Estimation of regional water-saving potential using remotely sensed evapotranspiration data

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ABSTRACT

Estimation of regional water-saving potential is useful to develop the appropriate irrigation scheme and manage water resources. A new calculation method of water-saving potential for crops, based on the remotely sensed evapotranspiration (RS ET) data, is presented in this paper. The regional crop water production function was established based on RS ET and RS yield data. And the ET under the highest crop water use efficiency (WUE) was determined by its crop water production function. A regional crop ET quota was proposed by comparing crop water requirement and the ET under the highest crop WUE. The regional water-saving potential in agriculture was determined by selecting a regional crop ET quota as a standard. The results indicated that: (1) the ET quotas for winter wheat and summer maize were 417 and 313 mm, respectively; and (2) as far as the regional water-saving potential for crops is concerned, summer maize is the largest, at 11.77 million m3, followed by winter wheat, at 0.73 million m3; and (3) the water-saving management area and water-saving volumes for main crops among different towns in Daxing county were analyzed. Meanwhile, the major water-saving management towns for wheat and maize were determined. The study will help planners and managers gaining a better insight into water management and water uses of crops.

Keywords: Remote sensing; Evapotranspiration; Crop production; Water use efficiency; Water-saving potential

1. Introduction

The global food crisis was mainly caused by water resources shortage [1,2]. The limit of water resources utilization has been reached or broken in many areas of main grain production, including the North China Plain (NCP). The NCP is the largest region of agricultural production in China [3]. It covers about 18 million ha of farmlands (18.3% of the national total) and produces about 21.6% of the total grain yield in China [4]. Therefore, agricultural production in this region plays an important role in relation to food security and economic development in China [5]. With the rapid development of agriculture and industry along with prolonged drought, there are serious shortage of water resources and serious contradiction between supplies and demands of water resources [6,7]; which has great influence on the development of national economy, improvement of living conditions, and protection of ecological environment [8,9]. In the NCP, irrigation is required to maintain high and steady crop production. However, excessive use of groundwater for irrigation has caused the rapid decline of groundwater levels at an average rate of about 1 m year−1 [10]. Therefore, it is of great importance to estimate the regional water-saving potential in agriculture, reduce agricultural water consumption and restore the groundwater resources [11–13].

Up to now, however, no unified method is available for the calculation and valuation of water-saving potential in...
agriculture [14–16]. According to quantity of water savings, agriculture water-saving potential could be divided into two categories: (a) engineering water-saving potential, defined as the difference between the water withdrawal in the source region and the amount of water delivered to field, and (b) natural water-saving potential, defined as reductions in ineffective evapotranspiration (ET), such as soil evaporation, irrigation water evaporation in fields and irrigation system, namely the real water-saving quantity, the detail could be found in the study by Shen et al. [17]. Due to the difficulty to acquire large-scale ET data by using conventional methods, previous studies mainly focused on the engineering water-saving quantity [18–25]; that is, water loss from canal seepage, operation spills, and field drainage. However, the seepage, spill, and field drainage are not lost and could be reused at the downstream site or by eco-environment [26]. On the other hand, with technical innovations in the field of remote sensing (RS), RS images have such attributes as high spatial-temporal resolution, bidirectional reflectance multi-spectral and others. Therefore, monitoring large-scale ET with high accuracy by using RS technology is feasible, which overcomes the limitations of calculation of regional ET using conventional methods based on monitoring data of weather stations [27–35]. Different from the conventional method of engineering water-saving, the regional water-saving potential in agricultural irrigation was calculated based on RS ET data, in which the water-saving effects are evaluated as the reduction of the regional water consumption rather than the quantity of water withdrawn for irrigation. Therefore, the regional water-saving potential in agricultural irrigation based on RS ET data belongs to natural water-saving potential.

2. Materials and methods

2.1. Materials

2.1.1. Study area

Daxing County, comprising of 14 towns and 2 farms, is located in the northeastern part of the NCP and north-central of the Haihe River basin (Fig. 1), between latitude of 39°26′ and 39°50′N, and longitude of 116°13′ and 116°43′E [36]. The elevation of the northwest is 50 m, while that of the southeast is 15 m, and the total study area covers 1,044 km². The study area soils in 1 m soil depth are silt loam formed by loess deposits, and continuous clay can be found in some areas. The winter wheat was planted by early October and harvested by mid-June in the next year, and the summer maize was planted immediately. The local climate is sub-humid, with mean annual precipitation of 490 mm, mean annual temperature of 12.1°C, annual accumulated temperature (>10°C) of 4,730°C, mean frost-free days of 185 d, and mean annual evaporation from a free water surface of 1,800 mm. The spatial-temporal distribution of precipitation is uneven, of which more than 70% of the total precipitation occur in the summer months (from June to September) [37].

2.1.2. Data used

The following datasets were used in this paper: (1) the monthly RS ET dataset of Daxing County with a 30 m-space resolution and for the period from October 2005 to December of the next year were used. (2) Land use dataset of Daxing County with a 30 m-space resolution were provided in Albers projection and an Arcshape data format. The Landsat TM and the field data were used to interpret land use maps by supervision classification and visual interpretation, two crops were identified, including winter wheat and summer maize (Fig. 2). The accuracy of 96% for land use data is validated by 114 sampling points of global positioning system. According to field observation, growth periods for
the crops were identified as follows: from 8th October to 15th June for winter wheat and from 20th June to 30th September for summer maize. (3) In accordance with the crop growth season, the cumulative amount of the net primary productivity is the field dry matter in the agricultural area, which is calculated by using the Carnegie Ames Stanford Approach (CASA) Biosphere model [38]. The CASA model calculates the seasonal biomass increment of terrestrial crops based on ecological principles, satellite data, and surface data. The biomass increment is converted from the amount of photosynthetically active radiation absorbed by plants, depending on vegetation type and cover. This model has been verified in Yucheng, Shandong, Fengqiu, Henan, and Daxing (Beijing) [39]. (4) Meteorological data, such as air temperature, relative humidity, global and net radiation, and wind speed and direction at 2 m height, and precipitation were collected using an automatic weather station at the Irrigation Experiment Station of the China Institute of Water Resources and Hydropower Research (IWHR) at Daxing, Beijing region (39°37’ N, 116°26’ E and 40.1 m a.s.l.), which is located in central south of the study area in Daxing County (Fig. 1).

2.2. Methods

The crop WUE is calculated based on pixel data, such as RS ET and RS crop production. The reasonable ET quota should be located between the ET under the highest crop WUE and the theoretical crop water consumption under the highest crop production. Considering the water resources shortage in Daxing County, the crop ET quota could be determined based on the ET under the highest crop WUE. To avoid the inconsistency between the ET under the highest crop WUE and the results in the field experiment, the crop ET quota was corrected further by the crop water requirement. Then, regional water-saving potential in agriculture is calculated using crop ET quota as an evaluation criterion. The crop ET value of a pixel over the ET quota is considered as excessive water consumption. When the water consumption is lower than the crop ET quota, the crop ET data for a pixel would be kept as is to account for other factors in determination of ET. Hence water-saving potential in agriculture based on RS ET can be achieved by controlling excessive water consumption for each pixel’s ET data.

2.2.1. ETWatch model

ETWatch is a software originally designed to estimate ET based on remotely sensed land surface data as well as meteorological data, by integrating “Residue Approach” and Penman-Monteith (P-M) model [40,41]. First, the surface energy balance algorithm for land model, dealing with 30 m resolution RS data, and surface energy balance system model, dealing with 1 km resolution RS data are used to compute the ET. Due to cloud cover and satellite overpass interval, an adequate solution for the intermittent period based on the P–M model is then used to calculate daily ET data under all sky conditions. And the detail about ETWatch model can be obtained from the study by Wu et al. [40,41].

The ET validation of ETWatch using field measurements at the study area suggests that the average deviation in the agricultural area is about 10% [42].

2.2.2. Crop yield

The crop yield (Y) is defined as total dry matter of a specific crop, reflecting the economic output [43]. According to Howell’s study [44], the harvest index (Hi) remains constant once the dry matter exceeded 8% of the maximum. Therefore, the Hi is set constant in many studies since the Hi becomes stable quickly. The linear relationship between the yield of the crop (i) and its dry matter is expressed in the following equation [3]:

$$Y_i = H_i \times \sum_{i}^{n} DM_i$$  \hspace{1cm} (1)

where i is the crop type, DM is the incremental of the dry matter (kg hm⁻²), Hi is the harvest index of the crop i, defined
as the ratio of yield and the ground dry matter [43]; ‘ts’ is the sowing time of the crop, and ‘te’ is the harvest time of the crop. The harvest index of food crops in China varies between 0.35 and 0.45. In the Hai Basin wheat and maize are the main crops based on the crop phonological calendar, the period from October to September of the following year is the growing season. The empirical coefficients of 0.361 for winter wheat and 0.433 for summer maize are used as the annual harvest index in this study. The dry matter and crop yield at the study area have been verified and analyzed in detail in previous studies [39,43].

2.2.3. Crop WUE

Crop WUE is defined as the crop yield produced for each unit of water consumed. The WUE is a comprehensive index to assess the performance of agricultural production and the rationality of agriculture water use [45–47]. It is defined as follows:

\[
W_{UE_{sci}} = \frac{Y_{sci}}{ET_{sci}} / 10
\]

where \(W_{UE_{sci}}\) is the \(i^{th}\) pixel’s crop WUE in kg m\(^{-2}\), \(Y_{sci}\) is the \(i^{th}\) pixel’s crop yield in kg ha\(^{-1}\) and \(ET_{sci}\) is the \(i^{th}\) pixel’s crop ET in mm, and 10 is the unit conversion coefficient.

2.2.4. Crop ET quota

With a 30 m space resolution of the RS ET dataset, there were thousands of pixels for one crop in the study area. If the crop water production function was established based on every pixel, data points would be too discrete to allow high-efficiency regression analysis. Considering the distribution of the RS ET dataset, the pixel value of RS ET was classified by an interval of 20 mm. As a result, the average values of RS ET could be divided into ranges, such as 60–80 mm, ..., 460–480 mm, ..., and so on. The average values of the classified RS ET were then calculated by using GIS techniques such as the tools of Reclassify and Zonal Statistics. The average values of crop WUE and crop yield were also calculated by using the classified RS ET. The relationship between crop WUE and water consumption for winter wheat simulated by the FAO 56 single-crop coefficient approach [49–53].

2.2.5. Water-saving potential in irrigated agriculture

The following formula was proposed to estimate water-saving potential (WSP) using ET quota:

\[
WSP = \sum_{i=1}^{n} 0.9 \times WSP_{sci}
\]

where WSP is the water-saving potential for some crop in m\(^3\), WSP\(_{sci}\) is the \(i^{th}\) pixel’s water-saving potential in mm, ET\(_{sci}\) is the \(i^{th}\) pixel’s ET in mm and \(n\) is the number of pixels for the crops in the study area, and 0.9 is the unit conversion coefficient under 30 m space resolution pixel.

3. Results and discussion

3.1. WUE and regional ET quota

As shown in Fig. 3, the winter wheat yield increases proportionally, almost linearly, with the ET until it reaches its peak and decreases afterwards. Up to an ET value of 573 mm, the yield of winter wheat increases slowly with ET, but then declined when the ET continues to increase [54]. Before the crop ET reaches a threshold, winter wheat WUE increased with an increase in the ET.

Once the ET reaches its threshold ET, winter wheat WUE then declined as the ET increase further. Based on the relationship between ET and WUE for winter wheat, the crop water production function for winter wheat was established based on the quadratic parabola-fitting equation Eq. (9) is derived as follows:

\[
W_{UE_{rc}} = -0.00008084ET_{rc}^2 + 0.00679ET_{rc} - 0.102 \quad (R^2 = 0.782)
\]

Based on the crop water production function for winter wheat, the threshold ET was determined as 417 mm, and its WUE was 1.31 kg m\(^{-3}\). Similarly, based on the relationship between crop yield and ET for winter wheat, the crop yield was determined as 5,649 kg ha\(^{-1}\) when its ET reaches the threshold of 417 mm.

As shown in Fig. 4, summer maize yield increases proportionally, almost linearly, with an increase in ET. When
the ET of summer maize goes over 400 mm, the wheat yield increases at a lower rate. The relationship between WUE and ET for summer maize is similar to that for winter wheat [55]. The WUE of summer maize increases with an increase of the ET until it reaches its peak and decreases afterward. The crop water production function for summer maize simulated by the quadratic equation Eq. (10) was obtained with a very high R-squared value (0.821).

$$\text{WUE} = -0.0000575\times \text{ET}^2 + 0.00466\times \text{ET} + 1.027 \quad (R^2 = 0.821) \quad (10)$$

Based on the crop water production function for summer maize, the threshold ET was determined at 405 mm, and its WUE was 2.05 kg m$^{-3}$. The corresponding yield was 7,984 kg hm$^{-2}$ at the threshold ET of 405 mm.

The average crop water requirements of winter wheat and summer maize were calculated as 434 and 313 mm, respectively. In this paper we choose the high yield and low ET at the largest crop WUE as evaluation criteria. The ET quota for winter wheat and summer maize were then determined as 417 and 313 mm, respectively.

### 3.2. Frequency distribution histogram of the ET, yield, and WUE of winter wheat and summer maize

Based on the mean values and variations of RS data, the distribution ratios of the ET, crop yield, and WUE for some crops were calculated using the NORMDIST function, which calculates the cumulative distribution function of the standard normal distribution. As a result, the normal distributions of their RS data were assessed. The frequency distribution histograms of the winter wheat ET, its yield and its WUE are shown in Fig. 5. The winter wheat ET mainly ranges from 200 to 560 mm with an average of 328 mm and a variation of 80 mm. Winter wheat yield mainly ranges from 800 to 10,400 kg hm$^{-2}$ with an average of 3,930 kg hm$^{-2}$ and a variation of 2,003 kg hm$^{-2}$. The winter wheat WUE mainly ranges from 0.80 to 2.60 kg m$^{-3}$ with an average of 1.18 kg m$^{-3}$ and a variation of 0.55 kg m$^{-3}$. Based on the water production function of winter wheat and the relationship between the ET and RS yield, its yield and WUE were determined as 5,649 kg hm$^{-2}$ and 1.31 kg m$^{-3}$, respectively, when the ET quota of winter wheat reached the threshold of 417 mm. Based on the NORMDIST function of RS data for winter wheat as shown in Fig. 5, the frequency ranges of the winter wheat ET quota, its yield and WUE were primarily located from 27% to 92%, 36% to 89%, and 24% to 87%, respectively. The frequency of ET, yield, and WUE was 89%, 85%, and 84%, respectively, when the ET quota of winter wheat reaches 417 mm. Therefore, the ET quota of 417 mm for winter wheat is a reasonable representation.

As shown in Fig. 6, the summer maize ET mainly ranges from 160 to 520 mm with an average of 302 mm and a variation of 68 mm. The summer maize yield mainly ranges from 800 to 10,000 kg hm$^{-2}$ with an average of 5,751 kg hm$^{-2}$ and a variation of 1,710 kg hm$^{-2}$. The summer maize WUE mainly ranges from 1.20 to 3.00 kg m$^{-3}$ with an average of 1.88 kg m$^{-3}$ and a variation of 0.26 kg m$^{-3}$. Based on the water production function of summer maize and the relationship between the ET and RS yield, its yield and WUE were determined as 5,999 kg hm$^{-2}$ and 1.91 kg m$^{-3}$, respectively, when the ET quota of summer maize reached its threshold of 313 mm. Based on the NORMDIST function of the normal distribution of RS data for summer maize, the frequency ranges of the summer maize ET quota, its yield and its WUE were primarily located from 38% to 62%, 61% to 80%, and 36% to 87%, respectively. The frequency of ET, yield, and WUE was 58%, 61%, and 52%, respectively, when the ET quota of summer maize reached the threshold of 313 mm. Therefore, the ET quota of 313 mm of summer maize is a reasonable representation.

### 3.3. Crop yield frequency distribution under the ET quota neighborhood

There are two principles in the determination of ET quota and its yield neighborhood. One is no difference of pixels’ value in the range of neighborhood, and the other is enough pixels for representativeness. When the interval of 10 mm was selected to determine the neighborhood of ET quota, there are about 5,000 pixels for winter wheat and 34,000 pixels for summer maize, respectively. The yield frequency distribution histograms of winter wheat under ET quota neighborhood are shown in Fig. 7(a). The neighborhood of winter wheat ET quota of 417 mm was in 410–420 mm. The frequency distribution of winter wheat yield in the neighborhood of ET quota mainly varied between 4,000 and 7,000 kg hm$^{-2}$, which accounted for about 74% of winter wheat yield in the neighborhood based on the NORMDIST function.
Fig. 5. Frequency distribution histogram of winter wheat ET, crop yield and water use efficiency.

Fig. 6. Frequency distribution histogram of summer maize ET, crop yield, and water use efficiency.

Fig. 7. Histogram of the crop yield under the ET quota neighborhood.
function. Approximately 52.29% of winter wheat pixel's yield in the neighborhood of ET quota was lower than the winter wheat yield of 5,649 kg hm\(^{-2}\) under ET quota. If the ET of winter wheat remained unchanged, winter wheat yield could be increased by adopting agricultural management practices such as balanced fertilization techniques and others.

As shown in Fig. 7(b), the neighborhood of summer maize ET quota 313 mm ranges from 310 to 320 mm, and the frequency distribution of summer maize yield in the neighborhood of ET quota ranges from 3,500 to 6,500 kg hm\(^{-2}\), which accounted for about 99% of that in the neighborhood of ET quota. It was estimated that 61.44% of summer maize pixel's yield in the neighborhood of ET quota was lower than the summer maize yield of 6,000 kg hm\(^{-2}\) under ET quota. If the ET of summer maize remained unchanged, summer maize yield could be increased by adopting some agricultural management practices. In sum, the calculated crop ET quota is feasible, and the crop yield under ET quota could be increased by implementing some agricultural management practices.

3.4. ET frequency distribution under the ET quota yield neighborhood

When the interval of 100 kg hm\(^{-2}\) was selected to determine the neighborhood of ET quota yield, there are over 3,000 pixels for winter wheat and 12,000 pixels for summer maize, respectively. The ET frequency distribution histograms of winter wheat and summer maize under ET quota yield neighborhood are shown in Fig. 8. The neighborhood of winter wheat ET quota yield of 5,649 kg hm\(^{-2}\) ranges from 5,600 to 5,700 kg hm\(^{-2}\), and the frequency distribution of the ET under the winter wheat ET quota yield neighborhood was normally distributed mainly from 360 to 450 mm, which accounted for 93.67%. It was estimated that, approximately, 21.74% of winter wheat pixel's ET in the neighborhood of winter wheat ET quota yield were higher than the winter wheat ET quota of 417 mm. If winter wheat yield remained unchanged, the winter wheat ET could be decreased by using water-saving measures such as optimal irrigation scheduling. The neighborhood of the summer maize ET quota yield of 6,000 kg hm\(^{-2}\) was from 5,950 to 6,050 kg hm\(^{-2}\), and the frequency distribution of ET under summer maize ET quota yield neighborhood was mainly from 260 to 420 mm, which accounted for over 99%. It was estimated that approximately 50.93% of summer maize pixel's ET in the neighborhood of the summer maize ET quota yield were higher than the summer maize ET quota of 313 mm. According to water-saving concept, namely a reduction in crop water consumption without a reduction in crop yield, the winter wheat and summer maize ET quotas were validated, proving that the calculated crop ET quota was feasible. It was further concluded that calculated crop ET quota could be further compressed or reduced.

3.5. Crop water-saving potential

The ET quotas for winter and summer maize were determined as 417 and 313 mm, respectively, as shown in the previous section. The crop water-saving potential under ET quota management for these two crops was analyzed, and the results are shown in Table 1. Considering the crop planting area, summer maize covers the largest area, accounting for 50.57% of Daxing County area. Summer maize was followed by winter wheat, accounting for 15.35%. Once crop ET quota was determined, crop water-saving potential could be

<table>
<thead>
<tr>
<th>Items</th>
<th>Wheat</th>
<th>Maize</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planting area (km(^2))</td>
<td>160.23</td>
<td>527.79</td>
</tr>
<tr>
<td>Proportion of Daxing County (%)</td>
<td>15.35</td>
<td>50.57</td>
</tr>
<tr>
<td>ET quota (mm)</td>
<td>417.00</td>
<td>313.00</td>
</tr>
<tr>
<td>Water-saving volume (10(^6) m(^3))</td>
<td>0.73</td>
<td>11.77</td>
</tr>
</tbody>
</table>

![Fig. 8. Histogram of the crop ET under the ET quota yield neighborhood.](image-url)
acquired by adjusting the current pixels’ ET value. Considering water-saving potential, summer maize would contribute the largest, with approximately 11.77 million m³, followed by winter wheat, with 0.73 million m³. The quantity of water-saving depends on two major factors: the crop planting area and the difference between the current average ET and the adjusted average ET. Therefore, we should target water-savings volume on wheat production because it grows in a dry season and depends on irrigation. However, it is difficult to control water consumption for maize production since that grows in a rainy season.

To demonstrate application of the new method, water-saving volumes for main crops among towns as well as water-saving management area within each town in Daxing county were analyzed. The results are shown in Table 2 and Fig. 9. Comparing water-saving volumes of wheat in the study area, we found that Qingyundian was the largest, with approximately $0.228 \times 10^6$ m³, followed by Jiugong, with $0.194 \times 10^6$ m³, then by Changziying with $0.130 \times 10^6$ m³, and the least by Tiantanghe farm, with no water-saving volume. In terms of water-saving volume for maize, Beizangcun was the largest, with approximately $1.843 \times 10^6$ m³, followed by

Table 2
Water-saving volumes for main crops within water-saving management areas among towns in Daxing county

<table>
<thead>
<tr>
<th>Towns and farms</th>
<th>ET quota management area (km²)</th>
<th>Water-saving volume ($10^6$ m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wheat</td>
<td>Maize</td>
</tr>
<tr>
<td></td>
<td>Wheat</td>
<td>Maize</td>
</tr>
<tr>
<td>Yizhuang</td>
<td>0.000</td>
<td>4.424</td>
</tr>
<tr>
<td>Jiugong</td>
<td>1.579</td>
<td>3.059</td>
</tr>
<tr>
<td>Xihongmen</td>
<td>0.190</td>
<td>1.923</td>
</tr>
<tr>
<td>Huangcun</td>
<td>1.128</td>
<td>21.503</td>
</tr>
<tr>
<td>Yinghai</td>
<td>0.753</td>
<td>4.924</td>
</tr>
<tr>
<td>Tuanhe farm</td>
<td>0.150</td>
<td>1.715</td>
</tr>
<tr>
<td>Qingyundian</td>
<td>6.064</td>
<td>17.261</td>
</tr>
<tr>
<td>Changziying</td>
<td>3.524</td>
<td>12.773</td>
</tr>
<tr>
<td>Caifu</td>
<td>1.229</td>
<td>19.931</td>
</tr>
<tr>
<td>Beizangcun</td>
<td>0.185</td>
<td>19.762</td>
</tr>
<tr>
<td>Weishanzhuang</td>
<td>1.815</td>
<td>27.401</td>
</tr>
<tr>
<td>Tiantanghe farm</td>
<td>0.003</td>
<td>1.355</td>
</tr>
<tr>
<td>Anding</td>
<td>0.083</td>
<td>14.937</td>
</tr>
<tr>
<td>Fanggezhuang</td>
<td>0.185</td>
<td>22.271</td>
</tr>
<tr>
<td>Lixian</td>
<td>0.362</td>
<td>15.007</td>
</tr>
<tr>
<td>Yufa</td>
<td>0.179</td>
<td>30.235</td>
</tr>
<tr>
<td>Total</td>
<td>17.428</td>
<td>218.481</td>
</tr>
</tbody>
</table>

Fig. 9. Maps of water-saving management area for wheat and maize in Daxing County.
Huangcun, with 1.416 × 10⁶ m³, then by Weishanzhuang with 1.337 × 10⁶ m³, and the least by Tianzhuanghe farm, with 0.069 × 10⁶ m³.

The water-saving management area for winter wheat was 17.428 km², which accounted for 10.88% of winter wheat planting area. In terms of water-saving management area for winter wheat, Qingyundian was the largest, with approximately 6.064 km², followed by Changziying, with 3.524 km², then by Weishanzhuang, with 1.815 km², and the least by Tianzhuanghe farm, with about 0.003 km². The water-saving management area for maize was 214.481 km², accounting for 41.40% of the maize planting area. In comparison of the water-saving management area for maize in the study area, Yufa was the largest, with approximately 30.235 km², followed by Weishanzhuang, with 27.401 km², then by Panggezhuang, with 22.271 km², and the least by Tianzhuanghe farm, with about 1.355 km².

Based on a comprehensive consideration of water-saving volume for main crops within the water-saving management area among towns, the major towns for winter wheat were Qingyundian, Changziying, and Jiugong; the major towns for maize were Beizangcun, Huangcun, and Weishanzhuang. For the water-saving management area, measures could be taken to reduce the water consumption, for example, the optimal irrigation schedule for winter wheat; the dry-land farming for summer maize.

4. Conclusions

The relationship among RS ET, RS crop yield and crop WUE was analyzed, a quadratic model between the RS ET and crop WUE was identified by using statistical regression, and the ET quota of main crops was determined. Basis of this, a new calculation of water-saving potential for crops is presented. The new method presented in this paper accounts for natural water-saving potential by assessing the water saving potential at a pixel scale, complementing other methods. The conclusions were drawn as follows:

- The rational ET quotas are the base for calculating the crop water-saving potential. The ET quotas of winter wheat and summer maize were 417 and 313 mm, respectively. The rationality of the calculated crop ET was validated by using frequency distribution histogram of RS ET, RS crop yield and crop WUE and water-saving concept, namely, by reducing crop water consumption without a reduction in crop yield and by increasing crop yield without an increase in crop water consumption.

- Regional water-saving potential was calculated by comparing the current ET values with the adjusted pixel's ET values using the selected crop ET quota as evaluation criteria. It was concluded that summer maize has the largest potential, at 11.77 million m³, followed by winter wheat, at 0.73 million m³.

- Furthermore, for winter wheat and summer maize, the towns of water-saving management were selected. Therefore, water-saving potential and water-saving management area for main crops could be calculated by the method, which is beneficial to regional agriculture water management.

Acknowledgements

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