Effects of drip irrigation on components of water cycle in arid inland areas: A case study of Manas river basin in northwestern China

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Abstract: Compared to either drip irrigation or mulching with plastic film, the two methods together can reduce water requirements of crops grown in arid areas by more than 30%. Such a combination deployed on a large scale (1) reduced the loss of soil water by 31.8% compared to that from drip irrigation alone; (2) narrowed the range of annual evapotranspiration from 1582.4-1780.3 mm, which is average for the basin, to 222.2-294.8 mm; and (3) increased the overall humidity in the central plain of the basin. However, the surrounding regions in which drip irrigation is not combined with mulching are getting more arid; thus, as a result of the water-saving technology, both oases and the desertification of the river basin are increasing at the same time. The results of the study further the understanding of the effects of drip irrigation combined with mulching on water cycles in the basin of the Manas river and suggest ways to protect the ecology and the environment of the basin.

Keywords: evapotranspiration, drip irrigation, arid inland areas, water cycle, Mann-Kendall rank test, MOD16, Manas river basin

DOI: 10.25165/j.ijabe.20191201.4031

Citation: Li P F, Yang G, He X L, Li F D, Yan K , Wang Z L. Effects of drip irrigation on components of water cycle in arid inland areas: A case study of Manas river basin in northwestern China. Int J Agric & Biol Eng, 2019; 12(1): 132–138.

1 Introduction

With the rapid development of the global economy and continued social progress, problems related to water resources such as water shortages, water pollution, overexploitation of groundwater, and secondary salinization have become increasingly serious, and the gap between the supply of and the demand for water has gradually widened. Water resources have become a limiting factor in the socio-economic development of many countries in the world and, since the 1990s, have been attracting increasing attention. Many international organizations have studied the effects of environmental changes on the water cycle and water resources and the related environmental issues on different spatial scales and using interdisciplinary approaches and have proposed and implemented a series of international collaborative projects and research programmes in hydrological sciences. These include the International Hydrological Programme (IHP), International Geosphere-Biosphere Programme (IGBP), Intergovernmental Panel on Climate Change (IPCC), World Climate Research Programme (WCRP), and Global Water System Programme (GWSP)[1].

The main component of water and energy balance in a water cycle is evapotranspiration, which guides the rational use of water resources[2-5]. In 1802, the British physicist and chemist Dalton proposed the law of evaporation, which deals with the rate of evaporation from the surface of the evaporating liquid and the factors that affect evaporation, and laid the foundation of the modern evaporation theory. The classic method of calculating potential evapotranspiration is the Penman–Monteith formula[6], a semi-empirical semi-theoretical formula for calculating evapotranspiration, as revised by the FAO (the Food and Agriculture Organization) through experimental data. Because of the spatial variability of surface conditions, the traditional methods of calculating regional evapotranspiration and scaling it over larger areas are not fully satisfactory, and accurate calculation of regional evaporation has always been a major scientific problem[7,8]. A great deal of research work has been conducted in China on water cycle as affected by the changing environment: Wang et al.[9] used the WEP-L model to study, in quantitative terms, the relationship between human activity and the evolution of water resources of the Yellow River; Sang et al.[10] developed and improved the SWAT model of irrigation and artificial water consumption modules to simulate the strong water cycle in the Tianjin water cycle; Ma[11] evaluated, also in quantitative terms, the relationship between climate change and human activity, the development and use of water and soil resources, and the reduction in run-off from the watershed; and Liu et al.[12] constructed a multi-objective regulation model of water supply and demand for a comprehensive evaluation of ecological, environmental, and economic factors related to the development and use of water resources of the basin. These scholars have analysed and simulated the water cycle taking into account changes in the environment due to climate change and

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Received date: 2018-04-19 **Accepted date:** 2019-01-05

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due to human activity. However, areas with strong human activity, especially the farmlands and the water cycle in such areas, including quantitative analysis of the conversion characteristics of four sources of water, namely precipitation, surface water, soil water, and groundwater have received limited attention. The technology of irrigation in the Manas river basin in the present study passed through four stages: river diversion, canal irrigation, canal irrigation supplemented with well irrigation, and drip irrigation together with mulching using plastic film. The area under drip irrigation accounted for more than 94% of the total irrigated area. The technology of drip irrigation in the watershed has greatly improved the utilization efficiency of water resources, changing some of the components of the water cycle in the basin. In particular, drip irrigation has affected the infiltration and movement of water in the soil and evapotranspiration from the cultivated area; these, in turn, have affected the recharge of groundwater, resulting in the declining levels of groundwater and partial degradation of desert vegetation downstream. The present paper selected the Manas river basin, the birthplace of drip irrigation technology in north-western China, for examining, through statistical analysis of data from remote sensing and outdoor experiments, the effects of drip irrigation, as affected by rainfall, evapotranspiration, and infiltration, on the regularity of the components of water cycle in the basin. The results provide a theoretical basis for the study of water cycle in the Manas river basin under the changing environment.

2 Data sources and research methods

2.1 Precipitation and run-off

Data on run-off for the Manas river basin were obtained from the Xinjiang Statistical Yearbook and subjected to Mann–Kendall non-parametric statistical tests (run-off from 1955 to 2015); data on precipitation in the basin were based on the data from the Ken Swat hydrological station and subjected to the Mann–Kendall rank test; and variations in precipitation and run-off were estimated based on changes in temperature.

2.2 Evapotranspiration

Data sets on actual evapotranspiration (ETa) and potential evapotranspiration (ETp) in the Manas river basin from 2000 to 2014 were obtained through general image processing of MOD16 evapotranspiration products after verifying the accuracy of different scales. By 2000, drip irrigation had been a popular and accepted technology. The data included annual evapotranspiration, typical monthly evapotranspiration during the year, and monthly evapotranspiration in 2000, 2005, 2010 and 2014. The temporal and spatial distribution of evapotranspiration in the Manas river basin as affected by drip irrigation was analysed.

2.3 Soil infiltration

Data on infiltration of water into the soil for the watershed were obtained through outdoor measurements at the research station in the middle reaches of the Manas river oasis irrigated by water from the river. Soil moisture and temperature were monitored, at 60 min intervals, by sensors (EM50 data logger, Decagon, Pullman, Washington, USA) buried at depths of 30 cm, 50 cm, 70 cm, and 100 cm.

3 Utilization of soil and water resources under water-saving technologies

3.1 Overview of the Manas river basin

The Manas river basin (Figure 1) lies at the centre of the northern foot of the Tianshan Mountain, Xinjiang. The total area of the basin is 34 050 km^2. The basin, being away from the ocean, has a dry climate, and is part of the temperate continental arid zone[13,14]. The average annual precipitation is 115-200 mm and the average annual evaporation is 1500-2100 mm. The total basin is divided, from the south to the north, into three major geomorphological units, namely the mountains, the plains, and the desert (the ratio is about 2.08 : 1: 1.07)[15]. The basin is the result of orogeny and the subsequent evolution of the water system[16,17]. In 1949, the irrigation quota was 12 000-15 000 m^3/hm^2 (800-1000 m^3/mu, mu being a Chinese unit of area, equal to about 1/15th of a hectare) and the water-use coefficient of the canal water was only 0.3; In 1977, because of seepage, the quota was down to

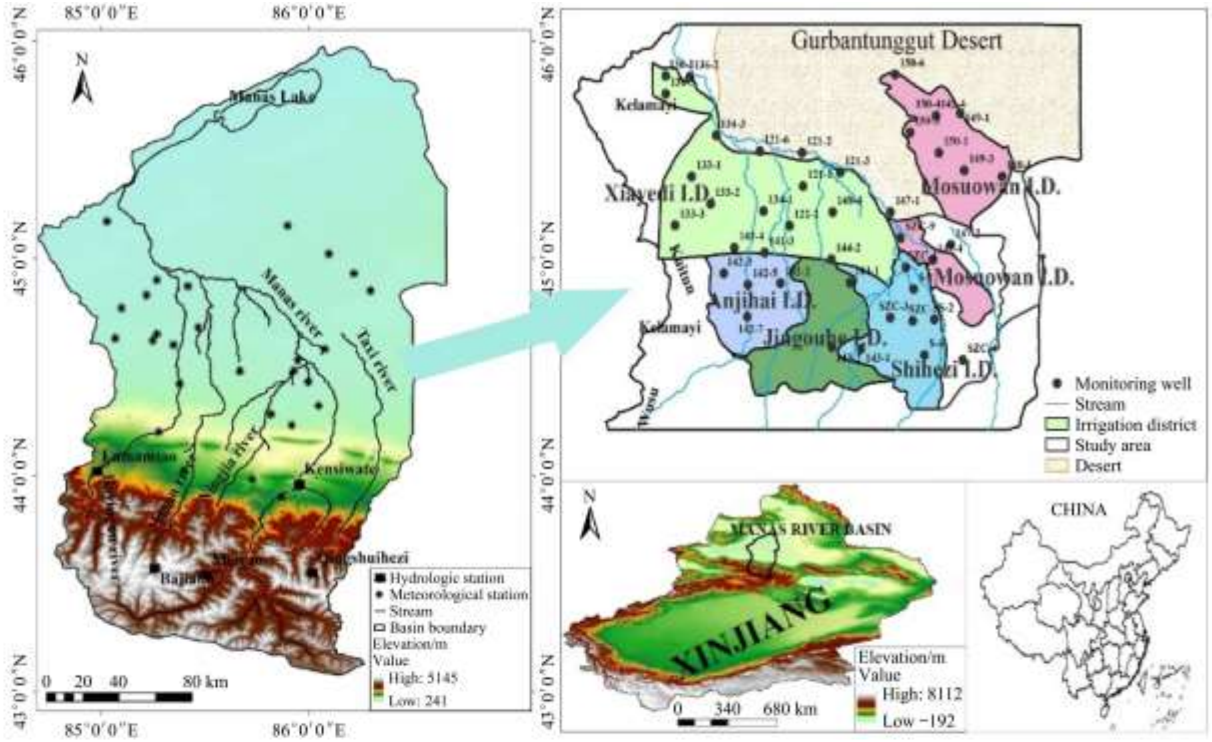

Figure 1 Manas river basin

6000-9000 m^3/hm^2; since 1999, following widespread use of drip irrigation combined with mulching with plastic film, the quota has been lowered to 5250-6000 m^3/hm^2. Obviously, water and land in the basin are being used more efficiently. Although irrigation accounts for a large proportion of water in the Manas river basin, waste of irrigation water is particularly serious and needs to be checked; promoting water-saving technologies will greatly ease the water shortage.

3.2 Development and utilization of water resources

3.2.1 Surface water

The central region of the northern slopes of the Tianshan Mountains is the origin of five rivers, namely Tahsi, Manas, Golden, Ning, and Bayinou. The middle part of the northern slope of Tianshan Mountains is connected with the Haber Gahe Mountain Range (5242.5 m), and together they are served by a total of 800 rivers[18]. The average annual run-off from the Manas river basin is about 2.076 billion m^3, 64.2% of which is from the Manas river. At present, the basin uses up to nearly 2 billion cubic metres of surface water annually, accounting for 95.6% of the available surface water, and has become one of the regions with the highest utilization of water resources in Xinjiang. Although the proportion of irrigation water has been maintained at above 94% for many years, it needs to be used more efficiently.

3.2.2 Changes in canal system

The irrigation system was built in the 1950s and comprises the main trunk canal, Anjihai main canal, Mosuo Bay trunk canal, Shacan canal, West Bank trunk canal, and Shihezi main trunk canal. The network was the fastest growing system from 1976 to 1997: its length increased by 0.89 times during the period. After 1999, with large-scale promotion of water-saving technologies, a large number of farm ditches were filled up and the canals were shortened to about 70% of the original length between 1997 and 2013 (Figure 2).

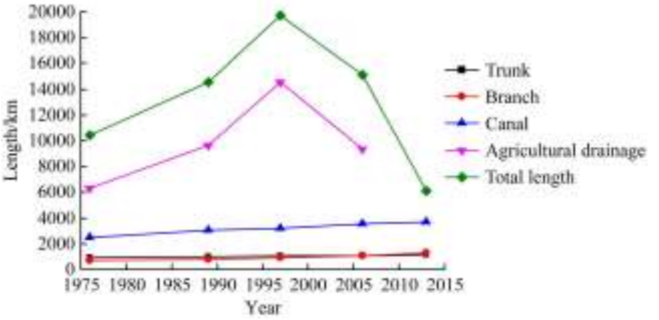

Figure 2 Length of artificial canal system in Manas river basin

3.2.3 Groundwater resources

Currently, groundwater in the Manas river basin is exploited at the rate of nearly 70%, and groundwater extraction has risen from 47% in 1984 to 61% at present. Water-saving irrigation technologies also have an impact on groundwater[19-21] and, since 1999, have been deployed over a large area; as a result, the amount of groundwater released for irrigation has decreased-which has led to greater exploitation of groundwater year by year. Inevitably, given the overexploitation and severe evaporation, the water table in the region has been receding steadily.

As shown in Figure 3, in the late 1990s, the depth of the water table (as the average value at 148 points) in the Manas river basin was 1.6-2.2 m. Due to the influence of irrigation and recharge, the level fell significantly over the years and was about 2.7 m in 2008, and has stabilized at that level since. The application of water-saving technologies has led to a decrease in the amount of irrigation water supplied, continued lowering of the water table, and narrowing of the range of water table. The average depth of the water table in 10 years increased by 26.4%, from 2.2 m in 1999 to 2.7 m in 2008.

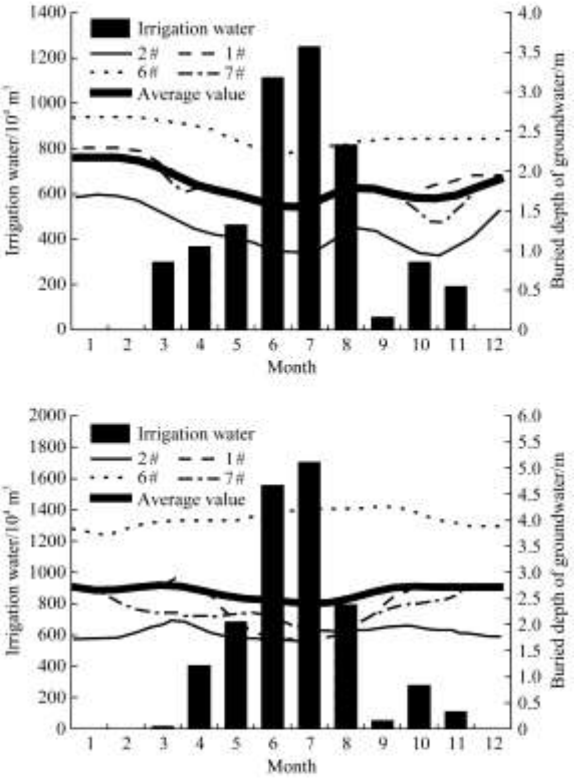

Figure 3 Relationship between groundwater levels and extent of irrigation with water-saving techniques (1999 and 2008)

3.3 Development and utilization of land

Prior to the promotion of water-saving irrigation technologies in the Manas river basin, the irrigated area showed a slight increase in fluctuation. In 1949, in the early days of the founding of the People's Republic of China, the irrigated area was roughly 24 735 hm^2 (371 000 mu). Until the introduction of water-saving irrigation technologies in 1999, the irrigated watershed was approximately 154 533 hm^2 (2 318 000 mu) with an average annual increase of approximately 2533 hm^2 (38 000 mu); from 1999 to 2015, the irrigated area increased by about 6265 hm^2 (94 000 mu) annually, representing a 1.47 times increase in the rate of growth, and a change from slight fluctuations to a sharp increase. From that time up to 2015, the cultivated area increased by 10 million hm^2 (150 million mu). Changes in the extent of irrigated areas in the Manas river basin are shown in Figure 4.

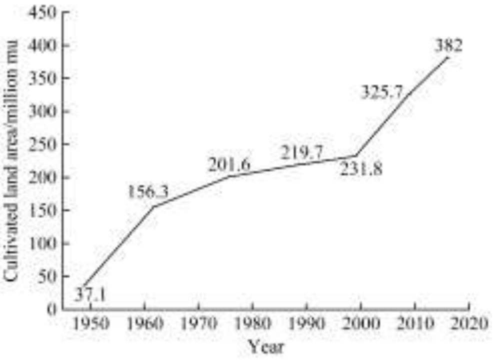

Figure 4 Changes in extent of irrigated area following introduction of water-saving irrigation technologies in Manas river basin (1949, 1999, and 2015)

4 Factors influencing water cycle in areas with water-saving methods of irrigation

Although water-saving measures in the Manas river led to more efficient use of water, they also disturbed the natural water cycle of the basin. Drip irrigation, in particular, changed the rate of infiltration of water into farmland soil, and mulching affected evapotranspiration in the oases of the basin. As a result of global warming, the climate of the Manas river basin has changed significantly, the change being more obvious in mountainous areas. Among the climatic factors, temperature and rainfall are critical to the water cycle and have affected the water cycle of the river basin directly.

4.1 Precipitation and run-off

With reference to precipitation and run-off in Manas river basin (Figure 5), a year can be divided into two periods, namely January-July and August-December. Over the first seven months, the temperature increases gradually; as a result, river run-off also increases gradually because of snowmelt and rainfall. Over the next five months, the temperature decreases gradually, and so do precipitation and run-off. High temperatures in summer, especially from June to August, lead to larger quantities of snow melting from the glacier and, together with higher precipitation, increase the run-off, which, in those months, accounts for 66.9%-70.3% of the total annual run-off. Maximum precipitation is received in May; however, the run-off is small, mainly because temperatures are not high enough for the snow to melt. Thus, temperature is particularly critical and, together with precipitation, governs the run-off from the Manas river[22,23].

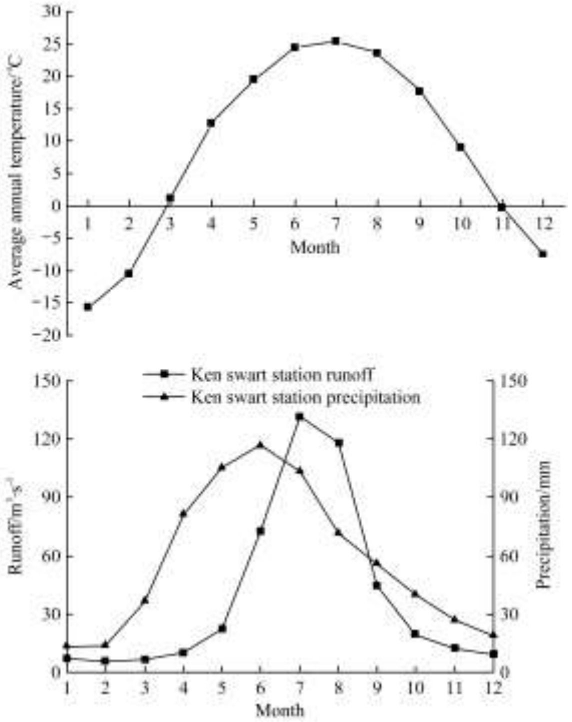

Figure 5 Monthly temperature, precipitation, and run-off in Manas river basin

Over 60 years (1955-2015), precipitation in the Manas river basin increased by 7.04 mm every decade, the increase being 11.02 mm for the summer months and 5.64 mm for the winter months. This increased precipitation during spring and summer is of great significance to the oases in the river basin because it helps crops to grow in areas affected by spring drought, and in reclaimed areas[24,25]. Annual precipitation at the Kendwawe Hydrological Station increased initially and then decreased from 1955 to 1965 and witnessed large fluctuations from 1966 to 1977, again an increase followed by a decrease[26], a pattern consistent with the trend for temperature in the basin. The Mann–Kendall rank test found that 1997 was the year of sudden change in precipitation in the Manas river basin when the accumulated anomalies in precipitation from 1955 to 2015 were analysed by the cumulative distance method.

In recent years, run-off from the Manas river basin has been increasing year by year, and the increase is closely related to the increase in temperature caused by climate change[27,28]. According to the Mann–Kendall test curve for annual run-off from the Manas river, the run-off increased annually from 1990 to 1990 with an abrupt change in 1995, crossing the point critical to the region. However, the increase is not significant. Since 2000, annual run-off has been increasing significantly. It can be seen from Figure 6 that, as the temperature changes, so does the amount of snowmelt and rainfall, resulting in a slight delay in the pattern of run-off. However, the trend in inter-annual variation in run-off coincides broadly with that of temperature.

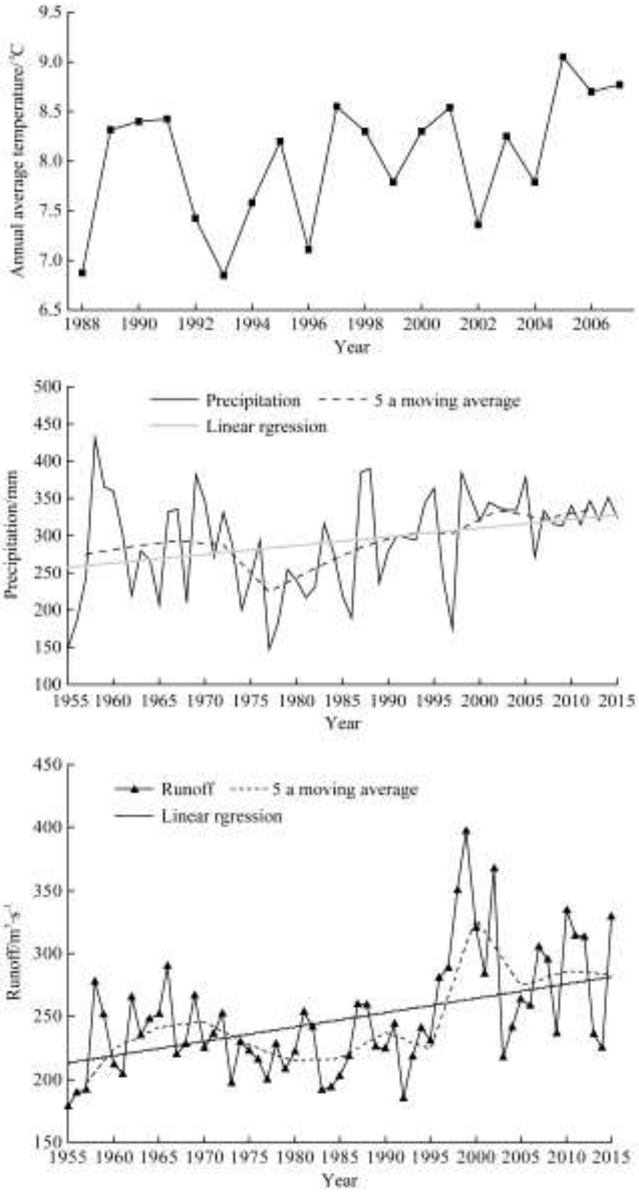

Figure 6 Annual variation in temperature, precipitation, and run-off in the Manas river

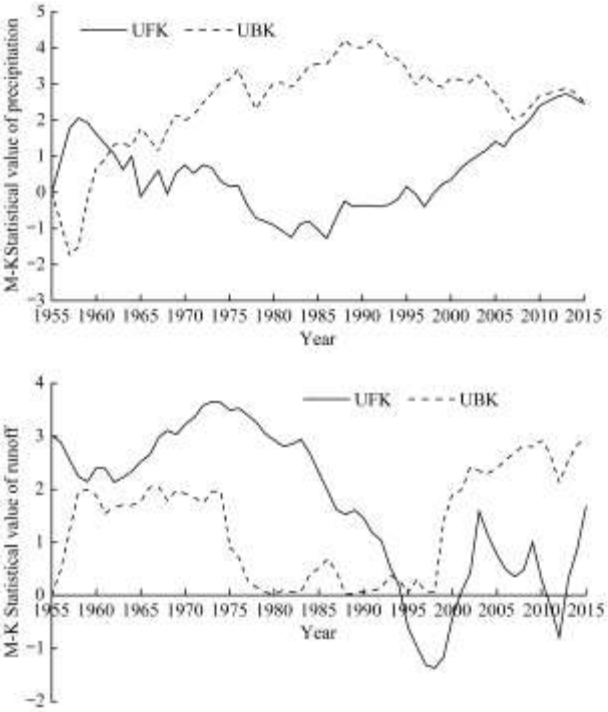

Figure 7 Mann-Kendall curves of annual precipitation and run-off in Manas river

4.2 Evapotranspiration

During the 15 years since the water-saving technology was popularized in the Manas river basin, both actual and potential evapotranspiration have been fluctuating: the actual (ETa), from 222.2 mm (in 2008) to 294.8 mm (in 2013), and the potential (ETp), from 1582.4 mm (in 2003) to 1780.3 mm (in 2008). However, ETa is more uniformly distributed than ETp. The pattern of actual evapotranspiration in the Manas river basin deviated from the normal in 2000, 2005, 2010 and 2014 (Figure 8) In these years, the actual evapotranspiration was lower in April and October and peaked in July and August (approximately 38% of the total ETa for the year occurs from May to August).

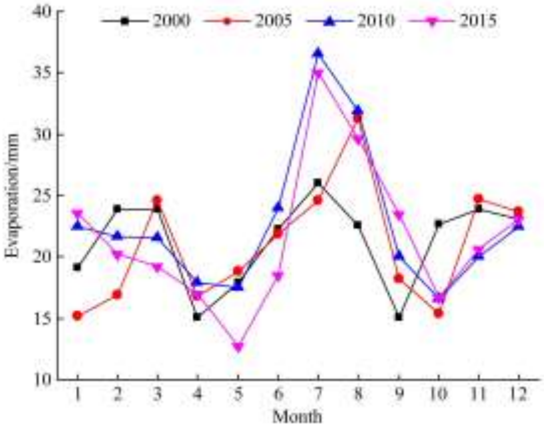

Figure 8 Monthly actual evaporation in Manas river basin in 2000, 2005, 2010 and 2014

The monthly average ETp for 2000, 2005, 2010 and 2014 was also analysed, and spatio-temporal variations in the ETp during the years were obtained. The curve traced an inverted ‘U’ (Figure 9): the values increased initially and then decreased. In January, February, November, and December, the ETp was 20-80 mm; March and April showed a rapid increase; September and October showed a rapid decrease; and from May to August, the value was 200-240 mm. Thus ETp is greatly influenced by the season and is very unevenly distribution during the year. However, ETp is similar to ETa in that about 35% of the total ETp for the year also occurs from May to August (for ETa, the share is 38%). In the central plains of the basin, ETp shows a decreasing trend, because the region is more humid and the area under oases continues to increase, whereas in the other regions, ETp shows an increasing trend, because droughts now occur more frequently in these areas and the area under oases continues to decrease.

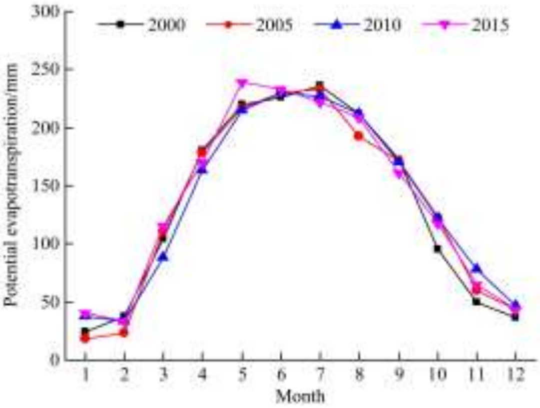

Figure 9 Monthly potential evapotranspiration (ETp) in Manas river basin in 2000, 2005, 2010 and 2014

4.3 Infiltration of water into soil

Water-saving technologies began to be popular in the late 1990s and, after 2000, the area using these technologies expanded rapidly in Xinjiang. The Manas river basin made particularly significant progress and led not only Xinjiang but also the entire country[29-31]. Compared to open irrigation and no mulch, drip irrigation maintains higher levels of moisture in surface soil but the levels in the deeper layers (70 cm or deeper) are low, which is the zone often occupied by the root systems of many crops. Water-saving technology also slows down the evaporation of soil moisture significantly because the moisture-rich top layer serves as an insulating layer, and thus soil moisture is retained longer.

Table 1 Moisture content of soil at different depths with and without mulching

Depth /cm	Film mulching			Natural conditions		
	15 July	15 Aug.	15 Sept.	15 July	15 Aug.	15 Sept.
30	0.238	0.224	0.219	0.148	0.140	0.162
50	0.202	0.184	0.176	0.162	0.167	0.175
70	0.176	0.165	0.158	0.151	0.148	0.143
100	0.196	0.182	0.176	0.172	0.148	0.148

The water-saving measures result in the formation of a relatively independent water circulation system in soil, which prevents the movement of water beyond that system, and thus leads to significant differences in the distribution of soil moisture and in its status, compared to the conditions before the introduction of such techniques. By comparing the data on evaporation before and after, we plotted its values on the scale of a site. It can be seen from Figure 10 that the trend of evaporation before the introduction of water-saving techniques is similar to that after it, but evaporation from soil before the introduction of those techniques is markedly greater than that after it. Water-saving measures were effective in reducing the loss of soil water by 31.8%. These measures can reduce transpiration in the seedling stage, reduce the loss of soil moisture, and meet the water requirements of crops during their growth.

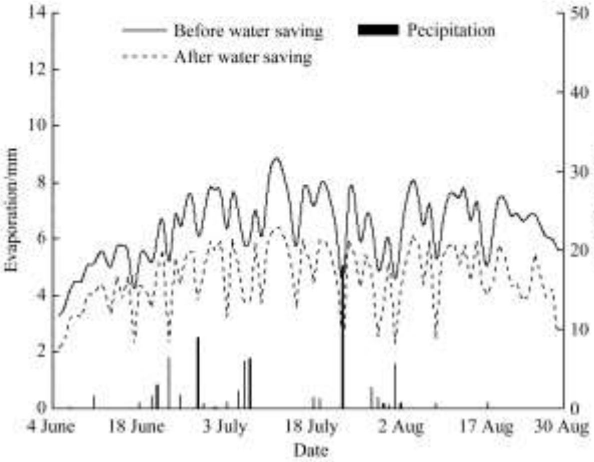

Figure 10　Evaporation of soil moisture from covered land and from bare land before and after water-saving techniques

5　Discussion

After 2000, by which time water-saving technology had been adopted on a large scale and the irrigated area had also increased rapidly, the pattern of water circulation in the basin changed substantially. Since 2000, both precipitation and run-off have been increasing annually, and significantly so in recent years. However, promoting the water-saving technologies has had little effect on precipitation and run-off. Water resources in oases are highly dependent on infiltration of surface water into soil, which is the main source of water for plants. Although water-saving technologies promote the development of agriculture in oases, the technologies also reduce infiltration[32,33]. The decrease in soil infiltration contributes greatly to the decline in the level of the water table, leading to overall degradation of vegetation, soil and ecology. The ultimate result is the decrease in the area under natural oases, as was also reported by Schmidt[34] with reference to the Atlas Mountains region and by Potchter[35] with reference to the oases in the Arava valley in southern Israel. Both the researchers believe that irrigation affects many natural processes such as infiltration, resulting in decreased extent of natural oases and the oasis effect. As a result of widespread use of water conservation methods, the range of inter-annual variation in both actual and potential evapotranspiration over the 15 years (taken into account in the present study) has been fluctuating, and both ETa and ETp showed a close negative correlation to inter-annual variation. This result is consistent with the law of ‘evaporation complementation’ proposed by such experts as Wei et al.[36], Cong et al.[37], Han et al.[38] and Lou et al.[39]. From 2000 to 2014, when water-saving technologies were being promoted, ETp showed a decreasing trend in the central plains and an increasing trend in the other areas, indicating that the central plains of the Manas river basin were getting wetter and wetter than the other parts of the basin, which showed increasingly frequent droughts. At the same time, the area under oases increased in the central plains but decreased elsewhere, as was also reported by Chehbouni et al.[40] and Goodrich et al.[41] in the Pedro basin in Mexico based on their analysis of the changes in the oases and their evolution.

6　Conclusions

Large-scale deployment of water-saving technologies has affected the water cycle in the Manas river basin. These technologies have changed (1) the extent of evapotranspiration from farmland soils in the basin, (2) the earlier pattern of distribution of water in those lands, (3) the original course of run-off, and (4) the distribution and movement of water. Simulations based on data from outdoor experiments and remote sensing to determine the impact of water-saving technologies on the components of the water cycle of the basin led to the following main conclusions.

(1) As a result of promoting water-saving technologies, the irrigated area of the river basin increased rapidly, thus promoting effective development of the regional economy. With large-scale application of water-saving technologies in the basin, the cultivated area increased by 0.1 million hm^2 (1.5 million mu) during 2000-2015 and the average annual rate of growth increased by 1.5 times compared to the rate before the adoption of the water-saving technologies. The rate of utilization of surface water resources reached 95.6%, and that of groundwater exploitation reached nearly 70%. The length of the canal system has gradually decreased, and the rate of utilization of water resources has continued to increase, encouraging the switch from traditional agriculture to water-saving agriculture in the basin.

(2) Although water-saving measures impede the infiltration of water into soil, they effectively reduced the loss of soil water by 31.8% in the present study.

(3) From 2000 to 2014, actual evapotranspiration in the basin increased in the central plains but decreased in the other areas of the basin; potential evapotranspiration, on the other hand, decreased in the central plains and increased in the other areas. The extent of both oases and deserts increased.

Acknowledgements

We acknowledge National Key Development Program (2017YFC0404304), the Natural Science Funds (U1803244, 41601579), Programs of Xinjiang Production& Construction Corps (2018CB023, 2018AB027, 2016AG014), Excellent Youth Teachers Program of Xinjiang Production & Construction Corps (CZ027204) and Youth Innovative Talents Program of Shihezi University (CXRC201801).

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