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Growing water scarcity, food security and government responses in China

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ABSTRACT

China's food production depends highly on irrigation, but irrigated agriculture has been threatened by increasing water scarcity. As such, the overall goal of this study is to provide a better understanding of the changing trends in water supply and demand balance, their impacts on food production, and government policy responses. The results show that water scarcity in China is a regional issue, mainly in northern areas. This is reflected in the limited and uneven distribution of water resources, decline of surface water resources, depletion of groundwater resources, degradation of water quality and increasing water demand. Climate change has further aggravated water scarcity in several river basins in northern China, resulting in the reduction of irrigated areas and a fall in food production. Consequently, the Chinese government has tried to control total water withdrawal, improve water use efficiency, and control water pollution. While these policy responses are encouraging, their effectiveness in resolving the growing water scarcity in China needs to be examined.

1. Introduction

China's food production significantly depends on irrigation; however, the sustainability of irrigated agriculture has been challenged by increasing water scarcity. Considering the higher productivity of irrigated land, since the 1950s, the Chinese government has invested huge amounts in irrigation infrastructure construction to deliver water from surface or groundwater resources (MWR, 2015b). To date, half the cultivated land has been equipped with irrigation facilities; over 70% of the national grain output, 80% of the national cotton output, and more than 90% of the national vegetable output comes from irrigated land (RWRD and CIDDC, 2010). However, water has increasingly become scarce; the increase has been noted since the late 1990s. In 1997, the lower reaches of the Yellow River (the second largest river in China) dried up for 226 days and significantly influenced the socioeconomic activities in the downstream rivers (Wang, 2009). Following this, there has been growing evidence of increasing water scarcity, particularly of the decline in groundwater table and degradation of water quality (Brown and Halweil, 1998; Wu et al., 1999; Liu et al., 2001; Foster et al., 2004; Wang and Jin, 2006; Qiu, 2010; Famiglietti, 2014). Recently, climate change has been considered another important driver of water scarcity in China (Xiong et al., 2010; Wang et al., 2013). As such, scholars believe that China has reached a point where critical decisions must be made to resolve its water crisis (Mu and Khan, 2009; Lu et al., 2015).

Increasing water scarcity and its pressure on ensuring food security have also attracted the attention of policymakers in China. Since 2004, the central government has annually issued the NO1 document to resolve agricultural, rural and farmers' issues. These documents emphasize how to improve the condition of irrigation facilities and enhance irrigation efficiency[1] to ensure food security. In addition, China's government has tried to change the water management strategies from supply side to demand side to ensure water security and promote sustainable socioeconomic development. In the late 2000s, the World Bank reviewed the overall water scarcity situation and major water management problems, and provided some suggestions on improving water management in China (Xie et al., 2009). However, the impacts of water scarcity on food security have not been emphasized in this review and the data and information used pertain to before 2007.

Whether irrigated agriculture can continue to play a significant role in ensuring China's food security in the future highly depends on how China's government responds to the current situation. Therefore, in order to assist policymakers to design effective policies, the following

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[1] In the paper, irrigation efficiency is the combined efficiency for delivery and field application.

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questions urgently need to be addressed: What is the history and current situation of China's water scarcity? What are the future trends of water scarcity driven by socioeconomic development and climate change? How does the change in water scarcity influence food security? How effective is the government's response to the increasing water scarcity and what progress has it made so far? This study aims to answer these questions based on comprehensive secondary data, unique primary survey data, simulation results from the China Water Simulation Model, as well as a literature review.

The remainder of the paper is organized as follows. Section 2 provides historical evidence on growing water scarcity in China and by river basin. Section 3 analyzes the future trend of water scarcity under climate change and its impacts on agricultural production in China by river basin. Section 4 introduces the government's response to deal with water scarcity through institutional and policy instruments to control total water withdrawal, improve water use efficiency, and control water pollution. Finally, Section 5 concludes the study with a discussion of such policy implications.

2. Historical evidence on growing water scarcity in China

The gap between water supply and demand in China has reached a current level of 53.6 billion m^3 and has resulted in obvious economic losses (GWP, 2015). Over the past two decades, water scarcity has resulted in an annual grain production loss of more than 27 million tons in China (Chen et al., 2014). Our study treats water scarcity as the lack of sufficient available water resources to meet water needs within a region. Therefore, scarcity is influenced not only by water supply, but also by water demand. The following section provides some historical evidence on the increasing water scarcity from both supply and demand perspectives.

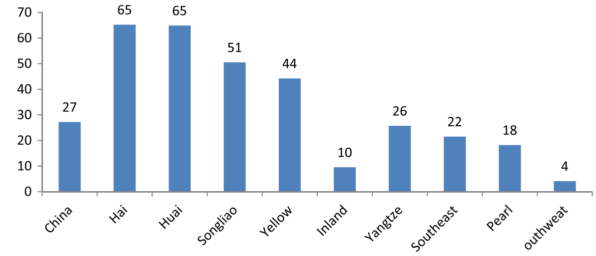
2.1. Historical evidence on limited endowment and declining water supply

2.1.1. Limited endowment and uneven spatial distribution of water resources

In addition to limited endowment, uneven distribution and a mismatch between supply and socioeconomic activities are issues involving water supply. China's total water resources rank sixth in the world; per capita water availability is only a fourth of the global average, ranking 121st (GWP, 2015). In addition, water is not evenly distributed geographically, as 81% of water resources are concentrated in southern China (MWR, 2015a). Despite only having 19% of water endowment, northern China supports more than 65% of national cultivated land, 50% of grain production and over 45% of national GDP (NBSC, 2015). In addition, with a strong monsoonal climate, China is subject to highly variable rainfall that contributes to frequent droughts and floods, particularly in northern China (Xie et al., 2009). Therefore, the temporal pattern of precipitation further intensifies the uneven spatial distribution of water resources.

2.1.2. Decline of surface water resources

Over the past 60 years (1961–2011), river runoff in six large river basins presented a declining trend: four (Hai, Yellow, Liao, and Songhua) in northern China, and two (Yangtze and Pearl) in southern China (Map 1). The most obvious reduction of river runoff was registered in Hai (18.2%), followed by Yellow (11.3%). In Liao and Songhua basins, the reductions were 8.3% and 3.4%, respectively. An important phenomenon is that even though they are a part of relatively water rich regions in southern China, river runoffs in Yangtze and Pearl also fell by 2.3% and 0.3%, respectively. This implies that increasing water pressure is faced not only by northern China, but also by southern areas. Due to a decline in river runoff, some river basins (e.g., Hai and Yellow) have changed from open to closed ones in some years, negatively influencing the ecological environment (such as causing biodiversity degradation, atrophy and sea water intrusion) (Wang et al., 2016a). More importantly, the decline of river basin has significantly influenced food production in China. In China, near 75% of irrigated grain production came from these river basins that experienced the reduction of river runoff in the past 60 years. For Hai and Yellow river basins having the most obvious reduction of river runoff, their contribution to national irrigated grain crop production reached near 40%.



Map 1. Change of river runoff in ten large river basins in China (1961–2011) Data sources: ECSNCCA, 2011.

2.1.3. Depletion and overdraft of groundwater resources

With the decline of surface water resources, water users (particularly farmers) have turned towards groundwater resources. As a result, groundwater extraction increased from less than 10 km^3 in 1950 to over 112 km^3 in 2014 (MWR, 2015a). The share of groundwater in total water utilization in China has increased from an insignificant amount in the 1950s to 18% in 2014 (MWR and Nanjing Water Institute, 2004; MWR, 2015a). Based on our field survey in nine provinces in 2012, we found that 83% of cultivated land in six provinces in northern China depended on groundwater irrigation. In southern China, the share of groundwater irrigated areas in three provinces (Jiangxi, Guangdong, and Yunnan) reached 58%, much higher than our expectation. Therefore, groundwater has not only become the dominant water source for irrigation in northern China, but has also gained importance in southern China, which cannot be overlooked.

Unfortunately, reliance on groundwater has resulted in overdraft and a number of adverse environmental effects. Since the late 1990s, groundwater overdraft has become one of China's most serious resource problems. Presently, there are 400 regions whose groundwater overdraft exceeds their sustainable capacity, and the total area of these regions is 11% of plain areas in China (MWR, 2012). In the Hai river basin, 91% of plain areas belong to overdraft regions. Consequently, the groundwater table of many regions presents a decreasing trend. For example, shallow groundwater tables in the Hai river basin have dropped at a rate as high as 1 m per year between 1974 and 2000 (Qiu, 2010), and the drop rate in deep groundwater table has even exceeded 2 m per year (Wang et al., 2009). Even in southern China, a drop in the groundwater table can be observed in some regions (Zhao et al., 2008). Moreover, over-drafting groundwater has caused land subsidence, the intrusion of seawater into fresh water aquifers, and desertification (MOE, 2015).

2.1.4. Deterioration of water quality

In addition to the decline in water supply, water quality has also been obviously degraded, and the situation is more serious in northern China. Based on MWR's monitoring data, the percentage of monitored surface water sections with poor quality that were not suitable for drinking (Grade IV-V and V+) reached 44% in 1998, while 16% were not suitable for any use (Grade V+) (Fig. 1).[2] After 2000, due to the

[2] Grade I–III is suitable for drinking, Grade IV and V is suitable industrial and agricultural water use, and Grade V+ is not suitable for any use.

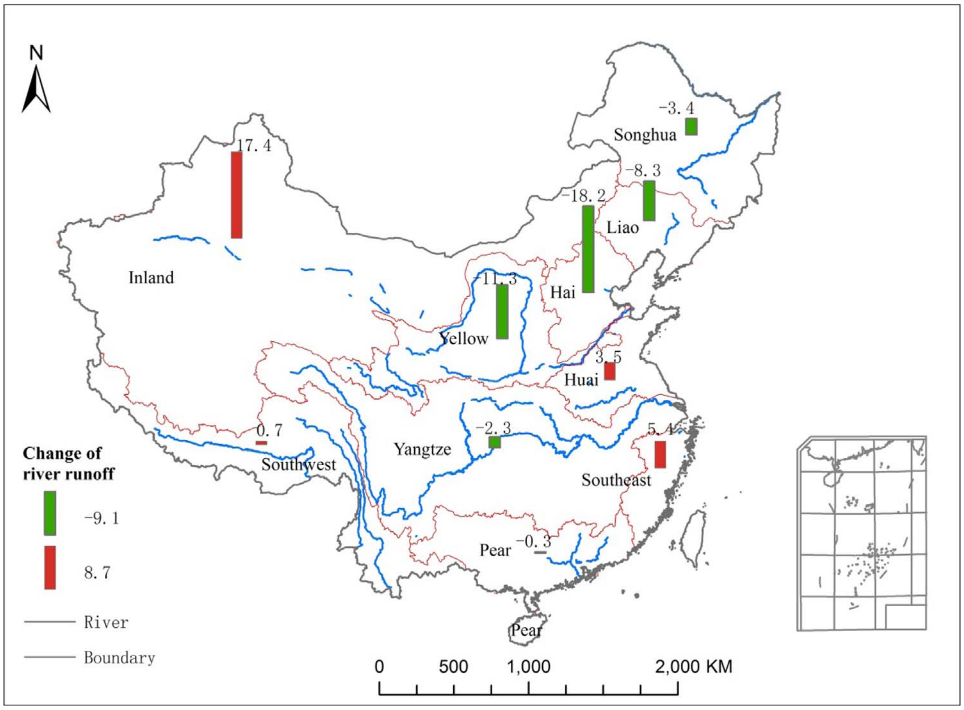


Fig. 1. Percentage of monitored water sections with poor water quality over time in China (1997–2014).
Data sources: China Water Resources Bulletin published by MWR in the respective years

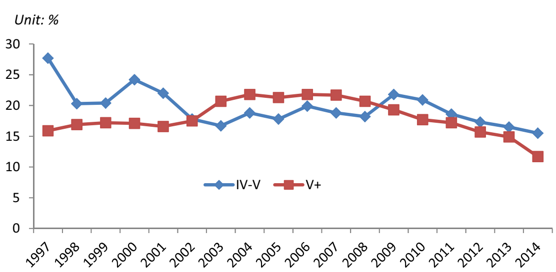


Fig. 2. Percentage of monitored surface water sections with poor quality (Grade IV-V+) in 2014.
Data sources: MWR (2015a)

implementation of some pollution control measures (such as closing down some industrial plants that discharged a large amount of pollutants), the situation improved, but the percentage of poor quality surface water sections was still as high as near 30% in 2013 and 2014; the percentage for Grade V+ did not decline significantly (15% in 2013 and 12% in 2014). Water quality has also presented significant inter annual fluctuation characteristics and variations over regions (Figs. 1 and 2). The pollution situation in most regions of northern China is much more serious than that in the southern regions. The percentage of poor quality surface water sections was as high as 65% in both Hai and Huai river basins, and 51% and 44% in Songhua and Yellow river basins, respectively (Fig. 2).

Apart from surface water, groundwater quality has also presented an obviously deteriorating trend that has accelerated in recent years. Based on monitoring data for 778 tubewells in 2006, groundwater in 61% of them was polluted and not suitable for drinking. In 2015, the monitored tubewells expanded to 2,013, and the percentage of tubewells whose groundwater was polluted was even higher, reaching 80% (MWR, 2015a). This indicates that controlling groundwater has not attracted enough attention from the government, and the pollution status continuously deteriorates. In the future, controlling groundwater pollution and improving its quality should be addressed by the government, scholars, and other stakeholders.[3]

2.2. Expansion of irrigated areas and increase of non-agricultural water withdrawal

Over the past 60 years, total water withdrawal in China has presented a significantly increasing trend, increasing by nearly 5 times (Table 1). The first important contributor to the increase of water withdrawal is the expansion of irrigated areas. Expanding irrigated area is also one of important measures by Chinese government to improve the national food security. From 1950 to 2014, the total irrigated area in China increased from 16 million ha to 65 million ha (NBSC, 2015). As a result, agricultural water withdrawal increased from 100 billion m^3 in 1949 to 387 billion m^3 in 2014. An observation of the water withdrawal increase over the period reveals that total water withdrawal for the agricultural sector presented a declining trend since 1978. However, though the growth rate has slowed down, the total water withdrawal for both the industry and domestic sectors has presented a continuous increasing trend (Table 1). Importantly, the government has also considered ecological water withdrawal in the water allocation in

[3] Based on a literature review, due to water pollution, water availability has been reduced and resulted in increasing water scarcity (Bao and Fang, 2012). However, the literature has not provided empirical evidence on the impacts of water pollution on water availability. In addition, we could not find rich literature that analyzes to what extent has water pollution contributed to agricultural production losses or what share of crops cannot be irrigated; this is the area that needs more studies in the future. We only found one case study in Huai river basin, which shows that due to increasing water pollution, farmers replaced rice by maize in 2002, and maize yield also had decreased over time due to polluted irrigation (Yang, 2010). Rather analyzing the impacts on production losses, some studies focus on the impacts of food quality and resulting impacts on health (Lu et al., 2010; Zhang et al., 2015).

Table 1
Water withdrawal by sector in various periods in China (1949–2014).
Data sources: Data in 1949, 1978 and 1993 are from Water Statistical Yearbook (1994) published by Ministry of Water Resources; data in 1998, 2000, 2005, 2010 and 2014 are from Water Resources Bulletins (various years) published by Ministry of Water Resources.

Year	Water withdrawal (billion cubic meters)				
	Total	Agriculture	Industry	Domestic	Ecology
1949	103	100	2	1	-[a]
1978	477	420	52	5	–
1993	525	410	92	24	–
1998	544	377	113	54	–
2000	550	378	114	58	–
2005	563	358	128	68	9
2014	610	387	135	77	10.4

[a] No date.

Table 2
Water supply and demand gap by river basin in China (%).
Data sources: China Water Simulation Model (CWSM)

	Base year (2010)	Reference scenario[a] (2030)	Change due to climate change (comparing with reference scenario)	
			RCP6.0	RCP8.5
China	−8	−39	−2	−3
River basins in the north				
Hai	−26	−44	−4	−5
Huai	−10	−33	−5	−7
Songhua	−8	−30	−1	−4
Liao	−12	−30	−1	−4
Yellow	−14	−41	−6	−9
Inland	−8	−28	−1	−3
River basins in the north				
Yangtze	−2	−43	−2	−2
Southwest	−9	−30	5	3
Pearl	−3	−38	−1	1
Southeast	−4	−47	−3	0

Note:
[a] Without considering climate change and only assuming socioeconomic development, such as growth of population, urbanization, industrialization, and expansion of irrigated areas, water use efficiency in various sectors is assumed to be similar to 2010. The detailed discussion on these assumptions can be found in Yan (2015) and Wang et al. (2013).

recent years (Table 1). In the future, with rapid urbanization, industry development, and increasing concerns over environment protection, agricultural water withdrawal will face sharper competition from other sectors.

3. Future trend of water scarcity and its impacts on food security in China

Based on the literature review, we found that though some studies predicted the influence of socioeconomic development on water scarcity in China, the impacts of water scarcity on food security have not been further analyzed. For example, MWR predicts that China will consume 750 billion m^3 of water a year by 2030, about 90% of total usable water resources in the country (Qiu, 2010). By 2050, China's total water deficit could reach 400 billion m^3 (roughly 80% of the current annual capacity of approximately 500 billion m^3) (Tso, 2004).

In recent years, a growing body of literature has focused on the impacts of climate change on water scarcity, but has generally ignored food security and has used climate scenarios that are outdated. For example, based on AR3 or AR4 climate scenarios, Zhang and Wang (2007), Zhang et al. (2011) simulated the impacts of climate change on river runoff at the national and river basin level, but without a focus on the further impacts on food security. Mu and Khan (2009), Xiong et al. (2010), and Wang et al. (2013) simulated the impacts of climate change on water scarcity and food security at the national and river basin level, but their climate scenarios are also based on AR4 or an assumption about climate change. By applying the climate scenarios of AR5 (RCP 6.0 and RCP 8.5) (the predicted temperature and precipitation are provided in Appendix A) and the China Water Simulation model (an introduction to the method can be found in Yan, 2015 and Appendix B), we simulate the impacts of climate change on water and agricultural production in ten large river basins by 2030.[4] The following section discusses the main simulation results.

3.1. Future trend of water scarcity with and without considering climate change

Simulation results indicate that even without considering the influence of climate change, socioeconomic development has already pressurized the water scarcity in all river basins (Table 2). In the base year (2010), the gap between water supply and demand already reached 8% at the national level. The gap at the river basin level was as high as 26% in the Hai and more than 10% in Yellow, Liao, and Huai river basins in the north. Water supply cannot satisfy water demand in all river basins in the south. By 2030, with further growth of population, urbanization, industrialization, and expansion of irrigated areas, the water scarcity situation will worsen (reference scenario). At the national level, if water use efficiency is not improved, the water supply and demand gap will increase to 39%. Importantly, the gap in most river basins (either in the north or south) will significantly increase.

Furthermore, climate change will aggravate water scarcity in all river basins in the north and some river basins in the south (Table 2). Simulation results show that due to climate change, the gap will increase by 1% (Songhua, Liao, and Inland) to 6% (Yellow) under RCP6.0 or 3% (Inland) to 9% (Yellow) under RCP8.5 in the north by 2030. For the Yangtze river basin in the South, the gap will increase by 2% under both RCP6.0 and RCP8.5. For the Southeast and Pearl river basins in the south, the gap will increase under RCP6.0, but not under RCP8.5. The water scarcity situation in the Southwest river basin will be mitigated by climate change by 5% under RCP6.0% and 3% under RCP8.5, but this mitigation cannot offset the negative socioeconomic development impacts in the future. It should be noted that our simulation only considers the long-term climate change; the influence of extreme weather events (such as drought and flood) have not been included. Extreme weather events are expected to have a notable influence on water scarcity (particularly in the short term); this is an important issue and should be addressed by further study (IPCC, 2014).

3.2. Impacts of increasing water scarcity on agricultural production

Increasing water scarcity will result in the decline of irrigated areas and negatively influence agricultural production. Simulation results show that increasing water scarcity has resulted in the decline of water availability for agricultural production, and water

[4] A review paper by Ali et al. (2016) shows that the increased food imports have significantly eased pressure on water in China and has also increasingly contributed towards global savings of virtual water.

has to be reallocated between irrigated and rainfed areas.[5] As a result, irrigated areas in river basins facing more serious water scarcity tend to decrease and be replaced by rainfed areas. Due to low productivity in the rainfed areas, the agricultural output will decrease, particularly for rice and wheat. For example, even without the influence of climate change, rice output in all river basins will decrease by 13% (Yangtze and Huai) to 16% (Southwest) by 2030. For river basins faced with increasing water scarcity, rice output will further reduce by less than 1% (Yanggtze) to more than 10% (Hai and Yellow) under RCP8.5. The influence is significant not only for rice, but also for wheat output. Even without considering climate change, increasing water scarcity driven by socioeconomic development will lead to reduction of wheat output by 4% (Liao) to more than 16% (Songhua and Southeast) by 2030. Climate change will further reduce wheat output by less than 1% (Yangtze) to more than 12% (Yellow) under RCP8.5. Compared with rice and wheat, the negative influence of increasing water scarcity on other crops is smaller. However, as they are two major crops ensuring food security in China, the reduction of rice and wheat output will remarkably influence the situation of food security. In recent years, China's food policy has been to ensure almost 100% of self-sufficiency for both rice and wheat. Therefore, it is imperative for China's government to address water scarcity issues to realize the food security objective in the future.

4. Government responses to deal with growing water scarcity in China

Traditionally, China's government relies on supply side management to resolve the water scarcity issue, that is, meeting the demand for water by increasing the supply (Xie et al., 2009; Wang, 2012). Under the guidance of such a management strategy, the government has not only invested in many water infrastructures to explore the local water resources, but has also tried to construct water transfer projects to overcome the uneven spatial distribution of water. The most famous water transfer project is South-North Water Transfer Project, the world's longest and largest water diversion project with a planned investment of 486 billion yuan (U.S. $77 billion) and involving 45 billion m^3 of annual water transfer (Liu and Wu, 2015). However, the contribution of this project to resolving water scarcity in northern China is considered to be limited and temporary, and its potential negative environmental impacts have also been widely debated (Liu and Kok-Chiang, 1994; Liu, 1998; Berkoff, 2013). In addition, with an increasing investment cost and limited available water that can be explored, exploring local water resources has become almost impossible in many regions of China.

More importantly, increasing evidence indicates that supply side water management has resulted in inefficient water use, deterioration of water quality and ineffective water management (Xie et al., 2009; GWP, 2015). In China, water use efficiency is not high; irrigation efficiency is only about 0.50 (versus 0.7–0.8 in developed countries) and water withdrawal per GDP (RMB 10,000) is a third of the world average (Wang, 2012; GWP, 2015). In addition, rapid socioeconomic development has not considered the potential constraint of water resources and its negative influence on the environment and, as a result, water quality has deteriorated. Finally, China's water resource management system is extensively fragmented and due to the high coordination cost among different institutions, resolving the water problem has become more difficult and has resulted in many conflicting issues (Xie et al., 2009; GWP, 2015; Wang et al., 2016a).

Therefore, in order to overcome the shortcomings of supply side management and effectively deal with water scarcity issues, China's government has recently begun to emphasize the importance of managing water demand and promote one of the strictest systems of water resource management in the world (State Council, 2012). This policy is called the "Three Red Lines" policy, created to establish clear and binding limits on water withdrawal, water use efficiency, and quality standard. According to the policy, by 2030, total water withdrawal in China should be below 700 billion m^3; irrigation efficiency should be increased to 60% and water withdrawal per GDP (RMB 10,000) should be less than 40 m^3; and the number of water function zones complying with the water quality standard should be more than 95% (State Council, 2012). Successfully implementing the "Three Red Lines" policy not only requires the government to establish an integrated water management institution and improve the legal system, but also needs an application of market oriented policy instruments to adjust the behaviour of water users. In the subsequent sections, we mainly focus on discussing how the government can use several major market oriented institutional and policy instruments to realize policy goals. A detailed discussion on an integrated water management institution and the improvement of the legal system can be found in Xie et al. (2009).[6]

4.1. Water quota management, water withdrawal permission system and water resources fee

In order to control the total water withdrawal, the central government requires the river basin management authorities and local water resources bureau to determine water quotas for various water users at different levels (i.e., river basin, provincial, city, county, irrigation district, and village). In addition, all water users should obtain water withdrawal permission from upper level water management authorities and their water withdrawal (both surface and groundwater) should not exceed their allocated quota. Although these two policies have been promoted by the central government since the early 2000s,[7] the implementation is slow and ineffective. Until now, quota allocation has not been completed for various users in many provinces and seems to be a tedious task for water managers (Cao and Fan, 2015). Wang et al. (2009) reveal that most farmers in northern China do not need to obtain permission for abstracting groundwater. As another policy instrument for controlling total water withdrawal, the policy of water resources fee has also been in place since 2006 (State Council, 2006). Hitherto, all provinces have been collecting a water resources fee for both industry and domestic water withdrawal, but an agricultural water resources fee is imposed only in few provinces (e.g., Gansu) (Gansu Provincial Government, 2014; Xue and Li, 2015). Presently, China's government is planning to charge the fee amount as tax instead to further enhance its potential role, and Hebei has been selected as the pilot reform province for 2016. In the future, the effectiveness of these policy instruments' implementation would be highly relevant to the realization of water control objectives and research in this field still needs to be strengthened.

4.2. Reform of water pricing policy

Since 2002, with the issuing of the new Water Law, China's government has accelerated the reform of water pricing policy. In recent years, the water pricing reform in both industrial and domestic sectors has made obvious progress, but the progress in the agricultural sector is unsatisfactory (Wang, 2012). The major concern of policymakers is that increasing prices will reduce farmers' income, and the

[5] Water was reallocated across sectors according to their share in the total water use in the base year.

[6] In addition to improve water management, adopting advanced crop technologies (such as drought resistant varieties) to increase food production is another important measure to resolve water scarcity issue.

[7] The implementation of water withdrawal permission system in some provinces in northern China (such as Hebei and Henan provinces) begun in the early 1990s (Wang et al., 2016a).

negative impacts of increasing irrigation fees on farmers' income has also been confirmed by scholars (Wang et al., 2016b). However, without rational water price, farmers do not have an incentive to increase irrigation efficiency (Dinar and Saleth, 2005). The challenge of increasing water prices while not influencing farmers' income exists not only in China but also in other countries (Dinar and Saleth, 2005). The good news is that the experience with the Hebei pilot reform indicates that designing a suitable subsidy program enables realizing a win-win strategy of agricultural pricing reform (Wang et al., 2016b). In 2016, the central government has issued a regulation on conducting comprehensive agricultural water pricing reform and providing subsidies for supporting water pricing reform (State Council, 2016). However, whether the reform can be effectively implemented in all provinces and how it can realize the expected objectives still needs to be examined by future studies.

4.3. Establishing a water rights system and promoting water markets

China's central government has been trying to set up a water rights system and optimize the allocation of water resources via market mechanisms since the early 2000s (NPC Standing Committee, 2002; Calow et al., 2009). In order to promote the work, some regulations have been issued. For example, Ministry of Water Resources issued the regulation on *Some Opinions on Water Rights Transfer* in 2005 and *Establishing Framework of Water Rights System* in 2010. In 2015, Ministry of Water Resources issued the Work Plan for Water Rights Pilot Projects. Until now, a few pilot projects of water rights transfer have been considered successful. These projects include water rights transfer between the two cities of Dongyang and Yiwu in Zhejiang province, transfer between agricultural and industrial water users in Inner Mongolia and Ningxia provinces, and even among individual farmers in the Shiyang and Heihe river basin in Gansu Province (Speed, 2009; Moore, 2015). Sun et al. (2016) found that in the Heihe river basin, the local government has issued water rights certification to farmers. Such reform played a significant role in reducing irrigation withdrawal before 2010, but its significance has been diluted in recent years. More importantly, cases of water rights transfer among individual farmers almost do not exist. In sum, despite some progress made on establishing a water rights system and developing water markets, China still has a long way to go. The major problem is that initial water rights have not yet been allocated to various water users in most regions. If the water rights system is not completely established, it would be impossible to develop water markets. In recent years, a water quota system has been considered to be an important measure to allocate initial water rights to users. More empirical studies on policy implementation in the future are required to determine whether quota management can realize the objective of establishing a water rights system.

4.4. Collecting pollution discharge fee

China started collecting pollution discharge fees since 1982 (State Council, 1982). To emphasize the role of this policy and realize pollution control objectives, the government issued regulations to further improve its implementation in 2014 (National Development and Reform Commission, 2014). As such, by the end of June 2015, the minimum pollution discharge fee was RMB 1.2/pollution equivalent for sulphur dioxide and nitrogen oxide in exhaust gas and RMB 1.4/pollution equivalent for chemical oxygen demand, ammonia nitrogen, and the five main heavy metals (i.e., lead, mercury, chromium, cadmium, and arsenic) in sewage. With the reform implementation, polluting enterprises are expected to reduce their pollution emissions by updating their production technologies (Zhou and Ma, 2015). However, the effectiveness of this policy in controlling water pollution needs to be examined by future studies. More importantly, as the focus of this policy is to adjust the point pollution behaviour of industry and domestic water users, its applicability to adjusting farmers' production behaviour to control non-point pollution is an even greater challenge for policymakers in China.

4.5. Reforming irrigation management

Since the mid-1990s, under the push of World Bank, China's government began to reform irrigation management (Wang et al., 2016a) with an aim to increase irrigation efficiency and promote the sustainable development of agricultural production through farmers' participation in water management. The major pattern of the reform is to replace collective water management by Water User Association (WUA). Despite the central government's great focus on the reform and the issuance of relevant regulations on promoting the reform since 2000, the overall reform performance has not been satisfactory (Wang, 2012). Based on a large field survey in northern China, scholars found that most reforms are nominal since only about 20% of reforms establish water saving incentives, and farmers' participation in the WUA is also limited (Wang et al., 2005, 2006, 2014). However, if suitable incentives are established, the reform can play significant role in reducing irrigation application and increasing water productivity. In addition, the negative impacts on agricultural production are also limited. Another challenge with the irrigation reform is the financial sustainability of WUAs since the latter lack funds to support their operation (Wang, 2012). Effectively implementing the reform and ensuring its sustainable development is still an important issue for policymakers in China.

4.6. Promoting the adoption of water saving technologies

In the past 30 years, China's government has invested much effort in extending water saving technologies in agricultural, industrial, and domestic sectors. Compared with non-agricultural water users, extending water saving technologies in agricultural sectors is more difficult due to many socioeconomic, financial, and technical problems and has been addressed to a great extent by policymakers and scholars (Blanke et al., 2007; Huang et al., 2017). In order to improve the condition of water conservancy projects in rural areas, the central government requires local governments to allocate 10% of land transfer revenue for water conservancy projects (Ministry of Finance, National Development and Reform Commission and Ministry of Water Resources, 2011). To ensure this allocation, 80% of revenues should be used for constructing small-scale irrigation infrastructure and developing water saving irrigation and 20% for their operation and maintenance (Ministry of Finance and Ministry of Water Resources, 2013). The central government has also set up a special subsidy fund to facilitate the operation and maintenance of water conservancy projects in central and western China, and other poor regions. For example, in 2011, the total subsidy fund was 1 billion Yuan. In the future, it is expected that China's government would invest more efforts in promoting the adoption of water saving technologies. The likelihood of farmers adopting suitable water saving technologies in their field would increase with the effectiveness of water price reform implementation (Cremades et al., 2015).

5. Concluding remarks

Based on historical data, we find that water scarcity has become more serious, particularly in northern China. The increasing water scarcity is reflected not only in the decline of river runoff in six large river basins (four in the north and two in the south), overdraft of groundwater, and environmental problems, but also in the degradation of both surface and groundwater resources. It should be noted that although water scarcity is more serious in northern China, it has also emerged in some regions of southern China. In addition, as irrigation highly depends on groundwater, resolving groundwater overdraft and the accelerated degradation of groundwater quality seems to be a major challenge for policymakers in the future. Importantly, if no effective measures are taken, the increasing water scarcity driven by socio-economic development and climate change will significantly reduce the output of rice and wheat by 2030. As both rice and wheat are major crops for ensuring food security in China, the government's realization of the food security objective highly depends on its capacity to resolve the water scarcity issues in the future.

With increasing water scarcity and considering the shortcomings of supply side management, China's government has begun to move towards demand side management and to initiate the implementation of the “Three Red Lines” policy to control total water withdrawal, improve water use efficiency, and control pollution. The central government has actively used institutional and policy instruments to realize policy objectives. In fact, all instruments referred to in this study (such as water quota management, permission system, water resources fee, water price, water rights, irrigation management reform, and water saving technology) are not new, and have been promoted for at least 10 years. Although these measures are expected to play a significant role in resolving increasing water scarcity, the key issue is how to improve the implementation effectiveness in practice. In addition, these new policy measures have received limited attention from the literature and need to be addressed in China.

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Appendix A. Change in the average annual temperature and precipitation under alternative climate change scenarios from 2010 to 2030

	Temperature (°C)		Precipitation (%)	
	RCP6.0	RCP8.5	RCP6.0	RCP8.5
River basins in the north				
Hai	1.18	1.80	0.65	−1.05
Huai	0.96	1.60	−0.94	−1.25
Songhua	1.82	2.19	7.07	5.59
Liao	1.36	1.90	6.16	3.41
Yellow	1.16	1.78	−1.00	−3.66
Inland	1.48	1.96	1.91	0.54
River basins in the south				
Yangtze	1.09	1.60	−0.05	1.86
Southeast	0.89	1.30	−2.88	4.01
Pearl	0.86	1.34	2.52	5.04
Southwest	1.17	1.61	8.92	7.07

The main indexes representing climate change scenario are temperature and precipitation. To obtain high-resolution changes in temperature and precipitation, 26 CMIP5 models are used. Given the temperature and precipitation under the two RCPs, the future changes in ET of crops and runoff, as well as water demand and water supply, are then simulated by the CWSM. More details can be found in Wang et al. (2013).

Appendix B. China Water Simulation Model (CWSM)

The model we used to estimate the impacts of climate change on water balance and agricultural production is the China Water Simulation Model (CWSM) developed by the authors. When the water balance is affected by climate change, water is reallocated among sectors (i.e. agricultural, industrial and domestic sectors) and within the agricultural sector. The CWSM integrates climate, hydrology, crop simulation and water allocation optimization and consists of two main modules, the water balance and the water allocation modules. The main approach used for water allocation modules is the Positive Mathematical Programming (PMP) model, the detailed description of which can be seen in our previous study (Wang et al., 2013). A production function with a constant elasticity of substitution (CES) is used, considering the substitution between irrigated land and irrigation water, the return-to-scale effect, and the relationship between crop yield and irrigation water. In addition, the shadow costs of the inputs are introduced into the cost function. The CES PMP model used in this study is more flexible, ensuring realistic responses to price changes, replicating the observed profits and taking into account yield response to irrigation water.

$$\underset{\begin{Bmatrix} A_{r,c,ir} \\ A_{r,c,rf} \\ W_{r,c,ir} \end{Bmatrix}}{\text{Max}} \prod_r = \sum_c \left[P_{r,c}(Q_{r,c,ir} + Q_{r,c,rf}) - (C_{r,c,a} + \mu_{r,c,a,ir})A_{r,c,ir} - \left(C_{r,c,a} + \mu_{r,c,a,rf}\right)A_{r,c,rf} - (C_{r,c,w} + \mu_{r,c,w})W_{r,c,ir} \right] \quad (1)$$

$$st. \quad \begin{cases} \sum_c (A_{r,c,ir} + A_{r,c,rf}) \le \sum_c (\overline{A}_{r,c,ir} + \overline{A}_{r,c,rf}) \\ \sum_c W_{r,c,ir} \le I_{cc} \end{cases} \quad (2),(3)$$

$$Q_{r,c,ir} = \alpha_{r,c,ir}(\beta_{r,c,ir,A}A_{r,c,ir}^{\rho_c} + \beta_{r,c,ir,W}W_{r,c,ir}^{\rho_c})^{\frac{\delta_{r,c,ir}}{\rho_c}} \tag{4}$$

$$Q_{r,c,rf} = \alpha_{r,c,rf}A_{r,c,rf}^{\delta_{r,c,rf}} \tag{5}$$

The model is run for each of ten large river basins in China separately. In the above program,[8] Eq. (1) is the objective function, which is to maximize the producer's profit subject to the land constraint (2), and water constraint (3). In the objective function, crop's total output changes with its sown area and irrigation water. Eq. (4) is a production function for irrigated crop with a CES between irrigated land and irrigation water. For rainfed crops, the production function can be simplified as Eq. (5).

References

Ali, T., Huang, J., J. Wang and Xie, W., 2016. Global Footprints on Water and Land Resources through China's Food Trade, Global Food Security, ⟨http://dx.doi.org/10.1016/j.gfs.2016.11.003⟩

Bao, C., Fang, C., 2012. Water resources flows related to urbanization in China: challenges and perspectives for water management and urban development. Water Resour. Manag. 26, 531–552.

Berkoff, J., 2013. China: The South–North Water Transfer Project— s it justified? Water Policy 5, 1–28.

Blanke, A., Rozelle, S., Lohmar, B., Wang, J., Huang, J., 2007. water saving technology and saving water in China. Agric. Water Manag. 87, 139–150.

Brown, L.R., Halweil, B., 1998. China's water shortage could shake world food security. World Watch 11 (4), 10–21.

Calow, R.C., Howarth, S.E., Wang, J., 2009. Irrigation development and water rights reform in China. Water Resour. Dev. 25, 227–248.

Cao, Y., Fan, K., 2015. Discuss the role of water quota in water resources management. Huai River Manag. 11, 37–38.

Chen, H., Wang, J., Huang, J., 2014. Policy support, social capital and farmers' adaptation to drought in China. Glob. Environ. Change 24, 193–202.

Cremades, R., Wang, J., Morris, Jd, 2015. Policy supports, economic incentives and the adoption of agricultural water-saving technology in China. Earth Syst. Dyn. 6, 399–410. http://dx.doi.org/10.5194/esd-6-399-2015.

Dinar, A., Saleth, R.M., 2005. Issues in water pricing reforms: from getting correct prices to setting appropriate institutions. In: Folmer, H., Tietenbirg, T. (Eds.), The International Yearbook of Environmental and Resource Economics 2005/2006. Edward Elgar, Cheltenham, UK.

ECSNCCA (Edition Committee of the Second National Climate Change Assessment), 2011. Second National Climate Change Assessment Report. Science Press, Beijing.

Famiglietti, J., 2014. The global groundwater crisis. Nat. Clim. Change 4 (11), 945–948.

Foster, S., Garduno, H., Evans, R., Olson, D., Tian, Y., Zhang, W., Han, Z., 2004. Quaternary aquifer of the north china plain—assessing and achieving groundwater resource sustainability. Hydrogeol. J. 12 (1), 81–93.

Gansu Provincial Government, 2014. Gansu province water-drawing licenses and measures for the management of water resources fee collection. June 21.

GWP (Global Water Partnership), 2015. China's water resources management challenge: The 'three red lines', Technical Focus Paper, ⟨http://www.gwp.org/Global/ToolBox/Publications/Technical%20Focus%20Papers/TFPChina_2015.pdf⟩.

Huang, Q., Wang, J., Li, Y., 2017. Do water saving technologies Save water? Empirical evidence from North China. J. Environ. Econ. Manag. 82 (2017), 1–16. http://dx.doi.org/10.1016/j.jeem.2016.10.003.

IPCC (Intergovernmental Panel on Climate Change), 2014. Working Group II Report "Climate Change 2014: Impacts, Adaptation, and Vulnerability", ⟨http://www.ipcc.ch/report/ar5/wg2/⟩

Liu, C., 1998. Environmental issues and the South–North water transfer scheme. China Q., 899–910.

Liu, C., Jingjie, Y., Kendy, E., 2001. Groundwater exploitation and its impact on the environment in the North China Plain. Water Int. 26 (2), 265–272.

Liu, J., Wu, Y., 2015. Sustain. China Beyond, Sci. 337 (6095), 649–650.

Liu, C., T. Kok-Chiang (guest eds.), 1994. Nanshui Beidiao—The South-to-North Transfer Project. Chinese Environment and Development. Summer 1994. M.E. Sharpe, Armonk, NY

Lu, L., Zou, B., Li, M., Li, Q., He, L., Yan, H., Wang, L., Chen, J., Mi, Y., 2010. Correlation between soil heavy metal pollution and quality of vegetable in representative sewage irrigation farming district. Acta Agric. Jiangxi 22, 152–155.

Lu, Y., Jenkins, A., Ferrier, R.C., Bailey, M., Gordon, I.J., Song, S., Liu, X., 2015. Addressing China's grand challenge of achieving food security while ensuring environmental sustainability. Sci. Adv. 1 (1), e1400039.

Ministry of Finance and Ministry of Water Resources, 2013. Administrative Regulations on Overall Funds of Central Finance for Farmland Water Conservancy Construction Provided from the Land Transfer Income. April 8.

Ministry of Finance, National Development and Reform Commission and Ministry of Water Resources, 2011. Management Measures for the Collection and Use of Fund for Water Conservancy Construction. January 10.

MOE (Ministry of Environment), 2015. Environment Situation Bulletin in 2015, Ministry of Environment in China, Beijing, China.

Moore, S.M., 2015. The development of water markets in china: Progress, peril, and prospects. Water Policy 17, 253–267.

Mu, J., Khan, S., 2009. The effect of climate change on the water and food nexus in China. Food Secur. 1 (4), 413–430.

MWR (Ministry of Water Resources), 2015a. China Water Resources Bulletin, Ministry of Water Resources, Beijing, China(separate bulletin in various years).

MWR (Ministry of Water Resources), 2012. Ministry of Water Resources: Delimiting Groundwater Overdraft Regions in the First Half of 2013, ⟨http://legal.people.com.cn/n/2012/0629/c42510-18410685.html⟩ (accessed on 29 June in 2016).

MWR (Ministry of Water Resources), 2015b. China Water Resources Yearbook, Ministry of Water Resources, Beijing, China.

MWR (Ministry of Water Resources) and Nanjing Water Institute, 2004. Groundwater exploitation and utilization in the early 21st century. China Water Resources and Hydropower Publishing House, Beijing.

National Development and Reform Commission, 2014. Notification of adjusting standard of pollution discharge fee.

NBSC (National Bureau of Statistics in China), 2015. China Statistical Yearbook, China Statistics Press, Beijing, China.

NPC Standing Committee, 2002. Water Law of the People's Republic of China. Available online: ⟨http://www.fdi.gov.cn/1800000121_23_67309_0_7.html⟩ (accessed 27. 05.16). (In Chinese)

Qiu, J., 2010. China faces up to groundwater crisis. Nature 466 (7304), (308–308).

RWRD (Rural Water Resources Department, Ministry of Water Resources) and CIDDC (China Irrigation and Drainage Development Center), 2010. China Water Saving Irrigation, China WaterPower Press, Bejing, China.

Speed, R., 2009. Transferring and trading water rights in the people's republic of China. Water Resour. Dev. 25, 269–281.

State Council, 1982. Regulation on Pollution Fee Discharge, February 5.

State Council, 2006. Management Regulations for Water Withdrawal Permission and Water Resources Fee Collection. February 21.

State Council, 2012. Opinions on the implementation of the strictest water resources management system. January.

State Council, 2016. Suggestions on Promoting Comprehensive Reform of Agricultural Water Price, No. 2 Document of State Council.

Sun,T., Wang, J., Huang, Q., Li, L., 2016. Assessment of Water Rights and Irrigation Pricing Reforms in Heihe River Basin in China, Water, doi: ⟨http://dx.doi.org/10.3390/w8080333⟩ (5 August 2016)

Tso, T.C., 2004. Agriculture of the future. Nature 428 (6979), 215–217.

Wang, J., 2009. Situation and strategies of dry-up of the yellow River. China Water Resour. (4), (Chinese).

Wang, J., 2012. Water management problem in establishing resource saving Society. Bull. Chin. Acad. Sci. 27 (4), 447–454.

Wang, J., Huang, J., Yan, T., 2013. Impacts of climate change on water and agricultural production in ten large river basins in China. J. Integr. Agric. 12 (7), 1267–1278.

Wang, J., Zhang, L., Huang, J., 2016b. How could we realize a win-win strategy on irrigation price reform: evaluation of a pilot reform project in Hebei Province. China, J. Hydrol. 539, 379–391.

[8] The subscript r refers to ten large river basins in China (i.e. Songhuajiang, Liaohe, Haihe, Huaihe, Yellow, Yangtze, Pearl, Southeast, Southwest and Inland river basins); c refers to crop group (i.e. rice, wheat, maize, soybean, sugar crops, edible oil crops, cotton, vegetable and other crops); ir refers to irrigated production, and rf refers to rainfed production; the subscript a refers to the parameter related to land, and the subscript w refers to the parameter related to irrigation water; cc refers to climate change scenarios (we used the average values from 26 cmip5 GCMs under different representative concentration pathways (RCP)); the reference information is indicated with bars. The following are the definitions of the variables in the model: $A_{r,c,ir}$ and $A_{r,x,rf}$: choice variables in this model, representing sown areas of irrigated and rainfed crops by river basin, respectively; $W_{r,c,ir}$: a choice variable in this model, indicating the irrigation water use by crop and by river basin; $P_{r,c}$: the crop commodity price by river basin; $Q_{r,c,ir}$ and $Q_{r,c,rf}$: irrigated and rainfed crop production by crop and river basin, respectively; $C_{r,c,a}$: the observed cost of inputs other than irrigation water, including seeds, fertilizer, pesticide, etc.; $C_{r,c,w}$: the observed cost of the irrigation water used by crop by river basin; $\mu_{r,c,a,ir}$ and $\mu_{r,xc,A,rf}$: the shadow costs of irrigated and rainfed land, respectively; $\mu_{r,c,w}$: the shadow cost of irrigation water; I_{cc}: the available water supply for irrigation by river basin under climate change; $\alpha_{r,c,ir}$ and $\alpha_{r,c,rf}$: the scaling parameters of the production function,$\alpha > 0$; $\beta_{r,c,ir,a}$and $\beta_{r,c,ir,w}$: the share parameters of production function, $(\beta_{r,c,ir,a}, \beta_{r,c,ir,w}) \in [0,1]$ and $\beta_{r,c,ir,a} + \beta_{r,c,ir,w}=1$; $\delta_{r,c,ir}$ and $\delta_{r,c,rf}$: the return-to-scale parameters of irrigated and rain-fed production,$\delta_{r,c} \in (0,1)$; ρ_c: the substitution parameter, $\rho_c \in (-\infty, 0) \cup (0,1)$.

Wang, J., Xu, Z., Huang, J., Rozelle, S., 2006. Incentives to managers and participation of farmers: which matters for water management reform in China? Agric. Econ. 34, 315–330.
Wang, J., Huang, J., Zhang, L., Huang, Q., 2014. Do incentives still matter for the reform of surface irrigation management in the yellow River Basin in China? J. Hydrol. 517, 584–594.
Wang, J., Huang, Q., Huang, J., Rozelle, S., 2016a. Managing Water on China's Farms for a Sustainable Future: institutionsPolicies and the Transformation of Irrigation under Scarcity. Elsevier, London, England.
Wang, J., Huang, J., Rozelle, S., Huang, Q., Zhang, L., 2009. Understanding the water crisis in Northern China: what government and farmers are doing? Int. J. Water Resour. Dev. 25 (1), 141–158, (March 2009).
Wang, J.Z., Xu, J., Huang, Rozelle, S., 2005. Incentives in water management reform: assessing the effect on water use, productivity and poverty in the yellow River Basin. Environ. Dev. Econ. 10, 769–799.
Wang, X.C., Jin, P.K., 2006. Water shortage and needs for wastewater re-use in the north China. Water Sci. Technol. 53 (9), 35–44.
Wu, C., Maurer, C., Wang, Y., Xue, S., Davis, D.L., 1999. Water pollution and human health in China. Environ. Health Perspect. 107 (4), 251–256.
Xie, J., Liebenthal, A., Warford, J.J., Dixon, J.A., Wang, M., Gao, S., Wang, S., Jiang, Y., Ma, Z., 2009. Addressing China's water scarcity: recommendations for selected water resource management issues, the International Bank for Reconstruction and Development. The World Bank, Beijing, China.
Xiong, W., Holman, I., Lin, E., Conway, D., Jiang, J., Xu, Y., Li, Y., 2010. Climate change, water availability and future cereal production in China. Agric., Ecosyst. Environ. 135, 58–69.
Xue, M., Li, H., 2015. Interpretation of the water-drawing Licenses and regulations on the administration of water resources Fee Levy. Shanxi Water Resour. 6, 50–51.
Yan, T., 2015. Optimal Allocation of Agricultural Water Use and Its Impacts on Crop Production under Climate Change Study in Five Large River Basins in Northern China (Phd Thesis). University of Chinese Academy, Beijing, China.
Yang, F., 2010. Infection of the blood: the impacts of water pollution on change of villages. J. Hohai Univ. 12 (2), 37–40.
Zhang, H., Huang, G.H., Wang, D., Zhang, X., 2011. Uncertainty assessment of climate change impacts on the hydrology of small prairie wetlands. J. Hydrol. 396 (1), 94–103.
Zhang, J., Wang, G., 2007. Climate Change Impact on Hydrology and Water Resources Research. Science Press, Beijing, 2007.
Zhang, X., Guo, Q., Shen, X., Yu, S., Qiu, G., 2015. Water quality, agriculture and food safety in China: current situation, trends, interdependencies, and management. J. Integr. Agric. 14 (11), 2365–2379.
Zhao, X., Zhong, H., Huang, C., 2008. Existed problems and counter measures for development and utilization of groundwater in south China. Ground Water 2008 30, 17–18.
Zhou, Y., Ma, J., 2015. What degree of effects of Increasing pollution discharge Fee? China Environ. News 02-05, 009.