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Review

China's water security: Current status, emerging challenges and future prospects

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ABSTRACT

China has been facing increasingly severe water scarcity that seriously threatens the socio-economic development and its sustainability of this country. This paper is intended to analyze and assess the water security of China. It first attempts to characterize the current status of water security within a risk-based, integrated framework that encompasses five key aspects critical to water sustainability, including water availability, water use patterns, wastewater generation and pollution control, water institutions and management, and health of aquatic systems and societal vulnerability. Based on the above assessment, the paper then analyzes emerging challenges for water security brought by climate change, population growth and rapid urbanization, and the water-food-energy nexus. In the end, the paper discusses China's future prospects on water security, including current achievements, government actions and policy initiatives, and recommendations for management improvement aimed at increasing water security.

1. Introduction

With rapid socio-economic development, China has been facing increasingly severe water scarcity (Jiang, 2009). On one hand, China's per capita water availability is low and unevenly distributed, both spatially and temporally, which are inconsistent with the rising socio-economic need for water; on the other hand, inefficient use, wastage, and pollution are common that have been negatively affecting the capacity of water systems to sustain China's socio-economic development. The constraint of water resources on China's future development is of great concern, both domestically and internationally, and is considered a grand challenge that the Chinese government has to address in years to come (NYT, 2007; Jiang, 2009; Schneider et al., 2011; Moore, 2013a).

This paper is intended to examine China's water security. It is motivated by the grand challenge imposed by water resources on China's socio-economic development. What is the current status of China's water security? What are the emerging challenges for achieving water security be China's development path? How will the future prospect for water security in China? These are important questions critical to China's sustainable development requiring policy attention but have not been systematically addressed in the literature.

Assessing water security is largely an empirical matter, with distinct conceptualizations, analytical methods and focuses having emerged from different disciplines over the past decade (Cook and Bakker, 2012). This paper attempts to frame and characterize the water security of China by examining based on literature review two questions: (1) to what extent China is exposed to water-related issues, and (2) at what level the capacity of China's institutional system stands in addressing water related issues and effectively managing water resources. These two questions help shape an integrated framework for assessing water security that is fundamentally rooted in the concepts of risk management, social resilience surrounding sustainable water use, and integrated water resource management.

In this paper, a framework was developed to examine water security from five aspects, including socio-economic assessment of water availability, water use patterns, wastewater generation and pollution control, water institutions and management, and health

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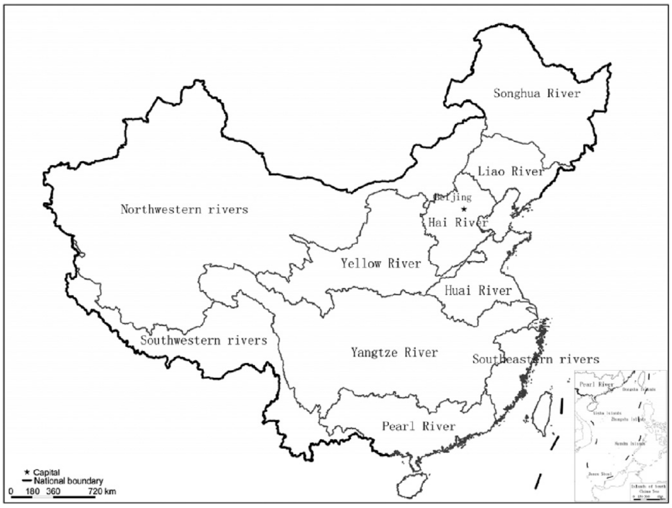


Fig. 1. Spatial distribution of level-I water resource zones in China.
Source: Adopted from Li et al. (2014).

of aquatic systems and societal vulnerability. The socio-economic assessment of water availability considers the biophysical condition of water resources within the social, demographic context, depicting the water-related risk while laying out the foundation and boundary for managing water resources for sustainable use. Within the water availability context, water use patterns and wastewater generation and pollution control look further into how water resources have been used and managed and to what extent the current water use increases China's exposure to difference water risks. Water institutions and management synthesize China's governance and administration of water and existing issues, providing an institutional perspective on China's capacity to address water issues. The dynamic evolution of the health of aquatic systems and societal vulnerability across the country presents an indirect measure partially reflecting the capacity and resilience of China's water institutions to address water-related risks.

Based on the status assessment laid out above, the paper elaborates on emerging challenges for achieving water security in China, including climate change, continuous socio-economic development, population growth and urbanization in particular, and the water-food-energy nexus. How do these three challenges play out affecting China's water security? To what extent do these challenges differentially or uniformly influence water security? The paper is motivated to develop a clear understanding addressing the above questions so as to inform water-related decision-making in China. In the end, the paper concludes with some discussion of current, ongoing government actions and policy initiatives aimed at tackling water issues, shedding some light on the future prospect for the water security of China.

2. Characterizing China's Water Security: the Current Status

2.1. Water availability: mapping water resource capital in the socio-economic context

The total volume of China's internal renewable freshwater resources on average is about 2813 billion m^3 per year (FAO, 2015). Although ranked the fifth in the world behind Brazil, Russia, Canada, and Indonesia (Jiang, 2009), China's water resources endowment is low on a per capita basis. As of 2012, with a total population of approximately 1.36 billion (NBSC, 2014), China's annual water availability on a per capita basis was about 2068 m^3, an amount that was 34% of the world average at 6016 m^3 per capita per year.[1]

China's water resources are spatially distributed, and this distribution unfortunately is inconsistent with local socio-economic needs for water, implying the risk of water shortages and crises in local areas. Geographically, water resources in China can be divided into 10 water resource zones of level I (Fig. 1). The Yangtze River by tradition is the dividing line between North China (or the North) and South China (or the South), with the river itself belonging to the South. Table 1 provides further details by catchment on water availability as compared to local population and the acreage of arable land. It shows that North China accounts for 45% of the country's total population and 65% of the total arable land but has only 19% of the total water resources. Consequently, water availability in North China is about 904 m^3 per capita per year, which is in sharp contrast to the level of 3280 m^3 per capita per year in South China. The situation is even worse at the catchment level. In the Hai River basin, for instance, water availability is only 314 m^3 per capita per year, which is even below the threshold level of 500 m^3 per capita per year that is commonly considered signaling absolute water scarcity (UN, 2014a).

China's spatially distributed water resources are subject to precipitation and its seasonal cycle, which further exacerbate the scarcity issue. In China, precipitation is the main driver for water resource availability and reliability (Lu et al., 2013). Dominated by strong monsoon climate, precipitation is characteristic of both intra- and inter-year variations. In most areas, four consecutive months can account for up to 70% of annual rainfall (MWR, 2007). The spatial-temporal feature of water resources represents a serious challenge for water management to maintain a reliable, sufficient supply to meet an increasing demand from socio-economic development, particularly in North China where water availability is already low across catchments.

2.2. Water use patterns

With limited water availability across space and time, how to effectively and efficiently use water at minimum risk of shortages becomes critically important. China's water use pattern, however, intensifies water scarcity, with increased exposure to the risk of severe water shortages, particularly in North China. At the national level, China's total water consumption has been steadily increasing, of which agriculture remains the biggest water user among sectors. As demonstrated by Fig. 2, China's total water consumption increased from 550 billion m^3 in 2000 to 614 billion m^3 in 2012, an average growth rate of 0.97% per year. Of the total water use, agriculture accounted for 61–69%, with industry 21–24%, domestic use 10–13%, and environment 1–2%. Moreover, agricultural water use steadily increased to 388 billion m^3 in 2012, despite its decrease from 378 billion m^3 in 2000 to 343 billion m^3 in 2003.

To examine water use within its socio-economic context, Table 2 compares the growth rates of total water consumption, gross domestic product (GDP), and population over the period 2000–2012 in China. While total water consumption seemed not to grow as fast as GDP, it outpaced population that increased by about 0.6% per year. As a result, per capita water consumption also increased from 435.4 m^3 in 2000 to 454.7 m^3 in 2012.[2] This is certainly of concern, given China's existing water scarcity and

[1] The world per capita freshwater resources was calculated based on the global total population of 7.04 billion in year 2012 and the world total freshwater resources of 42,370 billion m^3 in 2011, both of which were from the database of the World Bank (http://data.worldbank.org/indicator).

[2] Per capita water uses in different years were calculated based on national total water use and population.

Table 1
Spatial distributions of water resources, population, and arable land by water resource zones in China.

Region	Annual renewable water resources, billion m^3 (%)			Population[c], million (%)	Arable land, million ha (%)	Per capita water resources, m^3	Per hectare water resources, m^3
	Surface water	Groundwater	Total[b]				
North	450.7 (16.6)	255.1 (30.8)	535.8 (19.1)	592.4 (45.2)	71.8 (65.3)	904.1	7462.4
Song-Liao	165.3 (6.1)	62.5 (7.5)	192.8 (6.9)	119.6 (9.1)	22.2 (20.2)	1612.1	8684.7
Hai-Luan	28.8 (1.1)	26.5 (3.2)	42.1 (1.5)	133.9 (10.2)	12.4 (11.3)	314.4	3395.2
Huai	74.1 (2.7)	39.3 (4.7)	96.1 (3.4)	198.8 (15.2)	16.7 (15.2)	483.4	5754.5
Huang	66.1 (2.4)	40.6 (4.9)	74.4 (2.6)	110.6 (8.4)	14.2 (12.9)	672.4	5239.4
Northwest	116.4 (4.3)	86.2 (10.4)	130.4 (4.6)	29.5 (2.3)	6.3 (5.7)	4417.2	20,698.4
South	2260.8 (83.4)	591.7 (69.3)	2276.6 (80.9)	694.7 (53.0)	38.2 (34.7)	3279.6	59,596.9
Yangtze	951.3 (35.1)	246.4 (29.7)	961.3 (34.2)	428.3 (32.7)	26.1 (23.7)	2244.7	36,831.4
Pearl	468.5 (17.3)	111.6 (13.5)	470.8 (16.7)	171.0 (13.0)	7.4 (6.7)	2753.3	63,621.6
Southeastern	255.7 (9.4)	61.3 (7.4)	259.2 (9.2)	74.5 (5.7)	2.7 (2.5)	3481.3	96,000.0
Southwestern	585.3 (21.6)	154.4 (18.6)	585.3 (20.8)	20.9 (1.6)	2.0 (1.8)	28,064.7	292,650.0
National	2711.5 (100)	828.8 (100)	2812.4 (100)	1311.1 (100)	110.0 (100)	2145.1	25,567.3

[a] Water resources data adapted from UNESCAP (1997); population data derived from MWR (2007); arable land data adapted from FAO (2015).
[b] The sum of water resources from surface and aquifer may exceed the total water resources by the amount of overlap between them, since surface water interacts with groundwater with the river base flow formed by groundwater and part of groundwater recharge coming from percolation of surface water.
[c] The derived population data for watersheds may not sum up to the total population due to estimation error.

continuous population growth. Moreover, while the increase of total water consumption came from all sectors, domestic use grew faster than population and total water use, which may be attributed to urbanization with changing living style and water use. The water use pattern implies further competition among sectors for water with limited quantity.

As China's water scarcity is characteristic of spatial heterogeneity, the spatial scale of water use patterns does matter to water security. Sharing some similarity with its national counterpart, water consumption at the regional level also shows spatial heterogeneity, with increased water insecurity in local areas. Fig. 3 compares water use patterns in the period 2002–2012 between North and South China. In the North, although the region is particularly subject to water scarcity, agriculture still remained the biggest water user, with a share ranging between 74% and 78%, even higher than its counterpart either at the national level or in the water abundant South. Furthermore, agricultural water use in the North has been increasing, which is in contrast with the staggering agricultural water use in South China (also see Appendix I for the growth rate of water use by sector and region). As a matter of fact, the share of agricultural water use among all uses in South China has been decreasing. Management of agricultural water use in North China is necessary to achieving water security.

China's water use patterns increasingly strain the natural system of water resources, threatening water security. Over the period 2004–2012, China obtained about 82% of its water supply from surface water and 18% from groundwater, which implies a resource use rate of 16–22% for surface water, 13–15% for groundwater, or 19–26% for available water resources overall (see Appendix II). While the exploitation rate of water resources at the national level does not seem to be high, it can be much higher at the regional and local levels. In North China, over the period 2007–2012, the total water supply was 63–64% from surface water and 36–37% from groundwater, indicating a resource use rate of 31–45% for surface water and 33–40% for groundwater, and overall accounted for 41–57% of all water resources (see Appendix II). In the Hai river basin, as demonstrated by Table 3, groundwater was heavily used, contributing 65–67% of the total water supply, with the remaining 33–35% from surface water, and the total water supply represented a resource use rate of 54–140% for surface water, 80–133% for groundwater, and 82–176% overall. The water use combined with the low water availability suggests a high pressure on the water system in local areas, particularly for catchments in North China.

This unsustainable, insecure water use pattern as characterized above highlights the importance of integrated water resource management (IWRM) and government failure to implement IWRM in development planning and management in the past. With limited water resources, the spatial and temporal characteristics of water availability require sufficient attention and being accounted for in socio-economic development. In the water scarce North, policies or development scenarios should be carefully examined with explicit consideration of water use consequences in relation to water availability. Development involving intensive water use of low use value should be avoided or limited. Yet, the history of water use patterns as demonstrated above clearly shows that this was not the case in the past. Agriculture remained the biggest water use in the North, with a share higher than the national average, despite low water use value and local water scarcity, and has been expanding. The exploration rates of water resources, groundwater in particular, remained high, with no sign of reduced withdrawal. Changing water use patterns and promoting effective implementation of IWRM represent an important strategy for improving China's water security.

2.3. Wastewater generation and pollution management

Wastewater discharge can further threaten water security by polluting limited available freshwater. As demonstrated by Fig. 4, China wastewater discharge has been steadily increasing since 1990, particularly after1998. As of 2012, the total amount of wastewater discharge reached nearly 70 billion m^3. The increase has largely been driven by a rising discharge from domestic source, with its share increasing from around 30% in 1990 to 68% in 2012. Wastewater discharge from industry fluctuated across years and has been decreasing in recent years, with its share in the total wastewater discharge also decreasing.

The discharge of chemical oxygen demand (COD) gradually decreased until 2010, and drastically increased again due to change in the method for pollution calculation that was extended starting from 2011 to include discharge from agriculture. While industrial discharge has been decreasing, the discharge from the domestic source has been increasing. Among sectors, agriculture appears to be the biggest contributor to the total COD discharge, domestic the second, and industry accounting for the lowest share.

Despite increasing wastewater discharge, the development of treatment infrastructure has been relatively slow. While much progress has been made in increasing the capacity of wastewater treatment, China is lagged behind in constructing supporting pipeline networks to deliver wastewater to treatment facilities (SC, 2012a). Over the period 1995–2008, the total capacity of wastewater treatment facilities increased by almost 10 folds, but

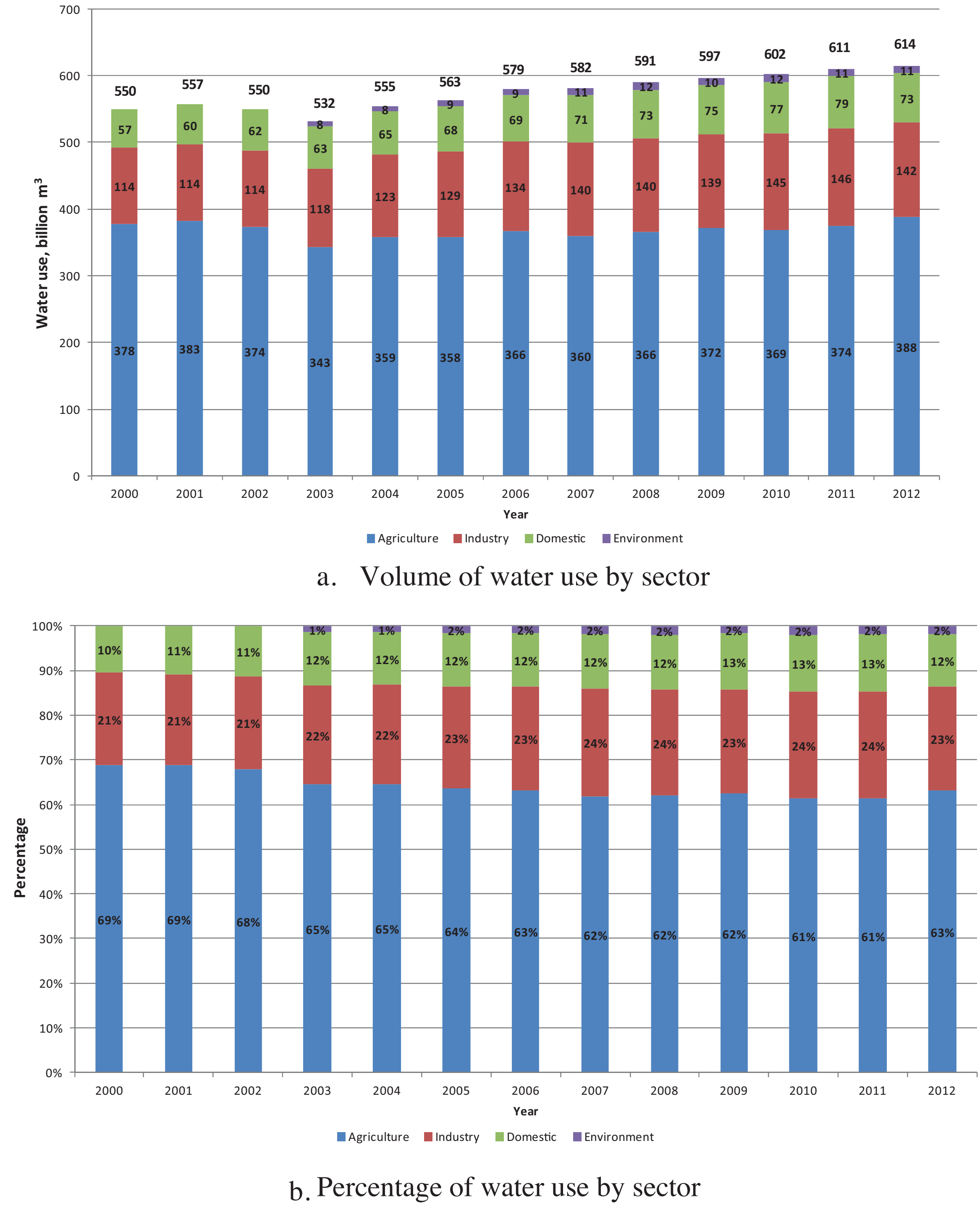


Fig. 2. National water use over the period 2000–2012 in China.
Data source: NBSC (2014).

the proportion of wastewater actually treated only increased by nearly 20–66% (MEP, 2009). In urban areas, wastewater treatment facilities often operate below capacity, do not operate at all, or are not well functioning with return flow meeting safe discharge standards (Zheng, 2012; Jin et al., 2014). In rural areas, only 1% of established villages and towns (about 25,000) have been equipped with wastewater treatment facilities, in contrast to the wastewater treatment penetration of nearly 82% in urban areas according to a report by Standard Chartered in 2014. As a result, a large amount of pollutants has been discharged into the environment, degrading the quality of receiving water bodies and aquatic ecosystems. This may partially explain why no evidence has been found that pollution treatment has improved the performance of regional pollution control although it has improved steadily (Wei et al., 2012). The main challenges for wastewater management include enforcement of pollution treatment, increasing treatment facilities and coverage in rural areas, and improving the removal efficiency of nutrients and emerging contaminants and sludge disposal.

In recent years, the focus of water pollution control has shifted to also cover agricultural runoff. Since 2011, agriculture has been

Table 2
Annual growth rates of GDP, population, and water consumption over the period 2000–2012 in China.

Year	GDP (%)	Population (%)	Water use				
			Total (%)	Agriculture (%)	Industry (%)	Domestic (%)	Environment (%)
2001	10.3	0.7	1.3	1.1	0.2	4.3	
2002	10.2	0.7	−1.3	−2.3	0.0	3.1	
2003	13.3	0.6	−3.2	−8.1	3.0	2.0	
2004	18.1	0.6	4.3	4.5	4.4	3.2	3.2
2005	15.2	0.6	1.5	−0.2	4.6	3.7	13.0
2006	17.6	0.5	2.9	2.4	4.6	2.8	0.3
2007	23.4	0.5	0.4	−1.8	4.4	2.4	13.7
2008	18.6	0.5	1.6	1.8	−0.4	2.7	13.6
2009	7.7	0.5	0.9	1.6	−0.4	2.6	−14.3
2010	17.5	0.5	1.0	−0.9	4.1	2.4	16.3
2011	17.2	0.5	1.4	1.5	1.0	3.1	−6.6
2012	10.2	0.5	0.6	3.7	−2.6	−7.7	−2.8
Average	14.9	0.6	0.9	0.3	1.9	2.0	4.1

Data source: NBSC (2014).

included, in addition to domestic and industrial sources, in government annual reporting of pollution. As illustrated by Fig. 4, agriculture contributes a major portion to the total discharge of COD. This is not surprising, given the excessive use of chemicals and fertilizer and the large scale of agricultural production (Lu et al., 2015). Regulating pollution from agricultural runoff, however, represents a realistic challenge, due to its diffusive, widespread, and non-point nature and the inevitable tradeoff between pursing food security by intensifying agricultural production and improving water quality by reducing chemical inputs or even retiring land from production. In addition, water pollution from small rural industries is also significant, requiring serious attention. Given that factors underpinning the economic success of rural industry are precisely the same factors causing serious water pollution, the control of rural water pollution is not simply a technical problem of designing a more appropriate governance system or finding better policy instruments or more funding, but lies in changes in the model underpinning rural development in China (Wang et al., 2008).

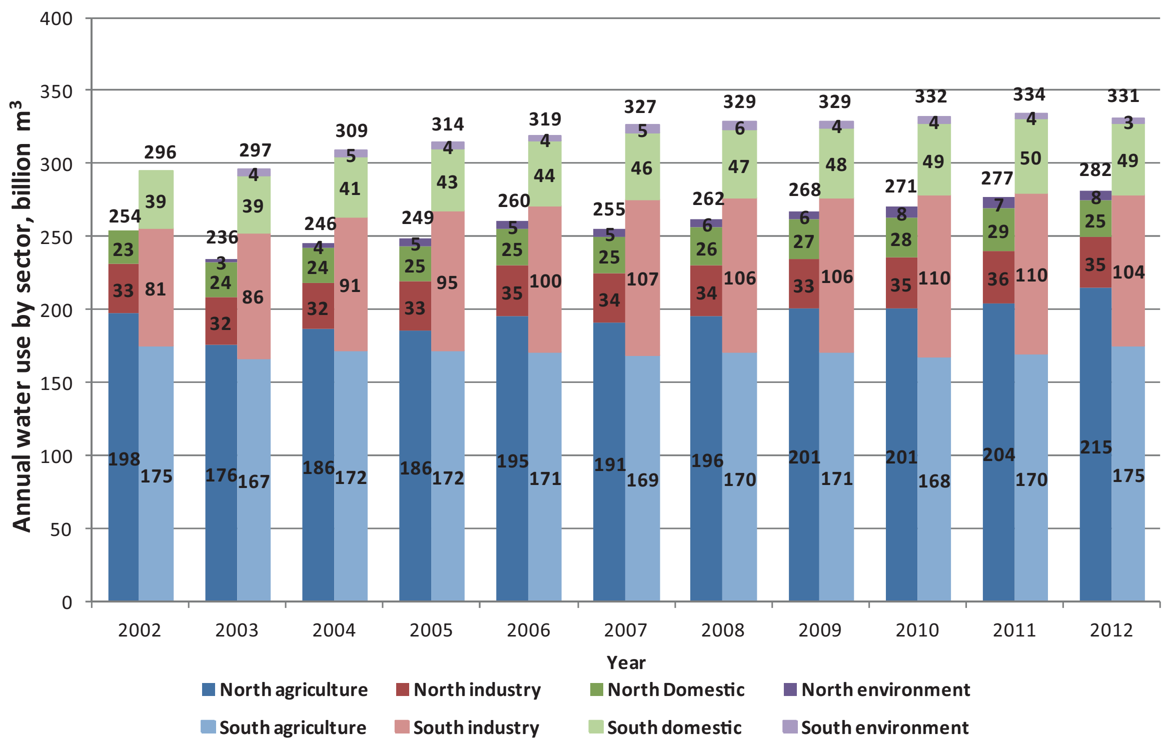
2.4. Water institutions and management

China's legal institution for water is a combination of laws, regulations and rules established by legislative and administrative entities of government at different levels (Fig. 5). At the national level, People's Congress as the legislative branch formulates national laws that address different aspects of water, including Water Law, Law on Prevention and Control of Water Pollution, and Flood Control Law. Within the framework of the national laws, the State Council as the administrative branch of the Chinese government issues regulations guiding water management by different administrative departments at the national level and by different branches of the government at the provincial level. National laws and rules set the general principles, and local governments determine how the laws and rules are implemented (Wouters et al., 2004)

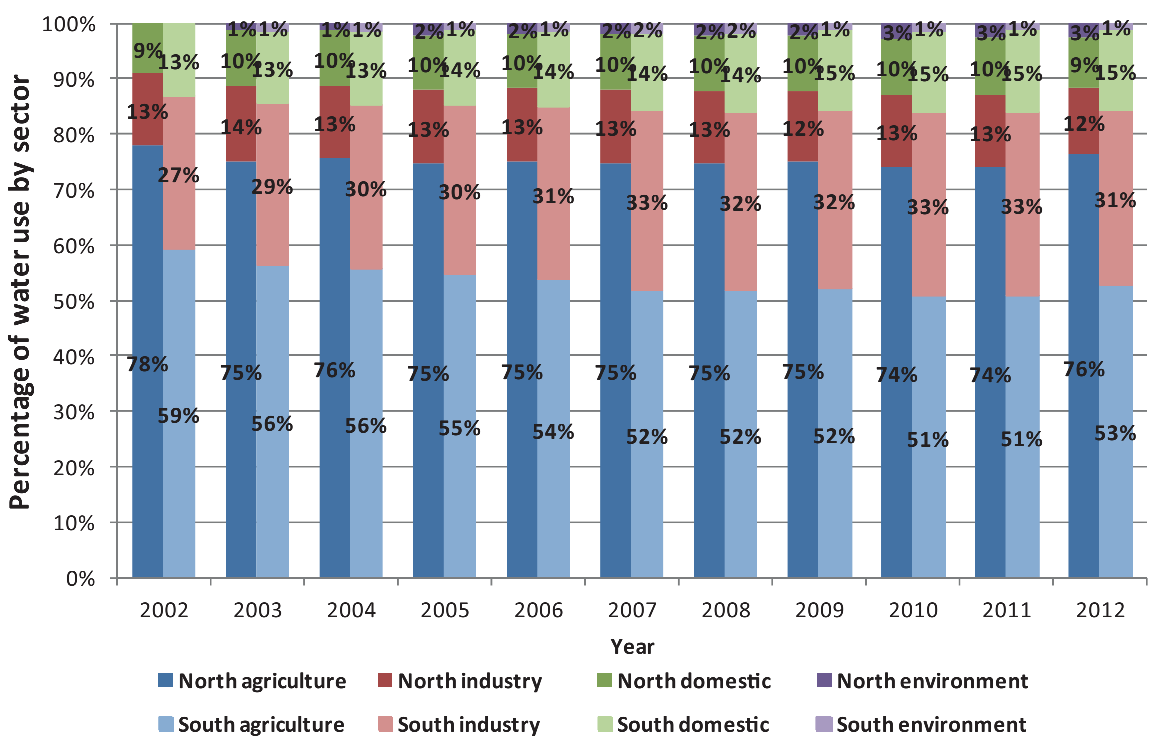
China's water institutions are complete yet complicated and fragmented, challenging effective management of water resources. The 2002 Water Law, as amendment to the 1988 Water Law, provides a comprehensive framework for water resource management, with provisions encompassing: (1) water allocation, water abstraction and use rights, (2) river basin management, (3) water use efficiency and conservation, and (4) pollution prevention and resource protection (Cheng and Hu, 2012; Liu and Speed, 2009). While covering all important aspects of water management, the Law depends much on government administration for implementation. An effective management of water as outlined by the Water Law requires not only well functioning government agencies but also their coordination, with a clear layout of individual responsibilities. This requirement certainly is a challenge for the Chinese political system of government administration that is characterized by a hierarchical structure involving different branches of government at different administrative levels (Fig. 6). On one hand, malfunction, lack of enforcement or insufficient capacity in the administrative chain of water management can lead to ineffectiveness or failure of the whole system; and on the other hand, there is no dedicated department or office across the system facilitating and supporting communication and coordination among involved institutions. The management of water is further complicated by and vulnerable to the political structure that local water bureaus or departments under the leadership of the central authorities also depend politically and financially on local governments (Cheng and Hu, 2012), whose main interest is economic development. Such a complex, internally interdependent but poorly coordinated institution, in combination with the bureaucratic processes, is a significant barrier inhibiting effective water management and pollution control (Liu and Speed, 2009; Winalski, 2009; Hu and Cheng, 2013). Unsurprisingly, ineffective water management or failure has arisen in the past, which can fundamentally be attributed to the complexity, interdependency, fragmentation, and flaws of China's water institutions and insufficient administrative capacity to address the huge water challenge of development.

The Chinese government has been taking actions to reform water management and reorganize water institutions (Xie et al., 2009). Nonetheless, the current institutional system of water management still involves multiple government agencies at different levels. Table 4 lists government agencies currently involved in water management, characteristic of overlapping functions and lack of coordination. For example, both the Ministry of Water Resources (MWR) and the Ministry of Environment Protection (MEP) have responsibilities cutting across water pollution control and transboundary water resource management, but there is no mechanism to effectively coordinate the administration of the involved responsibilities (Feng et al., 2006; Jiang, 2009). The Ministry of Housing and Urban–Rural Development (MHURD) is responsible for urban water supply and sewage treatment but water pollution control is mainly charged by MEP. The fragmented while overlapping water administration impedes effective water management while significantly increasing inefficiency and transaction cost (Jiang, 2009). Water quality management is another good example highlighting the importance of coordinated efforts and the risk of management failure (Jiang, 2009).

China's water resource management is dominated by engineering projects (Liu et al., 2013), a technology- or structure-oriented mindset with weak capacity in governance supported by



a. Volumes of water uses by sector



b. Percentages of water uses by sector

Fig. 3. Water use over the period 2002–2012 in North and South China.
Data source: MWR (2000-2014).

solid policy analysis and participatory and informed decision-making. Wherever a water issue arises, the government is inclined to engineering or technological solutions, without rigorous analysis and comparison of different strategies and integrated impact assessment of policy interventions. It is common that many water policies have not been critically evaluated and justified by an integrated biophysical, socio-economic analysis. Lack of scientific, integrated assessment with reliable data, China's water

Table 3
Available water resources and supply over the period 2007–2012 in the Hai river basin, China.

Year	Indicators	Surface water	Groundwater	Total
2007	Water resource, billion m^3, (%)	10 (41%)	21 (85%)	25 (100%)
	Water supply, billion m^3, (%)	13 (34%)	25 (66%)	38 (100%)
	Water resource use rate	126%	118%	153%
2008	Water resource, billion m^3, (%)	13 (43%)	24 (82%)	30 (100%)
	Water supply, billion m^3, (%)	12 (34%)	24 (66%)	36 (100%)
	Water resource use rate	97%	100%	123%
2009	Water resource, billion m^3, (%)	12 (41%)	23 (81%)	29 (100%)
	Water supply, billion m^3, (%)	13 (35%)	24 (65%)	36 (100%)
	Water resource use rate	109%	102%	127%
2010	Water resource, billion m^3, (%)	15 (49%)	22 (73%)	31 (100%)
	Water supply, billion m^3, (%)	12 (34%)	24 (66%)	36 (100%)
	Water resource use rate	83%	105%	117%
2011	Water resource, billion m^3, (%)	14 (46%)	24 (80%)	30 (100%)
	Water supply, billion m^3, (%)	12 (34%)	23 (66%)	36 (100%)
	Water resource use rate	90%	99%	120%
2012	Water resource, billion m^3, (%)	246 (54%)	29 (66%)	44 (100%)
	Water supply, billion m^3, (%)	13 (35%)	23 (65%)	36 (100%)
	Water resource use rate	54%	80%	82%

Data source: MWR (2000-2014).

management runs the risk of ineffectiveness, poor outcomes, or unintended policy consequences, which have turned out to be the case in many areas (Liu and Yang, 2012).

Relying on engineering projects for supply augmentation to meet water demand is a guiding principle characterizing China's water management, with less attention paid to demand management. This characteristic can be well illustrated by the supply-oriented indicators (e.g., acreage of newly increased irrigation) listed in government documents that report socio-economic development or resource management. For water resources, the supply-driven management is problematic as it ignores the economic nature of water being a common-pool resource and the potential conflict between locally limited water availability and the demand for water that can dramatically increase with much wastage or inefficient use. Pursuing supply augmentation without considering the constraint of resource availability has allowed for inefficiency in areas such as regional and urban planning, which has eventually led to increasing water insecurity limiting sustainable development.

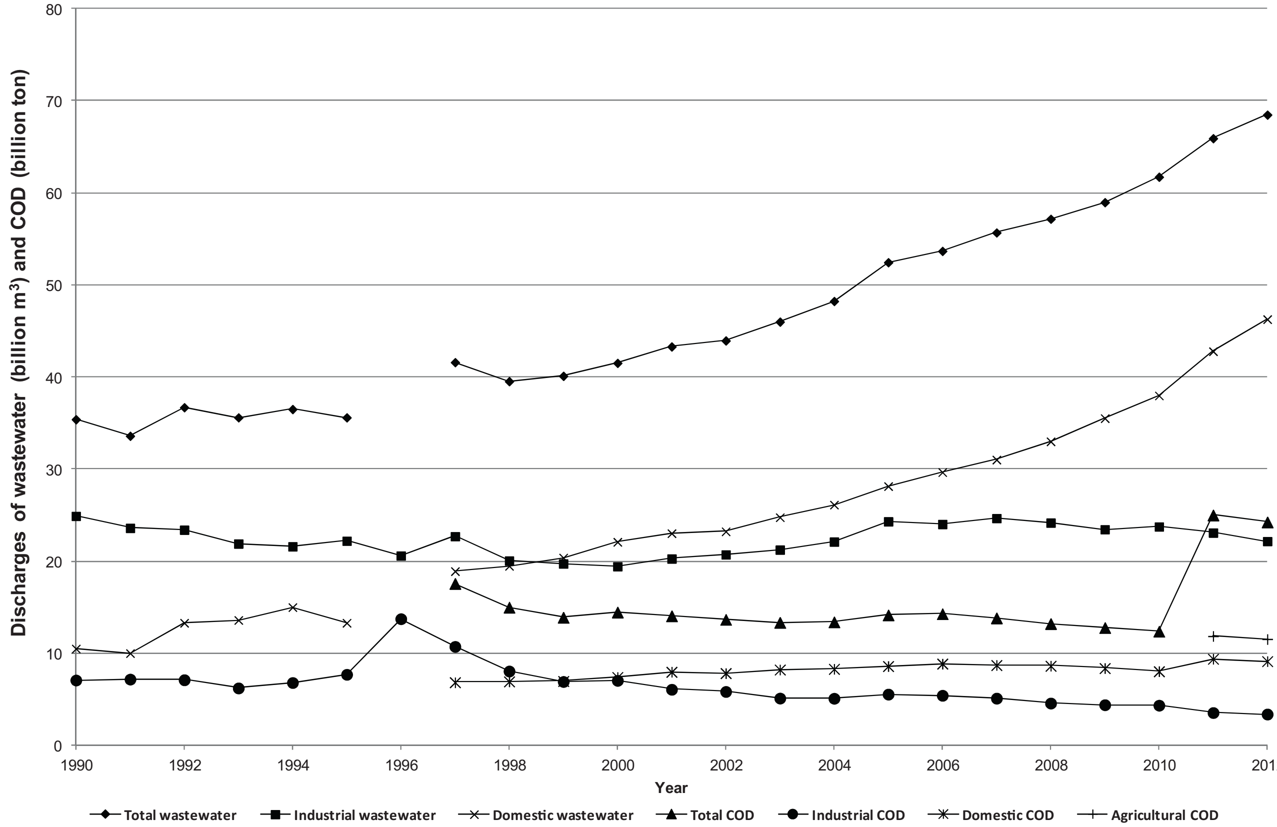
Since 2005, the Chinese government has started reforming its water management, promoting improvement of use efficiency and water saving. While this reform represents the right direction, the effectiveness of the strategy depends much on implementation including the approach, compliance, and policy enforcement. For example, water markets and trading have been proposed to improve water use efficiency, yet the actual management still depends largely on administrative command and control. Insufficient market institutions and policies have been identified as one barrier to water trading (Zhang, 2007). Pilot projects show that farmers did respond to incentives, implying that much of the inefficiency in water use may be attributed to the current management and policy failure to consider farmers' interests and incentives (Jiang, 2009).

China's water charge system is underdeveloped that is inadequate for managing water use and providing sufficient incentive for water saving and enhancing use efficiency. In theory, water use charge should be based on the volume of actual water use, with the price of water covering the full cost of per unit water supply, and thus guides water use in balance with supply by reflecting its full cost. Yet China's water prices are determined through a political top-down administration and are purposely set low, hardly covering the full cost of water supply. The current household expenditure for municipal water supply only accounts for about 1.2% of household disposable income, lower than the 2% level that would stimulate water saving and much lower than the 4% in developed countries (Zhang et al., 2007). Irrigation charges in many rural areas are not only insufficient to cover the full cost but also still tied to the acres irrigated rather than the actual amount of water used (Yang et al., 2003; Lohmar et al., 2007; MWR, 2014). As a result, maintenance of water supply infrastructure is poor with much leakage, and water users lack incentive to save water and improve use efficiency, all of which contribute to water use inefficiency in China (Webber et al., 2008; Jiang, 2009; Cheng and Hu, 2012).

In recent years, progress has been made in reforming water prices. Nonetheless, raising water prices appears to be a slow process because of concerns over water rights and equity issues as well as poor water utility operation and management (Jiang et al., 2011). The user charges for urban water supply and wastewater treatment still do not fully cover all operating and capital costs. Implementation of water use charge is also subject to problems such as unclear responsibilities, low collection rates, and poor institutional capacities, requiring more attention to the institutional aspect of pricing policy (Zhong and Mol, 2010).

2.5. Health of aquatic systems and societal vulnerability

The health status of aquatic systems such as rivers and wetlands has been dynamically evolving over the past decades, with significant ecological and social consequences. Because of extensive use of limited water resources, groundwater overexploitation has not only occurred but also intensified, with significant environmental, geological consequences (Wang et al., 2007a; Fang et al., 2010; Li, 2010; Zheng et al., 2010). Groundwater levels have declined throughout northern China in the last three to four decades, particularly in deep aquifers (Currell et al., 2012; Shi et al., 2011). Recent field investigation and monitoring indicated groundwater depletion in NCP, including: (1) the maximum depth to water in the shallow aquifer has exceeded 65 m, and the area where the water table is 10 m or deeper beneath the land surface has occupied more than 40% of the entire plain; and (2) the maximum depth to water in the deep aquifer has reached 110 m, and the area where the hydraulic head is lower than the sea level has accounted for more than 50% of the entire plain (Zheng et al., 2010).



a. Annual discharges of wastewater and COD by sector

b. Shares of wastewater and COD discharges by sector

Fig. 4. Annual discharges of wastewater and COD over the period 1990–2012 in China
Data source: MEP (1990-2013).

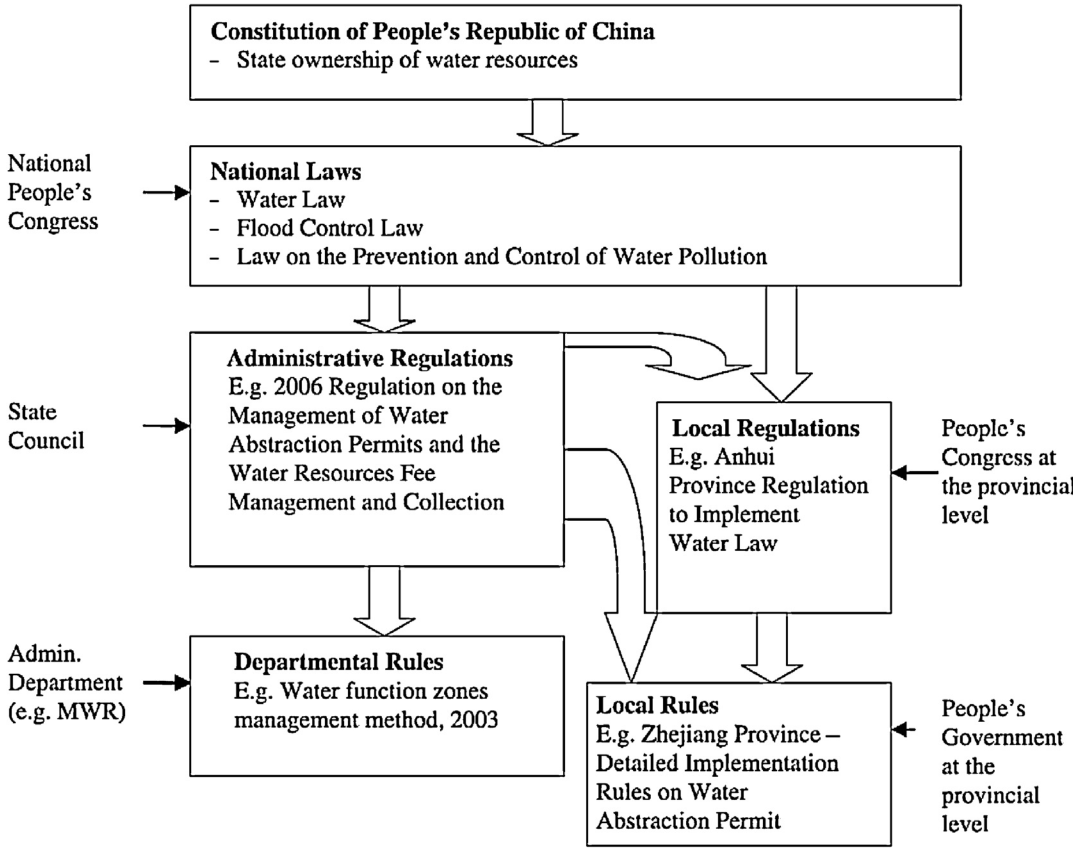


Fig. 5. Institutional framework for water management in China.
Adopted from Liu and Speed (2009).

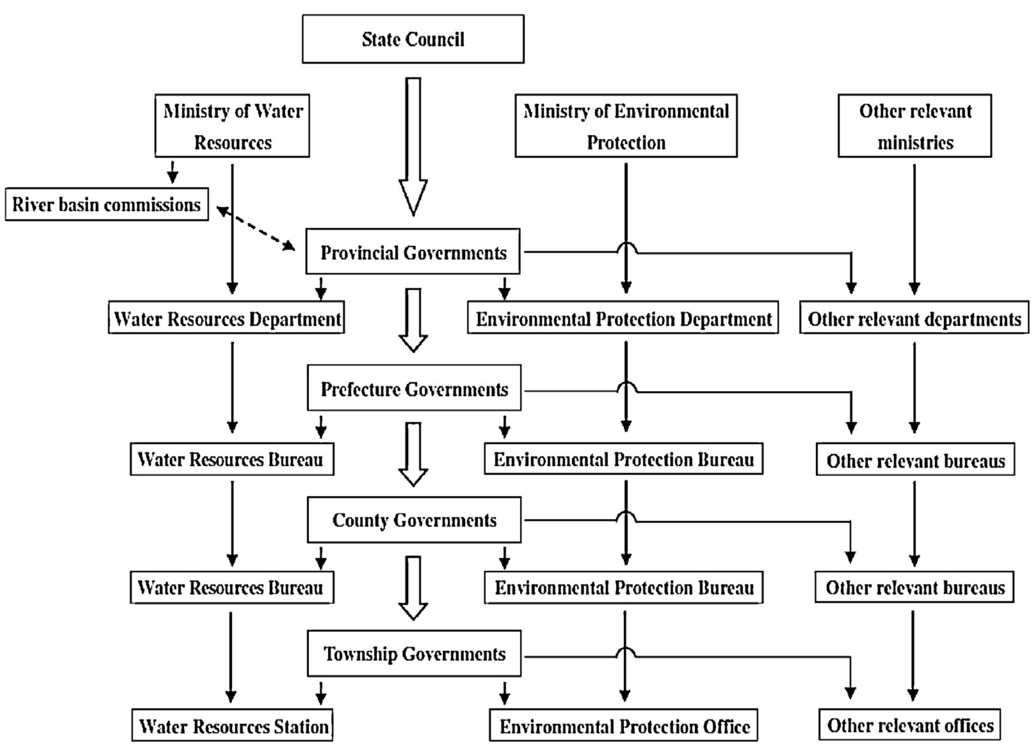


Fig. 6. China's institutional system for water management.
Adopted from Khan and Liu (2008).

Table 4
Water administration agencies under the State Council and functions in China.

Department	Water-related administration responsibilities	Major administrative functions
Ministry of Water Resources	Surface and ground water management, river basin management, flood control, water and soil conservation	The planning of water development and conservation, flood control, water and soil conservation, designation of water function zones, unified water administration
Ministry of Environmental Protection	Prevention and treatment of water pollution	Protection of water environment, water environment zoning, establishment of national water environmental quality standards and national pollutant discharge standards
Ministry of Housing and Urban–Rural Development	Urban and industrial water use, urban water supply and drainage	Planning, construction and management of water supply projects and drainage and sewage disposal projects
Ministry of Agriculture	Water uses for agriculture (irrigation), fishery aquatic environment protection	Non-point source pollution control, protection of fishery water environment and aquatic environmental conservation
State Forestry Administration	Water resources conservation	Forest protection and management for conservation of watershed ecology and water resources
State Electric Power Corporation	Hydro-power development	Construction and management of large and mid-scale hydro-power projects
National Reform and Development Commission	Participation in the planning of water resource development and ecosystem development	Planning of water resource development, allocation of production forces and ecological environmental development, coordinating the planning and policy of agriculture, forest and water resources, and development
Ministry of Transport	Pollution control related to navigation of ships on rivers	Pollution control and management of inland navigation
Ministry of Health	Supervision and management of environmental health	Supervision and management of drinking water standards

Adopted with modification from Feng et al. (2006).

The water quality of major river systems evolves temporally and spatially, with river basins in the North suffering severe degradation.[3] As demonstrated by Fig. 7, rivers in the South overall have a better quality than those in the North, which may be attributed to the abundance of water resources in the South. Indeed, only a small portion (or less than 30%) of the water bodies in the South was of poor quality across years. In contrast, most water bodies in the North had poor quality, although they have been improving in recent years. Among the rivers in North China, the Hai River is the most polluted. In 1991, 91% of the Hai river was polluted and highly polluted, which improved over the period 1991–1996 but worsened again from 1996 to 2002. After 2002, the Hai river slowly improved but still had 61% of monitored water bodies in poor quality as of 2012. The high pollution extent for Hai is consistent with the heavy use of locally scarce water resources that have low resilience to absorb and mitigate pollution, where scarcity and pollution interact and reinforce each other.

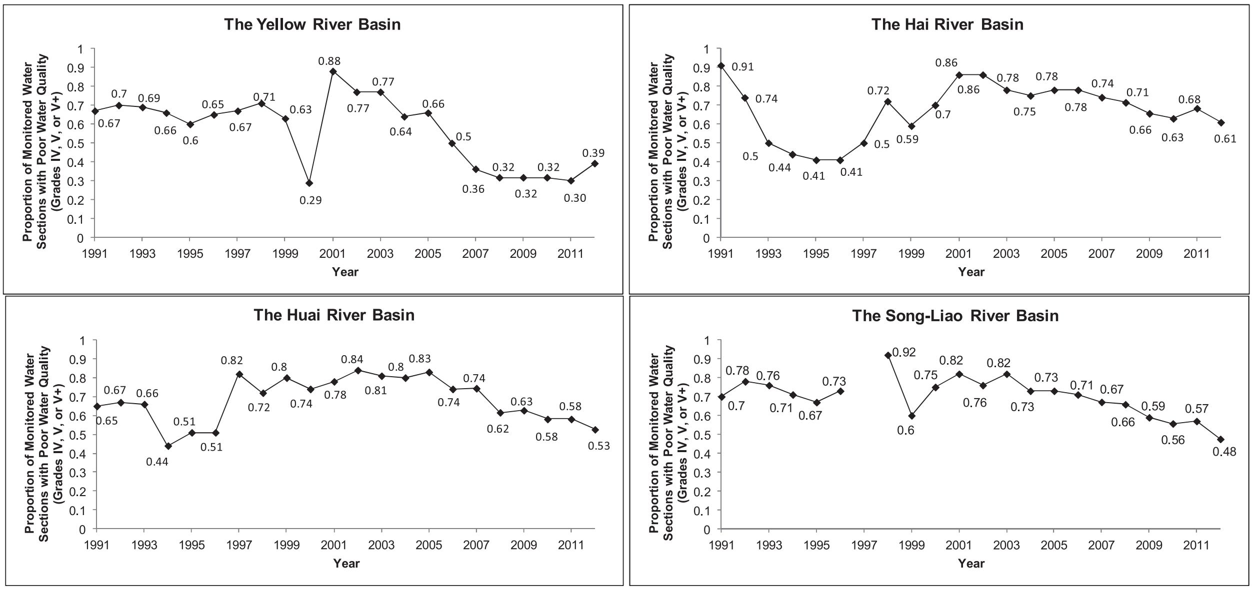
China's aquatic ecosystems such as wetlands and estuaries have been degrading with increased loss of biodiversity (An et al., 2007; Sun et al., 2015). In the central part of the Yangtze river, lakes and wetlands have decreased substantially in size and number; biodiversity loss has been observed among aquatic plants, fish, and waterfowl at community, population, and species levels; the species richness of aquatic plants in eight major lakes has decreased substantially; community composition has also been greatly altered (Fang et al., 2006a,b). In the coastal region, the trophic diversity and the body size of saltwater fish have both steadily decreased; harmful algal blooms have become more frequent and extensive; the coverage of coral reefs in the South China Sea has shrunk; the areas of marshes, mangroves, and tidal flats have decreased (He et al., 2014a). Wetlands near cities have been degrading, particularly in the middle and lower reaches of the Yangtze river and in the more industrialized eastern provinces of China (Fang et al., 2006a,b; Li. et al., 2006; Sun et al., 2015).

Supply of safe drinking water is increasingly threatened by the contamination and degradation of water systems. Interrupted drinking water supply due to pollution or poor water quality has occurred. For instance, in 2007, algal blooms due to non-point source pollution in Lake Tai interrupted drinking water supply in the city Wuxi, which affected two million residents for several days (Qin et al., 2010; Zhang et al., 2010a). Meanwhile, supply of drinking water also suffers quality deterioration. Leung et al. (2013) detected 17 out of 32 monitored pharmaceuticals in 89% of collected tap water samples from 13 cities in China, with cities in the Yangtze river basin and Guangzhou being contamination hot spots. Nearly half of more than 7000 water samples drawn from a variety of rural supplies were unsafe for drinking, many contaminated with untreated sewage (Zhang et al., 2010b). Fully 90% of China's wells and other shallow groundwater – an important source of drinking water for roughly 70% of Chinese – were polluted by chemicals such as heavy metals and organic solvents, and an alarming 37% were so foul that they could not be treated for use as drinking water (Qiu, 2011).

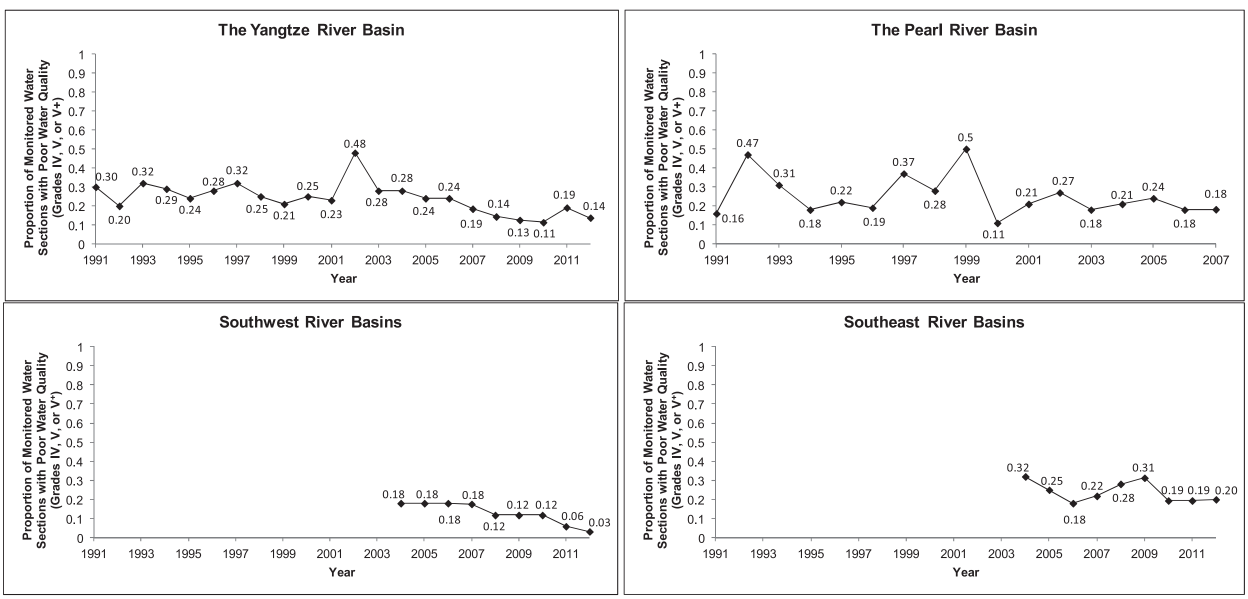
Water contamination increasingly threatens public health. Recent epidemiological studies suggest that drinking water contaminants like nitrate/nitrite and chromium are a major risk factor for digestive system cancers (i.e., stomach cancer, liver cancer, esophageal cancer, and colorectal cancer), and can increase the morbidity and mortality of cancers (Zhang et al., 2010b, 2014; Zhao et al., 2014). Concurrent with the declining water quality of rivers and lakes, incidents of digestive cancers have been increasing in rural areas (Ebenstein, 2012), and more than 400 cancer villages was found in China in a national survey (Gao, 2013). Cancer villages tend to cluster along major rivers and tributaries, especially in rural areas (Watts, 2008; Gong and Zhang, 2013; Lu et al., 2015), and are mainly located in the basins of the Hai river, the mid-lower reach of the Yellow river, the Huai river, the mid-lower reach of the Yangtze river, and the Pearl river delta, where many industrial parks can be found and where population density is also high (He et al., 2014b; Lu et al., 2015).

Cancer mortality has exhibited high correlation with water quality level (Ebenstein, 2012; Hendryx et al., 2012; Gao, 2013; Massaquoi et al., 2014; Zhang et al., 2014). In the Huai river basin, one of the major basins with dense population and intensive water network suffering from long-term serious water pollution, the mortality of digestive cancer in rural villages appears to be spatially remarkably associated with water pollution (Wan et al., 2011; Ren et al., 2015). Ebenstein (2012) found that a one-grade

[3] In China, water quality standards are determined by the function of water bodies/zones for their intended use such as drinking water or habitat for wildlife. Currently, the standards of water quality are classified into 5 grades that can be approximately described as "good" (grades I, II, and III) or "poor" (grades IV, V and V+, which in general cannot support drinking and direct human contact).



a. River basins in North China



b. Rivers basins in South China

Fig. 7. Trends of proportions of monitored water sections with poor water quality for major river basins in North and South China.
Data source: MEP (1990-2013).

decline in water quality increased the mortality of digestive cancers by 9.7% in China. Every year, an estimated 190 million Chinese fall ill and 60,000 die because of water pollution (Qiu, 2011).

3. Emerging challenges

3.1. Climate change

Climate change is one major challenge of increasing concern to water security in China (NDRC, 2007; Piao et al., 2010). A large number of studies have recently been devoted to analyzing the hydrological cycle and water resources of China in relation to the recent climate trend and to assessing the impact of future climatic change (e.g., Piao et al., 2010; Shen, 2010; Wang and Zhang, 2011; Zhang et al., 2014). Over the past fifty years, a strong warming trend has been observed in China, with the North warming faster than the South (Piao et al., 2010; Li and Shu, 2013). Annual precipitation on average decreased by 1 mm per year from 1950 to 2010 (Li and Shu, 2013) while exhibiting strong spatial and temporal variability across the country. The drier regions of north and northeastern China have been receiving less rainfall in summer and autumn, with an estimated decline of 12% since 1960; the wetter region of southern China has been experiencing more rainfall during both summer and winter (Piao et al., 2010). Over the period 1956–2000, the northern and northeastern part of China was dominated by decreasing annual and seasonal precipitation, in contrast with increasing precipitation in the northwest, east, and southeast part of China (Zhang et al., 2012b).

Fig. 8 compares changes in precipitation, surface water resources, and total water resources in major river basins between the period 1956–1979 and the period 1980–2000. Precipitation in

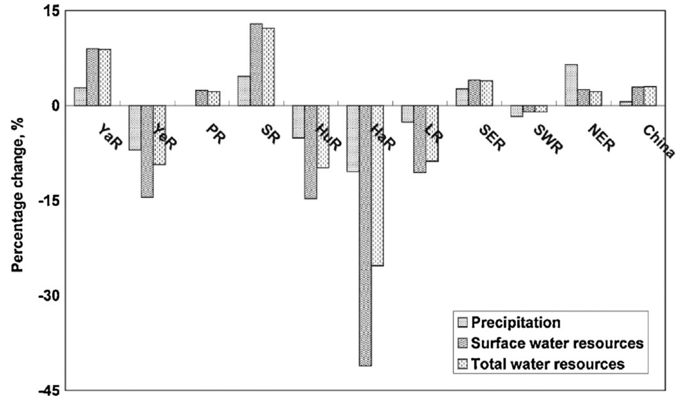


Fig. 8. Changes in precipitation, surface water resources, and total water resources in the major river basins between the (base) period 1956–1979 and the period 1980–2000 (adopted from Cheng and Hu (2012) based on data from Shen (2010)). In the figure, YaR, YeR, PR, SR, HuR, HaR, LR, SER, SWR, and NER represents, respectively, Yangtze River, Yellow River, Pear River, Songhua River, Huai River, Hai River, Liao River, Southeast river system, Southwest river system, and Northeast river system.

northern China declined, with a decrease of 10% in the Hai river basin, 6.9% in the Yellow river basin, and 2.6% in the Liao river basin (Shen, 2010). In contrast, most regions in the South, parts of the Northwest, and the northern part of the Northeast witnessed rising precipitation, with an increase of 3% in the Yangtze river basin, 2.6% in the Southeast, 4.6% in the Song river basin, and 6.5% in the Northwest (Shen, 2010). Despite the above changing precipitation across space, it is worth noting that these changes appear to still fall within the normal decadal variability of rainfall (Piao et al., 2010).

Over the past two decades, water resources have been evolving due to changes in both climate and land use altering the hydrological process. Precipitation is the main driver for water resource availability and reliability (Lu et al., 2013), and has been identified as the dominant cause of stream flow variations (Zhang et al., 2011). Human activities such as irrigation have also greatly influenced the variability and availability of water resources (Zhang et al., 2011). Runoffs and water resources has increased in South China but decreased significantly in North China, especially in the Yellow river basin, the Hai river basin, and the Liao river basin (Shen, 2010). Annually renewable freshwater resources have on average decreased by 19% and 17% in the Hai and Yellow rivers, respectively, and increased by 10% in the southern and northwestern river basins (Li et al., 2014). The inter-annual variation of water resources tends to decrease in the Hai and Yellow rivers where available water resources have significantly declined, and to increase in the northwestern and southwestern river basins (Li et al., 2014).

In the past 50 years, runoff of six large rivers in China has already declined, and groundwater table has also dropped significantly in north China (ECSNCCA, 2011). In the North China Plain, an important region for food production, a significant decreasing trend in runoff has been found for the Hai river and the middle and lower reaches of the Yellow river, with insignificant change for the Huai river and the upstream of the Yellow river (Wang and Zhang, 2015).

In the future, change in precipitation in a warming world will not be uniform: mean precipitation will likely decrease in many mid-latitude subtropical dry regions and increase in many mid-latitude wet regions; monsoon precipitation is likely to intensify (IPCC, 2014). In the coming 50–100 years, mean annual runoff will likely increase in parts of the water-abundant South but decrease in some northern provinces, implying more frequent floods in the South and droughts in the North (Shen, 2010; Wang and Zhang, 2011). The hydrological pattern of dry north and wet south will probably be exacerbated (Wang et al., 2012). The Yellow and Hai river basins will suffer more water shortages, while the lower and middle reaches of the Yangtze and Pearl river basins will have more floods (Wang and Zhang, 2011). Regions dominated by decreasing precipitation have also been found characterized by higher irrigation requirements in the future (Zhang et al., 2012b). Based on newly projected representative concentration pathways (RCP) scenarios, hydrological simulation suggests that water shortage in the North China Plain may be further aggravated by climate change (Wang and Zhang, 2015). Climate change will add to the challenges of water resource management by introducing greater variability in water systems and by changing flow conditions in surface water systems, amplifying the existing patterns of shortage and excess (Wang et al., 2012).

In addition, in the near future with climate change, drought severity, duration, and frequency will vary, and meteorological, agricultural and hydrological droughts will become more severe, prolonged, and frequent (Leng et al., 2015). The changing pattern of droughts is of great concern as China is a drought-prone country due to monthly, annual, and inter-annual variations in both precipitation and temperature (Dai et al., 2004; Zou et al., 2005). In the past decade, droughts were common across the country, which had serious social, economic and environmental impacts (Li et al., 2009; Wang et al., 2012; Yang et al., 2012; Zhang et al., 2012a, 2012c).

3.2. Socio-economic development

There are at least two types of changes associated with China's socio-economic development that threaten water security. These changes include the continuous growth of a big population and rapid urbanization. Both changes will boost water demand, further straining China's water resources that have already been found scarce and limiting.

China's population growth has been slowing down (Fig. 9). As of 2012, the annual growth rate of population decreased to less than 0.6%. Given its past trend, China's population is projected to reach its peak level of about 1.45 billion approximately in 2030 (UN, 2014c). With China annually available freshwater at about 2800 billion m^3, the continuous population growth means that per capita water resources will be further reduced from 2088 m^3 in 2010 to 1931 m^3 in 2030. Considering the current water scarcity and related challenges already faced by China, particularly at the local level, the rising population or the decreasing per capita water availability implies a water situation that will likely be worsening till 2030.

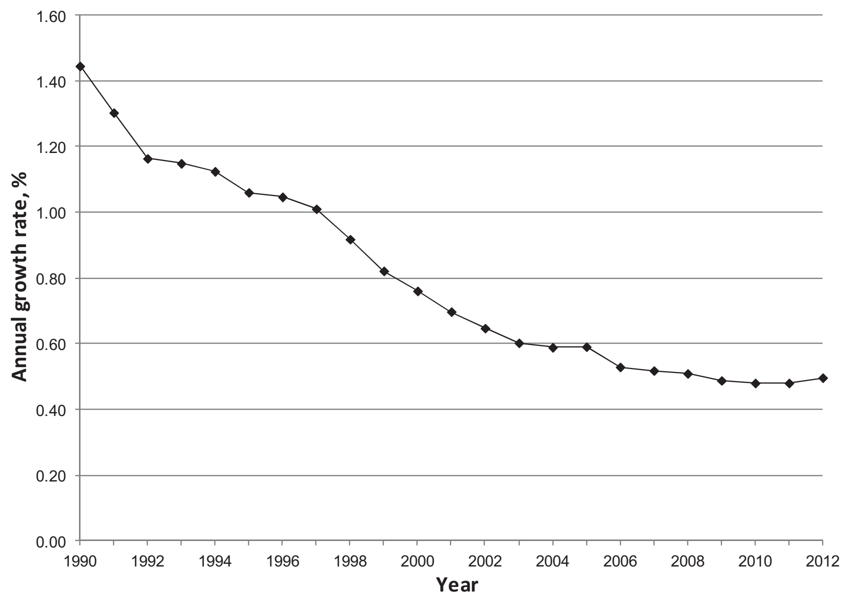


Fig. 9. Annual growth rate of population in China.
Data source: NBSC (2014).

Meanwhile, China is in the process of rapid urbanization. The number of cities with a population beyond 500,000 people rose from 40 in 1978 to 236 in 2013, and the urban population has increased by more 250% over the same period (Yeh et al., 2011; NBSC, 2014). China's urbanization grows at a speed faster than the world average, and will reach about 55% by the end of 2015 (Fig. 10). According to China's National Plan 2014–2020, urbanization will reach around 60% by 2020. Associated with the urbanization process are changing diets and habits, all of which will have important implications on water use. As of 2012, domestic water use on a per capita basis was estimated at 216 l/day in urban areas, a use rate that is 2.7 times the amount of 79 l/day in rural areas (MWR, 2000-2014). Moreover, a diet change toward more meat consumption implies a rising demand for more water (via grain production) from agriculture, and thus will further strain limited water resources (Giordano, 2007). Both changes will likely have a bigger impact than population growth, exacerbating water insecurity.

3.3. *Water-food-energy nexus*

The water-food-energy nexus is another challenge, which characterizes the interaction and the interlinked security risks of the water, food, and energy system (Hoff, 2011). Water, food, and energy are fundamental elements of sustainable development. Food and energy production and consumption can have important implications on water use while being constrained by available water resources. The interaction and mutual dependency of the 3 systems requires a nexus approach for management, which is aimed at increasing efficiency, reducing trade-offs, building synergies, and improving governance across sectors (Hoff, 2011).

The interaction between water and food is of particular interest and importance to China's sustainable development. As the most populous country, China accounts for 22% of global population but has only 10% of the freshwater and 6.5% of the arable land in the world (Peng, 2011). Furthermore, the majority of China's arable

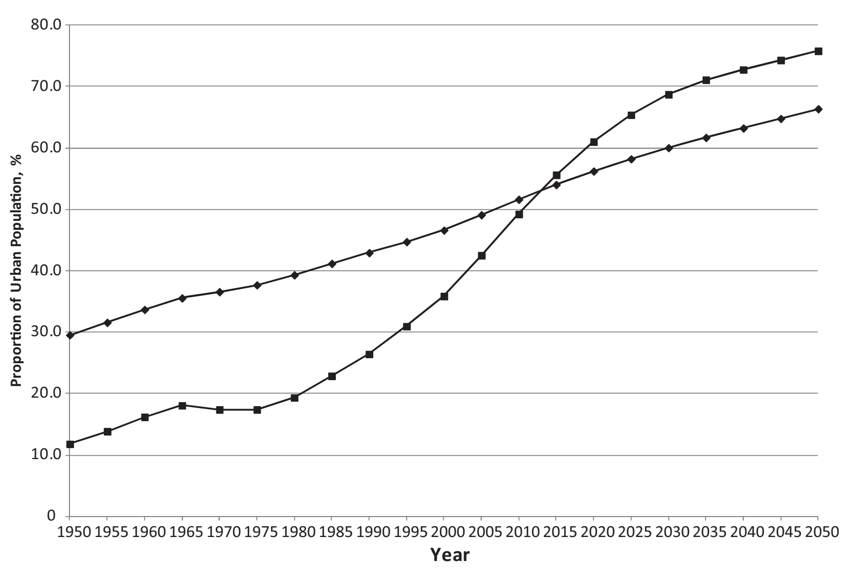


Fig. 10. Trends of urbanization in China and the world.
Data source: UN (2014c).

Table 5
Annual food production over the period 1990–2012 in China.

Year	Food production, million ton	Annual growth rate (%)
1990	446.24	
1991	435.29	−2.45
1992	442.66	1.69
1993	456.49	3.12
1994	445.10	−2.49
1995	466.62	4.83
1996	504.54	8.13
1997	494.17	−2.05
1998	512.30	3.67
1999	508.39	−0.76
2000	462.18	−9.09
2001	452.64	−2.06
2002	457.06	0.98
2003	430.70	−5.77
2004	469.47	9.00
2005	484.02	3.10
2006	498.04	2.90
2007	501.60	0.71
2008	528.71	5.40
2009	530.82	0.40
2010	546.48	2.95
2011	571.21	4.53
2012	589.58	3.22
Average	488.45	1.36

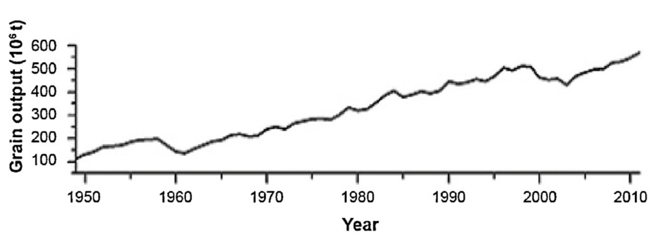
Data source: NBSC (2014).

land is located in the dry north, with this country's food supply largely depending on the northeast and north of China. Limited by insufficient surface water, food production in North China, on one hand, uses a large amount of groundwater, severely straining local water systems (Currell et al., 2012; Shi et al., 2011); on the other hand, socio-economic development driven by population growth, urbanization, and societal pursuit of high living quality combined with diet change toward increased meat consumption further pressurizes food production and water resources. Yet, domestic water use also rises associated with socio-economic development, increasingly competing with food production for limited water resources. Food security has become a legitimate concern to China's development. To achieve food security requires explicit consideration of the constraint imposed by increasing water scarcity and pollution, with coordinated and integrated strategies and policies.

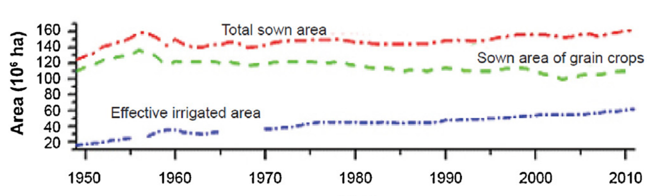
The next 15 years is most critical for China to address the challenge of food security. China is projected to reach its peak population level of approximately 1.45 billion in 2030 (UN, 2014b), a 7.4% increase as compared to the population level of approximately 1.35 billion in 2012 (NBSC, 2014). Will China also be able to increase food production by the same rate as population growth to maintain a stable food supply in the future? Since 1990, China's food production has been increasing with an average annual growth rate of 1.36%, and would reach 752.0 million ton in 2030 (if the growth remains constant), an increase of 27.5% as compared to the production level of 589.6 million ton in 2012 (Table 5). In other words, if the growing trend of food production continuously holds valid for the future, China cannot only meet the food demand of the additional 7.4% more people in 2030 but also further increase food supply for the whole population. The key question is whether China will be able to continuously maintain the same growth of food production as before in the future with more scarce freshwater resources and increasing competition for water from industrial and domestic sectors.

Maintaining an increasing food production is not an easy task. In the past decades, irrigation development has played a critically important role in boosting China's food production (Huang et al., 2006). As demonstrated by Fig. 11, the sown area of grain crops has been stable over the past 60 years, but the total grain output and the effective irrigated area have been increasing. Crop production across China has been found 61–320% higher with irrigation than without irrigation, depending on region and cropland (Wu, 2010). Currently, about half of China's cropland is irrigated that produces 75% of food, 80% of cotton and oil crops, and 90% of vegetables and fruits in the country (Kai et al., 2006). Sustaining the irrigation-dependent food production, however, is challenging, given the majority of arable land located in the water-scarce North depending heavily on groundwater for irrigation (Grogan et al., 2015).

With a slow recharging process, groundwater overexploitation and depletion are looming at an alarming rate, threatening the sustainability of food production (Wang et al., 2009; Fang et al., 2010; Li, 2010; Zheng et al., 2010; Shi et al., 2011). Climate change will exacerbate the situation by stimulating irrigation demand (Wang et al., 2013), reinforcing water scarcity while reducing irrigated area (Wang et al., 2009, 2013), and bring more frequent droughts of increasing duration and severity with more severe drought stress (Zhang et al., 2012a; Leng et al., 2015). Water availability will significantly limit food production in the future because of the combined effect of higher crop water requirements and increasing competition for water from domestic and industrial uses (Xiong et al., 2009; Wang et al., 2013; Yan et al., 2015).



a. Trend of annual grain production output in China



b. Trends of annual total sown area, sown area of grain crops, and effective irrigated area in China

Fig. 11. Trends of annual grain production, total sown area, sown area of grain crops, and effective irrigated area over the period 1950–2010 in China. Adopted from Zhu et al. (2013).

Effective water resource management to improve water use efficiency (WUE) is the key to China's food and water security in the next 15 years (Blanke et al., 2007; Zhang et al., 2011; Wang et al., 2013; Zhang et al., 2013). There is strong potential for improving agricultural WUE to boost food security. The WUE for food crops such as wheat and maize is still low, with inefficient irrigation technologies still dominating in many production areas (Zhang et al., 2006b; Fang et al., 2010). A large literature has been devoted to strategies for improving WUE, including tillage practice and soil management (Jin et al., 2006; Li et al., 2007b; Wang et al., 2007b), nutrient management (Fang et al., 2006a,b; Wu et al., 2008; Yi et al., 2008), irrigation innovation (Shan et al., 2006; Li et al., 2007a), crop genetic improvement and breeding (Zhang et al., 2006c), crop substitution and alternative efficient cropping systems (Liu et al., 2008a,b; Ye et al., 2008; Sun et al., 2011; Yang et al., 2015), production system modeling (Chen et al., 2007; Ma et al., 2007; Fang et al., 2008), and institutions and management approaches (Blanke et al., 2007; Wang et al., 2009). Fang et al. (2010) provides an extensive review of these strategies, with important implications on WUE improvement.

The water-energy nexus has been receiving much attention, largely due to the interlinked risk of water and energy insecurity critical to China's socio-economic development. One major concern over the water-energy nexus is the intensive water use of China's energy production in conflict with the scarcity of water resources. China's energy supply is fueled mainly by coal. Since 1990, the proportion of coal production and consumption in China's total energy mix has always been greater than 70%, considerably higher than the 20% in the U.S. and 30% globally (Huang, 2013). As of 2012, China's total installed power generation capacity was 1145 GW, with 758 GW (or 66%) from coal fired power plants (Fig. 12); in 2012, coal-fired power plants contributed 73.9% of the total electricity production of 4980 billion kWh in China (Huang, 2013). It was predicted that coal consumption will still account for more than 55% of China's primary energy in 2030 (Huang, 2013).

Meanwhile, the coal industry is the largest industrial user of water in China, responsible for 20% of all water withdrawals (Schneider, 2011a). Water is used through the main steps of the coal supply chain, including mining, coal preparation, transportation, conversion, and disposal of pollutants, emissions, and waste (Pan et al., 2012). Water is needed to extract, wash, transport, and burn coal, and to control coal ash; in the coal-fired power plant, water is heated to almost 600 °C to generate steam for driving a turbine, and additional water is used to cool down the steam before its release (Davidson et al., 2011). The intensive water use of coal-based energy production well justifies the concern over the security of energy in the future. Will there be sufficient water to sustain the energy production of China during its development? Will China be able to achieve simultaneously both water and energy security?

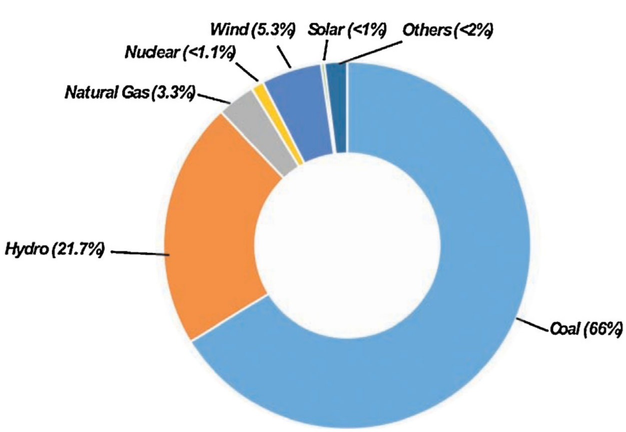


Fig. 12. Composition of China's electricity power generation capacity by source in 2012.
Adopted from Huang (2013).

The coal-dominated energy structure combined with the water-intensive coal industry is problematic for China, given its scarce and unevenly distributed water resources. China has around 15,000 coal mines, with roughly 70% located in water-scarce regions; 40% of those mines are expected to suffer severe water shortages, especially in the north of the country (Chan and Wai-Shin, 2013). Fig. 13 illustrates the distributions of coal reserves and the coal-to-chemicals plants versus water resources in China. While over 90% of China's coal reserves are in the North, with 39% in the Northeast and 52% in the Northwest, 84% of China's water resources are located in the South. The Northern China, despite its less than 20% of the country's renewable freshwater supply, hosts over 60% of the national thermal power capacity. China's "Big Five" state-owned power enterprises own and operate more than 500 gigawatts of thermal power plants, largely coal-fired, and all of them are highly exposed to water supply disruptions (Bloomberg Finance, 2013). With a coal-dominated energy supply, the interlinked risk of water and energy insecurity will remain a big challenge for China's socio-economic development over a long period in the future.

4. Future prospects

Given the current status and emerging challenges, what will be China's future prospects on water security? Can China achieve its water security in the future with sustainable socio-economic development? What actions should China take to improve its water security during the process of development and modernization? These are important questions of strong policy interest to the Chinese government. Given its complexity and huge challenges, achieving water security certainly is a daunting task requiring serious attention.

China has the ability to improve water management and reduce the risk of water insecurity. Over the past decade, significant progress has been made in water use efficiency across sectors. Water consumption per thousand yuan of GDP was reduced from 610 m^3 in 2000 to 109 m^3 in 2013 (MWR, 2000-2014). In agriculture, irrigation efficiency was raised from 0.38 in 2006 to 0.52 in 2013 (MWR, 2000-2014). Water consumption per thousand yuan for industrial added value was reduced from 288 in 2000 to 67 m^3 in 2013 (MWR, 2000-2014). Industrial wastewater and COD discharges have been steadily declining (see Fig. 4 in Section 2.3). The improvement can be attributed to many factors including change in both economic and industrial structure, technological advancement, and management and policy (Hu and Cheng, 2013).

Water management has been receiving great attention from government. In recent years, the Chinese government has adopted many policy initiatives to address the water problem. A most significant one was a policy document of high priority (or *No. 1 Document*) issued by the central government in 2011 that outlined government plan to accelerate water conservancy reform and development and to achieve sustainable use of water resources. In particular, it vowed to strengthen management to the most stringent level in water use and consumption control, efficiency improvement of water use, water pollution regulation, and management assessment and accountability. In 2012, the State Council further materialized and operationalized the requirements of the policy document, enacting *Advice on Implementing the Most Stringent Water Resource Management Scheme*. One guiding principle was to strengthen water resources allocation, conservation, and protection and to improve and enhance water institutions and management. It sets up three binding targets (or "redlines" in Chinese) with quantitative indicators for achieving the most stringent management in targeted areas (see Appendix III).

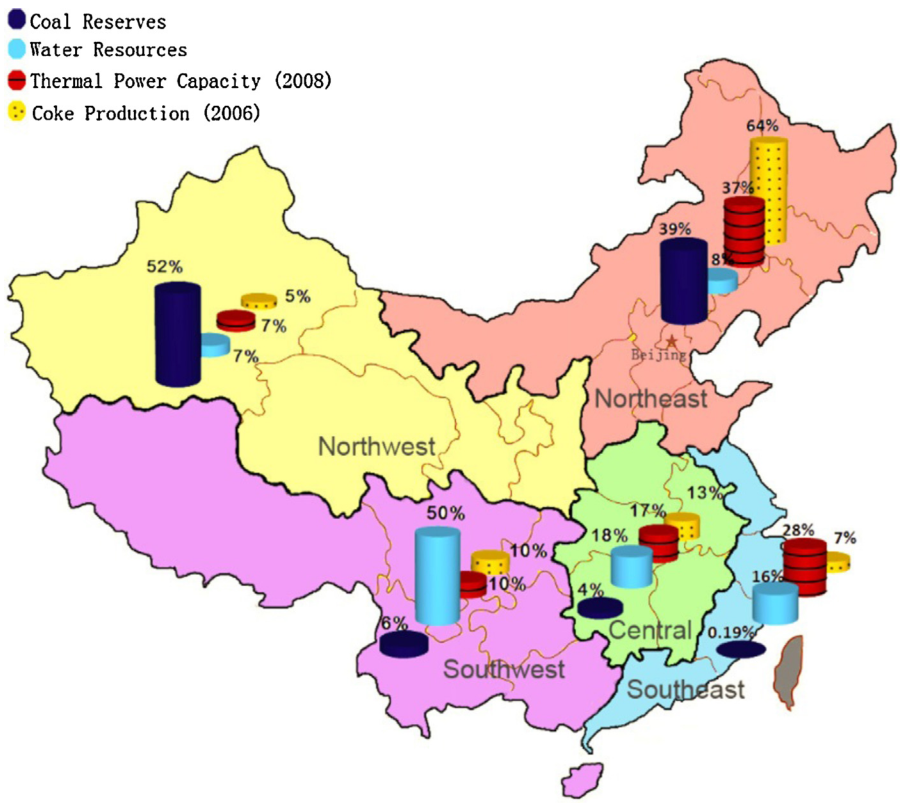


Fig. 13. Geographic distributions of coal reserves, water resources, thermal power capacity and coke production in China.
Adopted from Pan et al. (2012).

Associated with the policy initiative is the continued focus of government on reforming existing water institutions and management. One significant change has been more attention paid to market-based approaches. For example, in 2013, the National Development Reform Committee (NDRC), the Ministry of Finance (MoF), and MWR issued a joint guidance on water resource fees. In the same year, NDRC jointly with MOHURD published guideline on water pricing reform in urban areas. A new tariff system will be in place by the end of 2015 that will include a three-tiered pricing structure based on water use for households in all cities and some towns (Spegele and Kazer, 2014). In addition, pilot projects of water rights trading as part of the most stringent water management were also employed in 53 key rivers across the country in 2014.

Nonetheless, to improve water security requires a holistic, systematic, and integrated approach with joint effort across sectors to water management that the government currently falls short of and should pay more attention to. Most significantly, structure-dominated (or engineering-based) water management is deeply rooted and still heavily relied on to address water-related issues. For example, the management initiative to reallocate water from the wet South to the dry North is an approach that is still focused much on the supply side, i.e., how to further stretch the physical limit of water resources to meet human demand for water. While supply augmentation as part of systematic water management is necessary to some extent, the measure of water transfer has not been scientifically justified by rigorous integrated assessment that critically analyzes the tradeoffs among the biophysical and socio-economic consequences of different strategies within an integrated framework. Increasing the role of desalination might be more cost effective than transferring water from the South to the North. A systematic plan relocating and shifting some of the functions of the capital city from the dry North to the wet South might be a better solution than the water transfer project, particular if other environmental and development issues such as air pollution and imbalanced regional development are considered. Watershed protection and reforestation could be a cheaper alternative to capital-intensive water conservancy projects characterized by dams and reservoirs.

From the perspective of risk management, there are two principles that China should follow in water management that can help improve water security. The first one is to reduce societal exposure to the water-related insecurity risk. The water scarcity issue faced by China to a large extent is due to the uneven spatio-temporal distribution of water resources inconsistent with human needs. While certain engineering measures (such as storage reservoirs or water transfer projects) can temporally alleviate local water scarcity, these measures do not fundamentally reduce exposure to the system-wide security risk as the demand for water can expand continuously, unlimitedly and rapidly beyond local water availability. Thus, capital-intensive engineering measures, while being part of the solution portfolio, should not and cannot be relied on as the sole, main strategy to improve water insecurity. A more holistic approach that can reduce exposure to the water insecurity risk requires attention to socio-economic development planning within local water availability in addition to the supply side approach (if necessary).

The planning and management approach entails explicit, scientific assessment of both water use consequences and hydrological implication of socio-economic development. It requires, before decision-making, rigorous analysis of development scenarios in relation to local water availability of certain quality with and without physical supply augmentation and quality management measures. As water uses involve different hydrological and biophysical processes such as evapotranspiration and return flow at varying spatial scales, development decision-making should be based on critical development appraisal with integrated hydrological socio-economic modeling based on reliable data. Given the complexity of involved hydrological and biophysical processes, the assessment of water use and hydrological impact could even be an independent component of development appraisal separate from environmental impact assessment (EIA), depending on the local severity of water issues. The motivation and purpose for independent water and hydrological impact assessment is to explicitly account for water availability or quality as a constraint in development decision-making and to reduce exposure to water-related risks. Similar to EIA, water impact assessment could be legislatively established and administratively enforced, with mandates on management strategies, plans, and accountability.

The second principle for improving water security is to enhance resilience reducing societal vulnerability to water-related issues. Improving water management with adaptive capacity is an important component of resilience enhancement. A resilient water management requires an institutional framework of legislation and administration with strong capacity and coordination. It dictates a uniform, coordinated management in water administration. It emphasizes institution and governance capacity to effectively manage water and address issues. Grumbine and Xu (2013) argued that the government measured against adaptive capacity standards remains weak at solving complex, cross-cutting problems, and thus promoted open information exchange, government transparency, institutional coordination, public and private sector participation, iterative decision-making, and conflict resolution. In addition, given the feature of shared power and fragmentation characterizing China's water management, the government should reform current water laws and develop clear legal mandates on water management between provinces and water bureaus within river basins while encouraging more participation from citizens, NGOs, and businesses (Moore, 2013b). In particular, water management targets and implementation should be monitored, accounted, and incorporated in the evaluation and promotion of water managers and government leaders in relation to their responsibilities. Capacity of rigorous policy analysis and integrated assessment with reliable data is a key component of institutional resilience with adaptive capacity, and should be dramatically improved and play a bigger role in policy and decision-making.

In all, China has the ability to achieve water security in the long run, given its strong political will and administrative control, commitment for huge investment, and continuous institutional reform of water management. It is worth noting that the water issues, however, will likely further worsen before getting better, particularly before 2030. This is mainly because current water issues are cumulative results of water management failure in the past, and thus can hardly be addressed or remedied in a short time, particularly with the existing institutional deficits and the emerging challenges of biophysical and socio-economic changes. The Chinese government, however, can alleviate the extent of water issues and shorten the duration of degraded water systems and exacerbated water insecurity by strengthening the enforcement of water laws and regulations, capacity building in water management, particularly on integrated policy analysis and assessment based on reliable data, and a fundamental shift from a technology or structure dominated mindset to a holistic, systematic, and integrated approach focusing on both structure and non-structure measures for tackling water issues.

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Appendix I

Annual growth rates of water use by sector over the period 2003–2012 in the North and the South of China

Year	Annual growth rate of water use by sector in the North					Annual growth rate of water use by sector in the South				
	Agriculture (%)	Industry (%)	Domestic (%)	Environment (%)	Total (%)	Agriculture (%)	Industry (%)	Domestic (%)1	Environment (%)	Total (%)
2003	−11.2	−2.6	3.7		−7.4	−4.6	5.3	0.7		0.3
2004	5.8	−1.3	1.3	0.7	4.3	3.0	6.7	4.8	2.6	4.2
2005	−0.3	5.0	1.7	54.3	1.4	−0.1	4.3	4.6	−15.2	1.7
2006	5.2	3.9	2.0	−5.6	4.5	−0.6	4.7	3.3	7.7	1.6
2007	−2.3	−2.3	0.8	2.0	−1.9	−1.3	6.9	3.2	28.6	2.3
2008	2.6	0.6	3.6	15.4	2.7	0.8	−0.9	2.4	11.1	0.7
2009	2.7	−2.3	3.1	1.7	2.0	0.5	0.2	2.1	−30.0	0.1
2010	−0.1	4.2	1.9	24.6	1.1	−1.8	4.1	2.7	4.8	0.8
2011	1.8	3.7	4.7	−2.6	2.3	1.1	0.1	2.2	−13.6	0.7
2012	5.1	−3.9	−13.2	1.4	1.9	3.2	−6.1	−2.4	−10.5	−0.8
Average	0.9	0.5	0.9	10.2	1.1	0.0	2.5	2.4	−1.6	1.2

Data source: MWR (2000-2014).

Appendix II

National and regional water resources and supply over the period 2007–2012 in China.

Year	Indicators	National			North			South		
		Surface water	Ground water	Total[a]	Surface water	Ground water	Total	Surface water	Ground water	Total
2007	Water resource, billion m^3	2424	762	2526	404	244	492	2020	517	2033
	Water supply, billion m^3	472	107	579	161	93	254	312	14	326
	(%)	(82%)	(18%)	(100%)	(63%)	(37%)	(100%)	(96%)	(4%)	(100%)

Appendix II (*Continued*)

Year	Indicators	National			North			South		
		Surface water	Ground water	Total[a]	Surface water	Ground water	Total	Surface water	Ground water	Total
	Water resource use rate	20%	14%	23%	40%	38%	52%	15%	3%	16%
2008	Water resource, billion m^3	2638	812	2743	368	246	460	2270	567	2283
	Water supply, billion m^3	480	109	588	166	95	261	314	14	328
	(%)	(82%)	(18%)	(100%)	(64%)	(36%)	(100%)	(96%)	(4%)	(100%)
	Water resource use rate	18%	13%	21%	45%	39%	57%	14%	2%	14%
2009	Water resource, billion m^3	2313	727	2418	381	241	471	1932	486	1947
	Water supply, billion m^3	484	110	594	170	96	266	314	14	328
	(%)	(82%)	(18%)	(100%)	(64%)	(36%)	(100%)	(96%)	(4%)	(100%)
	Water resource use rate	21%	15%	25%	45%	40%	56%	16%	3%	17%
2010	Water resource, billion m^3	2980	842	3091	508	270	605	2471	572	2486
	Water supply, billion m^3	488	111	599	171	97	268	317	14	331
	(%)	(82%)	(19%)	(100%)	(64%)	(36%)	(100%)	(96%)	(4%)	(100%)
	Water resource use rate	16%	13%	19%	34%	36%	44%	13%	2%	13%
2011	Water resource, billion m^3	2221	722	2326	402	251	492	1819	471	1834
	Water supply, billion m^3	495	111	606	176	98	274	320	13	333
	(%)	(82%)	(18%)	(100%)	(64%)	(36%)	(100%)	(96%)	(4%)	(100%)
	Water resource use rate	22%	15%	26%	44%	39%	56%	18%	3%	18%
2012	Water resource, billion m^3	2837	830	2953	464	270	564	2374	559	2389
	Water supply, billion m^3	495	113	609	178	101	279	317	13	330
	(%)	(81%)	(19%)	(100%)	(64%)	(36%)	(100%)	(96%)	(4%)	(100%)
	Water resource use rate	18%	14%	21%	38%	37%	49%	13%	2%	14%

For water resources, the total volume is the sum of surface water and groundwater minus the overlapping part; for water supply, the total only includes surface water and groundwater, not including from other sources such as desalination.
Data source: MWR (2000-2014).

Appendix III

China's national targets for the most stringent water management.

Target area	Indicator	Timeline	Goal
Water resource development	National total water use	2030	$\leq 7.0 \times 10^{12}$ m^3
		2020	$< 6.70 \times 10^{12}$ m^3
		2015	$< 6.35 \times 10^{12}$ m^3
Water use efficiency	Water use quantity per CNY 10,000 industrial added value	2030	<40 m^3
		2020	<65 m^3
		2015	<63 m^3
	Effective irrigation use ratio	2030	>0.60
		2020	>0.55
		2015	>0.53
Water pollution control	Percentage of water function zones achieving water quality standard	2030	>95%
		2020	>80%
		2015	>60%

Adopted from SC (2012b).

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