Evaluation of relative water use efficiency (RWUE) at a regional scale: a case study of Tuhai-Majia Basin, China
Yao-Huan Huang, Dong Jiang, Da-Fang Zhuang, Jian-Hua Wang, Hai-Jun Yang and Hong-Yan Ren

ABSTRACT
Enhancing water use efficiency (WUE) is the key approach to maintain sustainable water resource supply. Due to the complexity of the water cycle, accurate estimation of WUE at the regional scale is a challenging task. Here we presented a framework of relative water use efficiency (RWUE). According to the linkage between RWUE and land use types, assessment of WUE at a regional scale could be performed operationally. This approach was evaluated in a study area, Tuhai-Majia Basin, North China. Based on remote sensing-derived evapotranspiration (ET) and land use data, regional WUE were assessed accordingly. The mean RWUE of agriculture, ecosystem and total basin in 2005 was 60.12, 30.07 and 62.5%, respectively. Spatial analysis showed that the agricultural WUE played the dominant role in water-saving of the study area; water management of unused land (RWUE of 2005 was 5.46%), especially wetland protection and other unused land development, will contribute significantly to ecological RWUE improvement. Temporal analysis indicated that there was considerable inter-annual variability in RWUE time series profiles. The agricultural interlude period might be important for enhancing WUE in the Tuhai-Majia Basin. In general, the results indicated that the RWUE-based method was an efficient and simple method to evaluate WUE at regional scale.

Key words | evapotranspiration, land use, relative water use efficiency

INTRODUCTION
Water is the most important limiting factor in regional development, and water shortage is likely to be exacerbated by increasing population, deteriorating soil and poor water quality (Chen et al. 2005). The common consensus is that the only method to maintain sustainable water resource supply is to improve water use efficiency (WUE). Enhancing WUE at field and regional scales via innovative management is the key to coping with the challenges of water shortage (Condon et al. 2004).

The WUE is initially used in agriculture system research, and is generally defined as the ratio of the amount of system output to the input or flux of water used in its production (Perry 2007; Moore et al. 2011). No consensus has been reached as to which output or which water flux should be used to compute this ratio (Perry et al. 2009). Different researches have used precipitation, irrigation or their sum, evapotranspiration (ET), and transpiration as the denominator of their WUE indices and gross primary production (GPP), grain yield, income and profit measures as the numerator. In fact, all these indices are what an economist would call the productivity of water. It is not a true ‘efficiency’, which is a term conventionally reserved for the dimensionless ratio of the output of a quantity to its input. Based on this definition, evaluation of WUE is always conducted by combining the dimensionless ratios of all aspects of the water cycle system. The International Commission on Irrigation and Drainage (ICID) defined ‘irrigation efficiency’ as the product of conveyance efficiency, distribution efficiency and field application efficiency (Bos 1979). Although other indices or methods have been proposed to compute the dimensionless ratios to evaluate WUE, little progress has been made based on the definition given by ICID (Lei et al. 2009). However, the choice of ratios of aspects of the water cycle system is largely determined by scale and complexity of the system concerned. When considering region or basin at large spatial scales, the question arises as to how to calculate WUE of multiple water cycle processes and to combine
them. For there is a need to understand the factors that result in a particular WUE, water cycle at regional or basin scales is complex, making WUE difficult to be evaluated. Furthermore, with the expansion of the study area to regional scales, the definition of boundaries and terminology might be an important factor to WUE evaluation precision as inter-connection of water in the sub-system can’t be ignored. Water loss at small scales may be reused at larger scales such as return flow (Willardson 1985), which might give rise to error in WUE estimation.

There is a clear consensus that WUE should be estimated in a wider scope. Although the WUE of the agriculture system that most current researches are focusing on is important, it is too microscopic and unilateral to WUE estimation at larger scales. Pei et al. (2009) pointed out that the WUE of ecosystems is also an important component besides domestic, industrial and agricultural WUE. Due to different compositions of ecosystems in different study cases, there is not a uniform or widely accepted index for ecosystem WUE estimation, which cannot be ignored at regional scales.

In general, WUE is very difficult to estimate accurately and systematically at regional scale. In this study, we: (1) proposed a conceptual scheme for RWUE estimation according to land use map, which was generic and had a wide range of possible applications at regional scale; and (2) estimated the agricultural, ecological and regional RWUE of Tuhai Majia basin, and evaluated the performance of this method.

**METHODS**

**Definition of water consumption efficiency based on land use**

Humans gain the benefit from water resource use through water consumption. Perry (2007) pointed out that the consumed fraction is essentially ET at larger scales, comprising beneficial consumption (for the purpose intended or other beneficial use such as environmental purposes) and non-beneficial consumption (e.g. weeds or resulting from capillary rise during a fallow period). The concept of ‘real water-saving’ was proposed in the project of ‘research of real water-saving’ founded by the World Bank in 2000, with the main objective to reduce the non-beneficial ET (Shen et al. 2000). Considering that humans benefit from water consumption, all fractions of water consumption are beneficial; there is only efficient and inefficient water consumption. Taking crops for example, evaporation of soil is less efficient than vegetation transpiration for photosynthesis for human benefit.

In this paper, ET was divided into two fractions, namely, efficient consumption and inefficient consumption, according to their benefit to humans. For land use is the carrier of water use in larger scales, and different constitutions of land use had different WUEs (Wang & Chen 2004). We established a linkage between the water consumption efficiency and land use type. Table 1 shows the framework of the land use classification system and corresponding definition of WUE. The land use data and classification system were derived from Data Center for Resources and Environmental Sciences (RESDC), Chinese Academy of Sciences (Liu et al. 2005).

<table>
<thead>
<tr>
<th>Categories</th>
<th>Sub-categories</th>
<th>Definition of water consumption (ET) efficiency</th>
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<tbody>
<tr>
<td>Crops land</td>
<td>Paddy field</td>
<td>ET of vegetation</td>
</tr>
<tr>
<td></td>
<td>Dry farming field</td>
<td>interception and transpiration is efficient,</td>
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<tr>
<td></td>
<td></td>
<td>other is inefficient</td>
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<tr>
<td>Forest land</td>
<td>Woodland</td>
<td>ET of vegetation</td>
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<tr>
<td></td>
<td>Shrub land</td>
<td>interception and transpiration is efficient,</td>
</tr>
<tr>
<td></td>
<td>Sparse forest</td>
<td>other is inefficient</td>
</tr>
<tr>
<td>Grass land</td>
<td>Dense grassland</td>
<td>ET of vegetation</td>
</tr>
<tr>
<td></td>
<td>Medium dense grassland</td>
<td>interception and transpiration is efficient,</td>
</tr>
<tr>
<td></td>
<td>Sparse grassland</td>
<td>other is inefficient</td>
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<tr>
<td>Water</td>
<td>River and trench</td>
<td>ET of trench is inefficient,</td>
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<tr>
<td></td>
<td></td>
<td>ET of river is efficient</td>
</tr>
<tr>
<td></td>
<td>Lake</td>
<td>Efficient</td>
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<td></td>
<td>Reservoir</td>
<td>Inefficient</td>
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<td></td>
<td>Permanent glacier and snow land</td>
<td>Inefficient</td>
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<tr>
<td></td>
<td>Shoal</td>
<td>Efficient</td>
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<td></td>
<td>Bottomland</td>
<td></td>
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<tr>
<td>Residential and build-up land</td>
<td>Urban land</td>
<td>ET of rainfall and water consumption of living</td>
</tr>
<tr>
<td></td>
<td>Rural residential land</td>
<td>and productions are efficient</td>
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<tr>
<td></td>
<td>Other build-up land</td>
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<tr>
<td>Unused land</td>
<td>Sand</td>
<td>Inefficient</td>
</tr>
<tr>
<td></td>
<td>Gobi</td>
<td>Inefficient</td>
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<tr>
<td></td>
<td>Alkaline land</td>
<td>Inefficient</td>
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<tr>
<td></td>
<td>Wetland</td>
<td>Efficient</td>
</tr>
<tr>
<td></td>
<td>Bare land</td>
<td>Inefficient</td>
</tr>
<tr>
<td></td>
<td>Barren lands</td>
<td>Inefficient</td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>Inefficient</td>
</tr>
</tbody>
</table>
For cropland, forest land and grassland, the definitions of water consumption efficiency are similar. Evaporation of the vegetation canopy interception reduces the temperature of the surface and body of plants to maintain their normal physiological needs, which is defined as efficient water. Vegetation transpiration is also efficient, for it is the sub-process of biomass production. Although soil evaporation can regulate the circumstances around the vegetation, it is inefficient in terms of phytomass output.

Land uses of rivers, lakes, shoals, bottomlands and wetlands play important roles in maintaining the ecosystem healthy. They are not only useful to sustain biological diversity and enrich the ecological landscape, but also perform hydrological functions. Therefore, we defined the ET of the water body as efficient water consumption.

Reservoirs and trenches were key components of ecological landscapes, playing an important role in regulating the regional microclimate. However, they are classified as artificial land uses for storing water. So we defined the ET of these land uses as inefficient consumption.

ET of precipitation in residential and build-up land is efficient, as it affects temperature and humidity adjustment, which benefits human health. Water consumption of living and production are necessary for economic and social activities, which are defined as efficient. ET of unused land, including sand, gobi, alkaline land, bare land and barren land, are defined as inefficient consumption.

Evaluation of RWUE

As the absolute WUE is hard to evaluate, we proposed the concept of relative water use efficiency (RWUE) based on the definition of consumption efficiency of generalized water resources shown in Table 1. RWUE is defined as the ratio of the water amount of system efficient consumption (ET) to system total consumption (ET):

\[ \text{RWUE} = \frac{\text{ET}_T}{\text{ET}_T} \]

where RWUE is relative water use efficiency (RWUE); ET_T is the amount of system efficient ET; ET_T is the amount of system total ET.

For the agricultural system, cropland is the main carrier of land use. We partitioned efficient ET of vegetation interception and transpiration and inefficient ET of bare soil evaporation with fractional vegetation cover \( f_{\text{veg}} \) in a mixed pixel (Table 1). Then the amount of efficient ET in agricultural system is:

\[ \text{ET}_{Ta} = f_{\text{veg}} \times \text{ET}_a \]

where ET_{Ta} is the amount of efficient ET in the agricultural system; ET_a is the total amount of ET in the agricultural system.

For the ecological system, we defined four land use categories as its land use carrier, i.e. forest land, grassland, water body and unused land. The efficiency of water consumption of grassland and forest land are similar to that of cropland, and the efficient ET of the water body and unused land is defined according to the sub-categories of land use (Table 1). The amount of efficient ET in the ecological system is expressed as:

\[ \text{ET}_{Tf} = f_{\text{veg}} \times \text{ET}_f + f_{g} \times \text{ET}_{g} + f_{s} \times \text{ET}_{s} + f_{b} \times \text{ET}_{b} + \text{ET}_{w} \]

where ET_{Tf} is the amount of efficient ET in the ecological system; ET_f is the total amount of ET in the forest system; ET_g is amount of ET in the grass system; ET_s is the amount of ET in rivers; ET_{sb} is the amount of ET of shoals; ET_b is the amount of ET in bottomlands; ET_w is the amount of ET in wetlands.

For the whole region, water use of living and production is so complicated that it is difficult to estimate efficient water consumption at macroscopic scales. As ET in residential and build-up land benefited humans to a greater or lesser extent, we computed the regional amount of efficient water consumption as follows:

\[ \text{ET}_{Tr} = \text{ET}_{Ta} + \text{ET}_{Tf} + \text{ET}_{rb} \]

where ET_{Tr} is regional amount of efficient ET; ET_{rb} is the amount of ET in residential and build-up land. The ET data were overlapped with the land use data layer. The ET of each land use type was derived using GIS spatial statistical method. Then, the components used in Equation (4) \((ET_{Ta}, ET_{Tf}, ET_{rb})\) were derived by accumulating the ET of certain types of land use.

CASE STUDY

Study area

The study area, Tuhai-Majia Basin, is an alluvial plain of the Yellow River with an area of 30,945 km². Elevation decreases from northeast to southwest, ranging from 1 to 65 m. The climate of this area is semi-humid monsoon
climate in a temperate zone. The mean annual temperature of this area is approximately 12.6 °C, and the mean annual precipitation is 567.3 mm. Tuhai-Majia Basin is an agricultural region with great water resources demand. However, the basin is one of the serious water shortage areas of China.

Data acquisition

Three types of data were adopted for RWUE evaluation: ET datasets from remote sensing images, land use data and fractional vegetation cover data.

Satellite-based ET evaluation

In this paper, ET was derived from hourly images from China’s geostationary meteorological satellite FY-2C. The VIS band (covering the wavelengths from 0.55 to 0.9 μm) and the IR1 band (covering the wavelengths from 10.3 to 11.3 μm) were used.

ET varies diurnally, which poses a challenge for ET estimation using instantaneous remote sensing images. Here we estimated ET based on evaporative fraction (EF) which could be assumed to be constant during the daytime (Crago & Brutsaert 1996). EF was calculated as:

\[
EF = \frac{\lambda ET}{A} = \frac{R_n - G - H}{R_n - G}
\]

where EF stand for evaporative fraction, ET (mm) is the daily actual evapotranspiration, \( H \) (W/m²) is the sensible heat, \( R_n \) (W/m²) is net radiation, \( G \) (W/m²) is soil heat flux, \( A \) (W/m²) is available energy, \( \lambda \) is the latent heat of vaporization (\( = 2.49 \times 10^6 \) (W/m²) · mm⁻¹).

Based on the assumption above, the daily actual ET could be estimated by:

\[
ET = \frac{86,400 \times EF \times R_{\text{day}}}{\lambda}
\]

where \( R_{\text{day}} \) is the daily surface net radiation (W/m²). We proposed a sinusoidal model for estimating \( R_{\text{day}} \) (Bisht et al. 2005). The ET dataset has been validated using Large Aperture Scintillometer (LAS) measurements from 9 sites in the basin. The remote sensing-derived ET and LAS-measured ET matched very well. The \( R^2 \) for clear days is larger than 0.85, and for both clear and cloudy days of the year 2005, the \( R^2 \) is about 0.80. More details can be found in our paper (Huang et al. 2009).

Land use

The land use dataset at the scale of 1:100,000 for 2005 was obtained from Landsat TM and CBERS-2 satellite images and interpreted by experts in RESDC (Table 1). A set of land data from field surveys was selected to guarantee the accuracy of land use classification and it is the most accurate land use dataset at this scale in China.

Vegetation cover fraction (\( f_{\text{veg}} \))

Enhanced Vegetation Index (EVI) retrieved from satellite images was used to calculate fractional vegetation cover. In our study, it was assumed that EVI was linearly related to \( f_{\text{veg}} \):

\[
f_{\text{veg}} = \frac{EVI - EVI_{\text{min}}}{EVI_{\text{max}} - EVI_{\text{min}}}
\]

where EVI_{min} and EVI_{max} are the signals from bare soil (LAI→0) and dense green vegetation (LAI→∞), which are set as invariant constants 0.05 and 0.95, respectively.

RESULTS AND DISCUSSION

Agricultural RWUE

We estimated agricultural RWUE of paddy field, dry farming field and cropland. The aggregated monthly agricultural RWUE in 2005 of Tuhai-Majia Basin showed remarkable inner annual variability (Figure 1).

By comparing three types of RWUEs, we found that RWUE of dry farming field (60.17%) was more efficient than that of paddy field (51.47%), which indicated that the
dry farming is more suitable for water shortage areas such as the Tuhai-Majia basin. RWUE of agriculture (60.12%) was similar to RWUE of dry farming field, which mainly resulted from the areas dry farming field reaching almost 95% of total cropland area. Agricultural WUE in the Tuhai-Majia Basin was dominated by WUE of dry farming field, indicating that the planting structure of the study area was relatively reasonable in terms of RWUE. It also revealed that changing plantation patterns might be a way to increase agricultural WUE.

Three time-series curves (Figure 1) showed that the maximum agricultural RWUE appeared in July and reached its minimum in December for the year. The seasonal variations of RWUE might be determined by both inherent biological characteristics and external environmental conditions. Furthermore, time-series RWUE profiles displayed a double-peak pattern, which implied the double-cropping of the study area. The double cropping rice is planted in the paddy field, meanwhile the dry farming field adopted the winter wheat-summer corn rotation cropping. The trough of RWUE value in May corresponded to the agricultural interlude after harvest period, with less water consumed for crop growth but more soil evaporation resulting in low efficiency. It revealed that improving the WUE in May was the key to agricultural water management of the study area.

**Ecological RWUE**

At present, numerous studies on WUE are focused on analyzing the WUE of the economic system such as agriculture, industry, and human living, rather than the ecosystem. Here we applied RWUE to evaluate the WUE of the Tuhai-Majia Basin. Four categories of land use, i.e. forest land, grassland, water body and unused land, are defined as RWUE evaluation carriers. Their RWUEs were calculated, as shown in Figure 2.

Time-series profiles showed that the ecological RWUE of the Tuhai-Majia Basin was relatively low (50.07%). The four types of ecological system in a decreasing order of RWUE were forest land, grassland, water body and unused land. The RWUE of forest land and grassland displayed a similar single-peaked pattern with the maximum appearing in July. Water use of grassland was less efficient than that of forest land. Due to the small area of forest land and grassland in the study area as well as inherent biological characteristics of the vegetation, they were not keys to WUE improvement of the Tuhai-Majia Basin.

However, the inner annual variability of water and unused land was less significant. The total water consumption was also statistically analyzed based on land use types. The water consumption of unused land (6.98 billion m$^3$) accounted for the major part (43.4%) in the ecological system. However, RWUE of unused land was relatively inefficient (with mean value of 5.46%). Based on the land use classification system shown in Table 1, the improvement of ecological WUE of the Tuhai-Majia Basin should be primarily focused on wetland protection and other unused land development.

**Regional RWUE**

The RWUE we proposed could be applied to evaluate the WUE at regional scale. Figure 3 shows the regional RWUE, taking Tuhai-Majia Basin as a whole. The water consumption of ET is also shown besides RWUE.

The time-series profile of regional RWUE clearly showed the double-peak pattern similar to that of
agricultural RWUE. And there was little difference in value between the RWUE of the region (62.5%) and that of agriculture (60.12%). Statistical analysis of land use showed that the area of cropped land of 2005 was 22,426 km², accounting for 77.1% of the total area of the Tuhai-Majia Basin. The WUE of agriculture contributed significantly to regional WUE in terms of both inner annual variability and magnitude. Therefore, for the Tuhai-Majia Basin, the agricultural water saving could greatly improve regional WUE, which was the focus of integral water use management of the Tuhai-Majia Basin.

Figure 3 shows an inflexion in May by comparing the profile of RWUE to that of ET. As the regional WUE was dominated by that of agriculture, the trough appearing in May could be attributed to an agricultural interlude period, whereas the ET profile displayed a typical single-peaked pattern and ET was relatively high in May. This indicated that most of the water was inefficiently consumed with less production for human beings. Therefore, improvement in the WUE in May was also significant to regional water management, as mentioned in the section on Agricultural RWUE above.

CONCLUSION

In this study, we developed a conceptual methodology of RWUE to evaluate agricultural, ecological and regional WUE at regional scales. With remote sensing-derived ET and the land use map, we applied the RWUE to evaluate the WUE of the Tuhai-Majia Basin.

Regional RWUE analysis implied that agricultural WUE was the focus of regional Tuhai-Majia Basin water management, and unused land was significant for ecological WUE improvement. As cropland accounted for 77.1% of the total area of the basin, the monthly time-series profile of regional RWUE was similar to that of agriculture in both magnitude and inner annual variability. The inter-annual variability of ecological RWUE was less significant. The mean value of ecological RWUE was 30.7%, which was relatively low. Water consumption of unused land (6.98 billion m³) accounted for the largest proportion in the ecological system, whereas RWUE of unused land (5.46%) was the lowest. This indicated that wetland protection and development of other unused land were significant to improve ecological WUE. Our analysis suggested that a more sophisticated water-saving and water management mechanism should be applied to the land uses of crop land and unused land. We found that in May an inflexion appeared in time-series profile analysis of RWUE and ET. Due to the adoption of a double cropping system of the study area, it was also important to improve WUE of the agricultural interlude period in May from a temporal perspective.

In general, this study provided an operational way to evaluate regional WUE of a large area. We have reason to anticipate that this new method will be of significant value to be applied in WUE evaluation for the purposes of water management.

ACKNOWLEDGEMENTS

This research was supported and funded by the State Key Laboratory of Resources and Environmental Information System of China, and China Postdoctoral Science Foundation (20100480437, 201104133).

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First received 17 November 2011; accepted in revised form 4 April 2012