Utilization of water resources and its effects on the hydrological environment of the Tarim River basin in Xinjiang, China

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Abstract This paper describes the characteristics of water resources utilization in the Tarim River basin in terms of both its quality and quantity. It is found that the water cycle and water qualities have changed greatly because of human activities in the last 50 years. Many canals have been built to transfer almost all stream waters for irrigation and farmland desalinization. As a result, about 37% of stream waters were $Ca^{2+}HCO_3^-$ type and more than 40% were either Na^+Cl^- type or $Na^+SO_4^{2-}$ type. The former can be found in natural hydrological conditions, while the latter was affected by agriculture activities. The relationships between water use, desertification and salinization are discussed, based on the water table, soil water content and evaporation in the study region. When the groundwater table is 4 m below the surface, evaporation almost stops. Soil moisture will decrease without supply by groundwater. It is therefore possible to cause desertification when the groundwater table is deeper than 4 m in the Tarim basin. Therefore, water resources issues concerning desertification and salinity must be dealt with at the same time with respect to water and mass balances.

Key words China; desertification; ecology; salinization; Tarim River; utilization of water; water resource management

INTRODUCTION

Desertification has become a serious disaster in the world. Water, as a "dynamic driver", controls the whole ecological system. Xinjiang is a typical arid region with annual evaporation ranging from 2000 to 2500 mm, and annual precipitation of 154 mm. The Tarim River is the biggest river that runs through the basin, with the Tianshan Mountains in the north, and Kunlun-Karakorum Mountain in the south (Fig. 1). In the past 50 years, water use in Xinjiang has caused many changes in the natural environment. Increase of farmland changed the vegetation distribution, and unsuitable use of water resources was a serious problem. In Xinjiang, desertification developed quickly in the last 50 years; for instance, the Taklimakan Desert has expanded by 170 km^2 per year, and this has been mainly caused by human activities (Fan, 1996). Also, salinity occurs near farmland since the water table is rising, and desertification occurs along the riverbanks since trees died with water table lowering. Without the protection barrier of trees, farmland was vulnerable to attack by desert invasion.

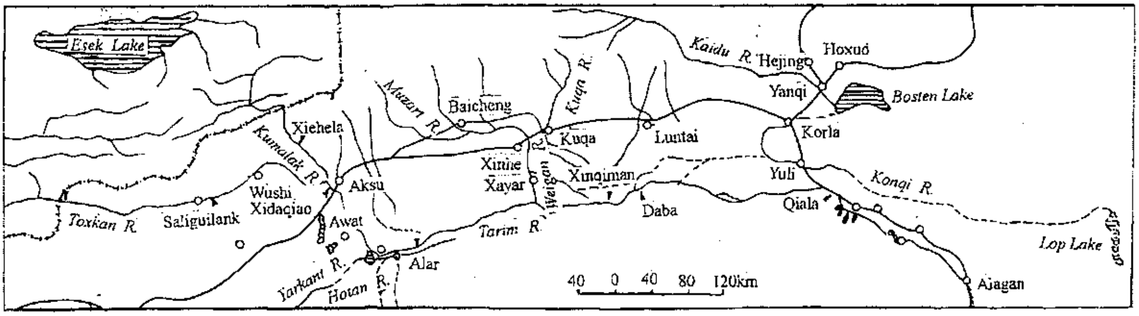

Fig. 1 Sketch map of the Tarim River system.

Many scientists have studied desertification, and the main opinion is that it is caused by over utilization of the land and lack of water (Zhu, 1981; Xia, 1991). In other words, the changes of the natural environment respond very sensitively to water utilization in arid regions. Therefore, in the arid environment, ecology and water distribution processes are strongly linked. In many cases, these processes are irreversible.

WATER USAGE IN THE TARIM RIVER WATERSHED

Surface water is one of important water resources in Xinjiang, and almost all rivers are inland water systems and end in lakes or deserts. There are 89 rivers flowing down from the south slope of the Tianshan Mountains. Except for large rivers that flow into the lakes of deserts, most rivers disappear and infiltrate into groundwater soon after leaving the mountain area. Most of the stream water from the Tarim River has been channelled into the agricultural area for irrigation. The irrigated area there has doubled from 3512 km^2 in 1949 to 7766 km^2 in 1996.

Along with the decrease of runoff in the tributaries, water consumption in the upper reaches and middle reaches of the Tarim River has increased gradually in the last 50 years. In the upper and middle reaches, 92.2% of the river water was used by irrigation, and annual runoff in the lower reaches has reduced from 27.7% of that in the Tarim River in the 1950s to 7.8% in the 1990s.

Annual runoff from tributaries to the main channel has reduced for 25–30 km^3 in the last 50 years; 74.2% of the river water consumed in the tributaries. Irrigation area in the three tributary watersheds is double that of 50 years ago and about 60% of river water is channelled out for irrigation (Fig. 2). Of river water in Yarkant River, one of the tributaries, 92% was channelled for irrigation and water could hardly reach the Tarim River after 1970. Water in the Hotan River can only reach the Tarim River in the flood season.

Runoff in the Tarim River decreased year by year because of the increase of water drawn for irrigation in the tributaries; and runoff at the lower reaches of the Tarim River reduced greatly as the amounts of water consumption in the upper and middle reaches increased. The expansion of new oases established after 1950 mainly depended on the utilization of river water, 70% of the river water in the tributaries of the Tarim River is drawn out for irrigation. For example, much water is channelled to the Alar Area in the upper reaches of the Tarim River every year, and water distributed on the surface increases for 1268 mm $year^{-1}$. However, river water has reduced by 20% in the

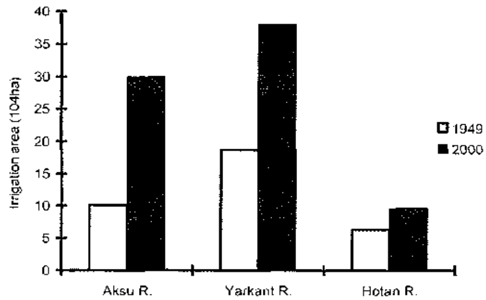

Fig. 2 Increase of the irrigation area at the tributaries of the Tarim River.

upper reaches of the river and about 80% in the lower reaches. Water in the Tarim basin has been redistributed—including surface water and groundwater—it has increased inside the oasis but decreased outside. The water table in the area at the lower reaches has dropped from 2–4 m depth in the 1960s to 8–12 m depth now, and desertification expands year by year because of lack of water.

WATER QUALITY

Mineralization of rivers ranged from 0.5 to 4.46 g l^{-1}, almost five times greater than that in the early 1960s. According to 52 sampling points on streams that come from the south slope of the Tianshan Mountains, it was found that about 37% of water quality was Ca^{2+}-HCO_3^- type. There were more than 40% of waters with either Na^+-Cl^- type or Na^+-SO_4^{2-}. In general, water of the former type was the water of natural streams that flowed down into the Tarim River. The water of the latter type was the waters of streams that flowed out from farmland, the middle-stream and the down-stream of the Tarim River, which showed the effects of agricultural activities on stream water quality. For example, the Cl^- ion concentration of waters disposed from farmland was 10 times higher than that before entering the farmland in the Aksu region.

Electrical conductivity (EC) was less than 230 µm cm^{-1} upstream, and increased downstream. High EC values were found in the streams discharged by the irrigation channels and the lakes at the end of stream. Despite water quality differences among streams, pH values of stream waters were all above 7.5, which means the waters in the research region were controlled by the geological conditions.

In the research region, irrigation water is also used to wash salt out from farmland. Waters with high salt content from farmland flowed back to streams and infiltrated into groundwater. As a result, the shallow groundwater contained higher concentrations of salts as saline water and brackish water. When the water table rose, evaporation and capillary flow brought salts up to the topsoil.

RELATIONSHIP BETWEEN WATER TABLE, EVAPORATION AND SOIL WATER CONTENT

The factors influencing evaporation of soil water include climate, soil character, soil moisture and groundwater table. The equation for evaporation and groundwater table in the Tarim basin has been established experimentally (Wu, 1992):

$$E_g = E_0\left(1 - \frac{H}{H_0}\right)^n \qquad n = 2.51 \pm 0.05 \qquad (1)$$

where E_g is average groundwater evaporation in a day (mm day^{-1}); E_0 is average evaporation from a water surface in a day (mm day^{-1}); H_0 is the average water table depth (m), n is a coefficient. In the area around the oasis and the lower reaches of the river, the water table has declined because of the decrease of surface flow. For instance, the water table in the lower reaches of the Tarim River was 1–1.5 m in the 1950s and 1960s, and it was at 4–12 m depth after 1980 (Table 1). According to the experiment, the evaporation rate for groundwater is 0.1–0.2 if the water table is 1–2 m deep from the ground surface; and evaporation will stop if the water table is deeper than 4 m from the ground surface. Therefore, evaporation in the lower reaches has changed from equalling surface water and precipitation inputs to equalling precipitation only. Annual evaporation in the lower reaches of the Tarim River has decreased from 200–400 mm to 40–50 mm in last 40 years. Water transformations inside the oasis has risen, and has obviously subsided out of the oasis.

Based on the measured soil moisture data at 35 sites in the Tarim basin, the relationship between soil moisture (Y) and groundwater table (H) can be described by the equation:

$$Y = 35.726\ e^{-0.185H} \qquad (2)$$

If the water table is 2.0–2.5 m deep from the ground surface, soil moisture will be 22.5–27.5%, corresponding to 90% of the saturation. If the water table is 6.0–10.0 m deep from the surface, soil moisture will be 8.7%. Vegetation water use at less than 10% soil moisture is very low. When the groundwater table is below 4 m depth from

Table 1 Change of groundwater table at Tarim River basin.

Year	Upper reaches	Middle reaches	Lower reaches
1950–1960s	3–6		1.0–5.0
1970s			2.9–7.9
1980s	5–7.2	3.4–4.5	4.0–12
1990s		1.7–3.5	8.0–12.7

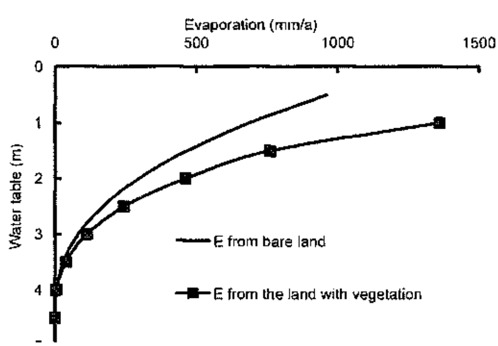

Fig. 3 Soil moisture evaporation for different water table in Tarim River basin.

the ground surface, evaporation almost stops (Fig. 3). Soil moisture contents will decrease without supply by groundwater. So it is possible to cause desertification when the groundwater table is deeper than 4 m in the Tarim basin.

THE EFFECTS OF WATER USAGE ON DESERTIFICATION

Desertification is closely related to water distribution along the river. Desertification in the Tarim basin was mainly caused by the moving of the river course hundreds of years ago with the river course moving around 80–100 km, and the zone near the old river bed became desert because of the lack of water. When runoff in the tributaries of the Tarim River had reduced, water consumption in the upper reaches and middle reaches of the Tarim River increased. For instance, the percentage of water consumption in the upper reaches was 14.77% of the whole river in the 1960s, and it was 23.0% in 1994. In the same period, the percentage of water consumption in the middle reaches increased from 61.54% to 72.56%. However, in the lower reaches, the percentage of water consumption was only 4.44% in 1994 (Fig. 4), and the desertification area in the lower reaches expanded year by year in the lower reaches. Some areas beside the river in the lower reaches became desert because of the destruction of vegetation and the decline of the groundwater table. From 1957 to 1996, annual runoff at Qiala reduced from 1.46 km^3 to 0.194 km^3. The stream dried up below Alagan after 1972; sand dune movement has increased by 20% there, and the sand area has expanded 116 km^2 by since 1959, and desertification became serious.

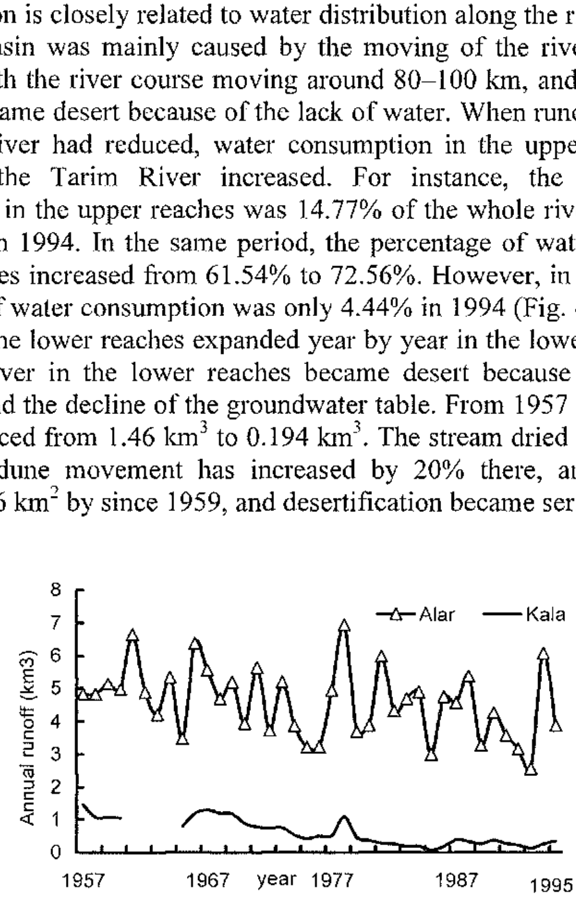

Fig. 4 Annual runoff at the upper reaches (Alar) and lower reaches (Kala) of Tarim River.

Table 2 Desertification area around Yingbaza (the middle reaches) and Alagan (the lower reaches).

Place	Year	Excessive desertification		Intensive desertification		Medium desertification		Light desertification		Total area of desertification	
		(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)
Yingbaza	1960	15.57	1.13	46.65	3.00	181.14	11.66	672.27	43.28	917.36	59.07
	1983	100.89	6.49	102.74	6.61	223.80	14.73	632.84	40.74	1065.27	68.58
	1992	114.56	7.37	116.55	7.50	227.90	14.67	522.44	33.63	981.45	63.18
Alagan	1959	476.15	30.20	95.78	6.08	393.2	24.96	405.87	25.74	1371.22	86.98
	1983	497.63	34.58	96.58	6.13	454.95	28.86	411.13	26.08	1460.29	92.63
	1992	532.24	33.76	145.01	9.20	438.01	27.78	372.00	23.60	1487.26	94.34

The Yingbaza area (84°00′–84°30′E, 41°00′–41°20′N, 1554 km^2) is typical of the flood plain in the middle reaches of the Tarim River; vegetation was good with the dense water system there. Desertification area had expanded from 917.63 km^2 in 1960 to 1065.27 km^2 in 1983, and had decreased to 981.45 km^2 in 1992 (Table 2).

As a result, desertification at the lower reaches developed more rapidly because the expansion of irrigated farmland has caused imbalances between the water cycle, salt movement and ecological environment in the Tarim basin.

ECOLOGICAL ENVIRONMENTAL CHANGE EFFECTS DUE TO HYDROLOGICAL CONDITIONS

Water resources distributions in the Tarim basin have changed greatly in space and time due to human activities. Within the oasis, the groundwater table has risen because of over irrigation; but it has dropped elsewhere. There was much forest beside the Tarim River. Along with the decrease of river water, groundwater has declined, and vegetation has degenerated; finally desertification appears. The area of poplar (*Populus diversifolia*) forest reduced by 74.8% from the 1950s to the 1970s. In the area below Alagan, in the lower reaches of the Tarim River, the groundwater table has dropped to 8–10 m deep from the ground surface, and salt content in groundwater reached 6.9–15.3 g l^{-1}. Most of the original vegetation is dead so that desertification occurred and the river bed is now covered by sand (Table 3).

Because of the low precipitation, water required for natural plant growth is supplied only by groundwater in the Tarim basin. Tamarisk and other trees or bushes grow well with the water table at 1–4 m, they grow quite well with a 4–6 m deep water table, grow relatively poorly with a 7–10 m deep water table, and die if the water table is below 10 m depth from the ground surface. A suitable water table depth for herb growth is 1.5–3.5 m, it grows quite well with a 3.5–4.5 m water table depth, grows relative poorly with a 5–6 m water table depth, and dies with the water table below 7 m. Tamarisk and *Populus diversifolia* have a relatively strong salt tolerance.

Since agriculture activities use much river water in oases for agriculture productions, the water table decreased in sediment fan outside the oases. Comparing with 1958, trees and grasslands in areas of the middle stream and downstream along the Tarim River has decreased by about 16% and 77%, respectively.

The vegetation and forest on the banks of the Tarim River make strong defences against wind erosion and protect the moisture distribution in the oasis. Since the water had been diverted at the upper branches zone, the river could not cope with the changed situation. With decreases of trees and bushes, desert area expanded and some oases have been attacked by mobile sand dunes. The environmental changes caused by

Table 3 Relationship between the growth of natural vegetation and groundwater table depth.

Vegetation type	Suitable range:		Extreme range:	
	Water table (m)	Salt content (g l^{-1})	Water table (m)	Salt content (g l^{-1})
Populus diversifolia	1.0–5.0	0.5–3.0	10.0	5.0
Red willow and frutex	1.0–6.4	0.5–5.0	10.0	10.0
Reed and bosk	<2.0	0.5–3.5	5.0	10.0

desertification are mainly manifested by the occurrence and growth of landscape similar to desert-like environment on the aboriginal non-desert regions or steppe. In the aboriginal vegetated dune areas, the acceleration and encroachment of mobile sands characterize desertification.

CONCLUSIONS

In order to maintain a good ecological balance, how to rationally utilize water resources is the key to solving the problems in arid and semiarid regions. In fact, agriculture activities cause the spatial and time redistribution of water, then change the ecological environment. The ecological environment in arid and semiarid region is very sensitive to hydrological conditions. The current situation and problems of the ecological environment of the study area were determined by natural factors while the change processes were intensified by human activities. The results shown here hint that the effects of human activities on the environment usually result from unsuitable water use. In other words, since available water in arid regions is very limited, redistribution of water in space and time means a change in the hydrological state and action style of water on the environment.

It is necessary to deal with ecohydrological issues including water use, salinity and desertification at the same time. Vegetation growth in the Tarim basin depends on groundwater and desertification is difficult to expand where vegetation grows well. Maintaining a suitable water table depth is the best way to prevent desertification. A suitable water table in the Tarim basin is 2–4 m deep, so that evaporation is not too much and vegetation can grow well to prevent soil erosion and desertification.

In the upper reaches, channelled water for irrigation should be controlled to allow more river water flow down to the lower reaches of the Tarim River. It is possible to prevent desertification by keeping suitable soil moisture and controlling the groundwater table at no deeper than 4 m.

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