Exploring Northwest China’s agricultural water-saving strategy: analysis of water use efficiency based on an SE-DEA model conducted in Xi’an, Shaanxi Province


ABSTRACT

Worldwide, water scarcity threatens delivery of water to urban centers. Increasing water use efficiency (WUE) is often recommended to reduce water demand, especially in water-scarce areas. In this paper, agricultural water use efficiency (AWUE) is examined using the super-efficient data envelopment analysis (DEA) approach in Xi’an in Northwest China at a temporal and spatial level. The grey systems analysis technique was then adopted to identify the factors that influenced the efficiency differentials under the shortage of water resources. From the perspective of temporal scales, the AWUE increased year by year during 2004–2012, and the highest (2.05) was obtained in 2009. Additionally, the AWUE was the best in the urban area at the spatial scale. Moreover, the key influencing factors of the AWUE are the financial situations and agricultural water-saving technology. Finally, we identified several knowledge gaps and proposed water-saving strategies for increasing AWUE and reducing its water demand by:

1. Improving irrigation practices (timing and amounts) based on compatible water-saving techniques;
2. Maximizing regional WUE by managing water resources and allocation at regional scales as well as enhancing coordination among Chinese water governance institutes.

Key words | agricultural water use efficiency, China, super-efficient DEA model, water saving

INTRODUCTION

A growing global population and demand for food, coupled with competition between different water use sectors, has increased the pressure on irrigation systems, as the main consumptive user, to release water for other uses and to improve performance (Sun et al. 2016). China’s situation in many respects exemplifies the global picture, especially water scarcity in much of the northern part of the country (Wu et al. 2013). Irrigation in these regions of limited rainfall dominates water use, often accounting for 60% of total water use (Ministry of Water Resources 2013). However, irrigation water scarcity in the region has been worsening due to accelerating industrialization and urbanization, but also because of environmental challenges, such as climate change and water pollution (Tang et al. 2015). In addition, water use efficiency (WUE) in agriculture is still low, and this is largely blamed for the poor irrigation management practices (such as tillage practice, water pricing policy instrument and so on) (Guan et al. 2015; Mamitimin et al. 2015) and lack of investment in infrastructure (Fang et al. 2015). Furthermore, water resources in China are scarce, with uneven distributions both spatially and temporally, which makes it difficult to achieve efficient agricultural water utilization. Therefore, the comprehensive utilization of water resources and increases in water resource efficiency have, to some extent, strategic importance.

Recently, water availability for agricultural production has encouraged researchers to focus on comparing and evaluating the agricultural water use efficiency (AWUE) of different regions in various water management strategies (Huang et al. 2003; Speelman et al. 2008; Rahil & Qanadillo 2015). AWUE was identified as one of the key water use indicators derived in the study of sustainable irrigated agriculture. It involves the interaction between the technology of the agricultural water-saving process and optimizing water management in practice. Thus, exploring AWUE is critical in saving agricultural water in very water-scarce
regions (Gencoglan et al. 2006). Over the years, agricultural water management and water-saving technology have become popular topics among researchers worldwide for improving AWUE (Li et al. 2005; Fan et al. 2014). However, AWUE has a far more complicated controlling mechanism than that at the irrigation scale. Climate change, economic status, farmers’ perceptions on conserving water and agricultural water prices have all been shown to have effects on AWUE (Shu & Ying 2011; Wang et al. 2014).

Accordingly, studies have been carried out to estimate AWUE from agro-ecosystems using different models. The most common model for non-parametric methods is the traditional data envelopment analysis (DEA) model that does not require the estimation of a production function (Liu et al. 2007). However, when multiple decision-making units (DMUs) are involved, the traditional DEA model presents difficulty in ranking the DMUs and thus makes further analysis unavailable. To overcome this, Andersen & Petersen (1993) proposed a super-efficiency data envelopment analysis (SE-DEA). It does not need any prior assumptions on the underlying functional relationships between inputs and outputs (Seiford & Thrall 1990). DMUs that receive a score of unity are deemed as being on the DEA (best-practice) frontier. Re-ranking the DMUs on the effective frontiers, the SE-DEA solves the distinguishing problems of effectively evaluating DMUs. For inefficient DMUs, the SE-DEA model yields the identical standard DEA score. In addition, it is easy to implement and, for the same sample size, provides more information (Nahra et al. 2009).

However, several studies have been conducted on energy use efficiency, intelligent traffic management system efficiency, and environmental efficiencies based on the SE-DEA model, but no study has investigated AWUE using this method. This indicates that the traditional DEA model can only rank DMUs without identifying the low-efficiency ones. Accordingly, the objectives of this study were as follows: (a) to investigate the AWUE of Northwest China on the temporal and spatial scale; (b) to identify factors that influence AWUE; and (c) to put forward a strategy of water saving by increasing the AWUE based on the SE-DEA model.

**POLICY BACKGROUND AND STUDY AREA**

**Policy background**

Considering the bleak and alarming state of water pollution, unprecedented water crises and other tough environmental challenges confronting China, its government has been tasked with a pilot program for the development of water-saving practices by the central government (NDRC et al. 2006). In 2012, China conscientiously began carrying out the strictest water resource management (SWRM) system that was proposed in 2009. This emerging SWRM approach was positioned in the 2011 Central Committee No. 1 Document of the Communist Party of China as a strategic move to achieve a sustainable utilization of water resource and human–water harmony. SWRM is symbolically dubbed ‘three red lines’, which represents a policy of: (1) the control of the development and utilization of water resources, (2) the control of WUE, and (3) the restriction of pollutants in water function areas (Ministry of Water Resources 2012). Because this paper explores a micro-agricultural water-saving strategy that affects agricultural inputs and outputs, we mainly focus on controlling WUE.

**Study area description**

The study area of this paper is Xi’an, the capital of Shaanxi Province, located in the northwest of the People’s Republic of China in the center of the Guanzhong Plain. According to the Statistics Bureau of Xi’an City (2013), the city covers 10,108 km² and encompasses 10 districts and three counties. In this study, the Lianhu, Xincheng and Beilin districts are not included because they have no agricultural development. Xi’an has a population of 8.59 million residents, of which 27.95% are located in rural areas. The study area is an irrigated district in Northwest China. The average annual rainfall is 426.70 mm. The water resources per capita of this region are 278 m³, approximately 1/6 of the national average, which is only 1/24 of the world average level. Meanwhile, there is a serious problem in the uneven distribution of water resources. For decades, approximately 55.16% of irrigation water has been obtained via deep groundwater exploitation. Following the development of the national economy, the increase in urban and rural population, and the process of urbanization and improvement in living standards, demand has increased greatly. To maintain its current social and environmental conditions, the city has to exploit 127.75 million m³ of groundwater each year. The over-exploitation of groundwater lowers the groundwater level. However, the water resource environment has deteriorated gradually (land subsidence, saltwater intrusion and other problems appeared in this region), and its WUE is low. All of these will lead to a worsening water supply and demand. Focusing on the present situation, we can see that increased AWUE is an inevitable choice in building a resource-saving and
environmentally friendly society and also in promoting the rational use of resources.

Although the study area is a seriously water-stressed region, it possesses a number of advantageous characteristics necessary for effective water governance, including good irrigation infrastructure, and sophisticated flow measurement equipment and institutions, such as water user associations (WUAs). Unfortunately, a lack of water-saving incentives has stymied efforts to promote effective water governance. The efficiency of agricultural water use is still low, and the technology promoted by the local water resources bureau has not been largely adopted by the farmers. This is why we explore alternative water-saving strategies to achieve increasing AWUE levels based on the SE-DEA model under the SWRM system.

**METHODOLOGY**

**Ethics statement**

The study was approved by the Institute for Historical Environment and Socio-Economic Development in Northwest China, Shaanxi Normal University, and the field studies did not involve endangered or protected species.

**SE-DEA model**

Andersen & Petersen (1993) developed the SE-DEA model for ranking efficient DMUs. This model compares the unit under evaluation with a linear combination of all other units in the sample (e.g., the DMU itself is excluded). SE-DEA excludes the DMU under evaluation from the reference set so that efficient DMUs may have efficiency scores greater than or equal to 1 (Huang et al. 2015). The approach provides an efficiency ratio of efficient units similar to the rating of inefficient units above. It is easy to implement, and for the same sample size, provides more information. The efficiency scores from SE-DEA models are obtained by eliminating the data on the DMUs to be evaluated from the solution set. This can result in values which are regarded as according DMUs the status of being ‘super-efficient’. These values are then used to rank the DMUs and thereby eliminate some (but not all) of the ties that occur for efficient DMUs. The input-oriented SE-DEA requires organizations to be freed from the constraint of the other model, as seen in the following program:

\[
\begin{align*}
\min \theta &- \varepsilon \left( \sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^- \right) \\
\sum_{j=1}^{n} x_{ij} \lambda_j + s_i^- &= \theta x_{i0} \quad i = 1, 2, 3 \ldots m \\
\sum_{j=1}^{n} y_{rj} \lambda_j - s_r^+ &= y_{r0} \quad r = 1, 2, 3 \ldots s \\
\lambda_j, s_i^-, s_r^+ &\geq 0, j = 1, 2 \ldots j_0 - 1, j_0 + 1 \ldots n 
\end{align*}
\]

where \( n \) is the number of decision union DMU; \( \theta \) is the efficiency score; \( \lambda_j \) is the index of input or output; \( x_{ij} \) represents the \( i \)th input of objective \( j \); \( S_i^- \) is the input slack variable; \( y_{rj} \) represents the \( r \)th output of objective \( j \); \( S_r^+ \) is the output slack variable. Denote the optimal solution to the model above as \((\theta, \lambda_j, S_i^-, S_r^+)\); DMU is identified to be efficient if \( \theta \geq 1 \) and all slacks are zero (i.e., \( S_i^- = 0, S_r^+ = 0 \)), meaning that DMU is located on the efficiency frontier without space to reduce its agricultural inputs and outputs; if \( \theta \geq 0 \) while its slacks are not all zero, DMU is weak efficient; otherwise, when efficiency score \( \theta < 0 \) and all slacks are not zero, DMU is inefficient.

**Data and variables**

With the above-mentioned approach, to gauge a clear picture of regional performance on AWUE, we wish to empirically evaluate the efficiency of 10 districts and three counties of Xi’an City in Northwest China using county-level data from 2004 to 2012. The data used in this study are obtained from the ‘Yearbook of China water resources’, ‘Statistical yearbook of Shaanxi’, and ‘Xi’an statistical yearbook’. In the calculation procedure, one year and one county are regarded as the DMUs at the temporal and spatial scale, respectively.

Assessment indexes are composed of input indicators and output indicators based on the SE-DEA model. Indexes should be chosen in conformity to four rules: reasonableness, comprehensiveness, representativeness, and practicability. The choice of inputs and outputs is usually a critical part of the analysis, as it involves different aspects of agricultural water uses. Indeed, it is impossible to fully capture the whole range of agricultural activities due to their multi-factor determinable nature.

Therefore, regarding the specification of the inputs and outputs, we employ the ecological, social and economic benefit indicators for the variable in the SE-DEA model. So, this paper takes the following six input indicators and...
two output variables as the model systems. The input and output indexes are defined as follows.

The input indexes:
1. The proportion of agricultural water consumption: this variable means the consumption proportion of agricultural water use in the total water consumption.
2. Irrigation consumption of water per hectare: this index means the water that farmers use when irrigating one mu of farmland.
3. The drought and flood insurance of farmland yield: this indicator is defined as the proportion of the area the farmer harvests when drought and flood occur.
4. Effective irrigation area: this factor indicates that the area of the farmland can be normally irrigated under general conditions in regions equipped with basic irrigation facilities and having a certain amount of water resources.
5. Water loss and soil erosion control area: this variable means the area of government control of soil erosion and water loss.
6. The total investment in water conservancy funds: this factor represents the total money the government invests in water facility construction, such as water canal redevelopment and drip irrigation construction, and so on.

The output indexes:
1. The added value of agriculture: this factor represents the economic benefit status, which is calculated as the total agricultural output minus the intermediate consumption in the agricultural production process.
2. The value of agricultural output per cubic meter of water: this index is used to describe the economic efficiency of water use and also represents the water-saving situations in the water resource use process.

**Grey systems analysis**

*Fundamental.* Grey systems analysis has been applied in many fields, and it can provide solutions for systems in which the model is uncertain, or the information is incomplete. The analysis is a method that measures the relevance between one event and every other event in turn by judging degree of similarity or dissimilarity about the development tendencies of two factors. If the change trend of the two factors is basically the same or closely related, then it means that the grey relational degree is higher; otherwise, it is called correlation small. If all factors affecting the selection of AWUE are taken as a system, it is a non-linear uncertain system with multi-parameters. Therefore, correlation is a quantitative description of the connection degree between factors in the system.

*Impact factor selection.* On the basis of the current research and the AWUE generating mechanism, with the principles of representation and scientific factors and data availability, this paper selected those above input and output assessment index as the factors which may affect AWUE. Because we simply know those factors have an effect on AWUE, but we do not know which one has the most influence on AWUE in this region, we call it grey correlation. And we take the AWUE as the mother-sequence, taking those influencing factors as the sub-sequence. Then the grey systems analysis will report the correlation values between the AWUE and those influencing factors. The greater the value is, the more the factor affects the AWUE. Therefore, we will ultimately know the major influencing factors and the secondary effect factors according to the grey relational degree, which will put forward a theoretical foundation for increasing AWUE.

**Statistical analyses**

Matlab 12.0 was used to evaluate the AWUE based on the SE-DEA model. We used the Statistical Package for Social Science version 16.0 for Windows to perform grey correlation analysis, which evaluated the influence of different factors (assessment index) on AWUE.

**RESULTS**

**Temporal variation of IWUE over the region**

To reveal the status of agricultural water use over time in Xi’an, the input and output data from 2004 to 2012 were primarily investigated. One year is regarded as every DMU in this temporal scale. The AWUE based on the model during different years is shown in Table 1. The variation range of the score was 0.52 to 2.05 over the 9 years, which demonstrated that the DMUs are all efficient or weakly efficient. Figure 1 shows that the AWUE presented a continuously increasing trend during the period 2004 to 2012. This is mainly because the government of the region strengthened the construction of water-saving agriculture and increased water conservation funding while facing a severe water deficit trend year after year. It can be observed that the minimum value was obtained in 2004 (0.52), which may be due to the agricultural water waste in serious conditions in addition to water not being fully utilized in this
In addition, the AWUE score was less than 1 (Table 1) except in 2009 and 2012, from which we can observe that there was considerable room for it to grow.

### Spatial variation of AWUE over the region

Taking full consideration of the aim of the agricultural water use evaluation mentioned above, this study identified all the districts and counties of this region in 2012, while three city blocks are not included as we describe above.

In the calculation procedure, one county was regarded as the DMU in this spatial scale. The results of the AWUE for the different districts and counties are shown in Table 2. They indicate that the AWUE of each district in this region is consistent with the performance of the local economy. From the result in Table 2, it can be observed that the variation range of the score was 0.59 to 1.70, which demonstrated that the DMUs are efficient. From the spatial distribution, Lan‘tian County obtained the peak value (1.70), which is exceptional. This result is not consistent with the reality, which will be discussed later. As expected, a higher AWUE score in the main metropolitan areas (Yanta District, 1.53; Baqiao District, 1.36; Weiyang District, 1.15 and Chang’an District, 0.98) was widely approved (Figure 2). In addition, reasonable calculation results were the same for the development of the local economy as well as the favorable geographical position in which they were sited. It should be noted that among the other five agricultural counties and districts (Yanliang District, Lintong District, Zhouzhi County, Huxian County and Gaoling County), satisfactory results for the AWUE were found in both Lintong County and Hu County in 2012 with values of 0.9584 and 0.9345, respectively (Figure 2). Interestingly, the findings were in accordance with our on-the-spot investigations. In contrast, the AWUE of Zhouzhi County received the lowest score. In a word, these influencing factors are representative of the local economic status and the irrigation mode and systems.

### Table 1 The results for AWUE of Xi’an City from 2004 to 2012 based on the SE-DEA model

<table>
<thead>
<tr>
<th>Year</th>
<th>Variables 2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>S₁</td>
<td>3.91</td>
<td>5.30</td>
<td>3.58</td>
<td>12.53</td>
<td>0.00</td>
<td>37.38</td>
<td>1.38</td>
<td>0.76</td>
<td>2.81</td>
</tr>
<tr>
<td>S₂</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>17.74</td>
<td>9.74</td>
<td>184.85</td>
<td>6.32</td>
<td>0.00</td>
<td>20.82</td>
</tr>
<tr>
<td>S₃</td>
<td>7.05</td>
<td>12.25</td>
<td>12.81</td>
<td>0.00</td>
<td>2.20</td>
<td>50.08</td>
<td>7.12</td>
<td>5.87</td>
<td>10.57</td>
</tr>
<tr>
<td>S₄</td>
<td>9.70</td>
<td>33.1</td>
<td>31.02</td>
<td>46.29</td>
<td>3.95</td>
<td>143.12</td>
<td>7.12</td>
<td>5.87</td>
<td>10.57</td>
</tr>
<tr>
<td>S₅</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>4.95</td>
<td>1.07</td>
<td>0.00</td>
</tr>
<tr>
<td>S₆</td>
<td>7.16</td>
<td>25.01</td>
<td>28.37</td>
<td>49.59</td>
<td>1.28</td>
<td>205.17</td>
<td>0.00</td>
<td>8.20</td>
<td>18.74</td>
</tr>
<tr>
<td>S₁+</td>
<td>3.79</td>
<td>3.26</td>
<td>2.33</td>
<td>3.43</td>
<td>3.81</td>
<td>0.00</td>
<td>1.22</td>
<td>0.00</td>
<td>1.07</td>
</tr>
<tr>
<td>S₂+</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>19.72</td>
<td>3.61</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>θ</td>
<td>0.52</td>
<td>0.62</td>
<td>0.66</td>
<td>0.81</td>
<td>0.89</td>
<td>2.05</td>
<td>0.84</td>
<td>0.96</td>
<td>1.20</td>
</tr>
</tbody>
</table>

S₁: the slack variable of the input parameters for the proportion of agricultural water consumption; S₂: the slack variable of the input parameters for the irrigation consumption of water per hectare; S₃: the slack variable of the input parameters for the farmland yield of drought and flood insurance; S₄: the slack variable of the input parameters for the effective irrigation area; S₅: the slack variable of the input parameters for the total investment in water conservancy funds; S₆: the slack variable of the input parameters for the area of water loss and soil erosion control; S₁+: the slack variable of the output parameters for the value added from agriculture; S₂+: the slack variable of the output parameters for the agricultural output value per cubic meter of water; θ: the value of the AWUE.
Effect of controlling factors on AWUE

AWUE is influenced by a large number of related factors and the regulating processes are highly complex and vary in both temporal and spatial conditions. The grey correlation analysis results shown in Table 3 indicated that the added value of agriculture, the area of water loss and soil erosion control and irrigation consumption of water per hectare had the greatest correlations with the AWUE, which were, respectively, 0.7987, 0.7901, and 0.7897. In addition, these factors were identified as the most important factors affecting the increasing AWUE. Greater correlations were the effective irrigation area, the proportion of agricultural water consumption and the agricultural output per cubic meter of water, which were 0.7650, 0.7585, and 0.7556.

### Table 2
The results for AWUE for all the districts and counties of Xi’an City in 2012 based on the SE-DEA model

<table>
<thead>
<tr>
<th>Districts and counties</th>
<th>Variables</th>
<th>Yan ta</th>
<th>Wei yang</th>
<th>Ba qiao</th>
<th>Changan</th>
<th>Yan liang</th>
<th>Lin tong</th>
<th>Lan tian</th>
<th>Zhou zhi</th>
<th>Hu</th>
<th>Gao ling</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_1</td>
<td>0.00</td>
<td>0.00</td>
<td>20.20</td>
<td>5.27</td>
<td>20.80</td>
<td>33.90</td>
<td>25.60</td>
<td>15.80</td>
<td>22.30</td>
<td>20.80</td>
<td></td>
</tr>
<tr>
<td>S_2</td>
<td>65.00</td>
<td>24.00</td>
<td>199.00</td>
<td>0.00</td>
<td>93.50</td>
<td>0.00</td>
<td>151.00</td>
<td>37.10</td>
<td>0.00</td>
<td>8.00</td>
<td></td>
</tr>
<tr>
<td>S_3</td>
<td>15.70</td>
<td>29.40</td>
<td>70.90</td>
<td>11.10</td>
<td>44.60</td>
<td>40.70</td>
<td>0.00</td>
<td>13.50</td>
<td>58.74</td>
<td>26.00</td>
<td></td>
</tr>
<tr>
<td>S_4</td>
<td>18.40</td>
<td>0.00</td>
<td>18.50</td>
<td>0.48</td>
<td>0.11</td>
<td>2.50</td>
<td>7.85</td>
<td>0.00</td>
<td>2.98</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>S_5</td>
<td>1.71</td>
<td>0.00</td>
<td>0.00</td>
<td>4.43</td>
<td>0.00</td>
<td>15.70</td>
<td>8.56</td>
<td>5.38</td>
<td>15.86</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>S_6</td>
<td>5.14</td>
<td>0.00</td>
<td>0.00</td>
<td>1.21</td>
<td>0.00</td>
<td>0.34</td>
<td>0.00</td>
<td>4.10</td>
<td>0.70</td>
<td>1.20</td>
<td></td>
</tr>
<tr>
<td>S_7</td>
<td>0.00</td>
<td>0.00</td>
<td>1.56</td>
<td>63.10</td>
<td>30.60</td>
<td>63.40</td>
<td>0.00</td>
<td>59.80</td>
<td>38.15</td>
<td>22.60</td>
<td></td>
</tr>
<tr>
<td>S_8</td>
<td>0.46</td>
<td>2.74</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>35.20</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>θ</td>
<td>1.53</td>
<td>1.15</td>
<td>1.36</td>
<td>0.98</td>
<td>0.73</td>
<td>1.70</td>
<td>0.59</td>
<td>0.93</td>
<td>0.77</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S_1: the slack variable of the input parameters for the proportion of agricultural water consumption; S_2: the slack variable of the input parameters for the irrigation consumption of water per hectare; S_3: the slack variable of the input parameters for the farmland yield of drought and flood insurance; S_4: the slack variable of the input parameters for the effective irrigation area; S_5: the slack variable of the input parameters for the total investment in water conservancy funds; S_6: the slack variable of the input parameters for the area of water loss and soil erosion control; S_7: the slack variable of the output parameters for the value added from agriculture; S_8: the slack variable of the output parameters for the agricultural output value per cubic meter of water; θ: the value of the AWUE.

### Table 3
Grey systems analysis results for AWUE influencing factors

<table>
<thead>
<tr>
<th>Influencing factors</th>
<th>Definition</th>
<th>Unit</th>
<th>Correlation degree</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic effect condition</td>
<td>Value added from agriculture</td>
<td>Billion Yuan</td>
<td>0.7987</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Agricultural output value per cubic meter of water</td>
<td>Yuan</td>
<td>0.7556</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Total investment in water conservancy funds</td>
<td>Billion Yuan</td>
<td>0.6688</td>
<td>8</td>
</tr>
<tr>
<td>Ecological effect condition</td>
<td>Area of water loss and soil erosion control</td>
<td>Ha</td>
<td>0.7901</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Proportion of agricultural water consumption</td>
<td>%</td>
<td>0.7585</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Irrigation consumption of water per hectare</td>
<td>m$^3$ ha$^{-1}$</td>
<td>0.7897</td>
<td>3</td>
</tr>
<tr>
<td>Social effect condition</td>
<td>Farmland yield of drought and flood insurance</td>
<td>%</td>
<td>0.7277</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Effective irrigation area</td>
<td>Ha</td>
<td>0.7650</td>
<td>4</td>
</tr>
</tbody>
</table>
respectively. As indicated, these three factors were not closely related to the AWUE, but the factors cannot be ignored, and it should be identified as a factor of secondary importance for AWUE; lower correlation indicators were farmland yield of drought and flood insurance and total investment in water conservancy funds, between which total investment in water conservancy funds (0.6688) had the least correlation. In addition, the two factors were not correlated to the AWUE in this region.

**Water-saving strategies based on the determinants**

According to the statistical and analysis results of influencing factors in this region, the factors that influence efficiency in Table 3 referred to the added value of agriculture, the area of water loss and soil erosion control and irrigation consumption of water per hectare, the effective irrigation area, the proportion of agricultural water consumption and the agricultural output per cubic meter of water according to the grey correlation analysis. These crucial factors undoubtedly stressed the water-saving measure in agricultural production, including the full use of natural precipitation as well as the efficient management of an irrigation network. Under the SWRM policy in China, which was carried out in 2012, the water-saving strategies for increasing AWUE based on the above analysis included the following three practices in Xi’an City as well as in the northwest of China. (1) Strategy to reduce agricultural water use. For the fast-growing mega-cites of Xi’an, keeping pace with urbanization is difficult for water allocation between different water users. To regulate residential and industrial water demand, reductions in agricultural water use can likely only partially achieve water-saving objectives. This involves trying to obtain as much produce as possible with the lowest water consumption. So, water-saving irrigation engineering (timing and amounts) is needed for adapting international metropolis development. The influencing factors (Table 3) indicated that this could achieve the aim of high-quality harvests with less water, more harvest and highly efficient water uses. (2) Sustainable water management policies enforcing strategy. This meant maximizing regional WUE by managing water resources and allocation on regional scales. The local government should strictly enforce the SWRM policy. China endeavors to limit the total quantity of water consumption by setting annual binding targets for agriculture, industry and drinking water to <700 billion cubic meters by 2030. So, this was issued to allocate goals in Xi’an City among the counties and districts. Moreover, based on our investigation, the current water governance structure, which is dominated by administrative systems, must be thoroughly reviewed to break the vicious cycle of tension and distrust between farmers and the government. Therefore, the key to overcoming the difficulty should be to build a number of farmer WUAs. (3) Regional structural adjustment strategy. This indicated the need to reduce economic crops that required high water consumption and enhance the coordination among different departments for this region.

**LIMITATIONS OF THE STUDY**

Understanding water-saving strategy based on increasing AWUE requires knowledge about specific variables and how these factors are related (Ostrom 2009). Indeed, one fixed set of indicators for each natural agricultural water management system is inappropriate, as every system is unique, and specific criteria and indicators may or may not be relevant for all cases (Geng et al. 2014). In our study, some simplification and the availability of the model parameters limited the results of this study, which should be improved in the future. For example, the selected indicators did not include water prices or management. Therefore, future comprehensive exploration should be conducted with pricing policies and water rights transactions. In addition, the issue of how to adequately address the uncertainty associated with evaluating the impact of different factors on AWUE remains a critical and challenging one.

**DISCUSSION**

One of the main problems in Xi’an City was serious water shortages, caused by water consumption in agriculture, industry and individual households. In addition, although water consumption by industry and households has increased gradually in recent years, agricultural usage was responsible for most of the total consumption. So, increasing AWUE for agricultural water saving was one of the most effective ways to solve the water shortage problem in this region. Our results indicated that the AWUE of this area presented a continuously increasing trend during the period 2004 to 2012 (Figure 1). Based on our field investigation, investment in water-related infrastructure for the municipal government increased year by year (2004–2012). Chen et al. (2014) also concluded that adequate infrastructure was identified as one of the necessary prerequisites for the successful implementation
of the water-saving mechanism, which agrees with our research. However, the score for the AWUE was less than 1 (Table 1) except in 2009 and 2012, from which we can observe that there was considerable room for improvement. In addition, we believe that this area had great potential to be scaled up. As mentioned regarding the spatial AWUE, Lantian was an exception. Of the total arable area in the region, approximately 19.60% was irrigated, and most of the land was mountain ridge, where agriculture was mainly dependent on the weather and rainy harvests and had no conditions amenable to irrigation. As the data we obtained for the output parameters covered all values for agriculture, the low input but high output resulted in high AWUE among all countries. The AWUE of the metropolitan areas such as Yanta, Baqiao District, Weiyang, and Chang’an District were all higher than other counties (Figure 2), which proved that the superior socio-economic and geographic position contributed to increasing the AWUE. The farmers’ greater water-saving consciousness of water-saving irrigation strategies had been developed for higher AWUE, in accordance with other studies (Howell 2001; Shan et al. 2006; Wang et al. 2006; Cui et al. 2008).

Many studies also confirmed that AWUE was affected by many factors, such as environmental factors, the principles and features of the pricing policies, efficient management and so on (Frone & Frone 2012; Wang et al. 2014; Li et al. 2015). However, this study confirmed that the AWUE was correlated to a larger extent with the value-added from agriculture, the area of water loss and soil erosion control and irrigation consumption of water per hectare (Table 3) and also presented a positive relationship with them, which was obviously distinct from previous studies. In summary, these determinants reflected the socio-economic development and ecological conservation conditions of the region. In the economically developed counties and districts, the irrigation practices (timing and amounts) based on compatible water-saving techniques were better than others, which was consistent with our investigation. The other reason was perhaps the increased scientific understanding of the effects of advanced irrigation systems and efficient management modes on AWUE across various counties (Blanke et al. 2007). In addition, different irrigation systems can, to a large extent, influence AWUE, which can vary significantly in different locations or even within the same region. Generally, micro-irrigation systems (drip emitters, drip tape, spray, and sprinklers) were all more efficient than furrow irrigation (Sezen et al. 2011; Tanwar et al. 2014).

In other research conducted by Cetin & Bilge (2002), the AWUE ranges for furrow, drip and sprinkler irrigation were 0.19–0.42, 0.35–0.61 and 0.17–0.66 kg m⁻³, respectively, which was in line with the above studies. However, among the various factors available to influence AWUE, water pricing policy and tradable water rights systems had been prioritized worldwide (Ahmad 2000; Dosi & Easter 2002). However, this research did not select the two factors as the model parameters mainly because the water prices did not change in different districts and counties in recent years. In addition, water rights trading in this area had not been implemented. So, this will be the most important aspect in our future research. The environment conservation status also affected AWUE in terms of the ‘area of water loss and soil erosion control’ indicated in Table 3. This may be the result of decreases in water loss and more water harvest for the depletion of flow that is needed for agricultural use (Cai 2004). Therefore, AWUE can also clearly reflect the conditions of the ecological effects of Xi’an City.

It is estimated that an increasing water shortage in the region could undermine irrigation-based agriculture if adequate countermeasures are not adopted (Brown et al. 2009). Facing serious water shortages and the SWRM policy, based on an understanding of the indicators that influence AWUE, some new strategies on agricultural water saving are required in this region. Among the strategies available to increase AWUE for agricultural water saving, water-saving irrigation strategies have been prioritized in this region. Because this refers to the use of irrigation farming practices with the most economical exploitation of water resources, at the same time, water leakage and evaporation from storage facilities and in transport had to be reduced to a minimum (Tang et al. 2015). However, most of the farmers in the counties stayed on the furrow irrigation system and did not adopt the advanced irrigation system. In addition, farmers often tended to over-irrigate as they did not have the required knowledge regarding the timing, frequency and rate of irrigation. This practice wasted a substantial amount of limited water resources; much less irrigation could yield similar productivity (Sarwar & Bastiaanssen 2001). The investment in the construction of the infrastructure may have exacerbated farmers’ burdens and may not have brought any benefits; thus, the strategy was not better implemented. Hence, the estimated water saving was analyzed in relation to the present irrigation practice to evaluate the implications for food production, the environment and the economy. Thus, the sustainable water management policies enforcing strategy should be appreciated. Inevitably, with participatory agricultural management and the full
involvement of small-scale farmers, farmer WUAs become increasingly common in the arid northwest of China (Wang et al. 2010). Hu et al. (2014) also stated that the current water governance structure, which was dominated by administrative systems, must be thoroughly reviewed to break the vicious cycle of tension and distrust between farmers and the government. Veettil et al. (2011) reported that water pricing and water rights were appropriate for agricultural water saving, which could also increase the willingness to pay for a change in scenario. On the contrary, Chen et al. (2014) stated that the new mechanism of ‘collect then refund’ appears to be a more promising alternative than increasing agricultural water prices or introducing water marketing, and it is currently adopted in northern China.

CONCLUSIONS

The SE-DEA model was employed for conducting AWUE and the study showed that Xi’an City in Northwest China failed to reach overall technical efficiency levels concerning water use from 2004 to 2012, although it increased year by year. It appeared that the smallholder irrigation farmers and local government in this study area had little incentive to use water in an efficient manner and implemented the advanced irrigation systems in the absence of infrastructure installation. Therefore, the water-saving strategies required to solve the serious water shortage and adapt to the development of the international metropolis of Xian should be: (1) decreasing agricultural water use (timing and amounts) based on compatible water-saving techniques; and (2) maximizing regional WUE by managing water resources and allocation on regional scales as well as enhancing the coordination among different departments for China’s government. Such information is valuable for extension services and policy-makers because it can help guide policies toward increased efficiency.

ACKNOWLEDGMENTS

This work was financially supported by the General Financial Grant from the China Postdoctoral Science Foundation (2015MS80807), the Fundamental Research Funds for the Central University (15SZYB22), the Ministry of Education project of key research institute of humanities and social sciences in universities (11JJJD790012), and the Ministry of Education project of humanities and social science (11YJA790027).

REFERENCES


Statistics Bureau of Xi’an city (SBXC) 2003 *Statistics Yearbook of Xi’an City*. Xi’an Press, Xi’an, Shaanxi, China (in Chinese).


First received 20 August 2015; accepted in revised form 31 May 2016. Available online 17 June 2016.