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ORIGINAL ARTICLE

How water saving irrigation contributes to climate change resilience—a case study of practices in China

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Abstract A warming climate system is now an indisputable fact. An effective response to climate change should include both mitigation and adaptation. Water is essential to human survival and social development. But the shortage of water resources is a worldwide problem, which in China has been exacerbated by climate change. In order to find out how to cope with climate change successfully, this study, on the basis of China statistical data 2007–2009, quantitatively analyzes the role of water saving irrigation (WSI) in addressing climate change. The study shows that water saving irrigation (WSI) can serve as a useful enabler in dealing with climate change. From the perspective of mitigation, the 3-year total CO_2 emission reduction stands at 34.67 (21.83~47.48) Mt, about per year 11.56(7.28~15.83)Mt. From the perspective of adaptation, the total water saved from 2007 to 2009 stands at 96.85 (61.81~129.66) Gm^3. If per unit farmland irrigation takes a 3-year average of agricultural water consumption, the water saved in 2009 is enough to irrigate additional 5.70 (3.80~7.80)Mhm^2, or to increase the grain yield by 22.04 (14.68~30.15) Gt. In addition, WSI can reduce soil salinization and conserve soil to sustain land productivity and environmental benefits. So WSI can be a positive measure in coping with climate change when it is rightly deployed. However, the costs and local context of such practices call for further studies.

Keywords Water saving irrigation · Climate change · Mitigation and adaptation · Greenhouse gases

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1 Introduction

Many natural systems are now being affected by climate change, such as widespread melting of snow and ice, rising global average sea level and increasing extreme climate events including drought, heavy precipitation and tropical cyclone, all of which have disrupted human life in many ways (IPCC 2007). In order to lower the adverse impacts, the international community has adopted multiple measures to deal with climate change. Adaptation measures may soften the adverse impact of climate change, but with the intensifying climate change, adaptation measures alone can hardly remove all these impacts. On the other hand, the social, environmental and economic costs of adaptation may increase. Mitigation measures can reduce long-term adaptation cost to a certain extent, but they cannot take away the current and committed impacts resulting from climate change (IPCC 2007). Therefore, to deal with climate change, it is necessary to adopt mitigation and adaption measures at the same time. However, mitigation and adaption actions interact with each other, either positively or negatively (Butt et al. 2006; Reilly et al. 2001). So the optimal practice should be one that leads to a win-win outcome: Mitigating coincides with adaptation, while the increased performance of the latter helps reduce greenhouse gas emissions.

Climate change has increased the possibility and intensity of drought (IPCC 2007). So the appropriate water management would be able to increase the resilience of agricultural production to climate change. Due to climate change, over the past 50 years, regions such as Northeast China, North China, Hetao Area, southeastern Loess Plateau and central and western Sichuan Basin have experienced a declining annual precipitation and an aggravating drought (Ren et al. 2005; Yang and Li, 2008). In 2008, drought claimed a grain loss of 16.1 Mt (CIDDC 2009), hindering China's grain production. In the case of China, for regions with irrigation facilities in place, the irrigated and non-irrigated farmlands make a difference in per unit yield: wheat is 1.67~1.89 times higher while corn is 1.47~1.53 times higher (CWRYCC 2008–2010). In the case of the whole world, the irrigated agricultural land accounts for only 19% of the total but supplies 40% of the world's food (Molden et al. 2010). Therefore, irrigation is essential for stable food production. However, China is a big agricultural country, in which agricultural water consumption accounts for 60%~70% of the total water supply (CWRYCC 2008–2010). And because of the growing water demand, the North China Plain is short of surface water, with ground water badly depleted (Kendy et al. 2004; Tamanyu et al. 2009; Moiwo et al. 2009) and falling by 1.5 m annually in average (Moiwo et al. 2010). So due to the constraint of water resources, the supply of agricultural irrigation water cannot be expanded blindly.

Studies have shown that enhanced water use efficiency holds the key to tackling water scarcity and food security issues (Hanjra and Qureshi 2010; Tejero et al. 2011). WSI can mitigate the negative impact of climate change on water resources available to agriculture (Loë et al. 2001) and overcome the constraint of water scarcity (Mushtaq et al. 2006) by reducing water consumption and increasing water productivity (Tuong et al. 2005, Belder et al. 2005; Kato et al. 2009). WSI has been highlighted as one of the Chinese basic national policies as well as an important practice for sustainable agriculture development. Du et al. (2010) found that WSI can reduce water consumption and increase grain production in North China. Yang et al. (2010) also found that agricultural water-saving is necessary prerequisites for comprehensively redressing the worsening water shortage problems in North China Plain; Liu et al. (2003) reported that sprinkler irrigation (SI) is a major contributor to the significantly increased yield and water use efficiency of winter wheat than border irrigation. Deng et al. (2006) pointed out that large-scale water-saving crop production systems need to be established in the near future if China is to continue to feed its growing population. But a systematic and quantitative study of the role of WSI in climate change adaptation is still absent in China.

In order to mitigate climate warming, it is necessary to minimize greenhouse gas emissions resulting from adaptation. There are different findings about the role of WSI in emission reductions. Some studies indicate that WSI is a good technology that saves water and energy (Ma and Feng 2006; Li et al. 1998; Dang et al. 2006; Guan 2004; Li et al. 2007). But others indicate that some WSI initiatives save water but not energy (Lin 1984; Ma 1989; Wang 2006; Liu 2001; Zhang 2001; Jiang 1995). Therefore, the energy consumption and GHG emission of WSI in China also need a systematic study.

Over the past 20 years, WSI has witnessed rapid progress in China, with irrigated farmland increasing from 1.10×10^7 hm^2 in 1995 to 2.58×10^7 hm^2 in 2009 (CIDDC 2009; CWRYCC 2008–2010). Moreover, the Chinese government has made an ambitious WSI development plan. Hence, a quantitative study of the effectiveness of WSI in coping with climate change is necessary and urgent. Based on the statistical data of China from 2007 to 2009, this paper calculates the energy consumed and water saved by the prevailing WSI practices, estimates the potentially increased irrigated acreage and grain yield, and quantitatively studies the role of the existing WSI measures in coping with climate change, with a view to provide technical support to appropriate actions to address climate change, reduce its adverse impact on agricultural production, and ensure food security.

2 Materials and methodology

In this paper, the study of the role of WSI in coping with climate change is divided into two sections: mitigation and adaption. The technical roadmap is given in Fig. 1.

The data of pumped irrigation acreage, sizes of different WSI measures and water consumed come from "*China Water Yearbook 2008–2010*" (CWRYCC 2008–2010). The heads of the pumping stations in different provinces are based on *"2008 China Irrigation and Drainage Development Study*" (CIDDC 2009) and "*Water Resources Record*" of 30 provinces and regions in China (The data of Hong Kong, Macao, Taiwan and Shanghai are not included, the same below). Parameters in the equations come from industry standards and expert advice. Water-saving rates come from previous findings. And the 95% confidence interval is adopted.

The main uncertainty of the paper rests with parameters setting. There could be differences in equipment parameters between different regions. But due to the lack of statistical data, the paper adopts the principle of industry limits plus the minim and expert advice in selecting parameters. For details on how parameters are set, please refer to 2.3.2. In order to reduce errors, the paper is based on provincial data in all its calculations. In the forecasts of expanded irrigated acreage and grain production, in order to reduce the differences caused by natural conditions, the 3-year average proportion of agricultural water usage (the proportion of agricultural water consumed accounting for the total water consumption), the 3-year average per unit acreage irrigated water and the 3-year average per unit acreage grain yield are used as parameters.

In this study, calculations are made in a relatively idealized state without considering the water lost or returned in the transport process.

Data and graphics are processed using Office 2007.

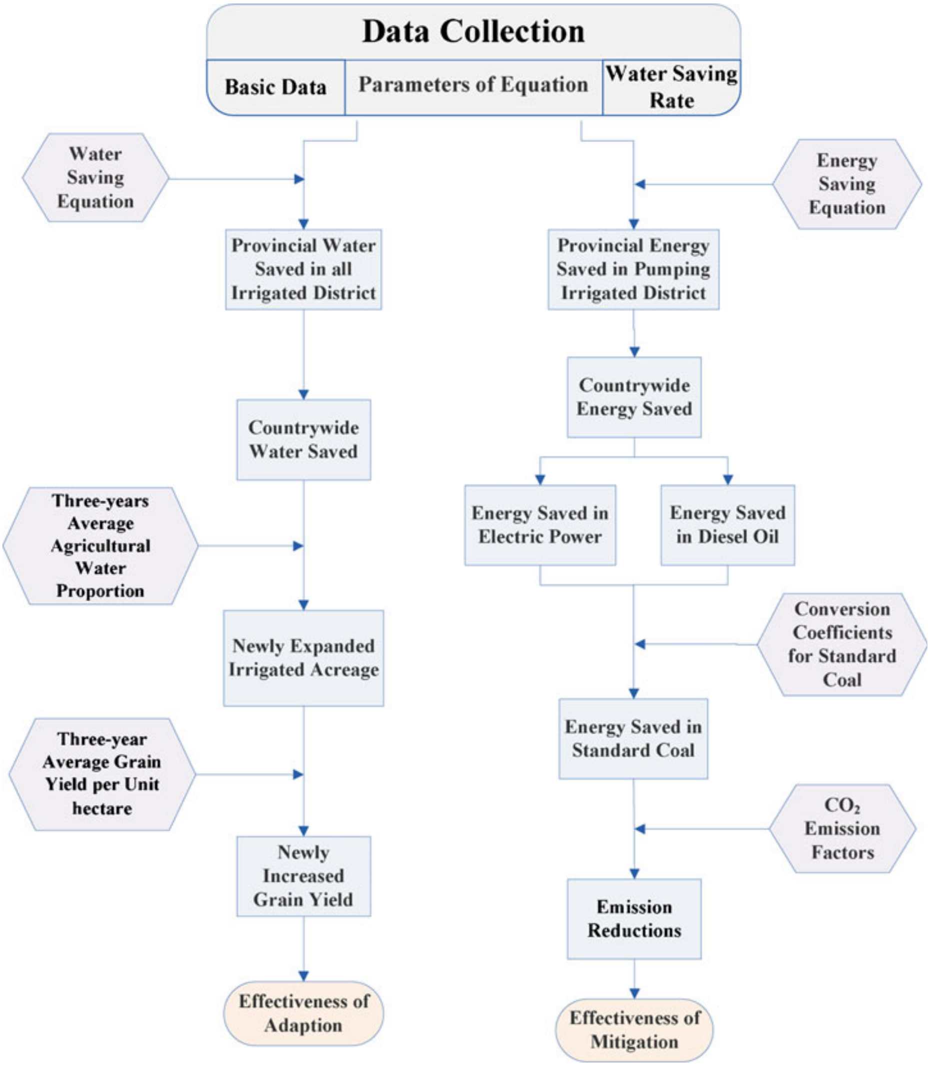

Fig. 1 Technical roadmap (page 3)

2.1 Irrigation structure and scale in China from 2007 to 2009

In China, irrigation falls into two type: traditional irrigation (TI) and WSI, the latter of which is further divided into five categories: sprinkler irrigation (SI), micro irrigation (MI) (which includes drip irrigation, mini sprinkler irrigation and bubbler irrigation), low pressure pipe irrigation (LI), canal lining irrigation (CI), and other (OI) WSI measures (CWRYCC 2008–2010). Details on the penetration rates of various irrigation measures from 2007 to 2009 are shown in Fig. 2.

The differences of WSI proportions in the 3 years are not significant, but the total WSI proportion in 2009 is a little bigger than in 2007 and 2008. Taking 2009 for

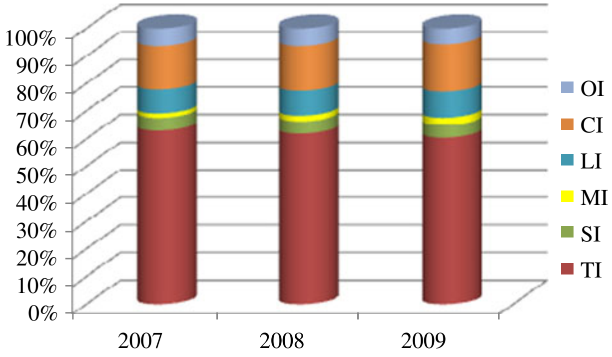

Fig. 2 The penetration rates of various irrigation measures from 2007 to 2009 (page 4)

example, the detailed acreages of different irrigation measures and their proportions are given in Fig. 3.

Energy is saved by WSI only in where irrigation is pumped. Therefore, the energy consumption calculation in this paper is limited to where irrigation is pumped. But the water savings calculation includes all the WSI areas. According to statistical data, the pumping irrigation is divided into two types: motor-pumped wells and pumping stations. The former refers to where power-driven machinery is installed to extract ground water from a well for irrigation purpose, while the latter refers to where power-driven machinery is used to extract surface water from a river, a lake and a reservoir for irrigation purpose, including fixed and mobile stations (CWRYCC 2008–2010). The irrigated sizes (A) of various irrigation measures (i) in different pumping irrigation areas (j) are equal to the products of pump irrigated sizes (A_j) and the penetration rates of various WSI measures (p_i), the detailed calculation of which is shown in Table 1.

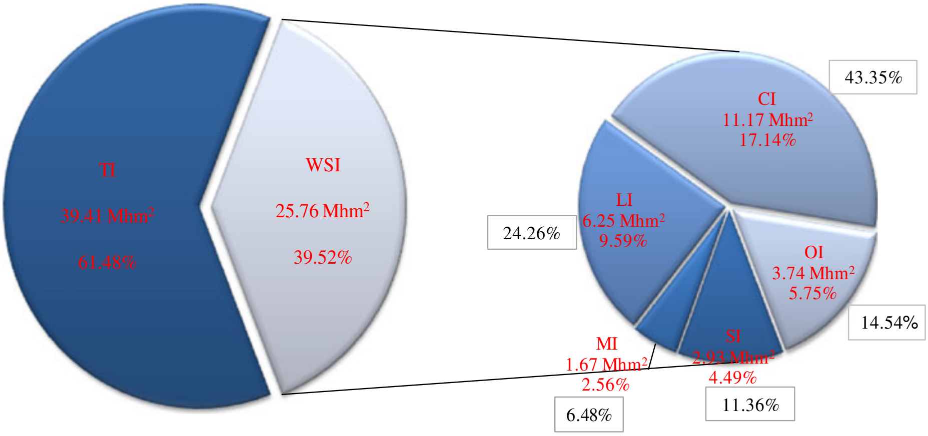

Fig. 3 The acreages and proportions of different irrigation measures in 2009 (page 4). Note: 1. Irrigated area includes the irrigated area of agriculture, forest, and pasture of the current year of China; 2. Penetration Rate: ratio of the irrigated area of various irrigation measures over the total irrigated area (percentage displayed by red characters in the Chart); 3. Figures in the box mean the size proportion of each WSI types over all the WSI sizes

Table 1 Irrigated size of the various irrigation measures under pumping well and pumping station district unit: Mhm^2 (page 4)

Year	Area	TI	SI	MI	LI	CI	OI
2007	Pumping station	9.71	0.46	0.087	1.03	2.50	1.17
	Pumping well	11.01	1.48	0.39	3.17	2.16	1.48
2008	Pumping station	9.73	0.48	0.11	1.15	2.81	0.98
	Pumping well	11.03	1.55	0.59	3.37	2.33	1.45
2009	Pumping station	9.90	0.46	0.082	1.09	2.47	1.18
	Pumping well	10.92	1.49	0.26	2.99	1.96	1.47

2.2 Methods for evaluating the role of WSI in climate change mitigation

2.2.1 Setting of energy consumption equations

1) **Pumping Energy Consumption Equation** (Lin 1984):

This equation is used for the calculation of energy consumed by WSI.

$$E_{\mathrm{i}} = \frac{\gamma m_{\mathrm{i}} \mathrm{A_i H}}{1000 * \eta} * E_b \tag{1}$$

Wherein:

E	energy consumed in pumping irrigation (kW·h or kg)
m	annual average irrigation water per unit acreage (m^3/hm^2)
H	head pumped during irrigation (including head loss) (m)
η	efficiency of a pumping device during irrigation (%)
E_b	energy consumption unit of a device (kW·h / (kt·m) or kg/ (kt·m))
γ	unit weight of water (1000 kg/m^3)

The meaning of other factors is the same as above.

2) **Water-Saving Rate (WSR) δ of WSI**:

$$\delta_{\mathrm{i}} = \frac{\mathrm{m_{TI}} - \mathrm{m_i}}{\mathrm{m_{TI}}} \times 100\% \tag{2}$$

Wherein:

δ	water-saving rate of WSI
m_{TI}	water saved by traditional irrigation

The meaning of other factors is the same as above.

3) **Energy-Saving Equation of WSI**:

$$\Delta E_{\mathrm{i}} = \frac{\gamma \delta_{\mathrm{i}} m_{\mathrm{i}} \mathrm{A_i H}}{1000 * \eta} * E_b \tag{3}$$

Wherein:

$\triangle E$ energy saved by WSI

The meaning of other factors is the same as above.

4) **Energy Consumption Equation for a Pressurizing Device**:

When adopting SI and LI, it is necessary to exert pressure to a water head. The energy consumed therein is calculated using:

$$E_{\mathrm{i}}{}' = \frac{\gamma(1-\delta_{\mathrm{i}})\mathrm{m_i A_i H_i}'}{1000 * \eta'} * \mathrm{E_b} \tag{4}$$

Wherein:

E' energy required for pressurizing a SI or LI device
H' pressure head for a SI or LI device
η' efficiency of a device for pressurizing SI or LI

The meaning of other factors is the same as above.

2.2.2 Setting of the parameters in the equations

1) **Unit Energy Consumption ($\mathbf{E_b}$)**

According to the "*Code of Practice for Technical Renovation of Pumping Station*", the unit energy consumption (that is, energy consumed to pump and lift 1000 t of water by 1 m) of an electrical irrigation station shall not be more than 5 kW·h/ (kt·m). The unit energy consumption of a mechanical irrigation station (diesel) shall not be more than 1.35 kg/ (kt·m) (MWRC 2000). Due to the lack of data on the proportion of mechanical and electrical irrigation stations, this paper assumes a ratio of 50% for each category when making a calculation.

2) **Efficiency of WSI Equipment (η)**

According to "*Code for Design of Irrigation and Drainage Engineering*", an axial flow pump or a mixed-flow pumping station with a net head higher than 3 m should meet a device efficiency of higher than 70%. An axial flow pumping station with a net head lower than 3 m should meet an efficiency of higher than 60%. An electrical motor-pumped well should meet an efficiency of higher than 45%. And diesel engine pumped well should meet an efficiency of higher than 40% (GAQS et al. 1999). Historical water statistical data show that the average water head of pumping irrigated areas at provincial level is higher than 3 m, and more than 90% of the well irrigated areas are equipped with electrical motor-driven wells. Therefore, in calculation, the value of device efficiency η of pumping station is set as 70%. Assuming a case that all pumping wells are electrical motor-driven, the efficiency η of pumping device is set as 45%.

As for the efficiency η' of a SI or LI pressurizing device, no definite data are available. According to experts, it is uniformly assumed as 50%.

3) **Setting of a Pressure Head for SI or LI (H')**

When SI is applied, the pressure head of the sprinkler in operation is mostly higher than 20 m (GAQS et al. 2007), while that of LI is much lower. Therefore, in calculation, the pressure head of SI is set as 20 m, and according to expert experiences, the pressure head of LI is set as 10 m.

4) Water Head (H)

Based on "*2008 China Irrigation and Drainage Development Study*" (CIDDC 2009) and "*Water Resources Records*" of 30 provinces and regions in China (see Appendix A), the data on water heads at provincial level have been statistically obtained (see Table 2), from which, it can be seen that most of the regions operate pumping wells of medium depth. Considering the general dropping of the ground water level in recent years, in calculation, according to expert experiences, the height of water head of pumping wells is uniformly set as 100 m.

5) Water-saving Rate (WSR)(δ)

The reference data of WSR are selected based on such factors that main crops are irrigated and no obvious crop yield reduction is caused. From 15 pieces of SI related literature (see Appendix B), the floating range of WSR is found to be between 30%~65%, with the average WSR being 45.3% and the 95% confidence interval being [0.293, 0.613] (see Fig. 4a for details). From 14 pieces of MI related literature (see Appendix C), the floating range of WSR is found to be between 35%~70%, with the average WSR being 52.7% and the 95% confidence interval being [0.376, 0.678] (see Fig. 4b). From 10 pieces of CI related literature (see Appendix D), the floating range of WSR is found to be between 16.2%~36.2%, with the average WSR being 24.5% and the 95% confidence interval being [0.138, 0.352] (see Fig. 4c). From 11 pieces of LI related literature (see Appendix E), the floating range of WSR is found to be between 20%~38%, with the average WSR being 29.4% and the 95% confidence interval being [0.208, 0.379] (see Fig. 4d). OI is not specifically indicated in the statistical data. Thus, the WSR cannot be determined. Following the minimum value principle, in the calculation, the WSR of CI is taken as OI WSR.

6) Unit Acreage Annual Irrigation Water (m) of Traditional Irrigation at Provincial Level

Details on water available for agricultural irrigation in 2007–2009 are given in Table 3, which is based on "*China Water Year book"*2008–2010 (CWRYCC 2008–2010).

Table 2 Head of pumping stations of various provinces and regions unit: m (page 6)

Province	Head	Province	Head	Province	Head
Hubei	29.37	Hebei	43.83	Gansu	471.30
Jiangxi	18.24	Henan	49.60	Shannxi	97.56
Anhui	24.50	Shandong	30.51	Qinghai	60.68
Jiangsu	7.80	Sichuan	36.87	Inner Mongolia	50.00
Zhejiang	4.81	Ningxia	38.9	Chongqing	39.58
Guangdong	9.30	Xinjiang	50.00	Tibet	50.00
Liaoning	7.00	Guizhou	56.70	Guangxi	25.85
Fujian	17.57	Hainan	42.00	Yunnan	78.83
Heilongjiang	14.56	Hunan	67.40	Shanxi	41.99
Jilin	16.51	Beijing	43.83	Tianjin	43.83

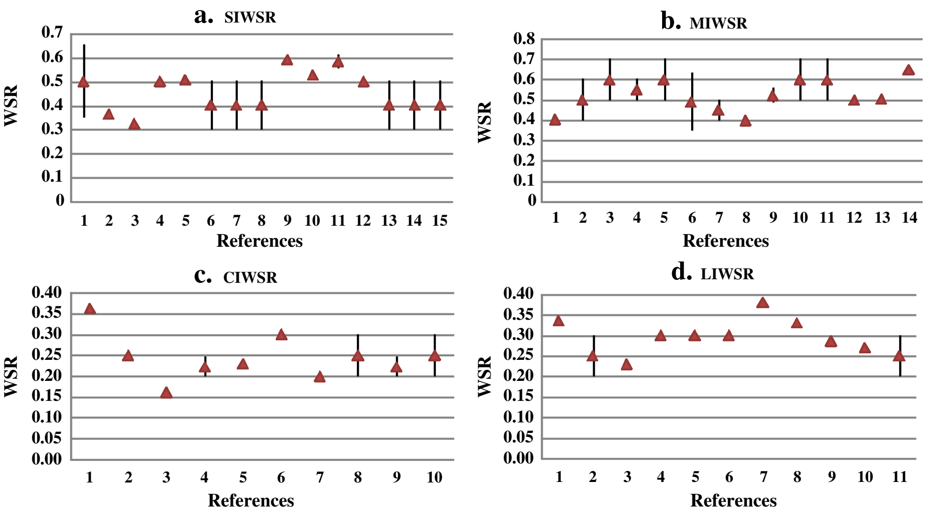

Fig. 4 The WSR statistical distribution of different wsi measures (page 6). Note: 1. In the chart, figure of the horizontal coordinate is the serial number of statistical literature, rather than quantity of literature; the serial number of literatures under the same measure is selected in random; there is no corresponding relation among the serial numbers of the four WSI types. 2. The *vertical line* indicates the range of WSR of the WSI types, the triangle on the *vertical line* indicates mean value of the WSR range

It is assumed that the unit acreage annual average irrigation water of traditional irrigation at provincial level ($m_{TI,g}$) is unknown. Formula (5) gives the unit acreage annual average irrigation water of various WSI measures ($m_{i,g}$) at provincial level. The value of $A_{i,g}$ can be obtained from "*China Water Yearbook*". The total water supply for pumping irrigation (M) was calculated in Table 3 and Formula (6) can give $m_{TI,g}$. On the basis of each year's unit acreage annual average irrigation water, the 3-year (2007–2009) average can be got. The detailed solution of 3-year average is shown in Table 4.

$$m_{i,g} = m_{TI,g} * (1 - \delta_i) \tag{5}$$

$$M = \sum \left(A_{i,g} * m_{i,g} \right) \tag{6}$$

Wherein:

M indicates the total water supply for pumping irrigation
g province

The meaning represented by other factors is the same as above.

Table 3 Water supply amount for agricultural irrigation in 2007–2009 unit: Gm³ (page 7)

Year	Pumping station	Pumping well	Total water supply
2007	48.36	62.65	111.01
2008	50.77	60.90	111.67
2009	51.71	66.68	118.39

Table 4 Three-year (2007–2009) average of unit acreage annual irrigation water of traditional irrigation unit: m^3/hm^2 (page 7)

Province	Irrigation water	Province	Irrigation water	Province	Irrigation water
Beijing	6616.12	Zhejiang	5715.56	Hainan	6434.23
Tianjin	3790.63	Anhui	1972.80	Chongqing	883.31
Hebei	3374.02	Fujian	6127.54	Sichuan	1058.26
Shanxi	2784.29	Jiangxi	4532.81	Guizhou	5097.24
Inner Mongolia	4103.74	Shandong	2121.05	Yunnan	4798.71
Liaoning	5716.97	Henan	1916.23	Tibet	8929.25
Jilin	2720.59	Hubei	2109.68	Shanxi	3655.92
Heilongjiang	7057.68	Hunan	2613.69	Gansu	9247.66
Jiangsu	4658.13	Guangdong	8160.51	Qinghai	4436.01
Xinjiang	5666.73	Guangxi	7837.52	Ningxia	8453.71

2.3 How to evaluate the role of WSI in climate change mitigation

The role of WSI in climate change mitigation is measured through the CO_2 emission reduction thanks to energy saving of WSI compared to traditional measures. Compared to traditional measures, all of the five styles of WSI measures can save energy through reducing the amount of pumping water, but SI and LI can also increase certain energy consumption for pressurizing. So the energy calculation included two sections: energy saving through reducing pumping water and energy consumption for pressurizing, the final total amount of energy saving is the difference of the two sections.

Based on energy calculation equations of Section 2.2.1, the energy saving amount of the five WSI measures and the energy consumption of SI and LI can be calculated separately. For uniformed quantitative comparison, converted the energy saving quantity into standard coal according to 1 kg diesel for 1.46 kg standard coal and 1 kWh for 0.404 kg standard coal (calculated according to coal consumption of fire power electricity generation) (SCCCT 2002); 2.277(UNFCCC 2008) was used as the value of CO_2 emissions factor of standard coal, calculated the CO_2 reduction of various measures so that to judge the mitigation effect of the WSI measures.

2.4 How to evaluate the role of WSI in climate change adaptation

The role of WSI in climate change adaptation is measured through the estimation of newly expanded irrigated acreage thanks to water saved and increased food production from the expansion. The expanded acreage refers to that of dry to wet farmland on the existing basis. In terms of the calculation of water saved, all irrigation areas (gravity and pumping) are involved.

2.4.1 How to calculate water saved

To calculate the water saved by a certain WSI measure, this paper adopts the following formula:

$$M_{si} = A_i * m_{TI} * \delta_i \tag{7}$$

Wherein:

M_s water saved by different WSI measures

The meaning represented by other factors is the same as above.

2.4.2 How to calculate newly expanded irrigated acreage

Considering the availability of saved water, it is assumed that 62.08% (percentage of average agricultural water consumption in the national total in 2007–2009) of saved water is used for the expanded irrigated acreage. According to the latest irrigation scale and structure (the data of 2009), the possibly newly increased irrigated acreage is calculated as follows.

$$A_t = (M_{st} * 0.62) \Big/ \sum (m_i * \delta_i) \qquad (8)$$

Wherein:

A_t possibly increased irrigated acreage
M_{st} total water saved

The meaning represented by other factors is the same as above.

2.4.3 How to calculate possibly increased grain yield from newly increased irrigated acreage

From 2007 to 2009, when the average yield of single-season grain crops (mainly cereals, pulses and potatoes) of China was 4872 kg/hm^2, the irrigated acreage accounted for about 52% (CAYEC 2008, 2009, 2010) of the total cultivated land, and the per unit acreage yield of irrigated grain crops was about 1.5 times that of dry farmland (NDRCC 2008). Therefore it can be derived that the per unit hectare yield of single season grain in dry farmland was 3866 kg. After conversion of dry farmland to irrigated land, the per hectare single season grain yield may increase by 1933 kg in average. Assuming that in all areas, two-season crops can be planted annually, the possibly newly increased grain yield annually per hectare from the newly increased irrigated acreage is 3866 kg.

3 Results and analyses

3.1 Contribution of WSI to climate change mitigation

From 2007 to 2009, the total energy saved from WSI was equal to 15.23 (9.59~20.85) Mt standard coal, and total CO_2 emission reduced was 34.67 (21.83~47.48Mt) (see Table 5 for details). CI ranked first in the energy-saving and emission reduction, accounting for 27.61%, followed by LI (22.16%), SI (21.08%), OI (17.91%), and MI (11.24%).

Because of the high WSR and no additional energy consumption, among all the WSI measures, MI with a share of 5.25% accounts for 11.24% of emission reduction, representing the highest per unit acreage reduction. This indicates that an improved WSR can not only save more water but also consume less energy. In the 3 years, energy saved by

Table 5 The total energy saved and CO_2 emission reduction of WSI from 2007 to 2009 unit: Mt (page 8)

		Energy saved						CO_2 emission reduction		
		Pumping station			Pumping well					
		2007	2008	2009	2007	2008	2009	2007	2008	2009
SI	Mean	0.0070	−0.0018	−0.0081	1.02	1.04	1.15	2.35	2.36	2.60
	Min	0.0045	−0.0011	−0.0053	0.66	0.67	0.74	1.52	1.52	1.68
	Max	0.0095	−0.0024	−0.011	1.39	1.40	1.56	3.18	3.19	3.52
MI	Mean	0.047	0.051	0.063	0.31	0.46	0.77	0.82	1.17	1.91
	Min	0.034	0.037	0.045	0.22	0.33	0.55	0.59	0.83	1.36
	Max	0.061	0.066	0.082	0.41	0.59	1.00	1.06	1.50	2.45
LI	Mean	0.054	0.069	0.057	1.03	1.02	1.15	2.46	2.47	2.75
	Min	0.038	0.049	0.040	0.73	0.72	0.81	1.74	1.75	1.95
	Max	0.069	0.089	0.074	1.32	1.31	1.48	3.17	3.19	3.55
CI	Mean	0.46	0.45	0.46	0.87	0.92	1.05	3.02	3.12	3.42
	Min	0.26	0.26	0.26	0.49	0.52	0.59	1.70	1.76	1.93
	Max	0.66	0.65	0.66	1.25	1.32	1.51	4.34	4.49	4.92
OI	Mean	0.10	0.10	0.10	0.76	0.80	0.86	1.97	2.05	2.19
	Min	0.06	0.058	0.055	0.43	0.45	0.49	1.11	1.15	1.23
	Max	0.15	0.15	0.14	1.09	1.14	1.24	2.83	2.94	3.15
Total	Mean	0.67	0.68	0.67	3.99	4.23	4.99	10.62	11.17	12.88
	Min	0.39	0.40	0.39	2.53	2.68	3.19	6.66	7.02	8.15
	Max	0.94	0.95	0.94	5.45	5.77	6.79	14.58	15.31	17.59

pumping stations in 2008 and 2009 was negative, but in 2007 was positive, which was mainly due to the fact that irrigation acreage with a high head in 2007 was larger than that in 2008 and 2009. And in pumping well irrigation areas, since the pumping lift is higher than the pressure head, more energy is saved. This suggests that the higher pumping head with the more energy saved when additional pressure is applied.

3.2 Contribution of WSI to climate change adaptation

The 3-year total water saved stands at 96.85 (61.82~129.66) Gm^3 (see Table 6), accounting for 5.6%~11.8% of the national total water consumption of the same year. The ranking of percentage from high to low is: CI (36.26%)>SI (19.02%)>LI (18.45%)>OI (14.74%)>MI (11.53%). WSR is a key factor that determines the quantity of water saved per unit acreage. From the studies of emission reduction and water saving, it can be found that WSR is very important for coping with climate change, or that an improved WSR means a better solution to climate change.

Details on possibly newly expanded irrigated acreage and grain yield from saved water are given in Table 7. In theory, the possibly newly increased irrigated acreage from saved water is about 5.70 (3.80~7.80) Mhm^2, which can increase grain yield by about 14.68~30.15Mt. This can ease the food crisis to some extent, lessen the drought impact of climate change on agriculture, and strengthen the resilience of agricultural production.

Table 6 The water saved of each WSI type from 2007 to 2009 unit: Gm^3 (page 9)

Year		SI	MI	LI	CI	OI	Total
2007	Average	6.03	2.85	5.88	11.73	4.74	31.23
	Range	3.90~8.16	2.03~3.66	4.16~5.36	6.61~16.86	2.67~6.81	19.37~40.86
2008	Average	5.92	3.37	5.51	11.17	4.74	30.70
	Range	3.83~8.01	2.18~4.5	3.57~7.46	7.23~15.12	3.06~6.41	19.86~41.55
2009	Average	6.47	4.95	6.48	12.21	4.80	34.92
	Range	4.19~8.76	3.20~6.70	4.19~8.77	7.90~16.53	3.10~6.49	22.58~47.25

4 Discussions

4.1 Role of WSI in climate change mitigation

At present, the research about the impact of irrigation on GHG emission is mostly focused on the effect of water management to agricultural GHG fluxes,without involving irrigation energy consumption. (Kallenbach et al. 2010; Sanchez et al. 2010; Yue et al. 2005; Zou et al. 2007). The existing research into irrigation energy consumption is mainly about implementation effect of water-saving irrigation rather than GHG emissions (Li et al. 2007; Wang 2006; Liu 2001). On the other side, the research on energy-saving and emission reduction is mostly concentrated on such fields as industry, transport, and building (Wilde and Voorde 2004; Ouyang et al. 2009; Kwak et al. 2010; Persson and Berntsson 2009; Zhang and Wang 2008; Yan and Crookes 2009) but not on irrigation. This paper is the first attempt to study the WSI in relation to climate change.

It is found that in China WSI can make positive contribution to GHG emission reduction. From 2007 to 2009, CO_2 emission reduction realized through WSI stands at 10.62~12.88 Mt each year, accounting for 21.92%~26.58% energy emission from the agricultural sector (NDRCC 2004). But it should be noted that for practices that need pressurization such as SI and LI, when the pumping head is lower than the critical energy-saving head, pressurization consumes more energy than what WSI can save and causes more emissions than the traditional irrigation. When the pressurized head is known, the critical energy-saving head (Hc) can be calculated by the equation: $HC = (1-\delta)^{*}H'^{*}\frac{\eta}{\eta'}$ (the meaning of each factor is the same as above). So when the two WSI measures are preferred, the local geographic conditions and equipment parameters should be taken into consideration.

But the positive effect of WSI in GHG emission reduction in China is confirmed, and with the expansion of WSI, more reductions will be achieved. According to the *"National water-saving irrigation planning"* (MWRC 2006), by 2020, the water-saving irrigation

Table 7 Newly expanded irrigated acreage and grain yield from saved water –take 2009 as an example (page 9)

Irrigated acreage (Mhm2)			Grain yields (Mt)		
Average	Min	Max	Average	Min	Max
5.70	3.80	7.80	22.04	14.68	30.15

acreage will be up to 51 Mhm^2. By that time the CO_2 emission reduced through water-saving irrigation can be up to about 20~25Mt per year.

Due to the lack of available data, in calculation, this paper does not consider the additional greenhouse gas emissions caused in the penetration of WSI (the process of production, transport, and installation of materials and equipment), which needs further research.

4.2 Role of WSI in climate change adaptation

Water scarcity is already a critical concern in parts of the world (Fedoroff et al. 2010) and the availability of water resources is one of the major crises with overarching implications for many other problems, especially poverty, hunger, ecosystem degradation, climate change, and even world peace (Khan and Hanjra 2009). Continued increase in demand for water by non-agricultural uses, such as urban and industrial uses have put irrigation water demand under greater scrutiny and threatened food security (Fedoroff et al. 2010). Further, it is believed that climate change will increase water scarcity in the coming decades (Lobell et al. 2008, Xiong et al. 2010). Therefore strategies that ensure sustainable use of the limited water resources are of absolute necessity. Such strategies should support not only the safety and health of the environment, but also ensure sufficient agricultural production to feed the growing population (Foster and Perry 2010; Moiwo et al. 2010; Yang et al. 2010).

Studies have indicated that these constraints can be overcome by adopting WSI practices, which can minimise the impact of water scarcity, partially meet water demand for food production (Falkenmark and Molden 2008) and increase water productivity (Belder et al. 2005; Kato et al. 2009). This study also indicates such results.

Based on this research, it is found that the exiting WSI in China can save water of about 30 Bm^3 per year, accounting for about 8% of the total agricultural water demand. Proportionally, speaking, the saved water can irrigate additional 3.8~7.8 Mhm^2 acreage. If the newly increased acreage is exploited for food production, according to the per capita average annual grain consumption (CAYEC 2008, 2009, 2010), the output can feed 0.73~1.51 hundred million people.

According to "*The National Medium and Long-Term Grain Security Program*" (2008~2020) of China (NDRCC 2008), in order to ensure national grain self-sufficiency at 95%, it is necessary for domestic grain output to increase by about 50 billion kg by 2020 on the basis of that in 2008. According to this study, about 44% of the said objective (50 billion kg) can be realized through the expanded irrigated acreage. If according to the *"National water—saving irrigation planning"* (MWRC 2006), by 2020, the irrigated acreage of China is doubled, about 90% of the increased amount of the said objective can be achieved, which can greatly alleviate the adverse impact of climate change on water availability and food production.

4.3 Reflections on WSI

A sustainable irrigation-based agriculture must be supported with environmental-friendly, economically feasible, and highly water productive practices (Oster and Wichelns 2003; Pereira et al. 2002). However, traditional irrigation can cause such problems as water shortage, depleted groundwater (Kendy et al. 2004; Tamanyu et al. 2009; Moiwo et al. 2009; Foster and Perry 2010), and salinized soil (Yu et al. 2010; Funakawa et al. 2000; Kitamura et al. 2006; Zhang et al. 1998), which get increasingly worse. WSI can play a positive role in coping with climate change. The available studies indicate that WSI can reduce water demand and negative environmental impacts at farm level (Pereira et al. 2002). The drip irrigation applied to saline-alkali soil, for example, which consumes limited fresh water but reduces substantial salinity, ensures that grain production is of high yield and water resources are optimally exploited (Romero et al. 2006; Rajak et al. 2006; Yohannes and Tadesse 1998).

But at present, there are some factors that constrain the development of WSI technology, including cultivation expense, output gain factor, production cost, electricity charge and irrigation requirements etc. (Pascual et al. 2006; Ramesh et al. 2003). Besides, due to the lack of necessary training and technical guidance, the management and maintenance of WSI equipment are still face problems, (Fang et al. 2010). Income is the most important driving factor for farmers to engage in agricultural production (Muhammad et al. 2007). But the implementation of WSI requires additional financial investment as compared with TI, especially SI and MI, which are a proven enabler in emission reduction and water-saving. Daleshwar et al. (2006) indicated that although MI can achieve a higher yield, but due to the high equipment investment, the cost/benefit ratio is lower than the conventional furrow irrigation. So the cost-effectiveness of WSI is a determinant of its future development. Whether WSI is economically feasible in the case that the benefit of mitigation and adaptation is taken into consideration needs further quantitative studies.

5 Conclusions

This study based on 3-years of data for China is aimed at quantitatively understanding the role of WSI in coping with climate change. The conclusion is that WSI is potentially highly appropriate for the climate change issue.

From 2007 to 2009, thanks to WSI, China reduced 21.83~47.48 Mt of CO_2 emissions and saved 61.81~129.66 Bm^3 of water. Using the 2009 data on water saved and the 3-year average on agricultural water consumed as a baseline, the saved water can expand the irrigated acreage by 3.80~7.80 Mhm^2 to increase grain production by 14.68~30.15 Mt, hence feeding 73~151 million people for one year.

Different WSI practices differ in GHG emission reduction potential. In the absence of pressurization, all the practices help reduce emission through reduced pumping water. But when there is pressurization, energy saving depends on the critical head. Therefore, WSI can be deemed a useful practice for addressing climate change so long as it is rightly deployed. However, the economic investment associated with climate change resilience calls for further study.

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