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Water conservancy projects in China: Achievements, challenges and way forward

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ABSTRACT

China's water policies in the past decades have relied heavily on the construction of massive water conservancy projects in the form of dams and reservoirs, water transfer projects, and irrigation infrastructure. These facilities have brought tremendous economic and social benefits but also posed many adverse impacts on the eco-environment and society. With the intensification of water scarcity, China's future water conservancy development is facing tremendous challenge of supporting the continuous economic development while protecting the water resources and the dependent ecosystems. This paper provides an overview of China's water conservancy development, and illustrates the socioeconomic, environmental and ecological impacts. A narrative of attitude changes of the central government towards water conservancy, as well as key measures since the 1950s is presented. The strategic water resources management plan set by the central government in its Document No. 1 of 2011 is elaborated with focus on the three stringent controlling "redlines" concerning national water use, water use efficiency and water pollution and the huge investments poised to finance their implementation. We emphasize that realizing the goals set in the strategic plan requires paradigm shifts of the water conservancy development towards maximizing economic and natural capitals, prioritizing investment to preserve intact ecosystems and to restore degraded ecosystems, adapting climate change, balancing construction of new water projects and rejuvenation of existing projects, and managing both "blue" (surface/groundwater) and "green" water (soil water).

1. Introduction

Over the past three decades, the economy of China has grown the fastest among major nations and now is ranked second in the world. However, China's development is increasingly constrained by limited water resources. As the biggest developing country with the largest population, China has been facing serious water scarcity (Yong, 2009). With only 6% of the world's total water resources and 9% of the world's arable land, China feeds 21% of the world's population. This achievement was not possible without a huge number of water conservancy projects, e.g. dams, reservoirs, irrigation infrastructure, and water transfer projects.

Today, China possesses the largest number of dams (about half of the world's total), the largest amount of hydropower generation (~20% of the world's total), the largest irrigated area (~21% of the world's total) (FAO, 2011), the largest hydropower project (i.e. Three Gorges Hydroelectric Project, TGHP) and water transfer project (i.e. South-to-North Water Transfer Project, SNWTP) of the world. These water projects have brought tremendous benefits in flood control, water scarcity alleviation, clean energy generation and have supported the food security and overall economic development (Mei, 2010; Wu et al., 2006). The benefits, however, come with high costs. The massive projects have caused many problems concerning the environment impacts (Li and Wilcove, 2005; Zhao et al., 2008), degradation of freshwater and soil ecosystems (Wang et al., 2006b), soil and river erosion (Yang et al., 2011), and large population resettlements (Chang et al., 2010).

China's water conservancy development is facing a number of challenges. Apart from the negative ecological, environmental and social impacts, water resources scarcity is posing increasing obstacles. The situation is particularly grave given the fact that

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most suitable sites for water conservancy projects have been developed. Hence, the potential for constructing new water supply projects is limited. The problem has been further aggravated by insufficient investment for water infrastructure and conservancy. Facing the serious water challenges, on January 29, 2011, the Chinese government issued the Central Document No. 1, titled "The Decision on Accelerating the Reform and Development of Water Conservancy." (CPC Central Committee and Council, 2010). Historically, every year's Central Document No. 1 is the most important policy for that year and beyond. This document is the first-ever comprehensive policy document released for water conservancy. It acknowledged the lagging water infrastructure investment in the last few decades and vowed to reverse the situation in the next 5–10 years. Development of water conservancy projects is given priority in the national infrastructure construction. On July 8–9, 2011, the central government held a high-profile conference, which reiterated the aspiration to upgrade the country's water infrastructure. This conference was the highest level on water conservancy issues since the founding of the People's Republic of China in 1949. Improving rural infrastructure with focus on irrigation and water conservancy is emphasized. China has planned to invest 4 trillion Yuan (US$618.8 billion) in water conservancy over the next decade to harness the resources of its rivers and lakes and to establish a water system that can shield the country from threats of floods and droughts.

There have been many studies investigating the environmental and ecological impacts of water conservancy projects in China. Most of them have focused on specific projects, e.g. impacts of the TGHP on ecological processes and biodiversity (Lopez-Pujol and Ren, 2009; Wu et al., 2003a, 2004; Xie et al., 2003), environmental and ecological effects of the SNWTP (Zhang, 2009), impacts of dam construction on river discharge and sediments in the Yellow River (Wang et al., 2006b), the Yangtze River (Yang et al., 2011) and the Peal River (Zhang et al., 2008). However, a comprehensive review of the path of China's water conservancy development and investigation of the achievements, problems and challenges has, to the best of our knowledge, not been available in the literature. A detailed elaboration of implications of the renewed aspiration of the central government on water conservancy development has been missing in the literature.

Understanding the achievements and problems of China's water conservancy development is a key to directing future construction and investment for new water conservancy projects. Meanwhile, China's experience can also provide valuable lessons for other developing countries where huge water infrastructure investments are planned. In this article, we provide an overview of China's water resources and development of the major water conservancy projects (see a few projects in Fig. 1), and illustrate their socioeconomic, environmental and ecological impacts. We also discuss future challenges that confront China's water conservancy projects. In particular, we elaborate the far-reaching implications of Central Document No. 1 for China's integrated water resources management. We conclude with some recommendations on the paradigm shifts to achieve the goals set by the Chinese government in the future water conservancy development.

2. Overview of water resources in China

China's annual average total freshwater resources are about 2800 billion m^3 (MWR, 2011b). Although the absolute freshwater volume is big, ranking as the sixth largest among all countries in the world, the per capita water resources were only 2040 m^3/cap/yr in 2008, about one-fourth of the world average (Wang et al., 2008). Besides the small per capita water resources, the uneven temporal and spatial distribution of water severely worsens the water scarcity problem (Fig. 2). Dominated by a continental monsoon climate, 60–70% of annual precipitation in most regions of China is concentrated in summer. The percentage is even higher in northern China (Cheng et al., 2009). Annual precipitation in

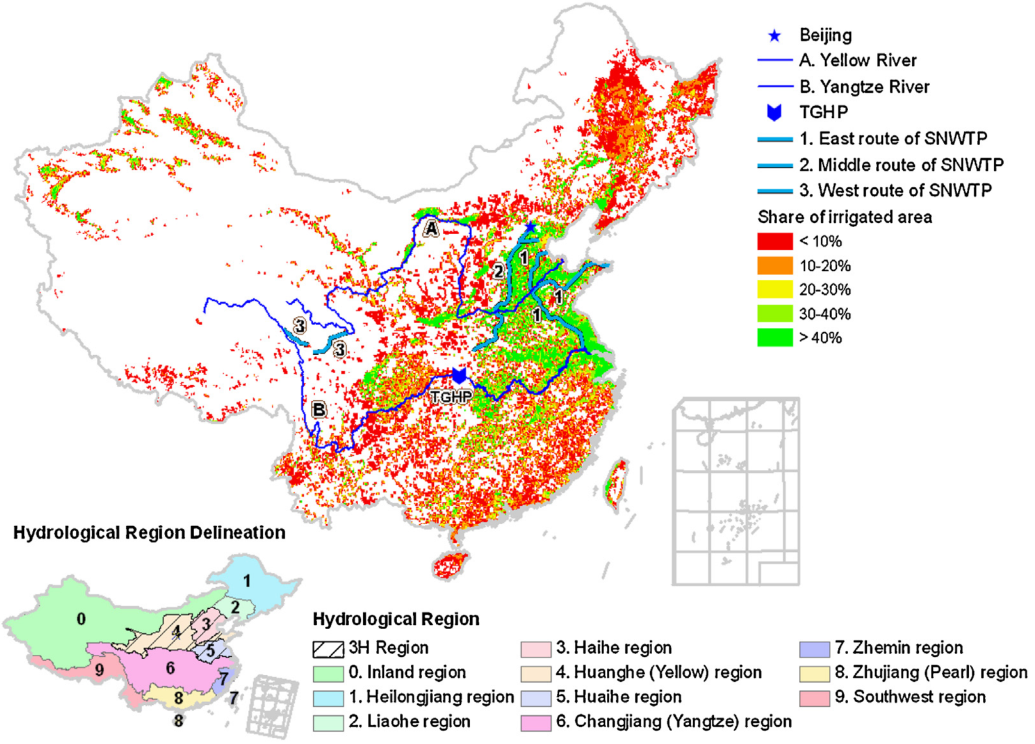
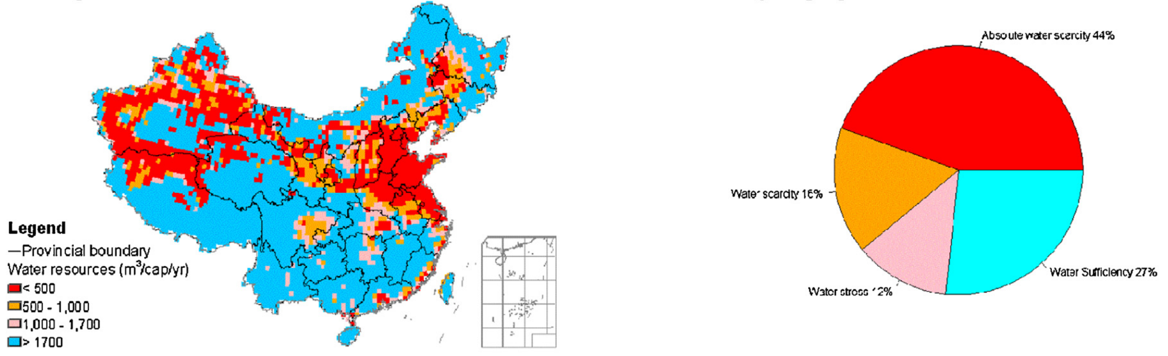
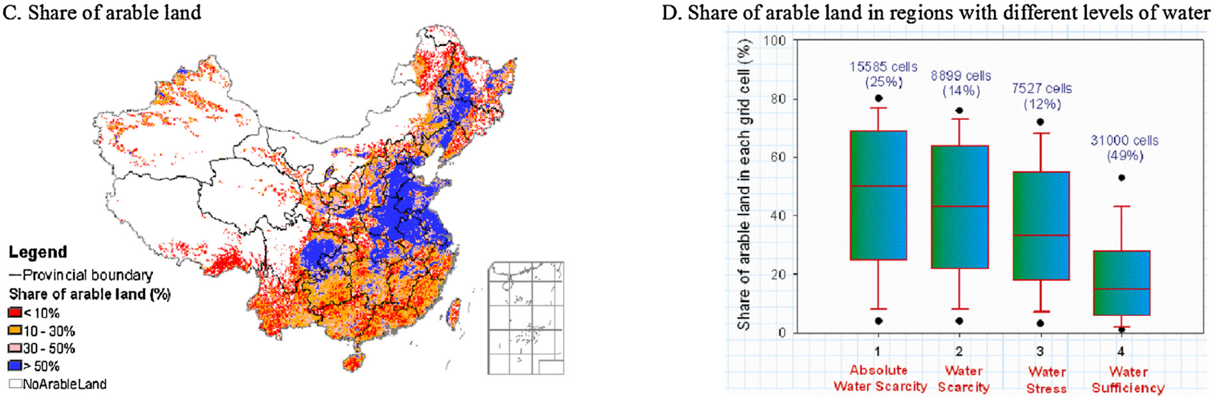


Fig. 1. Spatial distribution of irrigated area, and locations of the Three Gorges Hydroelectric Project (TGHP) and the South-to-North Water Transfer Project (SNWTP) in China with the hydrological region delineation.


A. Per capita water resources in China

B. Percentage of people under different levels of water stress


C. Share of arable land

D. Share of arable land in regions with different levels of water scarcity

Fig. 2. Spatial distribution of China's water and land resources. (A) Spatial pattern of per capita water resources. The data are based on the long-term average run-off assessment (GWSP Digital Water Atlas, 2008) and population for the year of 2000 (CIESIN, 2005) with a spatial resolution of 30 arc-minutes. (B) Percentage of population under different levels of water stress. (C) Share of cultivated land area. The cultivated land data are from Fischer et al. (2008) with a spatial resolution of 5 arc-minutes. (D) Share of arable land with different levels of water scarcity. In order to compare cultivated land area with water scarcity, we first convert per capita water resources data (A) into a spatial resolution of 5 arc-minutes. There are 15,585, 8899, 7527, and 31,000 grid cells falling into the category of absolute water scarcity, water scarcity, water stress, and water sufficiency, respectively. The shares of cultivated land in these grid cells are shown in (D) contrasted to levels of water scarcity.

China gradually decreases from the highest amount of over 2000 mm/yr along the southeast coast to the lowest amount of less than 100 mm/yr in the northwest inland. Per capita water availability shows even larger spatial heterogeneity. Water resources availability is low in the north, but rich in the south (Fig. 2A). For example, the Huanghe, Huaihe, and Haihe (3H) river basins, mainly located in the North China Plain, account for one-third of China's population, 35% of the industrial output, 40% of China's cultivated land and 50% of the national grain production, but this region has only 7.6% of the nation's water resources. The 3H basins are a region of acute water scarcity, where water resources management is of crucial importance to maintain water and food security, social stability, economic growth, and environmental health at both regional and national levels. Largely due to the uneven distribution of water resources and population, 44% of the population live in regions with absolute water scarcity (<500 m^3/cap/yr), and 16% live in regions with water scarcity (500–1700 m^3/cap/yr) (Fig. 2B).

A high imbalance between water and arable land resources worsens the water scarcity problem. China's arable land was only 0.08 ha/cap in 2008, less than 40% of the world average (FAO, 2011). The largest shares of arable land are located in the North China Plain, North East Plain, and the Sichuan Basin (Fig. 2C), but these regions are all suffering from serious water scarcity (Fig. 2A). Most cultivated land is in the water-scarce regions (Fig. 2D), such as the North China Plain – a bread basket of China. Precipitation is not sufficient to support the large crop production, and irrigation is needed to achieve high crop productivity. However, with the increasing demand for water from industrial and domestic sectors, and the increasing awareness of ecological water use of natural ecosystems, agriculture is under great pressure to obtain sufficient irrigation. Water scarcity becomes more crucial with the competitive water uses among sectors (Yang and Zehnder, 2001).

3. Development of water conservancy projects and the attitude changes of the Chinese government

The development of water conservancy projects in China has been predominated by the central government's ideology towards water conservation. After the establishment of the New China in 1949, the then – Chairman Mao Zedong stated that "water conservancy is the life vein of agricultural production". It spurred the massive construction of small- and medium-sized dams and fast expansion of irrigated land between the 1950s and 1970s. The investment in the water conservancy projects accounted for 8–10% of the total national capital construction investment during this period (Fig. 3). From the early 1980s to the end of last century, water conservancy was regarded as an important foundation and safeguard to support the rapid growth of the national economy. This period was characterized by fast growth of large-sized dams with consequently higher capacity of reservoir storage and hydropower generation, and construction of water diversion projects. Irrigated areas further expanded during the period. The investment in the water conservancy projects increased by 5.6 times during the period, although the share in the total capital construction investment declined to about 3%. The first decade of

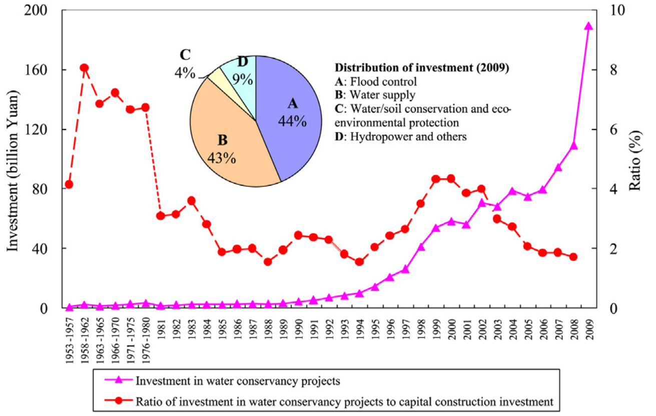


Fig. 3. Investment of water conservancy projects. The pie chart shows the distribution of investment in water conservancy projects, which is mainly used for the purposes of flood control and water supply.
Data for investment for water conservancy projects and the ratio of this investment to total capital construction investment before 2004 were obtained from the China Rural Statistical Year Book (State Statistics Bureau, 2008). Data for investment for water conservancy projects during 2004 and 2009 and its distribution for different purposes were obtained from the series of the Statistic Bulletin on China Water Activities (MWR, 2011a). Data for the capital construction investment during 2004–2008 were obtained from the web site of the Central People's Government of China (CPGPRC, 2009).

the twenty-first century has been characterized by continuous increase in large-sized dams, reservoir capacity, hydropower generation and water diversion. There has been a decline in irrigation water use while the irrigated area increased at a slower rate, as a result of the competition for water from the urban sectors and the implementation of water-saving measures in irrigation. A notable phenomenon is the skyrocketed investment in water conservancy projects and a diving share of the investment in total capital construction investment, due to even larger increases in other infrastructure investments in an economy with an annual growth rate of around 10%. During 2005–2009, water conservancy projects only accounted for less than 2% of the total investment of capital construction (Fig. 3).

With regard to the management, before 1990, China's water conservancy was dominated by the 'hard-path approach', which was characteristic by Gleick (2003) as emphasizing on the construction of massive infrastructure and increase in water supply. According to the main focuses of water conservancy projects, this period can be divided into three sub-periods (Chen et al., 2007). During 1949–1956, the New China was just established after long-time wars and the national main focus was to recover economic production and secure social life. The main focus of water conservancy was to repair river embankments, dredge flood channels, and release flood disasters. The period 1957–1979 was characterized by the balanced emphasis on disaster protection and comprehensive utilization of water resources. Due to the serious flood disasters in the 1950s and 1960s, flood control drew much attention of the government. During 1980–1989, the economic reform and open-door policy had brought about fast socio-economic development. The focus of water conservancy had shifted from flood control and irrigation to supporting all-around national economic development. Some attention began to be paid to water allocation among different sectors, water resources protection and water pollution control.

Between 1990 and 2010, China experienced a transition from hard-path to soft-path approach. The 'soft-path approach' emphasizes economic and institutional measures to manage water resources and improve water use efficiency. The main driver of the transition is the increasing water scarcity and water pollution in the country. Also, the huge and disastrous floods in 1998 gave a good lesson to water managers about the importance of ecological roles of natural ecosystems. This period had witnessed the implementation of some economic instruments, particularly water pricing, to curb the demand. Meanwhile, harmonizing human–nature relations, water markets and water rights were widely discussed (Grafton et al., 2011). Many water-related laws and regulations had been issued during this period, including the Law on Water and Soil Conservation (issued in 1991), Law on Prevention and Control of Water Pollution (issued in 1996), Flood Control Law (issued in 1997), and Water Law (revised in 2002). Building a water-saving society was first written in China's water law. Despite the efforts in promoting the soft-path approach, the enforcement is much lagged due to various obstacles. China's water conservancy is becoming increasingly difficult to meet the demand to support the continuous economic development.

4. Achievements, benefits and challenges of water conservancy projects

Water conservancy projects include construction, expansion, reconstruction, strengthening, and repair of water-related projects for the purposes of flood control, water supply (e.g. irrigation, industrial and domestic water supply, water transfer projects), water and soil conservation, ecological and environmental protection, power generation, and other supporting and ancillary works and activities (e.g. project-induced immigration). This section focuses on flood control dams, irrigation infrastructure and water transfer projects in addressing the achievements, benefits and challenges of China's water conservancy development.

4.1. Flood control: a focus on dams and reservoirs

4.1.1. Achievements

China has set up a flood control system by integrating dams/reservoirs with dykes, river channel management, flood diversion zones, and other non-project measures (e.g. afforestation and reducing soil and water erosion). Dam and reservoir construction is a major flood control measure and has been a major focus of the Chinese government. China has built 87,873 dams and reservoirs of all sizes. In addition, China has constructed about 294,104 km of embankments and dykes and about 43,300 water gates (MWR, 2011a). In 2010, the total storage capacity of reservoirs was 716.2 billion m^3, ranking the fourth in the world and accounting for almost 10% of the world's total storage capacity (MWR, 2011b). China's total hydropower generation was 721 billion kW h in 2010, ranking first in the world and accounting for around 21% of the world's total hydropower (IEA, 2010). This was equivalent to 17.4% of the total electricity generated in China.

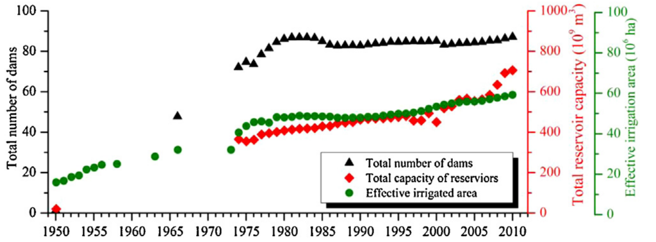


Fig. 4. Development of dams/reservoirs in China since the 1950s.
Data on number and storage capacity of dams are from Ministry of Water Resources of China (MWR) (MWR, 2010a). Data on number of dams higher than 30 m in 1949, 1999, and 2002–2005 are from Pan and He (Pan and He, 2000) and the Chinese Society of Hydroelectric Engineering (Chinese Society of Hydroelectric Engineering, 2009) and in other years are from MWR (MWR, 2010a).

There have been three major periods of dam construction in China. The first was the "slow-growth" stage in the 1950s. By then, the importance of water conservancy had been realized by the government, but due to technical limitations and capital constraints, large-sized dam construction was very difficult. The number of dams of all sizes was almost doubled from 1222 dams in 1949 to 2301 dams in 1957. The second period was the "fast-growth" stage in the 1960s and 1970s. Both the number of dams and storage capacity increased remarkably. The number of dams rose sharply to 86,822 by 1980. As a result, the total storage capacity of reservoirs increased substantially (Fig. 4). The third period has been the "stable in number but increasing in storage capacity" stage. After 1980, the increase in number of dams fluctuated from year to year. However, the reservoir storage capacity continued to increase, and particularly after 2000, the rate of increase was higher than before. This has been due mostly to large-sized dams with heights over 30 m (Fig. 4). Typical examples include the first (TGHP) and fourth (Longtan Hydroelectric Project) largest dam storage capacities in China, completed in 2008 and 2009, respectively.

4.1.2. Benefits

Mainly with the construction of dams and reservoirs but also with other forms of infrastructure (e.g. dykes), the flood control system in China has played an important role in managing flood disasters. As a result, 46.8 million hectares of farm land and 598.5 million people have been protected (MWR, 2011a). For example, the Xiaolangdi Dam has significantly reduced the flood threat below the Huayuankou Station in the Yellow River and enhanced the downstream flood control standard from 100-year to 1000-year recurrence interval, while the operation of the TGHP has increased the flood control standard of the Jingjiang section on the Yangtze River from 10 years to 100 years (Mei, 2010). The flood control systems on major rivers in China can basically defend the level of the largest floods occurred since the founding of New China in 1949 (Mei, 2010). The accumulated direct economic benefits of flood control between 1949 and 2009 totaled 4 trillion Yuan (about 12% of the national gross domestic product, GDP, in 2009), and the annual death toll caused by flooding has decreased by 83% from 8900 in the 1950s to 1500 in the early 2000s (Mei, 2010).

Besides flood control, dams and reservoirs also play a role in electricity generation, and irrigation water supply. Hydropower energy generation in China has increased from 1.2 billion kWh in 1949 to 721 billion kWh in 2010 (Fig. 5). The first hydropower station was built in Shilongba, Yunnan Province, in 1912, with only 500 kW installed capacity. In 2007, China's gross installed hydropower capacity and hydropower energy generation reached 145.3 million kW and 486.7 billion kWh (Huang and Yan, 2009), both ranking the highest in the world. The share of hydropower energy in total energy supply has remained relatively stable at around 16% since 1990. This share is expected to increase in the future. In 2007, China issued the *Medium- and Long-term Plan of Renewable Energy Development*, and proposed a gross installed capacity of hydropower of 300 million kW by 2020, which is more than double the size in 2007 (Huang and Yan, 2009). In the same year, China issued the national climate change programme, and planned to enhance the proportion of renewable energy (including large scale hydropower) in primary energy supply (Government of China, 2007). Considering the higher energy demand and more emphasis on clean energy, it is inevitable that China will continue its effort to explore hydropower in the near future (Chang et al., 2010).

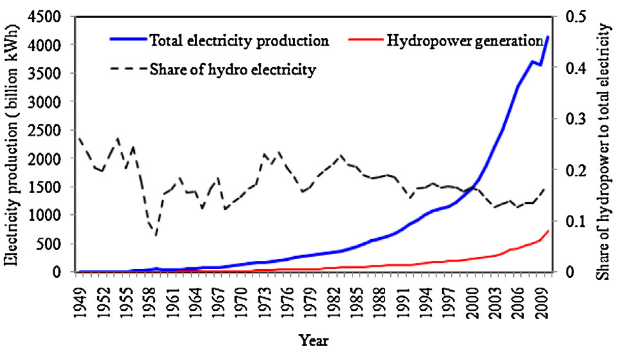


Fig. 5. China's annual total electricity production and hydropower electricity production. The share of hydroelectricity to total electricity of each year is also indicated (MWR, 2010a).

Another benefit of building dams and reservoirs is the ability to farm the huge areas of arable land that had not been usable before by temporally changing distribution of regional water resources to meet the seasonal demands of agricultural production. Dam/reservoir-fed irrigated land increased to account for about one-third of total effective irrigated area in 2009 (MWR, 2010a), indicating the significant role of dams/reservoirs in sustaining irrigation for agriculture in China.

4.1.3. Challenges

Most of China's dams were built between the 1950s and the 1980s (see Fig. 4), and many have approached or even exceeded their designed lifespan. About 36% of the dams, or some 30,000 dams, are at high risk due to structural obsolescence or lack of proper maintenance (Sheng et al., 2006). The aging dams that do not satisfy current flood or other loading criteria and do not adhere to current state-of-the-art practices pose significant risks to downstream regions. Hence, dam renovation or decommissioning has become a growing concern.

Dams/reservoirs pose many environmental and ecological challenges by reducing sediment flux and changing the temporal pattern of river discharge to downstream and ultimately the ocean. In water-rich river basins, the impacts on sediments are more obvious than on discharges. About 45,197 dams (MWR, 2011b) have been built so far throughout the Yangtze River basin. While having little impact on annual river discharge (Xu et al., 2010), they have caused downstream channel erosion, coarsening of bottom sediment, and erosion of the subaqueous delta (Yang et al., 2011). The sediment discharge of the Yangtze River, as measured at Datong Station located around 600 km from the river mouth, decreased by 94% from 490 million ton/yr in the 1950s and 1960s to 29 million ton/yr in 2008, mainly as a result of the trapping effect of the human-made dams, particularly the Three Gorges Dam (Yang et al., 2011). The water discharge measured at the Datong Station has remained more or less constant since the 1950s, averaging about 900 km^3/yr even after the construction of the TGHP (Xu et al., 2010). The estuary has experienced declining sediment loads, and a consequent decrease in coastal salt marsh accretion and net erosion in the subaqueous delta front. The sediment loads are likely to further decline, and the middle to lower river channel and delta will continue to erode as new dams are built and the SNWTP starts the operation. The lower sediment flux to the sea resulted in significant degradation of the Yangtze delta (Yang et al., 2006) and posed serious challenges to maintaining the geometry of the delta and protecting Shanghai and nearby wetlands (Xu et al., 2010). Similarly, the 387 large and medium-sized dams/reservoirs along the Pearl River (Zhujiang) basin (with a total storage capacity of 46.7 billion m^3, 15% of the total river discharge) did not affect the river discharge, but led to a 33% decrease in sediment flux to the ocean (Zhang et al., 2008).

In arid and semi-arid river basins, the dams/reservoirs have significant dual impacts on both discharges and sediments. For example, in the Yellow River basin, about 3150 dams/reservoirs had a total storage capacity of 57.4 billion m^3 by 2000, even higher than the long-term (1951–2000) mean annual water discharge (57.0 billion m^3) of the basin (Wang et al., 2006b). The construction of dams/reservoirs has led to dramatic decreases of discharges and sediments. The average annual water and sediment discharges from Yellow River to the sea in the 1990s were 13.2×10^9 m^3 yr^{-1} and 389.9×10^6 tons yr^{-1}, respectively. They were only 28.7% and 29.5% of annual fluxes in the 1990s, respectively (Wang et al., 2006b). Meanwhile, the dams/reservoirs weakened the natural seasonal variability and drastically decreased peak discharge of the Yellow River (Wang et al., 2006b). The decreases of water, sediment, and total dissolved solid flux of the river have resulted in profound physical, ecological, biogeochemical, and geomorphological impacts on the lower reaches, its delta-front estuaries, and the Bohai Sea (Bianchi and Allison, 2009; Wang et al., 2006b).

Dams and reservoirs affect biodiversity by inundation, flow manipulation, fragmentation of habitat, and the subsequent resettlement of human populations in new areas (Vörösmarty et al., 2010; Wu et al., 2004). Flow regulation of dams is considered one of the main adverse ecological consequences (Bunn and Arthington, 2002). Dams also fragment aquatic habitats (Nilsson et al., 2005), impeding not only the movement of species but also the delivery of nutrients and sediments to downstream and the reduction of riverine habitat-forming substrate available for critical life stages such as fish nesting and refuge (Lehner et al., 2011). For example, the building of over 3000 dams along the Pearl River (Zhujiang) and its tributaries since the 1950s has caused the blockage of fish migration routes and the decline of species such as *Tenualosa reevesii* and the Chinese sturgeon (*Acipenser sinensis*) (Dudgeon, 2005; Lopez-Pujol and Ren, 2009). The construction of the Gezhouba Dam in the 1980s in the Yangtze River resulted in large declines in the populations of three endemic, ancient, and nationally protected fish species because of the fragmentation of their populations and disruption of their migratory routes (Xie et al., 2003). The Chinese paddlefish (*Psephurus gladius*), one of only two species of paddlefish in the world, has become functionally extinct (Stone, 2007). After the construction of the TGHP, several endemic aquatic mammals, such as the Yangtze finless porpoise (*Neophocaena phocaenoides asiaeorientalis*) and the Chinese river dolphin (*Lipotes vexillifer*), have recently been categorized as "functionally extinct" (Wang et al., 2006a; Zhao et al., 2008). Overall, dam/reservoir construction has affected directly and indirectly about 14% and 18% of imperiled fish in China, respectively (Li and Wilcove, 2005).

Dam-induced resettlement is a big social concern in China and elsewhere. Construction of dams/reservoirs in China has led to over 22 million people being resettled to accommodate reservoirs (Chang et al., 2010). Displacement can cause a series of problems, including landlessness, joblessness, homelessness, food insecurity, community disarticulation, increased mobility, loss of community resources, depression among the displaced residents, and loss of cultural heritage sites (Michael, 1997). Prior to the mid-1980s, resettlement often led to a lower living standard because of the low compensation for loss of land, homes, and nature-based livelihoods. Since then, the Chinese government has shifted the resettlement paradigm to a longer-term process, coupling compensation with "mobilization" and economic development (Webber and McDonald, 2004). Nevertheless, with the growing economy and higher living standards, resettlement becomes more difficult. Relocated people have to adapt to sudden socioeconomic, cultural, and demographic changes, which is particularly difficult for many minority groups due to their unique religions and cultures.

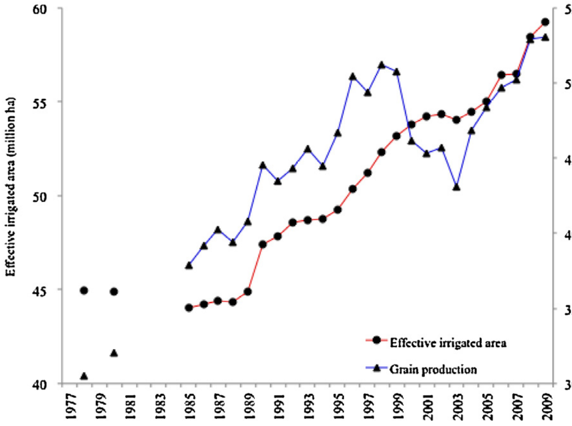


Fig. 6. Historical development of effective irrigated area (in million ha) and grain production (in million ton).
Data is from State Statistical Bureau of China (State Statistical Bureau, 2010).

4.2. Irrigation: water supply to agriculture

4.2.1. Achievements

Since 1949, the Chinese government has paid much attention to the development of irrigation infrastructure. The effective irrigated area of China was around 15 million ha in the early 1950s but increased sharply to 44.04 million ha by 1985 and to 60.35 million ha by 2010 (MWR, 2011a; State Statistics Bureau, 2010). The number of mechanical and electrical wells for irrigation increased from 114,000 in 1961 to 5.01 million in 2010 (MWR, 2011a). There are 402 large irrigation districts with more than 20,000 ha of irrigated area in each (Li and Zou, 2000). The large irrigation districts account for 12% of total arable land, but they produce 25% of the total national grain (Wu et al., 2006).

4.2.2. Benefits

Irrigation plays a key role in China's agriculture and food security. Accounting for about 45% of the arable land, irrigated land produces about 70% of the total grain, 80% of the cotton, and 90% of the vegetables and fruits in China (Wu et al., 2006). Irrigation has enabled an significantly higher crop yield in the main food-producing regions like the North China Plain, where irrigated wheat yield is 70% higher than rainfed wheat yield (Liu et al., 2007).

A strong relationship exists between grain production and irrigated areas in China, e.g. during 1985–1999 and 2004–2009 (see Fig. 6). In both periods, expansion of irrigated area was an important reason for the increased crop production. The exception was in 2000–2003, when irrigated area remained almost unchanged but grain production sharply decreased. This was mainly attributable to the decline in the planted area of grain due to urbanization and implementation of the 1999 Grain-to-Green Program—large-scale ecological projects to convert rainfed cropland on steep slopes to forest and grassland (Liu et al., 2008).

Despite the close relationship between expansion of irrigated area and growth of grain production, there is no clear correlation between agricultural water use and grain production (Fig. 6). This is largely due to the fast development and extensions of water-saving technology in China, especially since the 1990s. The Chinese government has been heavily investing in research on water-saving agricultural techniques since the beginning of the Seventh Five-Year Plan (1986–1990). Area equipped with water-saving technology increased from 15.24 million ha in 1998 to 27.31 million ha in 2010 (29.1–45.3% of total effective irrigated land) (MWR, 2011a; State Statistics Bureau, 2010). Largely due to the expansion of water-saving technology, agricultural water use even decreased by 12.5% from 392 billion m^3 in 1997 to 343 billion m^3 in 2003. Afterward, it increased slowly to 369.1 billion m^3 in 2010 (MWR, 2010b), still not as high as the 1997 level.

4.2.3. Challenges

Irrigation is often cited as a main cause for unsustainable water use (groundwater abstraction exceeds the groundwater recharge) in many regions, e.g. sharp declines in groundwater levels. For example, nearly 40% of water used in the main wheat production areas such as Hebei, Shannxi, Henan, and Shandong provinces is from groundwater (Lohmar et al., 2003). Among these provinces, Hebei has the highest share of groundwater in total irrigation water, as high as 68% (Lohmar et al., 2003). Abstraction of non-renewable groundwater for agriculture in China has reached 20 $km^3\ yr^{-1}$ since 2000 (Wada et al., 2012). The over-withdrawal of groundwater led to sharp declines in groundwater tables, large cones of depression, land subsidence, and intrusion of sea water (Lohmar et al., 2003). The groundwater level declined rapidly from about 10 m below the surface in the 1970s to 32 m in 2001 in Luancheng County in the North China Plain (Zhang et al., 2003).

Irrigation has been a key cause for river discharge decline in arid or semiarid areas (Wang et al., 2006b; Yang et al., 2004). Supported by the construction and operation of dams/reservoirs, agricultural water abstraction from the Yellow River increased from 155.4 m^3/yr in the 1950s to 294 m^3/yr in the 1990s while irrigated area increased by a factor of 10 to about 10 million ha in the 2000s (Yang et al., 2004). Another more representative example is the Tarim River, the largest inland river in China. Irrigated area in the Tarim River basin expanded from 350,000 ha in 1950 to 780,000 ha in the 1990s, and agricultural water use reached 0.148 billion m^3 in the 1990s (Zhang et al., 2011). Largely due to the increase of irrigation, the mainstream has continuously decreased during the past 50 years even though its headwaters typically have experienced an increasing discharge due to more rainfall (Tao et al., 2011). In the Haihe River basin, the total annual agricultural water use in the 1990s reached 28.5 billion m^3, 32% higher than the total river discharge, which led to a drop in the groundwater table (Zhang et al., 2011).

Despite the fast expansion of water-saving irrigation, wasteful water use still remains a big problem in agriculture. According to the Ministry of Water Resources, only about 45% of the water withdrawal can reach irrigated fields (Peng, 2011). This low water-use efficiency of 0.45 is much lower than the level of 0.7–0.8 in developed countries (Wu et al., 2003b). A dilemma lies between increasing investment in water conservancy projects and insufficient capital to maintain and rehabilitate existing irrigation infrastructure. Bulk of the capital channeled through the government has gone enthusiastically to new, giant water conservancy projects while channel leakage associated with old systems has often been ignored (Peng, 2011).

Irrigation is facing intense competition from the growing demand from municipal, industrial, and environmental uses, which will pose significant challenges for China to achieve its goals of increasing grain production by 50 million tons by 2020 (Peng, 2011). The steadily increasing water demand of other sectors, especially the industrial sector, has posed significant pressure to divert water away from agricultural production (Yong, 2009). The higher economic value of water use in industry leads local governments to put industrial use first when facing water-use conflicts between industry and agriculture. With decreasing water supply for irrigation, agriculture needs to increase water productivity and produce more crops for each drop of water (Marris, 2008). This has posed additional challenges to the existing irrigation schemes, which were designed primarily to maximize crop yield. The decrease in irrigation water supply renders a need for the development of irrigation scheme to be redirected to optimize irrigation volume to achieve the maximized crop water productivity.

4.3. Water transfer projects to alleviate water shortage problems across regions

4.3.1. Achievements

Currently, China has over 20 major inter-basin water transfer projects with a total length of over 7200 km, 16% longer than the Yangtze River. Appendix 1 summarized these major water diversion projects. A key attribute of the spatial distribution of the projects is that they are mainly located in northern China. According to statistics in 2006, the amount of water diverted by interbasin water transfer projects accounts for 2.5% of total surface water resources; the ratio may increase to 10% upon the completion of SNWTP in 2050 (Cheng et al., 2009). SNWTP, with its total length of 3187 km, is the longest water diversion project in the world.

4.3.2. Benefits

One direct benefit of water diversion projects is the transfer of water from water-surplus to water-deficit regions to alleviate water shortage in the receiving areas. These water diversion projects mainly aim to supply water for domestic and industrial uses, although some also serve for irrigation. For example, Tianjin is a city with the lowest per capita water resources in China (~180 m^3/cap/yr). The Yin Luan Ru Jin water diversion project was started in 1982 to alleviate the water shortage in Tianjin. By 2009, this project had diverted 19.2 billion m^3 of water into Tianjin mainly for domestic and industrial uses. Another example is the Yin Huang Ru Jin project to divert the Yellow River water to Shanxi Province, which has one-quarter of the total coal reserve in China. Each year the project diverted 0.56 billion m^3 to Datong City and Shuozhou City and 0.64 billion m^3 to Taiyuan City, three major coal production bases in China.

Environmentally and ecologically oriented water diversion projects also have recently emerged. A typical example for water quality improvement is the Yin Jiang Ji Tai project that diverts the Yangtze River water into Taihu Lake. As the third-largest freshwater lake in China, Taihu Lake serves as a major water source for drinking, aquaculture, and industrial needs, as well as being a popular tourist attraction. The Taihu basin accounts for 0.4% of the total area of China, 2.9% of the national population, but 14% of China's GDP (Yang and Liu, 2010). With economic growth and population increase, Taihu Lake began to suffer from several environmental problems, including deterioration of its water quality and consequently increasing frequency of noxious algae blooms (Yang and Liu, 2010). Started in 2001, the Yin Jiang Ji Tai project increased flow velocity, improved self-purification capacity, reduced the water exchange period, and alleviated degradation of Taihu Lake. By the end of 2006, it had transferred 7.42 billion m^3 of water from the Yangtze River into Taihu Lake basin, of which 3.24 billion m^3 went into Taihu Lake. Despite the positive short-term effect of improving water quality in Taihu Lake, its long-term function is a concern because of the large net input of nitrogen and phosphorus from the river to the lake (Yang and Liu, 2010).

Restoring degraded ecosystems caused by reduced water inputs is a typical application for ecologically oriented water diversion projects. For example, to alleviate the ecological degradation (degrading riparian vegetation and desertification) of the lower reach of the Tarim River, there have been eight times of water diversions from other basins in to the river since 2000, with a total volume of $2.27 \times 10^9\ m^3$ of water, to maintain environmental flows in the stream (Huang and Pang, 2010). These ecological water diversion projects raised water table depth and correspondingly restored partial riparian vegetation, resulting in significant improvement of the ecological function in the lower reach (Chen et al., 2008). Another example of ecological water diversion projects is associated with the Heihe River, the second-largest inland river. Due to the overexploitation of water resources in the middle reach of the river, serious environmental degradations, such as river-flow interruptions, shrinkage of lakes, groundwater-level drawdown, disappearance of vegetation cover, and desertification, occurred in the lower reach (Xi et al., 2010). To alleviate these environmental problems, the Heihe River Management Administration launched "Integrated Water Resource Management of the Heihe River Basin" in 2000. A core part of the plan was to increase stream discharge by diverting water from upstream and midstream man-made reservoirs to lower reaches using a man-made channel. From 2000 to 2006, a total volume of 5.29×10^9 m^3 of water was delivered to the lower Heihe River through intermittent water diversions for over 20 times (Xi et al., 2010). As a result, East Juyan Lake, which is the end of the river and dried up in 1992, was replenished to an area of 38.6 km^2 by 2006 (Xi et al., 2010).

4.3.3. Challenges

Water transfer projects artificially transfer a huge amount of water from its origin to the receiving areas. These transfers change the natural flow regime, which potentially leads to sea/saline water intrusion and loss of the ecological functions of the river channel and adjacent floodplain wetlands (Dudgeon, 1995). Water transfer projects also potentially function as expressways to accelerate the processes of biological invasion (Ding et al., 2008). Another common problem is that the groundwater level along the canals of water diversion projects rise significantly, leading to soil degradation caused by secondary soil salinization (Shao et al., 2003). Furthermore, water diversion projects require giant infrastructures that need huge capital investments. Water from the diversion projects is usually expensive, and normally can only be justified by political or strategic necessity (e.g. domestic consumption or strategic industrial use). Water consumption is thus usually subsidized as a burden on local and central governments.

In order to alleviate the water shortage in northern China, the SNWTP has been implemented with a total designed transferred volume of 43 billion m^3 per year. However, each year, the water-scarce north exports a large amount of food to the water-rich south, and the virtual water transfer embedded in the traded commodities is equivalent to 52 billion m^3 (Liu and Savenije, 2008; Ma et al., 2006), higher than the volume of the real transfer project. This contrast raises the question of whether such a huge water transfer project is necessary. Certainly, water is not the only factor influencing decisions about water transfer projects. Co-existence of the large real and "virtual" water transfer projects is also a result of uneven distribution of land and different economic structures in the south and the north. A more comprehensive assessment is required to study the feasibility as well as costs and benefits of water transfer projects, and decision makers should be extremely cautious and conservative in building water transfer projects.

In water-scarce regions, efficiency of water transfer projects is largely limited by local water use and water-saving incentives among different water user sectors. For example, the water diversions to the Tarim River helped reduce the length of the drying-up riverway from around 850 km in 2001 to about 400 km in 2002 and 2003, and shortened the drying-up period from 185 days in 2001 to 46 days in 2003. However, the length increased after 2003 to about 1200 km in 2009, while the drying-up period sharply increased to 302 days in 2009. The water diversion does not help reduce the drying-up length and period in the long run. One important reason is that local residents use more water from the river for irrigation and domestic or industrial activities. Without adjusting the economic structure and capping water use, the water diversion projects alone cannot solve water scarcity problems.

5. Renewed water conservancy aspirations and way forward

5.1. Combining the soft-path with the 'stringent control' in water resources management

Recognizing the increasingly prominent bottleneck of water scarcity to the economic development and the low investment in water conservancy projects is an important reason for the release of the Central Document No. 1 of 2011. It was an important milestone in China's strategic water development. For the first time, the Document explicitly pointed out that water constitutes "the origin of life, the key element of production, and the basis of ecology". It emphasized that "speeding up the reform of water conservation is not only important for flood control security, water supply security, and food security, but also important for economic security, ecological security and national security". Water conservancy projects are set as a priority area for the government's future investment. The annual investment to water conservancy is doubled compared to the level of 2010. A total of 4 trillion Yuan ($618.8 billion) is planned to be allocated for water conservation in the next 10 years.

Implementing stringent water resources management is a key feature of Document No. 1. Three "redlines" are set to control the national water use, water use efficiency and water pollution. As a

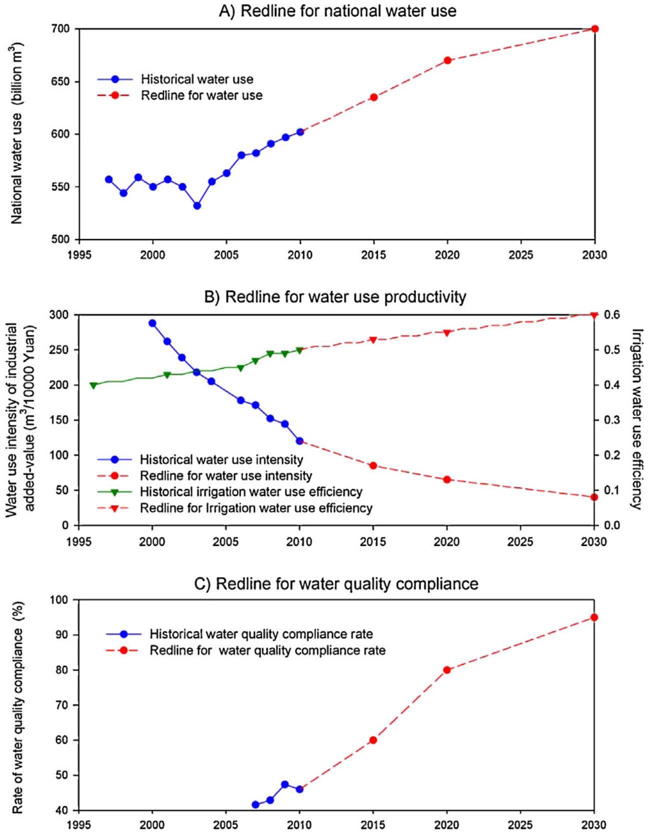


Fig. 7. Three "redlines" in comparison of historical development of national water use, water use productivity and pollution control. Historical data on national water use, water quality compliance rate and irrigation water use efficiency are obtained from a series of Water Resources Bulletin from the Ministry of Water Resources. The water use intensity of industrial added value is based on the constant price of 2000. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

follow-up document, in 2012, the Chinese Central Government released the "Opinions of the State Council on the Implementation of the Most Stringent Water Resources Management" (the "Opinions") (State Council, 2012). The Opinions concretized the three "redlines" mentioned in Document No. 1 by setting quantitative goals for 2020 and 2030 (Fig. 7). By 2030, the national total water use is controlled within 700 billion m^3; water use productivity should reach or be close to the world advanced level; water use intensity of CNY10,000 industrial added value (calculated according to the price in 2000) should be reduced to less than 40 m^3, and irrigation water effective utilization coefficient should increase to more than 0.6; total major pollutants into rivers and lakes will be controlled within the pollutant discharge capacity in the water function zones, and water quality compliance rate in the water function zone will reach 95%. The three "redlines" at the national level are now allocated to river basins, provinces, cities and even counties with quantitative targets (or local "redlines"). For example, China's seven river basins conservancy commissions have worked out their master plans for 2020 and 2030 in line with the "redlines" for each river basin. By early December 2012, all the seven river basins' master plans have been approved by the Ministry of Water Resources, and will be sent to the State Council for final approval. The realization of these goals will shed great and long-term impacts on China's water systems.

The quantitative indicators for the three "redlines" make sure that the water management achievements are measurable, reportable and verifiable. Officials at the level of county and above are responsible for meeting the regional water resources management targets. More importantly, the effectiveness of water resources management will be added to the evaluation and promotion system for officials. This requirement may to a large extent change the ideological stereotype and force the local officials to pay special attention to water resources management in line with the goals defined by the three redlines.

Document No. 1 also emphasized the renewed effort for rural infrastructure development and rehabilitation of water conservancy projects. Currently, only about 45% of the water withdrawal can reach irrigated fields, due partly to the impairment of irrigation infrastructure (MWR, 2011b). Repairing and upgrading existing irrigation facilities and technologies can substantially improve irrigation water-use efficiency. The document encouraged equal emphasis of investment on both large- and small-scaled rural water conservancy projects. In particular, many aspects that have been ignored in the past are addressed, e.g. rehabilitating small-scaled irrigation infrastructure and small dams, developing and improving rain-fed agriculture, removing or strengthening dangerous dams.

5.2. Paradigm shifts in the water conservancy development

The most stringent water resources management will provide a unique opportunity for grand-scale experiments on managing and planning water uses to support the continuous economic development. There are many challenges faced with China's future water conservancy development. Some paradigm shifts are necessary to ensure the meet of the goals.

Firstly, traditional water conservancy projects had aimed to maximize the economic values (e.g. GDP). The future water conservancy needs to emphasize maximizing the sum of economic and aquatic ecosystem service values. A framework integrating both economic capital and natural capital (i.e. values of nature's ecosystem services) (Carpenter et al., 2011) should be established to assess aquatic ecosystem services, competing uses for freshwaters, and the processes that underpin the long-term protection of freshwaters. Such effort has emerged in some individual cases but a general practice requires a formal institutionalization of the framework. One recent example was a proposal for the dam construction across the northern end of Poyang Lake, 27 km from the Yangtze River, to guarantee the water supply in Jiangxi Province. This proposal was seriously challenged by a group of prominent Chinese scientists for its detrimental effect on the delicate habitats for some rare aquatic species, including Yangtze finless porpoises (Jiao, 2009). Their appeal reached to Premier Wen Jiabao, leading to a halted approval of the project and a more comprehensive and holistic assessment of pros and cons of the dam construction. This case suggests a necessity for institutionalizing the framework to ensure a holistic assessment being conducted for all water conservancy project proposals.

Second, a strong will from the government is needed to prioritize the investment to preserve the intact ecosystems and restore those degraded. The past water conservancy in China has put a massive investment in physical infrastructure, with the primary goal of taming the river flows. The merits of investing in natural conservation are generally overlooked. For example, only around 3.3% of investments in water conservancy went to soil and water protection and ecological recovery projects in 2010. The future water conservancy needs to encourage nature-respected projects (Wang, 2006). Also important is to shift from merely "keeping the flood away" to "giving the flood way" (Yin and Li, 2001; Opperman et al., 2009). To this end, "let rivers and lakes recover themselves", promoted by the former Chinese president Hu Jintao in early 2008, may be one of the options.

Third, future water conservancy projects need to explicitly consider the shifting patterns of climate change. The existing water projects in China have been designed and operated generally without consideration of climate change. Such a stationary design of projects is fundamentally flawed (Matthews et al., 2011; Milly et al., 2008; Pittock and Hartmann, 2011). Climate change during the past decades has already caused significant alterations of water resources in China (Piao et al., 2010). One example is the solid evidence of a drying trend in the Hanjiang River basin (the tributary of the Yangzi River), which is the water source of the Central Route of the SNWTP currently under construction (Chen et al., 2007). If such a trend continues, the Hanjiang River would have no spare water for diversion, unless itself receives water transfer from somewhere else first. One adaptive approach to reduce impacts of climate change and maximize operational lifetimes of projects is to build infrastructure in stages as ecological response and climate trends become clear. This requires a shift from pursuing short-term achievements to long-term effective functions of the projects under uncertain future climate conditions.

Fourth, investment is needed to rejuvenate the effective functions of aging and impaired water facilities. Repairing and upgrading existing facilities and technologies could substantially improve irrigation water-use efficiency. Similarly, given the huge number of flood prevention works already in place and a large percentage of them in aging and unsound status (Kobayashi and Porter, 2012), rehabilitating the existing facilities might be much cheaper than starting new ones. However, allocating more investment to rehabilitation needs horrendous mentality changes because developing new and large projects often has higher visibility in the local governments' political achievements. Besides, construction of water conservancy projects often benefits local governments because they can obtain large amounts of money from the central government. This has been a key reason for the strong local interest in constructing new projects.

Last but not least, there is a need for a balanced emphasis on blue water and green water. The traditional definition of water conservancy is confined only to surface and groundwater, or so-called blue water. There is a general neglect of the management of another important water source, green water, which is soil moisture stored in unsaturated soil and eventually used by vegetation through evapotranspiration (Falkenmark and Rockström, 2006). The Central Document No. 1 of 2011 paid particular attention to blue water while neglected green water. In reality, green water dominates water use for agriculture by providing over 80% consumptive water use, and for natural ecosystems such as forests and grassland by providing almost all consumptive water use (Liu et al., 2009). Given the importance of green water, the future focus of water conservancy should be redirected from a blue-water project perspective toward considering the full water balance as "manageable," including green-water flow (Falkenmark and Rockström, 2006).

The development of Chinese water conservation is in a cross road. With the aspiration of the government to continuously lead the country on the fast track of economic growth and the gradual recognition of the importance of environmental and water protection to support its long-term economic development goal, paradigm shifts in water conservation projects towards harmonizing the needs for humans and nature is essential. The rapid increase in the national wealth and the investment capacity has provided the Chinese government with the financial means to break the new ground. The political will to take the necessary paradigm shifts remains to be made.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2013.02.002.

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