west. The Taklamakan Desert dominates the basin with the Tarim River flowing along its northern rim. The Tarim River forms at Alar City through the confluence of the Yarkant River from the west, Hotan River from the south, and Aksu River from the north (Fig. 1). The latter river contributes about 80 % to the Tarim River's discharge.

Due to the extremely arid climate with an annual precipitation of below 100 mm, the water supply along the Aksu and Tarim River solely depends on river water. This applies for anthropogenic activities (e.g. agriculture) as well as for the natural ecosystems so that both compete for water. Only during the past decade fossil groundwater has been exploited in significant amounts. The region is inhabited since several hundreds of years and some of the oldest oases of Asia are located in the Tarim River Basin. During the past six decades the Chinese Government has been promoting the development of the western provinces of China. The demographic development and socio-economic change has led to a rapid change of land use systems in the Tarim River Basin over the last decades and has substantially affected the quantity and quality of arable soil, surface water, and groundwater. These changes in soil and water affect the natural vegetation as well as the crop production (Bohnet et al., 1998, 1999; Hoppe et al., 2006).

The on-going settlement in this region has been enhancing the competition for water between human needs and nature. Furthermore, there is a classical upstream-downstream conflict along the Tarim and its tributaries similar to other river basins of

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Central Asia (Chriacy-Wantrup, 1985; Giese et al., 1998, cf. http://www.cawa-project.net/).

Based on the above mentioned issues, it is necessary to gain a holistic picture of the availability of water resources in the Tarim River Basin and of the impacts on anthropogenic activities and natural ecosystems caused by the water distribution within the Tarim River Basin. The impacts must include economic impacts as well as external and indirect effects.

Against this background, a consortium of 11 German and 6 Chinese universities and research institutes formed the consortium SuMaRiO (www.sumario.de). This consortium was formed in 2011 and is funded by the Federal Ministry of Education and Research of Germany. After the data collection phase has been finished this year, we aim at compiling the results from the fields of climate modeling, cryology, hydrology, agricultural sciences, ecology, and social sciences, in order to present a comprehensive understanding of the effects of different water distribution schemes on anthropogenic activities and on the natural ecosystems. The effects on the natural ecosystems are captured through the investigation and evaluation of their ecosystem services (MEA, 2005) provided.

2 Methods and study sites

The SuMaRiO Cluster aims at contributing to a sustainable land management for the whole Tarim River Basin, including the Aksu River (Fig. 1), which explicitly takes into account ecosystem functions and ecosystem services. In a trandisciplinary research process, SuMaRiO identifies management strategies, considering social, economic, and ecological criteria.

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2.1 Climate change

Climate trends were investigated in detail for the Aksu Catchment. Climate data provided by the National Climate Centre, China Meteorological Administration (CMA, personal communication, 2012), were used. In addition, the meteorological forcing dataset from the WATCH project that is based on ERA-40 data (Weedon et al., 2011) and the APHRODITE dataset (Yatagai et al., 2012) were used at a daily resolution. The trend analysis was performed using two methods: the linear regression and the Mann–Kendall Test. For the linear regression, the slope of the regression line and the standard error were estimated, and statistical significance of the trends was calculated.

In addition, an analysis of climatic trends in the historical period for the total Tarim River Basin was done, and the results compared with those published in the literature. Due to the scarcity of observations we relied on gridded datasets, namely: CRU-TS3.21 (temperature and precipitation, Harris et al., 2014), GPCC-FD v6 (precipitation, Becker et al., 2013) and APHRODITE_MA V1101 (precipitation, Yatagai et al., 2012). Furthermore we investigated a high resolution gridded dataset provided by the National Climate Centre, China Meteorological Administration, which has the most dense station network of all datasets, but only covers the Chinese part of the Tarim River Basin. The trends were estimated using the OLS-regression. The trend significance was tested using the Mann–Kendall Test.

To investigate possible future changes, we employed two regional climate models, namely the statistical climate model STARS (Werner and Gerstengarbe, 1997 and Orlowsky et al., 2008) and the dynamical climate model CCLM (Steppeler et al., 2003; Rockel et al., 2008). The CCLM and STARS simulations were evaluated for the historical period. The simulations were compared to the results of 23 GCMs of the Coupled Model Intercomparison Project Phase 5 (CMIP5, http://cmip-pcmdi.llnl.gov/cmip5/). The regional climate models were successfully calibrated and evaluated for a historical period (see for example Wang et al., 2013). The RCP2.6, RCP4.5 and RCP8.5 emission scenarios were considered (see Meinshausen et al., 2011).

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2.2 Hydrology

The runoff of the Tarim River is mainly delivered by the Aksu River. The Aksu River's runoff is generated from glacier and snow melt as well as from rainfall in the two headwater catchments of the Aksu, the Sari-Djaz Catchment (area: 13 000 km^2, 21 % glacier) and the Kokshaal Catchment (area: 18 400 km^2, 4 % glacier). These two catchments are highlighted in red in Fig. 1, with the Sari-Djaz and the Kokshaal being the eastern and western tributary of the Aksu River, respectively. Downstream of those two headwater catchments, the Aksu and Tarim River behave as so-called losing streams, i.e. they provide water for irrigation and other consumptive uses and drain water into the groundwater layer, but do not receive any further runoff. 80 % of the annual discharge is formed during the summer season from April to September (Song et al., 2000).

The cryosphere therefore was investigated in the western Tian Shan in the catchment area of the Aksu River, because that river is the major tributary of the Tarim. In order to get a better understanding of the natural hydrological system of the Aksu Catchment, trend and correlation analyses were performed for all gauging stations in the Aksu catchment, the Sari-Djaz catchment and the Kokshaal catchment. The water cycle was modelled for the three Tarim River tributaries: Aksu, Hotan and Yarkand and a test site in Yingbazar at the mid-stream of the Tarim River (results are shown here only partly).

First, trends in discharge during the high flow season (April–September) were analyzed, in order to demonstrate discharge changes in the past. Monthly stream flow data for the period 1957–2004 were available from Wang (2006). Trend significance was assessed with the Mann–Kendall Test, and trend magnitudes were calculated using Sen's Slope Estimator. In order to avoid overestimation of the trend caused by serial correlation, the approach of trend free pre-whitening (Yue et al., 2002) was applied.

Second, the relation between discharge and climate variability was investigated by analyzing correlations between summer discharge and summer precipitation and temperature. Mean monthly temperature and precipitation were retrieved from the GPCC

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v.6 (Schneider et al., 2011) and CRU 3.1 data sets (Mitchell and Jones, 2005), respectively. The analyses presented here are based on results described in Krysanova (2014) and Kundzewicz et al. (2014).

Third, a special analysis of high peaks in the river discharge time series, and interrelations between discharge dynamics (with a focus on high peaks) and climate parameters was performed for the gauges of the Aksu (Krysanova et al., 2014). It is known from literature that the Aksu and Tarim River experience near-annually reoccurring flood events originating in the Aksu headwaters from the Merzbacher Lake due to so-called Glacier Lake Outburst Floods (GLOFs). The implications of GLOFs for downstream areas and the related challenges for the hydrological modelling and the subsequent climate impact assessment were investigated in the Aksu River Basin using the SWIM model (Wortmann et al., 2013; Krysanova et al., 2014). Some partial results demonstrated the importance of GLOFs in the region are presented below.

Fourth, for an 85 km^2 test site at the middle reaches (Yingbazar) the whole water cycle was modelled by the software MIKE SHE (DHI-WASY).

2.3 Agriculture

In the field of agriculture, studies with respect to land and water use were carried out on different scales: water use, irrigation, soil conditions, and crop productivity of different land use systems were studied on plot scale, while the distribution of land use systems was investigated with remote sensing for the whole Tarim River Basin. Furthermore, the different land use systems were investigated with regard to agro-economy. Besides the native Uyghur land use practices, state farms, and farms of large investors control most of the arable land in the Tarim River Basin with cotton being the main crop. The water use efficiency of cotton cultivation under plastic mulched drip irrigation, which is the main irrigation type, was measured on soils of different degrees of salinization.

A remotely sensed time series of MODIS Enhanced Vegetation Index (EVI) Huete et al. (2002) data from the MOD13Q1 product (https://lpdaac.usgs.gov/products/modis_products_table/mod13q1) was used to assess land use and land use dynamics.

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The MODIS instrument provides data at a regional spatial scale (250 m) and at 16 day intervals. This coverage allows a consistent observation of the phenological cycle within a year as well as land use dynamics in the course of several years. To this end, a time series of eleven years (2001–2011) was compiled for the entire Tarim River Basin, from which a set of 22 phenological descriptors was calculated for every year in the time series. These descriptors were used to characterize the different land use systems and their dynamics. Thereby, we had two main objectives: firstly, to produce a map of land use systems for the most recent year in the time series, and secondly, to assess the increase in productive cropland during the entire time span. The latter problem we approached by applying suitable, knowledge based thresholds to individual phenological parameters. These knowledge based thresholds were calibrated by using small samples obtained in the field or from higher resolution imagery.

In the field of agro-economic research, secondary data were analysed, in order to understand the impact of the demographic development and socio-economic change on agricultural land use and water use in the region. These data included Statistical Yearbooks of Xinjiang (NBSCa, 1990–2012) and the Xinjiang Construction and Production Corps (NBSCb, 1990–2012), relevant policy documents (i.e. 5 year plans), and official ordinances related to land and water use. Furthermore, household interviews were conducted along the Aksu and Tarim Rivers. In total 256 farmers, selected by a stratified random selection process, were interviewed on their detailed crop management of the 2011 growing season using a standardized quantitative questionnaire; only farm production data of the 212 cotton producing farm households is presented in the current study.

2.4 Riparian ecosystems

The major natural ecosystems along the Aksu and Tarim River are riparian ecosystems: Riparian (Tugai) forests, shrub vegetation, reed beds, and other grassland. Within the SuMaRiO Cluster the focus was laid on the Tugai forests, because the most productive and species-rich natural ecosystems can be found among those forests. The Tugai forests are dominated by *Populus euphratica* with *Phragmites australis*, *Tamarix*, *Glycyrrhiza glabra*, *Alhagi sparsifolia*, and *Apocynum pictum* as main undergrowth species (Wang et al., 1996). Within SuMaRiO, the productivity and vitality, both in relationship to the water supply to those forests, and the water consumption (ET_a) of those forests were investigated.

The groundwater table, and thus finally the river runoff, which feeds the groundwater, plays a crucial role for the productivity, vitality, and ET_a (Wang et al., 1996; Thomas et al., 2006; Thevs et al., 2008a). So, the groundwater table, productivity, and vitality of trees and stands of *Populus euphratica* were investigated in three plots at the middle reaches of the Tarim River, near the village of Yingbazar, in order to understand the effect of the groundwater table and runoff on productivity and vitality. The plots were located at distances of 7–11 km from each other and displayed groundwater tables between 2.0 and 12.0 m. Each plot comprised a circular area with a radius of 50 m around a central tree.

On each plot, the position, tree height (with an ultrasonic hypsometer; Vertex IV, Haglöf, Långsele, Sweden) and stem diameter at breast height (dbh) were determined in all trees per plot. In addition, the crown projection area was measured in 20 trees per plot using a plummet connected to a sighting tube (Grube, Germany). From those 20 trees, two increment cores per tree were removed in a 90° angle at breast height with an increment borer (Suunto, Vantaa, Finland). Tree-ring width was analyzed using a Lintab 6 tree-ring analysis system (Rinntech, Heidelberg, Germany) and TSAP-Win Professional 4.67c software (Rinntech). From the individual tree rings and increment cores, tree-wise and plot-wise average values were computed. Plot-wise average ring widths were correlated to the river runoff of the preceding year after removing age trends of growth using standard methods (Rinn, 2003). Data on the annual runoff of the Tarim River at Yingbazar were provided by the Tarim Watershed Administration Bureau, Korla, China (Thevs et al., 2008b).

Additionally, the soil moisture and its connectivity were measured in a Tugai forest representative for the lower reaches of the Tarim nearby Arghan, in order to get a better

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understanding of the water support for the natural vegetation. The soil moisture has been measured using Decagon 10HS sensors (Decagon, 2014) since November 2011 in hourly intervals. Pedotransfer-functions (third degree regression) were used to describe the relationship between soil moisture content and pF values (Grashey-Jansen and Timpf, 2010; Grashey-Jansen et al., 2014). Applying this method, different sites with varying soil textures can be compared regarding the amount of plant-available water.

To estimate the connectivity between groundwater and soil moisture cross correlations between the two time-series were calculated. This indicates how long it took until the rising groundwater level has an effect on soil moisture in different layers.

Data on the vitality of the Tugai forests were collected in May 2013 at the same site in Arghan, because here we find the whole range of vitalities. At each soil moisture logger the surrounding *Populus euphratica* trees were surveyed using a classification scheme of six vitality classes (1 = "very good condition" to 6 = "dead"). The ranking was based on the visual impression of leaf density. Specimen of *Populus euphratica* that are in a good vitality condition will develop a higher density of leaves than those trees that suffer e.g. from water-scarcity and therefore are in a poorer condition.

The field assessment of the vitality of *Populus euphratica* was complemented by a satellite image survey, in which changes between 2005 and 2011 were assessed. The two times were chosen, in order to detect the response of *Populus euphratica* to restoration efforts in the lower reaches of the Tarim River. Thereby, an object based tree crown change detection method on two very high resolution satellite imageries from 2005 (QuickBird – QB) and 2011 (WorldView2 – WV2) was applied. A pixel based minimum/maximum filter was applied on derived Normalized Difference Vegetation Index (NDVI) values in order to identify crown peaks and delineated the extracted peaks into individual tree crown objects using the region growing approach.

Finally, the water consumption of the natural ecosystem (ET_a) was assessed. ET_a of the natural ecosystems along the Aksu and Tarim River was mapped from MODIS satellite images for the years 2009, 2010, and 2011 (Thevs et al., 2013, 2014). The

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ET_a was mapped after the S-SEBI approach as developed and described in detail by Roerink et al. (2000) and Sobrino et al. (2005, 2007) and as reviewed by Gowda et al. (2007, 2008). The following MODIS satellite data products were used, in order to cover the whole Aksu-Tarim River Basin: 8 day land surface temperature (MOD11A2), 16 day albedo (MCD43A3), and 16 day NDVI (MOD13A1). ET_a was mapped from 1st of April to 31st of October each year„ because this time span corresponds with the growing season of the natural vegetation (Thevs et al., 2014).

Additionally, one climate station was operated at a *Populus euphratica* forest from 2009, in order to calculate ET_a (Thevs et al., 2014). ET_a was calculated with the Bowen Ratio method (Malek and Bingham, 1993).

Afterwards, the ET_a values for the following vegetation types were retrieved: wetlands, dense forests, forests, shrub, sparse woodland, and *Apocynum pictum* stands. The definition is given in the header of Table 4 in the result section. The ET_a values of those different vegetation types were retrieved from MODIS pixels which represented the vegetation types. Those MODIS pixels were located with the help of two Quickbird satellite images, from which forests and shrub were detected and through field investigations from which the *A. pictum* stands were localized.

2.5 Economic valuation of environmental change

The overall goal of this interdisciplinary project is to optimize the land and water management and thus contribute to a sustainable implementation strategy in the region. This includes different water distribution and land use schemes along the Tarim River which have different effects on the local natural ecosystems. Efficiency in the water management and land use strategies are expected to lead to environmental improvements in the region. The question is, whether the improvements are worth the costs caused by enhanced measures like more efficient irrigation technologies. While the costs of an environmental project can be determined rather straightforwardly on the basis of market prices like wages, capital costs and material costs, the assessment of the benefits of improved environmental conditions is more complex. There are no

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market prices available for “goods” like wildlife, landscape beauty, improved air quality, etc. Therefore, particular valuation techniques have to be employed when determining the monetary value of a change in environmental quality.

In this study so-called direct valuation techniques were employed to assess the overall benefits of the preservation of the natural vegetation in the Tarim River Basin. Direct valuation techniques involve surveys, during which people are directly asked hypothetical questions concerning their willingness to pay for the environmental good in question. Since the restoration and maintenance of the natural vegetation along the Tarim River is likely to be especially beneficial for future generations which will have to deal with the adverse impacts of climate change and also because of the (presumably great) existence value of the rare desert ecosystems in the region, direct valuation techniques turn out to be most suitable for a comprehensive assessment of the benefits of new water management and land use strategies.

The so-called Contingent Valuation Method (CVM) is one of the most frequently applied direct valuation techniques (Mitchell and Carson, 1989). In CVM studies, the assessment of people’s willingness to pay is based on personal interviews (face-to face or by mail) with a representative sample of all households affected by a public project. The average willingness to pay of the households in that sample is then multiplied by the number of all households affected in order to obtain a monetary expression of the overall benefits accruing from the public project to society as a whole.

2.6 Transdisciplinary research and stakeholder participation

Transdisciplinary research (TR) has been implemented in SuMaRiO to support the generation of scientific output that can be used for supporting land and water management under climate change and uncertainty in the Tarim River Basin. The focus was specifically on joint knowledge integration among scientists from multiple disciplines and stakeholders from various sectors (Siew and Döll, 2012). Knowledge on land and water management as well as ecosystem services are elicited and integrated in a TR process that comprises interviews and workshops. A combination of methods namely

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actor modeling, Bayesian networks, and participatory scenario development is applied for knowledge integration which includes integration of results generated by SuMaRiO subprojects.

Initially it was planned to conduct interviews individually with representatives of relevant stakeholders who should also participate in a series of five workshops (Siew et al., 2014). Their problem perceptions should be elicited and integrated in a causal network (a perception graph). However, challenges of getting stakeholders involved in the process were encountered at the beginning. Therefore, the initial TR approach was adapted by adding a stakeholder analysis and intensifying efforts on knowledge integration between German and Chinese scientists as well as among multiple disciplinary German scientists who are involved in SuMaRiO.

In November 2011 and November 2012, altogether 13 interviews were conducted with Chinese scientists coming from various disciplines. An overall perception graph of Chinese scientists was constructed. Additionally, an overall perception graph of German SuMaRiO researchers was generated. Both overall perception graphs were used as an input for discussion in the first multilevel stakeholder dialogue (MLSD). The workshop was participated by Chinese scientists who were and were not interviewed and representatives from our key stakeholder the Tarim River Basin Management Bureau (TRBMB). The overall perception graphs were updated after the first MLSD. In the second and third MLSDs, another key stakeholder, a representative of Xinjiang Water Resources Bureau (represented by the vice president), together with representatives from other governmental institutions, was also present. The updated overall perception graphs were used for further discussion in the second MLSD to obtain a shared problem perception. In the third MLSD, which was only participated by Chinese stakeholders from government institutions (including water, agriculture, nature protection, and livestock husbandry), the system description of the DSS, storylines of two scenarios, and possible land and water management measures identified from the perspective of German scientists (developed in a workshop in Germany) were presented and discussed. In addition to using oral communication, questionnaires during workshops in

Xinjiang were used to allow collecting specific information even from those who did not participate in the discussion.

By adapting our TR approach and methods to suit ways of communication in the local socio-cultural and institutional setting, cross-sectoral and multidisciplinary communication and knowledge exchange was improved. Participants appreciated the format of the MLSD (including small group discussions in the form of World Café) which enabled interactive discussion. The interactive MLSDs allowed sharing of divergent perspectives on land and water management as well as the ecosystem services, while strengthening mutual understanding and learning among stakeholders and scientists.

3 Data management

Due to the interdisciplinary and international layout of the SuMaRiO project, it was necessary to establish standardized mechanism for scientific data management. The implementation of approved standards for geodata, metadata, software and interfaces were important to enable the interoperability and reusability of scientific spatial data. Our approach in this project was strongly influenced by international developments of Geoinformatics in general and Spatial Data Infrastructures (SDI) in particular. A number of SDIs were currently built on national, European and global level, or in scientific communities. All these efforts are based on the same set of standards and best practices, describing interfaces to webservices, interoperability of data sources etc. as there would be the standardization initiative OGC among others (OGC, 2014).

In order to achieve a standardized data management, an umbrella project GLUES (Global Assessment of Land Use Dynamics, Greenhouse Gas Emissions and Ecosystem Services) was established in the context of the Sustainable Land Management funding measure, funded by the German Federal Ministry of Education and Research (BMBF). The GLUES project supports several different regional projects of the LAMA initiative (GLUES, 2014). One of these regional projects is SuMaRiO. Within the framework of GLUES a Spatial Data Infrastructure (SDI) is implemented to facilitate

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publishing, sharing and maintenance of distributed global and regional scientific data sets as well as model results. The GLUES SDI supports several OGC webservices like the Catalog Service Web (CSW) which enables it to harvest data from varying regional projects. Each working group within SuMaRiO is dependent on results of another working group. Due to the spatial distribution of participating institutes the data distribution was solved by using the eSciDoc infrastructure at the German Research Centre for Geosciences (GFZ) (Ulbricht et al., 2014). The metadata based data exchange platform PanMetaDocs was established and could be used by participants' collaboration (Stender et al., 2014). PanMetaDocs supports an OAI-PMH interface which enables an Open Source metadata portal like GeoNetwork to harvest the information (OAI-PMH, 2014). Subsequently this data will be harvested by the GLUES Catalog as can be seen in Fig. 2. The figure shows the architecture of this new established SuMaRiO infrastructure node in a superordinate network of the GLUES infrastructure (Schroeder and Wächter, 2012; Schroeder et al., 2013). Furthermore, a WebGIS solution with the standard webservices Web Mapping Service (WMS) and Web Feature Service (WFS) was implemented. Both, the metadata application and the WebGIS solution are available via the Web Portal of SuMaRiO (SuMaRiO, 2014).

The data base of the project is used for the development of an indicator-based decision support tool (DST). This tool will enable stakeholders to see the consequences of their actions in terms of water and land management under climate and socio-economic scenario assumptions.

4 Results and major findings

4.1 Climate change

The observations show climate change in this region. There is a general agreement that both temperature and precipitation have been increasing during the last decades in the Aksu and Tarim basins (Tao et al., 2011). According to the analysis of Shangguan

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et al. (2009), that is based on data from 25 weather stations in the Tarim River Basin, a warming of 0.77 ± 0.16 K (0.019 K a^{-1}) and an increase in precipitation of 22.8 ± 7.9 % between 1960 and 2000 were found for the region.

Our results on observed trends in the Aksu Basin are based on data from CMA and the WATCH Project for the period 1961–2001. The statistically significant positive trends in temperature were found for 30 out of 40 grid points in the lower Chinese part of the drainage area, and the average increase for 30 stations was 0.017 K a^{-1} (equivalent to 0.66 ± 0.012 K in 40 years). All grid points without a significant trend are located in the western Chinese part of the basin. The temperature trends in the upper Kyrgyz part were statistically significant for all 10 grid points and higher than in the Chinese part: on average 0.026 K a^{-1}, or 1.027 ± 0.016 K in 40 years.

The positive, statistically significant trends in precipitation in the Aksu Basin in 1961–2001 were found for 24/30 out of 40 grid points in the Chinese part, where CMA data was used, for the Mann–Kendall/linear model tests, respectively. The average increase for the 24 stations was 1.04 mm a^{-1}, which is equivalent to 41.5 ± 0.8 mm in 40 years. The trends are not statistically significant according to both tests for points located in the western part of the basin. The precipitation trends in the upper Kyrgyz part using APHRODITE and WATCH data were all not statistically significant. The results on the detailed analysis of climatic trends in the Aksu Basin are described in two research articles (Krysanova et al., 2014; Kundzewicz et al., 2014).

In addition, we used available climatic datasets, in order to evaluate temperature and precipitation trends in the whole Tarim River Basin. A significant increase of temperature and precipitation within the period 1962–2006 was found, which is in agreement with several other studies (see, for example, Tao et al., 2011 and Chen et al., 2006). The results based on the CRU-TS3.21 and CMA datasets show a temperature increase of 0.3 K per decade. The results based on the CMA, GPCC-FD v6 and APHRODITE_MA V1101 datasets show an increase in precipitation of 6 mm per decade. All calculated trends were significant at a 5 % significance level based on a Mann–Kendall test. Only CRU-TS3.21 data show an insignificant precipitation increase, possibly owing to the

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scarcity of the underlying station network in the Tarim Basin (Harris et al., 2014). Therefore we can confirm the observation of a shift towards a warmer and wetter climate of Shi et al. (2007) on the basis of multiple datasets.

Climate scenarios were evaluated for three future periods: 2011–2040 (STARS, CCLM, CMIP5), 2041–2070 (CCLM, CMIP5) and 2071–2100 (CCLM, CMIP5). According to climate projections, the increase in temperature and precipitation will continue in the future. Comparing the near future period 2011–2040 with the baseline period 1981–2000 STARS projects a temperature change from 0.1 to 2.0 K and a precipitation change of −2 to 27 mm on the annual basis over all simulations and scenarios. CCLM shows a similar change for the near future with a temperature change of 0.9 K for all scenarios and a precipitation increase between 11 and 35 mm. The investigated GCMs show a similar change.

The precipitation increase is confined to late spring and early summer. We did not observe a statistical significant difference between the emission scenarios in the period 2011–2040. For the focus periods 2041–2070 and 2071–2100 the emission scenarios become distinguishable, with highest changes in precipitation projected for the high emission scenario RCP8:5. For the last future period 2071–2100 CCLM shows a temperature change between 0.8 and 4.5 K, and a precipitation change of up to 38 mm compared to the baseline conditions. Furthermore, CCLM and the CMIP5 GCMs show a precipitation increase for the winter season in the mid and last projection period. However, the overall change in all months is small (below 15 mm) for all periods and scenarios. Also it can be observed that the range in the change signal of the CMIP5 models is considerably higher than others for all scenarios and is growing with time. Some GCMs show a decrease of up to 49 mm in annual precipitation.

4.2 Hydrological trends and special features in the region

The trend analysis for the two headwater catchments of the Aksu showed significant increases in the summer discharge ($p < 0.01$) over the period 1957–2004. The discharge increased by 25 mm month^{-1}, or 23 % relative to the mean flow over this period

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in the Sari-Djaz catchment, while the discharge in the Kokshaal Catchment showed a lower change in absolute terms with 15 mm month^{-1}, but a stronger increase in relative terms with 35 % (Fig. 3). However, the discharge did not increase in a uniform way over the entire period. The increase was particularly pronounced during the last decade. A period with relatively high discharge was also observed in the mid to end of the 1960s, while the discharge level was rather low in the 1980s.

The correlation analysis of discharge and temperature/precipitation during the summer half year revealed a positive correlation of discharge with temperature for the highly glacierized Sari-Djaz Catchment (Spearman's rho = 0.63, $p < 0.01$), while there was no significant correlation with precipitation. In contrast, in the Kokshaal Catchment a weak but significant positive correlation with precipitation was found (Spearman's rho = 0.50, $p < 0.01$), but the correlation with temperature was not significant. This is due to the different characteristics of the two headwater catchments: temperature variations play a large role for inter-annual discharge variations in the highly glacierized Sari-Djaz Catchment, and precipitation is more important in the Kokshaal Catchment, where snow melt and rainfall have a stronger influence on the total annual discharge. At other time scales, these relations between climate and discharge vary, e.g. at a daily time scale, discharge variations are strongly correlated with temperature variations also in the Kokshaal Catchment, resulting from increased snow and glacier melt on warmer days (Krysanova et al., 2014).

An analysis of high peaks in river discharge, and interrelations between river discharge and climate parameters was performed for the headwater catchments of the Aksu, focusing on the Xiehela Station on the Kumarik River (see details in Krysanova et al., 2014). The annually reoccurring Glacial Lake Outburst Floods (GLOF) of the Merzbacher Lake, located in the Kyrgyz headwaters of the Aksu River cause the discharge records to peak at the Xiehela Station in late summer–autumn (end of August–October). This unique hydrological event had a significant impact on the discharge of the Aksu and Tarim Rivers in the past (Glazirin, 2010; Wortmann et al., 2013), and showed a high volatility in terms of occurrence, peak discharge and flood volumes.

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Although it is an erratic event, the occurrences show a high dependence on local weather as well as the dynamics of the damming Enylchek Glacier (Ng et al., 2007). Wortmann et al. (2013) analysed GLOFs by means of hydrological modelling with the SWIM model and using discharge records from the Chinese gauging station Xiehela, located some 200 km downstream of that lake. They were able to prove the occurrence of GLOFs in the discharge time series (see example in Fig. 4), and provided reliable flood volume estimations of between 100 and 250 million m^3 per event, accounting for 3 to 6 % of the total annual discharge at the Xiehela Station.

The outburst events alter the annual discharge regime and pose a threat to infrastructures downstream, as the floods' occurrence is shifting closer to the melt water peak, i.e. leading to increased peak discharges in late summer. The construction of reservoirs immediately upstream of the Xiehela Gauging Station has increased the importance of flood volume and peak discharge estimates and predictions. The Xiaoshixia Reservoir has been operational since 2012 with a maximum capacity of 69 million m^3, and the second, much larger Dashixia Reservoir is planned to be operational by 2019 with a maximum capacity of app. 1274 million m^3.

In a next step, potential impacts of climate change on water availability in the Upper Tarim Basin will be investigated using a scenario approach, i.e. by driving the hydrological models WASA and SWIM with climate scenario data. In such highly glacierized mountain catchments this approach has specific problems and particular requirements. A robust parameterization is important, considering that errors in simulated glacier melt may be compensated by precipitation errors. This problem can be solved applying a multiobjective calibration. The models also have to take into account dynamic changes of the glacier area. The ability to represent the discharge changes observed in the past can be an important check for the applied hydrological models.

In addition, a robust approach is necessary to account for GLOF dynamics in the future. Besides, in lower parts of the drainage area water use for irrigation on arable land, and transmission losses have to be properly accounted for. The ability to simulate river discharge in such a complex environment with satisfactory calibration and

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validation results is a prerequisite for applying climate scenarios and doing climate impact assessment.

The modeling of the whole water cycle at Yingbazar showed that in the year 2012 an amount of 114 mm a^{-1} of the groundwater recharge was contributed by the natural annual summer flood. The groundwater recharge is that amount of water which is stored in the aquifer after evapotranspiration and infiltration losses. Meanwhile dykes have been built along nearly the whole upper and middle reaches, except for Yingbazar. Though, there are locks at major river branches so that they may receive water from the Tarim River. If dams were built in Yingbazar, too, and the floods only entered through such a lock, the groundwater recharge by the flood would drop to 41 mm a^{-1} (Fig. 5) (Keilholz, 2014).

4.3 Agriculture

Over the last three decades, the land use area along the Tarim River extremely expanded. The total agricultural land use area more than doubled from 1989 to 2011. In recent years, cotton and tree fruits have become the main agricultural commodities (Fig. 6).

Apart from the steady increase in population and related agricultural labour force, the very good producer price developments for cotton and, especially, for tree fruits obviously drive the reclamation of crop land (Fig. 7).

The insufficient control of land reclamation supported the agricultural land expansion. This resulted in an increased water demand by the agricultural sector. The local governments have realized the urgency of the problem situation aiming for a stabilization of agricultural land, while shifting agricultural labour force into other sectors of industry (Feike et al., 2014). Increased investments into agricultural extension services seem a viable option, in order to improve farmers' management and water use efficiency and thus reduce agricultural water consumption, while the sole increase of water price for farmers may have no positive effect with regard to a reduction of the water consumption (Mamitimin et al., 2014).

The field survey revealed huge differences in agronomic and economic performance between farmers using drip irrigation and farmers using flood irrigation for cotton production. Table 1 displays that the total water consumption of farmers using drip irrigation is by more than 1500 m^3 ha^{-1} smaller compared to those using flood irrigation.

At the same time the average yield of drip irrigation farmers was more than 1500 kg ha^{-1} higher. Looking at the economic performance of cotton production (Table 2) drip irrigation entails nearly twice the variable cost for irrigation compared to flood irrigation. However, the higher yield level under drip irrigation led to an in average 2000 USD ha^{-1} higher gross margin compared to flood irrigation. Over the sampled farm households drip irrigation seems a viable option for cotton irrigation along the Tarim River performing better in agronomic and economic terms over flood irrigation. However, flood irrigation requires fewer cost and thus lower capital demand by the farmers.

The MODIS time series showed that the area of productive cropland increased from about 18 000 km^2 in 2001 to about 25 000 km^2 in 2011 for the Tarim River Basin, including the Aksu River Basin. Thereby, large scale highly productive cotton monoculture, less productive cotton systems, and small scale Uyghur cropping systems (including marginal agriculture mixed with semi-natural vegetation) covered 11 000, 4000, and 10 000 km^2, respectively. The traditional Uyghur land use system is characterized by fields in rather small parcels of land with permanent tree cultures (e.g. walnut or fruit trees) in combination with a rotation of crops, most frequently maize and winter wheat, planted under the trees. Cotton, on the other hand is typically grown in intensive monocultures, since it requires a certain light intensity to grow.

The largest increase of cropland occurred between 2004 and 2008. The most rapid changes were observed in Aksu and Korla, where there was an expansion of cotton production in state operated farms of the Xinjiang Construction and Production Corps at the fringes of the large oases located in these districts. In Aksu, it was estimated that the area of productive cropland increased by more than 300 km^2 every four years.

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Three soils with different degree of soil salinity were chosen, in order to investigate the cotton yields under different salinization levels: low soil salinity in Korla (17–25 $mS\,cm^{-1}$), medium soil salinity in Aksu (29–50 $mS\,cm^{-1}$) and high soil salinity in Aksu (52–62 $mS\,cm^{-1}$) over a soil profile of 100 cm. The highest cotton yield (6.6 t seed cotton ha^{-1}) was attained on the low saline soil in Korla. There, we also observed the highest water use efficiency (seed cotton yield/ET_a) of 0.01 $t\,ha^{-1}\,mm^{-1}$, which corresponds to an ET_a of 660 mm. On the high saline soil a seed cotton yield of 2.4 $t\,ha^{-1}$ was measured.

4.4 Riparian ecosystems

In the Tugai forests in Yingbazar, tree age was lowest at the shortest groundwater distance and highest on the plot with the largest distance to the water level (Table 3). The number of trees, the stand density, basal area, tree cover and tree height all decreased with increasing distance to the water table. These differences in the stand structure were also reflected in the stem morphology: dbh (stem diameter at breast height) was largest and the height-dbh-ratio was lowest on the plot with the largest distance to the groundwater.

Minimum, average and maximum tree-ring width decreased with increasing distance to the water table (Table 4). On the plot with the closest distance to the groundwater, but not on the plots with larger groundwater distances, the standardized stem diameter increment correlated significantly with the Tarim River's runoff of the preceding year for the time period of 1957 to 2005, for which runoff data were available (Fig. 8). This finding corresponds with the results of the soil moisture and groundwater measurements conducted along the Tarim lower reaches, which are introduced in the following text.

There, at the Tarim lower reaches, the soil water content was within the plant available range during the whole measuring period in all soil layers deeper than 50 cm from the surface (Fig. 9). Immediately after the rise of the groundwater level – which is induced by increased river discharge – the mean pF-Values react. Though, deeper levels show an earlier increase in soil water content than shallower ones that shallower ones (Fig. 9).

For groundwater levels deeper than at this site (like GD2 and GD3 from above), it can be assumed that the time lag becomes longer or that there even will not be any influence of the soil moisture by the groundwater. Therefore, tree rings do not correspond with groundwater distance on sites with deep groundwater levels (see sites GD2 and GD3).

Qualitative results show that the surface-groundwater-distance is not the only factor for vegetation condition within the examined corridor. Soil conditions, especially fine-sediment layers, play a crucial role. The soil moisture data indicate that water availability within the measurement period is sufficient to maintain the existing vegetation, disregarding other factors. But one decisive component within the Tugai ecosystem, the morphodynamic, is missing. A comparison of remote sensing data from 1964 and 2014 has shown that the river channel has not changed within that period. River dynamics are important for an establishment of juvenile trees and thus the formation of new forest stands, which is a major factor influencing the vitality – in a sense of rejuvenation – of the forest stands (cf. Thevs et al., 2008b).

In the same area in the lower reaches, the analysis of the Quickbird and Worldview satellite images showed that from 3610 *Populus euphratica* trees, which had been recognized in 2005, a number of 180 trees disappeared and 25 new trees were identified until 2011. This affirms that the missing river dynamics, as found along the lower reaches, results in the absence of young trees in the lower reaches.

The ET_a of the natural vegetation finally is shown in Table 5. In all vegetation types, except for sparse woodland, the ET_a of the growing seasons increases from 2009 over 2010 to 2011. This trend is most pronounced in the dense forests with an ET_a of 735, 777, and 1068 mm during the growing season 2009, 2010, and 2011, respectively. The ET_a calculated from the climate data (Table 5) follows this trend, too. The sum of the daily ET_a values over the vegetation season 2009 measured at the climate station Iminqak nearly equals the ET_a detected from the MODIS satellite images (Table 6). In

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2011, the MODIS ET_a is 10.8 % higher than the ET_a measured at the climate station. Thus, the ET_a of those dense forests is higher than the ET_a of cotton under intensive cultivation.

The trend of the ET_a (Tables 5 and 6) can be explained as follows: 2009 was an extremely dry year with no summer flood. 2010 was dry, too, until the summer flood started. The summer flood of 2010 was extremely high so that large areas of the natural vegetation, especially dense forests, were flooded and partly stayed flooded until early summer 2011. Therefore, in the second half of 2010 more water was available to be consumed by the natural vegetation. In 2011, there was abundant water available throughout the whole growing season. In addition, during spring and early summer water from flooded areas evaporated.

Species of the Tugai forest play a significant role for urban greening, shelterbelt forests around cropland and orchards (see Missall et al., 2014), and to prevent dust storms (see also Sect. 5.4). During the late 1970s and early 1980s, the local government of Aksu has realized the importance and urgency of urban greening for sustainable urban development, and since then has taken great efforts to increase the forest coverage. As a result, urban green coverage within the built-up area climbed up to 1350 ha in 2012, now occupying more than one third of the urban built-up area. Meanwhile, urban green coverage as percentage of built-up area (Green Coverage Ratio, GCR) also keeps increasing. In 1985, GCR was less than 15 %, and in 2012, it reached about 36 %. This indicates the continuous attentions and efforts of the relevant urban authorities on urban greening.

By the end of the year 2015, the total amount of water consumption on urban greening is estimated to reach about 21.3 million $m^3\,year^{-1}$ (Municipal Government of Aksu, 2007). For the irrigation of urban green space, water saving irrigation methods like sprinkler irrigation and drip irrigation will be predominantly used, and irrigation quota will be controlled to remain below 6750 $m^3\,ha^{-1}\,a^{-1}$ (Municipal Government of Aksu, 2007).

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4.5 Economic valuation of environmental change – willingness to pay

The restoration and maintenance of the natural vegetation along the Tarim River would have to be financed out of scarce public funds. Decision makers should compare the costs of the corresponding preservation project to the benefits of the environmental improvement when deciding whether or not the preservation project should be realized. In order to determine the benefits of the restoration and maintenance of the natural vegetation along the Tarim River a contingent valuation survey was conducted in summer 2013. It was expected that the benefits of an improvement of the environmental conditions in the Tarim River Basin would not be limited to the local population, but that also people living in other parts of China would enjoy the effects of a more sustainable land use policy in the Tarim River Basin. Hence, also the "long-distance benefits" would have to be assessed in a comprehensive valuation survey. The respondents were asked to express their willingness to pay (WTP) for the implementation of the preservation project. In accordance with economic welfare theory, individual WTP statements can be interpreted as the utility (in monetary terms) a respondent receives from the project in question. If the survey sample is representative of the population affected by such a project, the WTP statements from the sample can be extrapolated to all individuals affected. To assess the opinion and WTP of local people, standardized interviews were conducted in different cities of Xinjiang. The preferences of people living far away from the Tarim River were assessed in a representative survey in the urban areas of Beijing.

The mean WTP of the respondents from Xinjiang amounts to 48 RMB per month, corresponding to approximately 1 % of an average respondent's monthly disposable household income (4731 RMB). Respondents from Beijing had a mean WTP of 107 RMB, which is also about 1 % of a respondent's monthly disposable household income (8487 RMB). According to these results, the appreciation of the preservation project in the Tarim River Basin is approximately the same in both study sites. Apart from the WTP for the preservation project, people's opinion on different aspects of environmental preservation in the Tarim River Basin was assessed. Respondents were asked to

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rank several ecosystem services (ESS) provided by the natural vegetation according to their importance for society. In addition to that they also had to judge the seriousness of several environmental problems in the Tarim River Basin. The results are displayed in Figs. 10 and 11. The preferences for the different ESS turned out to be quite similar in both study sites. Respondents from Xinjiang and from Beijing considered the mitigation of dust and sandstorms as the most important ESS, the provision of useful herbs was perceived as least important. Also the ranking of environmental problems was the same in both study sites. Desertification of the landscape was considered most serious, followed by sandstorms and dust and the extinction of plants and animals was ranked least important.

The survey results show that also people living far away from the project site appreciate the benefits from environmental preservation in the Tarim River Basin as much as local people do. Therefore, confining valuation surveys to the local population only might lead to a systematic undervaluation of environmental improvements and thus to a rejection of a socially beneficial project by political decision makers. Hence, we recommend conducting nation-wide valuation surveys for a comprehensive appraisal of environmental projects.

4.6 Transdisciplinary research

Transdisciplinary research is an iterative and recursive process which requires continual reflection and adaption as new knowledge and surprises emerge. Our TR approach has in overall improved knowledge integration among multiple disciplines and enabled, although partially, knowledge integration from inside and outside of academia. The integration of existing knowledge, which takes stakeholder perspectives and needs into account, is essential for the development of a usable decision support tool (DST) as well as identification of actually implementable land and water management strategies that aim at maximizing ecosystem services in the Tarim River Basin.

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5 Discussion and outcomes

The key-resource in the Tarim River Basin is water, for which anthropogenic activities and natural ecosystems compete. Water is delivered from the headwaters of the Aksu River with currently increasing runoff. The competition for water has not eased, mainly because new land for agriculture, which completely depends on irrigation, has been reclaimed at a high speed. Furthermore, it is unsure, how the runoff from the Aksu headwaters will further develop in the course of climate change so that no weakening of the water competition can be expected from the supply side. Therefore, a sound allocation of water must be established, in order to balance the water competition on the demand side.

This interdisciplinary project will therefore result in a decision support tool (DST), build on the participation of regional stakeholders and models based on results and field experiments. This DST finally shall assist stakeholders in balancing the water competition acknowledging the major external effects of any water allocation. Though, the complexity of the project cannot fully be implemented in a DST, as the DST has to be understood and used by all kinds of stakeholders with different kinds of backgrounds. The simplicity of the DST will help them to understand the whole ecological system of the Tarim River Basin. The DST is based on simple rules, which can be filled with new actual data by every stakeholder according to his/her special background and data availability. Through this DST, the SuMaRiO Project brings a new kind of decision support to the region and will help to foster sustainable development of the region.

On the way to develop the decision support tool, the multi-level stakeholder dialogues (MLSDs) were an important tool to implement project results. With its help important indicators for the definition of climate and socio-economic scenarios and management alternatives have been carved out. Also representative indicators for all relevant ecosystem services have been identified and weighted for the presentation of land and water management consequences. These results form the basis of the DST.

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The workflow of the DST is as follows:

In the first step three different planning years for the climate and socio-economic scenarios and management alternatives can be chosen arbitrarily. For each of these years the DST-user can define up to three different climate and socio-economic scenarios by choosing assumed values for explaining indicators like increase in world market cotton price or increase in average daily temperature. Optionally the user can decide on probabilities for the realization of the scenarios defined before.

In the second step up to ten management alternatives can be planned for the upper, middle and lower reaches of the Tarim River Basin for the three different years. Alternatives differ, e.g. in the amount of water that is assigned to the different regions or the percentage of land that can be used for agriculture.

In the next step the weights of the ecosystems agriculture, which includes the economic benefits, (virtual) value of riparian forests, grassland and urban vegetation can be weighted, just as the corresponding ecosystem services and the representative indicators. The DST recommends choosing the settings from the stakeholder dialogues, but the user can overrule them. Furthermore the side-constrained multi-criteria goals of land and water managers can be defined. E.g. the one goal could be to maximize the water quality and at the same time to maximize the benefit originating from cotton production. As a side constraint a minimal virtual value of riparian forests has to be guaranteed.

The first three steps constitute the input phase and are followed by the computation and the analysis phase. In the fourth step the short- and long-term consequences of each management alternative are calculated in a quantitative way as well as in a semi-quantitative way for each part of the Tarim River Basin. Here "consequences" mean the development/change of the different indicators. This development/change is computed on the basis of the knowledge and models developed within the SuMaRiO project. For some computations Fuzzy-Logic is employed. With the help of the defined goals for each representative ecosystem indicator, one standardized utility value respectively standardized goal achievement value can be calculated. Based on the standardized

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utility value a comparison of each indicator with the result of the current year is enabled. It is shown if the alternative generates an improvement or a decline in the standardized utility value of the indicator. With the aggregation of the utility values to one significant value, in terms of utility analysis, all planned management alternatives can be compared among one another and is the first part of the output. In addition the DST performs sensitivity analyses by modifying crucial parameters of the chosen management alternatives before. This yields to more insight in the allocation problem and forms the last step of the DST process.

6 Conclusions from three years SuMaRiO

Sustainable land and water resource management in the context of an endorheic river basin need coupling of hydrological, ecological, and socio-economic understanding and models. Such an integration of hydrological, ecological, and socio-economic understanding and models requires inter- and transdisciplinary research, to which natural sciences, engineering sciences, economic sciences, and social sciences have to contribute as equal partners. The implementation requests stakeholder participation and public awareness raising. We see the DST tool, which will be the central outcome of SuMaRiO, as a means to bridge communication gaps between scientists of different disciplines within the consortium, because the different scientists have to integrate their disciplines into a visible product. Furthermore, the DST will act as a tool for stakeholder participation and public awareness raising, because stakeholders of any education level will be able to assess different scenarios of land and water resource management. So, stakeholders can understand the effects of different land and water resource management paths on their own livelihoods.

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References

Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., Schamm, K., Schneider, U., and Ziese, M.: A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901–present, Earth Syst. Sci. Data, 5, 71–99, doi:10.5194/essd-5-71-2013, 2013.

Bohnet, A., Giese, E., and Zeng, G.: Die Autonome Region Xinjiang (VR China) – Eine Ordnungspolitische und Regionalökonomische Studie (Band I), LIT Verlag, Münster, Hamburg, London, 1998.

Bohnet, A., Giese, E., and Zeng, G.: Die Autonome Region Xinjiang (VR China) – Eine Ordnungspolitische und Regionalökonomische Studie (Band II), LIT Verlag, Münster, Hamburg, London, 1999.

Chiriacy-Wantrup, S. V.: Natural Resource Economics, Selected Papers, Westview Press, Boulder, 1985.

Decagon: 10HS Soil Moisture Sensor Manual, Pullman, Washington, USA, 2014.

FAO: WRB – World Reference Base for Soil Resources, FAO, Rome, Italy, 2006.

Feike, T., Mamitimin, Y., Li, L., and Doluschitz, R.: Development of agricultural land and water use and its driving forces along the Aksu and Tarim River, P. R. China, Environmental Earth Sciences, Open Access, doi:10.1007/s12665-014-3108-x, Springer, Berlin, Heidelberg, 2014.

Glazirin, G. E.: A century of investigations on outbursts of the ice-dammed Lake Merzbacher (Central Tien Shan), Aust. J. Earth Sci., 103, 171–179, 2010.

GLUES Geoportal, Global Assessment of Land Use Dynamics on Greenhouse Gas Emissions and Ecosystem Services: http://geoportal.glues.geo.tu-dresden.de/index.php, last access: 22 July 2014.

ESDD
5, 1221–1273, 2014

Gowda, P. H., Chavez, J. L., Colaizzi, P. D., Evett, S. R., Howell, T. A., and Tolk, J. A.: Remote sensing based energy balance algorithms for mapping ET: current status and future challenges, Am. Soc. Agric. Biol. Eng., 50, 1639–1644, 2007.
Gowda, P. H., Chavez, J. L., Colaizzi, P. D., Evett, S. R., Howell, T. A., and Tolk, J. A.: ET mapping for agricultural water management: present status and challenges, Irrigation Sci., 26, 223–237, 2008.
Grashey-Jansen, S. and Timpf, S.: Soil hydrology of irrigated orchards and agent-based simulation of a soil dependent precision irrigation system, Adv. Sci. Lett., 3, 259–272, 2010.
Grashey-Jansen, S., Kuba, M., Cyffka, B., Halik, Ü., and Aishan, T.: Spatio-temporal Variability of Soil Water at Three Seasonal Floodplain Sites: A Case Study in Tarim Basin, Northwest China, Chinese Geogr. Sci., doi:10.1007/s11769-014-0717-y, Science Press, Northeast Institute of Geography and Agroecology, CAS and Springer Verlag, Berlin, Heidelberg, 2014.
Hoppe, T., Kleinschmit, B., Roberts, B., Thevs, N., and Halik, Ü. (Eds.): Watershed and Floodplain Management along the Tarim River in China's Arid Northwest, Shaker, Aachen, 2006.
Huete, A., Didan, K., Miura, T., Rodriguez, T., Gao, X., and Ferreira, F.: Overwiew of the radiometric and biophysical performance of the MODIS vegetation indices, Remote Sens. Environ., 83, 195–213, 2002.
Keilholz, P.: Auswirkungen von veränderter Landnutzung auf den Wasserhaushalt und die Auwaldvitalität in einer Flussoase am Tarim (China), Ph.D. thesis, Technical University Munich, Munich, 2014.
Krysanova, V., Wortmann, M., Bolch, T., Merz, B., Duethmann, D., Walter, J., Huang, S., Jiang, T., Su, B., and Kundzewicz, Z.: Analysis of current trends in climate parameters, river discharge and glaciers in the Aksu River basin (Central Asia), Hydrolog. Sci. J., doi:10.1080/02626667.2014.925559, Taylor & Francis, Florence, Kentucky, USA, 2014.
Kundzewicz, Z., Merz, B., Vorogushyn, S., Hartmann, H., Duethmann, D., Wortmann, M., Huang, S., Su, B., Jiang, T., and Krysanova, V.: Analysis of changes in climate and river discharge with focus on seasonal runoff predictability in the Aksu River Basin, Environ. Earth Sci., Open Access, doi:10.1007/s12665-014-3137-5, Springer, Berlin, Heidelberg, 2014.
Malek, E. and Bingham, G. E.: Comparison of the Bowen ratio-energy balance and the water balance methods for the measurement of evapotranspiration, J. Hydrol., 146, 209–220, 1993.

ESDD
5, 1221–1273, 2014

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Mamitimin, Y., Feike, T., Seifert, I., and Doluschitz, R.: Irrigation in the Tarim Basin, China: farmers' response to changes in water pricing practices, Environ. Earth Sci., doi:10.1007/s12665-014-3245-2, Springer, Berlin, Heidelberg, 2014.

MEA – Millennium Ecosystem Assessment: Ecosystems and Human Well-Being: Synthesis, Island Press, Washington, D.C., 2005.

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J. F., Matsumoto, K., Montzka, S. A., Raper, S. C. B., Riahi, K., Thomson, A., Velders, G. J. M., and Vuuren, D. P. P.: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300, Climatic Change, 109, 213–241, 2011.

Mitchell, R. C. and Carson, R. T.: Using Surveys to Value Public Goods – the Contingent Valuation Method, Resources for the Future, Washington, D.C., 1989.

Mitchell, T. D. and Jones, P. D.: An improved method of constructing a database of monthly climate observations and associated high-resolution grids, Int. J. Climatol., 25, 693–712, 2005.

Municipal Government of Aksu: Akesu shi chuangjian guojia senlin chengshi shenbao cailiao (declaration data for creating state forest city of Aksu), Aksu, 2007.

NBSCa: Statistical Yearbooks of Xinjiang, China Statistics Press, Beijing, China, 1990–2012.

NBCSb: Xinjiang Construction and Production Corps Statistical Yearbook, China Statistics Press, Beijing, China, 1990–2012.

Ng, F., Liu, S., Mavlyudov, B., and Wang, Y.: Climatic control on the peak discharge of glacier outburst floods, Geophys. Res. Lett., 34, L21503, doi:10.1029/2007GL031426, 2007.

OAI-PMH: Open Archives Initiative Protocol for Metadata Harvesting, Protocol Version 2.0 of 2002-06-14, Document Version 2008-12-07T20:42:00Z, available at: http://www.openarchives.org/OAI/2.0/openarchivesprotocol.htm, last access: 22 July 2014.

OGC: OGC Standards and Supporting Documents, Open Geospatial Consortium, available at: http://www.opengeospatial.org/standards, last access: 22 July 2014.

Orlowsky, B., Gerstengarbe, F.-W., and Werner, P. C.: A resampling scheme for regional climate simulations and its performance compared to a dynamical rcm, Theor. Appl. Climatol., 92, 209–223, 2008.

Rinn, F.: Time Series Analysis and Presentation for Dendrochronology and Related Applications V0.53, User Reference, Rinntech, Heidelberg, 2003.

Rockel, B., Will, A., and Hense, A.: The regional climate model COSMO-CLM (CCLM), Meteorol. Z., 17, 347–348, 2008.

ESDD
5, 1221–1273, 2014

Roerink, G. J., Su, B., and Menenti, M.: S-SEBI A simple remote sensing algorithm to estimate the surface energy balance, Phys. Clim. Earth B, 25, 147–157, 2000.
Schneider, U., Becker, A., Meyer-Christoffer, A., Ziese, M., and Rudolf, B.: Global Precipitation Analysis Products of the GPCCRep, Deutscher Wetterdienst, Offenbach a. M., Germany, 2011.
Schroeder, M. and Wächter J.: A Scientific SDI Node for Sustainable Land and Water Management, Pre-Conference Workshop: Testing Geospatial Web Services – Scientific SDIs, 15th AGILE International Conference on Geographic Information Science, 24 April 2012, Avignon, France, 2012.
Schroeder, M., Stender, V., Klump, J., Wächter, J., and Kunkel, R.: The Design of Monitoring and Data Infrastructures – Applying a forward-thinking Reference Architecture, 2013 IEEE 10th International Conference on Networking, Sensing and Control (ICNSC), Paris-Evry, France 2013, 216–220, doi:10.1109/ICNSC.2013.6548739, Institute of Electrical and Electronics Engineers, New York, USA, 2013.
Siew, T. F. and Döll, P.: Transdisciplinary research for supporting the integration of ecosystem services into land and water management in the Tarim River Basin, Xinjiang, China, J. Arid Land, 4, 196–210, 2012.
Siew, T. F., Döll, P., and Yimit, H.: Experiences with a transdisciplinary research approach for integrating ecosystem services into water management in Northwest China, in: The Global Water System in the Anthropocene, edited by: Bhaduri, A., Bogardi, J., Leentvaar, J., and Marx, S., Springer Cham, Heidelberg, New York, Dordrecht, London, 2014.
Sobrino, J. A., Gómez, M., Jiménez-Muñoz, J. C., and Olioso, A.: Application of a simple algorithm to estimate daily evapotranspiration from NOAA–AVHRR images for the Iberian Peninsula, Remote Sens. Environ., 110, 139–148, 2005.
Sobrino, J. A., Gómez, M., Jiménez-Muñoz, J. C., Olioso, A., and Chehbouni, G.: A simple algorithm to estimate evapotranspiration from DAIS data: application to the DAISEX campaigns, J. Hydrol., 315, 117–125, 2007.
Song, Y. D., Fan, Z. L., Lei, Z. D., and Zhang, F. W.: Research on Water Resources and Ecology of the Tarim River, China, Xinjiang Peoples Press, Urumqi, 2000.
Stender, V., Ulbricht, D., Schroeder, M., and Klump, J.: Automatic Publishing ISO 19115 Metadata with PanMetaDocs using SensorML information, EGU General Assembly 2014, 27 April–2 May 2014, id.2597, Vienna, Austria, 2014.

ESDD
5, 1221–1273, 2014

Steppeler, J., Doms, G., Schättler, U., Bitzer, H. W., Gassmann, A., Damrath, U., and Gregoric, G.: Meso-gamma scale forecasts using the nonhydrostatic model LM, Meteorol. Atmos. Phys., 82, 75–96, 2003.

SuMaRiO Webportal, available at: www.sumario.de/project, last access: 7 October 2014.

Thevs, N., Zerbe, S., Peper, J., and Succow, M.: Vegetation and vegetation dynamics in the Tarim River floodplain of continental-arid Xinjiang, NW China, Phytocoenologia, 38, 65–84, 2008a.

Thevs, N., Zerbe, S., Schnittler, M., Abdusalih, N., and Succow, M.: Structure, reproduction and flood-induced dynamics of riparian Tugai forests at the Tarim River in Xinjiang, NW China, Forestry, 81, 45–57, 2008b.

Thevs, N., Rozi, A., Kubal, C., and Abdusalih, N.: Water consumption of agriculture and natural ecosystems along the Tarim River, China, Geo-Öko, 34, 50–76, 2013.

Thevs, N., Peng, H. Y., Rozi, A., Zerbe, S., and Abdusalih, N.: Water allocation and water consumption of irrigated agriculture and natural vegetation in the Aksu-Tarim river basin, Xinjiang, China, J. Arid Environ., doi:10.1016/j.jaridenv.2014.05.028, Elsevier, Amsterdam, the Netherlands, 2014.

Thomas, F. M., Foetzki, A., Arndt, S. K., Bruelheide, H., Gries, D., Zeng, F. J., Zhang, X. M., and Runge, M.: Water use by perennial plants in the transition zone between river oasis and desert in NW hina, Basic Appl. Ecol., 7, 253–267, 2006.

Ulbricht, D., Klump, J., and Bertelmann, R.: Publishing Datasets with eSciDoc and panMetaDocs, Geophysical Research Abstracts Vol. 14, EGU2012-7058-2, 2012, General Assembly European Geosciences Union, Vienna, 2012.

Wang, D., Menz, C., Simon, T., Simmer, C., and Ohlwein, C.: Regional dynamical downscaling with CCLM over East Asia, Meteorol. Atmos. Phys., 121, 39–53, 2013.

Wang, S. J., Chen, B. H., and Li, H. Q.: Euphrates Poplar Forest, China Environmental Science Press, Beijing, 1996.

Wang, Y. (Ed.): Local Records of the Akesu River Basin, Fangzi Publisher, Beijing, 719 pp., 2006.

Weedon, G. P., Gomes, S., Viterbo, P., Shuttleworth, W. J., Blyth, E., Oesterle, H., Adam, J. C., Bellouin, N., Boucher, O., and Best, M.: Creation of the WATCH forcing data and its use to assess global and regional reference crop evaporation over land during the twentieth century, J. Hydrometeorol., 12, 823–848, doi:10.1175/2011JHM1369.1, 2011.

ESDD
5, 1221–1273, 2014

Werner, P. C. and Gerstengarbe, F.-W.: Proposal for the development of climate scenarios, Clim. Res., 8, 171–180, 1997.
Wortmann, M., Krysanova, V., Kundzewicz, Z., Su, B., and Li, X.: Assessing the influence of the Merzbacher Lake outburst floods on discharge using the hydrological model SWIM in the Aksu headwaters, Kyrgyzstan/NW China, Hydrol. Process., doi:10.1002/hyp.10118, Jon Wiley & Sons Ltd., New York, USA, 2013.
Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N., and Kitoh, A.: Aphrodite: constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges, B. Am. Meteorol. Soc., 93, 1401–1415, 2012.

ESDD
5, 1221–1273, 2014

Table 1. Average water consumption and yield level of cotton production of drip and flood irrigating farm households along the Tarim River.

Irrigation method	Number of farms	Water consumption: Irrigation $[m^3\,ha^{-1}]$	Water consumption: Flushing $[m^3\,ha^{-1}]$	Water consumption: Total $[m^3\,ha^{-1}]$	Yield $[kg\,ha^{-1}]$
Drip irrigation	112	4119.2	2816.3	6935,4	5554.9
Flood irrigation	116	5409.1	3006.2	8415.2	3927.9
Total (column 2)/ average (columns 3–6)	228	4775.4	2912.9	7688.3	4727.1

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Table 2. Economic key figures of cotton production of drip and flood irrigating farm households along the Tarim River.

Irrigation method	Number of farms	Total variable cost	Irrigation variable cost	Revenue	Gross margin
		[USD ha^{-1}]			
Drip irrigation	112	5241.9	904.1	7170.0	1928.1
Flood irrigation	116	4320.2	511.5	5119.2	799.0
Total (column 2)/ average (columns 3–6)	228	4773.0	704.4	6126.6	1353.6

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Table 3. Stand structure and tree morphology of the three *Populus euphratica* study plots near Yingbazar with close (GD1; 2.0 m), intermediate (GD2; 7.5 m) or large distance (GD3; 12.0 m) to the groundwater (means ± standard deviations, if applicable). *n*, number of trees. Different lower-case letters indicate statistically significant differences among the plots (Kruskal–Wallis *H* test, followed by multiple pairwise Mann–Whitney *U* tests).

Plot	GD1	GD2	GD3
Number of trees per plot	367	297	53
Stand density (trees ha^{-1})	467	378	67
Basal area (m^2 ha^{-1})	18.7	15.7	13.3
Tree cover (%)	81 ($n = 26$)	35 ($n = 6$)	6 ($n = 3$)
Maximum tree age (years)	68	141	314
Tree height (m)	10.6 ± 5.3 a	7.6 ± 1.8 b	5.2 ± 2.2 c
Diameter at breast height (dbh) (m)	0.20 ± 0.10 b	0.21 ± 0.08 b	0.44 ± 0.24 a
Height: dbh	55.4 ± 15.7 a	39.2 ± 12.3 b	15.5 ± 9.3 c

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Table 4. Minimum, average and maximum tree-ring widths of *Populus euphratica* and time period covered by tree-ring analyses in stands with small (GD1), intermediate (GD2) and large distance (GD3) to the groundwater (mean values of all available years with standard deviations). Different lower-case letters indicate statistically significant differences among the stands (Kruskal–Wallis *H* test, followed by multiple pairwise Mann–Whitney *U* tests).

Plot	Minimum width (µm)	Mean width (µm)	Maximum width (µm)
GD1 (1946–2011)	100	1794 ± 452 a	8865
GD2 (1862–2011)	50	1085 ± 277 b	8515
GD3 (1683–2011)	30	526 ± 207 c	2880

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Table 5. ET_a [mm] of the natural vegetation along the Aksu and Tarim River during the vegetation seasons 2009, 2010, and 2011. *N* – number of MODIS pixels, Std. Dev. – standard deviation. Natural vegetation: dense forest – total coverage > 50 %, forest – total coverage > 25 % and ≤ 25 % with tree coverage higher than shrub coverage, shrub – total coverage > 25 % and ≤ 25 % with tree coverage lower than shrub coverage, sparse woodland – total coverage > 10 % and ≤ 25 %. *A. pictum* stands cover more than 50 % of the MODIS pixels (Thevs et al., 2013).

Vegetation	*N*	ET_a mean [mm]	Std. dev.	*N*	ET_a mean [mm]	Std. dev.	*N*	ET_a mean [mm]	Std. dev.
Wetlands	10	1687	373	10	1660	298	10	1790	248
Dense forest	41	735	135	41	777	149	66	1068	210
Forest	90	554	221	90	612	247	129	725	296
Shrub	24	292	221	24	295	218	38	346	190
Sparse woodland	33	230	225	33	277	238	59	224	272
A. pictum	2	31	65	2	86	22	5	142	80

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Table 6. Sum of ET_a during the growing seasons (2009 to 2011) measured with the climate station Iminqak and detected through remote sensing (Thevs et al., 2014).

Year	Sum of ET_a during growing season [mm]		
	Climate station	Remote sensing	Deviation [%]
2009	612	611	0.2
2010		794	
2011	836	929	10.8

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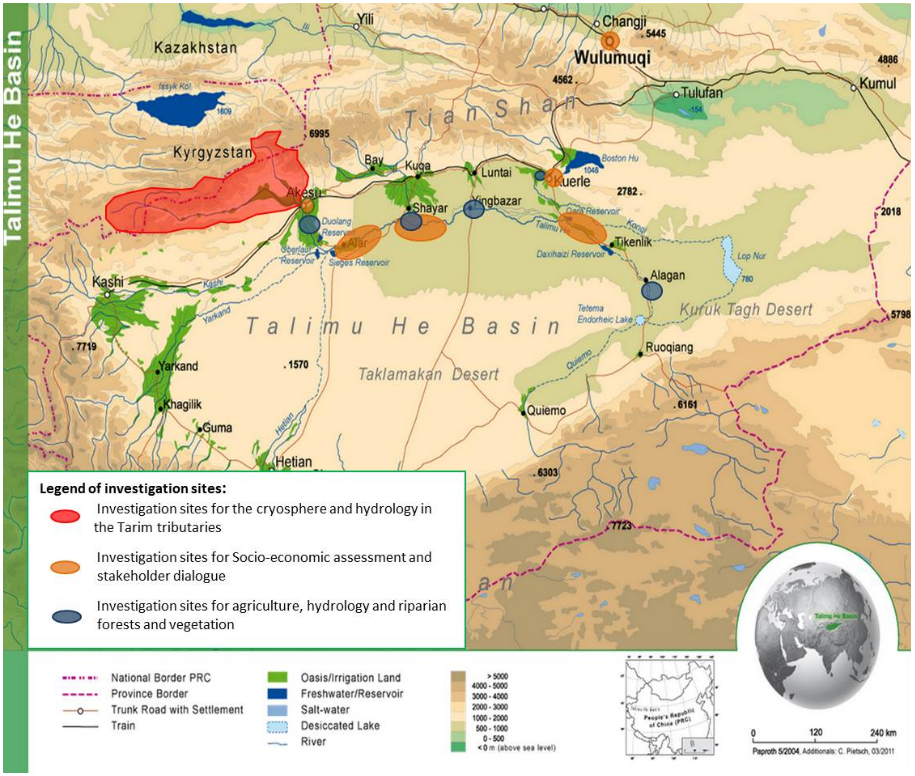

Figure 1. Map of the research area and investigation sites structured by the different scientific disciplines that contribute to SuMaRiO.

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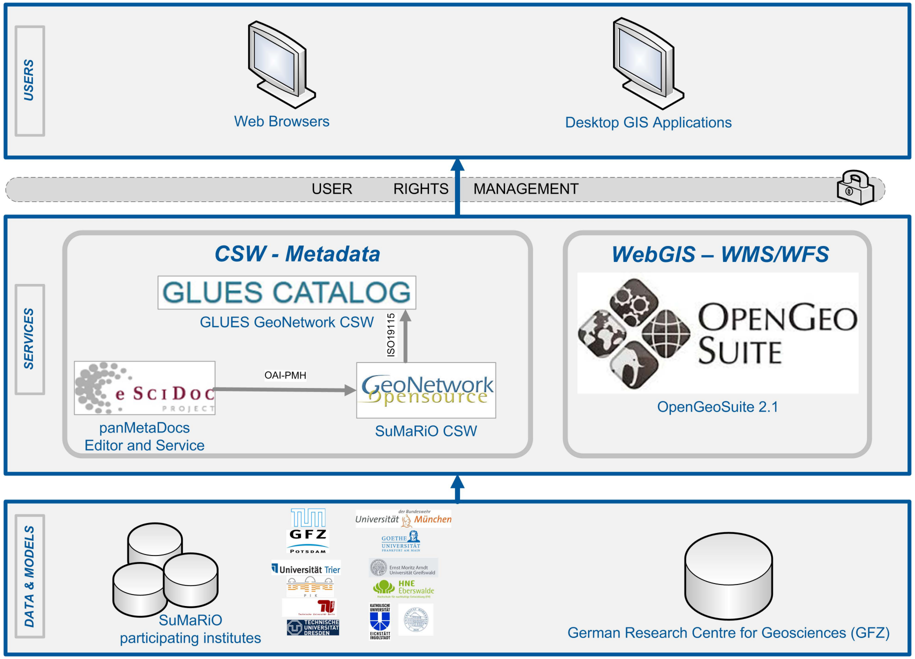

Figure 2. SuMaRiO's workflow schema of a Scientific SDI node.

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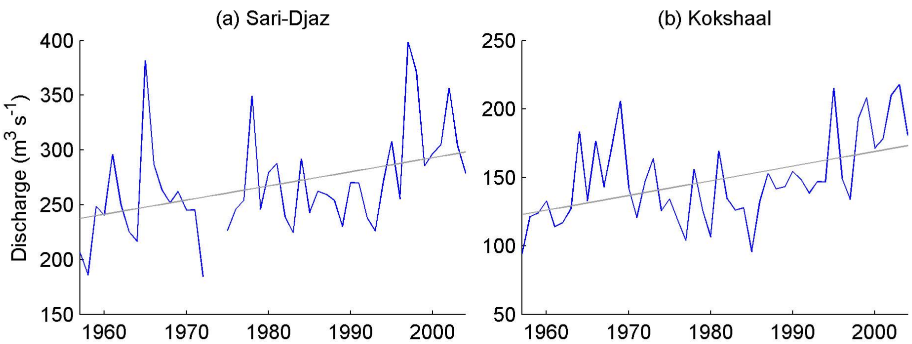

Figure 3. Average discharge for the summer season (April–September) for two headwater catchments of the Aksu River. **(a)** Sari-Djaz Catchment; **(b)** Kokshaal Catchment. Observations are shown in blue, and the estimated trend line in gray.

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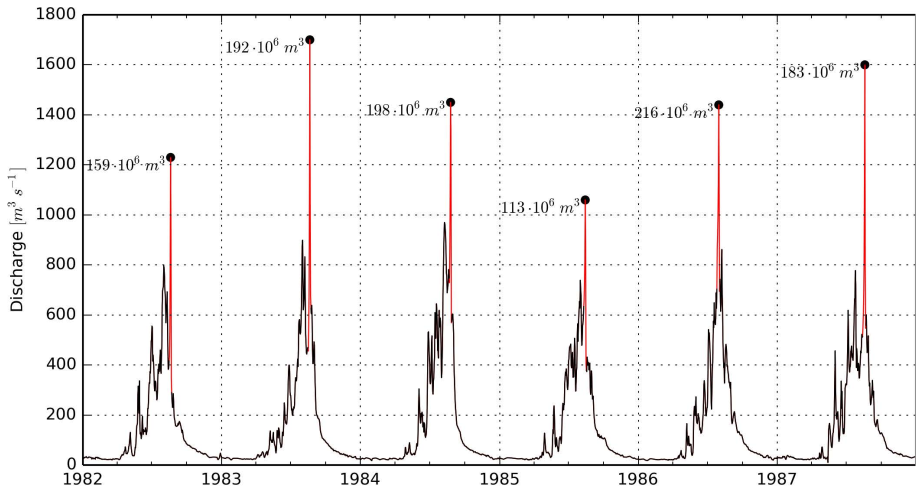

Figure 4. Discharge at Xiehela station (China) from 1982–1987 with the annual Merzbacher Lake outburst floods (red) identified by model application (see Wortmann et al., 2013). Peak discharges are marked with the respective flood volumes.

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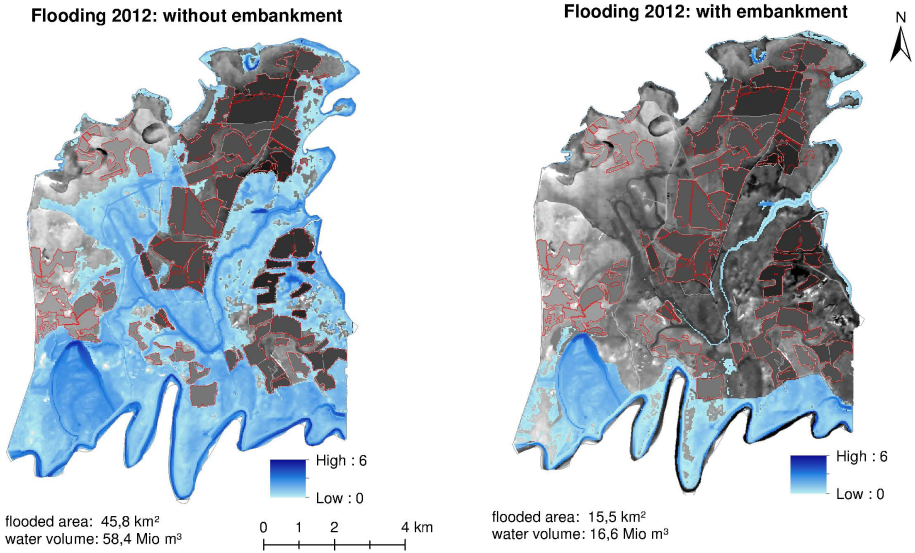

Figure 5. Different modeled flooding scenarios without (right panel) and with embankment (left panel) along the Tarim River using the discharge volume of the flood of 2012.

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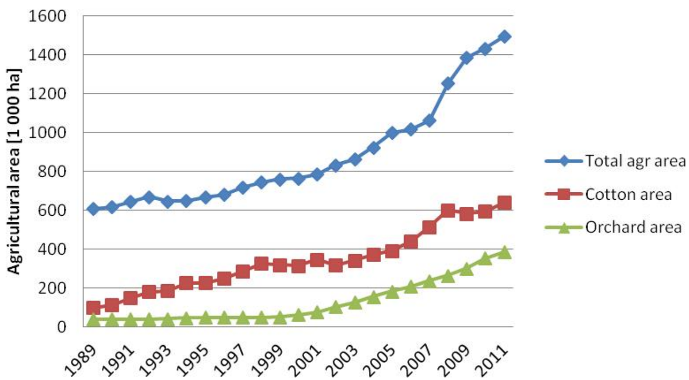

Figure 6. Development of total agricultural land use area, as well as cotton and orchard area in the Tarim Region in the last two decades (calculated from NBSCa 1990–2012 and NBSCb 1990–2012).

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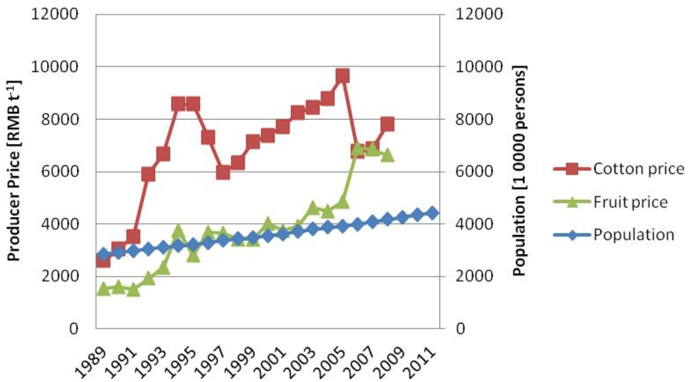

Figure 7. Development of Producer Prices of the major agricultural commodities cotton and tree fruits, as well as population development in the Tarim Region in the last two decades (calculated from NBSCa, 1990–2012 and NBSCb, 1990–2012; FAOSTAT, 2012).

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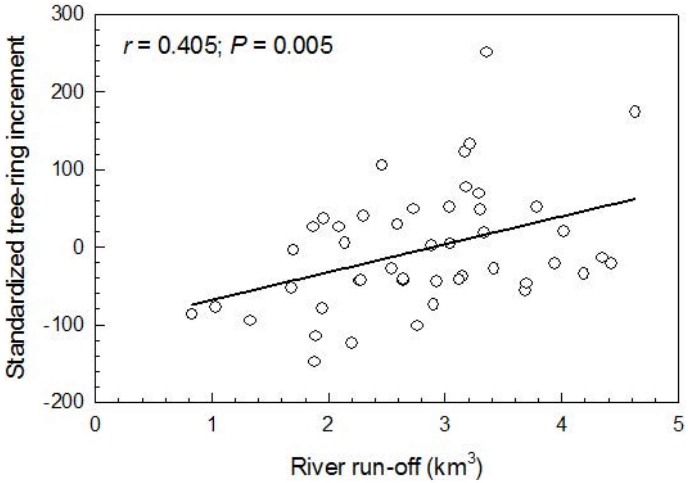

Figure 8. Standardized annual stem diameter increment of *Populus euphratica* trees growing on study plot GD1 at close distance (2.0 m on average) to the water table plotted against Tarim River's runoff of the preceding year at Yingbazar during the time period 1957–2005. $n = 47$. r, Pearson correlation coefficient.

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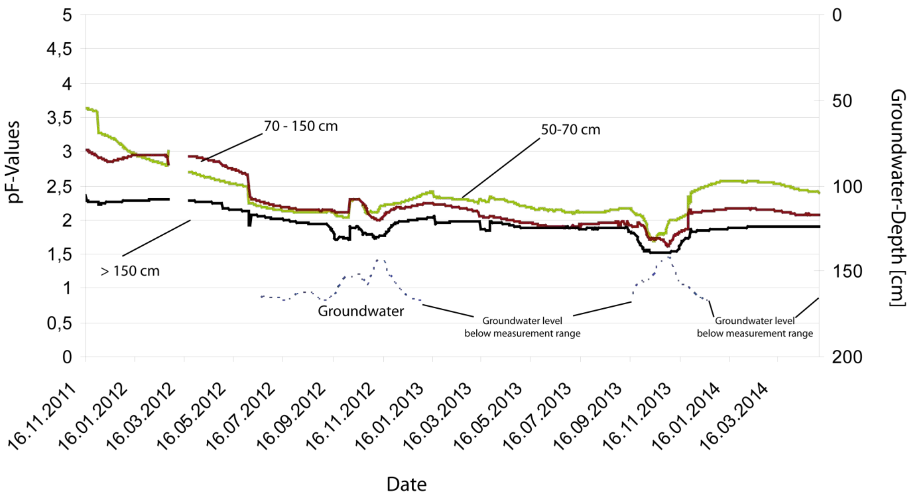

Figure 9. Mean pF-Values of all soil moisture stations for different soil layers.

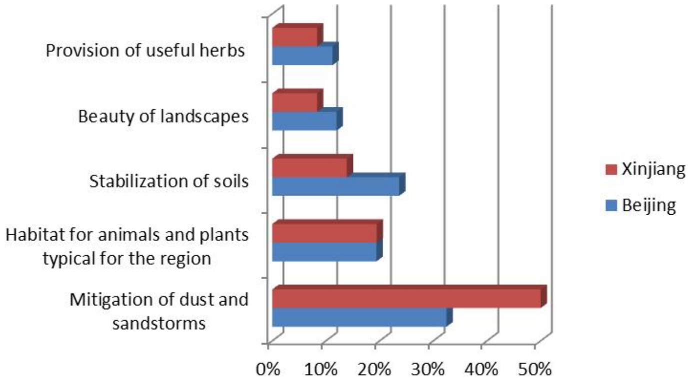

Figure 10. Common people's opinion on the restoration and maintenance of the natural environment in the Tarim River Basin – importance of ecosystem services.

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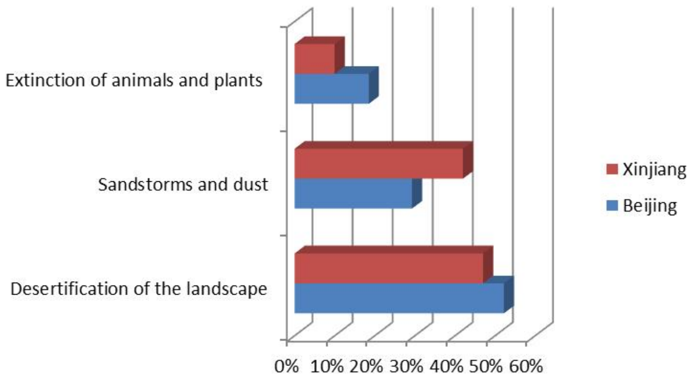

Figure 11. Common people's opinion on the restoration and maintenance of the natural environment in the Tarim River Basin – importance of ecosystem services – seriousness of environmental problems.

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