A BROWSER/SERVER FRAMEWORK FOR CROP ET CONTROL AND IRRIGATION MANAGEMENT IMPROVEMENT USING REMOTE SENSING DATA

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ABSTRACT

Agriculture accounts for 70% of the total water consumption in North China. With socioeconomic development, the consumption of industry and domestic supply is increasing sharply. The shortage of irrigation water is a critical problem affecting agriculture production and food security. The research focuses to water demand management rather than water supply management to meet the constraint of regional water resources. A crop ET management tool based on Browser/Server structure and GIS technique was developed to assess irrigation management options and improve water use efficiency at regional scale. The frame work extracted cultivated land ET control target from regional ET control target and then analyzed present water consumption distribution based on remote sensing and field observation data. Crop ET management tool is the kernel of the framework which provided four main function modules including crop ET quota control, crop pattern improvement, water saving potential calculation and irrigation quota estimation. A regional crop ET quota was proposed by comparing crop water requirement and economical ET. High water consumption crops were reduced according to cultivated land ET control target. The regional water-saving potential in irrigation was determined by selecting a regional crop ET quota as an upper limit. The framework was flexibly applied in four counties and irrigation districts in arid or semi-arid area in North China. The new calculation method for water-saving potential for crops will help planners and managers gaining a better insight into water management and water uses of crops, which will in turn provide information and guidelines needed for regional water plans, water rights allocation and agricultural water applications.

Keywords: ET management, Crop ET quota, Remote sensing data, Irrigation quota, Irrigation schemes, Water saving potential.

1. INTRODUCTION

Agricultural production in North China plays an important role in relation to food security and economic development (Liu et al. 2005). Most farmlands in this area have high water demand due to large plantation area, climate variability, and irrigation water resources scarcity and population growth. With the rapid development of agriculture and industry along with prolonged drought, there are serious water shortage, groundwater exploitation and serious contradiction between supplies and demands of water resources (Song et al. 2010). For low efficiency of agriculture water use, agriculture is in inferior status during the competition of water resources use therefore, the future water supplies for agricultural application will become worse.

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Reducing agricultural water demand requires a more efficient and sustainable use of irrigation water resources to ensure food security.

The first task of water consumption management is determining the regional water consumption (ET) target that is suitable for different regions, development stages, regional water balance and sustainable economic development. Then ET control target for cultivated lands is analyzed according to landuse distribution and development condition.

Regional irrigation water saving potential is key information for evaluation of agricultural water saving plans, water use efficiency and optimal allocation of water resources. Up to now, however, no unified method is available for calculation and valuation of irrigation water saving potential. In this paper, the regional crop water production functions were derived based on the analysis of the relationship among actual ET, crop production and Water Use Efficiency (WUE) by using GIS and RS techniques. The economical ET of the crop is defined as the theoretical water requirement, when the increase amplitude of the crop yield is equal to that of the water resources consumption (Liu et al. 2005). A crop ET quota was then determined by comparing the crop water requirements and economical ET. Then the regional irrigation water-saving potential was evaluated using the selected ET quota for each kind of crops and an optional improved crop pattern. At last, the tool provided irrigation scheduling and water allocation plan based on selected crop ET quota and optimization objective.

2. METHODS

2.1 Case study: Daxing County

Daxing County, comprising of 14 towns and 2 farms, is located in northeastern part of the NCP and north-central of the Haihe River basin (Figure 1), between latitude of 39° 26’ and 39° 50’ N, and longitude of 116° 13’ and 116° 43’ E (Meng et al. 2004). Daxing County tilts slightly from the northwest (elevation 50m) to the southeast (elevation 15m), and is part of the Yongding River alluvial plain. The total study area covers 1,044km². The study area soils in 1m 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, and the summer maize was immediately after to be harvested in October, before wheat planting, as it is usual in North China Plain. The local climate is sub-humid, with mean annual precipitation of 490mm, mean annual temperature of 12.1°C, mean annual pan evaporation of 1021mm, cold and dry winters, and hot and humid summers. The spatial-temporal distribution of precipitation is uneven, of which more than 70% of the total precipitation occurs in the summer months (from June to September).

![Figure 1. Location of the study area.](image-url)
2.2 Datasets

The following data sets of Daxing County were used in this paper: (1) The monthly RS ET dataset with a 30m-space resolution and for the period from October 2005 to December 2006. (2) Land use dataset with a 30m-space resolution were provided in Albers projection and an Arcshape data format. The Landsat TM and the actual field data were used to interpret land use maps by supervision classification and visual interpretation. From the land use, four crops were identified, including winter wheat, summer maize, cotton, and turf. According to field observation, growth periods for the crops were identified as following: from 1st October to 15th June for winter wheat, from 20th June to 1st October for summer maize, from 1st May to 15th October for cotton and from 1st April to 31st October for turf. (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 CASA model (Field et al. 1995). This was verified in Yucheng, Shandong and Fengqiu, Henan, modified with the water stress factor (Du et al. 2010). (4) Meteorological data such as air temperature, relative humidity, global and net radiation, and wind speed and direction at 2m 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 Daxing County (see Figure 1).

2.3 Structure of ET management model

Main functions of the model include: query, statistics and analysis of current remote sensing data, goal ET decomposition, ET quota allocation, planting structure adjustment, analysis of water saving potential, and estimation of irrigation quota, refer to Figure 2.

![Figure 2. Structure of ET management model.](image)

2.4 ET quota management

When implementing ET management, distinguish the controllable ET and uncontrollable ET at first. The controllable ET refers to the ET that may be regulated and controlled by artificial management measures, for example, for most cultivated lands and artificial forest land and grassland, the ET consumption of crop or vegetation may be reduced by improving the irrigation system, irrigation technology, adopting appropriate farming or covering methods; while for some rainfed cultivated lands, natural forest land and grassland, wet land and so on without irrigation conditions and management measures, the ET cannot be regulated and controlled. Only the controllable ET has potential of water saving, that is also the key points for ET management. ET from cultivated lands takes large part of total ET in North China,
while the ET from uncultivated land is hard to regulate. Thereby this paper takes the cultivated land ET as the study object for ET quota management research.

The model analyzed ET distribution in the county with remote sensing ET data and landuse data, and then extracted the actual ET of cultivated land and uncultivated land ET under the conditions of the status quo. Considering the development planning of regional economy and society and water resource conditions, the ET control target for total region, cultivated land and uncultivated land in the future scenarios can be calculated by the following function:

\[ ET_{\text{total, target}} \times A_{\text{total}} = ET_{\text{cultivated, target}} \times A_{\text{cultivated}} + ET_{\text{uncultivated, target}} \times A_{\text{uncultivated}} \]  \( (1) \)

Where, the total regional area \( A_{\text{total}} \) is the sum of the cultivated land area \( A_{\text{cultivated}} \) and the uncultivated land area \( A_{\text{uncultivated}} \), \( ET_{\text{total, target}} \) is the total regional ET control target, \( ET_{\text{cultivated, target}} \) and \( ET_{\text{uncultivated, target}} \) are the ET control targets for both cultivated land and uncultivated land, the relation between the ET control target \( ET_{\text{uncultivated, target}} \) and current actual water consumption \( ET_{\text{a, uncultivated}} \) of the uncultivated land is \( ET_{\text{uncultivated, target}} = \alpha \times ET_{\text{a, uncultivated}} \), where \( \alpha \) is the variation coefficient of the uncultivated land ET under planned scenario. If the planned uncultivated land ET rises from the current situation, then \( \alpha > 1 \), otherwise, it is less than 1.

Two ET quota management methods for the cultivated land ET control target are considered: Crop ET quota control and crop pattern improvement. Set the water saving scenarios with various strengths, control the ET quota of each main crop, eliminate luxurious water consumption, adjust plant areas of high water-consuming crop, until the cultivated land water consumption \( ET_{\text{cultivated}} \) after regulation is not more than the control target \( ET_{\text{cultivated, target}} \) finally.

Crop WUE is defined as the crop yield produced from each unit of water consumption. The WUE is a comprehensive index to assess the performance of agricultural production and the rationality of agriculture water use.

It is defined as follows,

\[ WUE_{sci} = \frac{Y_{sci}}{ET_{sci}} \times 10 \]  \( (2) \)

where \( WUE_{sci} \) is ith pixel’ s crop WUE in kg.m\(^{-3}\), \( Y_{sci} \) is ith pixel’ s crop yield in kg.hm\(^{-2}\) and \( ET_{sci} \) is ith pixel’ s actual crop ET in mm.

According to analysis on winter wheat field test (Zhao 2010) from 2006 to 2009 at Daxing experiment station of IWHR, when the yield is high, the crop yield \( Y \) and water use efficiency \( WUE \) appear the trend of rising first and falling later along with increasing of ET as Figure 3 shown. CropET should be controlled within the high range of WUE and yield (Between the economicalET and theoreticalET). By this way, luxurious irrigation water use is eliminated, the irrigation water use efficiency is improved, in addition, high crop yield is guaranteed.

The relationship between crop WUE and actual water consumption is determined as a parabolic function (Zhang et al. 2004). The economical ET is calculated by the conic parabola as defined in equation 4. At last, the crop ET quota is corrected by the crop water requirement. The formula for the ET quota is listed as following:

\[ WUE_{rc} = aET_{rc}^2 + bET_{rc} + c \]  \( (3) \)
where \( WUE_{rc} \) is the average value of crop WUE classified in kg.m\(^{-3}\), \( ET_{rc} \) is the average value of RS ET classified in mm, \( ET_q \) is the crop ET quota in mm, \( ET_c \) is crop water requirement in mm, \( ET_0 \) is the reference crop evapotranspiration in mm, \( K_c \) is the crop coefficient, and \( a \) and \( b \) are coefficients of the conic parabola. Here, the reference evapotranspiration is calculated by using the FAO 56 Penman-Monteith’s equation, and the crop coefficient is calculated by using the FAO 56 single-crop coefficient approach (Allen et al. 1998).

![Figure 3](image_url)

**Figure 3.** Schematic diagram of crop ET quota control.

### 2.5 Water saving potential

The relation proposed to estimate water-saving potential (WSP) using ET quota is:

\[
WSP = \left( ET_{scv} - ET_{adj} \right) \times A / 1000
\]

(6)

\[
ET_{scv} = \frac{1}{n} \sum_{i=1}^{n} ET_{sci}
\]

(7)

\[
ET_{adj} = \frac{1}{n'} \sum_{i=1}^{n'} ET_{adj,i}
\]

(8)

\[
ET_{adj,i} = \begin{cases} ET_{sci} & \text{if } ET_{sci} \leq ET_q \\ ET_q & \text{if } ET_{sci} > ET_q \end{cases}
\]

(9)

where WSP is the water-saving potential in million m\(^3\), \( ET_{scv} \) is the present average ET in mm, \( ET_{adj} \) is the adjusted average ET in mm, \( A \) is the cultivated area for some crops in km\(^2\), \( ET_{sci} \) is the \( i^{th} \) pixel’s actual ET in mm, \( ET_{adj,i} \) is the adjusted ET for \( i^{th} \) pixel in mm, \( n \) and \( n' \) is number of pixels for the crops in the study area before and after crop pattern improvement.
2.6 Irrigation quota management

The model provides two methods to calculate irrigation quota from crop ET quota, thus irrigation scheduling can be made.

1. Estimated by the effective rainfall: the net irrigation water requirement of crop can be estimated by $I_{net} = ET_a - P_e$, the effective rainfall $P_e$ is the sum of each effective rainfall in the year.

2. Calculated by the water balance model. This method includes simulation of the relation between ET and irrigation water quantity and optimization of the irrigation schedule. Establishing the regional ET simulation model based on the field water balance model comprises two steps. First, divide the whole study area into several irrigation areas with the GIS tool according to remote sensing and observation data such as planting structures, soil types, ground elevations, in combination with the cultivation methods, irrigation water source, irrigation conditions and so on. The model is organized in a set of calculation units in which the soil type and the crop type are single. In each unit, different irrigation scenarios make up a modeling set. Secondly, perform continuous simulation within crop growth period using the field water balance model. Setting of simulation parameters for each modeling set includes: calculation parameters of the model, such as the year of simulation, the irrigation area, crop type, growth period, irrigation conditions and amounts, cover condition; soil parameters: Set the hydrodynamic parameter for model calculation by selecting the soil type; Setting meteorological data: Set the observed meteorological data within the calculating interval by selecting the weather station.

At last optimized irrigation scheduling is determined by user selected optimization objective, which is also restricted by crop ET quota.

2.7 Irrigation water sources allocation

Based on optimized irrigation scheduling, total net irrigation water demand $W_{net}$ in the region can be calculated from net irrigation water demand $w_{ni}$ and area $A_i$ of each crop:

$$W_{net} = \sum_i w_{ni} \times A_i$$  \hspace{1cm} (10)

The gross irrigation water demand quantity $W_{gross}$ can be calculated with the irrigation water utilization coefficient $\eta$. Considering surface water and ground water resource in the region, irrigation water can be allocated ten-day by ten-day, using more surface water ($W_S$), and reducing ground water exploitation ($W_G$) (Formula 11).

$$W_{gross} = \frac{W_{net}}{\eta} \quad , \quad W_G = W_{gross} - W_S$$  \hspace{1cm} (11)

3. RESULTS AND DISCUSSION

3.1 WUE and regional ET quota

As shown in Figure 4 the winter wheat yield increases proportionally, almost linearly, with the actual ET until it reaches its peak and decreases afterwards. Up to an ET value of 573mm, the yield of winter wheat increases slowly with ET, but then declined when the actual ET continues to increase. Before the actual crop ET reaches a threshold, winter wheat WUE increased with increase in the actual ET. Once the
actual ET reaches its threshold ET, winter wheat WUE then declined with further increase in the actual ET.

Based on the crop water production function for winter wheat, the threshold ET was determined as 388mm, and its WUE was 1.25kg.m\(^{-3}\). Similarly, based on the relationship between crop yield and actual ET for winter wheat, the crop yield was determined as 4,980kg.hm\(^{-2}\) when its ET reaches the threshold of 388mm.

The same analysis is made for maize, cotton and turf respectively. The crop water-saving potential under ET quota management for these four crops was analyzed, and the results are shown in Table 1.

**Table 1.** Water saving potential for key crops under ET quota management

<table>
<thead>
<tr>
<th>Items</th>
<th>Wheat</th>
<th>Maize</th>
<th>Cotton</th>
<th>Turf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planting area (km(^2))</td>
<td>160.23</td>
<td>527.79</td>
<td>1.10</td>
<td>14.91</td>
</tr>
<tr>
<td>Proportion of Daxing County (%)</td>
<td>15.35</td>
<td>50.57</td>
<td>0.11</td>
<td>1.43</td>
</tr>
<tr>
<td>Present average ET (mm)</td>
<td>327.50</td>
<td>302.12</td>
<td>598.94</td>
<td>711.23</td>
</tr>
<tr>
<td>ET quota (mm)</td>
<td>388.00</td>
<td>313.00</td>
<td>494.00</td>
<td>608.00</td>
</tr>
<tr>
<td>Adjusted average ET (mm)</td>
<td>318.15</td>
<td>280.84</td>
<td>479.93</td>
<td>522.90</td>
</tr>
<tr>
<td>Difference between the present and the adjusted (mm)</td>
<td>9.35</td>
<td>22.30</td>
<td>119.01</td>
<td>106.01</td>
</tr>
<tr>
<td>Water-saving volume (106 m(^3))</td>
<td>1.50</td>
<td>11.77</td>
<td>0.13</td>
<td>1.58</td>
</tr>
<tr>
<td>Contribution to reduce comprehensive ET (mm)</td>
<td>1.44</td>
<td>11.27</td>
<td>0.13</td>
<td>1.51</td>
</tr>
</tbody>
</table>

As far as crop planting area was concerned, summer maize covers the largest area, which accounted for 50.57% of Daxing County area. Summer maize was followed by winter wheat, which accounted for 15.35%, while the third was turf, which accounted for 1.43% and the smallest was cotton, which only accounted for 0.11%. Once crop ET quota was determined, crop water-saving potential could be acquired by adjusting the current pixels’ ET value. As far as water-saving quantity was concerned, summer maize was the largest, with approximately 11.77 million m\(^3\), followed by turf, with 1.58 million m\(^3\), then by winter wheat, with 1.50 million m\(^3\), and the least by cotton, with
about 0.13 million m$^3$. 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. In addition, the contributions of the comprehensive ET reduction were compared among crops in Daxing County. The results show that in Daxing County, the largest contribution to reducing comprehensive ET is summer maize, at about 11.27 mm, followed by turf, at about 1.51 mm, and the smallest is cotton, at about 0.13 mm. In brief, in order to increase the water-saving volume and to improve agriculture water use efficiency, water consumption quota management for summer maize has the greatest potential.

### 3.2 Irrigation quota management

As Figure 5 shows, soil types in Daxing are mainly moisture soil and cinnamon soil. Sampling investigation is made for main soil types and land use types to get hydrodynamics parameters. The water balance model is validated with filed observed soil moisture profile (see Figure 6) and ET, crop yield. The comparison shows that the water balance model has good simulation results.

![Figure 5. Soil type and survey spots in study area.](image)

![Figure 6. Comparison of observed and simulated soil moisture in study area.](image)
Taking summer corn in 2006 as the example, a modeling sets with different irrigation methods and irrigation amount, considering with and without surface cover, form several scenarios. Calculate and optimize the irrigation quota restricted by the crop ET quota in Table 1, the results are shown in Figure 7.

![Figure 7. Relation between ET, yield and irrigation amount in study area.](image)

When the yields of summer corn are similar, the ET is smaller after covering; at the same irrigation amount, about 20mm of ET can be reduced. By using efficient irrigation methods with the minimum single irrigation amount (Such as sprinkling irrigation and drop irrigation), deep seepage may be reduced obviously, thereby the total irrigation water quantity can be reduced. The disadvantage is high economic input, so it is more appropriate for economic crops.

4. CONCLUSIONS

Based on RS ET data during the period from October 2005 to December 2006, land use data and RS yield data for crops in 2006, WUEs of winter wheat and summer maize were calculated. Considering RS ET distribution, the average values of RS ET, RS crop yield and crop WUE were then evaluated by using a classified RS ET map. Finally, the relationship among RS ET, RS crop yield and crop WUE was analyzed, and a conic parabola model between the RS ET and crop WUE was identified by using statistical regression. Economical water consumption under the highest crop WUE level was achieved by using the conic parabola model.

Water-saving potential under the ET quota management was calculated by comparing the present ET values with the adjusted pixel’s ET values using the selected crop ET quota as evaluation criteria. It can be interpreted as that the largest contribution to reducing the overall ET in Daxing County is summer maize, at about 11.27 mm.

In irrigation management, water saving methods such as efficiency irrigation methods, and tillage methods such as land surface cover shows significant effect on crop ET reduction. At the same time, there’s little influence on crop production.

The regional irrigation management method based on remote sensing ET data and crop water consumption quota control can be widely used for water consumption management in agriculture in the basins and areas lack of water. The methods for regional water consumption quantity control and crop ET quota management provided by the model can give technical support to carry out the strictest water resource management in the whole nation, thereby guarantee sustainable efficient utilization of water resource and promote harmonious development of economic society.
REFERENCES


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