The Regulation and Management of Water Resources in Groundwater Over-extraction Area based on ET

fawen li (lifawen@tju.edu.cn)
Tianjin university
Wenhui Yan
Tianjin University
Yong Zhao
China Institute of Water Resource and Hydro-power Research, Beijing
Rengui Jiang
Xi'an University of Technology

Research Article

Keywords: Blue water, Green water, Evapotranspiration, ET management, Groundwater over-extraction

Posted Date: May 27th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-547398/v1

Version of Record: A version of this preprint was published at Theoretical and Applied Climatology on July 19th, 2021. See the published version at https://doi.org/10.1007/s00704-021-03713-x.

The regulation and management of water resources in groundwater over-extraction area based on ET

Fawen Li[1], Wenhui Yan[1], Yong Zhao[2], Rengui Jiang[3]

(1. State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, PR China; 2. State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resource and Hydro-power Research, Beijing 100038, PR China; 3. State Key Laboratory of Eco-hydrologic Engineering in Northwest in the Arid Area, Xi'an University of Technology, Xi'an, Shanxi 710048, China)

Abstract： Because of the shortage of water resources, the phenomenon of groundwater over-extraction is widespread in many parts of the world, which has become a hot issue to be solved. The traditional idea of water resources management only considering blue water (stream flow) can't meet the demand of sustainable utilization of water resources. Blue water accounts for less than 40% of total rainfall, while green water (evapotranspiration) accounts for more than 60% of total rainfall. In the natural environment, vegetation growth mainly depends on green water, which is often neglected. Obviously, the traditional water resources management without considering green water has obvious deficiencies, which can't really reflect the regional water consumption situation in the water resources management. And only by limiting water consumption can achieve the real water saving. In addition, the mode of water resources development and utilization has changed from "supply according to demand" to "demand according to supply". In this background, for many regions with limited water resources, it is impossible to rely on excessive water intake for development, and sustainable development of regional can only be realized by truly controlling water demand. This paper chooses Shijin Irrigation District in the North China Plain as the research area, where agricultural water consumption is high and groundwater over-extraction is serious, and ecological environment is bad. In order to alleviate this situation, comprehensive regulation of water resources based ET is necessary. Therefore, this paper focuses on the concept of ET water resources management and includes green water into water resources assessment. Based on the principle of water balance, the target ET value of crops in the study area is calculated, and the ET value is taken as the target of water resources regulation. The actual water consumption is calculated by Penman-Monteith formula, and reduction of crop water consumption is obtained according to the difference between actual ET and target ET. The reduction in crop water consumption leads to a reduction in demand for water supply, which reduces groundwater extraction. The results of this study can provide necessary technical support for solving the problem of groundwater over-extraction and realizing real water saving.

Keywords: Blue water; Green water; Evapotranspiration; ET management; Groundwater over-extraction

The corresponding author:

Fawen Li, Email: lifawen@tju.edu.cn; Yong Zhao, Email: zhaoyong@iwhr.com

1 Introduction

Under the background of global water shortage, to realize the sustainable utilization of water resources, some new ideas were put forward to manage water resources. Falkenmark proposed to divide precipitation into blue water and green water in 1995. Blue water and green water resources participate in the operation of environment and ecosystem as well as social production, affecting the storage of groundwater resources and food production, especially in arid and semi-arid areas with water shortage. The use of blue and green water for water resource management is to comprehensively consider the water balance among land, water and ecosystem, and solve the conflict between future food production demand and ecosystem balance (Falkenmark et al. 2004). However, the traditional water resource management only considers the surface water and groundwater, that is, blue water, and ignores the green water resources that support rain-fed agriculture and maintain the balance of land ecosystem. The annual flow of green water on the earth's surface is about 72500km^3 / year, accounting for 63.88% of the annual flow of water resources (Falkenmark et al., 2004). Green water (evapotranspiration ET) as water consumption, it is more reasonable and comprehensive to introduce green water into water resource evaluation and management. On the one hand, evapotranspiration directly affects the process of runoff generation and concentration by changing the composition of water in different water sub-systems, and then affects the redistribution of precipitation on the land surface; On the other hand, evapotranspiration affects the regional ecological water condition by affecting the distribution of soil heat flux, sensible heat flux and latent heat flux (Wang et al., 2009). In 2004, the World Bank put forward the concept of "ET Management", namely "real water-saving", based on the Global Environment Facility (GEF) -- Haihe River Basin water resources and water environment integrated management project. The core of "ET Management" is based on reducing water consumption and controlling ET in the process of water circulation, to realize the efficient utilization of water resources.

At present, water resource management based on ET has become one of the hot issues in water resource research. Wu et al. (2017) took winter wheat in Haihe River Basin as the research object, put forward that the water-saving estimation result based on total water volume supplied is far greater than the water-saving estimation result based on water consumption. Only by reducing the water consumption of cultivated crops, the current situation of water shortage can be fundamentally alleviated. Zwart et al. (2004) reviewed 84 documents and 25 years' experimental results, concluded that more food could be produced with less water by increasing crop water productivity (CWP), especially in the water shortage area. It is recommended to use less water to irrigate wheat and corn for maximum yield. Peng et al. (2009) constructed the crop water production function based on the remote sensing ET data by using the classification mean method, and put forward the model of crop ET quota estimation in the vulnerable area of water resources considering the principle of low water consumption and high water productivity. Wang et al. (2009) used the WEP-L distributed hydrological model to discuss the total amount and utilization efficiency of soil water resources in the Yellow River basin. The results showed that the modern water resource management strategy based on ET can not only avoid the waste of water resource, but also improve the efficiency of water resource utilization. Rost et al. (2008) quantified the global blue and green water consumption in 1971-2000 by using the Lund-Potsdam-Jena managed land model framework. It was found that global cropland consumed >7200 km^3 $year^{-1}$ of green water, representing 92% of total crop water consumption. Even in irrigated farmland, 35% of the water consumption was also composed of green water. Rockström et al. (2009) used LPJML dynamic vegetation and water balance model to analyze the availability and water demand of blue-green water on a global scale. The results showed that many water-scarce countries can produce enough food for their population if green water was considered and managed well.

The above research showed that the water resource management based on ET can ensure the efficient and sustainable development of regional water resources, especially for the water shortage areas. Due to the lack of water resources, groundwater over-extraction exists in many places, which often leads to hydrogeological problems such as groundwater level decline and land subsidence. How to reasonably allocate water resources in these over-extraction areas has become an urgent problem to be solved. Based on the theory of "ET Management", regional water resources management based on target ET is presented. Target ET refers to the water consumption in a basin or region at a specific development stage, based on its water resources conditions and constrained by the benign cycle of ecological environment, to meet the requirements of sustainable economic development and the construction of a harmonious society (Qin et al., 2008). The difference between the current ET and the target ET is the amount of compressible water resources, which is mainly provided by the over-extraction of groundwater in the water shortage areas. Through the adjustment of industrial structure and the application of water-saving technology, the regional groundwater should be exploited reasonably, and the balance between exploitation and supplement of groundwater should be gradually realized under the average situation for many years. Mao et al. (2011) proposed to use target ET and predicted groundwater level as evaluation benchmark, and compared it with the actual groundwater level calculated by remote sensing and regional evapotranspiration, so as to realize the evaluation of regional water-saving effect in the Daxing District of Beijing. Qin et al. (2008) and Liu et al. (2009) combined the distributed hydrological model and soil moisture model to calculate the regional target ET of 2010 in Tianjin. Zhang et al. (2016) calculated target ET, actual ET and ET reduction in Luannan Country of Hebei Province, and put forward to include the over-extraction of groundwater into the target ET in the groundwater over-extraction area. The above studies showed that the regulation of water resources based on ET was very important in the over-exploited areas of groundwater. Now, there is a lack of relevant research in the Ziya River Basin.

In this paper, Shijin Irrigation District was selected as the research area, which is located in groundwater over-extraction regions of North China Plain. Because of the development of city and industry, part of the water supply originally belonging to agriculture has been occupied, resulting in the reduction of the water diversion volume of the canal system in the irrigation area, which can only be supplemented by the exploitation of groundwater. Therefore, the selection of the study area is representative, which fully reflects the water resource management problems caused by the limited water resource conditions and extreme contradiction between supply and demand in the over-exploited area.

2 Study area and data

2.1 Study area

Shijin Irrigation District is a large-scale national irrigation area, located in Ziya River Basin, in the south central part of Hebei Province, the east foot of Taihang, the south of the lower reaches of Hutuo River, the north and west of Fuyang River. The irrigation district includes the eastern region and the western region, where the western area is 53.68 km^2, the eastern area is 1573 km^2. The irrigation district has a total agricultural population of 1.08 million, designed irrigation area of 162,820 hm^2, and a control area of 4144 km^2. Shijin Irrigation District is a typical temperate continental monsoon climate, which is suitable for planting summer maize, winter wheat and other crops. The general situation of Shijin Irrigation District is shown in Fig 1.

The average annual precipitation in the irrigation area is about 500mm, which is unevenly distributed throughout the year, concentrated in June-August, accounting for about 70% of the annual precipitation. The irrigation water is mainly from Gangnan and Huangbizhuang reservoir located in the upper reaches of the Hutuo River, which is diverted to the farmland by irrigation channels, of which a great deal of irrigation water is consumed by evapotranspiration.

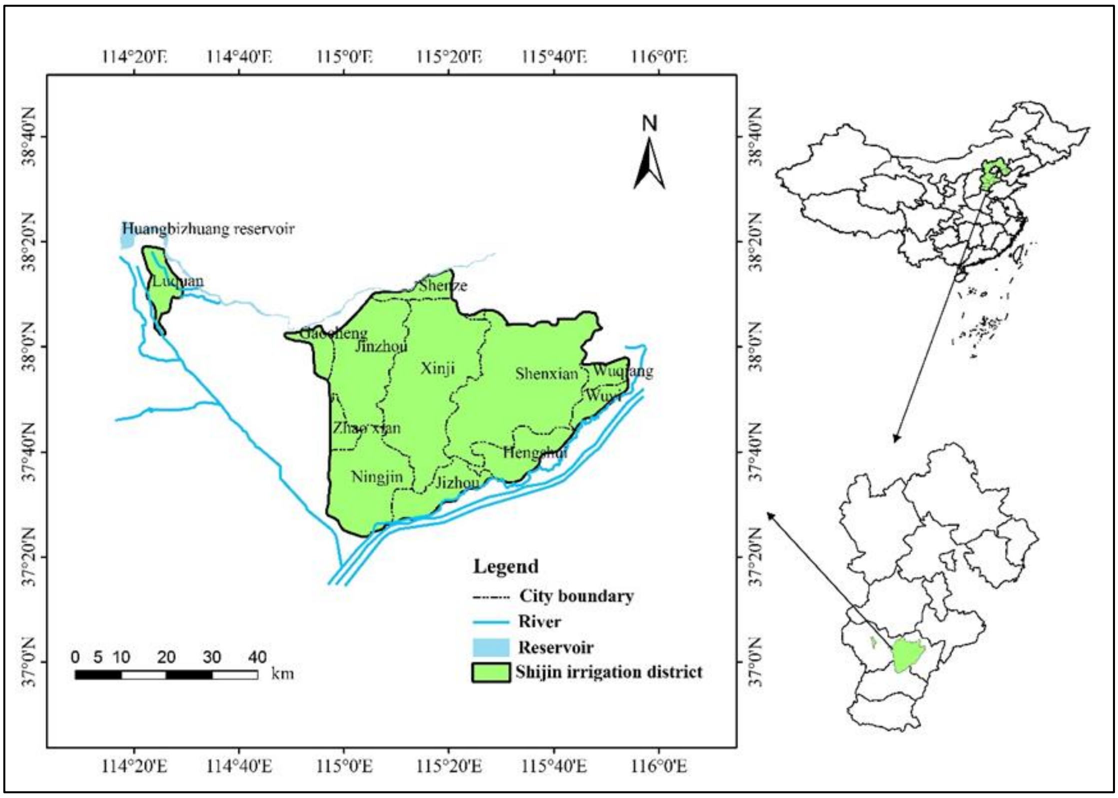

Fig. 1 Overview of Shijin Irrigation District

2.2 Data

The data used in the evaporation model include meteorological data and remote sensing data. Meteorological data (2008, 2009 and 2015) include seven meteorological stations in Ziya river basin (Fig. 2), which comes from the National Centers for Environmental Prediction (CEP) and the China Meteorological Science Data Sharing Service network (http://cdc.cma.gov.cn/home.do), mainly include precipitation and maximum temperature, minimum temperature, wind speed, relative humidity, solar radiation.

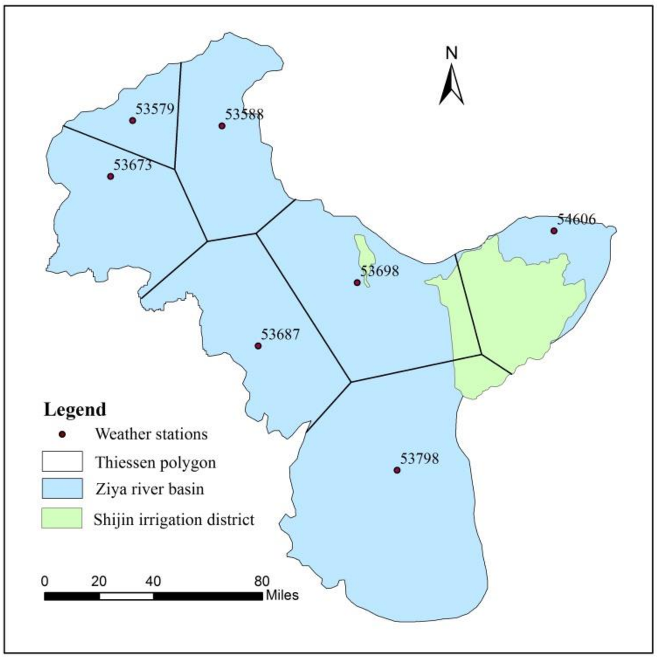

Fig. 2 Meteorological stations in Ziya river basin (including Shijin Irrigation District)

Remote sensing data mainly include normalized difference vegetation index (NDVI), surface temperature and surface reflectance, which are from the Geospatial Data Cloud (http://www.gscloud.cn/). The products include the MODND1D daily product (500m), MODLT1D daily product (1km) and MOD09GA daily product (500m). Also, the evapotranspiration observation value used to verify the accuracy of the P-M model come from Li et al. (2015).

3 Methods

3.1 Regional target ET determination

Target ET refers to the allowable water consumption that meet the need of economic development in a region on the premise of sustainable utilization of water resources. The essence of water resources management based on target ET is to replace water volume supplied management with water consumption management, highlighting the concept of water conservation of total water resources control and water utilization efficiency improvement. Reasonable setting of target ET is the key to realize the sustainable utilization of water resources and the coordinated development of social economy and ecological environment.

According to the principle of water balance, the water balance equation of a region can be expressed as shown below.

$$(P+I)-(O+ET_{ACT})=\Delta G \qquad (1)$$

Where P is the annual precipitation of the region; I is the amount of water flowing into the area; O is amount of water flowing out of the area; ET_{ACT} is the actual ET; ΔG is the annual water storage variable of the region.

For groundwater over-extraction areas, $\Delta G < 0$, that is：

$$(P+I)<(O+ET_{ACT}) \qquad (2)$$

The input of regional water is less than the output, and the groundwater is in the state of over-exploitation.

The water resources planned reduction ET_{Δ} is

$$ET_{\Delta}=ET_{ACT}-ET_{TAR} \qquad (3)$$

where ET_{TAR} is the target ET of the region.

Bringing ET_{ACT} into formula (1)

$$(P+I)-(O+ET_{TAR}+ET_{\Delta})=\Delta G \qquad (4)$$

According to the formula (4), ET_{TAR} can be further obtained.

$$ET_{TAR}=P+I-O+(|\Delta G|-ET_{\Delta}) \qquad (5)$$

In order to meet the social and economic development in over-extraction areas, a total ban on over-extraction groundwater is still hard to achieve. Therefore, the reduction can only be partial or overall of over-extraction. The allowable exploitation of groundwater is

$$G_{OVR}=|\Delta G|-ET_{\Delta}\geq 0 \tag{6}$$

Bringing formula (6) into formula (5)

$$ET_{TAR}=P+I-O+G_{OVR} \tag{7}$$

3.2 Determination of crop ET

To improve the problem of groundwater over-extraction in irrigation areas, the most important problem is to solve the problem of agricultural use water. And, crops with high water consumption usually consume the main water in irrigation areas, so crops with high water consumption can be taken as the main target of regulation.

The crop water demand (ET) can be calculated by the following formula:

$$ET=K_c\times ET_0 \tag{8}$$

where ET is the crop water demand (mm); ET_0 is the potential evapotranspiration(mm), which can be calculated by Penman-Monteith potential evapotranspiration model; K_c is the crop coefficient.

3.3 Penman-Monteith（P-M）model

The calculation model of potential evapotranspiration is mainly divided into aerodynamic method, energy balance method and comprehensive method of aerodynamics and energy balance (Pan 2017). In this paper, Penman-Monteith model is used to calculate potential evapotranspiration, and its accuracy is higher than other models (Donohue et.al., 2010). The calculation formula is as follows:

$$ET_0=\frac{0.408\Delta(R_n-G)+\gamma\frac{900}{T+273}u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)} \tag{9}$$

where ET_0 is the potential evapotranspiration (mm); Δ is the slope of temperature saturated vapor pressure curve (kPa/°C); R_n is the net radiation flux (W/m^2); G is the soil heat flux (W/m^2); γ is the thermometer constant (kPa/°C); T is the average temperature at 2m from the ground (°C); u_2 is the average wind speed at 2m from the ground (m/s); e_s is the saturated vapor pressure at 2m from the ground (kPa); e_a is the actual water vapor pressure at 2m from the ground (kPa).

The data from meteorological stations are generally the wind speed at 10m above the ground.

$$u_2=\frac{4.87u_{10}}{ln(67.8\times h-5.42)} \tag{10}$$

where h is the height from the ground when measuring the wind speed (m).

3.3.1 Net radiation flux (R_n)

Net radiation is the algebraic sum of the radiation energy budget of the underlying surface from short wave to long wave. It includes not only the scattering radiation and reflection radiation of the direct solar radiation, but also the long wave parts such as the atmospheric inverse radiation and the ground radiation. Net radiation is a measure of surface effective energy and an important factor in the study of surface energy conversion, watershed evapotranspiration and water cycle. The calculation formula of net radiation (R_n) is:

$$R_n=(1\text{-}a_c)R_S-R_{nl} \tag{11}$$

where a_c is the surface reflectance; R_S is the measured solar short wave radiation (W/m^2); R_{nl} is the net long wave radiation (W/m^2).

Surface albedo refers to the albedo of wide band. With the single band surface albedo product provided by MODIS, the albedo of wide band can be calculated by the following inversion formula:

$$\alpha_c=0.160\alpha_1+0.291\alpha_2+0.243\alpha_3+0.116\alpha_4+0.112\alpha_5+0.081\alpha_7-0.0015 \qquad (12)$$

where $\alpha_{1,2,3,4,5,7}$ is the surface reflectance of band 1, 2, 3, 4, 5, 7.

Net long wave radiation is also called long wave radiation difference and long wave net radiation. In the process of long wave radiation exchange between the ground and the atmosphere, the net income or expenditure on the ground is equal to the effective radiation on the ground, and its calculation formula is (Allen et al., 1998):

$$R_{nl}=\sigma\left(\frac{T_{max,k}^4+T_{min,k}^4}{2}\right)(0.34-0.14\sqrt{e_a})\left(1.35\frac{R_s}{R_{so}}-0.35\right) \qquad (13)$$

where σ is the Stefan Boltzmann constant, $\sigma=5.6\times10^{-8}$ W/(K^4•m^2); $T_{max,k}$ and $T_{min,k}$ are the maximum and minimum temperature within 24 hours respectively (K); R_{so} is the solar radiation in clear sky (W/m^2); e_a is the actual vapor pressure (kPa).

The calculation formula of solar radiation in clear sky is as follows:

$$R_{so}=(0.75+2\times10^{-5}Z)R_a \qquad (14)$$

where Z is the altitude of the weather station (m); R_a is the solar terrestrial irradiance (W/m^2).

Solar terrestrial irradiance R_a can be calculated by the following formula:

$$R_a=37.59E_0[\omega T_{SR}\sin\delta\sin\phi+\cos\delta\cos\phi\sin(\omega T_{SR})] \qquad (15)$$

where E_0 is the earth orbit eccentricity correction factor; ω is the angular velocity of earth rotation; δ is the solar declination in radians; ϕ is the geographic latitude in radians; T_{SR} is the time interval between sunrise and noon.

$$T_{SR}=\frac{arccos(-\tan\delta\tan\phi)}{\omega} \quad (16)$$

The correction factor for the eccentricity of the earth's orbit E_0 can be calculated by:

$$E_0=1+0.033\cos\left(\frac{2\pi d_n}{365}\right) \quad (17)$$

where d_n is the sequence number of the date in the year, from 1 (January 1) to 365 (December 31).

The declination of the sun, also known as the declination angle, refers to the latitude of the earth where the incident sun light is perpendicular to the earth's surface. The formula for calculating declination is:

$$\delta=\sin^{-1}\left\{0.4\sin\left[\frac{2\pi}{365}(d_n-82)\right]\right\} \quad (18)$$

where δ is the solar declination (rad).

3.3.2 Soil heat flux (G)

Due to the temperature difference between the surface temperature and the deep soil temperature, the amount of energy transferred from the surface soil to the deep soil in the form of heat conduction per unit area. In this paper, the calculation formula proposed by Su (2002) is used to estimate the soil heat flux. For the ground covered by vegetation:

$$G=R_n[\tau_c+\left(1-f_c\right)(\tau_s-\tau_c)] \quad (19)$$

where τ_c is the ratio of soil heat flux to net radiation under full vegetation cover, with a value of 0.05; τ_s is the ratio of soil heat flux to net radiation in bare area, with a value of 0.315; f_c is the vegetation coverage.

$$f_c=\frac{(NDVI-NDVI_{min})}{(NDVI_{max}-NDVI_{min})} \quad (20)$$

where $NDVI$、$NDVI_{max}$ and $NDVI_{min}$ are the mean value, maximum value and minimum value of vegetation normalization index respectively.

3.3.3 Thermometer constant

The thermometer constant γ represents the balance between the sensible heat obtained from the air through the wet bulb thermometer and the sensible heat converted into latent heat. The calculation formula is as follows:

$$\gamma=\frac{c_p P}{0.622\lambda} \tag{21}$$

$$P=101.3-0.01152Z+0.544\times10^{-6}Z^2 \tag{22}$$

where c_p is the specific heat of wet air under constant pressure, 1.013×10^{-3} MJ/(kg•℃); λ is the latent heat of vaporization (MJ/kg); P is the pressure (kPa).

3.3.4 Saturated vapor pressure

The pressure of water vapor in the air is a part of the whole atmospheric pressure. The number of water molecules that can be contained in the air is controlled by the air humidity. Under a certain temperature, the air can contain a certain amount of water molecules. When the water molecules in the air reach saturation, the water vapor pressure under the corresponding temperature is called saturated vapor pressure. The calculation formula is:

$$e_s=exp\left(\frac{16.78T_{av}-116.9}{T_{av}+237.3}\right) \tag{23}$$

where T_{av} is the daily average temperature (°C).

When the relative humidity R_h is known, the actual vapor pressure e_a is

$$e_a=R_h e_s \tag{24}$$

3.3.5 Slope of temperature-saturated vapor pressure curve

The slope of saturated vapor pressure curve is obtained by differential calculation of saturated vapor pressure.

$$\Delta=\frac{4098e_s}{(T_{av}+237.3)^2} \tag{25}$$

4 Results and analysis

4.1 Determination of crop target ET in Shijin Irrigation District

4.1.1 Average annual rainfall

The rainfall in Shijin Irrigation District can be represented by the three nearest rain stations (#53698, #54606 and #53798). The precipitation process of these three rain stations from 1998 to 2017 is shown in Fig.3. The control area of stations #53698, #54606 and #53798 is 12663.89 km^2, 25912.82 km^2 and 35838.71 km^2, respectively. The average annual rainfall can be calculated by the Thiessen polygon method, with a value of 458.86 mm, which is taken as the rainfall reference value when calculating the regional target ET.

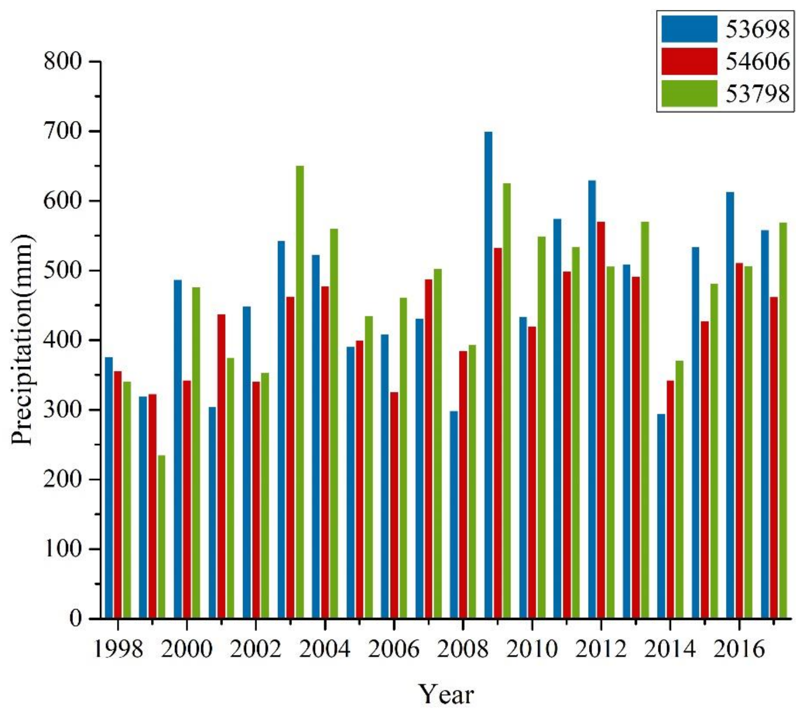

Fig. 3 Precipitation from 1998 to 2017 in Shijin Irrigation District

4.1.2 Average annual water diversion

The diversion water of irrigation district mainly from Gangnan and Huangbizhuang Reservoirs, two large reservoirs in the upper reaches of Hutuo River. The statistics data of water diversion from 2000 to 2018 (2012 and 2013 data missing) is shown in Fig. 4. The average annual water diversion is 179.62 mm, which is taken as the reference value when calculating the regional target ET.

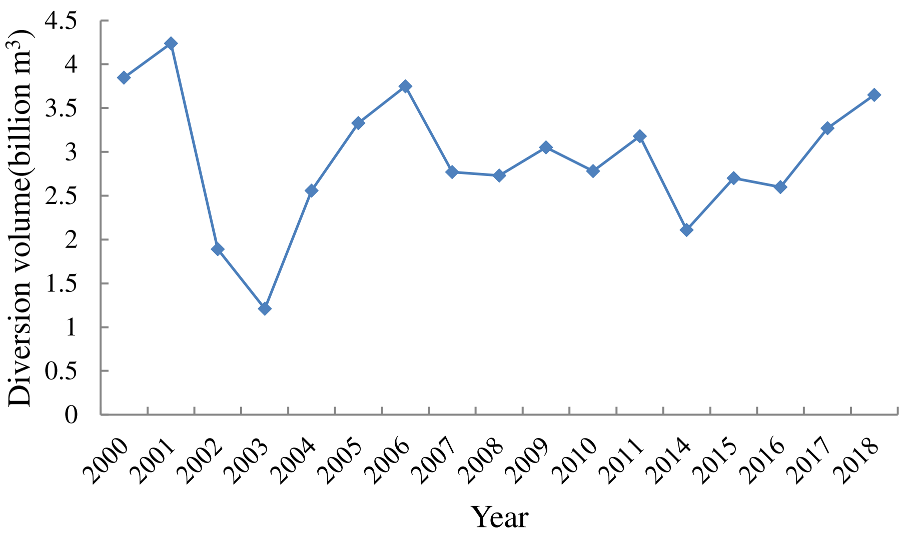

Fig. 4 Water diversion from 2000 to 2018 in Shijin Irrigation District

4.1.3 Calculate crop target ET value

The multi-year average rainfall and the multi-year average water diversion in the irrigation district are selected as the input variables to determine the regional target ET. At present, the Shijin Irrigation District is implementing the groundwater planning project, the future goal is to achieve that groundwater will be not over-extracted. So, when setting goals ET, G_{OVR} can be set to 0, namely ET reduction amount is equal to the over-exploitation volume. According to formula (7), under the premise of ensuring that groundwater is not over-extracted, the sum of annual precipitation and water diversion minus the amount of water flowing out of the region is the regional target ET value.

Winter wheat and summer maize occupy a large proportion of the cultivated areas. So, the calculated regional target ET value can be taken as the crop (winter wheat and summer maize) target ET in the irrigation district.

Table 1 Target ET of winter wheat and summer maize

Crop	P (mm)	I (mm)	O (mm)	Target ET(mm)
Winter wheat	458.86	179.62	0	638.48
Summer maize				

4.2 Verification of P-M model

Due to the lack of evapotranspiration data of recent years, this paper selects the 2008 and 2009 with observed data as the verification periods of the model, and evaluates the model precision by using the model precision evaluation model. The Penman-Monteith model with good precision can be applied to simulate evaporation in the study area.

In this paper, the potential evapotranspiration in 2008 and 2009 is calculated by using the Penman-Monteith model. On this basis the actual evapotranspiration of crops is calculated by using formula (8), in which the crop coefficient is the value recommended in the work by Liu et al. (2002). Specific crop coefficients are shown in Table 2 and Table 3.

The growth stages of the winter wheat and summer maize in the North China Plain are shown in Table 4 and Table 5.

Table 2 Crop coefficient of winter wheat in North China Plain

Month	10	11	12	1	2	3	4	5	6

K_c	0.60	0.82	0.86	0.43	0.38	0.57	1.23	1.42	0.72

Table 3 Crop coefficient of summer maize in North China Plain

Month	6	7	8	9
K_c	0.59	1.24	1.38	1.17

Table 4 Growth period of winter wheat in North China Plain

Growth period	Time
Sowing	Early October
Seedling emergence	Mid-late October
Tillering	Early November~ Early December
Overwintering	Mid-December ~ Late February
Reviving	Late February ~ Early March
Jointing	Mid-March ~ Early April
Heading and Flowering	Mid-April ~ Early May
Milk filling	Mid-May ~ Early June

Table 5 Growth period of summer maize in North China Plain

Growth period	Seedling	Jointing	Blooming	Filling	Maturation
Time	Mid-June	Late June ~ Late July	Late July ~ Mid-August	Mid-August ~ Late August	Late August ~ Late September

The evapotranspiration of 2008-2009 is estimated by the P-M model and formula (8), and compared with the evapotranspiration observation value to verify the accuracy and applicability of the model. See Table 6-8 for the comparison results. It can be seen from Table 6 that the relative errors are all within 10%. The relative errors are less than 20% in Table 7 and Table 8, and the simulation results are good.

Table 6 Comparison of evaporation simulation value and reference value

Year	Simulation value (mm)	Reference value (mm)	Absolute error (mm)	Relative error (%)
2008	548.73	500.42	48.31	9.65

2009	555.53	511.15	44.38	8.68

Table 7 Comparison of evaporation simulation value and reference value in 2008

Month	Reference value (mm)	Simulation value (mm)	Absolute error (mm)	Relative error (%)
1	2.93	3.42	0.49	16.72
2	8.73	9.45	0.72	8.25
3	19.09	18.67	0.42	2.20
4	53.67	59.02	5.35	9.97
5	79.68	80.54	0.86	1.08
6	60.74	58.50	2.24	3.69
7	105.64	124.24	18.60	17.61
8	94.39	112.23	17.84	18.90
9	53.83	58.68	4.85	9.01
10	15.36	16.52	1.16	7.55
11	4.8	5.62	0.82	17.08
12	1.56	1.84	0.28	17.95

Table 8 Comparison of evaporation simulation value and reference value in 2009

Month	Reference value (mm)	Simulation value (mm)	Absolute error (mm)	Relative error (%)
1	4.04	4.76	0.72	17.82
2	7.41	8.02	0.61	8.23
3	20.84	22.61	1.77	8.49
4	51.88	54.33	2.45	4.72
5	89.48	106.76	17.28	19.31
6	61.52	59.33	2.19	3.56
7	101.13	95.29	5.84	5.77
8	99.98	119.07	19.09	19.09
9	52.62	62.64	10.02	19.04
10	16.49	17.73	1.24	7.52
11	4.19	3.36	0.83	19.81
12	1.57	1.63	0.06	3.82

Figure 5 and Figure 6 show the scatter diagram of the simulation value and observation value of evapotranspiration in 2008 and 2009, with R^2 of 0.9883 and 0.9742 respectively, indicating that the model is applicable in Ziya River Basin. As the Shijin Irrigation District belongs to Ziya River Basin, the model is also applicable in the Shijin Irrigation District.

The inverse distance weight interpolation method (IDW) is used to interpolate the observation value and simulation value of evapotranspiration in 2008 and 2009. The spatial distribution of 2008 and 2009 is shown in Figure 7 and Figure 8.

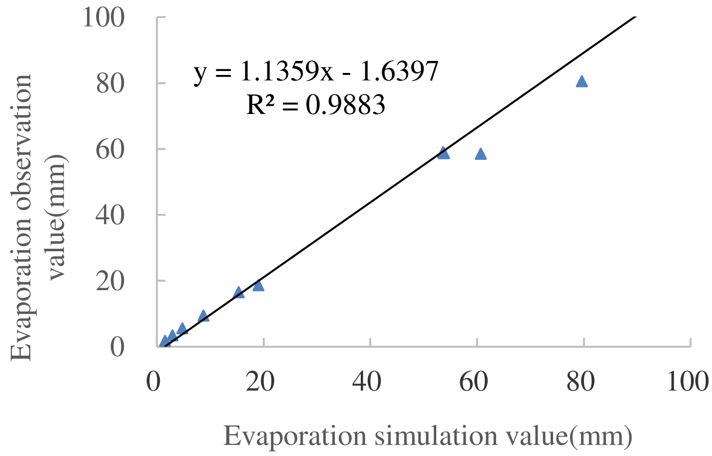

Fig. 5 Scatter diagram of evapotranspiration simulation value and observation value in Ziya River Basin in 2008

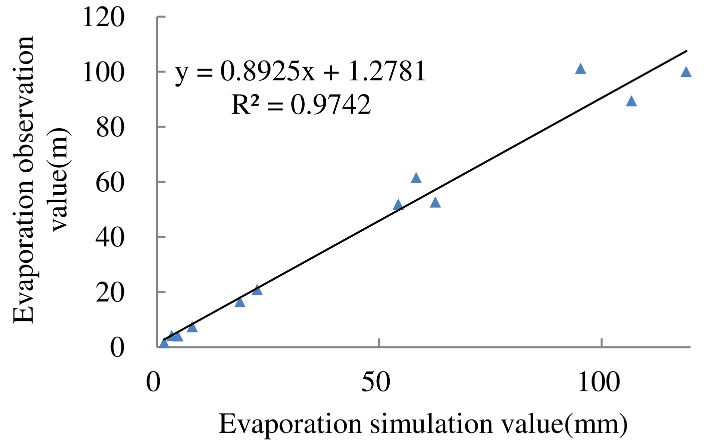

Fig. 6 Scatter diagram of evapotranspiration simulation value and observation value of Ziya River Basin in 2009

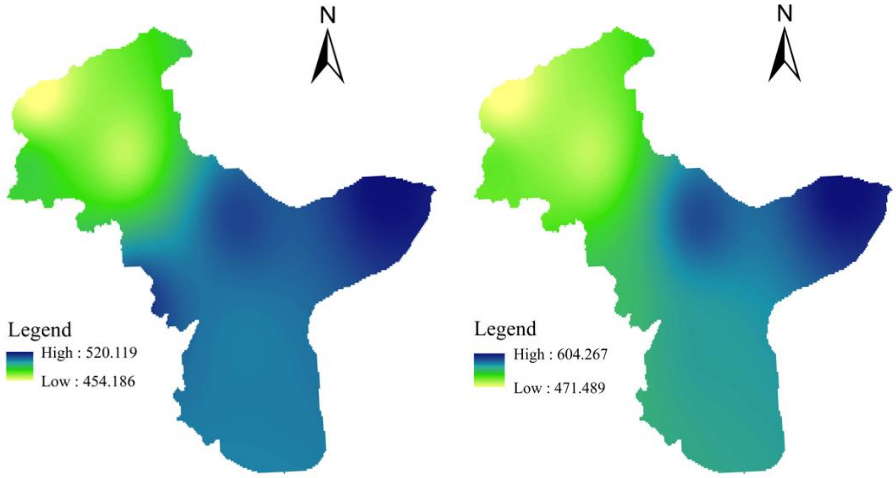

Fig. 7 Spatial distribution of evapotranspiration observation value (left) and simulation value (right) in Ziya River Basin in 2008

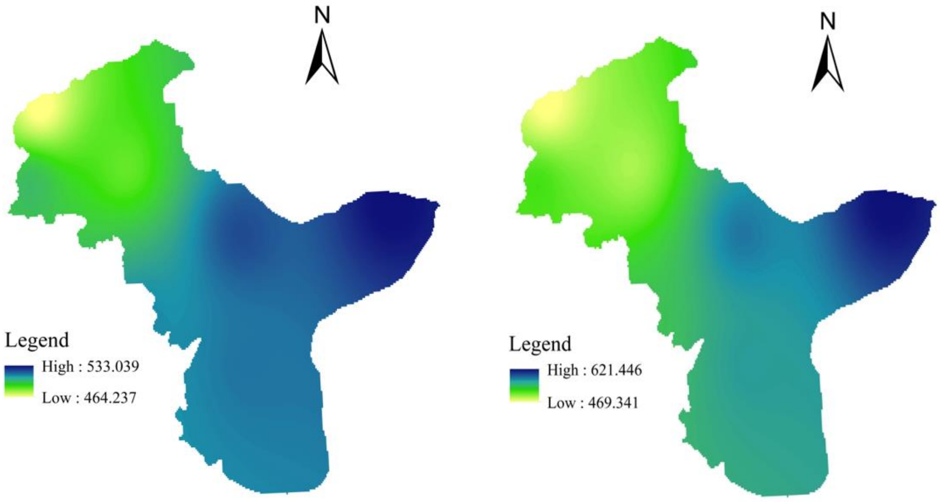

Fig. 8 Spatial distribution of evapotranspiration observation value (left) and simulation value (right) in Ziya River Basin in 2009

4.3 Target of groundwater reduction based on ET

Taking 2015 as the base year, the potential evapotranspiration of crops in different growth periods in 2015 is calculated by using the meteorological and remote sensing data and P-M model. The current water demand of crops (ET) can be obtained by formula (8), which is compared with the target ET value of crops. The difference between the two ET is the target of groundwater reduction.

The designed irrigation area of the Shijin Irrigation District is 162,820 ha, and the planting areas of winter wheat and summer maize account for 81%. Therefore, the adjustment of water consumption of crops is the key to reduce groundwater exploitation in the Shijin Irrigation District. According to the calculation results in Table 9 and Table 10, the current water demand of winter wheat in 2015 is 402.92mm, that of summer maize is 251.32 mm. The total water demand for both crops is 653.24 mm. The target ET calculated by water balance is 638.48 mm. Obviously, the amount of water consumed by crops includes groundwater. According to the target ET regulation, the groundwater in the Shijin Irrigation District can be compressed by 14.76 mm in 2015. It can be seen that the groundwater in the Shijin Irrigation District has great potential to be further compressed exploitation in a base year. Of the two crops, summer maize is by far the most likely to reduce irrigation water. The research results show that watering only once can be realized in summer maize in the Shijin Irrigation District (Li et al. 2019). And winter wheat can also reduce irrigation water by optimizing the irrigation system. Therefore, it is feasible to limit crop water consumption based on ET.

Table 9 Calculation results of water demand of winter wheat in 2015

Growth period	Time	Water demand (mm)
Sowing~ Seedling emergence	October 5th ~October 20th	20.57
Seedling emergence ~ Tillering	October 21st ~December 5th	26.62
Tillering ~ Overwintering	December 6th ~February 25th	34.95
Overwintering ~ Reviving	February 26th ~March 5th	5.92
Reviving ~ Jointing	March 6th ~April 5th	80.38
Jointing ~ Blooming	April 6th ~May 5th	101.53
Blooming ~ Mature	May 6th ~June 5th	131.96
Whole growth period		402.92

Table 10 Calculation results of water demand of summer maize in 2015

Growth period	Time	Water demand (mm)
Seedling ~ Jointing	June 15th ~June 25th	17.24
Jointing	June 26th ~July 25th	78.02
Blooming	July 26th ~August 15th	57.42
Filling	August 16th ~August 31st	51.69
Maturation	September 1st ~September 25th	46.95
Whole growth period		251.32

The Shijin Irrigation District is located in the world's largest groundwater descending funnel area, and the groundwater resource is one of the main water sources in the irrigation district. The groundwater is seriously over-extracted, and the shallow groundwater depth is deep, mostly 10-20m, and the groundwater depth in some areas is up to 30m. In recent years, the average groundwater exploitation is about 67 million m^3. According to the calculation results of the base year (2015), if the target ET of crops is taken as the control basis for the irrigation water consumption of crops, the compressed exploitation of groundwater is about 19.47 million m^3, which accounts for 30% of the original exploitation. By controlling the crop water consumption, the groundwater can be significantly compressed, the recovery speed of groundwater level can also be accelerated.

In this paper, 2015 was taken as the base year, and groundwater exploitation was compressed based on ET water resources management，which shows that the method in this paper has good technical support for the control of groundwater exploitation in the over-extraction groundwater areas. For the over-extraction area of groundwater, due to long-term over-extraction, the groundwater should be further compressed or even banned if it is to recover to a good state. At the same time, in order to restore the ecological environment of the downstream river, the amount of water flowing out of the region needs to be increased. So, the target ET can be further reduced in future planning.

Controlling the water consumption of crops will inevitably affect the yield of regional crops. Under the premise of controlling the amount of water used for crop irrigation, the water use efficiency must be improved, especially in the peak period of crop water demand. According to the characteristics of regional agriculture, the following measures are proposed for improving water use efficiency:

(1) The high-efficiency engineering water-saving technical measures and agricultural water-saving measures shall be closely combined. Agricultural measures such as straw returning to the field, mulching and soil moisture conservation should be carried out to reduce soil water evaporation.

(2) The irrigation system should be optimized in the process of irrigation, and the water-saving, drought-resistant and high-yield crop varieties should be popularized.

(3) Adjusting the planting structure, reducing the multiple cropping index of crops and the planting area of winter wheat with two crops in one year, and increasing the planting area of corn that grows at the same time as the heat and rain.

(4) The water-saving cultivation management technology should be large-scale applied in the main grain-producing areas.

5 Discussion and Conclusion

Based on the principle of water balance, the target ET value of crops in the study area is calculated, and the ET value is taken as the target of water resources regulation. The actual water consumption is calculated by the Penman-Monteith formula, and a reduction of crop water consumption is obtained according to the difference between actual ET and target ET. The reduction in crop water consumption leads to a reduction in demand for water supply, which reduces groundwater extraction.

It is enough to support an expected gross grain yield for current water demand 653.24mm under climate conditions of 2015. However, for meeting the water demand of crops, it must be at the cost of overdrawing groundwater. In order to analyze the impact of reduced groundwater extraction on crop yield, the AquaCrop model constructed by Li et al., (2019) was used to simulate the yield of winter wheat and summer maize. The applicability and accuracy of the model in Ziya River Basin have been verified by Li et al., (2019). Under the condition of no over-exploitation of groundwater (G_{OVR}=0), the total irrigation is 179.62mm (Table1). The simulated yield values of winter wheat and summer maize in 2015 were 6.983 t/ha and 7.251 t/ha respectively; Under the condition of over-exploitation of groundwater (other simulation conditions remain unchanged), which is the current situation of water use, the total irrigation is 202.33mm (179.62mm+ $\frac{ET_{\Delta}}{0.65}$, "0.65" is the utilization coefficient of irrigation water in Shijin Irrigation District; ET_{Δ}=14.76mm). The yield values of winter wheat and summer maize in 2015 were 7.050 t/ha and 7.272 t/ha respectively. Compared with the grain yield under the two conditions above, the yield of winter wheat and summer maize decreased by 0.95% and 0.29% respectively. It can be seen, if the exploitation of groundwater is compressed, there is a risk of reducing grain yield, but this risk is low, and the risk can be avoided by water-saving irrigation, optimizing planting structure and adjusting industrial structure.

The main conclusions are as follows:

(1) The evapotranspiration of Ziya River Basin in 2008-2009 is estimated by the Penman-Monteith model. The simulation results show that the relative error of the model is less than 20%; The simulation values of 2008 and 2009 are fitted with observation values, with R^2 of 0.9883 and 0.9742 respectively, indicating that the model is applicable in Ziya River Basin.

(2) Based on the principle of water balance, the target ET calculated by water balance is 638.48 mm. The current water demand of winter wheat in 2015 is 402.92 mm, that of summer maize is 251.32 mm. The total water demand for both crops is 653.24 mm. According to the target ET regulation, the water consumption of crops in the Shijin Irrigation District can be compressed by 14.76 mm in 2015.

(3) In recent years, the average groundwater exploitation is about 67 million m^3. According to the calculation results of the base year (2015), if the target ET of crops is taken as the control basis for the irrigation water consumption of crops, the compressed exploitation of groundwater is about 19.47 million m^3, which accounts for 30% of the original exploitation.

Conflict of interest

The authors declare that they have no conflicts of interest.

Funding Statement

This work provided by the National Natural Science Foundation of China (Grant no.51879181).

Author's Contribution

Fawen Li contributed in conceptualization, design, data analysis, and drafting the manuscript; Wenhui Yan contributed in calculation, drawing charts and data analysis; Yong Zhao and Rengui Jiang contributed in data curation, supervision, validation, writing—review and editing.

Availability of data and material

The data used in this research are openly accessible. See “2.2 Data” for details.

Code availability

Not applicable. Software application or custom code is not involved in this study.

Ethics approval

Complied with the Ethical Standards of TAAC Journal.

Consent to participate

All authors give their consent for participate of this paper.

Consent for publication

Informed consent to publish has been obtained from each participant.

Acknowledgements

The authors would like to acknowledge the financial support for this work provided by the National Natural Science Foundation of China (Grant no.51879181).

References

Allen RG, Perreira LS, Raes D, et al. (1998) Crop evapotranspiration: Guidelines for computing crop water requirements. Irrigation and Drainage (01):56.

Donohue RJ, Mcvicar TR, Roderick ML. (2010) Assessing the ability of potential evaporation formulations to capture the dynamics in evaporative demand within a changing climate. Journal of Hydrology 386(1-4):186-197.

Johan R, Falkenmark M, Karlberg L, et al. (2009) Future Water Availability for Global Food Production: The Potential of Green Water for Increasing Resilience to Global Change. Water Resources Research 45(7):1-16.

Li MS, Jin XL. (2001) Agricultural water use and water saving measures in Haihe River Basin in the early 21st century. Haihe Water Conservancy (01):1-3.

Li FW, Yu D, Zhao Y. (2019) Irrigation Scheduling Optimization for Cotton Based on the AquaCrop Model. Water Resources Management 33(1):33-55.

Liu C, Zhang X , Zhang Y. (2002) Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter. Agricultural and Forest Meteorology 111(2):109-120.

Liu JH, Qin DY, Wang MN, Sang XF, Lu JY, Zhang RM. (2009) Theory and calculation method of area target ET: application example. Science in China 39(02):318-323.

Li FW, Cao RX, Zhao Y, et al. (2015) Remote sensing Penman–Monteith model to estimate catchment evapotranspiration considering the vegetation diversity. Theoretical & Applied Climatology 127(1-2):111–121.

Malin F, Johan R. (2004) Balancing Water for Humans and Nature. Earthscan Publishing, America

Mao D, Zhou H, Ming HU, et al. (2011) Application and study on evaluation method of the overall effect of water saving efforts in a region based on remote sensing.

Journal of Remote Sensing 15(2):340-348.

Pan SL. (2017) Potential evapotranspiration and hydrological processes in Zhejiang Province. Zhejiang University, Zhejiang

Peng ZG, Liu Y, Yu D, Wang L. (2009) Estimation of regional crop water saving potential based on RS data and GIS. Journal of Agricultural Engineering 25(07):8-12.

Qin DY, Lu JY, Liu JH, Wang MN. (2008) Theory and calculation method of area target ET. Science Bulletin (19):2384-2390.

Rost S , Gerten D, Bondeau A, et al. (2008) Agricultural green and blue water consumption and its influence on the global water system. Water Resources Research 44(9):n/a-n/a.

Su ZB. (2002) A Surface Energy Balance System (SEBS) For Estimation of Turbulent Heat Fluxes From Point to Continental Scale. Hydrology and Earth System Sciences 6(1):85-99.

Wang H, Yang GY, Jia YW, Qin DY, Gan H, Wang JH, Hang CM. (2009) Taking the soil water resources of the Yellow River Basin as an example, the necessity and feasibility of modern water resources management with "ET Management" as the core are illustrated. Science in China 39(10):1691-1701.

Wang H , Yang GY , Jia YW , et al. (2009) Necessity and feasibility for an ET-based modern water resources management strategy: A case study of soil water resources in the Yellow River Basin. Science in China 52(10):3004-3016.

Wu BF, Yan NN, Zeng HW, et al. (2017) Spatial cognition and suggestion of water saving irrigation agriculture. Journal of the Chinese Academy of Sciences (01):76-83.

Zhang HB, Lan T, Wang B, et al. (2016) Study on water resource management of plain district and county based on ET control. Journal of hydraulic engineering 47(2):127-138.

Zwart SJ, Bastiaanssen WGM. (2004) Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agricultural Water Management 69(2):0-133.

Figures

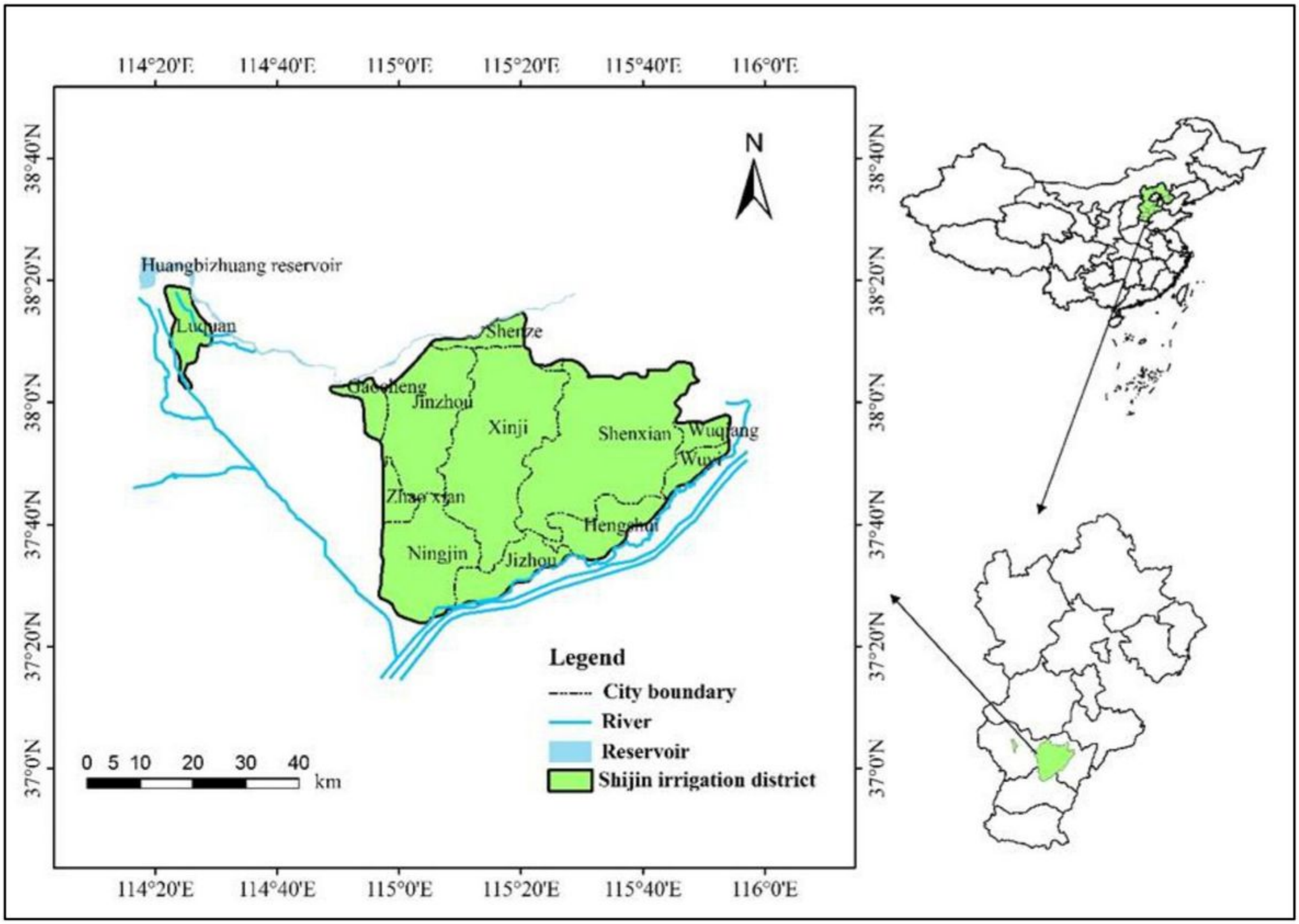

Figure 1

Overview of Shijin Irrigation District Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

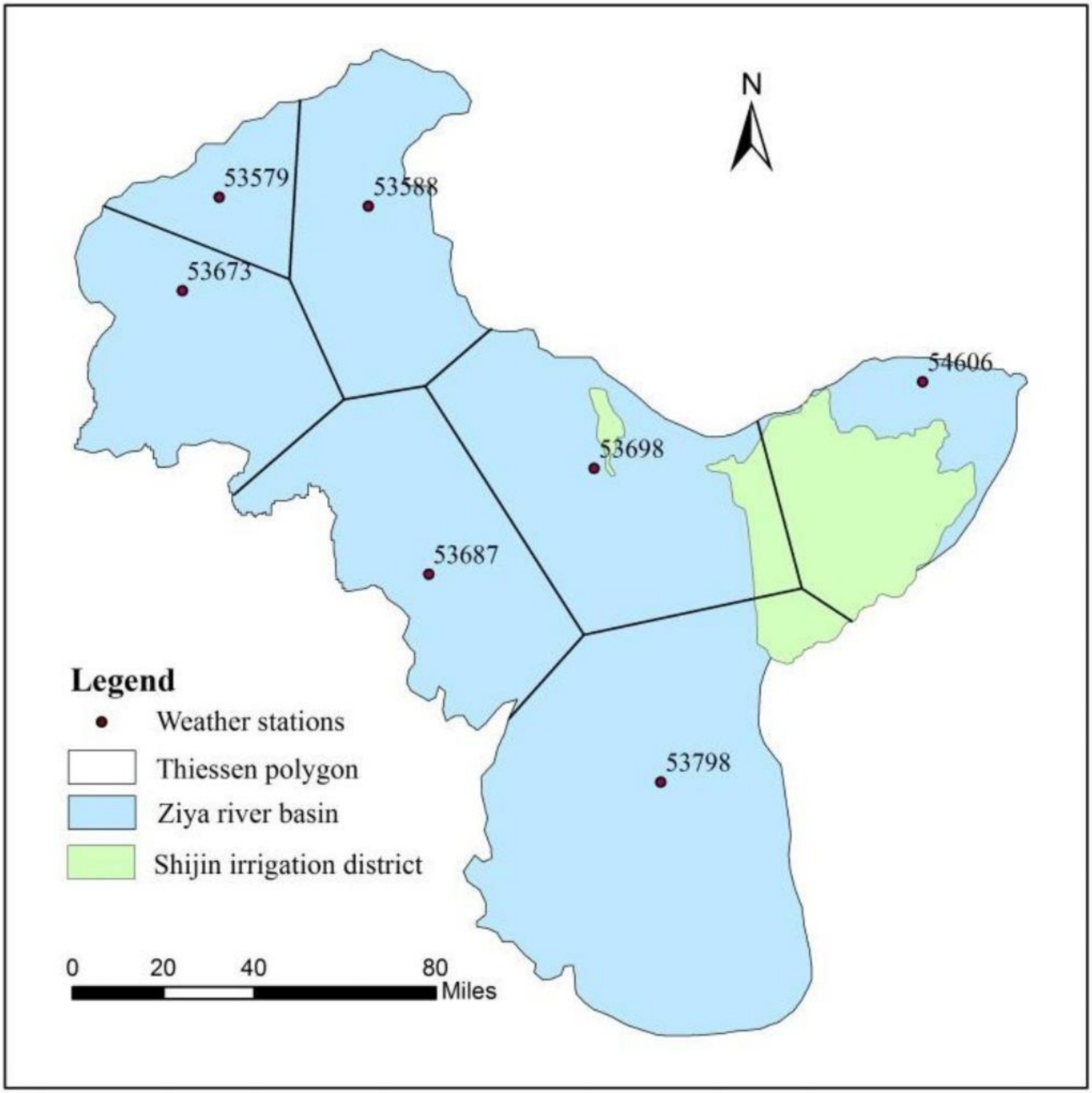

Figure 2

Meteorological stations in Ziya river basin (including Shijin Irrigation District) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

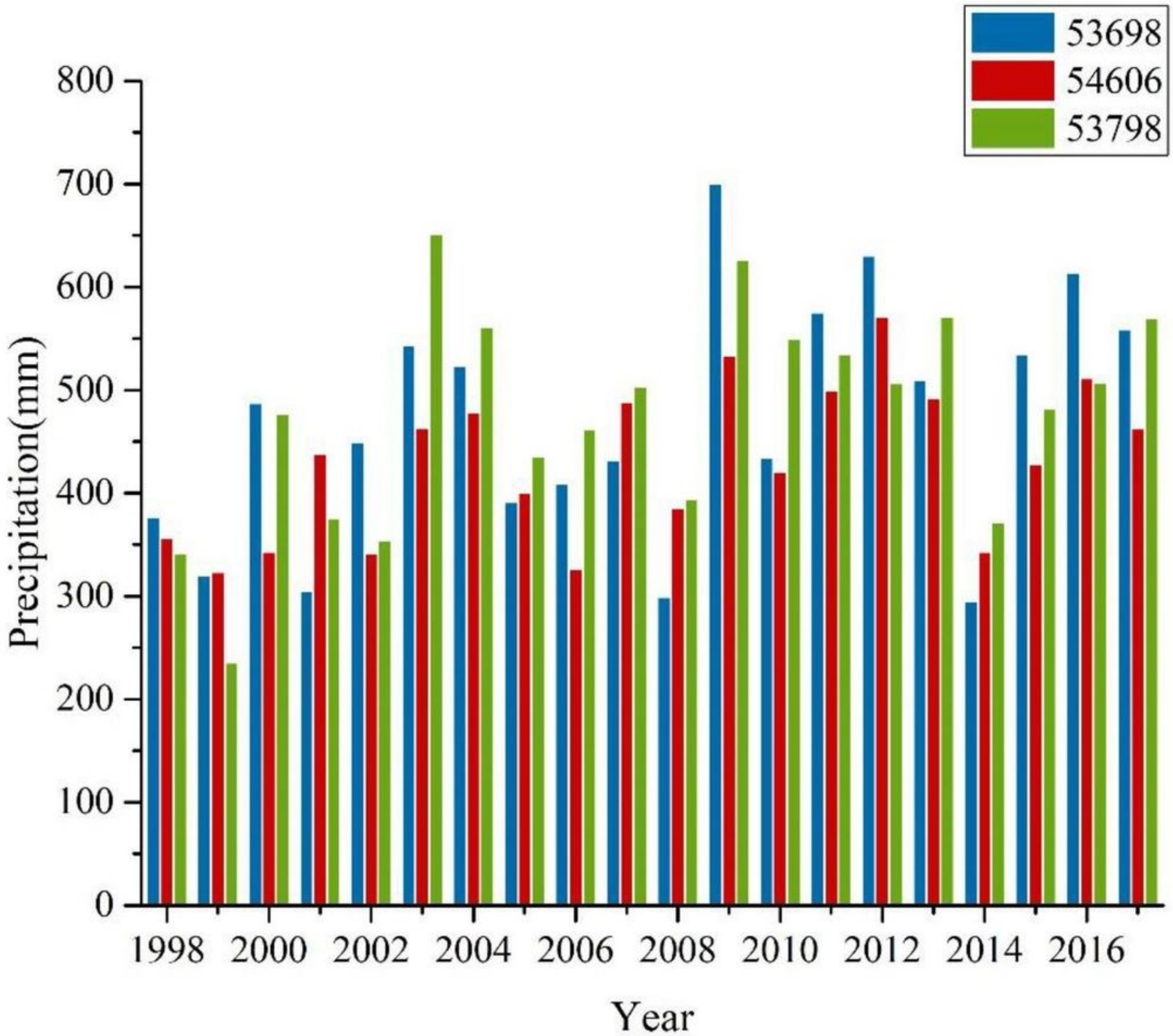

Figure 3

Precipitation from 1998 to 2017 in Shijin Irrigation District

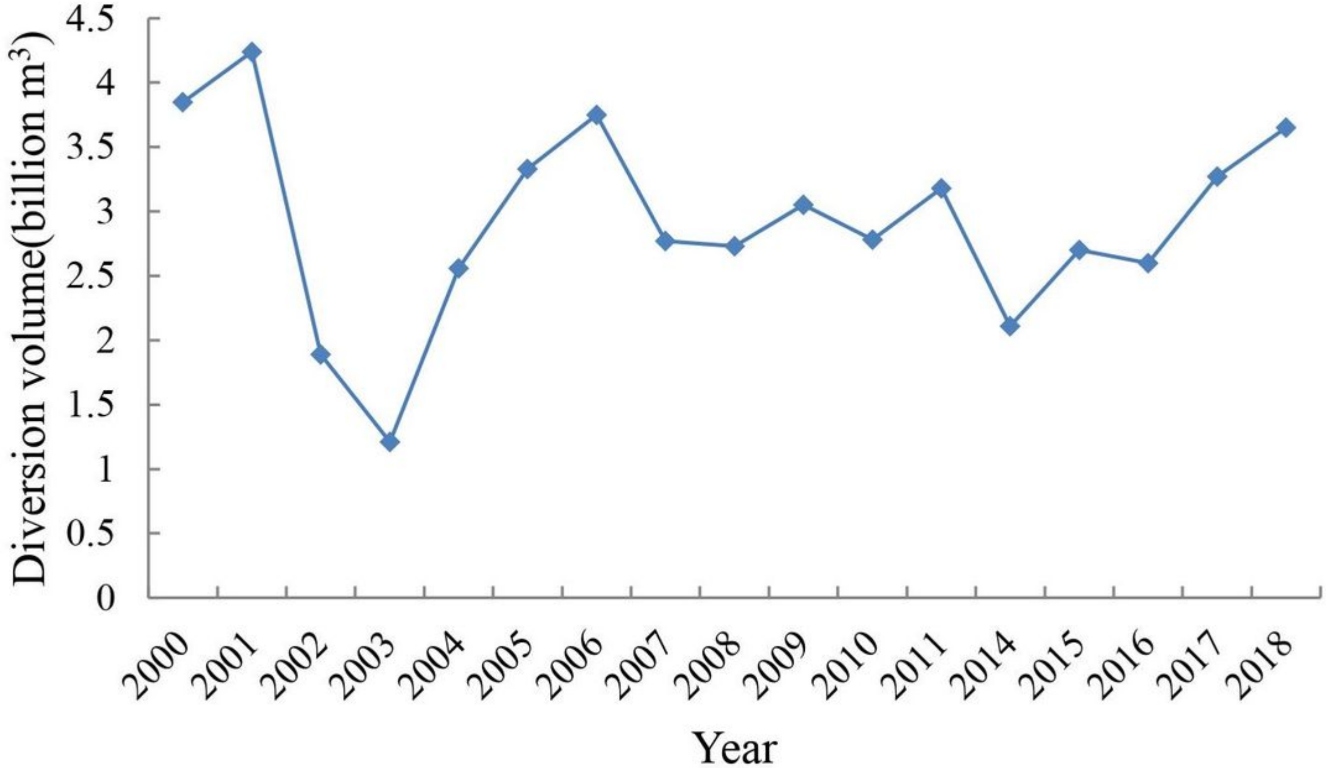

Figure 4

Water diversion from 2000 to 2018 in Shijin Irrigation District

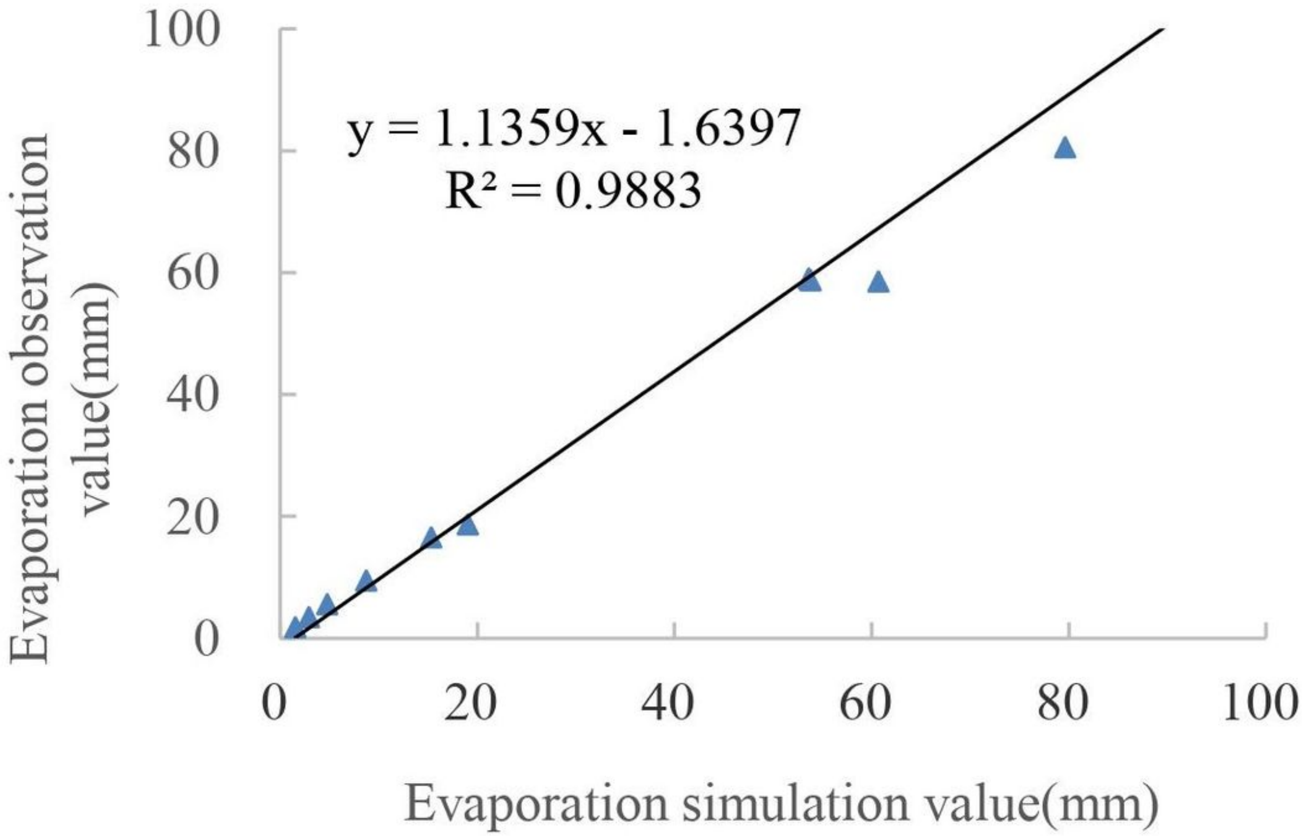

Figure 5

Scatter diagram of evapotranspiration simulation value and observation value in Ziya River Basin in 2008

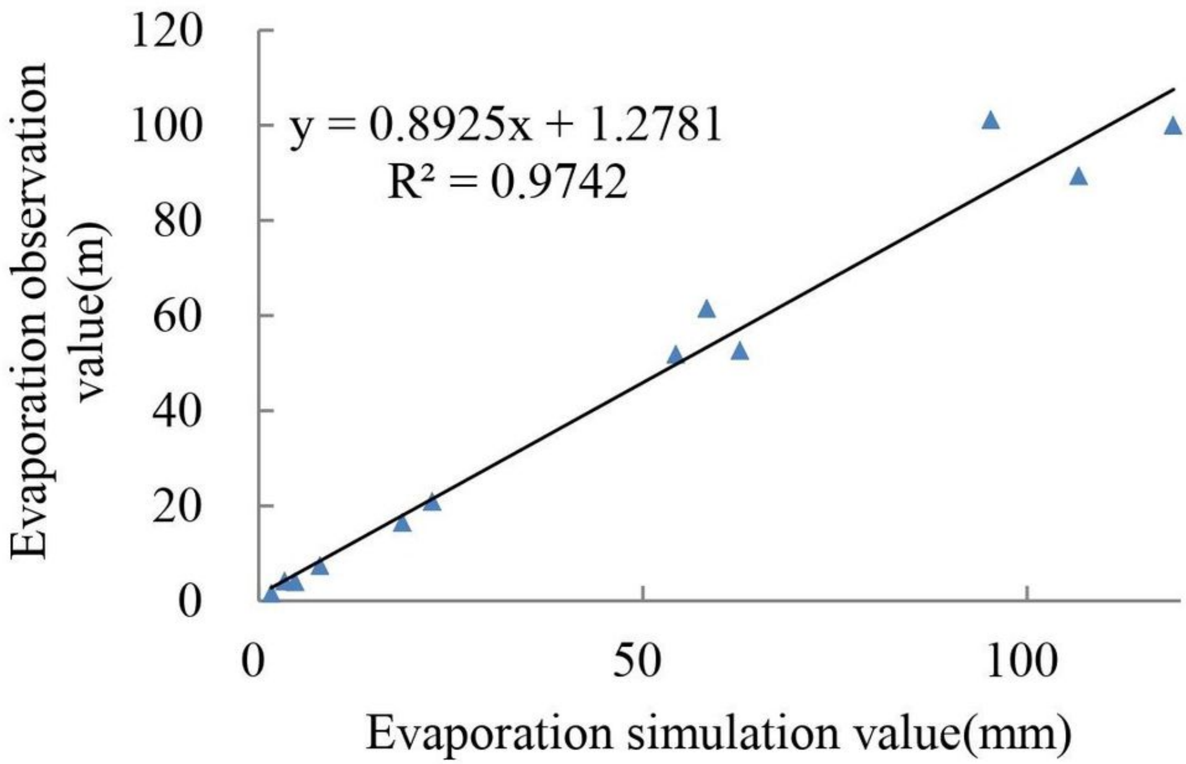

Figure 6

Scatter diagram of evapotranspiration simulation value and observation value of Ziya River Basin in 2009

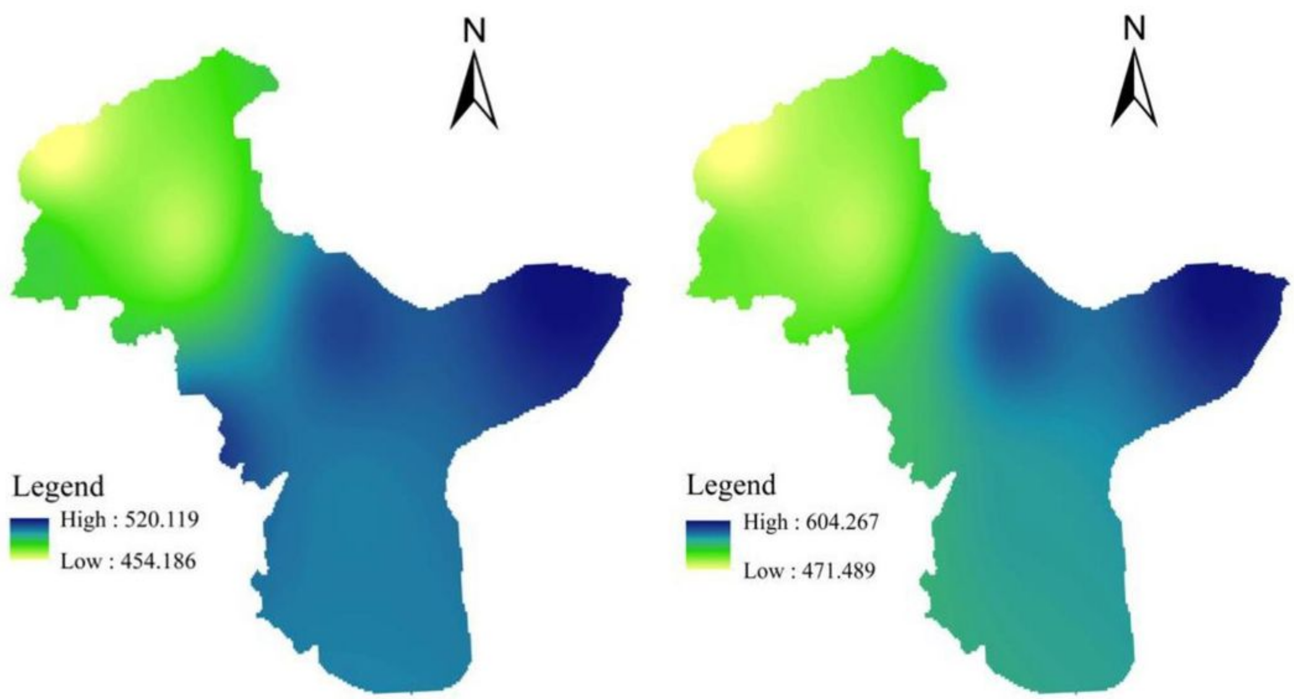

Figure 7

Spatial distribution of evapotranspiration observation value (left) and simulation value (right) in Ziya River Basin in 2008 Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

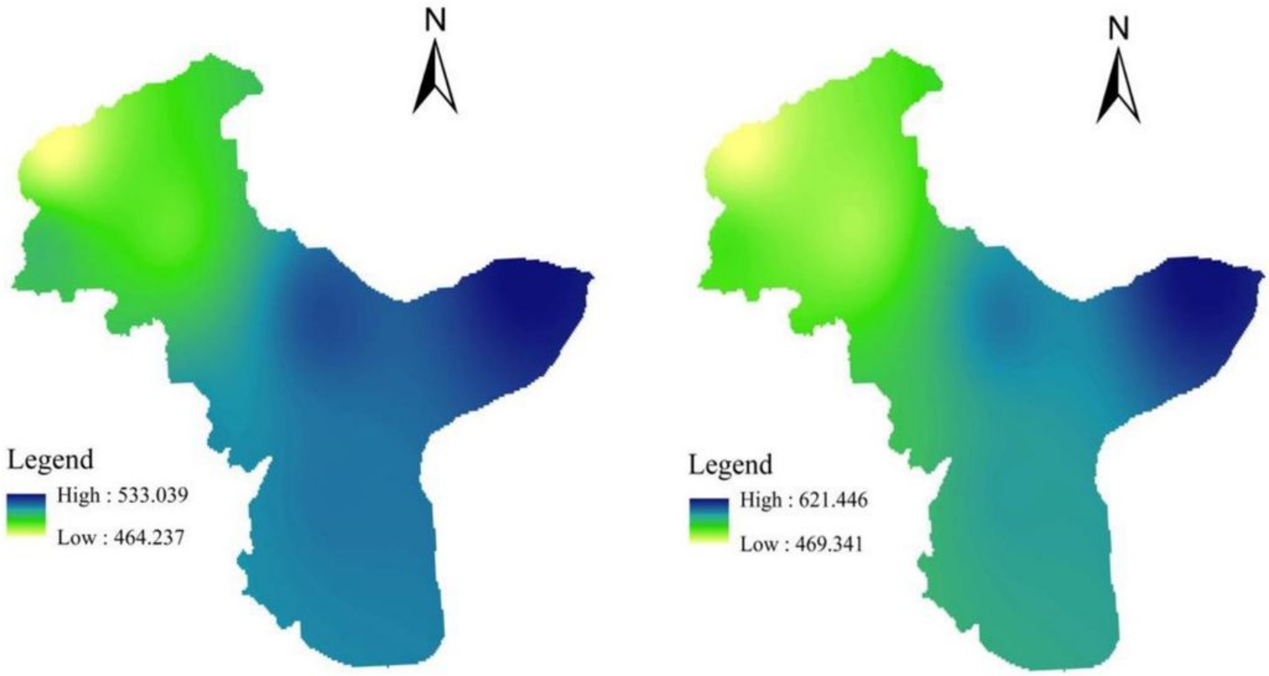

Figure 8

Spatial distribution of evapotranspiration observation value (left) and simulation value (right) in Ziya River Basin in 2009 Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.