

# Impact of Intensive Irrigation Activities on River Discharge Under Agricultural Scenarios in the Semi-Arid Aksu River Basin, Northwest China

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Received: 9 August 2013 / Accepted: 17 October 2014 /  
Published online: 8 November 2014  
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**Abstract** The Aksu River is a principal headwater tributary of the Tarim River in northwest China providing 70–80 % of its water supply. This study aims to simulate the impact of potential future irrigation and cropping schemes on river discharge in the semi-arid and irrigation intensive part of the Aksu River basin. To achieve this goal, the eco-hydrological model SWIM (Soil and Water Integrated Model) was developed further by including an irrigation module and a river transmission losses module. The performance of the SWIM model in the region was then compared with that of another water management model, WEAP (Water Evaluation And Planning). The results show that both models are capable of reproducing the monthly discharge at the downstream gauge well using the local irrigation information and the observed upstream inflow discharges as inputs. Still, the SWIM model performs better than the WEAP model because it accounts for both hydrological processes and agricultural impacts. Therefore, SWIM was used for the scenario study. Different irrigation scenarios were developed based on the recent trends of agricultural practices. The study showed that the improvement of irrigation efficiency was the most effective measure for reducing irrigation water consumption and increasing river discharge downstream. The expansion of irrigation area in the basin leads to an increase in water consumption while the changes in crop structure (composition of crop types) on arable land do not have significant impact on the river discharge downstream.

**Keywords** SWIM · WEAP · Aksu · Tarim · Irrigation

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**Electronic supplementary material** The online version of this article (doi:10.1007/s11269-014-0853-2) contains supplementary material, which is available to authorized users.

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## 1 Introduction

Located in the arid area of northwestern China, the Tarim River is the largest continental river in China. The river is mainly fed by snow and glacier melting water from the headwaters in mountains. In the plain areas, it receives extremely rare and low rainfall that does not exceed 50 mm per year. Therefore, all kind of economic activities, especially agriculture in river oases and urban life, as well as natural ecosystems in this basin depend on river water as the primary water source.

Since the 1960s, water resources in the Tarim River basin became excessively exploited, and the runoff was reduced by 20 % in the upstream reach and by 95 % in the lower reach from 1965 to 1995, although the streamflow from the headwaters showed a statistically significant increasing trend in this period due to warming climate (Lei et al. 2001). The whole oasis ecosystem is becoming adversely affected by the decrease in river runoff downstream (Xu et al. 2008). To establish a sustainable development in this region, the very important question is how much water would be available for the Tarim River oases in the future.

There are three upstream tributaries feeding the mainstream of the Tarim River, but only one of them, the Aksu River, has permanent flow and supplies 70–80 % of the total water discharge to the Tarim River (Yang and He 2003). The Aksu is also heavily exploited along its downstream areas before it reaches the Tarim River course. According to Mtalip et al. (2009) about 59 % of its water was consumed by irrigation and municipal purposes in 2004. Hence, the evaluation on the impacts of human activities on the Aksu River discharge is the key factor to decide the future land and water use strategies in the Tarim River.

However, there are only few and simple analyses available on the historical impact of the agriculture development on river discharge for the Aksu basin (e.g. Zhang et al. 2012), and evaluation of impacts under land use scenarios is even more rare in literature. Our paper intends to fill this gap, and quantify the effects of various irrigation practices on river discharge for this important region.

One possible method for assessing the water uses is to apply a water management tool, such as WEAP (Water Evaluation And Planning, SEI 2005) (e.g. Harma et al. 2012). Another potential method is to use a hydrological model accounting for water uses (e.g. Dechmi et al. 2012; Tornqvist and Jarsjo 2012; Aus der Beek et al. 2011 and Tang et al. 2007). In this study, we specifically developed an irrigation module and a river transmission loss module for the eco-hydrological model SWIM (Soil and Water Integrated Model, Krysanova et al. 1998) based on available data, and applied this model. In addition, we tested and compared both the WEAP and SWIM models, and selected the more suitable tool for evaluating irrigation practices in the semi-arid and irrigation intensive Aksu region.

Hence, this paper aims 1) to develop an irrigation module based on local information and a transmission losses module for the eco-hydrological model SWIM; 2) to test and compare the performance of two models: WEAP and SWIM for simulating the Aksu River discharge using local irrigation data and observed headwater discharges as input, and 3) to simulate the impact of the potential future irrigation and cropping schemes on river discharge in the Aksu River basin.

## 2 Study Area and Research Strategy

The Aksu is an international river, originating in the Central Tien Shan Mountains in Kyrgyzstan and draining into the Xinjiang province in China. The total drainage area is about 52,000 km<sup>2</sup>, and the Chinese part is about 33,000 km<sup>2</sup> (Wang 2006). There

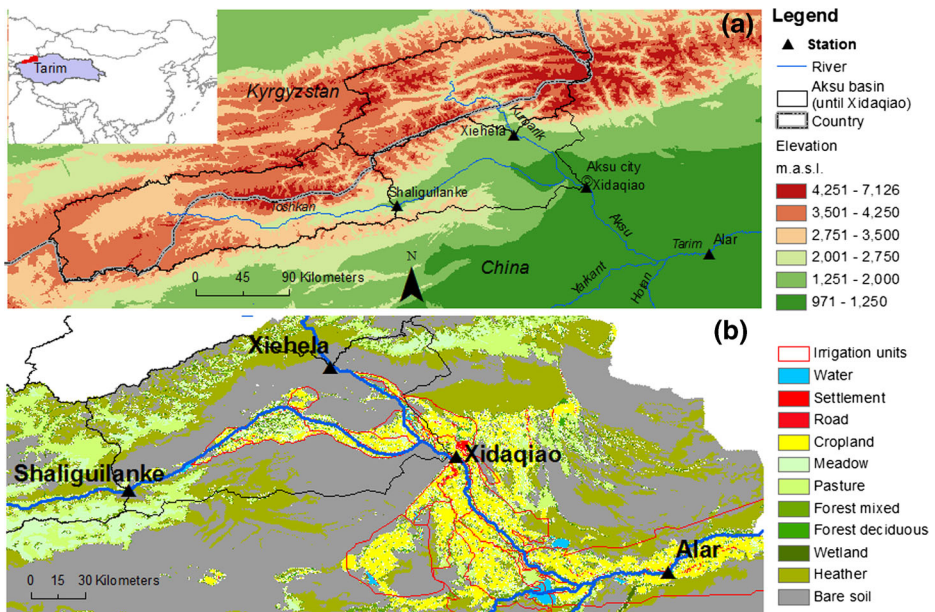
are two headwaters called Kumarik River and Toshkan River (Fig. 1a). These two rivers confluence near the Aksu city.

According to Tang et al. (2007), the deposits of the Quaternary age cover the alluvial plains of the Kumarik and Toshkan Rivers as sand, gravel and clay occurring mostly as alluvial deposits. The thickness of the alluvium is reaching usually more than 250 m (Liang et al. 2003). The upper parts of the area are generally composed of coarse sand and gravel, and the lower parts are typically made up of clay and fine sand. The water table depth in this area ranges from 2 to 4 m (Tang et al. 2007). The mountain torrents and springs usually percolate to groundwater through the loose dry soil before reaching the main stream.

The two headwaters of the Aksu are gauged by hydrological stations Xiehela and Shaliguilanke at the edge of mountains (Fig. 1a). Upstream of these two gauges, the rivers are fed mainly by snow and glacier melting water in the mountains and are hardly influenced by human activities. The annual average discharges at the gauges Xiehela and Shaliguilanke are about 154 and 86 m<sup>3</sup>/s (1957–2004), respectively (estimated using data from Wang 2006).

The Aksu River is gauged by the station Xidaqiao (Fig. 1a). The average annual precipitation between the two headwater gauges and Xidaqiao is about 98 mm, and the average annual temperature is about 5 °C (period 1961–2000). The average discharge at this gauge is about 198 m<sup>3</sup>/s (period 1957–2004), which is notably lower than the sum of two headwater discharges (240 m<sup>3</sup>/s). Unlike in natural river basins, the river discharge decreases further in downstream river reaches. At the lower gauge station Alar along the Tarim River (Fig. 1a), the average discharge is only 145 m<sup>3</sup>/s for the same period, though it also includes the inflows from the Hotan and Yarkant rivers.

The decrease in discharge between the two upstream gauges and Xidaqiao is mainly attributable to the abstraction of river water to irrigated agricultural land. The water use for irrigation measured in the irrigation channels (data from Wang 2006) is about  $1,877 \cdot 10^6 \text{ m}^3 \text{ a}^{-1}$



**Fig. 1** Digital elevation map of the Aksu basin (a), and the land use map of the irrigated area in the lower part of the Aksu basin (b)

on average in the period 1998–2003. The difference in the average annual discharge between the two upstream gauges and the gauge Xidaqiao is a little smaller, ca.  $1,584 \times 10^6 \text{ m}^3 \text{ a}^{-1}$ , for the same period, possibly due to the irrigation return flow and other inflows in this basin.

Figure 1b shows the land use map of the Chinese part of the Aksu basin in 2000. In the mountainous regions, the heather and grassland are the dominant land covers, but in the lower area the bare soil is dominant due to low precipitation and high potential evapotranspiration. However, along the Aksu River, extensive agricultural land is allocated between the gauges Xiehela, Shaliguilanke and Alar. The crop growth in the Aksu region is highly dependent on irrigation water which is directly diverted from the river or stored in reservoirs.

As one objective of this study was to develop a tailored irrigation module for this region and test it, the major focus was on the Aksu subcatchment between the headwater gauges Xiehela and Shaliguilanke and the gauge Xidaqiao (Fig. 1b). The most important reason for choosing this study area is that the observed discharge data is only available at the gauge Xidaqiao along the Aksu River. In addition, the irrigation conditions in this region are relatively simple compared to the further part downstream (see Fig. 1b) due to smaller irrigation area and smaller number of irrigation units (administrative management units). This helps to understand better the complex irrigation system, and to test the newly developed modules. After testing and comparing the models, five irrigation scenarios were developed based on the changes and trends in agricultural practices over the past 10 years. The impacts on water discharge at the gauge Xidaqiao were then assessed under scenario conditions. Finally, the results obtained from the main study area were used to estimate water uses in the downstream reaches between the gauges Xidaqiao and Alar.

### 3 Methods and Data

#### 3.1 WEAP

WEAP (Water Evaluation And Planning), developed by the Stockholm Environment Institute, is a software tool for integrated water resources planning (SEI 2005). The simulated system (e.g. municipal and agricultural systems) can be represented in terms of supply sources (e.g. river discharge, groundwater, reservoirs etc.); withdrawal, transmission and wastewater treatment facilities; water demands; pollution generation; and ecosystem requirements. WEAP calculates water balance for every node in the system at a monthly step. However, WEAP requires river discharge as input, which can be taken either from observed data or generated by another hydrological model. Therefore, WEAP is often coupled with other hydrological models to analyze water resources under both climate and water management scenarios (e.g. Droogers et al. 2012).

#### 3.2 SWIM

The dynamic process-based eco-hydrological model SWIM (Soil and Water Integrated Model) (Krysanova et al. 1998) was developed for climate and land use change impact assessment on the basis of the models SWAT (Arnold et al. 1993) and MATSALU (Krysanova et al. 1989).

SWIM simulates the hydrological cycle, vegetation growth and nutrient cycling at daily time step by disaggregating a river basin to sub-basins and hydrotopes. The hydrotopes are sets of elementary units in a sub-basin with homogeneous soil and land use types. It is assumed that a hydrotope behaves uniformly regarding the hydrological processes and nutrient cycling,

given the same meteorological inputs. More detailed information about the process description in the standard SWIM model can be found in Krysanova and Wechsung (2000).

*The Irrigation Module* A simplified irrigation module was developed for SWIM to take into account the local water diversion data in this region. The total irrigated area in the Aksu basin is subdivided into so-called irrigation units, for which specific data on water diversion is available. The hydrotopes were further discretized by the boundaries of the irrigation units (see Fig. 1b). The hydrotopes belonging to one irrigation unit receive the abstracted water from one specific river reach.

In general, the following information must be provided to the module for each irrigation unit: the river reach from which the water is diverted, the link between the river reach and the irrigation unit, channel loss coefficient, water use coefficient in the field, the annual water use and monthly water use share in percent. Firstly, it is assumed that the monthly abstraction is evenly distributed into daily time steps, and the daily abstraction quota is calculated for each irrigation unit. Then the actual daily abstraction is estimated by the minimum value of the calculated daily quota and the discharge of the linked river reach.

The actual abstracted water is then separated into two parts by the channel loss coefficient: channel transmission loss and irrigation water. The irrigation water is directly applied to the agricultural hydrotopes while the channel transmission loss is applied to the other hydrotopes within the same irrigation unit as SWIM cannot represent the diversion canals and field channels in detail.

Both the irrigation water and channel transmission losses are added to the precipitation input of the hydrotopes before calculating hydrological flow components, such as evapotranspiration, infiltration and groundwater recharge. There are no further changes in the modules describing these hydrological components in SWIM. As a result, the additional irrigation water together with precipitation can evaporate, infiltrate and recharge groundwater at the hydrotope level simulated by SWIM.

*The River Transmission Loss Module* The river transmission losses are important processes for rivers in arid regions (Hughes 2008). Two dominant processes associated with the losses are infiltration and evaporation. The transmission loss module introduced to SWIM combines the transmission loss modules from SWAT (Arnold et al. 1993) and WASA (Water Availability in Semi-Arid Environments, Güntner and Bronstert 2004) models.

The SWAT model estimates the infiltration losses as a product of hydraulic conductivity, travel time, wetted perimeter and length of channel, and the evaporation losses as the product of potential evaporation, channel length and surface channel width. The channel characteristics (length, depth and top width) are estimated by preprocessing of elevation information. It is assumed that channels have a trapezoidal shape with 2:1 channel slopes. The wetted perimeter and surface channel width can be estimated by the water level and the shape of the channel cross-section. This method can also account for water losses in floodplains when discharge is larger than the bank full discharge. The floodplain is defined to have a width of five times the top channel width and 4:1 side slope. The parameter hydraulic conductivity can be used for calibration. Since the channel shape does not change in this method, it is assumed that the whole river bed is always wetted by flowing water. However, in the arid rivers during dry seasons the top channel width can be decreased as only part of river bed can be wetted. As a result, this method may overestimate the losses during dry period.

To avoid such overestimation, we applied the estimating procedure used by the WASA model specifically for semi-arid environments (Hacker 2005). In this method, the mean channel width ( $w$  in meter) is estimated from the inflow ( $Q_{in}$  in  $m^3/s$ ) to the subbasin after Leopold (1994) (Eq. 1), so the river characteristics vary based on the flow conditions.

$$\log w = \log Q_{in} * 0.494 + 1.031 \quad (1)$$

The transmission losses are then derived from the linear regression equation used by Lane (1990) (Eq. 2), where the regression intercept ( $i(l,w)$ , Eq. 3) and slope ( $s(l,w)$ , Eq. 4) are functions of hydraulic conductivity ( $K$  in inch per hour), the mean duration of inflow to the reach (here  $D=24$  h), the mean volume of inflow ( $Q_{in}$  in acre-feet), the channel length ( $l$  in mile) and width ( $w$  in feet) (Eqs. 5–7):

$$Q(l, w) = i(l, w) + s(l, w) * Q_{in} \quad (2)$$

$$i(l, w) = (a/(1-b)) * (1-s(l, w)) \quad (3)$$

$$s(l, w) = \exp(-k * l * w) \quad (4)$$

$$a = -0.00465K * D \quad (5)$$

$$k = -1.09 \ln(1 - 0.00545K * D/Q_{in}) \quad (6)$$

$$b = \exp(-k) \quad (7)$$

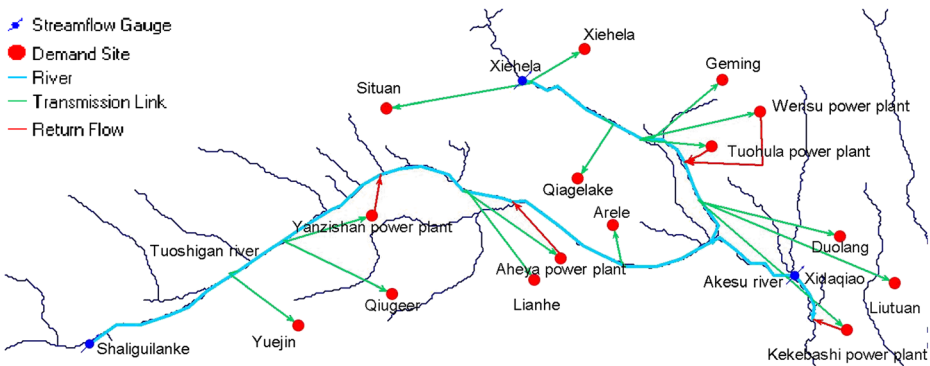
where  $Q$  is the outflow in acre-feet.

Finally, the transmission loss module in SWIM was included by using the method of WASA, and only for the bank full conditions the transmission losses are calculated as in SWAT.

### 3.3 Data

For the main study area, a schematic diagram of the water management system is shown in Fig. 2. This system comprises 15 demand sites (10 irrigation units and 5 power plants), 15 transmission links which divert water from the river to the demand sites, and 5 return flows from the power plants. Here, only the irrigation units are considered as the major water consumption sites because the return flow from the power plants is assumed to be the same as the inflows (according to Wang 2006).

The 10 irrigation units are classified under different administrative offices and water abstraction locations (Fig. 1b, Fig. 2 and Table 1 in the supplementary material). They are governed by two counties (Wushi and Wensu), the Aksu city and the First Agricultural Division (FAD) from Xinjing Production and Construction Corps. For each irrigation unit, data on the amount of annual water use is available for the years 1998 and 2000–2003 from the book (Wang 2006). The water use in 1999 was estimated by averaging data from 1998 to 2000.



**Fig. 2** Schematic diagram of the water management system in the main study area

The share of monthly water use is available for each irrigation unit only for 1998, and this share was assumed to be valid for other years. In general, more than 70 % of water use is abstracted from April to September and diverted to the irrigation units. Besides, the channel loss coefficient and water use coefficient in fields in each irrigation unit are available for 1998. The channel loss coefficient ranges from 0.43 to 0.52 with a mean value of about 0.5. The water use coefficient in fields is above 0.8. So, the average irrigation water use efficiency coefficient combining both coefficients above is about 0.4 in the Aksu basin (Wang 2006).

In addition to the actual water use records, each county and corps have their own irrigation instruction (Wang 2006). These instructions list the irrigation schedule and quota for 13 kinds of crops and landscapes which are irrigated (see more details in the [supplementary material](#)).

The monthly discharge data at the gauges Shaliguilanke and Xieheja were used as the water supply sources for this region, and the observed discharge at the gauge Xidaqiao was used to compare the model results at this point.

In addition to the irrigation and discharge data used by both SWIM and WEAP models, four spatial maps (the digital elevation map, the soil map, the subbasin map and the land use map) as well as daily climate data are required to setup SWIM. The digital elevation map provided by the NASA Shuttle Radar Topographic Mission (SRTM) (Farr et al. 2007) was used. The soil information was obtained from the Harmonised World Soil Database (HWSD) (FAO et al. 2012), and the Chinese land use map for 2000 was available for the study area. The daily precipitation and temperature (mean, minimum and maximum) interpolated to a 0.25 arc degree grid for the Chinese part of the Tarim basin was provided by China Meteorological Administration for 1961–2004. The air humidity and SOLAR radiation data available from the reanalysis data at 0.5 arc degree for the period 1957–2001 (Weedon et al. 2011) was used.

#### 4 Historical Irrigation Conditions and Scenarios

According to Zhang et al. (2012), there was a moderate increase in agricultural area in the Aksu region from 1949 to 1984. From 1985 to 1999, the annual increase became significant due to the expansion of cotton planting area as farmers received higher economic benefits by planting cotton. Flood irrigation was the main irrigation style in this period.

In the recent 10 years (2000–2009), the whole agricultural area increased by ca. 20 %. Planting of forest and orchard, which consume almost the same amount of water as cotton, was developed. The ratio of grain (rice, wheat and maize), cotton, forest and orchard areas (later referred to as “crop structure”) changed from 44:50:6 in 2000 to 29:48:23 in 2009. The irrigation efficiency was still quite low despite improvements of channel efficiency and new water-saving technologies. As a result, water stress problems in the region still remain.

Based on the historical changes, especially in the recent 10 years, one base scenario and five future scenarios were developed to analyze the impact of different agricultural practices and technology improvements. The base scenario was selected using the calculated annual water use and monthly share data in 1998 based on the irrigation instructions, as the detailed planting area of each crop is available in this year.

*Scenario 1* focuses on further increase of agricultural area as a continuation of former tendencies. Hence, in scenario 1 we increase the total irrigation area by 20 % while the crop structure remains the same.

*Scenario 2* aims in investigating the impact of changing crop structures. According to the changes in cropping structure between 2000 and 2009 we assume that in this scenario the area of grain would decrease by 20 % of the total irrigation area, the area of orchard and forest would increase by 20 %, and the area of cotton would remain the same.

*Scenario 3* is a combination of scenarios 1 and 2, so the total irrigation area increases by 20 % and the crop structure changes as in scenario 2.

*Scenario 4.1 and Scenario 4.2* consider the improvement of leakage-proofing channels and irrigation technologies. According to the Ministry of Agriculture of the People’s Republic of China, it aims to improve the irrigation efficiency coefficient in Xinjiang province to 0.53 by the end of 2015 and to 0.57 in 2020. Hence, the irrigation efficiency coefficient changes to 0.53 and 0.57 in our scenarios 4.1 and 4.2, respectively. There are no other changes in agricultural practices in these scenarios.

## 5 Results

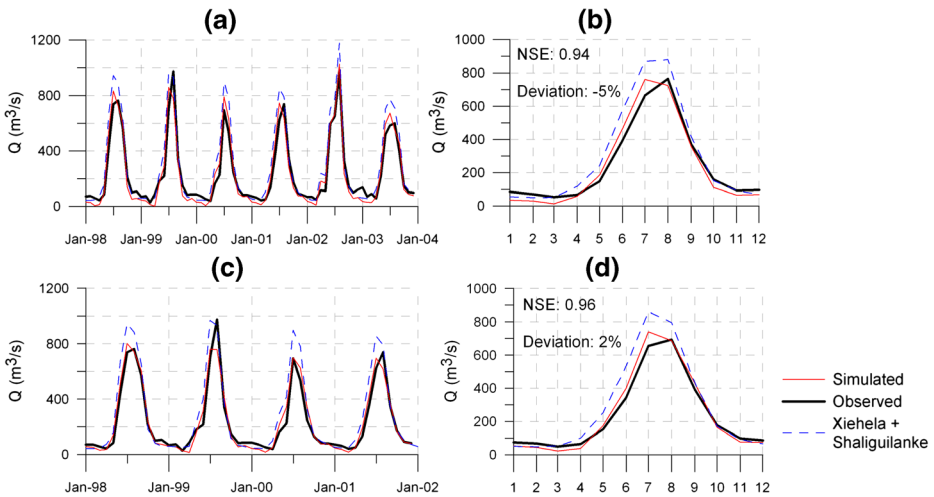
### 5.1 Simulating the Downstream Discharge with WEAP

The input data for the WEAP model includes the monthly discharge at the gauges Shaliguilanke and Xiehela, the annual water use and monthly shares in each irrigation unit for the period 1998–2003 (see the schematic diagram in Fig. 2).

Figure 3a shows the observed and simulated monthly discharge with WEAP at the gauge Xidaqiao, and the sum of discharges at two headwater gauges. When the observed discharge at Xidaqiao is compared with the sum of discharges coming from the headwaters, all summer peaks downstream are notably lower than the incoming water mainly due to irrigation. In total, there is 18 % more water entering from the headwaters than measured at the lower gauge Xidaqiao.

When the abstraction water is introduced in the WEAP model, the simulated summer peaks at Xidaqiao are effectively reduced compared to input and approach the observed ones. It





**Fig. 3** Simulated and observed monthly discharge at the gauge Xidaqiao using model WEAP and SWIM with observed monthly discharge at the gauges Shaliguilanke and Xiehela as the input (a and c) and the corresponding average monthly discharge for the same stations (b and d) respectively

should be noted that the water abstraction data for 1999 was extrapolated from 1998 to 2000. This could probably explain the higher deviation from the observed records in 1999. The monthly Nash-Sutcliffe efficiency (NSE) between the monthly observed and simulated discharges is 0.94 and the deviation in water balance is  $-5\%$ , indicating a good simulation result. This result shows that the WEAP model is a robust tool for assessing water resources in the intensive agricultural systems.

However, the low flows from November to April are considerably underestimated, by  $42\%$  on average, and the river discharge approaches to zero in March (Fig. 3b). The water abstracted in January and February is mainly used by the Kekebash power plant, which discharges the return flows downstream the gauge Xidaqiao. In March and April, when soil moisture is very low after a cold and dry winter, the land is usually irrigated before sowing to ensure crop growth. Since there is no other water input except the headwater discharges, abstraction of water in these months directly leads to an underestimation of low flow in the WEAP results. The hydrological processes in the studied region, such as precipitation and groundwater discharge, still contribute to the river discharge in this period. Therefore, a more comprehensive approach which considers both hydrological processes and water management information could improve the simulation results.

## 5.2 Simulating the Downstream Discharge with SWIM

Since the WATCH climate data was only available until 2001, the monthly discharge at the gauge Xidaqiao was simulated by SWIM for a shorter period, from 1997 to 2001, with the observed input discharges at the two headwaters and the same water abstraction information. The simulation in 1997 was used to initialize the model.

Figure 3c shows a good agreement between the simulated and observed hydrographs between 1998 and 2001. The monthly NSE is 0.96 and the deviation in water balance is  $2\%$ . Although precipitation adds more water to the studied system, the simulated summer peaks in 1998 and 2000 are lower and better

comparable with observations than the WEAP results because of river transmission losses. The winter low flows are also better reproduced without zero discharges (Fig. 3d). Hence, the adjusted hydrological model SWIM is a more appropriate tool to simulate river discharge in the lower Aksu basin compared to the WEAP model, and this model was applied for the scenario runs.

### 5.3 Evaluation of Data on Irrigation Instructions

The irrigation instructions are a basis to calculate the annual water use and monthly variations under different scenarios. Thus, the first step was to verify the use of the instruction data for the year 1998.

Figure 4a shows the comparison of the calculated (based on the irrigation instructions) and actual annual water use (from Wang 2006, p197–199) in 10 irrigation units in the study area in 1998. In most irrigation units, the calculated values are well comparable to the actual water use and the bias of the total calculated value is about 7 %. In addition, the irrigation instructions can generally represent the seasonal dynamics of water use, as the major amount of water is consumed in summer months (see examples for two irrigation units in Fig. 4b and c). The small bias between the observed and calculated values may be attributable to the difference between the actual practice and irrigation instructions, inaccurate data on crop area or irrigation efficiency coefficient or other unknown reasons. Hence, we can conclude that using the irrigation instructions is a reliable and practical approach for estimating the annual and monthly water use rates.

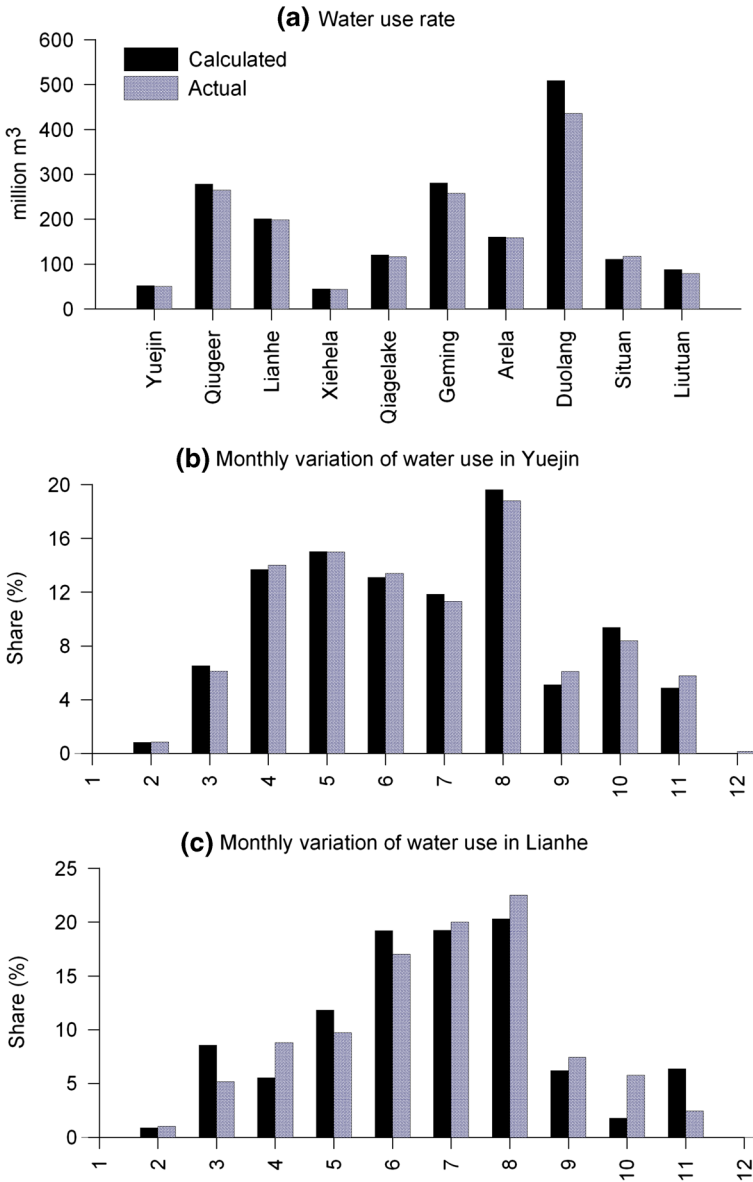
### 5.4 Simulating the Impact of Agricultural Scenarios on River Discharge Downstream

Using the instruction data, the annual and monthly water uses for each irrigation unit under different scenarios were calculated. The total annual water use in the studied area is 1,845 million m<sup>3</sup> for the base scenario, and 2,215, 1,732, 2,079, 1,414 and 1,314 million m<sup>3</sup> for the scenarios 1, 2, 3, 4.1 and 4.2, respectively.

The SWIM model simulated daily discharge (unit: m<sup>3</sup>/s) at the gauge Xidaqiao, actual evapotranspiration (ETa, unit: mm/year) and groundwater recharge (GWR, unit: mm/year) for the studied area driven by the irrigation demands under different scenarios. The relative differences in these three variables between the 5 scenarios and the baseline results are shown in Fig. 5a.

It shows that the annual river discharge decreases by 4 and 2 % when the irrigation area increases by 20 % without and with changes in crop structure (scenarios 1 and 3). If 20 % of the grain crops are replaced by orchard and forest, about 1.2 % of river discharge can be saved for the downstream river reaches (scenario 2). The improvement of leakage-proofing of the channels and irrigation techniques can save water more effectively. About 4 and 5 % (ca 343 and 441 million m<sup>3</sup> per year) more water would be discharged at Xidaqiao if the irrigation coefficient would increase to 0.53 and 0.57, respectively.

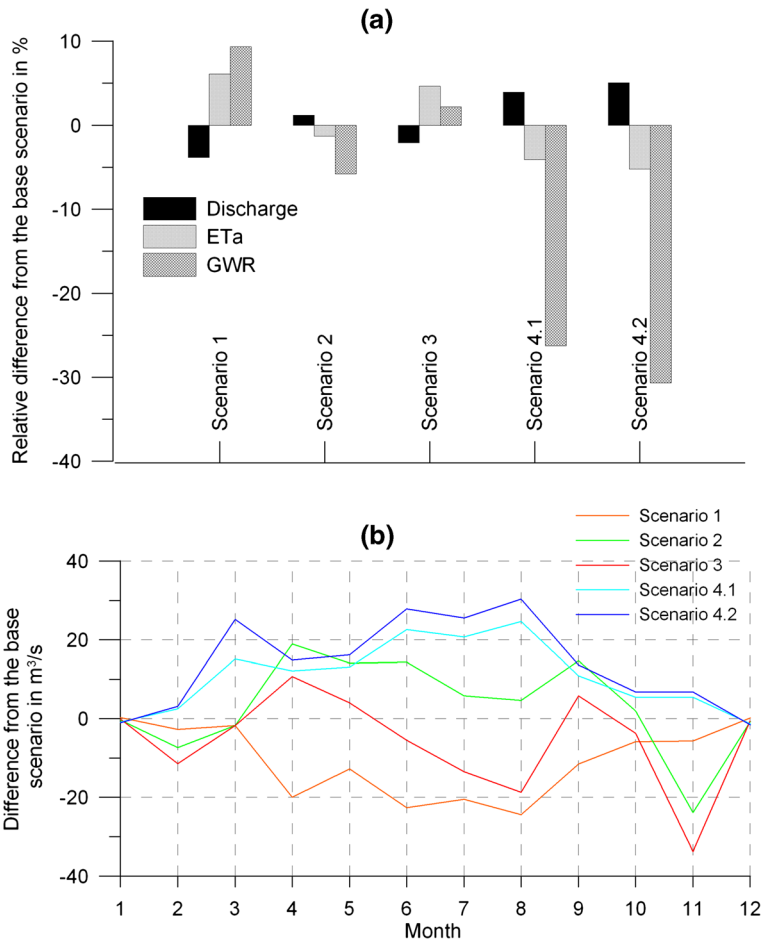
The differences between the monthly discharge under the scenario conditions and the base scenario are presented in Fig. 5b. In scenarios 4.1 and 4.2, the river discharge increases during the whole irrigation period, but in December and January it is slightly decreased due to less irrigation water which recharges groundwater. In scenario 2, the change of crop structure leads to higher river discharge from April to October but demands more irrigation water in February and November. This is because the whole irrigation period for rice starts from April and ends in September. While for orchard and forest the first irrigation is carried out in February, and the



**Fig. 4** The calculated and actual annual water use rate in 10 irrigation units (a) and the monthly share of water use in the Yuejin and Lianhe irrigation units in 1998

last irrigation ends in November. In scenario 1, less river water is available during the whole irrigation season, and in scenario 3, the changes reflect the combination of the outputs in scenarios 1 and 2.

When more irrigation water is needed for the agricultural land (scenarios 1 and 3), the ETa and GWR increase by less than 10 % in the studied area. In contrast, less irrigation water leads to a decrease in ETa and GWR. The decrease is particularly significant for GWR under scenarios 4.1 and 4.2 (26 and 31 %), which relate to a decrease in irrigation water by 23 and



**Fig. 5** The relative difference in annual river discharge, actual evapotranspiration (ETa) and groundwater recharge (GWR) from the base scenario (a, unit: %), and the difference in monthly river discharge from the base scenario at the gauge Xidaqiao (b, unit: m<sup>3</sup>/s)

29 %. This shows how sensitive the hydrological cycle is in such a semi-arid region with intensive irrigation.

Although the annual changes in river discharge under scenarios in Fig. 5a seem to be not so significant when compared to the total river discharge ( $\leq 5\%$ ), one should remember that only about 18 % of the incoming river water is exploited upstream the gauge Xidaqiao, and much more is abstracted downstream. For example, according to Mtalip et al. 2009, 59.4 % of the Aksu River water was consumed before it was flowing into the Tarim River in 2004. So, the relative changes in the total Aksu River discharge would be 3.3 times higher than the changes shown in Fig 5a, assuming that all irrigation units between the Xidaqiao and the Tarim River would apply the same scenarios and have a similar effect on river discharge as the ones investigated in this study. Consequently, the exploitation rate of the Aksu River can range from 42.9 % ( $59.4 - 5\% \times 3.3$ ) to 72.6 % ( $59.4 + 4\% \times 3.3$ ) between the considered scenarios. This means that the contribution of the Aksu River discharge to the Tarim can vary within ca. 30 % range between the worst and the best scenarios (in the sense of water saving) applied in this

study. Hence, a good planning of the agricultural practices in the whole Aksu basin is essential for the sustainable management of the Tarim River.

## 6 Discussion

### 6.1 Application of WEAP and SWIM Model in the Semi-Arid and Irrigation Intensive River Basin

In this study, we tested a water management model, WEAP, and an eco-hydrological model, SWIM, to simulate the downstream river discharge in the Aksu basin. Both models can provide satisfactory results in terms of the downstream river discharge using the upstream inflows and the irrigation practices data as the main drivers. The WEAP model is easier to apply and faster to compute than the SWIM model. But the SWIM model performs slightly better as it accounts for hydrological processes in both irrigation areas and the mountainous regions in the study area. Another advantage of using a hydrological model like SWIM is that it can simulate the upstream inflows (Wortmann et al. 2013) and downstream discharges simultaneously under both climate and agricultural scenarios. Hence, an application of a model like SWIM for the future scenario studies could be recommended.

However, it should be noted that the current irrigation module developed in SWIM is highly dependent on the availability of local data. It requires detailed information on irrigation area, crop structures, irrigation instructions and irrigation coefficients for each irrigation unit. For regions with poorer datasets, e.g. for the other two tributaries of the Tarim, Hotan and Yarkant, further adjustment of the irrigation module would be needed depending on data availability.

### 6.2 Best Agriculture Practices for Water Resources

According to the scenario results in this study, the increase of the irrigation efficiency coefficient is the most effective measure to reduce the irrigation water consumption and increase water supply for the oases downstream. In contrast, an expansion of irrigation area ultimately leads to an increase in water consumption in the Aksu basin, and reduces water availability in the Tarim River.

The changes in crop structure do not have significant impacts because water demands of all crops range from 4,000 to 6,000 m<sup>3</sup>/ha except rice (13,500 m<sup>3</sup>/ha). In reality, the rice area was decreasing continuously in the recent years, and it covered only 2–3 % of the total irrigation area in the Aksu basin in 2009 (Zhang et al. 2012). Hence, significant changes in water resources use due to different crop structures cannot be expected in the future. To summarize, the best agricultural practice we perceive in this study is to improve the leakage-proofing of channels and irrigation techniques without further expanding of irrigation areas. If the irrigation coefficient can achieve 0.57 by the end of 2020, there would be 13.2 % (4 %\*3.3) more water in the Tarim River, which is already a great contribution for the sustainable water managements in the oases downstream.

## 7 Conclusions and Outlook

As the first study for analysis of water resources availability under agricultural scenarios in the Aksu River, this study developed an irrigation module and a river transmission losses module

for the eco-hydrological model SWIM. Both the water management model WEAP and the adjusted ecohydrological model SWIM were capable to simulate the downstream discharge adequately using the local irrigation information and observed headwater inflows. The SWIM model performed some better than the WEAP model as it accounts for both hydrological processes and irrigation management.

Different scenarios were developed based on the recent trends of agricultural practices in the Aksu region. The increase of the irrigation efficiency coefficient was found to be the most effective measure for reducing the irrigation water consumption and increasing the river discharge downstream based on the SWIM scenario results.

However, this study accounted only for the irrigation practices until the gauge Xidaqiao, which consumes about 18 % of the incoming headwater resources. According to our estimates and literature data (Mtalip et al. 2009), about 30 % additional water is consumed along the river reaches between Xidaqiao and Alar. So, the next step is to setup the SWIM model for the whole Aksu River as well as the other two headwaters of the Tarim until the Alar station, and evaluate scenario runs.

Moreover, this study used only the observed river discharge data as input, and did not account for any impacts of future climate change. More headwater inflows to the Aksu River would be expected due to the increasing trend in precipitation and increasing snow and glacier melt in the near future. The available water resources would be reduced when most glaciers would shrink or disappear in the far future. Hence, the next step is to use the simulated river discharge in the glaciated headwater catchments under various climate scenarios as the input for lower parts with irrigated agriculture. The changes in inflows will directly influence the agricultural practices and the whole ecosystem downstream in the arid lowland regions. The next studies should do a comprehensive analysis of the potential availability of water resources in the future accounting for both climate and agricultural changes. These results could provide valuable information for stakeholders for adapting water managements in this region.

**Acknowledgments** The study was financially supported by the German Ministry for Research and Education (BMBF), within the project Sustainable Management of River Oases along the Tarim River/China (SuMaRiO, Code: 01 LL 0918). It was also supported by The National Basic Research Program of China (973 program) (No. 2012CB955903).

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