

Demand control and quota management strategy for sustainable water use in China

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Abstract With enhanced economic development and population growth in recent years, total water consumption has increased significantly around the world. As the most populated and most rapidly developing country in the world, one of the major challenges for the Chinese government is to guarantee a continuous water supply to improve the livelihood of the growing population and maintain the fast development of the economy. An ever-increasing trend of water consumption has led to the construction of hydraulic structures and degradation of the ecosystem in China. Through the analysis of water consumption and water-use efficiency around the world, this

study concluded that water demand management is the only option to assure a continuous supply of water to a growing population and developing economy. In this paper, water supply and demand of China over the time period 1980–2009 are analyzed to formulate water demand management strategies for a sustainable water supply. The study proposes that a water demand management strategy, based on demand control and quota management, could be a better option for sustainable water management in China. An example of the Haihe River Basin is provided to show the success of water demand management using total demand control and quota management. It can be expected that through the encouragement of a water conserving society, by water demand management, it is possible to harmonize the relationship among water, the environment, ecosystems, and human beings in China.

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Introduction

Despite apparent abundance of water resources, China is considered one of the most water-deficient countries in the world (Wang et al. 2012b, 2014a). The country ranks first in population (1.3 billion) and sixth in total water resources (2.8 trillion m³) in the world, while the annual per capita renewable freshwater water resources availability is less than 2,200 m³, or 1/4 of the world's average (Qian and Zhang 2001; Blanke et al. 2007; Cosier and Shen 2009; MWR 2011). Vast areas of East China and most parts of South China are dominated by the Eastern Asian monsoon climate, which causes most the rainfall to accumulate in the months of July and August. This causes an uneven

distribution of water resources between the south and the north, both spatially and temporally (Qian and Zhang 2001; Cosier and Shen 2009). The water shortage is further aggravated by pollution. Statistics show that total wastewater increased from 20×10^8 to $768 \times 10^8 \text{ m}^3$ during the time period from 1949 to 2009. This caused serious water pollution and degradation of the ecological environment and an apparent increase in the gap between water supply and demand.

With the rapid economic development, the shortage of water resources at the national level has become extremely critical. It has also become a matter of great concern to the Chinese government and various communities, in recent years (Vörösmarty et al. 2002; Cosier and Shen 2009; Qian et al. 2009). Typically, whenever there is a shortage of water, the solution relies on the capital investment in new treatment and distribution networks to meet the anticipated demand. This has caused the construction of huge hydraulic structures in China to meet the ever-increasing water consumption (Stephenson 1999; Mohamed 2000; White and Fane 2002; Gumbo et al. 2005; Zhang 2005; Wang et al. 2012b). Similar trends were also observed in other parts of the world, such as the North–South Carrier in Botswana, the Great Man Made River in Libya, the Lesotho Highlands Water Project in South Africa, and the National Water Carrier in Israel. The supply driven approach can solve the problem for a time but always fails to provide a long-term solution. Expansion of the infrastructure and development of new water sources have become more expensive nowadays. Besides that, several research studies have revealed that development projects (dams and diversions) destroy aquatic and land habitat, and, therefore, are unsustainable from both economic and environmental points of view (Stephenson 1999; Mohamed 2000; Huang and Chen 2000; Herman 2002; Butler and Memon 2010; Qian et al. 2009; Wang et al. 2012a).

Instead of following the supply augmentation strategy, water demand management can be a sustainable and more cost-effective option to guarantee a continuous water supply for the growing population and developing economy. The main objective of the present paper is to develop a

framework for water demand management for China, to ensure an uninterrupted water supply from limited resources. For this purpose, water supply and demand in China over the time period 1980–2009 have been analyzed to understand the driving forces behind the changing pattern of water demand. Water consumption and water-use efficiency for different countries of the world have also been analyzed to show the need for water demand management. This follows a discussion on the principle of the proposed water demand management strategies. Finally, an example of the Haihe River Basin is provided to show the success of water demand management strategy in China.

Water consumption and management in China

Water consumption in China

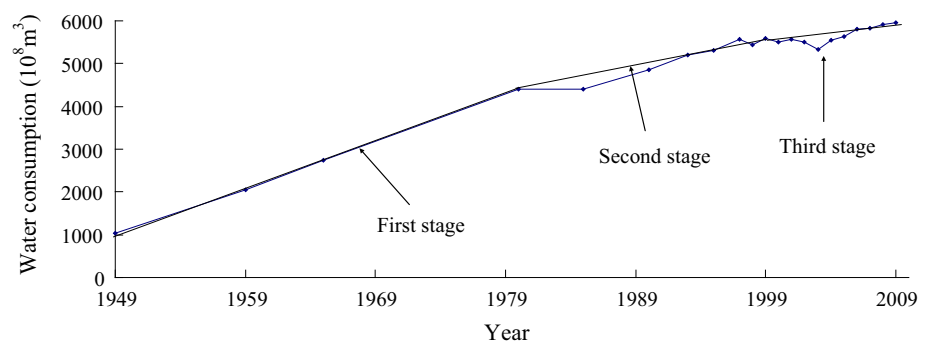
Population growth and economic development have caused an enormous increase in total water consumption in China in the last 60 years. The change of total water consumption in China over the time period 1949–2009 is shown in Fig. 1. The figure shows total water consumption has increased from $1,031 \times 10^8$ to $5,965 \times 10^8 \text{ m}^3$ in the last 60 years, which is almost 5.8-fold or nearly 2.92 % per year.

The line representing water consumption in Fig. 1 shows three distinct slopes, which means that total water consumption in China has changed during three periods.

The first stage, from 1949 to 1980, is a period with a significant increase in water consumption. Expansion of irrigated agriculture to meet the growing demand for food leads to a sharp increase in total water consumption during this period. Data show that total water consumption has increased by $373 \times 10^8 \text{ m}^3$ during this period, which is almost 4.3-fold or nearly 4.6 % per year (MWR 2011).

The second stage, from 1981 to 1999, is a period with a comparatively lower increasing rate in water consumption than the first stage. This is due to industrial development at this stage. Water consumption in industry is lower than it is for agriculture. Total water consumption during this period

Fig. 1 Water consumption from 1949 to 2009 in China (MWR 2011)



increased by $1,187 \times 10^8 \text{ m}^3$, which is nearly 1.27-fold or almost 1.2 % per year (MWR 2011).

The third stage, from 2000 to 2009, shows the slowest increasing rate of water consumption. The total water consumption at this stage increased only by $467 \times 10^8 \text{ m}^3$, which is nearly 1.08-fold or 0.8 % per year. Consequently, this stage is much more stable when compared to the other two earlier stages. This means that the society is gradually transforming to a water-saving society, where people realize that water resources are limited and should be used with high efficiency. Examples from developed countries show that industrial development and water-saving technology do slow down the trend in increasing water consumption (Wang et al. 2013).

The characteristics of different water consuming sectors are also different because of diverse driving factors. The amount of water consumption by agriculture was $1,001 \times 10^8 \text{ m}^3$ in 1949, which was 97.1 % of total consumption. In 2009, the amount increased to $3,723 \times 10^8 \text{ m}^3$, but the proportion decreased to 62.4 % of total water consumption (MWR 2011). In contrast to agricultural water consumption, industrial water consumption increased by 58 times over the period 1949–2009. Data show that total industrial water consumption increased from $24 \times 10^8 \text{ m}^3$ in 1949 to $419 \times 10^8 \text{ m}^3$ in 1980, and then to $1,391 \times 10^8 \text{ m}^3$ in 2009. Rapid urbanization also caused a substantial increase in domestic water consumption over the same period. Data

show that domestic water consumption, which was only $6 \times 10^8 \text{ m}^3$ or 0.6 % of total consumption in 1949, has risen to $748 \times 10^8 \text{ m}^3$ or 12.5 % of total consumption in 2009 (MWR 2011).

The global pattern of water consumption

The water consumption pattern in different countries of the world (Fig. 2) shows that the percentage of water use by different sectors has a distinct difference from the world average of 70 % in agriculture, 20 % in industry and 10 % in domestic consumption (Rekacewicz 2005; UNWATER 2009). The percentage of water use by agriculture, industry and domestic sectors in some of the high-income countries is 43, 42 and 15 %, respectively, in contrast to 90, 5 and 5 %, respectively, in some of the low-income countries (UNWATER 2009; PWC 2012). Agricultural consumption accounts for 98 % of total water withdrawal in Cambodia, in contrast to only 8 % in Poland (Harrison 2007; McCornick 2012). The water consumption structure of China is near to the world average, i.e., 68, 26 and 7 % for agriculture, industry and domestic sectors, respectively (Carmody 2010; Mekonnen and Hoekstra 2011; OECD 2013). In order to have a more stable water consumption structure like the developed countries, it is necessary to change the water consumption structure and use the limited water resources with greater efficiency (Peter 2000; Xiaohe 2006).

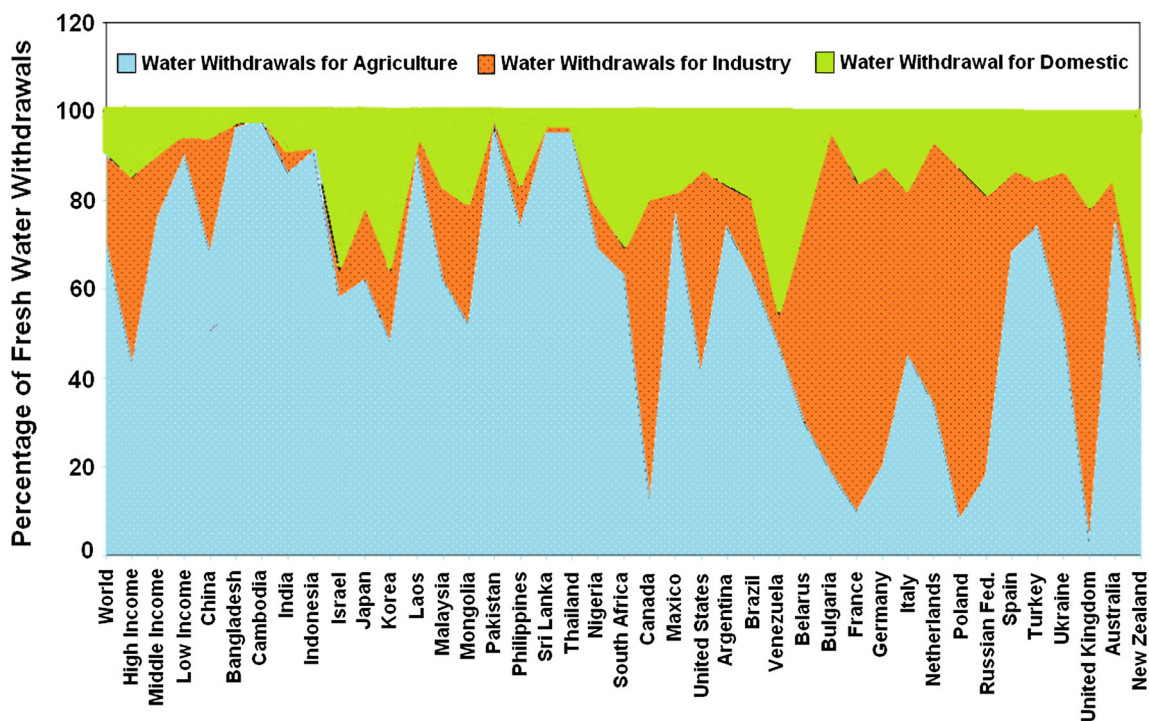


Fig. 2 Water consumption structure of different countries in 2007 (UNWATER 2009)

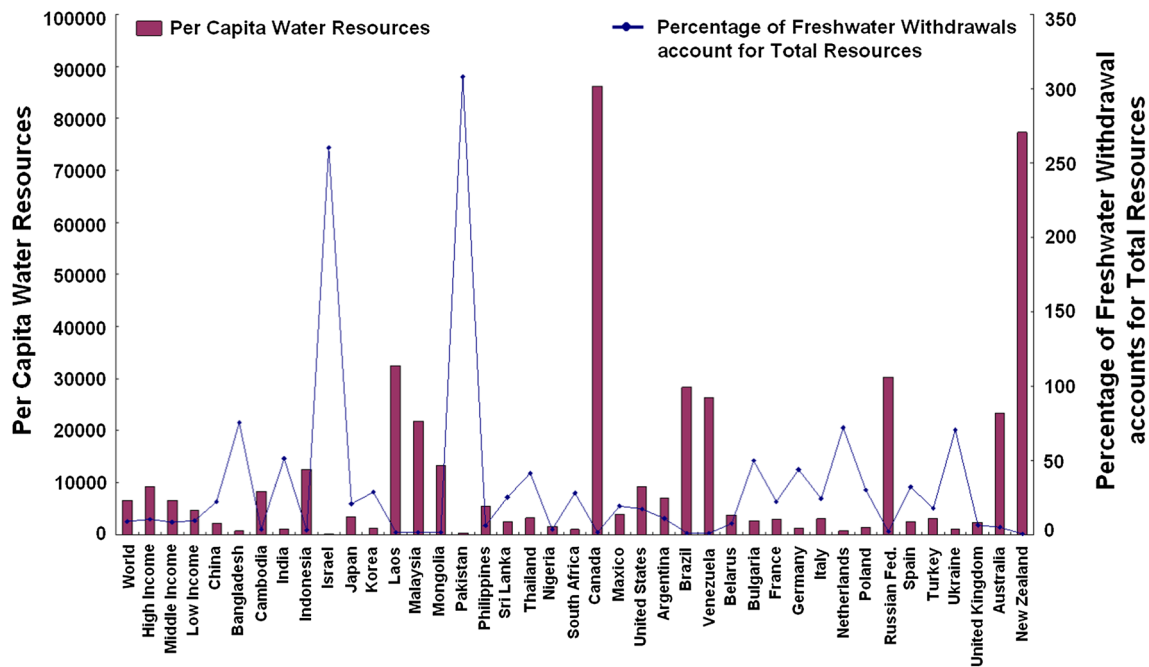


Fig. 3 Water utilization in different countries of the world (UNWATER 2009)

The percentage of freshwater withdrawal to total water resources, i.e., water utilization, also has a distinct difference among different countries. Water utilization rates (Fig. 3) in different countries (UNWATER 2009; Palaniappan and Peter 2009) show that Pakistan has the highest water utilization rate of 308 %, and New Zealand has the lowest of only 0.6 %, in contrast to the world average level of 9 %. On average, the freshwater utilization rate in China is 22.4 % (FAO 2003; Becken et al. 2013). The surface water, groundwater and total water utilization rates in different river basins of China are shown in Fig. 4. Lessons from different parts of the world show that water management, based on recycling and treatment, considers fresh water as a virtually limitless resource. However, it rarely takes into full account the environmental or economic impacts of water services and assumes that current levels of water demand are unaffected by policy and behavioral changes.

Water supply management in China

Water supply patterns in China (Fig. 5) show that the total water supply has increased over the time period 1980–2009 to meet growing demand, due to industrial development and population growth. This has been achieved through an acceleration of engineering construction in the last three decades. Approximately 87,151 reservoirs with a total water storage capacity of over 7,064 billion m³ were built (MWR 2011), which benefited the economy of the country tremendously during the past years. However, it has also

caused a number of environmental and ecological problems, such as the drying-up of river systems, subsidence of the land surface due to over-exploitation of groundwater, degradation of lakes and wetlands, and depletion of other natural water resources. This problem is being aggravated by climate change in recent years. It is anticipated that climate change may worsen the water shortages and intensify the conflicts among water users in China (Downing et al. 2003; IPCC 2007; Wang et al. 2012a).

Demand control and quota management strategy

Water demand management

The conflict between economic development and environmental degradation has raised the question of the technical reliability and institutional capacity of water supply management, which has finally led managers and planners to slowly move towards a Water Demand Management (WDM) approach. It has been demonstrated that WDM is less costly when compared with new supply schemes and better resource conservation (Stephenson 1999; Gumbo et al. 2005). Some countries like Zambia and Malawi have adopted WDM, mostly for economic reasons. Some countries do not experience acute and widespread water shortages but have adopted WDM to reduce water losses and costs. As a result, more people can be provided with safe drinking water, and more water can be used for productivity (e.g., industry). On the other hand, in some

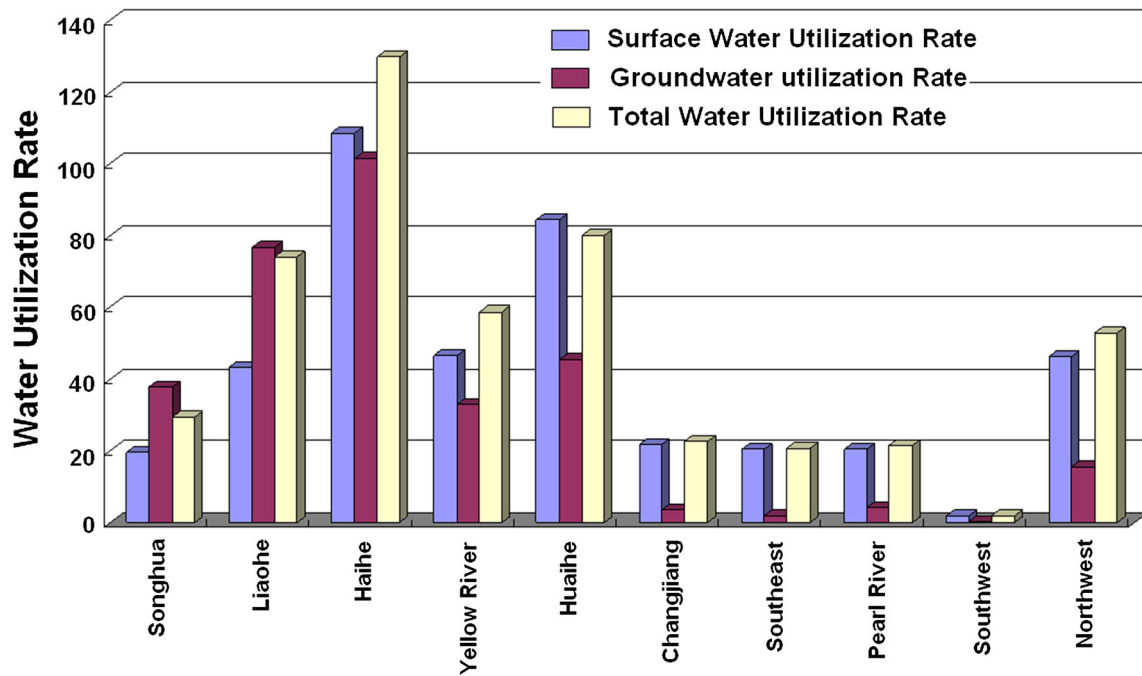
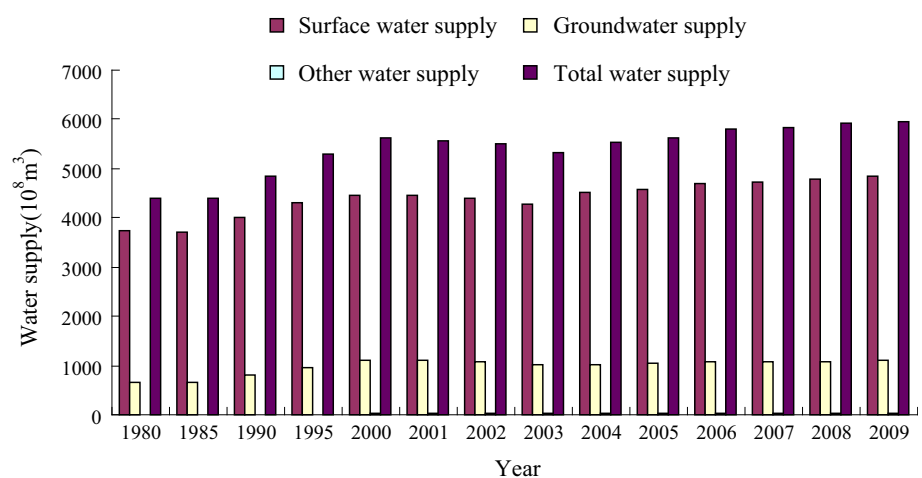


Fig. 4 Water utilization rates in different river basins in China (MWR 2011)

Fig. 5 Water supply from different sources during 1980–2009 in China (MWR 2011)



countries like Namibia, Botswana and South Africa, water resources are extremely scarce, and water needs to be used efficiently to safeguard future economic growth and prevent resource depletion. In those countries, WDM can serve both the environment and the economy in a better way. In the Middle East, WDM can be a major option for resolving Israeli–Palestinian water conflicts (Tate 1990; Stephenson 1999; Gumbo et al. 2005; Kolokytha and Mylopoulos 2004).

Adaptation measures in water resources management policies and practices are necessary to meet the challenges posed by current and upcoming changes in climate. Both supply-side and demand-side adaptation strategies can be

adopted to ensure an adequate water supply in the context of climate change. Supply-side options, such as water storage capacity, extraction from underground and water courses, and water transfers have already been implemented on a large scale in China. Climate change may affect the function and operation of existing water-related infrastructures, including hydropower, structural flood defenses, drainage and irrigation systems, as well as water management practices (Gleick 2002; Latinopoulos 2008; Zhang 2005; Butler and Memon 2010; Wang et al. 2012b, 2014b). Therefore, demand-side adaptation strategies can be the best option to meet the challenges posed by climate change.

Principles of demand control and quota management

It can be concluded from the discussions made in the above sections that economic development and population growth have caused an increase in total water consumption throughout the world. Water resources are limited resources. Therefore, increased water demand may lead to serious water shortages in different parts of the world. It is necessary to take measures for water demand management. As demand management and water-use efficiency are the most important factors for water demand, total demand control and quota management could be the core strategy to deal with water shortages in China. Total demand control and quota management strategies are described below.

Total demand control

With a given basin or area, the water resources system has a limited ability to assure economic development and population growth. As the water supply reaches a critical phase, people try to cope with the situation through expansion of these high-throughput water systems, which, in turn, puts an increasing pressure on the limited water resource, as well as on the integrity of local aquatic ecosystems. For a given basin or area, the water carrying ability can be calculated as:

$$PWD_i^t + DWD_i^t + EWD_i^t \leq CWD_i^t \quad (1)$$

where PWD_i^t is production water consumption, DWD_i^t is domestic water consumption, EWD_i^t is ecological water consumption, and CWD_i^t is water carrying ability. The Eq. (1) shows the relationship between water resources and economic development, population growth and ecological construction. If this relationship is broken, then a water crisis between different sectors will arise. Therefore, it is necessary to keep the total water demand below the carrying ability of water systems, as well as having water distributed among different consuming sectors.

Quota management

Water quota is the standard of quantity of water intake per capita, or per area, or per product in unit time. Quota is an important factor in reflecting water-use efficiency. It is a core strategy for water demand management. China has imposed quotas for different sectors in recent years for the management of water resources. At present, each province has a quota for water management within different sectors.

Quota is a factor which is influenced by technology, water supply, water users, and other issues. It is a dynamic factor that changes with time. Therefore, it is necessary to consider all the issues when defining quota. A quota management system can be defined by the equation below:

$$\begin{aligned} S^t - IEW_{pk}^t - \sum_{j=1}^n (S_j \times AQ_n) - M_f A - \sum n_i \cdot m_i \\ - \sum_{i=1}^n (X_i^t \times IQ_i^t) - Po_i^t \times LQ_i^t \times 365/1,000 - PW_{pj}^t \\ - OEW_{pk}^t = 0 \end{aligned} \quad (2)$$

where S^t is the total water supply, which includes water supply from reservoirs, river diversion and groundwater pumping; IEW_{pk}^t is in-stream water consumption; S_j is the area covered by different crops; AQ_n is irrigation quota for different crops; A is fishery pond area; M_f is the quota for fishery water consumption; n_i is the amount of animal husbandry; m_i is the quota for animal water consumption; X_i^t is industrial development; IQ_i^t is the quota for industrial production; Po_i^t is population growth; LQ_i^t is the quota for daily life; PW_{nk}^t is the quota of ecological water consumption; and OEW_{pk}^t is out-stream water consumption.

Framework of total demand control and quota management

With ecological deterioration, the Chinese government has paid additional attention to the sustainable use of water resources in recent years. The basic principle of water management policy of the Chinese government is to meet the needs of the present without compromising the ability of future generations to meet their own needs. Therefore, China is leaning towards water demand management to achieve sustainability in water resource management (Zhang 2005; Macleod et al. 2007; Cosier and Shen 2009). Recently, the Chinese government has adopted the strictest water resource management measures to grapple with water shortages. The measures focus on three “red lines” or security lines: (1) to limit the scale of water exploitation; (2) to improve the efficiency of water usage; and (3) to curb water pollution. The Chinese government is considering water demand management as the most suitable option to comply with these three “red lines” of water resource management. A framework of water demand management is developed in this study to fulfill the goal of the Chinese government to achieve sustainability in water resources, shown in Fig. 6. The proposed framework consists of two major components, namely, total demand control and quota management, which should be implemented together for water demand management. The components of the framework are discussed below.

Total demand control in China

Total demand control refers to a strategy that helps in improving water-use efficiency through system

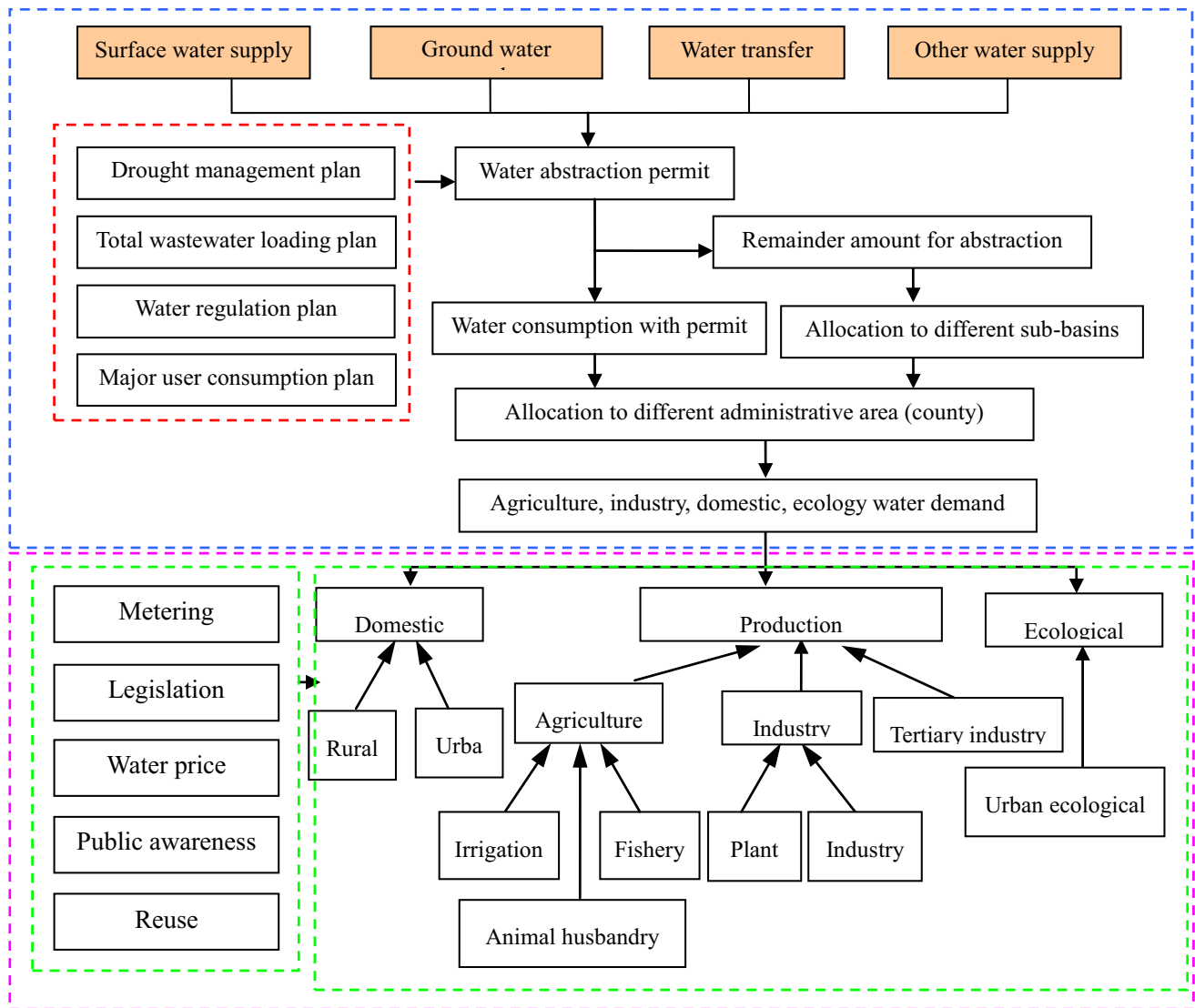


Fig. 6 Frameworks of water demand management based on total demand control and quota management in China

improvement, accountability, capacity building, regulation reinforcing, and accelerating the creation of a water-saving society. Consequently, it can help to promote sustainable use of water resources and transformation of the economic development pattern, match socioeconomic development with carrying capacities of water resources, and, thereby, safeguard sustainable socioeconomic development. However, the total quantity control program should be made under full consideration of the water supply system, water abstraction permit system, water function zones, the water regulation plan, and major water consumers (Pei et al. 2009; Chen et al. 2009; Liu and Speed 2009). Therefore, the framework of total demand control is developed by considering all of those components, which are shown in Fig. 6. The water supply system component of the total demand control framework will provide information regarding

available water from all possible sources, including surface water, groundwater, water transfer, and other sources of water supply, such as re-use and recycling. Water abstraction permit systems will function according to the availability of water from all sources and the government’s plans for water use. The plans may include a drought management plan, wastewater loading plan, water regulation plan, and major user consumption plan. The exploited water-using abstraction permit will be allocated to different administrative areas. A part of the extracted water will be allocated to different sectors, such as agriculture, industry, residences, and ecosystems, according to water consumption permits. The rest of the extracted water will be allocated to different sub-basins for ecological consumption. The water consumption permits for agriculture, industry and residences will be given according to quotas allocated for those sectors.

Quota management in China

Quota management is considered a core strategy in developing a water resources governance model for water demand management, aiming at establishing a water-saving society (Jiang et al. 2010). Water quota is also a comprehensive reflection of the users' water demands and levels of water-saving and water management. Therefore, quota management of water consumption should be reinforced by making a timely amendment to water-use quotas. Furthermore, a quota management system should be set up under potential legislation, technology of water saving, metering and leakages, wastewater re-use and water pricing, which are widely recognized around the world. Based on this concept, the framework of a quota management system is developed in this study, which is also shown in Fig. 6.

The proposed quota management system considers the amount of water required for each sector. The amount of water required by different sectors varies. It is also different within each sector. For example, paddy cultivation needs more water than wheat cultivation. Similarly, various types of industry require different amounts of water for production. The proposed quota management system would define quota according to the types of crops, pond areas, amount of animal husbandry, industrial production, and the like. The quota management system will operate under legislation. The amounts of the quota will continuously be monitored and re-adjusted according to available water-saving technology, wastewater re-use and water pricing.

The proposed water demand management framework, based on total demand control and quota management, can be an efficient way for future water management in China. Through the creation of a water-saving society by total demand control and quota management, it is possible to harmonize the relationship among water, environment, ecosystems, and human beings in China.

Water demand management in the Haihe River Basin of China

The Ministry of Water Resources in China has already done some work in water demand management, which has improved water-use efficiency. China has adopted four important laws for water management, for example: (1) Water Law (adopted in 1988 and revised in 2002); (2) Law on Water Pollution Control (adopted in 1984); (3) Soil and Water Conservation Law (adopted in 1991); and (4) Flood Control Law (adopted in 1997). Those four laws are the fundamental laws for water resource utilization, protection, management and flood control in China (Zhang 2005). Unfortunately, China still does not have any legislation on a quota for water consumption. Therefore, it is necessary to

introduce legislation for quota management in China (Zhang 2005; Pei et al. 2009; Liu and Speed 2009; Wang et al. 2012b). Initiatives of the Chinese government toward water demand management have improved water-use efficiency in some river basins of China. The Haihe River Basin is one such river basin, which has experienced success in water demand management.

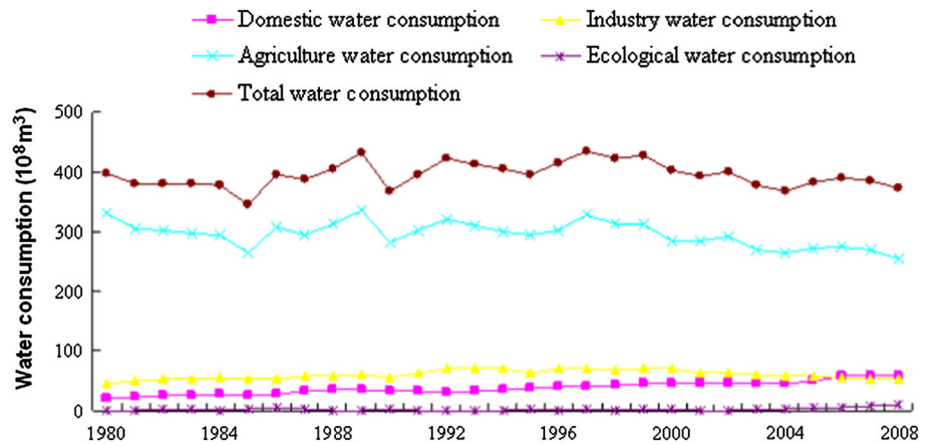
The Haihe River Basin is the political, economic, and cultural center of China. The two most important and populated cities in China, namely, Beijing and Tianjin, are situated in the Haihe River Basin. Following economic development in the late 1990s, the urban areas of the basin have expanded greatly, with many areas that were formerly farmland now developed residential or commercial districts. With the significant influx of migrants from various regions of the country, especially rural areas, the population of the basin has increased rapidly in the last two decades. Significant industrial growth was also observed in the Haihe River Basin within the past two decades (Yang et al. 2010; Ji et al. 2012; Wang et al. 2013).

Rapid population growth and economic development caused changes in water demand in the basin, which are shown in Fig. 3. It can be seen from the figure that water demand, especially in domestic and industrial sectors, increased rapidly in the 1980s and early 1990s. Meeting an ever-increasing water demand only through augmentation of the water supply became very difficult. Therefore, water demand management, along with water supply management, was emphasized, in order to manage the increasing water demand in the Haihe River Basin (Wang et al. 2014b). The government introduced a series of national water strategy actions. Initiatives to increase water-use efficiency in industry and irrigation were created; these imposed water prices and water quotas (Pang and Zhang 2001; Yang 2002; Wu et al. 2007; Yang et al. 2010; Wang et al. 2013).

Agricultural areas declined significantly in response to total demand control measures by imposing higher water prices (Xiao and Shen 2008; Yang et al. 2010). At the same time, water-use efficiency in agriculture increased, due to the adoption of new irrigation technology. According to Pang and Zhang (2001) and Yang (2002), by the year 2000, water use per unit of land in the Haihe River Basin had decreased by 20 %. Therefore, the governmental initiatives of total demand control and quota management were successful in reducing agricultural water consumption in the Haihe River Basin (Ji et al. 2005, 2012; Wu et al. 2007; Wang et al. 2013).

Despite the industrial growth in the basin, it was also possible to keep industrial water demand stable by adopting total demand control and quota management strategy (Wang et al. 2013). The Haihe River Basin achieved high efficiency in industrial water consumption by adjusting industrial structures and arrangements, limiting high levels

Fig. 7 Changes in water consumption in the Haihe River Basin during the time period 1980–2008 (Wang et al. 2013)



of water consumption in production, adopting water-saving technology, and gradually increasing the proportion of new technology industries that use less water (United Nations 2005). This caused the average water consumption quantum for every Chinese Yuan Renminbi (RMB) 10,000 output value to decrease from 160 m³ in the early 1990s to 51 m³ in 2004 (Wang et al. 2013). In Beijing, a water quota, along with high penalties for exceeding the water quota, led to a 37 % reduction in industrial water use in the 1980s (Bhatia and Falkenmark 1992). Tianjin was able to increase its rate of industrial output per cubic meter of water from \$18.5/m³ in 1981 to \$45.5/m³ in 1988—a reduction of 14 % per year in average industrial water consumption per unit of industrial output (Bhatia et al. 1995). Consequently, water consumption in the industrial sector stabilized, even with the continuous industrialization in the basin (Wang et al. 2013). It can be concluded from the above analysis that water demand management using demand control and quota management have successfully reduced the total water demand of the Haihe River Basin. Therefore, for achieving water resource sustainability in the contexts of population growth, economic development and climate change, it is recommended that more emphasis be given to demand control and quota management (Fig. 7).

Conclusions and discussion

As the most populated and most rapidly developing country in the world, one of the major challenges for the Chinese government is to guarantee a continuous water supply to improve the livelihood of its growing population and to maintain the rapid growth of the economy. Water supply and demand for China during the time period 1980–2009 have been analyzed in this paper to formulate water demand management strategies for a sustainable water supply. The study proposes that water supply management strategy, based on demand control and quota

management, is the best option for sustainable water management in China, instead of supply augmentation by engineering construction. It can be hoped that total demand control and quota management can help in building a water-saving society in China.

However, the authors recommend that further research be required on the following issues: (1) Because of the unavailability of data, only 60 years of total water consumption data for China are used in the present study. These data showed that water consumption in China has changed during three periods. Further study can be carried out in the future, with a longer timeframe to determine other periods of water consumption. (2) Total quantity control and quota management can be the most efficient way to effect future water management in China. However, these means for water management should be further studied for their practical implementations. Most especially, further research is needed to legislate demand control and quota management laws.

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