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Improving China's water resources management for better adaptation to climate change

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Abstract Challenged by insufficient water resources and by degraded water quality caused by widespread pollution, China faces an imbalance between the supply and the demand of water for supporting the rapid social and economic development while protecting the natural environment and ecosystems. Climate change is expected to further stress freshwater resources and widen the gap between the demand for and supply of water. As a legacy of the earlier planned economy, water resources management has been primarily supply-driven, which largely fails to account for the economic nature of water resources in relation to their natural characteristics. This paper presents a historical perspective on the water resources management policies and practices in China, and recommends demand management and pollution control as key measures for improving water resources management to adapt to climate change based on the current political, socio-economic and water resources conditions. The past and future impacts of climate change on water resources in China and the general adaptation strategies are also presented. How demand management through increasing water use efficiency, improving water rights and rights trade, and effective regulation enforcement, along with pollution control could improve China's water resources management are discussed in details. Ultimately, China should develop a sustainable water resources management strategy based on both supply- and demand-side management options to make the limited water supplies meet the demands of economic development, social well-being and the conservation of ecosystems in the context of global climate change.

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1 Introduction

Water is a renewable, but finite resource with global and regional constraints. The future effects of climate change on water resources in China will depend on trends in both climatic and non-climatic factors. Climate affects the hydrological cycle at both global and regional scales, and consequently the availability of, and demand for, water resources (Arnell 1999; Parry et al. 2007; Rosenzweig et al. 2004). Non-climatic factors, including urban growth, landscape changes, pollution, population growth, and increased living standards, are exerting increasing pressures on ecosystems and water resources (World Water Assessment Programme 2009). Figure 1 shows the inter-connections among human activities, climate change, water supply and demand. Population growth, economic growth, and improvement in living standards drive the changes in freshwater resources through changes in land use, water withdrawals, and climate related to food production and the emissions of the greenhouse gases (Kundzewicz et al. 2007).

Climate change directly affects water resources through changing the quantity, variability, timing, form, and intensity of precipitation, and indirectly impacts water resources through increasing water temperature, increasing evapotranspiration rate, and decreasing water quality (Arnell 1999; Bates et al. 2008; Kundzewicz et al. 2007; Parry et al. 2007). Table 1 summarizes the major projected impacts of climate change on ecosystems, water resources, and human society based on projections

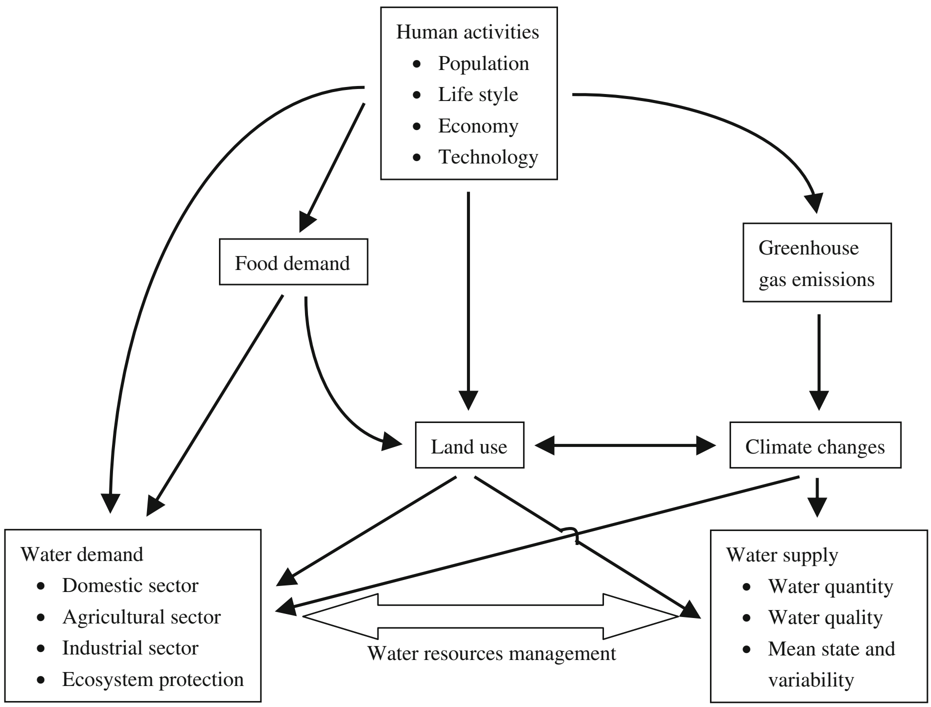

Fig. 1 Inter-connections among human activities, climate change, and water supply and demand (after Oki 2005)

Table 1 Possible impacts of climate change due to changes in extreme precipitation-related weather and climate events predicted for the mid- to late twenty-first century assuming no changes or developments in adaptive capacity (after Bates et al. 2008)

Phenomenon and direction of trend	Projected likelihood of future trend	Examples of major projected impacts by sector			
		Agriculture, forestry and ecosystems	Water resources	Industry, community and society	Human health
Heavy precipitation events: frequency increases over most areas	Very likely	Damage to crops Soil erosion Waterlogging of soils preventing land cultivation	Degradation of surface and groundwater quality Contamination of water supply Water scarcity may be relieved	Flooding causing disruption to homes, businesses, transport and utilities, with consequent cost to societies Pressures on urban and rural infrastructures Property loss	Increased risk of deaths, injuries and infectious, respiratory and skin diseases
Area affected by drought increases	Likely	Land degradation Lower crop yields due to damage and failure Increased livestock deaths Increased risk of wildfire	More widespread water stress	Water shortages for municipal and industrial uses Reduced hydropower generation potentials Potential for population migration	Increased risk of food and water shortage Increased risk of malnutrition Increased risk of water- and food-borne diseases
Intense tropical cyclone activity increases	Likely	Damage to crops Windthrow of trees Damage to coral reefs	Power outages disrupting public water supply	Disruptions caused by flooding and high winds Withdrawal of risk coverage in vulnerable areas by private insurers Potential for population migration Property loss	Increased risk of deaths, injuries, water- and food-borne diseases Post-traumatic stress disorders

to the mid- to late twenty-first century. Many water supply sources (rivers, lakes, groundwater basins, etc.) in China are already over-exploited and heavily polluted, and are often not able to sustain natural aquatic ecosystems (Cheng et al. 2009; Liu and Diamond 2005; Shao et al. 2006). Climate change has already aggravated and may further aggravate the water challenge in China, worsening the water shortages and intensifying the conflicts among water users (Arnell 1999; Rosenzweig et al. 2004; Xiong et al. 2009a).

Adaptation measures in water resources management policies and practices are necessary to meet the challenges of the current and upcoming climate change. Both supply-side and demand-side adaptation strategies can be taken to ensure water supply during average and drought conditions. Table 2 lists the major supply-side and demand-side adaptation options available, and the potentials for their successful implementation in China. Supply-side options generally involve increases in storage capacity, abstraction from underground and water courses, and water transfers, which have already been implemented in large scales and have already brought some adverse environmental consequences (as discussed in Sections 3 and 6). Meanwhile, climate change affects the function and operation of existing water-related infrastructure, including hydropower, structural flood defenses, drainage and irrigation systems, as well as water management practices (Bates et al. 2008; Harrington and Morgenstern 2004).

In the context of limited water resources availability in China and the uncertainties in supply brought by climate change, demand management becomes critical for sustainable management of the country's water resources. Various supply management approaches, such as building large-scale infrastructures of water storage and long-distance, inter-basin transfers, and development of alternative water resources through rainwater harvesting, precipitation enhancement, desalination, and wastewater reclamation, have been carried out to balance the spatial and temporal availability and to increase the supply of water resources (Cheng et al. 2009). Here we argue that demand-side water resources management through increased water use efficiency, development of market-based water allocation framework, and effective regulation enforcement, along with water pollution control are key for China to adapt to the future impacts of climate change on its water resources. We first present an overview of China's water resources and give a historical perspective on the water resources management policies and practices in China. The past and future impacts of climate change on water resources in China and the general adaptation strategies are summarized. Based on the current political, socio-economic and water resources conditions in China, we recommend that immediate measures on increasing water use efficiency, improving water rights and rights trade, effective regulation enforcement, and on pollution control to improve the overall quality of freshwater resources should be taken in water resources management to adapt to climate change.

2 Overview of China's water resources

China is the 3rd largest country in the world, with 9.6 million km^2 of land mass extending from the Tibetan Plateau in the west to the coastal plains of the east. The country's scale and complex topography have resulted in diverse river and climatic systems, including tropical, subtropical, semi-arid, arid, inland and coastal

Table 2 Major adaptation options for water supply and demand and their status in China

Supply-side[a]	Current status	Demand-side[a]	Current status
Prospecting and extraction of groundwater	Groundwater accounted for 18.3%, or 108.2 billion m^3, of China's water supply in 2008 (MWR 2010) Groundwater has been extensively extracted in northern China Seawater intrusion in coastal areas and land subsidence in areas of extensive groundwater extraction have occurred	Improvement of water-use efficiency by recycling water	The national integrated irrigation water use efficiency was only 0.38, and the mean irrigation water consumption in China was as high as 6,735 m^3/ha/year in 2006 (MWR 2007) The water consumption for 10,000 Yuan industrial output was 178 m^3 and the industrial water recycling rate was 60–65% in 2006, in contrast to the <50 m^3 water consumption and 80–85% recycling rate in the developed countries (MWR 2007; NDRC 2007) There is significant room for improving the efficiency of water use in China, which can offset the increasing water demands from all sectors
Increasing storage capacity by building reservoirs and dams	A total of 308.3 billion m^3 water was stored in 500 large (>0.1 billion m^3) and 2,980 medium (0.01–0.1 billion m^3) dams and reservoirs in 2008 (MWR 2010) Water storage accounted for 33.8%, or 162.1 billion m^3, of China's surface water supply in 2008 (MWR 2010)	Reduction in water demand for irrigation by changing the cropping calendar, crop mix, irrigation method, and area planted	Changes in cropping patterns based on available water resources are being made nation-wide Farming practices are being changed by adjusting cultivation period, applying appropriate crop rotations, and adopting new varieties that are resilient to climate variability

Table 2 (continued)

Supply-side[a]	Current status	Demand-side[a]	Current status
	Based on the definition of the International Commission on Large Dams (ICOLD), large dams are those with a height of 15 m from the foundation or having a reservoir capacity of more than 3 million m^3 if the height is between 5 to 15 m, and over 45,000 such large dams exist around the globe. China has almost half of these dams with more than 22,000, followed by the United States (6,600), India (4,300), Japan (2,700), and Spain (1,200) (Silk et al. 2005).		Crop research oriented towards adaptation to environmental stress, such as rising temperatures and water scarcity, is being carried out
Water transfer	Inter-basin water transfer accounted for 2.7%, or 12.9 billion m^3, of China's surface water supply in 2008 (MWR 2010).	Reduction in water demand for irrigation by importing agricultural products, i.e., virtual water	China maintains a long-term policy of self-sufficiency in agriculture Although controversial, it is unlikely for China to rely on imported agricultural products
Desalination of sea water	More than 20 seawater desalination plants with 30–5,000 m^3/day capacities were in operation in 2005, producing 31,000 m^3/day desalinated water (Zhang et al. 2005) The total brackish water desalination capacity was 28,000 m^3/day in 2005 (NDRC 2005b) Expansion of desalination is limited by capital cost and by energy supply	Expanded use of water markets to reallocate water to highly valued uses	Water rights in China are poorly defined and not well established, inhibiting market-based water allocation Water rights and water rights trade are being developed and promoted as effective mechanisms of water allocation in China

Table 2 (continued)

Supply-side[a]	Current status	Demand-side[a]	Current status
Expansion of rainwater storage	Widely promoted for agricultural and household uses in the semi-arid loess regions since the 1980s About 12 million water cellars, tanks and small ponds were built with a total storage capacity of 16 billion m^3, supplying water for household use of 36 million people and supplemental irrigation for 260 ha of dry farming land by 2001 (Khaka et al. 2005) Rainwater harvesting contributed to 1.3 billion m^3 of water supply in 2006 (MWR 2007) Also practiced in cities in northern China, with the collected rainwater used for not-potable applications	Expanded use of economic incentives including metering and pricing to encourage water conservation	Under-pricing of water has been a major cause of low water use efficiencies in China. Despite price increases in recent years, China's water is still among the world's cheapest, and the price of water remains below cost in most places Implementing market-driven prices will play a key role in deterring water waste and pollution in all sectors China is gradually introducing a market-based pricing mechanism in the water industry
Precipitation enhancement	Regularly practiced in semi-arid and arid regions to augment freshwater supplies From 1995 to 2003, 23 provinces conducted precipitation enhancement operations, covering more than 0.3 billion ha of land with a total rainfall volume of 210 billion m^3 (Gao 2004)		

Table 2 (continued)

Supply-side[a]	Current status	Demand-side[a]	Current status
Municipal wastewater reclamation	Popular in water-stressed cities in northern China, and limited to non-potable reuse About 4% of the 24.4 billion m^3 of municipal wastewater discharged was reclaimed in 2006 (MHURD 2007) Still in its infancy in China, with further development limited by cost of advanced treatment		

[a] Adaptation options are after Bates et al. (2008) and Cheng et al. (2009); the supply-side and demand-side measures are not paired comparison

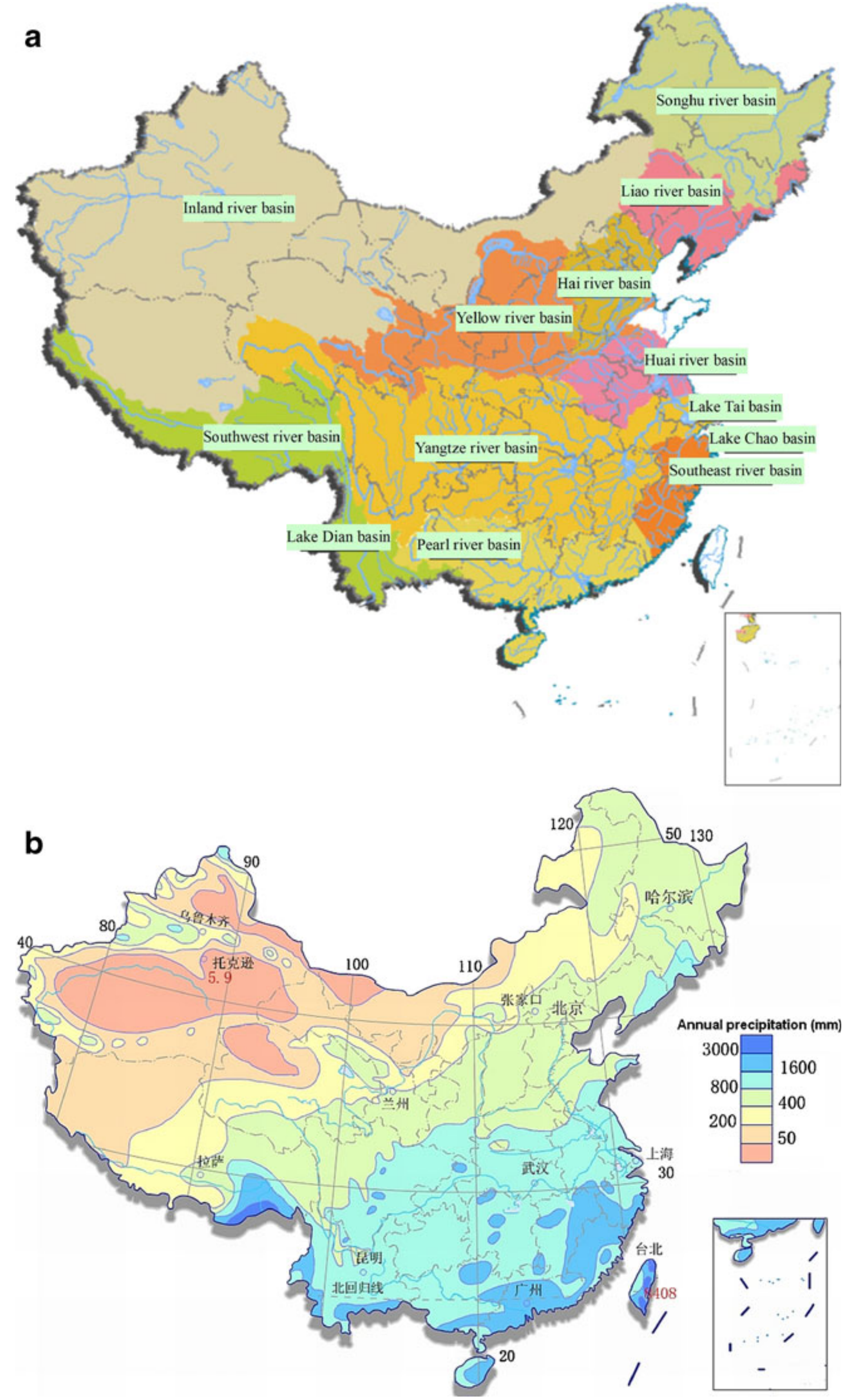

Fig. 2 China's water resources: **a** distribution of the major watersheds; and **b** long-term mean annual precipitation

systems (Liu and Speed 2009; Speed 2009a). Figure 2a shows the distribution of China's major watersheds. There are more than 1,500 rivers draining areas over 1,000 km^2, and more than 50,000 rivers with catchment areas greater than 100 km^2. The majority of these rivers are located in the eastern parts where the monsoonal climate produces abundant rainfall (Liu and Speed 2009). Most of the rivers flow eastward or southeastward into the Pacific Ocean in accordance with the topography. China has more than 2,800 lakes with water surfaces of over 1 km^2, most of which are located in the middle and lower reaches of the Yangtze River (mainly freshwater lakes) and the Tibetan Plateau (mainly saltwater lakes). In addition, approximately 500 large-scale reservoirs (>0.1 billion m^3) and 3,000 middle-scale reservoirs (0.01–0.1 billion m^3) with a total water storage capacity of over 300 billion m^3 have been built (MWR 2010). China also has significant reserves of groundwater; the groundwater resources in flatland (mainly pore water) and hilly land (mainly fissure water and Karst water) are approximately 160 and 6,200 billion m^3, respectively (MWR 2010). Surface water and groundwater account for approximately 80% and 20% of China's freshwater supply (591 billion m^3 in 2008), respectively (MWR 2010).

China is one of the 13 water-deficient countries in the world, despite the apparent abundance of water resources. The country ranks the first in population (1.3 billion) and the 6th in total water resources (2.8 trillion m^3) in the world, while the annual per capita renewable freshwater availability is less than 2,200 m^3, or 1/4 of the world's average (MWR 2010). Besides the shortage in total quantity, China's water resources are unevenly distributed, both spatially and temporally (Cheng et al. 2009). The annual precipitation declines gradually from >1,600 mm in the coastal provinces of the southeast to <50 mm in the northwest (Fig. 2b). Due to the marked continental monsoon climate, 60–70%, even up to 80% in the north, of the precipitation occurs during summer (June to September), causing alternating drought spells and flood disasters (Cheng et al. 2009). In addition, large annual variability, particularly in the more arid north, also exists, with the wettest years having eight times the precipitation of drier years (Liu and Speed 2009). The water shortage is further aggravated by pollution, which renders some of the water sources unusable as drinking water and industrial water supplies and causes "water scarcity" despite abundance of quantity (Cheng et al. 2009; Cheng and Hu 2011; Jiang 2009). The rapid industrial growth and insufficient attention paid to environmental protection in the past three decades have caused widespread pollution of the country's surface water and groundwater (Liu and Diamond 2005; Jiang 2009; Shao et al. 2006). A recent national water quality survey showed that only 61.2% of the river sections, 44.2% of lake areas, 80.2% of reservoirs, and 26.2% of groundwater wells could meet the quality criteria of drinking water sources (MWR 2010).

China's water resources scarcity and widespread water pollution, combined with the increasing demands resulting from the rapid social and economic growth limit its further development and sustainability (Cheng et al. 2009; Cheng and Hu 2010a, 2011; Yang and Pang 2006). Water supply shortage in China could also threaten global sustainable development and have worldwide impacts if the country's ability to produce sufficient food to feed a large and growing population can no longer be maintained (Cai and Ringler 2007; Xiong et al. 2009a, b; Tso 2004). In the context of global climate change, making the limited freshwater supply meets the demand from social and economic development while protecting the natural environment and ecosystems is a crucial yet challenging task for water resources management in China.

3 Evolution of China's water resources management

3.1 China's political-economic system

Water resources development and management refers to the actions required to manage and control freshwaters to meet human and environmental needs (Lenton et al. 2005). Such actions range from water governance and management measures, investments in water-related infrastructures, and investments and actions undertaken to protect groundwater, control salinity, and promote water conservation (Lenton et al. 2005). The administrative arrangements for water resources reflect the hierarchical nature of China's political system (Speed 2009a). Since the foundation of the People's Republic of China (PRC) in 1949, it has been a single-party socialist republic, with the leadership of the Chinese Communist Party stated in the constitution. Local institutions are under the dual leadership of both the central authorities and the local government, as illustrated for the administration system related to water resources management in Fig. 3. The central government directs the laws, policies and activities of the provincial and local governments, although negotiations and tensions between them may arise over funding, government priorities and the implementation of certain policies and laws (Speed 2009a). Given the political and financial dependence of local institutions on the local government, the control exerted by the local government can compromise the centralized command at the national level. Past and current water resources management policies and practices have been, and are being influenced by the underlying social, political, and economic factors, as discussed below.

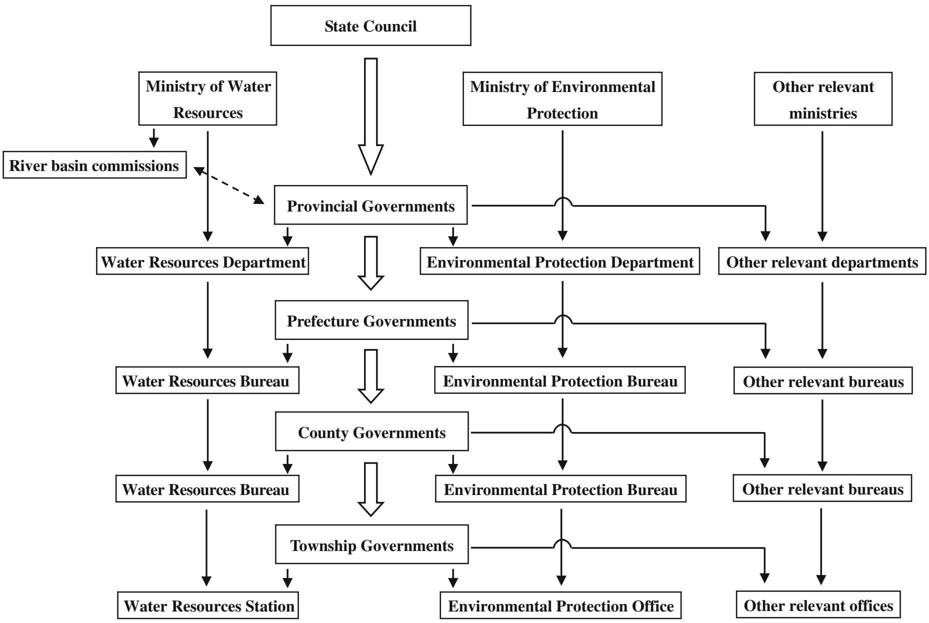

Fig. 3 China's institutional arrangement related to water resources management (after Khan and Liu 2008)

3.2 Water resources management under planned economy (1949–1978)

The Ministry of Water Resources (MWR) proclaimed that rivers and lakes are state resources and publicly owned, and should be managed by MWR and its subordinate offices upon the foundation of PRC. Water rights, the rights to use water and to benefit from it, should be obtained prior to the construction of any water resources development projects (Wang 2007). The first constitution issued in 1954 established that water resources are owned by the state, on behalf of the people. The state (in its various forms) led water resources development, including a major expansion of reservoirs and irrigation districts from the 1950s to 1970s (Calow et al. 2009). Large-scale and capital-intensive projects that emphasized power-generation, irrigation and flood control dominated the water resources management efforts between 1949 and 1957 (Qian 1992; Shen 2004). In 1958, China embarked on the Great Leap Forward, aiming to achieve great technical and economic accomplishments quickly. Large-capital projects were put aside in favor of low cost, locally funded projects, and efficient use of resources and agricultural production were promoted as means of attaining economic independence (Liang 2005). Following the disastrous failure of the Great Leap Forward, the focus of water resources management was turned away from pure engineering to improving existing water works, and revising and rehabilitating the river, drainage, and irrigation plans from 1961 to 1965 (Chi 1965). A widespread social and political upheaval (the Cultural Revolution) occurred over the next 10 years, resulting in nation-wide chaos and economic disarray. Nonetheless, with the country's food self-sufficiency policy that emphasized agriculture's paramount importance, significant progresses were made on development of agricultural irrigation and drainage networks (Qian 1992). On the other hand, water resources management at the national level barely existed due to the elimination of relevant administrative offices and technical personnel.

During the period of the centrally planned economy, the central government monopolized the allocation of resources by administrative orders, mandatory plans, and administrative personnel appointments and removals (Zhang and Wu 2006). The central government allocated and managed water with a hierarchical administrative system through water-related departments at various levels, which often had incoherent management policies and practices (Shen 2004). The bureaucratic, top-down allocation mechanism was inefficient yet bore high management costs, and the public at large had few opportunities to influence government's decisions over local water management (Jiang 2009).

3.3 Water resources management during the planned-to-market economy transition (1978–2001)

At the end of 1978, China launched a series of political and economic reforms, which laid the foundation for the country's economic take-off in the 1990s. Orthodox socialist doctrines were abandoned and the national focus was shifted away from ideological struggles toward economic development (Xie 1993). As a result, China experienced a dramatic transformation from a planned economy to a market economy, and a political transition from centralized governance to decentralized governance in the 1980s and 1990s (Gu and Wong 2008). A new constitution, which reiterated the state's ownership of water resources and defined China's new legal approach to decision making, was introduced in 1982. This spurred a long line of national legal documents governing water, including the Water Law passed in 1988 (Liang 2005). Under the Water Law, the central government allocated the right of water to administrative regions, which further distributed the water to end users (People's Congress 1988). With the government focused heavily on economic growth, water resources management received little attention and funding during this period. Meanwhile, the ambiguities over system ownership and maintenance responsibilities led to deterioration of irrigation infrastructure in the 1980s, which fueled groundwater development and eventually over-exploitation in northern China (Lohmar et al. 2003). The once heavily regulated industrial sector grew rapidly and put a much higher demand on water supply, while the agricultural water demand also experienced fast paced growth. These growing demands made water scarcity an emerging problem for water resources management.

With the government oversight on private industries further lessened, China's industrial growth expanded rapidly in the 1990s. The sustained rapid economic growth and urbanization brought increased demands for water from all sectors, while the accompanying pollution exacerbated water scarcity, which became a greater threat than flooding (Liang 2005). Public became increasingly aware of the pollution and degradation of the natural environment brought by the rapid economic growth. In the late 1990s, the concept of "water resources management" was redefined, downplaying the role of engineering in managing the water while focusing on the management of water as a resource (Boxer 2001, 2002). Local and provincial bureaus were given the authority to make decisions about water distribution and infrastructure development based on the best market instruments, which take a more comprehensive account of agricultural, domestic and industrial water supply, water quality, and water conservation (Liang 2005).

3.4 Toward right-based water resources management (2002–present)

With increasing demands on water resources and awareness of environmental issues, China's Water Law was amended in 2002 to introduce measures for more equitable and sustainable management of the country's water resources in a socialist market-led economy. The amended Water Law focused on four topics: (i) water allocation, right and permit; (ii) river basin management system; (iii) water use efficiency and conservation; and (iv) protection of water resources from pollution (People's Congress 2002). It set up a water rights licensing system along with a compensation system, and marked the transition from a development phase focused almost exclusively on infrastructure development to a phase where attention was switched to the management and protection of water resources (Zhou 2008). The functions and legal status of basin commissions were defined for the first time, and they were given greater authority in allocation and centralized control over all diversion projects (Shen 2004). In reality, obscure delineation of authority and responsibilities among government agencies involved in water resources management at different levels undermines the ability of basin commissions to allocate water resources, coordinate water resources exploitation and conservation, and enforce water resources planning at the basin level (Jiang 2009). In stead, water resources administration is largely based on political boundaries rather than on watersheds. Following the amended Water Law, the National 11th Five-Year Plan (2006–2010) further required improvement of the existing water use license and water resources compensation systems, and set a goal on establishing an initial water rights allocation system and a water rights transfer system (State Council 2006).

Despite the recent efforts in re-organizing various ministries by the central government to streamline governmental functions and reduce unnecessary bureaucracy, the current institutional system of water resources management still involves multiple government agencies at different levels. There are 8 central government agencies that hold certain responsibilities of water resources management, as detailed in Table 3. Inconsistent policies and conflicting interests among different ministries on water and their lack of cooperation actually weaken water resources management, instead

Table 3 Water-related government agencies under the State Council and their functions in water resources management (after Feng et al. 2006)

Department	Scope of water administration	Major responsibilities
Ministry of Water Resources (MWR)	Surface and ground water management, river basin management, flood control, water and soil conservation.	Water resources survey and assessment, planning of water development and conservation, flood control, water and soil conservation, designation of water function zones, unified water resources administration.
Ministry of Environmental Protection (MEP)	Prevention and control of water pollution.	Water environment protection, water environment function zoning, establishment of national water environment quality standards and national pollutant discharge standards.
Ministry of Housing and Urban-Rural Development (MHURD)	Urban and industrial water use, urban water supply and drainage.	Planning, construction and management of water supply projects, drainage and sewage disposal projects, urban water conservation.
Ministry of Agriculture (MOA)	Agricultural water uses and fishery habitat protection.	Construction and management of irrigation infrastructure, irrigation water conservation, non-point source pollution control, protection of aquacultural environment, aquatic environmental conservation.
State Forest Administration (SFA)	Water resources conservation.	Forest protection and management for protecting watershed ecology and water resources.
National Development and Reform Commission (NDRC)	Supervision of the planning of water resources development and ecosystem building.	Guidance on the planning of water resources development, allocation of production force and ecological environment construction, coordination of the planning and policy of agriculture, forest and water resources development.
Ministry of Transport (MOT)	Pollution control related to navigation of ships on rivers.	Pollution control and management of inland navigation.
Ministry of Health (MOH)	Supervision and management of environmental health.	Supervision and management of the drinking water standards.

of building a combined force to increase the efficiency of water administration (Feng et al. 2006). Although these ministries are entrusted with the administrative power related to water, their responsibilities are not clearly defined and there are significant overlaps, as illustrated for those of MWR and Ministry of Environmental Protection (MEP) in Table 4. On the local level, the subordinate departments of these agencies, as well as certain local governmental offices all play a role in water resources management. The lack of effective coordination and cooperation among these administrative units impedes effective management of water resources and significantly increases the administrative transaction costs (Jiang 2009).

Water pollution caused by rapid industrialization and urbanization became increasingly severe in a number of large cities in China by the end of the 1980s. Besides

Table 4 Major overlaps and intersections of responsibilities undertaken by MWR and MEP on water resources protection and administration (adapted from Feng et al. 2006)

Responsibility	Ministries involved	Major overlaps in functions
Water pollution control	MWR and MEP	(i) Both are involved in developing and designating water environment function zones (ii) Both are involved in defining the relationship between the capacity of a water body to accept pollutants and the prevention of pollution of the watershed (iii) Both have the responsibility of water quality monitoring
Coordination and management of trans-boundary pollution control	MWR and MEP	(i) MEP has administrative authority and responsibility to guide and coordinate the trans-regional environmental problem and pollution disputes (ii) Carrying the responsibility of watercourse management, MWR also has the power to manage and coordinate trans-boundary water pollution disputes
Enforcement of laws and regulations and supervision of water management	MWR and MEP	(i) Both have the responsibility for regulating pollutant discharges in river basins (ii) Both have the authority to establish plans, policies and regulations, to enforce regulations, and to supervise the enforcement of laws and regulations
Urban water resources use, protection and management	MWR, MEP and MHURD	(i) MWR and MEP both have the responsibility on development, protection and management of urban water resources (ii) MHURD is responsible for urban infrastructure construction projects related to the development of water resources and the protection of the water environment, including pipeline construction for water supply, drainage and sewers (iii) All three ministries hold responsibilities regarding water supply, urban water recycling, drainage and sewerage handling and discharge monitoring

the obvious engineering solutions to control water pollution (e.g., construction of new sewage treatment plants and sewers), some cities started to realize the importance of integrated water resources management (IWRM) to ensure high quality water (Lee 2006a). With the creation of the Shenzhen Water Authority in July 1993, Shenzhen led the adoption of IWRM framework, followed by Sanya in Hainan Province, Yantai in Shandong Province, Taizhou in Zhenjiang Province, and Suqian in Jiangsu Province (MWR 2003). Shanghai, a centrally administered municipality, established the first provincial level IWRM institution, the Shanghai Water Authority, in May 2000. The supervisory and planning functions of water conservancy and resource management were integrated into this single institution, which carries the ultimate responsibility for improving information exchange and cooperation among various related government departments, and solving conflicts of interest among them (Lee 2006a, b). A total of 1,360 water authorities and equivalent bureaus had been established by over 57% of provincial, municipal, and county level governments in China by early 2006 (Jiao 2006).

Despite the establishment of various water authorities and equivalent bureaus as the overarching authorities over water resources management, the responsibility for urban water supply and sewage treatment still lies with the various branches of Ministry of Housing and Urban-Rural Development (MHURD) while the responsibility for water quality control is held by those of MEP (Lee 2006a, b). Several major challenges still exist for the water authorities and equivalent bureaus, such as poor enforcement of laws and regulations, competition and conflicts of interests among various government agencies in the sector. They are not strictly integrated water resources management bodies due to lack of authority over urban water supply and sewage treatment, and water quality control (Lee 2006a, b). By examining China's current socio-political landscape against the three critical requirements for successful implementation of IWRM proposed by the Global Water Partnership, Reynolds (2008) argued that China is not ready to implement IWRM in any successful way, and that IWRM is not a viable option unless it can be adapted to China's political landscape or the political landscape changes. Nonetheless, the emergence of these various water authorities and equivalent bureaus shows positive developments in China's water resources management. Reforms in water resources management to create an integrated, efficient, and effective institutional system in the long-term are necessary in China. The new water resources management should focus primarily on management approaches, including planning, policy design, monitoring, and regulation enforcement, instead of engineering projects.

4 Impact of climate change and adaptation measures

4.1 Impact of climate change on water resources in China

Pronounced warming has occurred in China over the last several decades, which produced significant impact on the water resources. Melting of glaciers driven by rising temperature and increased precipitation increased runoff in the west; warmer conditions and decreased rainfall were accompanied by increased drought in the northeast; while the southeast experienced increased extreme rainfall events (Piao et al. 2010). Figure 4 compares the water resources in the major river basins in China

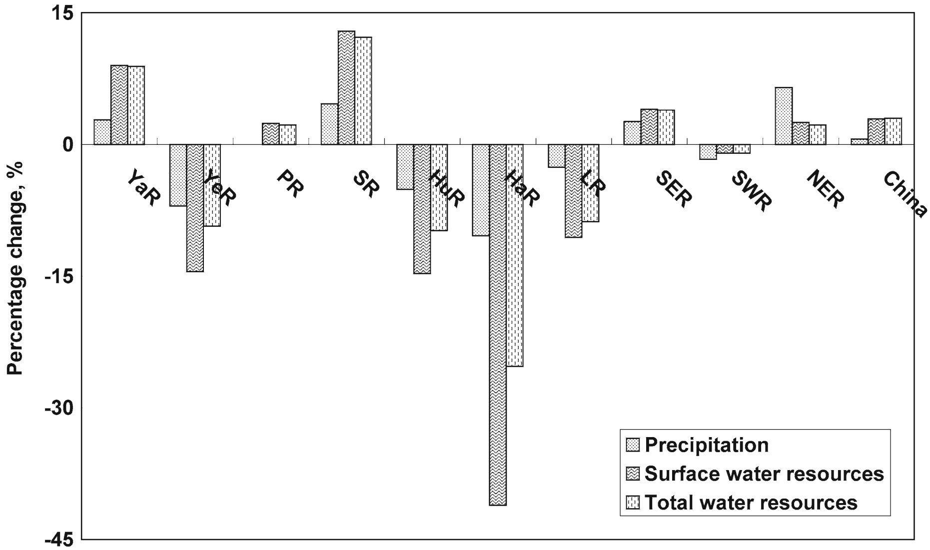

Fig. 4 Changes in precipitation, surface water resources, and total water resources in the major river basins between 1956–1979 (basis of comparison) and 1980–2000 (data from Shen 2010). *Abbreviations*: *YaR* Yangtze River, *YeR* Yellow River, *PR* Pearl River, *SR* Songhua River, *HuR* Huai River, *HaR* Hai River, *LR* Liao River, *SER* Southeast River System, *SWR* Southwest River System, *NER* Northeast River System

between the periods of 1956–1979 and 1980–2000. Precipitation in northern China has been somewhat less, especially in the Hai river basin, the middle and down reach of the Yellow river basin, since the 1980s, while most regions in southern China, parts of northwest China and northern part of northeast China had more precipitation during 1980–2000 (Shen 2010). Meanwhile, water resources decreased significantly in northern China, especially in the basins of the Yellow, Hai and Liao rivers, while runoff and total water resources increased by 5% in southern China (Shen 2010). The Hai river basin, in particular, experienced a 10% decrease in precipitation, 41% decrease in runoff, and 25% decrease in total water resources. The decline in water resources in northern China resulted from reduced precipitation and landscape change due to human activities, with reduction in precipitation being the main factor. It was estimated that 75% of the decrease in surface water resources in the basins of the Yellow, Huai, Hai and Liao rivers was due to decrease in precipitation (Shen 2010). A recent study shows that the consequences of recent climate change on water resources and agriculture in China on a countrywide basis have been limited because of the moderate climate trends in comparison with natural variability, together with the overriding benefits derived from technological progress, in particular improved agricultural practices (Piao et al. 2010).

The vulnerability of hydrological cycle and water resources system to climate change varies among river basins. In the semi-dry regions of northern China, the runoffs in the basins of the Liao, Hai and Huai rivers are small or even zero during dry season (October to May) and are very sensitive to temperature increase and rainfall decrease (Guo et al. 2002). In contrast, the river basins in the humid southern China, such as the Yangtze river basin, are less vulnerable to climate change

(Guo et al. 2002). Accelerated melting of glaciers, and reduced glacier area in western China will significantly impact rivers fed by the glaciers and cause major rearrangement in the water supply (Piao et al. 2010; Shen 2010). By contrast, the uncertainty of future river runoff in northern China is dominated by the uncertainty of global climate models in projecting rainfall (Piao et al. 2010). The rain-fed crops in the north China plain and northeast China are projected to face water-related challenges in coming decades due to the expected increases in water demands and soil-moisture deficit, and decreases in precipitation (Tao et al. 2003; Shen 2010). Xiong et al. (2010) studied the potential impacts of climate change and socio-economic development on agricultural water availability in China using models integrated with climate change and socio-economic scenarios. The results suggest that the impacts of climate change on water availability for agriculture are small compared to the role of socio-economic development, and that there will be insufficient water for agriculture in China in the coming decades, caused primarily by increases in water demand for non-agricultural uses (Xiong et al. 2010).

4.2 Adaptation to climate change

Climate change poses a significant challenge to water resources management in all countries, particularly China, which already suffers widespread water shortages (Cheng et al. 2009). Current water resources management policies and practices in China are having trouble meeting the increasing water demand brought by socio-economic development, yet climate change brings additional uncertainty in water supply (Guo et al. 2002). China has been active in mitigating and adapting to the impacts of climate change on water resources over the past decade (Piao et al. 2010). One of the goals of the amended Water Law was to implement sustainable use of water resources to meet the needs of national economic and social development (People's Congress 2002). Based on current water resources strategies and projected impact of climate change on water resources, a comprehensive list of adaptive management measures have been proposed (Shen 2010). These include (i) changing water policy from supply management to demand management; (ii) incorporating climate change into water resources planning; (iii) strengthening the construction of water infrastructure; (iv) strengthening water resources protection; (v) strengthening non-traditional water resources; and (vi) promoting implementation of integrated river basin water resources management (Shen 2010). They cover all aspects of water resources management, but do not contribute equally to the relieving of water stress in China.

Infrastructure development and new water sources development, which are essentially supply management practices, have been actively pursued in China's water resources management. Nonetheless, these options are expensive and are subjected to the uncertainty brought by climate change (Cheng et al. 2009). China has long emphasized the importance of enlarging regional water storage and strengthening the water resources and management infrastructure. The country's supply-driven, engineering-based water resources policies and management practices have put intensive efforts on capturing a greater percentage of available surface water and increasing total water storage via infrastructure building (Cheng et al. 2009; Cheng and Hu 2011; Jiang 2009). Water reservoirs and inter-basin water transfers, such as the Three Gorge Dam and the South-to-North Water Diversion Project, which serve the purposes of optimizing the allocation of water resources, controlling floods on major rivers, and alleviating drought, will continue to be a significant feature of China's future water resources development (MWR 1998; Cheng et al. 2009). Policy and institutional changes to incorporate climate change into water resources planning and to implement IWRM should be the long-term goals of water resources management in China. However, accurately predicting the impact of climate change on water resources is difficult, particularly with the rapid development in economy, land use and natural resources use in China (Guo et al. 2002; Shen 2010). Meanwhile, China's current socio-political landscape makes it difficult, if not impossible, to successfully implement IWRM at all levels, as discussed earlier (Section 3.4).

Demand management and water pollution control are immediate steps that can be taken to improve water resources management and help to adapt to the impact of climate change on water resources in China. Climate change brings uncertainty in future water supply, while the demand on water resources can be predicted and managed. Demand management focuses on strengthening water resources allocation, conservation and protection, and regulation of industrial structures according to the water resources available to increase overall water-use efficiency and benefits (Shen 2010). Poor water quality caused by pollution intensifies the quantitative shortage of the naturally available freshwater (Jiang 2009; Shen 2010). Severe pollution even causes some water to lose beneficial uses, while controlling the pollution of surface water and groundwater resources can increase the supply of good quality water by restoring the practical value of such polluted water.

Besides the climate factor, adaptation for the impact of climate change should consider a number of social, technical and economic aspects of water resources management in China. Detailed measures such as regulating the industrial structure and industrial distribution, changing agricultural structure, improving flood control, and preventing seawater intrusion can be taken based on the settings of given region (Thomas 2008; Shen 2010; Xiong et al. 2009a). On a countrywide basis, we believe demand management and pollution control are key for adaptation to climate change in China's water resources management, as discussed in the following sections. It should be noted that climate change and the alteration of rainfall and temperature regimes can affect hydropower generation, which accounts for about 15% of China's supply of electricity, while more energy will be required with increased water transfer and water treatment activities (Cheng et al. 2009). Therefore, securing the country's energy supply, which is already a challenge (Cheng and Hu 2010b), is also important in developing adaptation measures to cope with the impacts of climate change on water resources.

5 Recommendations for water demand management

As a legacy of the earlier planned economy, China's water resources policies and management practices are largely supply-driven, engineering-based, single-sector, and usually involve only a single stakeholder. Intensive efforts have been placed on the assessment and development of new water sources and installation of delivery systems to meet socio-economic needs for water. Such supply-driven water resources management largely failed to account for the economic nature of water resources in

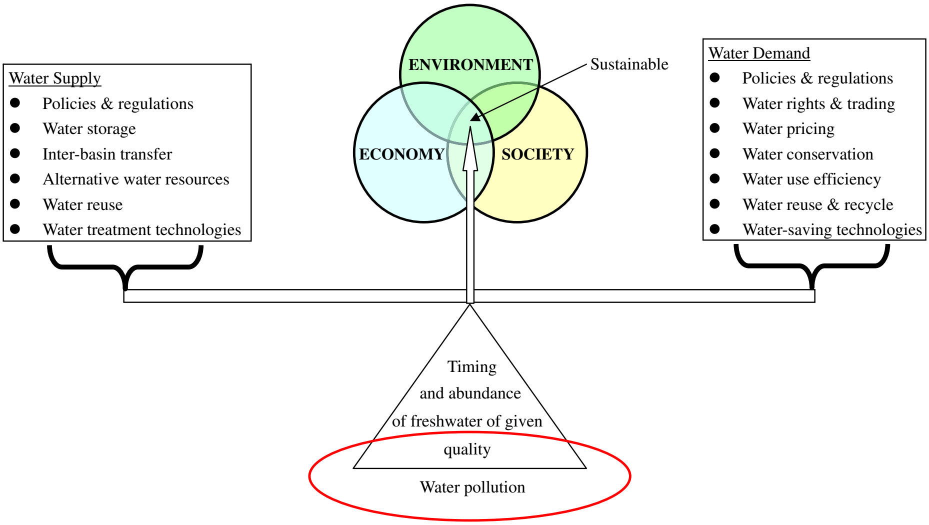

Fig. 5 Schematic illustrations for sustainable water resources management

relation to their natural characteristics and aggravated the natural water shortages (Jiang 2009). Little attention was put on exploring efficiency and demand management solutions to reduce the wasteful water consumption until recently.

Poor water resources management increases China's vulnerability and further intensifies the water shortages (Jiang 2009). Ultimately, China's water resources management policies and practices should aim at maximizing utilization of water, reducing water waste, and promoting water use efficiency and water conservation, while enhancing the social and economic benefits of water use, and preserving and restoring natural ecosystems. A sustainable water resources management strategy is vital to minimize the potential conflicts among economic development, social well-being and the conservation of ecosystems arising along with continued economic growth and in the context of global climate change (Schnurr and Holtz 1998). Both supply-side management options and demand-side management options are available to secure water resources of sufficient quantity and quality at affordable costs, and to balance various demands on the resources, as illustrated in Fig. 5. Given the constraint of natural availability and the impacts of climate change on the availability, quality, and demand of water resources, demand management becomes critical for sustainable management of water resources. As opposed to supply management, demand management through increasing water use efficiency, more effective distribution, and effective regulation enforcement can help China effectively cope with the impacts of climate change on its water resources.

5.1 Increase water use efficiency

Water wastage due to distributional and transmission losses, over-exploitation, and practices of inefficient use is a major contributor to China's water shortages.

China's water use efficiency is quite low compared to those in the industrialized countries (Cheng et al. 2009). China's water use per 10,000 Yuan gross domestic product (GDP) was 329 m^3 in 2006, three times of the world's average and six times of that in the US and other developed countries (MWR 2007). Agriculture is the single largest consumer of water, and accounts for more than 60% of the total water demand. Currently, agriculture only has an integrated irrigation water use efficiency of 0.38, or half of those in developed countries (MWR 2007). Even a marginal saving in irrigation water use can release substantial amounts of water for agricultural expansion as well as for meeting the needs of other sectors (Reddy 2009). Similarly, significant reduction in industrial and municipal water demands can be achieved through increasing water use efficiency, water recycling, and promoting water saving technologies. Improving use efficiency is becoming the primary means of balancing limited water supplies with growing demands in China (NDRC 2005a, 2007).

Under-pricing is the major cause of poor water use efficiency in China (World Bank 2007). China's water is among the world's cheapest, with the price remains below cost in most places. This not only perversely encourages waste but also discourages the development and implementation of water-conserving technologies. As one of the most important policy tools for managing water demand (Dinar 2000; Tsur et al. 2004), water pricing signals to users the relative scarcity in water resources and provides incentives to save water. Current reform in water sector in China is centered on water pricing, and priorities are given on setting right water price, water rights and tradable permits, and full cost recovery of water services over traditional water policies (Zhong and Mol 2010). Pricing mechanism has been implemented nationwide to encourage the shift from "engineering water" to "resource water" (Yang et al. 2003). Water-price reform in China is mainly affecting urban users, although irrigation water prices have also increased significantly over the past two decades. China is developing an advanced system of pricing water resources and water use to cover the increasing costs, to protect the scarce natural resources, and to introduce economic stimuli for water use efficiency. However, the development and implementation of water pricing is focused primarily on the economics of setting "right" prices with little attention on the institutional dimensions of natural resource pricing policies (Zhong and Mol 2010).

5.2 Clarify water rights and promote water rights trade

Water rights permit the orderly allocation and sustainable use of valuable water resources, and provide an effective mechanism for ensuring the proper management of water resources (Hodgson 2006). The key features of modern water rights should include (i) the volume of water that is subject to the right, (ii) duration, (iii) the conditions to which the right is subject, and (iv) the formal mechanisms that guarantee the security of the right (Hodgson 2006). Since the introduction of the amended Water Law in 2002, regional water rights, abstractor water rights, and user-level water rights have been granted in various ways across China, with some regions implemented sophisticated allocation systems while others at a more basic level (Shen and Speed 2009). A number of water rights transfer projects in recent years have contributed to the water rights reform in China (Calow et al. 2009). The water allocation agreement between Dongyang and Yiwu in Zhejiang province reached in 2000 is widely regarded as the first regional water rights transfer in China (Gao 2006). Water rights allocation and management in the populous but water-scarce Yellow river basin have been at the forefront of innovation in China's modern water rights system (Calow et al. 2009; Speed 2009b). The Hangjin Irrigation District on the south bank of the Yellow river in Inner Mongolia is well known as a pilot area for the transfer of water rights from agricultural to industrial users in China (Shen and Speed 2009; Zheng et al. 2009). In contrast to regional and abstractor water rights, water rights at the farmer level have been granted only to a limited extent to date, mostly as part of pilot water efficiency programs in the most water-scarce regions, such as the Hei river basin in Gansu Province (Speed 2009b). Some of these water rights transfers were facilitated by the central government, while others were developed by local governments within the current management framework to meet particular local demands (Gao 2006; Speed 2009b).

The water transfers made to date can achieve their primary objective of allowing water and water rights to move to where they are most needed, but a number of issues undermine the strength and effectiveness of the current water rights system in China (Speed 2009b). These include: (i) the right being allocated is not always well defined, (ii) lack of integration and consistency between all levels of the allocation process, (iii) little consideration for in-stream ecological water requirements, (iv) poor implementation of water resources allocation plans due to their ill-defined legal/regulatory status (Calow et al. 2009; Shen and Speed 2009; Speed 2009b). Based on the current conditions and the wider international experience in water rights reform, a number of actions, such as establishing well-defined water rights and defining water sharing rules, ensuring an integrated and consistent approach to rights definition and allocation at all levels, setting the regulatory role for water resources allocation plans to ensure their implementation, and incorporating environmental flows into allocation plans, have been recommended to improve the development of water rights and water rights trade in China (Calow et al. 2009; Shen and Speed 2009; Speed 2009b).

Long term, clearly defined and secure water rights amount to a form of property right over the use of water. Tradable water rights, which are a form of demand management, can make it possible to deploy the existing supply of water more effectively, rather than committing to the large-scale infrastructures of long-distance, inter-basin transfers (Hodgson 2006). Besides ensuring the proper management of water resources, water rights trades also promote a more economically efficient use of water resources. Trading of transferable rights will eventually allow markets to determine the "true" value of water, as uses migrate from lower value to higher value activities, driving water savings and more economically efficient use of water resources (Hodgson 2006). China should improve the legal and policy framework of water rights and make appropriate institutional arrangements to promote water rights trade as a sustainable solution to the allocation of water resources. In assigning the water rights, the government should make sure that the total rights granted are within the sustainable hydrological and ecological limits of the system, and effective mechanisms should be developed to satisfy changeable environmental water demands while not acting against market-based water rights (Zhou 2008).

5.3 Enforce laws and regulations effectively

The water-related legal system in China is comprised of national laws, ministerial regulations, and provincial and local governmental regulations and rules (Fig. 6). The national laws and rules set the principles, and are often general in nature, while local rules and regulations are formulated according to different needs and situations. Water resources management system and policy implementation are far from being effective and efficient in China (Schiller 2009), due to lack of coherence of law and regulation enforcement among different regions, conflicting interests at different levels of the administration, and insufficient authority and resources available to institutions to carry out their duties (OECD 2006). The general policy framework favoring development over the environment and natural resources in China compromises the work of enforcement bodies at local levels (Cheng and Hu 2010c). As indicated in Fig. 3, the subordinate departments of MWR are also institutional and financial subordination to provincial and local governments, which are more concerned with economic growth, often have difficulty in regulation enforcement. Because of the involvement of multiple local governments, effective enforcement of regulations is particularly problematic regarding water transfers and trans-boundary water pollution. Reducing the implementation gap, in particular at the provincial and local levels, is challenging, but critical to improve water resources management.

Several areas are critically important to successful implementation and enforcement of China's water policy. Effective policy and legal frameworks are prerequisite for developing, implementing and enforcing the laws and regulations on water resources management. A thorough review of the laws and regulations on water resources management is needed to eliminate important discrepancies and gaps between the principal laws and executive regulations (OECD 2006). The environmental standards in China are becoming increasingly comprehensive, strict and

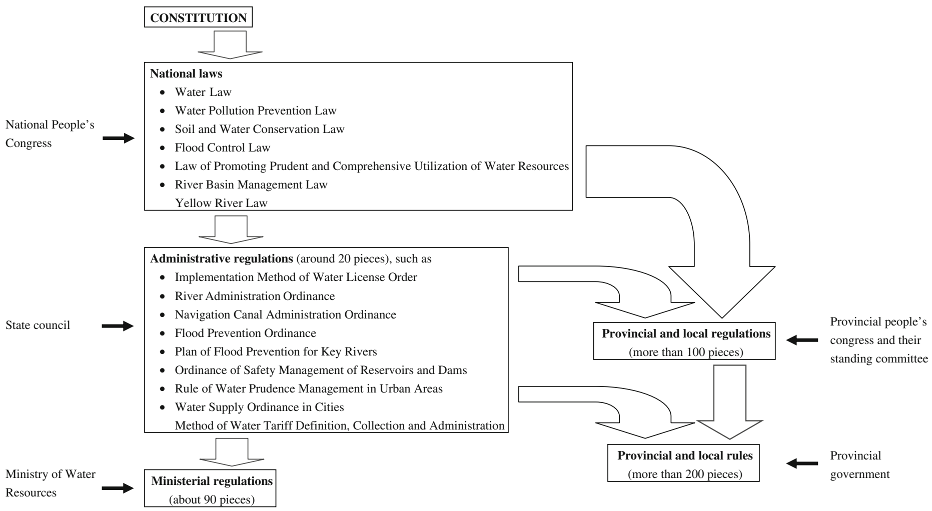

Fig. 6 China's legal framework of water resources management (after Liu and Speed 2009)

comparable to international common practice. On the other hand, environmental monitoring system still needs to be improved to provide technical support for policy implementation and environmental enforcement. With the multi-tiered system of environmental law enforcement, the MEP has limited influence and oversight on local actions (Winalski 2009). The administrative power and institutional capacity of the MEP should be enhanced to solve trans-boundary water pollution disputes and to supervise law enforcement. The government has relied mainly on regulatory instruments for controlling water pollution, which are inefficient for achieving most pollution control objectives (Bernstein 1997). Economic instruments (such as pricing, pollution charges, tradable permits, and subsidies) should be used to supplement the existing regulatory framework for effective implementation and enforcement of water resources management laws and regulations. The official promotion system in China focuses heavily on economic growth while ignoring the cost of environmental degradation and resource depletion. Fundamental changes must be made to change this practice, and evaluation of environmental performance of provincial and local governments should become routine activities along with evaluating impacts of enforcement actions (OECD 2006). Finally, lack of public participation is one major obstacle to environmental protection in China (Winalski 2009). Promoting public participation in the regulatory process at all stages, from drafting environmental legislation to enforcement activities, can help improve policy effectiveness and promote environmental compliance (OECD 2006; Winalski 2009).

6 Water pollution control

Water pollution caused by industrial and municipal wastewater, household wastes, agricultural and aquacultural activities, has become one of the most serious environmental issues in China (Liu and Diamond 2005; Cheng et al. 2009). Figure 7 depicts the changes in water quality of the 13 major basins in China over the last decade. Overall, water quality at only approximately half of the river sections could meet the criteria for drinking water sources. Water quality improved slightly over the last several years, due to the government's efforts at curbing surface water pollution and protecting source water. In particular, the central government recently initiated the Special Programme on Water Pollution Control and Treatment, which would invest a total of 35.6 billion Yuan on controlling water pollution and improving water quality nationwide between 2008 and 2020 (MEP 2008). Currently, water from 20.6% of the river sections, 23.3% of lake areas, and 4.2% of reservoirs has no practical use due to heavy pollution (MWR 2010). Protection of water resources is a crucial component in water resources management, as water pollution can negatively impact other water-related efforts and investments, such as water transfers and water abstraction, exacerbates water scarcity problems, and brings damage to human health and ecosystems. However, because of the inter-sectoral nature of the issue, and the fragmented responsibilities for addressing it, the control of pollution has the weakest institutional system among those in the water sector (Xie et al. 2009). Coordinated actions should be taken towards strengthening and enhancing industrial and municipal wastewater treatment and reducing pollutant discharges to aquatic environment. Wastewater treated to an appropriate standard can be reused for a variety of beneficial purposes, such as potable-water, industrial uses, irrigation, and

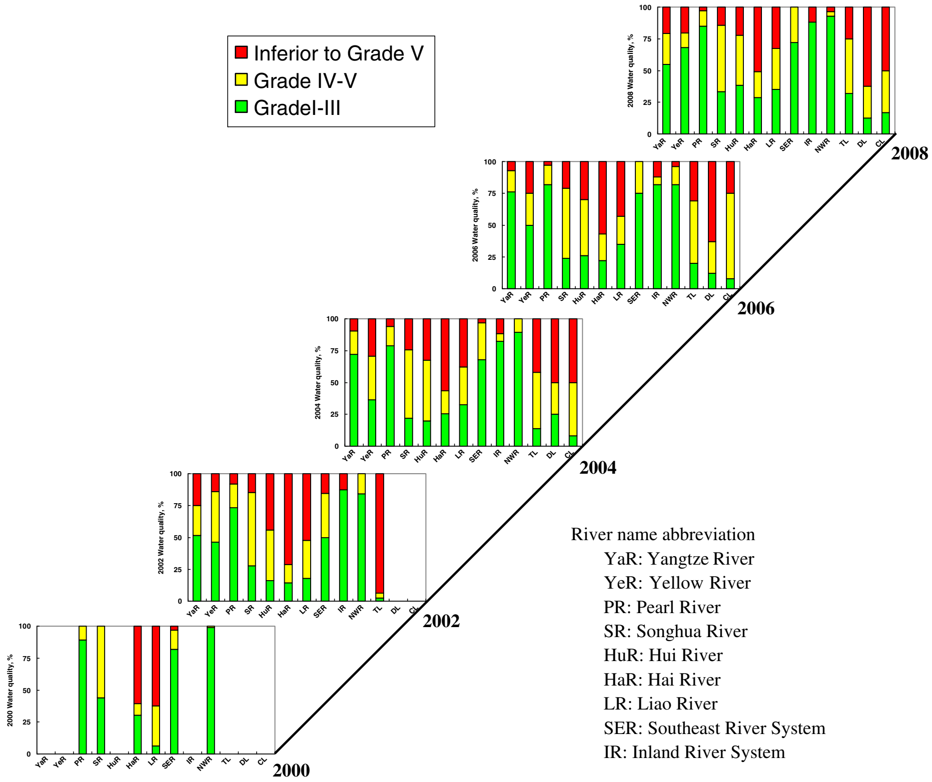

Fig. 7 Changes in water quality of the 13 major basins in China over the last decade (data from MEP 2009). *Grade I–III* water can be used as drinking water sources; *grade IV–V* water can be used for general industrial uses, recreation (no direct skin contacts), agricultural irrigation, and general landscape; water with quality inferior to grade V has no practical use

environmental restoration, which not only lessens water pollution, but also reduces the need for abstracting additional freshwater.

Healthy river and lake ecosystems possess diverse values and service functions, however, most of such ecosystems in China have been damaged by excessive water abstraction, pollution, and mismanagement in the past three decades (Yang and Pang 2006). Traditional water allocation practices in China failed to take account of the environment and neglected the ecological and aesthetic functions of water bodies, with over-exploitation often caused the rivers to run dry in northern China during the drought season (Xie et al. 2009). Table 5 shows the total water resources available and the water abstraction of the major river basins in 2008. Withdrawals accounted for over half of the renewable water resources in most basins. In the case of the Hai river basin, the water abstraction exceeded the available water resources by 26.2%, and water had to be transferred in from the Yellow river basin. The water flow is quite low due to excessive withdrawals for the rivers in northern China, except when they are stressed with flooding problems during the monsoon season. Although environmental flows have been implemented in several river basins and with some improvement of ecological conditions, the provision of environmental

Table 5 Total water resources and water abstraction (unit: billion m^3) in China's major river basins (data from MWR 2010)

River basin	Total water resources	Total water abstraction	Sources of abstracted water			Uses of abstracted water			
			Surface water	Groundwater	Others	Domestic	Industrial	Agricultural	Eco-environmental
Songhua	98.27	41.10	23.61	17.49	0	3.34	7.921	29.42	0.43
Liao	39.39	20.26	8.83	11.17	0.26	3.17	3.04	13.71	0.33
Hai	29.45	37.16	12.33	24.06	0.77	5.71	5.13	25.4	0.91
Yellow	55.90	38.42	25.39	12.81	0.22	3.98	6.08	27.72	0.65
Huai	104.72	61.12	43.24	17.58	0.3	8.19	9.86	42.17	0.90
Yangtze	945.72	195.15	186.17	8.32	0.66	25.05	71.8	94.81	3.49
Southeast	173.52	34.35	33.34	0.91	0.10	4.95	11.98	16.26	1.16
Pearl	569.68	88.12	83.70	4.01	0.41	15.57	21.03	50.23	1.29
Southwest	594.44	11.18	10.84	0.32	0.02	1.19	0.83	9.12	0.04
Northwest	132.34	64.132	52.182	11.81	0.14	1.76	2.043	57.51	2.82
Sum	2,743.43	590.99	479.63	108.48	2.88	72.91	139.71	366.35	12.02

flows remains a challenge (Wang et al. 2009). In planning for water transfers and abstractions, certain volumes of water should be left in the water bodies to sustain natural aquatic ecosystems, protect biological diversity, dilute polluted flows, and restore the damaged river eco-systems.

7 Conclusion

The current water resources management in China is largely supply-driven and is increasingly difficult to meet the increasing water demands from agricultural, industrial and municipal sectors while adequately protecting the natural environment and ecosystems. The natural water shortage, combined with the widespread water pollution, significantly constraints the further development and sustainability of the country. Climate change is expected to further stress freshwater resources and widen the gap between the demand for and supply of water. Based on the current socio-economic and water resources conditions, China should adopt demand management as the primary strategy while controlling water pollution to quench the increasing water demands from the rapid social and economic growth and to adapt to climate change. Important issues such as water use efficiency, water rights and water rights trade, and effective enforcement of laws and regulations, should be addressed while switching to demand management. Meanwhile, control and prevention of water pollution to improve the overall quality of the freshwater resources is also a crucial component in water resources management. Ultimately, China should develop a sustainable water resources management strategy based on both supply- and demand-side management options to make the limited water supplies meet the demands of economic development, social well-being and the conservation of ecosystems in the context of global climate change.

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