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Water Balance within Intensively Cultivated Alluvial Plain in an Arid Environment

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Abstract The Tuoshigan–Kumalake River alluvial plain is an oasis located in the Tarim River Basin of Xinjiang, China. Large water consumption reduces the discharge and jeopardizes the ecosystem of the lower reaches of the Tarim River. Therefore a recent regulation is enacted to limit water use in the plain. The objective of this paper is to investigate the hydrological cycle inside an intensively cultivated plain at upstream Tarim River. A conceptual water balance methodology was used for evaluating groundwater movement among riverway, irrigation ditches, irrigation area and non-irrigation area, based on the recorded water diversion. Results show that both irrigation area and non-irrigation area are supported by the water from river way in hyper-arid environment. Irrigation area is supported by surface water through canal system and non-irrigation area is supported by groundwater from canal loss and irrigation area. Nearly half of the water in the non-irrigation area comes from the irrigation area in the form of groundwater. This indicates that water supply of natural plants relies on the water from agricultural ecosystem. Tight water connection between irrigation area and non-irrigation area suggests that natural ecosystem needs to be considered in agricultural management in arid environment.

Key words hydrological processes · irrigation · ecosystem · arid environment · groundwater

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1 Introduction

The plain of the Tuoshigan–Kumalake River is an oasis with vast evaporation in Xinjiang, China. It is located northwest of the Tarim Basin and south of the Tianshan Mountain, in the upper Tarim River Basin. This land has a long irrigation history and its ecological integrity is tightly linked to both natural hydrology and human impact. The local population uses the river water and spring water for free or at a very low cost. From 1980 to 2002, the irrigation area grew by a factor four (Figure 1). The climate change and anthropogenic activities make the downstream drying up increased (Xu et al., 2004; Feng et al., 2001). To counter these problems, a new regulation of water use for the Tarim River, has been developed. The regulation, which started operating at the end of 2001, was enacted to limit water use in the upper reaches of the Tarim River and rehabilitate the fragile ecosystem of lower reaches. The Tuoshigan and Kumalake River that converge at the Akesu River, the largest source of the Tarim River, are supposed to save water for the downstream areas. Civil works such as lining of irrigation ditches are planned or ongoing to help the area save water. Though the environmental impact studies that were performed before the civil works construction, the knowledge concerning the hydrological processes and water balance inside the Tuoshigan–Kumalake River plain is still limited. There are some studies generally presented environmental effects of water resource development and use in the Tarim River Basin, such as Feng et al. (2005) and Cui and Shao (2005). However, most studies only focused on the middle and downstream of the river, there is still no description of how the native plants are supplied with water and how the agricultural ecosystem affects the environment at upstream.

This study provides an integrated assessment of sources and quantities of discharge from the Tuoshigan–Kumalake River plain, offering recent records of agricultural water diversion entering the irrigation area, as well as calculated evapotranspiration from the irrigation area, native plants land and waste land inside the plain. The water supply to non-irrigation area and the groundwater exchange between irrigation area and non-irrigation area are focused to investigate how the agricultural ecosystem affects the environment in hyper-arid area. Due to data constrains, the study is limited to the period 1999-2002.

2 Study Area

The Tuoshigan–Kumalake River plain lies at the northwest edge of the Takelamagan desert, it is characterized by low precipitation (79 mm/year) and high evaporation

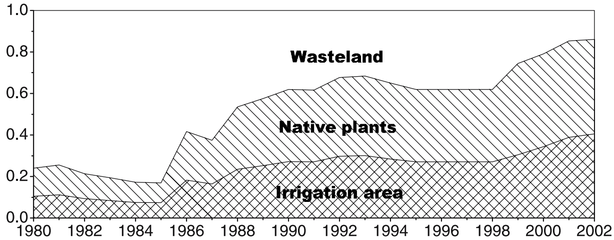

Figure 1 Comparative changes in land use from 1980 to 2002.

rates (20 cm pan evaporation 1,894 mm/year) (Tang, 2003). Vegetation is distributed mainly along the river main stem and irrigation ditches, and the landscape becomes Gobi where out of the reach of water supply. In this study, the plain boundaries were drawn based on images from the first China Brazil Earth Resources Satellite (CBERS-1) acquired in 2001 with spatial resolution of 20 m by contouring the edge of the oasis, encompassing a land area of 2,105 km^2. Three land use types (vegetation, wasteland, water surface) were determined from the satellitic image. In order to estimate evaporation accurately, the vegetation area was divided into irrigation area and native vegetation. The extent of the irrigation area was determined based on information collected from the local statistics bureau. The irrigation area was further specified to crop types such as wheat, cotton, paddy, and corn according to data from the local statistics bureau.

The Xiehela and Shaliguilanke national hydrometric stations mark the northernmost and westernmost limits of the plain. Kaladouwei, the conjunction of the Tuoshigan River and the Kumalake River marks the lowermost limit of the plain. There is no surface water gauge station at Kaladouwei, but the Xidaqiao gauge station is located 15.8 km downstream of the conjunction. The river length is 68 km from Xiehela to Xidaqiao station and 156 km from Shaliguilanke to Xidaqiao station. In this study, the discharge at the Xidaqiao gauge station is used as a proxy for the discharge at Kaladouwei.

2.1 Previous Studies

In the flood season (July to September), there is sporadic runoff generated from the mountainous area beside the plain. This water, which is ungauged, enters the plain as mountain torrents or springs. The springs can be considered as being a constant flow while the mountain torrents vary from year to year. A prior field study was performed in 1999 by Akesu Water Resources Reconnaissance and Survey Team (AWRRST, 2000) to investigate the ungauged runoff. A total of 32 mountain

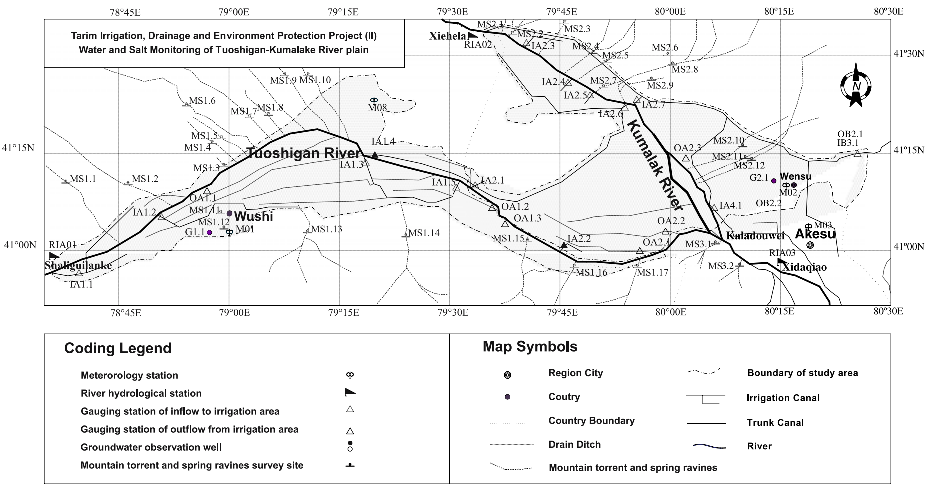

Figure 2 Major hydrological features and monitoring sites of the Tuoshigan–Kumalake River plain.

torrents and spring ravines that lead into the plain were surveyed. The locations of these torrents and spring ravines are shown in Figure 2. The spring ravines to the north of the Tuoshigan River originate from mountainous area outside the study area. This means that these springs can be regarded as runoff generation. But the springs that flow to the Kumalake River are generated from plain area inside the study area, and geological analysis shows that part of the springs are formed from confined water originated from the Kumalake River (RDI, 1989). Therefore, these springs can be regarded as transformation of river water. It is worth mentioning that the investigation was performed only in a single year, 1999. Data for other years are unavailable. The surveyed spring and mountain torrents data is directly used in unsurveyed years.

2.2 Hydrogeological Context

The deposits of Quaternary age blanket the alluvial plain as sand, gravel, and clay occurring mostly as alluvial deposits. These deposits make up the primary aquifer for the Tuoshigan alluvial plain and Kumalake proluvial fan. The thickness of the alluvium is general more than 250 m (Liang et al., 2003). The upper parts of the plain are generally composed of gravel and coarse sand, and the lower parts are typically made up of fine sand and clay. There is a phreatic water layer and two confined water layers at the lower portion of Kumalake proluvial fan within 200 m depth underground. The first confined layer is 10–15 m underground, and the second confined layer is about 50 m underground. The water table depth in the study area ranges from 2 to 4 m (Tang et al., 2004). There are intense surface water and groundwater transformations inside the plain. The mountain torrents and springs usually percolate through the loose dry soil and transform into groundwater before they can reach the main stem. The confined water then spurts out as artesian in the plain. Part of the artesian spring water is diverted for irrigation by local population, and the remaining water flows to the main stem.

The mountain torrents and the springs are not the only sources of the artesian spring. Research shows that large volumes of river water penetrate into groundwater at the mountain gaps and becomes artesian around the conjunction of the two rivers

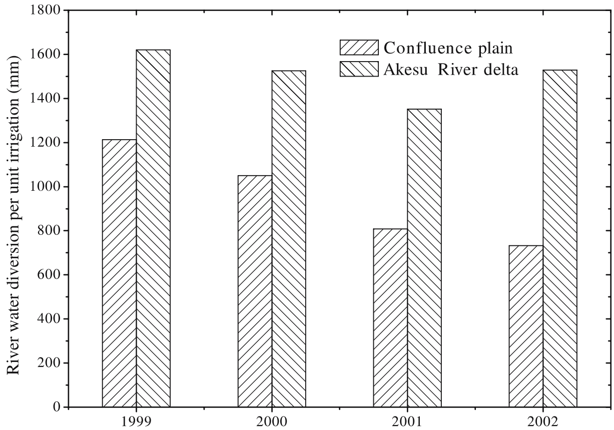

Figure 3 Comparison of river water diversion per unit irrigation area for the Tuoshigan–Kumalake River plain and the Akesu River delta 1999–2002.

(RDI, 1989). The use of artesian spring reduces the water diversion from the river main stem. Figure 3 compares the river water diversion per unit irrigation area in the Tuoshigan–Kumalake River plain with the river water diversion per unit irrigation area in the Akesu River delta, a neighbouring area with similar climate, geographical characteristics and cropping system.

3 Material and Methodology

The study developed a water balance for the Tuoshigan–Kumalake River plain using existing flow records, estimated evaporation, calculated agricultural drainage, and estimated outflows. Discharge records for the main stem at the Xiehela and Shaliguilanke station were supplemented by local gauge station records for the Xidaqiao station and agricultural diversion records obtained from the Akesu River Administrative Agency (ARAA). Loss due to evaporation in the conjunction plain was calculated by the runoff-evaporation (RE) model described below. Atmospheric forcing data such as temperature, sunshine duration, and wind speed were collected from the Wushi and Wensu stations, two meteorological stations within the study area. Agricultural diversion records from 1980 to 1998 were available. Even though these data are not fully reliable, they were still used to provide the initial conditions for the RE model in this study. The agricultural diversion records after 1998 were provided by a Water and Salt Monitoring Project and were deemed reliable, limiting the study to the period 1999–2002.

The study area was divided into three hydrological sub-systems: the Tuoshigan–Kumalake River main stem, the Wushi sub-area (sparse dotted area in Figure 2) and the Wensu sub-area (dense dotted area in Figure 2). There are surface and ground water connections among these three hydrological sub-systems. Water balance is calculated for every month during the study period.

3.1 River Main Stem

A mass balance of the river main stem is used to characterize discharge. The mass balance equation (Cohen et al., 2001) can be described as:

$$Q_{ds} = Q_{us} + Q_{rf} + P_r + T_r - E_r - \Delta S_a - Q_{sb} \tag{1}$$

where, Q_{ds} is flow at the downstream boundary, Q_{us} is flow at the upstream boundary, Q_{rf} is return flow to the river, P_r is precipitation to river, T_r is tributary inflow, E_r is evaporation from river open water surface, ΔS_a is change in aquifer storage, and Q_{sb} is flow to sub-areas.

Discharges at the upstream boundary (Q_{us}) are from records of two national hydrometric stations. Return flow to the river (Q_{rf}) consists of agricultural and municipal drainage. Records of agricultural drainage, where available, were obtained from the Water and Salt Monitoring Project. However the agricultural drainage is mixed with spring water. Therefore these data are considered uncertain. Then the estimated agricultural drainage was used in this study, and the available drainage data were used to calibrate the irrigation model of sub-areas. There were no records of municipal water deliveries available, so the municipal water use is estimated from estimated per capita consumption, population, GDP, etc. The population and GDP data were obtained from the local statistics bureau. Estimations of municipal effluent discharge to the river were based on the assumption that 35% of municipal water use became effluent discharge to the river. It is worth mentioning that the volume of municipal drainage water (8×10^6 m^3/year) is small in comparison with the volume of water discharged at the upstream boundary ($8{,}000\times10^6$ m^3/year).

Precipitation to rivers (P_r) is calculated from averaged precipitation records of the three hydrometric stations and open water surface area from the CBERS-1 images. The tributary runoff (T_r) is usually generated from mountainous area outside the plain, and flows into the study area as mountain torrent and spring. There are not gauged precipitation data for the runoff generating area, thus the results of the mountain torrent and spring ravines investigation in 1999 were used as the basis of the tributary runoff. The Akesu Hydrological Bureau (AHYB) estimated runoff by extending the runoff isopleth map to the mountainous area and correlating this with an extended isohyetal map to project an annual tributary runoff of 600×10^6 m^3. The projection is roughly consistent with the result of the investigation in 1999 (560×10^6 m^3). Therefore, the spatial and temporal distributions of annual runoff were taken from the 1999 investigation and were scaled to fit the projection of AHYB (600×10^6 m^3/year). Evaporation from river open water surface (E_r) is calculated from averaged pan evaporation records of the three hydrometric stations and open water surface area from the CBERS-1 images. Estimation of change in storage in the alluvial aquifer (ΔS_a) was based on an assumption that the storage change is in direct proportion to the averaged stream flow as follow:

$$\Delta S_a = \alpha \frac{Q_{us} - Q_{ds}}{2} \tag{2}$$

where, α is the proportionality constant derived from linear regression analysis of available observations. The storage change in the alluvial aquifer is connected to the groundwater of two sub-areas, meaning that the river-groundwater interaction could affect the groundwater (i.e. water table depth) of the alluvial plain. Water from the river main stem (Q_{sb}) has discharged into the Tuoshigan–Kumalake River plain as water diversion for irrigation. The net water diversion data were available from ARAA.

3.2 Sub-area

A runoff-evaporation (RE) land surface hydrological model, which was developed by Hu et al. (2004); Tang et al. (2004), was used to calculate the water balances inside the two sub-areas. A schematic diagram of the RE model is presented in Figure 4. The model consists of three land use components: irrigation area, native plants land and wasteland with the associated surface and ground water dynamic relationships defining the interactions among them. The irrigation area is described by seven crop types: cotton, wheat, paddy, corn, melon, gardens and irrigated pasture. The three components are connected through a ditch system (surface water) and groundwater exchange. The field infiltration and phreatic evaporation are considered because the water table is shallow in the study area. The water balance of the ditch system, irrigation area and non-irrigation area are then calculated according to the model.

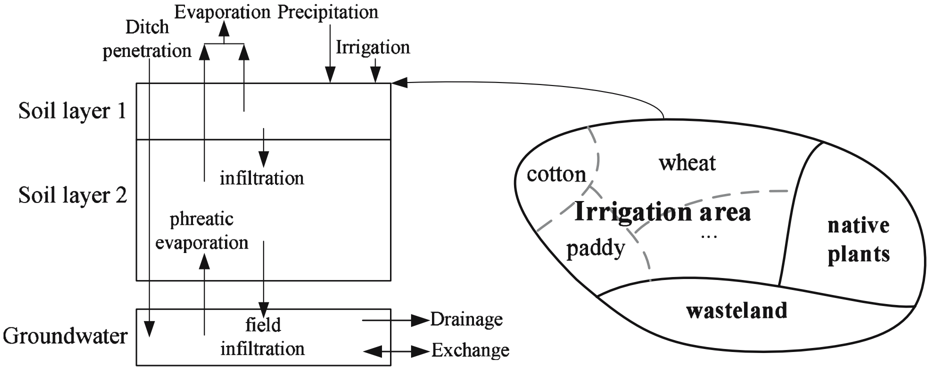

Figure 4 Schematic diagram of the runoff-evaporation (RE) hydrological model.

3.2.1 Ditch System

A mass balance of ditch system is used to represent the human dominating process. The mass balance equation can be described as:

$$D_o = D_i - D_e - D_g \tag{3}$$

where, D_o is ditch outflow to irrigation area, D_i is total ditch inflow, D_e is evaporation from open ditch water surface and surrounding saturated zone, and D_g is ditch penetration to groundwater. Total ditch inflow (D_i) consists of net water diversion from the river main stem and artesian that was used for irrigation. The water diversion from the river main stem was obtained from ARAA. The spring data from the investigation in 1999 was used for the whole study period. The ditch loss was assumed to be in direct proportion to the ditch inflow, and the proportionality constant was identified according to the actual situation of the ditch system. One part of ditch loss was arbitrarily considered to recharge groundwater (i.e. D_g) with a ditch penetration coefficient fluctuating at 0.6–0.8 in this study because the water table was very shallow, and the remaining part (i.e. D_e) was considered to evaporate from the open ditch water surface and the surrounding saturated area. The ditch penetration coefficient highly depends on underlying soil properties, water table depth, and vegetation nearby the ditch. Further research is needed to better understand the ditch loss.

3.2.2 Irrigation Area

According to the RE model, the water balance of the irrigation area can be summarized as:

$$D_o + P_i + G_i - E_i - D - X - \Delta S_{is} - \Delta S_{ig} = 0 \tag{4}$$

where, P_i is precipitation over irrigation area, G_i is groundwater recharge to irrigation area, E_i is evaporation from irrigation area, D is drainage, X is groundwater exchange with non-irrigation area, ΔS_{is} is soil water storage change in irrigation area, and ΔS_{ig} is groundwater storage change in irrigation area. Groundwater recharge to irrigation area consists of irrigation ditch penetration, river seepage and groundwater recharge from mountain torrent and spring. Evaporation from irrigation area (E_i) is characterized by reference evapotranspiration, together with crop factor and soil moisture. The reference evapotranspiration is calculated from the FAO Penman–Monteith method (Allen et al., 1998). The integrative crop factor over the irrigation area is computed as the sum of crop types weighted by the respective area fractions. An irrigation area model with two unsaturated layers and one groundwater layer was used to estimate irrigation area evaporation affected by soil moisture, and the change in soil water storage in irrigation area (ΔS_{is}) was characterized in the model. The field infiltration and phreatic evaporation are considered in the model because the water table depth is shallow in the study area. This water exchange between the unsaturated zone and the groundwater also changes the groundwater storage in the irrigation area (ΔS_{ig}) and the water table. The drainage (D) is therefore estimated from the difference between water table and drainage level in the following way (McDonald and Harbaugh, 1988):

$$D = \begin{cases} \gamma A_d (h - h_d) & : \quad h > h_d \\ 0 & : \quad h \leq h_d \end{cases} \tag{5}$$

where, γ is a drainage coefficient, describing water table decrease ratio due to the difference between water table and drainage level, A_d is drainage area, h is water table level, and h_d is the bottom level of drainage. The drainage coefficient (γ) depends highly on the underlying soil conductivity and the average distance between the drainage ditches. It is a regionalized parameter which represents the drainage system state. The drainage area (A_d) means the area where groundwater can recharge the drainage. Because the drainage system is fully developed, the whole irrigation area is taken as drainage area in this study. The groundwater exchange with non-irrigation area (X) is also estimated based on the water table difference between irrigation and non-irrigation area.

3.2.3 Non-irrigation Area

The water balance equation for the non-irrigation area is similar to the one for the irrigation area, except for the items where humans are directly involved, D_o and D, as follows:

$$P_{ni} + G_{ni} + X - E_{ni} - S - \Delta S_{ni} = 0 \tag{6}$$

where, G_{ni} is groundwater recharge to non-irrigation area, E_{ni} is evaporation from non-irrigation area, S is artesian outflow, and ΔS_{ni} is change in soil and ground water storage in non-irrigation area. Two land use types, native plants land and waste land in non-irrigation area, were specified in this study. Based on the formulation of Gardner (1958); van Bavel and Hillel (1976); Mao et al. (1997), evaporation from non-irrigation area was estimated as:

$$E_{ni} = \min\left(E_0 \cdot e^{\alpha_s (H-R)}, \beta_s \cdot (H-R)^{\gamma_s}\right) \tag{7}$$

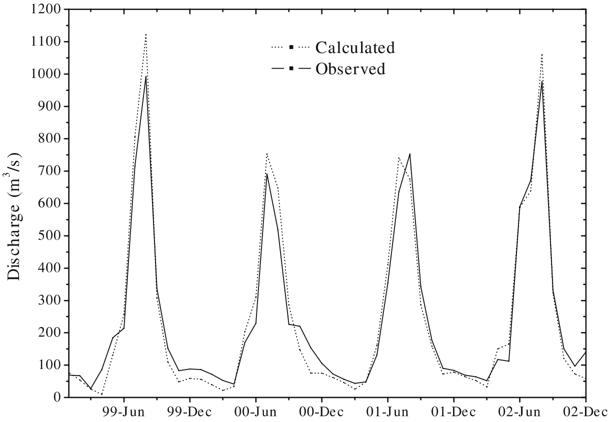

Figure 5 Calculated (*dotted*) and observed (*solid*) discharge to downstream for Xidaqiao station.

where, E_0 is water surface evaporation, H is water table depth, R is mean root depth of vegetation, α_s, β_s, γ_s are empirical soil parameters. The artesian outflow inside the study area was computed from the investigation and was assumed to be constant.

4 Results

Figure 5 shows modeled and observed discharge to downstream from 1999 to 2002. Generally, the stream flow is fairly well reproduced, except the peak and low flow in 1999. It is surprising because the investigation of mountain torrent and spring ravines was performed in that year. One possible reason is that the mountain torrent and spring did not rush into the main stem as expected but were absorbed by the plain. The widespread existence in the plain of sand loam and sandy soil with high water permeability supports that hypothesis. The purpose of this study is not mainly to reproduce the hydrograph, but a good reproduction indicates that the study is providing a reasonable water budget.

Table I shows the water budget for the Tuoshigan–Kumalake River main stem from 1999 to 2002. The flow to sub-areas Q_{sb} (1,613×10^6 m^3/year) was obtained from observations, including water diversion (54% of Q_{sb}) to the two sub-areas in

Table I Water balance for the Tuoshigan–Kumalake River main stem, 1999–2002 (10^6 m^3)

Inflows and outflows	1999	2000	2001	2002	Average
Inflow at upstream boundary (Q_{us})	9,374	8,567	8,704	10,295	9,235
Return flow to the river (Q_{rf})	349	222	180	271	255
Precipitation to river (P_r)	6	7	12	9	9
Tributary inflow (T_r)	186	186	186	186	186
Evaporation from river (E_r)	142	133	138	123	136
Change in aquifer storage (ΔS_a)	198	181	156	320	214
Flow to sub-areas (Q_{sb})	1,664	1,698	1,520	1,569	1,613
Outflow at downstream boundary (Q_{ds})	7,911	6,969	7,269	8,748	7,724
Observed river outflow (Q_{obv})	7,933	6,754	7,332	8,871	7,722

Table II Water balance for the ditch systems, 1999–2002 (10^6 m^3)

Inflows and outflows	Wushi	Weusu
Ditch diversion from river (D_{ir})	384	463
Ditch diversion from spring (D_{is})	481	318
Evaporation from ditch (D_e)	103	93
Penetration to groundwater (D_g)	414	373
Ditch outflow to irrigation area (D_o)	348	314

the study area and water transfer (46% of Q_{sb}) to outside the study area. The shallow water table and numerous artesian springs contributed to large water regeneration, and besides, the planting of paddy field caused large drainage. The return flow (Q_{rf}) and tributary inflow (T_r) were 440×10^6 m^3/year, near half of the water diversion into the study area (870×10^6 m^3/year). Due to the low precipitation and high evaporation rate, it is expected that the precipitation affected the water budget little and the evaporation from open water surface was substantial. Most notable is the storage change in aquifer (ΔS_a), which is larger than the tributary inflow. Detailed investigation of the monthly variation of aquifer storage change shows that large volumes of river water are stored in the alluvial plain in the flood season (July to September) and the river-groundwater interaction is relatively small during the low flow season. This indicates that the river loss to the aquifer is consumed in the alluvial plain or regenerates as surface water.

The mean annual water budget for the ditch systems in the two sub-areas is shown in Table II. Artesian spring flow from outside or inside study area (D_{is}) is as large as the water diversion from the riverway (D_{ir}), indicating that surface water-groundwater interaction is intensive in the study area. Nearly 60% of total water diversion is ditch losses (D_e and D_g), and the remaining 40% reaches the farmland. This is possible because of the high water permeability of the underlying sandy soil and earth ditches without liner. Large ditch loss recharges the groundwater because water table is shallow and this contributes to lifting up the water level in the aquifer. The utilization of ditch liner to prevent water loss will increase the water transfer efficiency, but it may also lower the water table. Groundwater discharge of artesian spring, which originates from groundwater recharge, such as ditch penetration and river seepage, is freely used by the local population. The methods to prevent ditch water loss will inevitably disturb the artesian springs. It is clear that much additional

Table III Water balance for the irrigation area, 1999–2002 (10^6 m^3)

Inflows and outflows	Wushi	Weusu
Ditch outflow to irrigation area (D_o)	348	314
Precipitation to irrigation area (P_i)	50	50
Groundwater recharge to irrigation area (G_i)	198	374
Evaporation from irrigation area (E_i)	276	318
Drainage (D)	19	170
Groundwater exchange with non-irrigation area (X)	298	270
Soil water storage change in irrigation area (ΔS_{is})	0	−14
Groundwater storage change in irrigation area (ΔS_{ig})	4	−6

Table IV Water balance for the non-irrigation area, 1999–2002 (10^6 m^3)

Inflows and outflows	Wushi	Weusu
Precipitation to non-irrigation area (P_{ni})	81	73
Groundwater recharge to non-irrigation area (G_{ni})	91	324
Groundwater from irrigation area (X)	298	270
Evaporation from native plants land (E_{native})	240	233
Evaporation from waste land (E_{waste})	26	32
Artesian outflow (S)	200	434
Storage change in non-irrigation area (ΔS_{ni})	5	−30

work will be required before a complete understanding of the magnitude of the disturbance can be reached.

The mean annual water budget for the irrigation area in 1999 to 2002 in the two sub-areas is shown in Table III. Ditch diversion and groundwater recharge compose the major water recharge in the irrigation area. Evaporation from the irrigation area, the water consumption, amounts to about half of the total water supply. It is notable that the groundwater exchange with the non-irrigation area (X) is as large as the water consumption. The flood irrigation system is believed to contribute to the large lateral groundwater flow. Fourteen percent of the water supply is drained out of irrigation area, and the proportion is 23% in Wensu sub-area, where paddy field is cultivated.

Table IV shows the mean annual water budget for the non-irrigation area in the two sub-areas from 1999 to 2002. It is notable that the precipitation over the non-irrigation area is much less than the total water consumption, i.e. the sum of evaporation from native plants land and waste land. Actually, precipitation stands for only 14% of the total water supply. The remaining 86% of the water supply comes from groundwater recharge (G_{ni}) and groundwater from the irrigation area (X), meaning that the natural ecosystem of the arid area relies on the managed agricultural ecosystem for water supply. The storage change is small in Wushi but relatively large and negative in Wensu sub-area, indicating that there might be a water table drawdown in this sub-area. Unfortunately for Wensu sub-area, data from only one groundwater gauge well from the years 2000 to 2002 was available to validate drawdown. These show a mean 18 cm drop during the 3 years.

The results indicate that both irrigation area and non-irrigation area are supported by the water from river way. The water to irrigation area is from river way through a canal system directly. However, the water to non-irrigation area comes from canal loss and groundwater from irrigation area. This manifests that water supply of natural plants relies on the water from agricultural ecosystem in the hyper-arid environment. Tight water connection between irrigation area and non-irrigation area suggests that natural ecosystem needs to be integrated in a comprehensive agricultural management in arid environment.

5 Conclusion and Discussion

Streamflow of the Tuoshigan–Kumalake River decreases along the main stem with a 9,200×10^6 m^3/year discharge at the upstream boundary and 7,700×10^6 m^3/year discharge at the downstream boundary. The dominating hydrological processes are related with the river water dispersion to the alluvial plain, i.e. dispersed flow, rather than runoff concentration to the riverway. Intensive surface water-groundwater interaction and human disturbances make these processes complex and limits our knowledge of the hydrological cycle in the alluvial plain. Four years of fieldwork was performed by our project group to investigate the agricultural ecosystem inside the Tuoshigan–Kumalake River plain.

Mean annual evaporation over irrigation area in two sub-areas, 276×10^6 and 318×10^6 m^3 respectively, corresponded to only 46 and 43% of the ditch diversion respectively, showing that the local irrigation system, using long earth ditches on sandy soil and a relatively small flow of water, is inefficient. However, the ditch losses contribute to recharging groundwater (787×10^6 m^3/year) and raise the water table. The artesian springs, which originate from the groundwater in non-irrigation area, partly recharged by ditch and irrigation area, are usually led back into ditch system, making the water transformation inside the plain more complicated.

Mean groundwater flows from the irrigation area to the non-irrigation area in the two sub-areas, 298×10^6 and 270×10^6 m^3 respectively, stood for 63 and 40% of the non-irrigation area water supply respectively, indicating that the "surplus" irrigation and the losses from the irrigation system were transferred to natural ecosystem through groundwater in the Tuoshigan–Kumalake River alluvial plain. This conclusion is confirmed by the increase of native plants area accompanying with the increase of irrigation area from 1980 to 2002 (Figure 1). Tight hydrological connections between agricultural and natural ecosystem suggest that any changes in the irrigation system, such as the building of large civil works, might affect the surrounding natural ecosystem and human water supply from springs negatively.

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