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Hydrological processes within an intensively cultivated alluvial plain in an arid environment

QIUHONG TANG[1], **HEPING HU**[2] **& TAIKAN OKI**[1]

1 *Institute of Industrial Science, University of Tokyo, Tokyo 153-8505, Japan*
tangqh@iis.u-tokyo.ac.jp

2 *Institute of Hydrology & Water Resource, Tsinghua University, Beijing 100084, China*

Abstract The Tuoshigan-Kumalake River alluvial plain is a vast evaporation oasis (annual rainfall of less than 100 mm) located in the upper Tarim River, a large inland river in central Asia. Regulations have been enacted recently to limit water use in the plain because large water consumption reduces the discharge to downstream and jeopardizes the ecosystem of the lower reaches of the Tarim River. Engineering works are planned, or are under construction, to save water but without consideration for the hydrological connections within the plain. The objective of this paper is to investigate the hydrological cycle inside the plain, which is impacted by intensive cultivation, and to highlight the interactions between the cultivation system and the natural ecosystem. A conceptual water balance methodology was used for evaluating the water transformations between the river channel irrigation ditches, irrigation area and non-irrigation area based on the records of water diversion, spring flow studies, and monitoring of precipitation, temperature and other hydrological parameters. Water budgets for the mainstem of the Tuoshigan-Kumalake and the Wushi and Wensu sub-areas were calculated for the alluvial plain for the period 1999–2002. Results show that the irrigation system is inefficient in using earth ditches on sandy soil and that groundwater exchange between the irrigation and non-irrigation areas accounts for nearly half of the water supply to the non-irrigation area, which suggests that any human disturbance to the irrigation system might rapidly influence the surrounding natural ecosystem.

Key words ecosystem; groundwater flow; hydrological processes; irrigation; water balance

INTRODUCTION

The plain of the Tuoshigan-Kumalake River is a vast zone where evaporation dominates. It is located northwest of the Tarim Basin and south of the Tianshan Mountains, in the upper Akesu River Basin. This land has a long irrigation history and its ecological integrity is closely linked to both natural hydrology and human impact. Despite a long historical development, the hydrological observations are limited to the main river channel and the irrigation ditches. The local people are generally poor and make use of springs or river water. Recently, there has been environmental disturbances involving unplanned reclamation following expansion of the agro-industry and in consequence the incidence of downstream drying up of the watercourse has increased. New rules for regulating water use in the Tarim River have been developed. This regulation, which started operating at the end of 2001, is designed to limit water use in the upper reaches of the Tarim River and rehabilitate the fragile ecosystem of lower reaches. The Tuoshigan and Kumalake rivers, which converge at the Akesu River, provide the largest source of water to the Tarim River and are supposed to supply more water downstream. Many engineering works, such as lining irrigation ditches and pumped irrigation schemes, are planned or under construction to help the area save water. In spite of the environmental impact studies undertaken before the engineering works began, the knowledge concerning the hydrological processes and water balance inside the Tuoshigan-Kumalake River plain is still very limited. Some studies (e.g. Li & Li, 1997; Liang *et al*., 2003) have focused on particular aspects of the hydrology of the area. However, most studies have focused only on the irrigation area, and there is still no description of how the natural vegetation is supplied by water and how the agricultural ecosystem affects the environment.

The present study provides a robust assessment of the sources and quantities of discharge to the Tuoshigan-Kumalake River plain, based on recent records of agricultural water diversion to the irrigation area, as well as calculated water consumption over farmland, uncultivated land and wasteland inside the plain. Due to data constraints, the study is limited to the calendar year period 1999–2002.

Study area

The Tuoshigan-Kumalake River plain lies at the northwest edge of the Takelamagan desert, which is characterized by low precipitation (79 mm year^{-1}) and high evaporation rates (20 cm pan evaporation, 1894 mm year^{-1}) (Tang, 2003). Because most vegetation is distributed surrounding the river mainstem, the boundary of the plain in this study has been defined using images from the first China Brazil Earth Resources Satellite (CBERS-1). These were acquired in 2001 with a spatial resolution of 20 m and a contouring of the edge of the oasis defined an area of roughly 2105 km^2. Three land use types (vegetation, bare land, and water surface) over the plain were determined from the remote sensing map. In order to calculate evaporation precisely, the vegetation area was divided into irrigation area and uncultivated land. Information on the area under irrigation was collected from statistics available at a local bureau, and the uncultivated land area was calculated as the difference between the areas of vegetation detected on the remote sensing imagery and the area of vegetation. Information was also available on crop cover types, such as wheat, cotton, paddy, corn, grove, etc. for the area under irrigation.

The districts of the Tianshan Mountains, where the Xiehela and Shaliguilanke national hydrometric stations are located, mark the northernmost and westernmost limit of the plain, respectively. Kaladouwei, which lies at the confluence of the Tuoshigan and Kumalake rivers, marks the lowermost limit of the plain. Although a gauging station is not located at Kaladouwei, there is one at Xidaqiao, 15.8 km downstream. In this study, the discharge at Xidaqiao is used as a proxy for that at Kaladouwei.

There is ungauged runoff generated from the mountain area in the flood season (July to September), which flows into the plain as mountain torrents or from springs. The latter are regarded as having a constant flow, but the runoff from the mountain torrents varies from year to year reflecting the occurrence of rainstorms in the mountains which are ungauged. Previous field work was undertaken in 1999 by the Akesu Water Resources Reconnaissance and Survey Team (AWRRST, 2000) to investigate the ungauged runoff. A total of 32 mountain torrent and spring ravines that flow into the plain were surveyed. The locations of the flood and spring ravines are shown in Fig. 1. Most spring ravines to the north of the Tuoshigan River are generated from the mountainous area outside the study area. However, most spring ravines that flow to the Kumalake River are generated from the plain area inside the study area, and geological analysis shows that the springs are formed from confined water originating from the Kumalake River (RDI, 1989). Therefore, the springs can be considered as a transformation rather than a source of river water. Because the spring flow is relatively steady, the spring flow data were extended to other years without further investigation. The surveyed mountain torrent flow for 1999 is also directly used for other years in this investigation despite the uncertainty involved in this projection.

The water table depth in the study area ranges from two to four metres (Tang *et al.*, 2004). There are strong surface water and groundwater transformations inside the plain. The mountain torrent and springs usually are dewatered by infiltration into the loose dry soil or penetration into the groundwater before they can reach the main stem. The confined water then emerges as artesian springs in the plain. Most springs are diverted for irrigation by local people and gauged, and the remnant springs flow continues to the mainstem or is consumed somewhere inside the plain. The mountain torrents and springs are not the only sources of artesian springs. Research shows that large volumes of river water also penetrate into the groundwater in the mountain valleys and become artesian springs around river confluences (RDI, 1989). Use of artesian spring water obviously has cut down the need to divert water from the mainstem of the river. Figure 2 compares the water diversions in the vegetated area for the Tuoshigan- Kumalake River plain and the nearby Akesu River delta, which has a similar climate, geographical characteristics and cropping system. It is clear from this

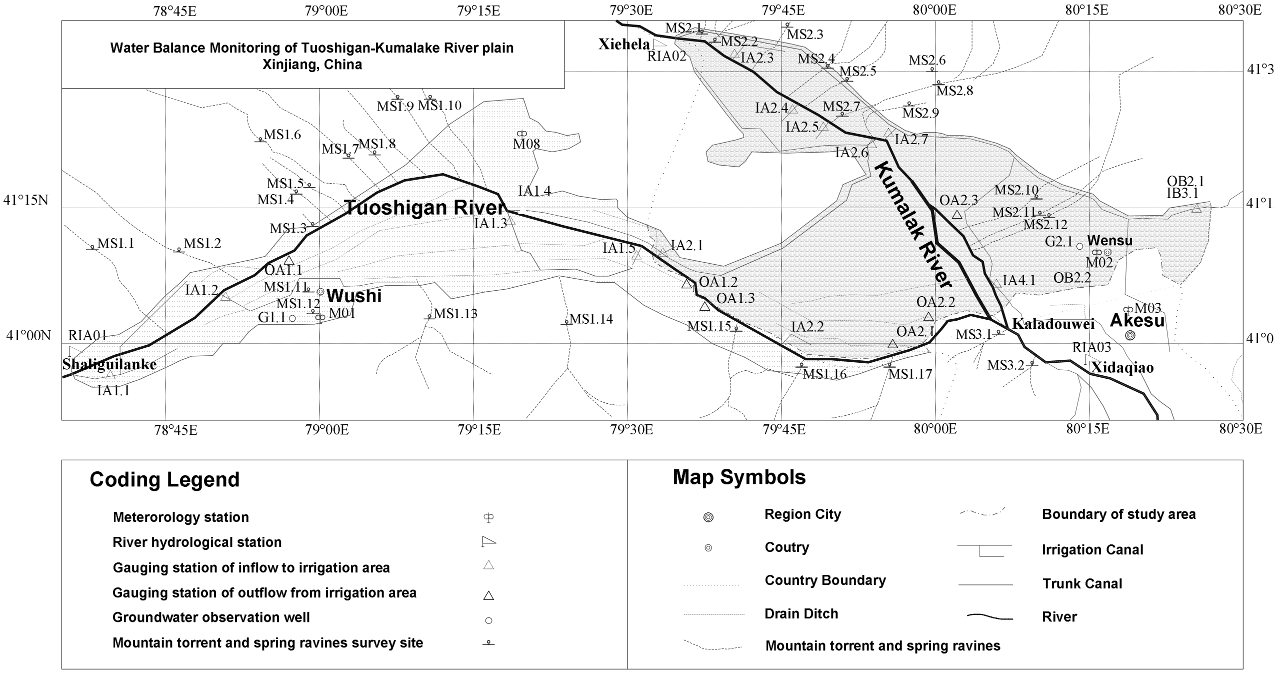

Fig. 1 Major hydrological features and monitoring sites of the Tuoshigan-Kumalake River plain.

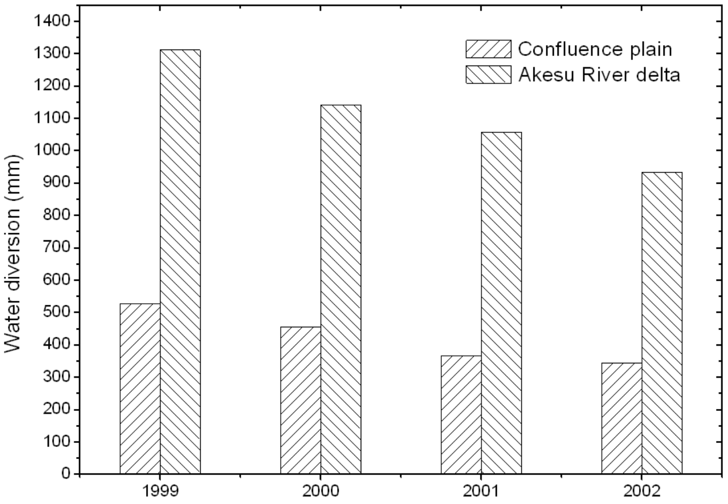

Fig. 2 Comparison of the magnitude of water diversion for the Tuoshigan-Kumalake River plain and the Akesu River delta in the period 1999–2002.

comparison that usage of artesian spring water significantly reduces the need to divert water from the river channel to the plain.

MATERIALS AND METHODS

The study developed a water balance for the Tuoshigan-Kumalake River plain using existing flow data, estimated evaporation, calculated agricultural drainage, and estimated outflows with a mass balance. National discharge records for the river mainstem at the Xiehela and Shaliguilanke station were supplemented by local gauging station records at the Xidaqiao station and by agricultural diversion records obtained from the Akesu River Administrative Agency (ARAA). Loss due to evaporation over the plain was calculation by the runoff–evaporation (RE) model mentioned below. The data on atmospheric forcing factors, such as temperature, sunshine duration, and wind speed, etc. were collected from the Wushi and Wensu weather stations in the study area. Agricultural diversion records were available from 1980 to 1998 but were not integrated and reliable. Nevertheless 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 reliable, limiting the study to the period 1999–2002.

In order to refine the assessment, the study area was divided into three hydrological sub-systems: the Tuoshigan-Kumalake River mainstem, the Wushi sub-area (sparsely dotted area in Fig. 1) and the Wensu sub-area (densely dotted area in Fig. 1).

River mainstem

A mass balance of river mainstem is used to characterize discharge. The mass balance equation (Owen-Joyce *et al.*, 1996; Cohen *et al.*, 2001) can be described as:

$$Q_{ds} = Q_{us} + Q_{rf} + P + T_r - E - \Delta S_a - Q_{sb}$$

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 is precipitation on the open water surface; T_r is tributary inflow; E is evaporation from the open water surface; ΔS_a is change in aquifer storage; 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 drainage data were not integrated and reliable because some drainage was mixed with runoff from spring ravines and ungauged during the study period. Therefore, 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 available records of municipal water supply, so the municipal water use is estimated from water use quota and population, GDP, etc. The population and GDP data were available from the local statistical bureau. Estimations of municipal effluent discharge to the river were based on an assumption that 35% of municipal water use became effluent discharge to the river. It is worth mentioning that the municipal drainage is quite small, at about 8×10^6 m^3 $year^{-1}$, compared to the discharges at the upstream boundary (7.5×10^9 m^3 $year^{-1}$). Precipitation (P) is calculated from averaged precipitation records for the two weather stations, and the open water surface area was derived 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 torrents and springs. There are no gauged precipitation data in the runoff generating area, thus the results of the investigation in 1999 into the mountain torrents and spring ravines were used as the basis for calculating the tributary runoff. The Akesu Hydrological Bureau estimated runoff by extending the runoff isopleth map to mountainous area and correlating this with an extended isohyetal map to project an annual tributary runoff of 0.6×10^9 m^3. The projection is roughly consistent with the result of the investigation in 1999 (0.56×10^9 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 (0.6×10^9 m^3 $year^{-1}$). Evaporation from open water surfaces (E) is calculated from the averaged pan evaporation records of three hydrometric stations and the open water surface area. 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 follows:

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

where, α is the proportionality constant derived from linear regression analysis of available observations. The storage change in the alluvial aquifer is connected with 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 mainstem (Q_{sb}) is also diverted into the Tuoshigan-Kumalake River plain for irrigation. The net water diversion data were available from ARAA.

Sub-areas

A runoff-evaporation (RE) land surface hydrological model, which was developed by Hu *et al*. (2004) and Tang *et al*. (2004), was used to calculate the water balances inside the two sub-areas. In the RE model, the water balance of the ditch system, irrigation area and non-irrigation area were calculated and the connection between them via groundwater was represented.

A mass balance of the ditch system was used to represent the processes dominated by human activity. The mass balance equation can be described as:

$$D_o = D_i - D_e - D_g$$

where D_o is ditch outflow to irrigation area; D_i is total ditch inflow; D_e is evaporation from the open ditch water surface and surrounding saturated zone; D_g is infiltration to groundwater.

Total ditch inflow (D_i) consists of net water diversion from the river mainstem and artesian spring flow that was used for irrigation. The water diversion from the river mainstem was obtained from ARAA. It is worth mentioning that not all the water diversion from the mainstem contributed to ditch inflow because part of this water was diverted directly out of the study area. The artesian springs used for irrigation were not gauged in real time for the study period. Monitored spring flow velocities were used in combination with the assumption that the spring flows were constant. 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 between 0.6–0.8 in this study because the water table was very shallow, while the remaining part (i.e. D_e) was considered to evaporate back to atmosphere from the open ditch water surface and the surrounding saturated area. The ditch seepage coefficient is highly dependent on the characteristics of the underlying soil, water table depth, and vegetation around the ditch, and further research should be undertaken to investigate the ditch loss.

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

$$D_o + P + C_{ig} - E_i - D - X - \Delta S_{is} - \Delta S_{ig} = 0$$

where C_{ig} is channel infiltration to the groundwater in the irrigation area; E_i is evaporation from irrigation area; D is drainage; X is groundwater exchange with the non-irrigation area; ΔS_{is} is the change in soil water storage in the irrigation area; ΔS_{ig} is the change in groundwater storage in the irrigation area.

Channel infiltration consists of irrigation ditch infiltration, river seepage and groundwater recharge from mountain torrents and springs. Evaporation from irrigation area (E_i) is characterized by reference evapotranspiration, together with a crop factor and soil moisture stress. The reference evapotranspiration is calculated from the FAO Penman-Monteith method. The integrative crop factor over the irrigation area is computed as the sum of crop cover types weighted by the respective area fractions. An irrigation area model with two unsaturated layers and one groundwater layer was used to estimate the irrigation area evaporation affected by soil moisture, and the change in soil water storage in the irrigation area (ΔS_{is}) was characterized in the model. The irrigation 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 groundwater also changes the groundwater storage in the irrigation area (ΔS_{ig}) and the water table. The drainage (D), therefore, is estimated from the water head difference between water table and drainage level in a lumped way (McDonald *et al.*, 1988):

$$D = \begin{cases} \gamma \cdot A_d \cdot (h - h_d), & h > h_d \\ 0, & h \leq h_d \end{cases}$$

where γ is the drainage coefficient describing the water table decrease ratio due to head difference between the water table and drainage level; A_d is drainage area; h is water table level; h_d is the bottom level of drainage.

The drainage coefficient (γ) is highly dependent on underlying soil conductivity and the spacing between offtakes. It is a regionalized parameter which represents the drainage system state. The drainage area (A_d) refers to 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. Estimation of the groundwater exchange with the non-irrigation area (X) is also based on the water head difference of irrigation and non-irrigation areas.

The water balance equation for the non-irrigation area is similar to that for the irrigation area, except for the tems related to human activity (D_o and D) and is as follows:

$$P + C_{nig} + X - E_{ni} - S - \Delta S_{ni} = 0$$

where C_{nig} is channel infiltration to the groundwater in the non-irrigation area; E_{ni} is evaporation from the non-irrigation area; S is artesian spring outflow; ΔS_{ni} is change in soil and groundwater storage in the non-irrigation area.

Two land use types, uncultivated land and bare land, were specified in this study for the non-irrigation area. Based on the formulations of Mao *et al.* (1997, 1999) and Zhao *et al.* (2000), evaporation from the non-irrigation area was estimated as:

$$E_{ni} = \min\left(E_0 \cdot e^{\alpha(H-R)}, \quad \beta \cdot (H - R)^{\gamma}\right)$$

where E_0 is water surface evaporation; H is water table depth; R is mean root depth of vegetation; α, β, γ are empirical parameters.

The outflow of artesian springs inside the study area was computed from the 1999 investigation and was assumed to be constant. All the items will affect the water storage and water table in the non-irrigation area.

RESULTS

Figure 3 shows calculated and observed downstream discharge for the period 1999 to 2002. In general, the streamflow is fairly well reproduced, except that the magnitudes of the peak and low flows in 1999 are subject to major errors. This was surprising because the investigation of mountain torrents and spring ravines was undertaken in that year. One possible reason is that the mountain torrents and springs did not discharge into the river mainstem as expected but were absorbed by the plain, reflecting the high water permeability of the sand loam and sandy soil, which are widely distributed in the plain. A reasonably good reproduction of the discharge hydrograph suggests that the study has provided a reasonable water budget.

Table 1 shows the water budget for the Tuoshigan-Kumalake River mainstem from 1999 to 2002. The flow to sub-areas Q_{sb} (16.13×10^8 m^3 year^{-1}) was based on observations, including water diversion (54% of Q_{sb}) to the two study sub-areas and water transfer (46% of Q_{sb}) to outside the study area. The shallow water table and numerous artesian springs contributed to a large volume of regeneration water, and, in addition, the planting of paddy fields caused large amounts of drainage. The return flow (Q_{rf}) and tributary inflow (T_r) were 4.4×10^8 m^3 year^{-1}, nearly half of the water diversion into the study area (8.7×10^8 m^3 year^{-1}). Due to the low precipitation and high evaporation rate, it is expected that the precipitation affected the water budget little but the evaporation from open water surfaces was remarkable. Most notable is the storage change in the aquifer (ΔS_a), which is larger than the tributary inflow. Detailed investigation into the monthly change in aquifer storage shows that a large amount of river water goes into storage 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 2. Artesian spring flow from outside or inside the study area (D_{is}) is as large as the water diversion from river channel (D_{ir}), indicating that surface water–groundwater interaction is intensive in the study area. Nearly 60% of total water diversion is accounted for by ditch losses (D_e and D_g), and the remaining 40% reaches the farmland. This is possible because of the high permeability of the underlying sandy soil and absence of liners in the earth ditches. The large ditch loss recharges the

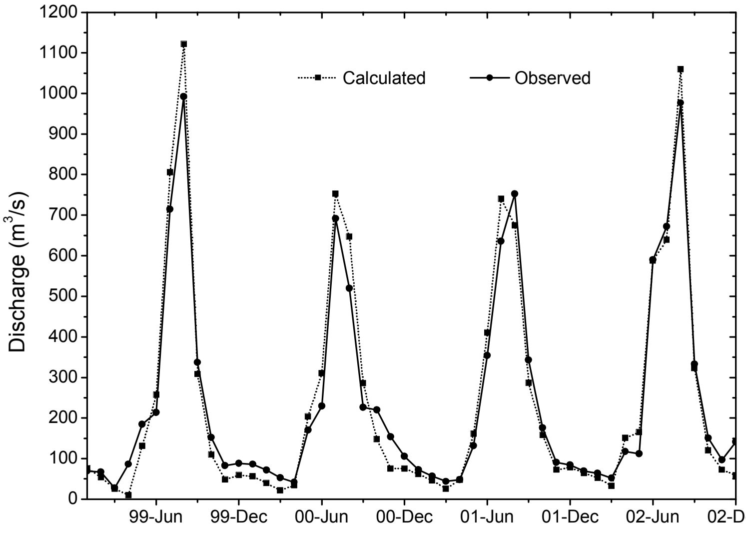

Fig. 3 Calculated (dashed) and observed (solid) downstream discharge for Xidaqiao station.

Table 1 Water balance for Tuoshigan-Kumalake River mainstem, 1999–2002 (10^8 m^3).

Inflows and outflows	1999	2000	2001	2002	Average
Inflow at upstream boundary (Q_{us})	93.74	85.67	87.04	102.95	92.35
Return flow to the river (Q_{rf})	3.49	2.22	1.80	2.71	2.55
Precipitation on open water surface (P)	0.06	0.07	0.12	0.09	0.09
Tributary inflow (T_r)	1.86	1.86	1.86	1.86	1.86
Evaporation from open water surface (E)	1.42	1.33	1.38	1.23	1.36
Change in aquifer storage (ΔS_a)	1.98	1.81	1.56	3.20	2.14
Flow to sub-areas (Q_{sb})	16.64	16.98	15.20	15.69	16.13
Outflow at downstream boundary (Q_{ds})	79.11	69.69	72.69	87.48	77.24
Observed outflow (Q_{real})	79.33	67.54	73.32	88.71	77.22

groundwater because of the shallow water table and it also contributes to raising the water table. The utilization of ditch liners to prevent water loss might both increase the water transfer efficiency and decrease the level of the water table. Artesian springs discharging groundwater, which should originate from groundwater recharge such as ditch infiltration and river seepage, are freely used by local people. The methods employed to prevent ditch water loss will inevitably disturb artesian springs. It is clear that much additional work will be required before a complete understanding of the potential disturbance can be obtained.

The mean annual water budget for irrigation area in the two sub-areas is shown in Table 3. Ditch diversion and channel infiltration contribute the major water recharge of the irrigation area. Evaporation from irrigation areas and water consumption, accounts for 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 losses. The flood irrigation system is believed to contribute to the large lateral groundwater flow. 14% of the water supply is drained out of irrigation area, and the proportion is 23% in the Wensu sub-area, where paddy fields are extensively cultivated.

Table 2 Mean annual water balance for the ditch systems, 1999–2002 (10^8 m^3).

Inflows and outflows	Wushi	Wensu
Ditch diversion from river (D_{ir})	3.84	4.63
Ditch diversion from spring (D_{is})	4.81	3.18
Evaporation from ditch (D_e)	1.03	0.93
Infiltration to groundwater (D_g)	4.14	3.73
Ditch outflow to irrigation area (D_o)	3.48	3.14

Table 3 Mean annual water balance for the irrigation area, 1999–2002 ($10^8 m^3$).

Inflows and outflows	Wushi	Wensu
Ditch outflow to irrigation area (D_o)	3.48	3.14
Precipitation (P)	0.50	0.50
Channel infiltration in irrigation area (C_{ig})	1.98	3.74
Evaporation from irrigation area (E_i)	2.76	3.18
Drainage (D)	0.19	1.70
Groundwater exchange with non-irrigation area (X)	2.98	2.70
Soil water storage change in irrigation area (ΔS_{is})	0.00	–0.14
Groundwater storage change in irrigation area (ΔS_{ig})	0.04	–0.06

Table 4 shows the water budget for the non-irrigation area in the two sub-areas from 1999 to 2002. It is remarkable that the precipitation over non-irrigation area is much less than the total water losses, i.e. the sum of evaporation from the uncultivated and wasteland. Actually, precipitation accounts for only 14% of the total water supply. The remaining 86% of the water supply comes from channel infiltration (C_{nig}) and groundwater from the irrigation area (X), meaning that the natural ecosystem of arid area relies on the managed agricultural ecosystem for water supply. The data from the 1999 investigation were used in this study to quantify artesian spring outflow, which accounted for half of the groundwater recharge of the non-irrigation area. The storage change is small in Wushi but is a relatively large negative value in the Wensu sub-area, indicating there might be a lowering of the water table in this sub-area. Unfortunately, only one groundwater gauging well with records from 2000 to 2002, was available to validate the water table lowering, and this revealed a mean 18 cm drop during the three years.

Table 4 Mean annual water balance for the non-irrigation area, 1999–2002 (10^8 m^3).

Inflows and outflows	Wushi	Wensu
Precipitation (P)	0.81	0.73
Channel infiltration in non-irrigation area (C_{nig})	0.91	3.24
Groundwater from irrigation area (X)	2.98	2.70
Evaporation from wilding land (E_{wild})	2.40	2.33
Evaporation from wasteland (E_{waste})	0.26	0.32
Artesian spring outflow (S)	2.00	4.34
Storage change in non-irrigation area (ΔS_{ni})	0.05	–0.30

DISCUSSION

Streamflow of the Tuoshigan-Kumalake River decreases along the mainstem with a discharge of 92 × 10^8 m^3 $year^{-1}$ at the upstream boundary and 77 × 10^8 m^3 $year^{-1}$ at the downstream boundary. The dominating hydrological processes involve dispersion of river water to the alluvial plain rather than concentration of runoff in the river channel. Intensive surface water–groundwater interactions and human disturbance confuse our understanding of the hydrological cycle inside the allusive plain and challenge efforts to balance the water budget. Four years of demanding fieldwork were undertaken to investigate the agricultural ecosystem inside the Tuoshigan-Kumalake River plain.

Mean annual evaporation over the irrigation area in two sub-areas comprised 2.76 × 10^8 m^3 and 3.18 × 10^8 m^3 and accounted for only 46 and 43%, respectively, of the water diverted in drainage ditches. This indicates that the local irrigation system is inefficient by using earth ditches on sandy soil with a long length of run and a relatively small stream of water. The ditch losses contribute 7.87 × 10^8 m^3 recharge to groundwater per year and raise the water table. The artesian springs, which originate from the groundwater in the non-irrigation area, are partly recharged by the ditches and the irrigation area and are usually led back into ditch system, which makes 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, were 2.98 × 10^8 m^3 and 2.70 × 10^8 m^3 and accounted for 63 and 40%, respectively, of the non-irrigation area water supply, which indicates that the "surplus" irrigation was transferred to the natural ecosystem through phreatic water. A tight hydrological connection between the agricultural and the natural ecosystem suggests that any human disturbance in irrigation system, such as building large engineering works, might rapidly spread to the surrounding natural ecosystem.

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