Evapotranspiration management based on the application of SWAT for balancing water consumption: A case study in Guantao, China

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Rapid social and economic development results in increased demand for water resources. This can lead to the unsustainable development and exploitation of water resources which in turn causes significant environmental problems. Conventional water resource management approaches, such as supply and demand management strategies, frequently fail to restore regional water balance. This paper introduces the concept of water consumption balance, the balance between actual evapotranspiration (ET) and target ET, and establishes a framework to realize regional water balance. The framework consists of three stages: (1) determination of target ET and actual ET; (2) quantification of the water-saving requirements for the region; and (3) reduction of actual ET by implementing various water saving management strategies. Using this framework, a case study was conducted for Guantao County, China. The SWAT model was utilized to aid in the selection of the best water saving management strategy by comparing the ET of different irrigation methods and crop pattern adjustments. Simulation results revealed that determination of SWAT model parameters using remote sensing ET is feasible and that the model is a valuable tool for ET management. Irrigation was found to have a greater influence on the ET of winter wheat as compared to that of maize, indicating that reduction in winter wheat cultivation is the most effective way to reduce regional ET. However, the effect of water-saving irrigation methods on the reduction of ET was not obvious. This indicates that it would be difficult to achieve regional ET reduction using water-saving irrigation methods only. Furthermore, selecting the best water saving management strategy by relying solely on the amount of reduced ET was insufficient, because it ignored the impact of water conservation measures on the livelihood of the agricultural community. Incorporating these considerations with our findings, we recommend changing the current irrigation method to sprinkler irrigation and replacing 20% of the winter wheat-maize cultivated area with cotton, as the best strategy to achieve water balance in the study area.

Keywords. Water consumption balance; target evapotranspiration; actual evapotranspiration; SWAT.

1. Introduction

Water is one of the most indispensable natural resources for human survival and development

(Vörösmarty *et al.* 2010). Socio-economic development and an increasing population, combined with the effects of climate change, mean

that water scarcity has become a critical issue that attracts global attention (Frederick and Major 1997; Vörösmarty *et al.* 2000; Forsee and Ahmad 2011; Dawadi and Ahmad 2013; DeNicola *et al.* 2015). In the past, approaches to managing water resources have focused on increasing the water supply through developing new water diversion, pumping, transfer and storage projects, in order to satisfy increasing water needs (Gleick 1998; Wu *et al.* 2014). However, water supply management considers water demand as a requirement that must be met, leading to a decrease in natural flows, resource wastage, and pollution problems (Barnett and Pierce 2008; Wang *et al.* 2011; Pengra 2012). Thus, driven by environmental protection concerns, there is an increasing need for the implementation of water saving measures that focus on the demand side.

Water demand management is an essential complement to supply management, which seeks to make water use more efficient and sustainable through modifying patterns of water demand, lowering water demand itself, and reducing losses during water movement (Brooks 2006). Effective demand management can contribute to a slower increase in water demand, relieving the growing stress on water resources associated with population increases and climate change. However, it is difficult to fundamentally decrease water demand. With the continuous growth in water demand, water supplies in many countries are insufficient to satisfy their current urban, industrial, environmental, and agricultural water requirements (Perry *et al.* 2009; FAO 2012; Gallopín 2012; UNESCO 2012).

Irrigation plays a crucial role in crop production globally, insofar as approximately 69% of the world's fresh water withdrawals are used for crop irrigation (FAO 2014). As rapid economic development continues, urban areas are allocated priority over water resources (Beltran 1999; Wang *et al.* 2001), requiring irrigated agricultural regions to become more efficient in their use of the available water (Jury and Vaux 2006; Rockstrom *et al.* 2007). Water conservation is often used synonymously with water demand management in irrigation (Russell and Fielding 2010). Conventional irrigation systems mainly rely on engineering measures to improve irrigation efficiency, including the reduction of channel and field leakage, channel return water, and drainage water. These measures are generally thought to conserve more water, and hence make more water available for cities and

the environment, as compared to flood irrigation (Ward and Pullido-Velazquez 2008). However, the water saved using these conventional water-saving irrigation technologies cannot all be recognized as real water savings (Davenport and Hagan 1982).

Water conservation measures can be categorized into efficiency and resource measures (Gardner and Stern 1996). Water savings achieved using efficiency measures tend to increase crop yield for the same volume of water consumption. Consequently, due to the pursuit of increased crop production, the absolute volume of water saved using efficiency measures is insignificant. Water savings achieved using resource measures include a recoverable and irrecoverable fraction (Davenport and Hagan 1982). When the conserved water can be reused in other areas or for expanded production, it is considered to be recoverable water. For water resources in water scarce areas, farm efficiency improvements may allow for more irrigated acreage or permit more water intensive crops to be grown, but the volume of recoverable water generally cannot satisfy new water requirements, which increase demand and, consequently, water shortages. Irrecoverable water refers to the amount of water that is consumed by evapotranspiration (ET) and cannot be reused. Reducing the volume of irrecoverable water is the real water saving in a given area. Thus, at the basin or regional level, limiting irrecoverable water depletion, and achieving water balance is critical.

Evapotranspiration is the transport of water from the Earth's surface to the atmosphere, and represents the main depletion of water within a basin or region (Falkenmark and Rockström 2004). Initially, ET was only considered by the field of irrigation research. However, in December 1998, the World Bank proposed ET management as the main factor for maintaining regional water balance in water saving irrigation projects in China. Consequently, ET management expanded from agricultural irrigation to regional water resource management, representing a theoretical leap in water management. Now, ET management receives extensive attention, and is the most important aspect of water management. ET is widely measured and monitored under different land uses and spatial scales. However, little research has been done on the use of ET management to guide structural changes of water use in basins or regions to achieve water balance. A notable exception is the work of Wu *et al.* (2014), which describes a framework for water resource management based on ET

at the basin scale, and divides ET management into four steps. This work presents a new approach to water management, but the challenge of how to use the concept to guide the practical application of alternative water management strategies, and quantify their effects on regional ET, needs further study.

This study introduces the concept of water consumption balance, and uses a physically based simulation model, the SWAT model, to assist ET management in Guantao County, China. The study has the following specific objectives: (1) define the steps to achieve regional water balance based on the concept of water consumption balance; (2) assess the capabilities of the SWAT model for regional ET management; and (3) choose the most appropriate water saving management strategy to achieve regional water balance in the study area.

2. The concept of water consumption balance

Evapotranspiration, which occurs during processing of water cycle and the utilization of water resources, is considered to be irrecoverable water consumption. According to the principle of water balance, the water balance equation of a region can be expressed as:

$$ET = P + I - O \pm \Delta V \quad (1)$$

where ET is evaporation and transpiration of a region, P is precipitation, I and O are water inflows and outflows, respectively, and ΔV is the variation in water storage. Under average annual conditions, $\Delta V = 0$, and the water balance equation (1) is expressed as:

$$ET_n = P + I - O_n \quad (2)$$

which represents the state of the region in a natural state, with humans having a small impact. However, when water resources in a region are excessively utilized, water balance will not be maintained as per equation (2). Under these conditions, the natural flow O_n decreases, the water table recedes (ΔV is negative), ET increases, and the water balance equation for average annual conditions is as follows:

$$ET_a = P + I - O_a - \Delta V_g \quad (3)$$

where P and I are basin precipitation and inflows, ET_a and O_a are actual ET and inflows under intensive human impacts, and ΔV_g is overexploited groundwater. Assuming regional precipitation and inflows remain constant, equation (3) can be rewritten as:

$$ET_a = ET_n + O_n - O_a - \Delta V \quad (4)$$

and

$$\Delta ET = ET_a - ET_n = O_n - O_a - \Delta V. \quad (5)$$

It is apparent that the increased water consumption of a region is contributed of the reduction of runoff and the over-exploitation of groundwater. Considering the sustainable utilization of a water resource, it is necessary to preserve the environmental flow (so that O_a is not less than river ecological flows) and not to overexploit groundwater ($\Delta V_g = 0$). The ΔET cannot be increased indefinitely. As such, the ET from a region must be limited to a single value, called the target ET (ET_{tar}). When actual ET (ET_a or ET_{act}) is larger than ET_{tar} , the utilization of water resources in the region is unsustainable, and it becomes necessary to take water-saving measures to reduce water consumption, so that the ET_{act} does not exceed the ET_{tar} . Thus, the concept of water consumption balance refers to the balance between ET_{act} and ET_{tar} .

2.1 Confirmation of target ET

Target ET (ET_{tar}) is the maximum allowable value for water consumption in a region to sustainably maintain water resources. This value should incorporate future regional socioeconomic development, non-continuous overdrafts of groundwater, and ensure that ecological flow in the river system can be preserved. The confirmation of ET_{tar} should be based on formula (2), in which precipitation can be measured at hydrological and meteorological stations, and inflows are measured at hydrological stations or major control points. Inflows include surface/underground runoff originating outside the region, and water that has been transferred through water diversion projects. Outflows include surface/underground runoff and transferred water, which should consider downstream ecological and environmental water demands.

When water balance is achieved, commonly, the outflows exceed inflows, and ET is lower than precipitation. In contrast, when water balance is not achieved, the opposite is generally true. If outflows are equal to inflows, with consideration given to minimum river ecological demands, then regional water resources can be maintained sustainably as ET_{tar} does not exceed mean annual precipitation. Therefore, ET_{tar} should equal mean annual precipitation. When the water supply in a region includes transferred water, ET_{tar} should also include this volume of water.

2.2 Determination of actual ET

Actual ET (ET_{act}) is the volume of water consumed in a region under the influence of the natural water cycle and artificial water resource utilization. The ET of a region includes ET from domestic, industrial, environmental, agricultural, and other sources (such as the ET from non-cultivated land).

$$ET_{act} = ET_{dom} + ET_{ind} + ET_{env} + ET_{agr} + ET_{oth}. \quad (6)$$

The various ET components in this equation can be obtained by direct calculation and indirect estimation. Due to the complexity of domestic ET (ET_{dom}) and industrial ET (ET_{ind}), they are estimated indirectly. ET_{dom} can be estimated using population and per capita water consumption data, while ET_{ind} can be calculated using production data and the water consumption per unit of product (Wu *et al.* 2014). The environmental ET (ET_{env}), agricultural ET (ET_{agr}) and other ET (ET_{oth}) can be obtained using hydrological model simulations (Abbott *et al.* 1986; Beasley and Hyggins 1995; Arnold *et al.* 1996) or remote sensing (Su 2002; Bastiaanssen *et al.* 2005; Allen *et al.* 2007; Wu *et al.* 2012).

2.3 Reduction of actual ET while aiming for target ET

In areas affected by water shortages, reducing actual ET to the target ET can be achieved by decreasing excessive domestic, industrial, environmental, and agricultural water consumption. In conjunction with socioeconomic development, ET_{dom} , ET_{ind} and ET_{env} will inevitably rise. Thus, decreasing ET_{agr} is the primary means to reduce ET_{act} . Reducing agricultural water consumption

can be achieved by implementing engineering and agronomic water-saving measures. Engineering water-saving measures focus on reducing the volume of water extraction, as well as reducing water consumption from exposed water surfaces, water logged areas, and the excessive irrigation of farmland. Agronomic water-saving measures are the most effective methods to reduce water consumption, and these include straw mulching, conservation tillage, changing crop varieties, and so on (Blanke *et al.* 2007). In this study, we model scenarios using different irrigation methods and crop pattern adjustments to achieve water consumption balance targets in the region by reducing excessive agricultural water consumption.

In areas where water for irrigation purposes predominates water use, domestic and industrial water consumption is often ignored for simplicity. Reducing ET_{act} to ET_{tar} requires the assistance of water management models, which are used to select the best water saving management strategies to satisfy regional water-saving requirements through the comparison of various water management scenarios.

3. Case study

3.1 The SWAT model

A number of distributed watershed models, such as MIKE SHE (Abbott *et al.* 1986), ANSWERS (Beasley and Hyggins 1995), IHDM (Beven *et al.* 1987) and SWAT (Arnold *et al.* 1996), have been used for water resources management. Of these models, the physically based SWAT model has been widely used for assessing the impacts of different land use patterns and water resource management strategies on watershed hydrological cycles, due to its many distinctive features (Ritchie 1972; Su *et al.* 2003; Holvoet *et al.* 2007; Van Liew *et al.* 2007; Cao *et al.* 2009; Zhang *et al.* 2010). SWAT subdivides a catchment into sub-basins and further divides them into individual hydrologic response units (HRUs) as homogeneous blocks with respect to land use, soil properties and management. However, the ARCGIS interface of the SWAT model that pre-processes the digital elevation model (DEM) data cannot automatically extract the river network from the DEM of the plain. Consequently, in this study, the sub-watersheds and HRUs were manually divided into 69 and 483 units respectively, according to a DEM,

Figure 1. Map of Guantao County with the location of rain-gauging stations marked.

soil, and land use maps. The Penman–Monteith method was selected to estimate the ET in this model (Neitsch *et al.* 2005; Gao *et al.* 2008).

3.2 Study area

Guantao County covers a total area of 456.3 km² and is located in the Haihe River Basin, between 26°27′–36°47′N and 115°06′–115°28′E in north-eastern China (figure 1). Regional terrain is relatively flat and gently levels-off from the SW to the NE. There are no rivers traversing Guantao County, however, the Weiyun River delineates most of the eastern boundary of the county, and the artificial diversion channel, the Wexi Canal, flows through the region from south to north. Guantao County is situated in a semi-humid to semi-arid climatic zone. The annual average temperature

is approximately 13.4°C, and the mean average precipitation is 549.4 mm. The precipitation is uneven in spatial and temporal distribution, with more than 60% of the precipitation occurring during June–September. The county has 29,000 hectares of irrigated land area, much of which is used to cultivate the crops of winter wheat and maize. More than 89% of the region’s water consumption is used for agricultural irrigation. Due to a serious shortage of surface water and increasing water demand driven by rapid economic development, groundwater has become overexploited in the region. Groundwater declined from a depth of 14.9 m in 1994 to 23.0 m in 2012, equating to an annual average fall in groundwater levels of 0.45 m. Resolving the continuous overexploitation of groundwater is an urgent requirement for the local authorities.

Table 1. SWAT parameters ranked in order of sensitivity to ET.

Parameter	Definition	Rank
ESCO.hru	Soil evaporation compensation factor	1
SOL_AWC.sol	Available water capacity of the soil layer	2
CN2.mgt	SCS runoff curve number	3
EPCO.hru	Plant uptake compensation factor	4
CANMX.hru	Maximum canopy storage	5
SOL_K.sol	Saturated hydraulic conductivity	6
GW_REVAP.gw	Groundwater revap coefficient	7
GW_DELAY.gw	The delay time of groundwater	8

3.3 Model inputs and outputs

The SWAT model requires a variety of inputs. To establish the model, the following datasets were prepared: (1) DEM (1×1 km) provided by the Haihe River Water Conservancy Commission, MWR; (2) 1:10,000 scale land-use map (2000) provided by the government of Guantao County; (3) a 1:100,000 scale soil map generated from the Hebei Soil Handbook; (4) daily climate data (precipitation, wind speed, relative humidity, maximum and minimum air temperature and solar radiation) time series from 2001 to 2005 provided by the Guantao Bureau of Meteorology; and (5) monthly ET data from 2002 to 2005 produced by the ETWatch model (Wu *et al.* 2008).

3.4 Model calibration and validation

The model must be calibrated and validated using a long series of observed data, before it can be used to study the impact of various management scenarios. In this paper, a warm-up period from January 1, 2001 to December 31, 2001 was set for the model, allowing state variables to assume realistic initial values for the calibration period. The model was then calibrated using remote sensing derived ET data from January 2002 to December 2003, and the remaining ET data from January 2004 to December 2005 were used as the validation period.

Statistical measures were used to evaluate model performance (Santhi *et al.* 2006; Moriasi *et al.* 2007). In this study, Nash–Sutcliffe efficiency (NSE; Nash and Sutcliffe 1970), coefficient of determination (R^2), and root mean square error (RMSE; Yang *et al.* 2009; Singh *et al.* 2010) were used

$$NSE = \frac{\sum_{i=1}^T (ET_{ob,t} - \overline{ET}_{ob})^2 - \sum_{i=1}^T (ET_{ob,t} - ET_{s,t})^2}{\sum_{i=1}^T (ET_{ob,t} - \overline{ET}_{ob})^2} \quad (7)$$

$$R^2 = \left[\frac{\sum_{i=1}^T (ET_{ob,t} - \overline{ET}_{ob})(ET_{s,t} - \overline{ET}_s)}{\sqrt{\sum_{i=1}^T (ET_{ob,t} - \overline{ET}_{ob})^2 \sum_{i=1}^T (ET_{s,t} - \overline{ET}_s)^2}} \right]^2 \quad (8)$$

$$RMSE = \sqrt{\frac{1}{T} \sum_{i=1}^T (ET_{ob,t} - ET_{s,t})^2} \quad (9)$$

where $ET_{ob,t}$ and $ET_{s,t}$ are the observed and simulated data values at time unit t , respectively, and $t = 1, 2, \dots, T$; $\overline{ET}_{ob}$ and $\overline{ET}_s$ are the mean values for the total evaluation period. T is the total number of observations.

3.5 Parameter sensitivity

There are many parameters that influence the ET process in the SWAT model, and as such, analyzing parameter sensitivity is an important step in understanding the performance of the model. The parameter sensitivity analysis helped to reduce parameter dimension and time spent in the model calibration period. In SWAT, the method Latin Hypercube One-factor-At-a-Time (LH-OAT) was used for sensitivity analysis (Griensven 2005). Through the parameter sensitivity analysis, we selected the eight most sensitive parameters (ESCO, SOL_AWC, CN2, EPCO, CANMX, SOL_K, GW_REVA, GW_DELAY), and then manually adjusted these parameters. The parameter sensitivity results, ranked from most to least sensitive, are listed in table 1.

3.6 Scenarios description

After calibration and validation, the SWAT model can be used to analyze the impacts of different irrigation methods and crop pattern adjustments on regional ET. For each scenario, local agromonic practices were adopted and kept constant.

Table 2. The volume of water used per irrigation and irrigation frequency under the three irrigation methods.

Irrigation method	Wheat-maize		Cotton	
	Volume of water per irrigation (mm)	Irrigation frequency	Volume of water per irrigation (mm)	Irrigation frequency
Ditch plus white plastic pipe (D+P)	83	5	83	2
Low pressure pipe	66	5	66	2
Sprinkler	49	5	49	2

Note: The five irrigation dates for winter wheat-maize are March 10, April 20, June 15, July 15, and October 10. The two irrigation dates for cotton are April 22 and June 8.

Table 3. Detailed descriptions of the water management scenarios.

Scenario no.	Irrigation method	Crop pattern adjustments	Objective of scenario analysis
S1	(D+P)	Maintain the status quo	Effects of irrigation on ET
S2	Low pressure pipe	Maintain the status quo	
S3	Sprinkler	Maintain the status quo	
S4	(D+P)	T1	Effects of crop pattern adjustment on ET
S5		T2	
S6		T3	
S7	Low pressure pipe	T1	Water management scenarios comparison
S8		T2	
S9		T3	
S10		T4	Water management scenarios comparison
S11		T5	
S12		T6	
S13	Sprinkler	T1	
S14		T2	
S15		T3	
S16		T4	
S17		T5	
S18		T6	

In this study, three irrigation methods including ditch plus white plastic pipe (D+P) irrigation, low pressure pipe irrigation, and sprinkler irrigation were simulated to analyze the effects of irrigation on ET. The D+P irrigation method has been widely used throughout Guantao County, and as such represents the current irrigation scheme of the region. Low pressure pipe irrigation and sprinkler irrigation are two water-saving irrigation methods implemented in the scenarios analysis, which reduced irrigation water by 20 and 40%, respectively, over D+P. The volume of water used per irrigation and the irrigation frequency under the three irrigation methods are shown in table 2 (Agricultural Bureau of Guantao County). During predictive simulations, six crop pattern adjustment modes were implemented for the different irrigation methods. Details of the six

adopted crop pattern adjustment modes are given as:

- T1. Winter wheat-maize planting area decreased by 10%.
- T2. Winter wheat-maize planting area decreased by 20%.
- T3. Winter wheat-maize planting area decreased by 30%.
- T4. Winter wheat-maize planting area decreased by 10% and replaced with cotton.
- T5. Winter wheat-maize planting area decreased by 20% and replaced with cotton.
- T6. Winter wheat-maize planting area decreased by 30% and replaced with cotton.

According to the analysis, there were a total of 18 scenarios used to analyze the impact of different water saving management strategies on ET.

Table 4. The fitted values after calibration of sensitive parameters.

Parameter	Final value	Parameter	Final value
ESCO	0.127	CANMX	10
SOL_AWC	0.10–0.11	SOL_K	0.35–173.20
CN2	71	GW_REVAP	0.2
EPCO	0.175	GW_DELAY	30

Figure 2. Comparison between remote sensing ET and calibrated ET during 2002–2003.

Figure 3. Linear regression between remote sensing ET and calibrated ET during 2002–2003.

Detailed descriptions of the scenarios are given in table 3.

4. Results and discussion

4.1 Calibration and validation of SWAT

The results of the sensitivity analysis are given in table 4. CN2, EPCO, ESCO, CANMX and soil variables were the most sensitive parameters, and

Figure 4. Comparison between remote sensing ET and validated ET during 2004–2005.

Figure 5. Linear regression between remote sensing ET and validated ET during 2004–2005.

it is apparent that regional ET is mainly affected by surface runoff, soil type and vegetation species.

The comparison between calibrated ET and remotely sensed ET is shown in figure 2, and confirms that the calibration results during the year 2002–2003 matched reasonably well with the remotely sensed ET. A linear regression analysis of the remotely sensed ET and the simulated ET is shown in figure 3, which generated a coefficient of determination (R^2) of 0.94. Additionally, the Nash-Sutcliffe efficiency (NSE) and root mean square error (RMSE) values from the calibration were calculated as 0.94 and 9.89 mm, respectively, indicating that the SWAT model parameters were optimized. A good agreement between simulated values and remotely sensed values was also achieved during the validation results. The values of R^2 , NSE, RMSE were 0.90, 1.0 and 14.5 mm, respectively, for the year 2004–2005. It is apparent from figures (2–5) that the

Table 5. Simulated ET of D+P irrigation (S1), low pressure pipe irrigation (S2) and sprinkler irrigation (S3) (mm).

Scenarios	2002	2003	2004	2005	Average
S1	521.2	695.5	560.1	660.7	609.4
S2	511.9	692.7	549.9	655.6	602.5
S3	483.8	678.7	524.4	639.8	581.7

SWAT simulated ET is basically consistent with the remotely sensed ET, that the SWAT performed very well in predicting ET, and is thus useable in a variety of management and planning simulations.

4.2 Effect of different water management scenarios on ET

4.2.1 Effects of irrigation on ET

Irrigation had a great impact on the regional hydrological cycle, especially on the accurate simulation of ET. In order to elucidate the effect of irrigation on water balance, three different scenarios, including D+P irrigation (S1), low pressure pipe irrigation (S2) and sprinkler irrigation (S3), were simulated. The results of the simulations are shown in table 5, which reveal that low-pressure pipe irrigation and sprinkler irrigation reduced ET by 1.12 and 4.55%, respectively, over the D+P irrigation method. Low pressure pipe irrigation and sprinkler irrigation could save 20 and 40% water, respectively, over the D+P irrigation method. However, the amount of water saving only refers to the reduction in water extraction, because ET did not show the same decreasing tendency, indicating that the relationship between reduced water extraction and declining ET is not proportional. This can be attributed to the fact that low-pressure pipe irrigation and sprinkler irrigation only reduce the volume of water loss relative to D+P irrigation during the process of transpiration. Because a component of the irrigation water from D+P irrigation returns to groundwater through leakage, there is little overall difference in ET between the three irrigation patterns. Consequently, the effect of low-pressure pipe irrigation and sprinkler irrigation on ET is not very significant. Put simply, water-saving irrigation methods are not very effective in reducing ET.

Furthermore, although the effect of winter wheat irrigation on ET is obvious, there is little effect on ET during the maize growth period. In order to

reveal the effect of irrigation on ET, the 43rd HRU (an area of 3.5 km²) is examined in greater detail. A winter wheat-maize rotation is implemented, and two scenarios, S1 and S3 are simulated. The results are shown in figure 6, which highlight that the effect of irrigation on the ET of winter wheat, when turning green to mature, was significant, but the effect of irrigation on the ET of maize was very small. For winter wheat, S3 uses less irrigation water as compared to S1 by 40%, and ET is reduced by 5.8%. For maize, the reduction in irrigation water is the same (40%), however the reduction in ET is only 1.9%. This discrepancy exists because the growth period for maize coincides with the region's rainy season, when demand for irrigation is low, while the growing season for winter wheat is dry, and the dependence on irrigation is higher.

4.2.2 Effects of crop pattern adjustments on ET

Crop pattern adjustments can alter the hydrologic response by changing the land cover and land use across watersheds or regions. Quantifying the impact of crop pattern adjustments on watershed hydrology was one of the important prerequisites for the scenario settings. In this study, scenarios in which the winter wheat-maize planting area was decreased by 10, 20 and 30% were simulated. The results of the simulations are shown in table 6, and it is apparent that ET reductions caused by crop pattern adjustments in the wet years were smaller than in the dry years. In dry years, when precipitation was low, and crop growth mainly depended on irrigation. Consequently, crop pattern adjustment could greatly reduce the volume of water required for irrigation and the corresponding ET. Conversely, in wet years, irrigation demand was small. Precipitation could meet the majority of crop water requirements, and as such the impact of crop pattern adjustments to reduce irrigation water and the corresponding ET was not significant. This indicates that, in arid to semi-arid areas, where irrigation predominates, crop pattern adjustment is one of the most effective water saving methods.

4.3 Effect of different water management scenarios on surface runoff and groundwater recharge

Different irrigation methods and crop pattern adjustments not only affect regional ET, but also have an influence on other hydrological variables. In this paper, based on the above analysis of

Figure 6. Comparison of monthly average ET values (2002–2005) under scenarios S1 and S3.

Table 6. *ET and impacts of decreasing winter wheat–maize planting area.*

Year	Precipitation mm	S1 mm	S4		S5		S6	
			mm	%	mm	%	mm	%
2002	384.8	521.2	507.0	−2.7	492.5	−5.5	478.2	−8.3
2003	880.0	695.5	688.4	−1.0	681.3	−2.0	674.2	−3.1
2004	374.6	560.1	547.3	−2.3	534.2	−4.6	521.3	−6.9
2005	689.6	660.7	652.5	−1.2	644.1	−2.5	635.9	−3.8

ET, the impact of different water management scenarios on regional surface runoff and groundwater recharge is considered. These results can be seen in tables 7 and 8. It is apparent that surface runoff is declining as water savings increase; for example, from S1 to S3. This can be attributed to the fact that, as water savings increase, there is less ineffective irrigation water discharged, and consequently lower soil moisture content. The same level of precipitation onto drier soil will therefore produce less surface runoff.

Using the same irrigation mode, as the irrigated area gradually reduces, surface runoff shows an increasing trend. This is due to the lack of crop interception, as shown in scenarios S4–S6, S7–S9, and S13–S15. However, when the irrigated area of winter wheat–maize is replaced with cotton, the effect of crop interception increases and the surface runoff is gradually reduced. This is demonstrated by S7 *vs.* S10, and S13 *vs.* S16.

Generally, groundwater recharge is inversely related to surface runoff. For example, S4–S6, S7–S9, and S13–S15 highlight that, when the irrigated area decreases and the same irrigation method

Table 7. *Simulated surface runoff under different water management scenarios (mm).*

Scenarios	2002	2003	2004	2005	Average
S1	31.6	137.0	7.0	94.9	67.6
S2	30.0	136.4	6.1	93.6	66.5
S3	27.5	135.1	4.3	91.1	64.5
S4	32.4	140.5	7.0	97.7	69.4
S5	33.1	144.1	7.0	100.6	71.2
S6	33.9	147.7	7.0	103.5	73.0
S7	30.8	139.4	6.1	90.2	66.6
S8	31.6	143.1	6.1	93.7	68.6
S9	32.3	146.7	6.1	97.0	70.5
S10	32.8	134.0	6.8	90.0	65.9
S11	34.0	136.3	7.1	92.6	67.5
S12	35.6	136.6	7.5	95.1	68.7
S13	28.3	136.6	4.3	86.7	64.0
S14	29.1	140.5	4.3	90.3	66.0
S15	29.8	144.3	4.3	93.7	68.0
S16	30.0	131.9	4.7	86.5	63.3
S17	30.8	133.4	4.8	88.5	64.4
S18	32.4	134.4	5.1	91.3	65.8

is used, the area of bare land increases, and the recharge of groundwater decreases, which is the

Table 8. Simulated groundwater recharge under different water management scenarios (mm).

Scenarios	2002	2003	2004	2005	Average
S1	15.7	104.7	2.9	57.4	45.2
S2	13.4	103.8	1.9	55.0	43.5
S3	10.6	103.3	0.2	49.7	41.0
S4	14.4	98.3	2.6	52.7	42.0
S5	13.1	91.7	2.3	47.8	38.7
S6	11.8	85.3	2.1	43.0	35.5
S7	12.3	95.5	1.7	33.7	35.8
S8	11.2	89.2	1.5	31.0	33.2
S9	10.1	83.0	1.3	28.2	30.7
S10	12.6	95.9	1.7	34.2	36.1
S11	12.0	92.7	1.6	32.8	34.8
S12	11.3	88.0	1.5	30.8	32.9
S13	9.8	89.6	0.2	31.0	32.6
S14	8.9	84.0	0.2	28.5	30.4
S15	8.1	78.5	0.1	26.1	28.2
S16	10.1	90.8	0.2	31.7	33.2
S17	9.6	88.1	0.2	30.5	32.1
S18	9.1	84.0	0.2	28.8	30.5

opposite to the observed behavior of surface runoff. Furthermore, when the reduced irrigated area is replaced with cotton, the amount of groundwater recharge decreases and runoff increases as the area of crop replacement increases. This is because the cotton crop uses less water as compared to the winter wheat-maize crop (S10–S12 and S16–S18). However, in S1–S3, groundwater recharge is positively correlated with surface runoff because, as water savings increase, groundwater recharge decreases as the volume of ineffective irrigation water is reduced.

4.4 Assessment of irrigation management scenarios

Simulated ET for low-pressure pipes and sprinklers under different crop pattern adjustments are given in table 9. It is apparent that the main factor influencing regional ET is precipitation. Regional ET was higher in wet years as compared to dry years, which could not be altered by improvements in irrigation methods or adjustments to the crop pattern. Regional ET is positively correlated with precipitation. Precipitation not only had a significant impact on ET during the current year, but also had an impact on ET for the following year. For example, in 2004, the regional precipitation was 374.6 mm, which was lower than in 2002, but the simulated ET in 2004 was larger as compared to

Table 9. Simulated ET for low pressure pipe and sprinkler irrigation using different crop pattern adjustments (mm).

Precipitation and scenarios	2002	2003	2004	2005	Average
Pcp	384.8	880.0	374.6	689.6	582.3
S7	498.3	685.9	537.8	646.3	592.1
S8	484.5	679.0	525.5	638.4	581.8
S9	470.8	672.2	513.3	630.6	571.7
S10	498.1	684.1	540.5	646.7	592.3
S11	490.5	679.9	534.3	642.3	586.7
S12	479.9	673.6	526.5	636.5	579.1
S13	472.5	672.7	514.4	630.0	572.4
S14	461.0	667.3	504.0	623.4	563.9
S15	449.7	661.9	493.8	616.9	555.6
S16	471.5	671.3	515.9	629.3	572.0
S17	465.1	668.0	510.5	625.4	567.2
S18	455.8	663.0	503.5	619.9	560.5

2002. The abundant rainfall in 2003 supplemented soil water and groundwater through infiltration, and thus maintained relatively wet regional subsurface conditions. Thus, the regional simulated ET in 2004 was influenced by the high rainfall in 2003.

Using low-pressure pipe and sprinkler irrigation, when the winter wheat-maize planting area was reduced by 10%, the simulated average ET from 2002 to 2005 was 592.1 mm (S7) and 572.4 mm (S13), respectively. When 10% of the growing area of winter wheat-maize was replaced with cotton, the simulated average ET from 2002 to 2005 was 592.3 (S10) and 572.0 mm (S16), respectively. This indicates that replacing 10% of the growing area of winter wheat-maize with cotton did not consume significantly more water than simply reducing the planting area of winter wheat-maize by 10%, because cultivating cotton results in relatively little ET. However, as the area of the winter wheat-maize planting was further reduced, water savings were substantially larger when the land was left in fallow as compared to being replaced with cotton. Despite these findings, reducing the winter wheat-maize planting area would inevitably affect agricultural income which can be seen in figure 7, thus decreasing the enthusiasm of farmers to employ water-saving techniques. From scenarios S7–S9 and S13–S15, with the gradual reduction of the winter wheat-maize planting area, the yield and monetary value are also reduced proportionately. Selecting the best water management strategy based on the amount of reduced ET in this instance is likely to encounter resistance during

Figure 7. Average crop yield and monetary value of scenarios S7 to S18 in 2002–2005.

implementation. To ameliorate this, we follow the principle of maximizing water savings, while not reducing agricultural income too much, during the selection of the appropriate irrigation management strategies in this study.

4.5 Regional water management analysis

Based on precipitation, inflows and outflows, and the amount of water transferred via the South–North Water Transfer Project, target ET for Guantao County was determined to be 566.0 mm (ignoring domestic and industrial water consumption). The average ET for the county between 2002 and 2005 was 627.9 mm (Wu *et al.* 2008), which does not include domestic and industrial ET, and exceeds the target ET by 61.9 mm. To reduce excessive ET, 12 water saving management scenarios (S7–S18) were simulated. A comparison of the simulated ET for low pressure pipe irrigation and sprinkler irrigation using different crop pattern adjustments is shown in figure 8. Six scenarios of crop pattern adjustments were simulated using low pressure pipe irrigation, and these show that low pressure pipe irrigation was not able to save enough water to meet the target ET for Guantao County. For example, in the best water conservation scenario S9, in which the winter wheat-maize cultivated area was reduced by 30%, simulated ET was still 5.7 mm higher than the target ET. Hence, we conclude from these results that low pressure

pipe irrigation is not a suitable water saving measure in Guantao.

Six scenarios of crop pattern adjustments were also simulated using sprinkler irrigation. Results show that simulated ET for S14, S15, and S18 were lower than the target ET level, while simulated ET for S17 was only 0.2% larger than target ET. Of the models that had simulated ET lower than target ET, S15 was rejected because a reduction of 30% of the winter wheat-maize planting area would significantly affect agricultural incomes. As shown in figure 7, the crop yield and income of S15 are 232.8×10^3 t and 601.9×10^6 CNY, respectively, markedly less as compared to other scenarios. Both S14 and S17 reduced the planting area of winter wheat-maize by 20%, however, S17 replaced the winter wheat-maize with an alternate, low ET crop of cotton, preserving agricultural income levels. Because it did not preserve agricultural income levels, S14 was rejected. When S17 and S18 are compared, S18 has a greater reduction in ET, however it also results in lower crop yield and agricultural income (figure 7). Furthermore, although S18 ensured that the reduction in overall yield and income were not extensive, the scenario is detrimental to regional food security because the planting area, and hence yield, of winter wheat-maize was significantly diminished. As such, S17 was adopted as the best water saving management strategy to achieve regional water resources consumption balance in Guantao.

Figure 8. Comparison of simulated ET for low pressure pipe irrigation and sprinkler irrigation under different crop pattern adjustments.

5. Conclusions

1. Maintaining water balance as water demand increases is an enormous challenge. Traditional supply and demand management strategies have not achieved this goal based on practical experience. The concept of water consumption balance, which refers to the balance between actual and target ET, converts control of abstractions from surface water and groundwater to water consumption (ET) control, providing a new direction for regional water resource management.
2. The control of regional ET is complex, involving water conservation across many aspects of water use, including domestic, industrial, environmental, and agricultural. However, water consumption for domestic, industrial, and environmental applications is not easy to manage, and consequently, meeting target ET through water conservation in agriculture is critical.
3. The SWAT model can assess changes to ET using various irrigation methods and crop pattern adjustments, and is a valuable tool for investigating ET management. SWAT model parameters can be determined by remote sensing of ET, which in turn provides a means to verify the model.
4. Precipitation is the predominant factor affecting regional ET. Because precipitation during the winter wheat growing season is much less than during the maize growing season, the winter wheat is more dependent on irrigation. Thus, the irrigation of winter wheat has a larger influence on ET as compared to that of maize. Consequently, reducing the area of winter wheat cultivation is the most effective way to reduce regional ET in Guantao County.
5. The reduction of ET by adopting water-saving irrigation methods, such as low-pressure pipe irrigation and sprinkler irrigation, is not as promising as the amount of water these methods save on extraction. While water-saving irrigation methods minimize the wastage of water in the transportation process, their impact on reducing ET is insignificant.
6. It is not appropriate to rely solely on minimizing ET when selecting the best water saving management strategy. To facilitate the support and adoption of water conservation measures by the agricultural community, strategies need to be chosen that benefit farmers in the region. Through comparative analysis of 12 water saving management scenarios, we ultimately recommend scenario S17 as the best water saving management strategy in the study area. Under this scenario, 20% of the planting area for winter wheat-maize is replaced by cotton, and the current irrigation method is changed to sprinkler irrigation. While S17 simulated ET is 1.2 mm larger than target ET, it considers the livelihood of the agricultural community.

7. The estimation of domestic and industrial ET is very difficult when determining actual and target ET levels. To simplify the calculation in this study, domestic and industrial ET were not considered because agricultural water use accounted for approximately 90% of total water use in the Guantao region. In future research, domestic and industrial ET should be accounted for.

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