

# An improved approach for modeling spatial distribution of water use profit—A case study in Tuhai Majia Basin, China



Yaohuan Huang, Dong Jiang\*, Dafang Zhuang, Yunqiang Zhu, Jingying Fu

State Key Lab of Resources and Environmental Information System, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

## ARTICLE INFO

### Article history:

Received 5 December 2012

Received in revised form 21 April 2013

Accepted 15 July 2013

### Keywords:

Water use profit (WUP)

Spatial distribution

Economic

Ecological

## ABSTRACT

Water use profit (WUP) has been recognized as an important indicator of water resources management. This paper presents a set of models for evaluating the spatial distribution of economic and ecological WUP. The outputs of the models are detailed with a higher resolution than those in traditional WUP evaluation. Evapotranspiration (ET), which can be retrieved from remote sensing images, is regarded as the water consumption at the basin scale. The gridded GDP and ecosystem service value (ESV) are derived as indices of economic and ecological profits respectively. This method is applied in the Tuhai Majia Basin, North China. Agriculture is both economically and ecologically fundamental in the study area. The economic WUP of the whole basin ( $4.87 \text{ Yuan/m}^3$ ) is slightly higher than the value of primary industry ( $3.39 \text{ Yuan/m}^3$ ) and lower than the value of the secondary industry and tertiary industry ( $9.84 \text{ Yuan/m}^3$ ). The ecological WUP of the whole basin ( $87.29 \text{ Yuan/m}^3$ ) is quite close to the value of farmland. Water and wet land conservation and the development of barren land are important for ecological WUP improvement. Moreover, the dataset of WUP generated based on our method in this paper can be used for multi-scale analysis and be helpful to basin water resource management.

© 2013 Elsevier Ltd. All rights reserved.

## 1. Introduction

Water use profit (WUP) is an important index for policy makers, environmental managers and conservation practitioners for water-saving (Smajgl et al., 2010). Due to exacerbated water shortages resulting from a growing population and deteriorating soil and water quality, enhancing the WUP has been an essential way to maintain a sustainable water resources supply and to ensure a healthy social development.

In this paper, WUP is defined as the profits brought to human society by water consumption in a socio-economic and ecological system. All indices proposed to evaluate WUP can be classified into three categories, namely, economic profit, social profit and ecological profit. Traditionally, WUP was evaluated by econometric approaches. Based on the theory of marginal utility, economic WUP could not exceed the least cost of water resources (Young, 1973). Other economic theories were introduced into economic WUP studies to evaluate WUP in the subsequent decades, such as the theory of economic levers (Fakhraei et al., 1984; Moncur, 1987, 1988), duality value theory (Huang, 1994) and theory of ground rent (Zhang, 1996), which led to a succession of water resources management practices. With the progress made in water resources

research, the social profit of water use was proposed as a public welfare attribute of water resources (Luo, 2003). However, the social WUP is too vague to be evaluated quantitatively, and there are no universal methods or indices for evaluation. Furthermore, recent social WUP studies are mainly focused on urban areas because application of the methods or indices of these studies to regional scales is difficult. During the 1990s and 2000s, more and more ecological problems caused by water shortages gave rise to a new field of WUP, i.e., the ecological profit of water use. Ni defined ecological WUP as the impact of changing water resources on an ecological environment (Ni et al., 2003). A number of methods were proposed to evaluate the ecological WUP including Green GDP accounting (Gao et al., 2005), GPP (Lu and Zhuang, 2010), etc. Water resources are indispensable for the habitats of numerous creatures and as regulators of the earth's energy balance. Therefore, ecological WUP is difficult to evaluate unless the regulatory function has been completely lost (Li and Hui, 1999). Thus, the evaluation of ecological WUP needs to consider the whole ecosystem in addition to the surface water system (He et al., 2000).

With the development of geo-information technologies and hydrological models, water resources research is being improved by providing methods of retrieving spatially distributed hydrological parameters of water use including evapotranspiration (ET), precipitation, water consumption, etc. However, profit (economic) data are traditionally collected based on administrative boundaries, which cannot meet the needs of spatial WUP evaluation because of

\* Corresponding author. Tel.: +86 10 64889681; fax: +86 10 64855049.

E-mail addresses: [jiangd@igsnrr.ac.cn](mailto:jiangd@igsnrr.ac.cn), [jiangd@lreis.ac.cn](mailto:jiangd@lreis.ac.cn) (D. Jiang).

(1) the low spatial resolution of the datasets; and (2) incompatibility with the spatially distributed water use data such as ET. A new “spatialization of anthrop factors” proposed in the 1990s can be used for the generation of spatially distributed profit data (Yang et al., 2009; Jiang, 2007). There is a perceived need by various stakeholders for the integration of spatially distributed profit and water use data that provide support for water resources management.

In this paper, we propose a deterministic approach that uses the ET retrieved from remote sensing and gridded GDP and ecosystem service value data to model regional WUP. The GDP and ecosystem service value data are obtained by pixel-based GIS methods. From the model results the spatial and temporal variability of WUP can be estimated. To demonstrate the applicability of this method, we present a case study of the Tuhai Majia Basin in North China.

## 2. Methodology for evaluating WUP

Humans gain profit from water resource use through water consumption. In this study, WUP equals the ratio between the profit and water consumption. According to in-depth consultations and widely circulated previous papers, the division of water resources into consumed and non-consumed fractions is recommended. At the basin scale, consumed water can be defined as the water used and removed from a water basin to the extent that it is permanently unavailable for further use. The consumed fraction (essentially ET) is comprised of beneficial consumption (water evaporated or transpired for the intended purpose, e.g. evaporation from a cooling tower, transpiration from an irrigated crop) and non-beneficial consumption (water evaporated or transpired for purposes other than the intended use, e.g. evaporation from water surfaces, riparian vegetation, waterlogged land) (Perry, 2007; Molden and Sakthivadivel, 1999; Sarwar and Perry, 2002; Shen et al., 2000). Both consumed fractions contribute to WUP, but the reduction in non-beneficial evaporation loss locally often implies more available water for downstream areas and thus the achievement of a higher WUP at the basin scale (Khan et al., 2008; Cai and Rosegrant, 2004; Cai et al., 2011). Therefore, basin-scale WUP was estimated in this study as the profit (Pw) per total water consumption (ET):

$$WUP = \frac{Pw}{ET} \quad (1)$$

In an economic system, various parameters (e.g., crop yield, gross primary productivity) are used as indicators of the profit brought by water consumption. However, they are not comparable when evaluating real profit to human among different types of products. In this study, we chose gross domestic product (GDP) as indicator of economic profit in the basin context. In China, GDP statistics brings another problem: its statistical unit (county) is inconsistent with the spatial resolution of ET retrieved from remote sensing images ( $1\text{ km} \times 1\text{ km}$  pixel). We processed GDP statistics with a spatial distribution model to grid form, which will be detailed in the section of data acquisition. The economic WUP was calculated as:

$$WUP_{en} = \frac{GDP_s}{ET} \quad (2)$$

where  $WUP_{en}$  is the economic WUP,  $GDP_s$  is the spatially distributed GDP.

In an ecological system, it is difficult to measure ecological profit accurately due to the complexities of the structure and function of an ecosystem. The economic valuation of ecosystem services is more widely applied to understand the multiple profits provided by ecosystems (Guo et al., 2001). In this study, the ecosystem service

value was adopted to evaluate ecological profit. The ecological WUP was calculated as:

$$WUP_{el} = \frac{ESV_s}{ET} \quad (3)$$

where  $WUP_{el}$  is the ecological WUP and  $ESV_s$  is the spatially distributed ecosystem service value.

## 3. Case study

### 3.1. Study area

The study area, the Tuhai Majia Basin, lies in North China from  $35^{\circ}41'N$  to  $38^{\circ}08'N$  and from  $114^{\circ}51'E$  to  $118^{\circ}58'E$  (Fig. 1). It is an alluvial plain of the Yellow River with area of  $30,945\text{ km}^2$ . The mean annual precipitation of this area is 567.3 mm. It is the main agricultural region with a great water resources demand. However, the basin stands in an area of China with a serious water shortage (Huang et al., 2009).

### 3.2. Data acquisition

To evaluate the economic and ecological WUP at the basin scales, we acquired four types of data: (1) land use map, (2) ET evaluation datasets from remote sensing images, (3) spatially distributed GDP datasets, and (4) datasets of spatially distributed ESV.

#### 3.2.1. Land use

The land use dataset at the scale of 1:100,000 for 2005 were used in this study. The dataset was obtained from Landsat Thematic Mapper (TM) and China–Brazil Earth Resources Satellite (CBERS-2) satellite images and was interpreted by experts in the Data Center for Resources and Environmental Sciences (RESDC) at the Chinese Academy of Sciences (Liu et al., 2003). The land use types fell into six categories (including crops land, forest land, grass land, residential and build-up land, water and unused land) and 25 sub-categories. The land use map is a fundamental dataset that will be used for evaluating the ET, spatially distributed GDP and ESV datasets.

#### 3.2.2. 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  $0.9\text{ }\mu\text{m}$ ) and the IR1 band (covering the wavelengths from 10.3 to  $11.3\text{ }\mu\text{m}$ ) were used. Here, we estimated ET based on evaporative fraction (EF), which could be assumed to be constant during the daytime (Cragoa and Brutsaert, 1996). EF was calculated as:

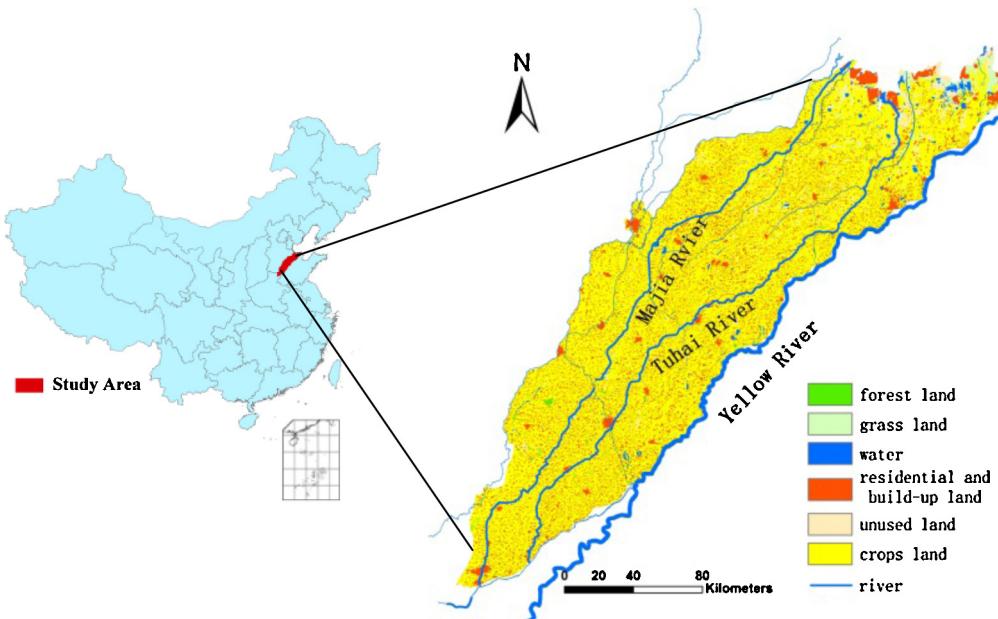
$$EF = \frac{\lambda ET}{A} = \frac{R_n - G - H}{R_n - G} \quad (4)$$

where EF stand for evaporative fraction, ET (mm) is the daily actual evapotranspiration,  $H(\text{W/m}^2)$  is the sensible heat,  $R_n(\text{W/m}^2)$  is net radiation,  $G(\text{W/m}^2)$  is soil heat flux,  $A(\text{W/m}^2)$  is available energy and  $\lambda$  is the latent heat of vaporization ( $=2.49 \times 10^6\text{ (W/m}^2)\text{ mm}^{-1}$ ).

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

$$ET = \frac{86400 \times EF \times R_{day}}{\lambda} \quad (5)$$

where EF is the evaporation fraction, ET is the daily actual evapotranspiration (mm) and  $R_{day}$  is the daily surface net radiation ( $\text{W/m}^2$ ). We proposed a sinusoidal model for estimating  $R_{day}$  (Bisht et al., 2005). According to the validation of using large aperture scintillometer (LAS) measurements, the derived ET and LAS-measured ET matched very well. The  $R^2$  for clear days was larger than 0.85, and



**Fig. 1.** Study area.

for both clear and cloudy days of the year 2005, the  $R^2$  was approximately 0.80. More details of ET retrieval method can be found in the relevant literature (Huang et al., 2009).

### 3.2.3. Spatially distributed GDP

GDP is a fundamental index of annual economic census. Given that the unit of the administrative boundary (county), GDP statistics have a low spatial resolution compared with the ET retrieved from satellite images. To maintain the spatially distributed attribute of the WUP evaluation result, we proposed a model to generate grid-based GDP based on GDP data and land use map.

China's GDP datasets are collected for primary industry, secondary industry and tertiary industry. Primary industry includes agriculture, forestry, animal husbandry and fishery. Secondary industry includes industry and construction. Tertiary industry includes all industries other than primary or secondary industries including transportation, warehousing, postal service, etc.

Based on the correlation between the land use types and three industries, we proposed an “intelligent” gridded GDP mapping technique that used the ratio of class densities to redistribute GDP into corresponding land use areas. The regional GDP can be expressed by the three components as:

$$\text{GDP} = \text{GDP}_{PI} + \text{GDP}_{SI} + \text{GDP}_{TI} \quad (6)$$

where  $\text{GDP}_{PI}$  is GDP of primary industry (Yuan, the basic unit of money in China),  $\text{GDP}_{SI}$  is GDP of secondary industry (Yuan) and  $\text{GDP}_{TI}$  is GDP of tertiary industry (Yuan).

By the definition of primary industry,  $\text{GDP}_{PI}$  can be expressed as:

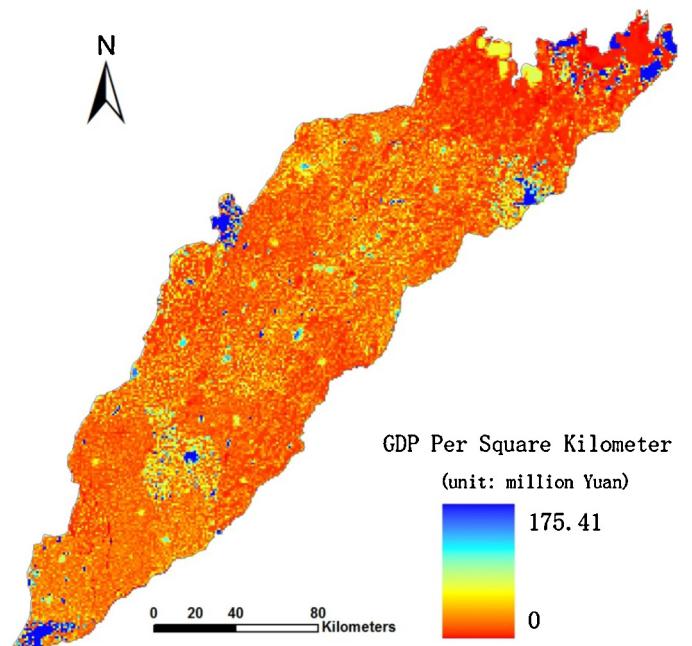
$$\text{GDP}_{PI} = \text{GDP}_{Ag} + \text{GDP}_{Fo} + \text{GDP}_{Ah} + \text{GDP}_{Fi} \quad (7)$$

where  $\text{GDP}_{Ag}$  is GDP of agriculture (Yuan),  $\text{GDP}_{Fo}$  is GDP of forestry (Yuan),  $\text{GDP}_{Ah}$  is GDP of animal husbandry (Yuan) and  $\text{GDP}_{Fi}$  is GDP of fishery (Yuan). GDP distribution among the industries can be calculated as:

$$\text{GDP}_{(SI, TI, Ag, Fo, Ah, Fi)j} = \sum_{i=1}^n (g_i \times L_{ij}) + B_j \quad (8)$$

where  $\text{GDP}_{(SI, TI, Ag, Fo, Ah, Fi)j}$  is GDP data of the  $j$ -th country (sample) of all types of industries (secondary industry, tertiary industry,

agriculture, forestry, animal husbandry and fishery),  $g_i$  is GDP density of the  $i$ -th sub-category of land use types for different industries (Yuan/km<sup>2</sup>),  $L_{ij}$  is the area of the  $i$ -th sub-category of land use types of the  $j$ -th country (sample) and  $B_j$  is intercept. The GDP density  $g_i$  can be calculated by the least square method using data from all counties (samples) in the study area. The sub-categories of land use types of the tertiary industry were determined after correlation analysis and principal component analysis of GDP of the tertiary industry and area of all sub-categories of land use types. Then, the gridded GDP data was generated by associating GDP density with land use map. Fig. 2 shows the gridded GDP data in the study area in 2005.

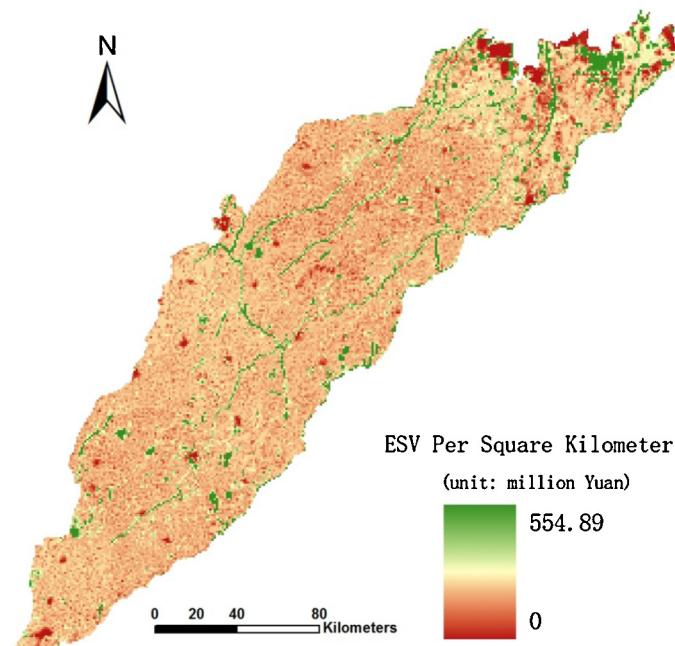


**Fig. 2.** Gridded spatially distributed GDP measured in RMB of Tuhai Majia Basin in 2005.

**Table 1**

Chinese ecosystem services value unit area of different ecosystem types (Yuan/(hm<sup>2</sup> yr)).

Land use	Forest land	Grass land	Crops land	Wet land	Water	Barren land
Value coefficient	19334	6406.5	6114.3	55489	40676.4	371.4



**Fig. 3.** Gridded spatially distributed ESV measured in RMB of Tuhai Majia Basin in 2005.

### 3.2.4. Spatially distributed ESV

ESV is the profits that living organisms derive from ecosystem functions that maintain the Earth's life support system. In this study, the total value of the ecosystem services used for the ecological WUP estimation was obtained by multiplying the estimated size of each land category by the value of the biome used as the proxy for that category:

$$\text{ESV} = \sum A_K V C_K \quad (10)$$

where ESV is the estimated ecosystem service value,  $A_K$  is the area (hm<sup>2</sup>) and  $V C_K$  is the value (Yuan/(hm<sup>2</sup> yr)) of land use category ' $k$ ' (Kreuter et al., 2001).

Costanza et al. (1997) proposed values for different land use types, which were modified according to the situation in China. The value presented by Xie et al. (2003) was adopted in this study as shown in Table 1.

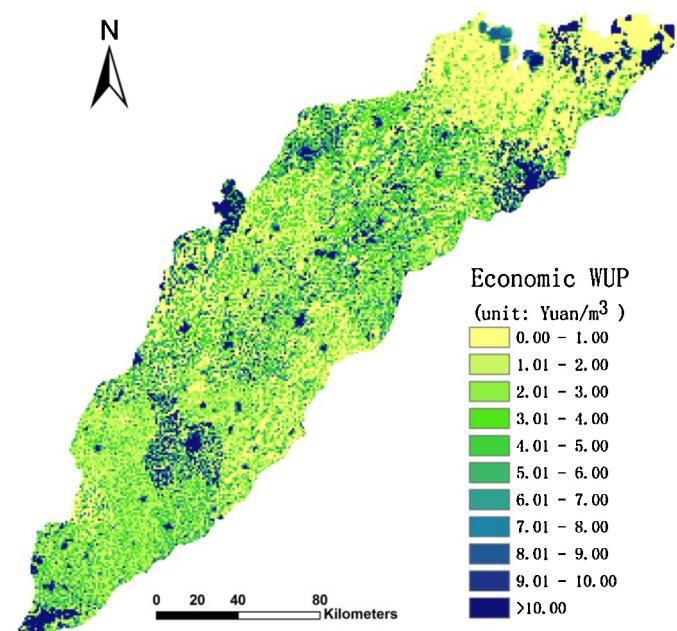
ESV for each 1 km × 1 km pixel was calculated by associating land use map with the values in Table 1. Fig. 3 shows the gridded ESV data of Tuhai Majia Basin in 2005.

## 4. Results and discussion

The economic WUP and ecological WUP of Tuhai Majia Basin in 2005 were derived using the above-mentioned methods with detailed spatial variation.

### 4.1. Economic WUP

Based on the gridded aggregated daily ET estimates and GDP in 2005, economic WUP was estimated, which showed a large variability (Fig. 4).



**Fig. 4.** Gridded spatially distributed economic WUP of Tuhai Majia Basin in 2005.

The areas with high economic WUP were found irregularly in the study area. By comparing the spatially distributed economic WUP (Fig. 4) with land use map, a large area of low economic WUP was found to correspond to the distribution of crop lands, which accounted for 77.1% of the study area in 2005. The region surrounding residential settlements and constructed land had high economic WUP, which indicated that the economic WUP of secondary industry was higher than that of primary industry. Furthermore, the area with high economic WUP (Fig. 4) was larger than that of the residential settlements and constructed land, indicating that urbanization led to an increase in the economic WUP of tertiary industry and primary industry in the surrounding areas.

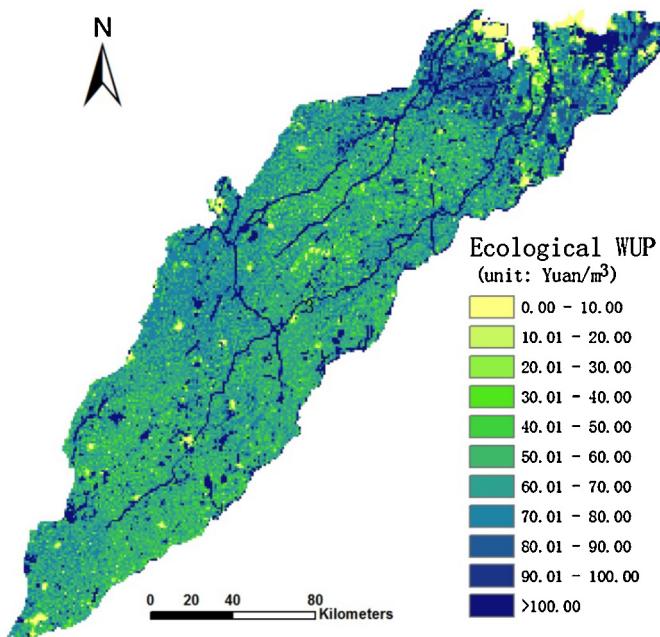
Table 2 compares the water consumption (ET), GDP and economic WUP of agriculture with those of the entire basin in 2005.

As shown in Table 2, ET of primary industry (16.4 billion m<sup>3</sup>) accounted for 76.9% of total water consumption of whole basin (21.3 billion m<sup>3</sup>) in 2005, meaning that agricultural water consumption was the major consumption fraction in Tuhai Majia Basin. The proportion of GDP of primary industry (55.5 billion Yuan) in the entire basin was only 53.5%. Thus, the economic WUP of primary industry was relatively lower than those of secondary industry and tertiary industry. Further statistical analysis showed that the economic WUP of secondary industry and tertiary industry was 9.84 Yuan/m<sup>3</sup>, nearly three times of that of primary industry. However, the economic WUP of whole basin (4.87 Yuan/m<sup>3</sup>) was

**Table 2**

Economic WUP of primary industry and entire basin of Tuhai Majia Basin in 2005.

	ET (billion m <sup>3</sup> )	GDP (billion Yuan)	Economic WUP (Yuan/m <sup>3</sup> )
Primary industry	16.4	55.5	3.39
Whole basin	21.3	103.7	4.87



**Fig. 5.** Gridded spatially distributed ecological WUP of Tuhai Majia Basin in 2005.

relatively low, which was closer to that of primary industry, indicating that the economic WUP of Tuhai Majia Basin was predominantly influenced by agricultural water consumption with low economic WUP. Improving the agricultural economic WUP was the focus of comprehensive water use management of Tuhai Majia Basin.

#### 4.2. Ecological WUP

In addition to analyzing the productivity of water resources, we gridded the aggregated ecological WUP of Tuhai Majia Basin in 2005 based on our gridded ET and ESV estimates (Fig. 5). Ecological WUP and its spatial distribution were analyzed.

Fig. 5 shows that the spatial distribution of low ecological WUP in the study area corresponded to that of residential settlements and constructed land (Fig. 1). The regions with high ecological WUP were mainly found near water and wet land, which could improve the ecological condition of the surrounding areas.

In the increasing order of ecological WUP, we can arrange the land types in this way: barren land, farm land, grass land, forest land, water and wet land. The ecological WUP of wet land (923.68 Yuan/m<sup>3</sup>) and water (612.68 Yuan/m<sup>3</sup>) were much higher than that of other ecosystems, indicating that these two ecosystems should be protected first in the study area. Ecological WUP of forest land was in the middle (281.98 Yuan/m<sup>3</sup>). Forest protection is also important in Tuhai Majia Basin due to the effect of on climate regulation, water conservation, soil protection and biodiversity conservation. However, because the area of forest land only accounted for 0.51% of entire basin, we suggested that avoiding urban and farm land encroachment on forest land reforesting cultivated land were two major measures. Ecological WUPs of grass land (99.21 Yuan/m<sup>3</sup>) and farm land (90.85 Yuan/m<sup>3</sup>) were relatively low. Agriculture was also the major carrier of economic WUP of the basin, which was confronted with the conflicts between economic and ecological WUPs of the study area. Due to the important role of agriculture in water use management of the basin, harmonizing economic and ecological WUPs of farm land is necessary to ensure economic development without ecological deterioration. The ecological WUP of barren land was the lowest (6.21 Yuan/m<sup>3</sup>), but its water consumption (0.66 billion m<sup>3</sup>) ranked the second highest in

the entire basin. This finding implies that the development of barren land is significant to improving ecological WUP, which is the priority of ecological conservation of Tuhai Majia Basin.

#### 5. Conclusion

Evaluating WUP at regional scale is crucial for innovative management estimation to cope with water shortage. However, the resolution of WUP evaluation results by the existing methods is low, lacking the details of spatial distribution of WUP. In this study, we developed a method for evaluating spatially distributed WUP at the basin scales. The most important parameter of water consumption, ET, was estimated from FY-2C meteorological satellite images and other auxiliary data. In economic WUP estimation, grid-based GDP was used as indicator of economic profit. Based on land use map, we generated gridded ESV, which was adopted as the indicator of ecological profit. The method we proposed can generate an integrated spatially continuous WUP map with intra-regional difference at resolution of 1 km, which enables economic and ecological WUPs to be spatio-temporally comparable (valued by RMB with the units of Yuan/m<sup>3</sup>).

The economic and ecological WUP estimation of Tuhai Majia Basin indicated some new findings. The agricultural (primary industry) economic and ecological WUP contributed greatly to that of whole basin. The economic WUPs of secondary industry and tertiary industry were relatively higher than that of primary industry, and the distribution of areas with high value indicated that urbanization increased economic WUP in the surrounding regions. In the ecosystem, barren land consumed the second largest amount of water resources but had the lowest ecological WUP, which is a major problem related to the ecological conservation of the basin. Meanwhile, water and wet land had a great effect on ecological WUP improvement, not only in their location but also in their surrounding areas. The conservation of wet land and water should be the priority in the study area.

The new approach of WUP evaluation that we proposed can be used to generate gridded economic and ecological WUPs at the basin scale, with higher spatial resolution than traditional county-based results, and is useful for water resources management. Furthermore, gridded WUP dataset is more compatible with other geographical or hydrological datasets for further analysis. For these reasons, it is expected that the new method can be applied to construct WUP datasets to be used as inputs in hydrological researches, such as distributed hydrological model, water resources allocation and management and terrestrial ecosystem models.

#### Acknowledgements

This research was supported and funded by Chinese Academy of Sciences (Grant No. KZZD-EW-08).

#### References

- Bisht, G., Venturini, V., Islam, S., Jiang, L., 2005. Estimation of the net radiation using MODIS (moderate resolution imaging spectroradiometer) data for clear sky days. *Remote. Sens. Environ.* 97, 52–67.
- Cai, X., Rosegrant, M.W., 2004. Optional water development strategies for the Yellow River basin: balancing agricultural and ecological water demands. *Water. Resour. Res.* 40, W08S04, <http://dx.doi.org/10.1029/2003WR002488>.
- Cai, X., Yang, Y.C.E., Ringler, C., Zhao, J., You, L., 2011. Agricultural water productivity assessment for the Yellow River basin. *Agr. Water. Manage.* 98, 1297–1306.
- Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., 1997. The value of the world's ecosystem services and natural capital. *Nature* 387, 253–260.
- Cragoa, R., Brutsaert, W., 1996. Daytime evaporation and the self-preservation of the evaporative fraction and the Bowen ratio. *J. Hydrol.* 178, 241–255.
- Fakhraei, S.H., Narayanan, R., Hughes, T.C., 1984. Price rigidity and quantity rationing rules under stochastic water supply. *Water Resour. Res.* 20, 664–670.

- Gao, W., Chen, Y., Chen, D., 2005. A new index system of agricultural green accounting based on value of agroecosystem services. *Res. Agr. Modern.* 26, 1–5.
- Guo, Z., Xiao, X., Gan, Y., Zheng, Y., 2001. Ecosystem functions, services and their values—a case study in Xingshan County of China. *Ecol. Econ.* 38, 141–154.
- He, J., Chen, G., Su, C., 2000. Problems of valuation and allocation in the sustainable utilization of water resource. *Chq. Environ. Sci.* 22, 14–17.
- Huang, X., 1994. Duality value theory and scarcity price of natural resource. *Chn. Popu. Res. Envi.* 4, 34–41.
- Huang, Y., Wang, J., Jiang, D., Zhou, Q., 2009. Regionalization of surface water shortage of China based on evapotranspiration. *J. Hydrol. Eng.* 40, 927–933.
- Jiang, D., 2007. Study on the progress of spatialization of anthrop factors. *J. Gans. Sci.* 19, 91–94.
- Khan, S., Hafeez, M.M., Rana, T., Mushtaq, S., 2008. Enhancing water productivity at the irrigation system level: a geospatial hydrology application in the Yellow River basin. *J. Arid. Environ.* 72, 1046–1063.
- Kreuter, U.P., Harris, H.G., Matlock, M.D., Lacey, R.E., 2001. Change in ecosystem service values in the San Antonio area. *Texas. Ecol. Econ.* 39, 333–346.
- Li, F., Hui, Y., 1999. On concept of value and ethics on sustainable utilization of water resources. *J. Northwest Univ. Nat. Sci. Ed.* 29, 353–356.
- Liu, J., Liu, M., Zhuang, D., Zhang, Z., Deng, X., 2003. Study on spatial pattern of land-use change in China during 1995–2000. *Sci. China. Ser. D* 46, 373–384.
- Lu, X., Zhuang, Q., 2010. Evaluating evapotranspiration and water-use efficiency of terrestrial ecosystems in the conterminous United States using MODIS and AmeriFlux data. *Remote. Sens. Environ.* 114, 1924–1939.
- Luo, D., 2003. Application of the fuzzy mathematics on the assessment of water resources value. *Groundwater* 25, 181–182.
- Molden, D., Sakthivadivel, R., 1999. Water accounting to assess use and productivity of water. *Int. J. Water. Resour. Dev.* 15, 55–71.
- Moncur, J.E.T., 1987. Urban water pricing and drought management. *Water. Resour. Res.* 23, 393–398.
- Moncur, J.E.T., 1988. Drought episodes management: the role of price. *Water. Resour. Bull.* 24, 1752–1688.
- Ni, H., Wang, H., Ruan, B., Wang, D., 2003. Water pricing based on environment value theory. *J. Hydrol. Eng.* 34, 201–207.
- Perry, C., 2007. Efficient irrigation; inefficient communication; flawed recommendations. *Irrig. Drain* 56, 367–378.
- Sarwar, A., Perry, C., 2002. Increasing water productivity through deficit irrigation: evidence from the Indus plains of Pakistan. *Irrig. Drain* 51, 87–92.
- Shen, Z., Wang, L., Yu, F. (Eds.), 2000. *A New Water-Saving: Research and Application of Real Water-Saving*. Water Press, Beijing.
- Smajgl, A., Larson, S., Hug, B., Freitas, D.M.D., 2010. Water use benefit index as a tool for community-based monitoring of water related trends in the Great Barrier Reef region. *J. Hydrol.* 395, 1–9.
- Xie, G., Lu, C., Leng, Y., Zheng, D., Li, S., 2003. Ecological assets valuation of the Tibetan Plateau. *J. Nat. Resour.*, 189–196.
- Yang, X., Huang, Y., Dong, P., Jiang, D., Liu, H., 2009. An updating system for the gridded population database of China based on remote sensing, GIS and spatial database technologies. *Sensors* 9, 1128–1140.
- Young, R.A., 1973. Price elasticity of demand for municipal water: a case study of Tucson, Arizona. *Water. Resour. Res.* 9, 1068–1072.
- Zhang, Z., 1996. Price of natural water resources. *Water. Conser. Sci. Tech. Econ.* 2, 101–103.