A Study on Agricultural Water Saving Potential at Different Scales in the Tuhaimajia River Catchment

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Abstract: Based on understanding of the current status and existing issues in the study of agricultural water saving potential, discussion is made on the concepts of agricultural water saving potential at different scales; the relationship between resource water saving and irrigation water saving is identified; and a framework is developed for the calculation of agricultural water saving potentials at different scales with consideration of associated economic, social and ecological and environmental responses. A WACM model is used for the study, the Tuhaimajia River Catchment is selected as a case study area, and agricultural water saving options at different scales are developed. Then simulation calculation is made on agricultural irrigation water saving potential and resource saving potential in the river catchment, and integrated assessment is made to derive a water saving option that is technically feasible, economically reasonable, socially acceptable and ecologically harmonious, concluding that, in the Tuhaimajia River Catchment, the agricultural irrigation water saving potential is 1.641 billion m^3 and the agricultural resources water saving potential is 712 million m^3, and the river catchment's resource water saving potential is 728 million m^3.

Key words: the Tuhaimajia River Catchment, WACM model, agricultural water saving potential

In order to assess agricultural water saving potential at different scales, the biggest water saving capacity suitable for the regional development needs to be considered which integrates agricultural water saving measures at different scales. Though many studies have been carried out on agricultural water saving potentials at the crop, field, irrigation district or river basin scale (Dong et al., 2005; Xie et al.,2007; Li et al.,2004), but difference exists in the conceptual understanding. Therefore, this paper will start with the identification of concepts and connotations of water saving potential, and then a study is made on agricultural water saving potentials at different scales based on the Tuhaimajia River Catchment, in order to provide support for the water resources planning and management in the river catchment.

1. Concepts and Connotations of Agricultural Water Saving at Different Scales

1.1 Water saving potential

There is still no consistent understanding of the concepts and connotations of water saving potential and are still many issues to be solved, mainly: 1) there is no accepted consistent definition; 2) the current water saving potential considered is mainly of irrigation water saving, rarely of resource water saving; 3) most of the existing studies of agricultural water saving do not consider the impacts of agricultural water saving measures on the society, economy, ecology and environment in the surrounding areas, thus the calculated water saving potential may be biased; and 4) there are no methods for the quantification of resource saving potential.

The supply/use and consumption of water resources are the two aspects for the representation of water resources utilization. According to the different connotations of water saving, water saving can be divided into the two levels of irrigation water saving and resource water saving. At the scale of irrigation works, water saving is the decrease of water supply/use achieved by applying water saving measures of various kinds. At the scale of a region or river basin, while reducing water abstraction and use, application of water saving measures also results in a decrease of drainage of irrigation system and groundwater recharge. Because drainage and groundwater recharge may be re-used, they should not be taken as water saving, that is, from

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resource point of view, water saving is the decrease of water supply/use minus the decrease of groundwater recharge and surface drainage, i.e., the decrease of consumption of water resources (Pei et al.,2008).

Therefore, water saving potential is the maximum regional water saving capacity based on the current level of water use, to be achieved by applying possible social, economic and scientific & technical measures under the precondition of maintaining the regional ecological stability and sustainable economic and social development. It embodies the threshold value of water saving for the maintenance of regional sustainable economic and social development, and is the maximum regional water saving capacity combining irrigation water saving and resource water saving.

1.2 Water saving potentials at different scales and their mutual relationships

Agricultural water saving relates the four scales of crop, field, irrigation district and river basin, and there is a big difference between water saving potentials at different scales. Crop water saving potential refers to the water saving capacity at crop scale, to be achieved by applying certain moisture stress to crops during some phases of water requirement in the growing period, without affecting normal crop yield (Shan et al., 2000). Field water saving potential refers to the water saving capacity to be achieved by applying structural or non-structural field level measures, such as straw or film cover, adjusting crop composition, etc, without affecting crop yield. Irrigation district water saving potential refers to the water saving capacity to be achieved by applying irrigation district level water saving measures such as water saving irrigation, canal lining and management measures, without affecting crop yield and the eco-environment of the irrigation district (Fu et al., 2003). River basin water saving potential refers to the regional or river basin's water saving capacity to be achieved by developing and applying an appropriate water saving program for the river basin which optimally combines water saving measures at the crop, field and irrigation district scales under the precondition of maintaining the harmony and stability of the regional ecology and sustainable economic and social development (Li, 2007). The existing studies of agricultural water saving are focused on the crop and field scales, and rarely on the irrigation district and river basin scales with very complex scale effects.

The application of water saving measures at a scale will inevitably affect water saving at other scales, that is, there are certain relationships in water saving potential between the different scales, i.e., crop, field, irrigation district and river basin scales. These relationships integrate the five forms of water, atmospheric moisture, crop moisture, surface water, soil moisture and groundwater, and affect the temporal and spatial distribution and allocation of water resources. Therefore, in studying water saving potential at different scales, consideration needs to be given not only to the water saving level of crop physiological water saving measures of various kinds, but also to that of cropping water saving measures, engineering water saving measures and management water saving measures and appropriate scales for them; and not only does the water saving capacity of water saving measures at individual scales needs to be considered, but the accumulated effects of combined water saving measures at different scales also need to be considered. Therefore, the most suitable water saving measures need to be selected by optimizing the option composed of the most appropriate measures for each scale according to the local conditions. In the study on the relationships between agricultural water saving potentials at the crop, field, irrigation district and river basin scales, simulation needs to be made on the natural-man made water cycle process and rational allocation of water resources, in order to understand the overall situation of the natural-man made water cycle process and water resources allocation and thus allow for the quantification of relationships between resource water saving potential and irrigation water potential at different scales.

2. Methods for the Assessment of Agricultural Water Saving Potentials at Different Scales

2.1 Assessment framework

A framework the assessment of agricultural water saving potentials at different scales is developed as shown in Figure 1, which is composed of the following steps: assessment on water saving effects of water saving measures at different scales; establishment of options of agricultural water saving measures at different scales; prediction of economic, social ecological and environmental water demands of each option; rational water resources allocation in the broad sense, simulation of the natural-man made water cycle process, and analysis of economic, social, ecological and environmental responses to different water saving measures; comparative analysis of irrigation water saving capacity and resource saving capacity with and without application of water saving measures; and integrated assessment of water saving effects of different water saving measures to find out the option that has the advantages of economic rationality, technical feasibility, eco-environmental health and high efficiency utilization of water resources, and the corresponding agricultural water saving potentials at different scales.

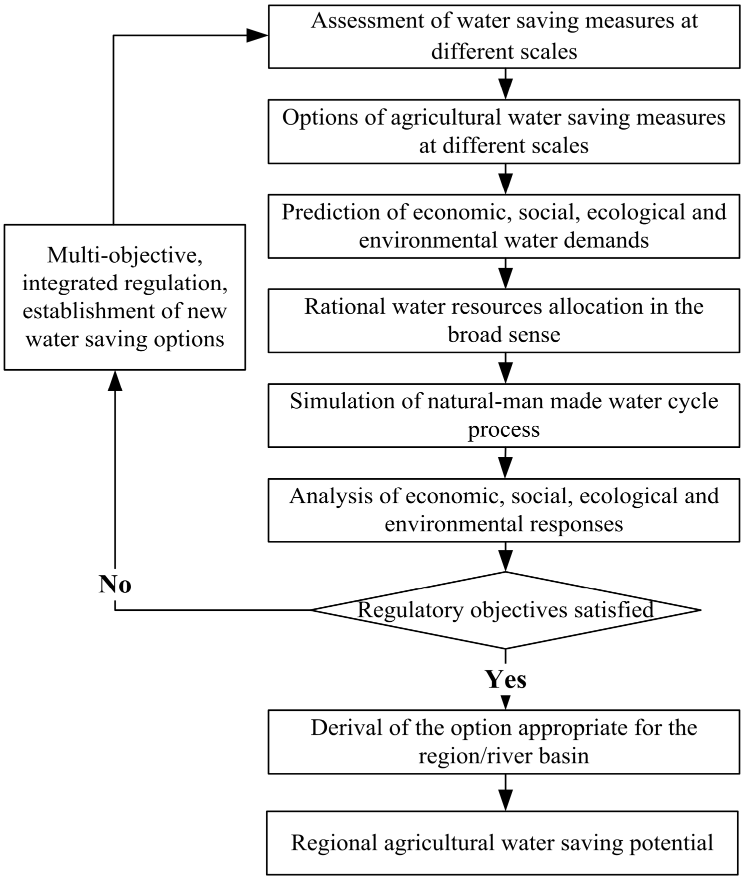

Figure 1 The framework for the assessment of regional water saving potential.

2.2 Methods for the calculation of agricultural water saving potentials at different scales

According to the purpose of the study, methods for the calculation of agricultural water saving potentials and a WACM model for the assessment and analysis of agricultural water saving potentials of the representative area have been developed. The purpose of the WMCM model is to study the regularities of water allocation and cycle in areas with frequent man kind activities and the associated material and energy processes, thus providing an instrument of simulation and analysis for the study of regional agricultural water saving, etc. The application of agricultural water saving measures will surely re-construct the water cycle process and result in re-allocation of water resources between sectors. Therefore, modules of vegetation growth simulation and soil erosion are added to an originally developed WACM model with the functions of simulation of rational water resources allocation, simulation of natural-man kind water cycle and water environment simulation, as shown in Figure 2, in order to better reveal the effects of agricultural water saving measures on interaction between the five forms of water, precipitation, crop moisture, surface water, soil moisture and groundwater, and, at the same time, clearly present the relationships between those forms of water with water saving implemented, hence allowing for better assessment of water saving effects of different water saving options and their effects on the regional economy, society, ecology and environment.

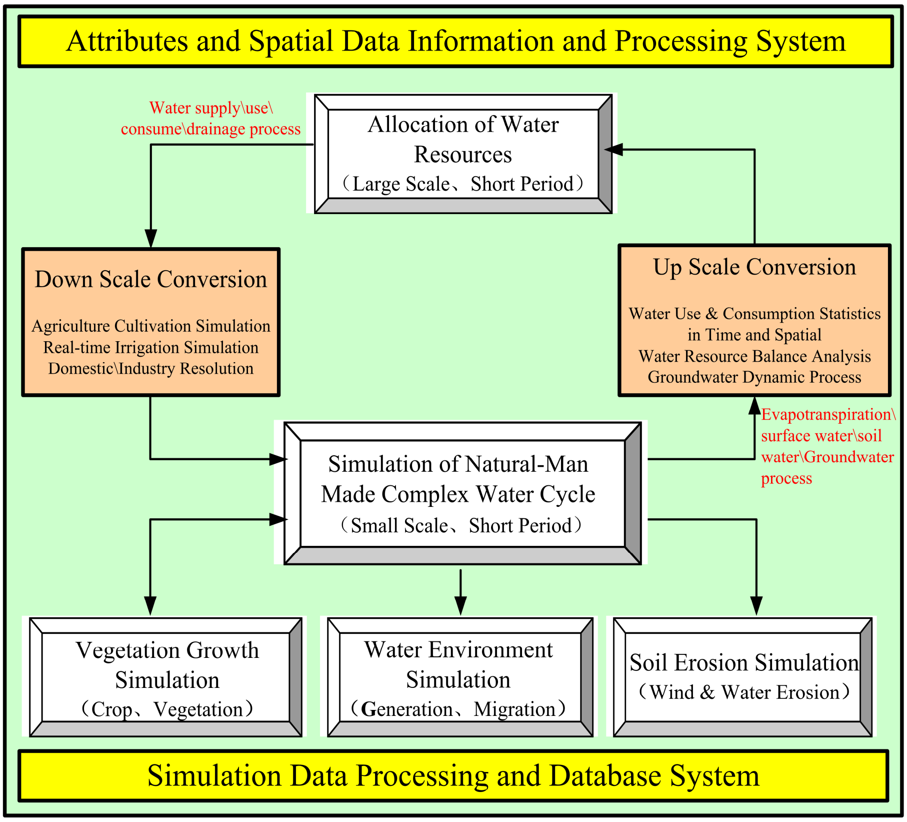

Figure 2 The structure of the WACM model.

3. Assessment of Agricultural Water Saving Potentials at Different Scales in the Tuhaimajia River Catchment

3.1 Facts of the Tuhaimajia River Catchment

The Tuhaimajia River Catchment is situated in the southern part of the Haihe River Basin, belongs to the Yellow alluvial plain with a flat terrain, deep soils and a gentle slope. The main river systems in the river catchment include the Tuhai River, Majia River and New Dehui River. The total catchment area is 31000 km^2, and the average annual precipitation is 557 mm, most of which, 80%, occurs during July-September. The Tuhaimajia River Catchment belongs to the zone of plain meadow vegetation. There is limited natural vegetation, and artificial vegetation dominates with a small number of varieties and a simple composition. There are 11 large-sized irrigation districts with a total area of 16.22 million mu. The main grain crops include wheat, corn, millet, sorghum, sweet potatoes, soybeans, etc; the cash crops include cotton, vegetables, peanuts, sesame, hemp, melons, and so on. According to the 2006 Water Resources Bulletin of the Haihe River Basin, the total water use in the Tuhaimajia River Catchment is 7.52 billion m^3, of which agriculture occupied 6.25 billion m^3, accounting for 83.1% of the total water use. With the rapid economic and social development and continuous enhancement of urbanization, the catchment would see an increasingly big gap between water supply and demand and face increasing pressure for agricultural water saving.

3.2 Assessment of effects of different water saving measures

Regulated deficient irrigation (RDI) is an irrigation technology for promoting water use efficiency without affecting crop yield by actively applying certain moisture stress in some phases of crop growth and thus affecting the distribution of products of photosynthesis assimilation to different organs of crops. According to surveys and analysis, RDI for wheat is the most likely applied crop physiological water saving measure in the river catchment and in theory RDI may also be applied to corn, cotton, etc. But those crops grow in a period with synchronous occurrence of precipitation and hot climate, with limited irrigation water volume and times required, thus it is unlikely to apply RDI to them. Therefore, this study is mainly targeted to RDI for winter wheat. According experiences of years of Zhang X.Y. et al.(2003, 2005), Yu S.Z. et al. (2006), application of RDI may reduce the average water consumption of wheat by about 70 mm in the river catchment.

The water saving measures at field scale mainly include field cropping water saving measures such as straw and film cove and coupled application of water and fertilizer, and adjustment of crop composition. According to the economic, social and technical realities of the Tuhaimajia River Catchment, the field water saving measures than can be extended on a large scale mainly include straw/stalk cover for wheat and corn and film cover for cotton, vegetables and melons. Wheat straw cover for summer corn is worth extending on a large scale because of its low cost and good effects of water saving and yield increase, but summer corn stalk cover for winter wheat does not produce obvious water saving effect. According to relevant experiments and studies, wheat straw cover for summer corn can reduce water consumption by 30-40 mm during each growing season, and film side furrow irrigation for cotton usually reduce water consumption by over 45 mm. Adjustment of crop composition is at present the most effective water saving measures in water scarce areas in China. Winter wheat accounts for the biggest percentages of planted area and irrigation water use among all the crops in the river catchment, and, with increasingly scarce water resources, the area of winter wheat needs to be appropriately adjusted. But, considering the needs for the national and regional food safety, it is unlikely to reduce the area of wheat cultivation to a large extent.

The main water saving measures at irrigation district scale include enhancement of canal efficiency and high efficiency irrigation technologies such as sprinkler- and micro-irrigation, furrow/border irrigation, etc. Canal lining can not only significantly raise canal system efficiency by reducing canal leakage, but also improve conveyance efficiency, reduce maintenance and repair cost, etc. The canal system efficiency in the Tuhaimajia River Catchment is about 0.65 and so there is a big room for improvement. Sprinkler- and micro-irrigation is the main engineering measure for field water saving in the river catchment, and applicable to all grain crops except rice, and vegetables, melons and orchards. According to the local conditions and the economic benefit of crops, application of sprinkler- and micro-irrigation on a large scale is mainly made for cash crops such as vegetables, melons, etc. A lot of experimental data (Li et al., 2005; Wang et al., 2008)show that application of greenhouse drip irrigation or under-film drip irrigation for vegetables such as tomato, cucumber and pepper can reduce water consumption by about 80 mm as compared with furrow/border irrigation.

The water saving potential at river basin scale is mainly embodied in three aspects: 1) the application of crop physiological measures, field water saving measures and irrigation district water saving measures are aimed at plant, crops and agriculture, respectively, will surely affect the water consumption by the natural eco-environmental systems within the river basin and in its surrounding areas while reducing crop water consumption, thus result in a change of water saving at river basin scale; 2) because of the effects of water reuse between different irrigation districts within a river basin, water saving achieved by applying water saving measures to an irrigation districts may affect water use and consumption in other irrigation districts, thus assessment needs to be made at river basin scale; 3) different water saving measures mutually interact with the water potential of one measure likely affecting that of others, therefore, assessment of water saving effects of different measures at river basin scale may eliminate the errors from simply adding up the effects of individual measures.

3.3 Agricultural water saving options

In order to make quantitative assessment of water saving potentials of different options at the scale of the Tuhaimajia River Catchment, appropriate water saving measures at different scales are selected, possible proportions of various measures are defined, and different water saving options composed of measures with different proportions are developed for catchment scale as shown in Table 1. And the assessment of agricultural water saving potential at catchment scale is made by simulating the use and consumption of water resources and the associated economy, society, ecology and environment in the river catchment.

Table 1 Agricultural water saving options in the Tuhaimajia River Catchment.

Type of measure	Candidate measures	Option 1	Option 2 (Recommended)	Option 3	Option 4	Option 5
Crop	RDI for wheat, 10% coverage	√				
	RDI for wheat, 20% coverage		√			
	RDI for wheat, 40% coverage			√		
	RDI for wheat, 60% coverage				√	
	RDI for wheat, 80% coverage					√
Adjustment of crop composition	5% of wheat and 50% of rice replaced with spring corn and other crops	√	√			
	10% of wheat and 50% of rice replaced with spring corn and other crops			√		
	10% of wheat and 50% of rice replaced with spring corn and other crops				√	
	15% of wheat and 80% of rice replaced with spring corn and other crops					√
Film and straw cover	Wheat straw cover for corn increased to 80%, film cover for cotton 40%	√				
	Wheat straw cover for corn increased to 80%, film cover for cotton 60%		√			
	Wheat straw cover for corn increased to 80%, film cover for cotton 80%			√		
	Wheat straw cover for corn increased to 100%, film cover for cotton 60%				√	
	Wheat straw cover for corn increased to 100%, film cover for cotton 80%					√
Border irrigation, Sprinkler- & micro-irrigation	Furrow/border irrigation applied to rapeseed, soybeans, sorghum, millet, peanuts	√	√	√	√	√
	Sprinkler- & micro irrigation applied to 40% of vegetable and melons, and 30% of fruit trees	√				
	Sprinkler- & micro irrigation applied to 40% of vegetable and melons, and 50% of fruit trees		√			
	Sprinkler- & micro irrigation applied to 60% of vegetable and melons, and 50% of fruit trees			√		
	Sprinkler- & micro irrigation applied to 60% of vegetable and melons, and 70% of fruit trees				√	
	Sprinkler- & micro irrigation applied to 80% of vegetable and melons, and 50% of fruit trees					√
Canal lining	Canal efficiency increase 0.06	√				
	Canal efficiency increase 0.09		√	√		
	Canal efficiency increase 0.12				√	√

3.4 Water saving potentials of different options

(1) Water savings of different options

Based on the developed options, water supply and demand balance at catchment scale is calculated for each option. Allocation of water resources from both natural and artificial sources is made, and the water cycle of the river catchment is simulated to work out the water uses and consumptions of 12 main crops as shown in Table 2. According to the simulated results, water consumption of wheat, corn, cotton and vegetables account for over 80% of the total farmland water consumption for all the options. By comparing the irrigation water use and consumption of the river catchment with the current situation, agricultural irrigation water saving and resource water saving of different options at catchment scale are derived as shown in Table 3, in which water resources consumption of the river catchment is one in a broad sense including contribution of precipitation. Considering the effect of change in agricultural irrigation water use on the eco-environment in the surrounding areas, the resource water saving of the river catchment is more than the agricultural resource water saving only taking into account crop water consumption and canal water loss.

Table 2 Water consumptions of different crops in 10^6 m^3.

Itemize	Wheat	Rapeseed	Bean	Corn	Cotton	Sorghum	Millet	Peanut	Vegetable	Melon	Fruit tree	Rice	Total
Present	4116	34	161	3257	2359	25	229	305	2474	434	952	98	14445
Option 1	3756	33	158	3051	2361	126	304	329	2337	417	928	49	13849
Option 2	3756	33	155	3032	2407	127	304	322	2290	397	915	49	13787
Option 3	3489	33	154	2867	2297	167	425	365	2331	419	916	49	13512
Option 4	3358	33	155	2772	2357	167	444	367	2259	398	904	20	13234
Option 5	2945	33	155	2676	2383	229	524	397	2207	382	903	20	12854

Table 3 Irrigation water saving and resources water saving at catchment scale in 10^6 m^3.

	Irrigation water use and saving		Water resources consumption			Resource water saving	
	Use	Saving	Total	Agricultural consumption	Natural system consumption	Agriculture	River Catchment
Present	6132	-	20743	15011	3284	-	-
Option 1	4776	1256	20094	14375	3270	635	650
Option 2 (recommended)	4491	1641	20015	14299	3268	712	728
Option 3	4209	1923	1973	14024	3258	987	1013
Option 4	3675	2457	19426	13722	3256	12.89	1317
Option 5	2982	315	19015	13321	3246	1690	1729

(2) Assessment of the rationality of different options

In order to select an appropriate option of agricultural water saving for the river catchment, feasibility assessment is made for different options from the economic, technical, social and ecological angles with the results shown in Table 4. Options 1 and 4 are feasible in all the economic, technical, social and ecological terms because of the small percentage of application of measures. Application of RDI for wheat targeting 40% with option 3 is difficult to achieve because it is mainly applicable to well irrigation districts, and 80% of film cover for cotton is also socially unacceptable because of the high cost. For option 4, in addition to the technical and social acceptance issues, the wind erosion modulus is increased to a large extent on the current basis. For option 5, in addition to the technical, social and ecological problems, it is also economically infeasible to increase canal efficiency to a large extent. Therefore, option 2 is considered scientific and rational and its water saving capacity is taken as the water saving potential of the river catchment. With this option, the agricultural water saving potential of the river catchment is 1.641 billion m^3, the agricultural resource water saving potential is 712 million m^3, and, with the effect of water saving on the ecology taken into account, the total resource water saving potential of the river catchment is 728 million m^3.

Table 4 Assessment of rationality of integrated agricultural water saving options in the Tuhaimajia River Catchment.

Option	Technical	Economic	Social	Ecological
1	Feasible	Rational	Acceptable	Good
2	Feasible	Rational	Acceptable	Good
3	RDI 40% for wheat difficult to achieve	Rational	80% film cover for cotton is socially unacceptable	Good
4	RDI 60% infeasible	Rational	100% straw cover for corn and 70% sprinkler-& micro-irrigation for fruit trees unacceptable	Good, with a slight effect on soil wind erosion
5	RDI 80% infeasible	A big rise of canal efficiency is uneconomic	100% straw cover for corn and 70% film cover for cotton unacceptable	Good, with a slight effect on soil wind erosion

3.5 Agricultural water saving potentials of the recommended option at different scales

Figure 3 shows the agricultural water saving potentials of the recommended option at different scales. The crop water saving potential only refers to the agricultural water saving potential in the river catchment under the RDI for wheat only scenario. In the river catchment, RDI is only applied to wheat in well irrigation districts, and the ratio of resource water saving potential to irrigation water saving potential is about 78%. The field water saving potential refers to that achieved by applying adjustment of crop composition, wheat straw cover for corn and film cover for cotton at the field level, with the ratio of resource water saving potential to irrigation water saving potential being about 55%. The irrigation district water saving potential refers to that achieved by applying measures such as canal lining, border irrigation and sprinkler- and micro-irrigation, with the ratio of resource water saving potential to irrigation water potential being about 33%. The water saving potential of the river catchment is integration of water saving potentials of the measures applied at different scales, with the ratio of resource water saving potential to irrigation water saving potential being about 44%.

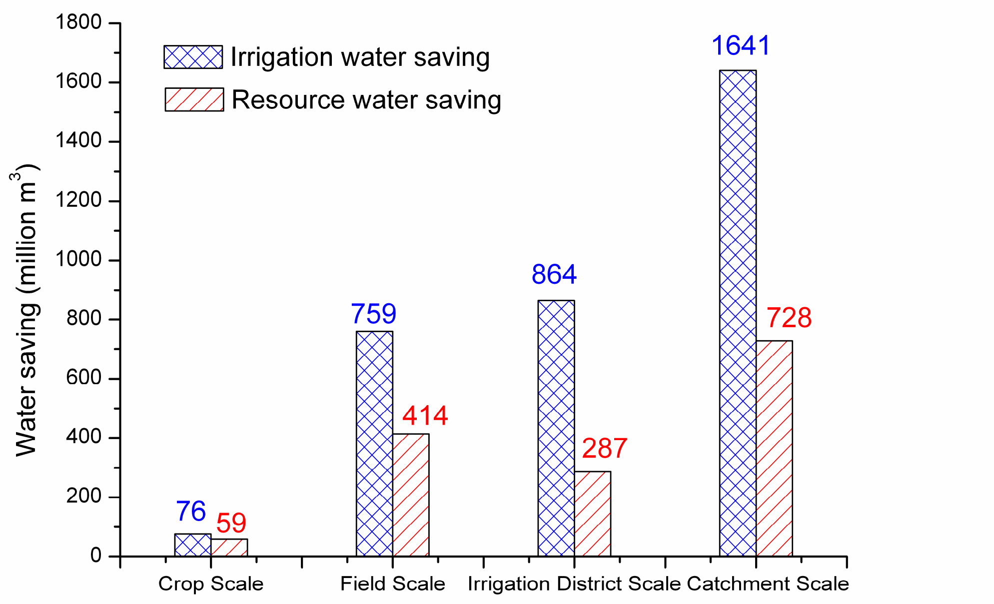

Figure 3 Agricultural water saving potentials of the recommended option at different scales

4. Conclusions

Agricultural water saving potentials at different scales are a hot topic of current studies. In this paper, based on surveys and experimental data, crop varieties and water saving measures at the crop, field, irrigation district and catchment scales appropriate for the Tuhaimajia River Catchment are selected to form five water saving options based on the possibility of the measures; a WACM model is used to calculate the agricultural irrigation water saving potential and resource water saving potential in the river catchment; and integrated assessment is made on each option to find out the water saving option most suitable for the river catchment.

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