Situations, challenges and strategies of urban water management in Beijing under rapid urbanization effect

Wen Liu, Weiping Chen, Qi Feng and Ravinesh C. Deo

ABSTRACT

As the capital and a major political hub for China, Beijing has undergone a rapid urbanization effect with significant population growth in recent years. At the same time, Beijing has also been suffering from severe water problems such as water scarcity, urban flooding and other issues related to water pollution. These have increasingly generated severe water problems and stymied the pace and scope of sustainable urban development. The critical challenges faced by water resource administrations pertains to the issues of sustainable management of water resources and the relevant actions to be put in place in order to address these water-related problems. In this study, the current water situation of Beijing is described in great detail focusing on water resource amounts, water supply, water consumption and water pollution changes analyzed from historical to recent years. The challenges of Beijing urban water management systems are also analyzed to offer possible solutions in light of the current trends. Finally, a number of useful strategies and action-oriented measures are provided for Beijing's urban water resource administration to assist them in overcoming the current water management challenges and for them to move towards a more sustainable developmental city.

Key words | urban flooding, urbanization, urban water management, water pollution, water scarcity

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INTRODUCTION

Water is a fundamental resource for the social and economic development of all major and minor cities (Sun *et al.* 2014). A rapid urbanization process is expected to lead to a series of water problems, such as water resource scarcity, flooding and waterlogging and water environment pollution in most urban areas. These issues have drawn increased public attention and produced significantly difficult challenges for urban water resources management (Bonta 2004; Apel *et al.* 2009). With the projected increase in urbanization, the underlying surface conditions have been changed by several factors (such as land use and cover change, which in turn can potentially disturb the natural hydrological cycle), which is likely to cause localized flooding and non-point pollution of receiving waters (Du *et al.* 2012; Suriya & Mudgal 2012). Moreover, climate change is also expected to generate additional stress on aging water infrastructure mainly due to changes in precipitation patterns leading to more extreme events such as flooding and drought events (IPCC 2012). Simultaneously, the increase in urban population and expanded business activities may also lead to a dramatic increase in water consumption, which can result in contradiction in water resource supplies and an intensification of demand, mainly in urban areas (Jenerette & Larsen 2006). Compounding this effect is also the possible deterioration of urban water pollution control and a decrease in the quantity of safely available water resources for human use (Liang 2011). As a consequence of these, sustainable urban development is likely to be

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hampered by the increasing tendency of severe water problems especially in moderate to large urban cities such as Beijing.

A comprehensive understanding of urban water systems is a major foundation for formulating urban water management strategies (Mitchell 2006). Three primary components of urban water management systems can be denoted as: the water supply, wastewater disposal and stormwater drainage (Heaney *et al.* 2000). Conventional urban water management aims to meet the water supply and demand and drain stormwater and wastewater away from cities (Makropoulos *et al.* 2008). However, stormwater and wastewater are increasingly being regarded as valuable resources that need to be recycled and reused as a goal to make urban cities more sustainable (Tong 2009). Therefore, an integrated system put in place for the water supply, wastewater reuse, and reduction in stormwater discharge into a sustainable water management system are much needed in both developed and developing nations (Mitchell *et al.* 2001).

In general, the major urban water management strategies used in urban cities are classified into sustainable urban water management (SUWM) and integrated urban water management (IUWM) systems. SUWM is a proactive approach characterized by integrated water supply, wastewater and stormwater management systems, which aims to manage urban water resources to generate more benefits for the residents (Heaney *et al.* 2000; Marlow *et al.* 2013). Moreover, IUWM is a proactive approach implemented for the management of urban water systems with a clear view to minimize their impacts on the water environment, through a reduction in the consumption of water resources, and a consequent decrease in the discharge of treated wastewater into the natural water systems (Alwi *et al.* 2008). IUWM, on the other hand, is concerned with a general transition towards a more sustainable solution for water, sewerage and stormwater systems (Wilcox *et al.* 2016).

In accordance with the trends of recent urbanization, rapid social and economic development within the city of Beijing has culminated a series of water-related issues, such as water scarcity, flooding and water pollution (Liu & Speed 2009). However, despite the urgency, adequate and effective solutions for Beijing's water problems have not yet been determined (Li 2012). Previous research on urban water management in Beijing has mainly focused on water supply networks, water pollution control and wastewater treatments (Yang & Abbaspour 2007; Zhong *et al.* 2008). Considering the paucity of investigations on these very important issues, more comprehensive studies that analyze the holistic situation of Beijing's water resources and the underlying challenges faced by water resource authorities drawn from the experiences of advanced management strategies not yet applied in the current study region are necessary to increase the scope of and to improve Beijing's overall water management.

In this paper, we provide a detailed overview of the changes of water resources amounts, water supply, water consumption and water pollution situations in Beijing in recent years. Furthermore, careful attention is also paid towards analyzing the current challenges in Beijing's water management strategies. The study then proposes a number of key strategies and action-oriented solutions for urban water resource administrations to assist them in overcoming the current water challenges and for moving towards greater water-savings and more sustainable water resource development within the city of Beijing.

WATER RESOURCE SITUATION IN BEIJING, CHINA

Water resource scarcity

Beijing is located in the northern part of the North China Plain (i.e., E115°25′–117°30′, N39°26′–41°05′) and this region belongs to the Haihe River Basin. Its total land area is around 16,416 km^2, among which almost 10,014 km^2 (or about 61%) forms the mountainous area and about 6,402 km^2 (or about 39%) is the plains area. This region has a typical monsoon influenced by semi-humid continental climate with an annual mean temperature of 13.1 °C and an annual mean evaporation of about 980 mm (Wei 2005). Surface water, surface water inflow, and groundwater comprise the whole water resource system of Beijing (Ma 2011). In recent years, with the increasing population and a significant degree of climatic variability, the water scarcity condition in this city has become more severe.

As the capital of China, Beijing is one of the world's ten largest cities with about 21.148 million residents, and it is also one of the most water-scarce cities in the world (Wang & Wang 2005). The available water resources in Beijing mainly consist of surface water and groundwater, which are about 0.645 Gm^3 and 1.38 Gm^3 respectively, and together, this adds up to 2.025 Gm^3 in 2014, which is almost 15% less than the average annual water resources since 2001 (2.39 Gm^3) (BWA (Beijing Water Authority) 2002, 2015). The per capita water resources of Beijing were 94 m^3 in 2014, which was only four-hundredths that of China (2,200 m^3) and three-hundredths that of the world on average (3,000 m^3) (Wang *et al.* 2008). Notably, this is far below the internationally recognized lower limit (of about 1,000 m^3/capita according to Falkenmark *et al.* (1989)).

Precipitation is the main source of surface water and groundwater replenishment. The average precipitation of Beijing during the past 60 years (i.e., 1951–2010) has been about 585 mm (Zhai *et al.* 2012). About 80% of the annual precipitation occurs from June to September, and thus, flooding events frequently occur in the wet season (Liu *et al.* 2015). The average amount of precipitation in Beijing is around 547 mm/year. It is important to note that the observed precipitation has shown a declining trend from 1964 to 2014 (Figure 1). This indicates that the available water resources of Beijing have, in fact, decreased in recent decades.

Besides precipitation as a major source, surface water inflow is also a major main source of surface water in the city of Beijing. In this city, there are four river basins (known as: Jiyun River, Chaobai River, Yongding River and Daqing River) with their main river streams flowing through the region, except for the Beiyun River Basin (Tisherman 2013). In this context, the changes of freshwater resources in Beijing mainly depend on surface water inflow from the upstream areas of the river basin (Ma 2011). Average annual surface water inflow of this region was about 1,531.7 Mm^3, with the highest value of 4,334.3 Mm^3 in 1964 and the lowest value of 260 Mm^3 in 2002 (Ma 2011). As precipitation has been lower than the annual mean value in recent years and due to the large demands for water in upstream regions for social and economic developments, the surface water inflow into the Guanting and Miyun reservoirs has exhibited a reduction in its overall trend.

Groundwater is the major source of water supply for Beijing, and accounted for almost 52% of water supply in 2014 (BWA 2015). The amount of renewable groundwater is recovered by the aquifer in Beijing, and it mainly depends on precipitation amounts (Sun *et al.* 2014). However, it is noteworthy that groundwater infiltration has exhibited a declining trend because impervious surfaces have potentially been increasingly building up, which is likely to hinder the infiltration of rainfall (Chithra *et al.* 2015). Meanwhile, groundwater has been over-used due to massive water consumption by municipal and industrial activities (Nie & Schilling 2000). Therefore, the abstraction of groundwater is expected to be greater than the replenishment of the aquifer, thus resulting in a decline in the groundwater table (Figure 2). The average groundwater level of the plains

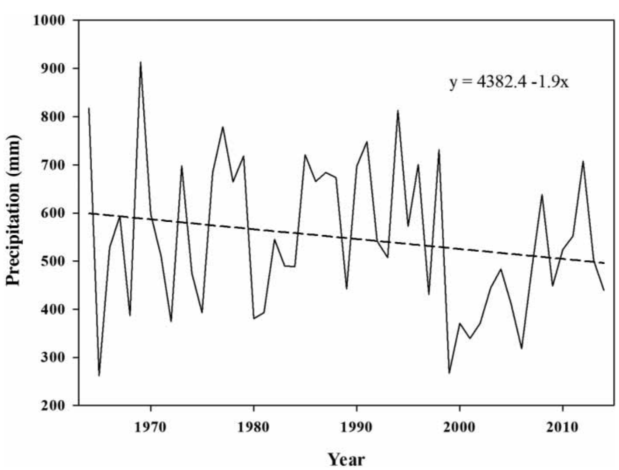

Figure 1 | The observed precipitation in Beijing from 1964 to 2014.

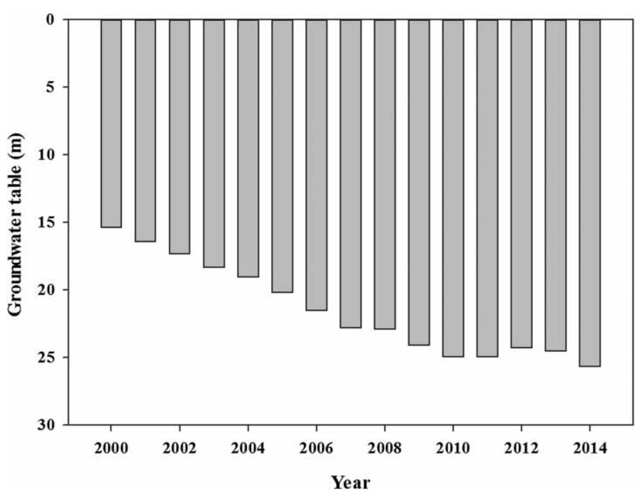

Figure 2 | The changes in groundwater table in the plains area of Beijing from 2000 to 2014.

area in Beijing was about 25.66 m at the end of 2014, which exhibits a decrease of 13.78 m compared with that at the end of 1998. Correspondingly, there has been a reduction in groundwater storage to an amount of about 70.6 Gm^3 (BWA 2015).

Considering the above analysis, it is ascertained that the composition of Beijing's water resources (i.e., surface water, surface water inflow and groundwater) have all exhibited significant decreases in recent years, resulting in the scarcity of water resources for this major socio-economic and political hub of China.

The contradiction between water supply and consumption

Rising population and urbanization coupled with climate change is expected to reduce urban water supply in developing countries (O'Hara & Georgakakos 2008), and China as a major growing world economy is no exception. Considering the limited freshwater resources, a large amount of water demand may then cause intensive water allocation conflicts among different water sectors (Aheeyar *et al.* 2008). From the structure of the water supply sources, the major water supply source for Beijing's municipality is groundwater, and the secondary supply source is surface water and reclaimed water (Figure 3). From 2005 to 2014, the percentage of groundwater supply amounts accounted for a total decrease in water supply from about 77% to 52%, and the percentage of surface water and rainwater and reclaimed water increased from about 17% to 23% and 6% to 23%, respectively (BWA 2015).

Therefore, in the last 10 years, the traditional water supply sources such as the groundwater supply have continuously decreased, and the new water supply sources such as reclaimed water have increased rapidly.

Although the available water resources in the Beijing area have a decreasing trend, water consumption is rapidly increasing, primarily attributable to the increase in population (Bao & Fang 2012). It is important to note that water consumption in Beijing was about 3.75 Gm^3 in 2014, which included about 1.70 Gm^3 for residential uses, 0.82 Gm^3 for agriculture uses, 0.51 Gm^3 for industrial uses, and 0.72 Gm^3 for environmental use to account for about 45%, 22%, 14% and 19% of the total water consumption, respectively (BWA 2015). As indicated in Figure 4, the total amount of water use has decreased from 2001 to 2014, while the amount of water used in agriculture and industries has decreased gradually, and the amount of domestic water and environmental water has increased rapidly. Interestingly, domestic water use has increased by about 41.7% from 2001 to 2014. During the same period, environmental water consumption has increased from about 0.3 Gm^3 to 7.2 Gm^3 (BWA 2002, 2015). Therefore, in light of this evidence, it is reasonable to conclude that the contradiction between declining water supply sources and rising water consumption has been intensified in the city of Beijing.

Frequency of urban flooding and waterlogging events

Nowadays, flooding and waterlogging has been a frequently occurring disaster in mega-cities (Jha *et al.* 2012). Urbanization generates a large area of impervious surface, which

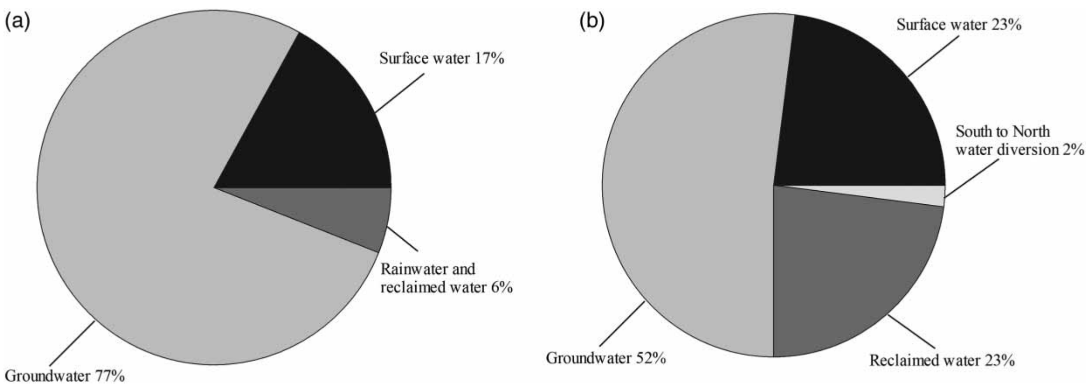

Figure 3 | The percentage composition of Beijing water supply sources: (a) year 2005 and (b) year 2014.

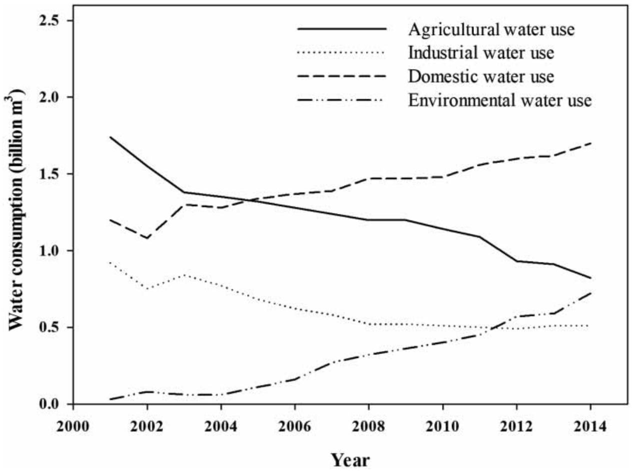

Figure 4 | The water consumption amounts of Beijing from 2001 to 2014.

can hinder the rainfall infiltration process, and increase the stormwater runoff and accelerate the flow concentration process, thus resulting in frequent flooding events in urban areas (US EPA 2005). In recent years, flooding and waterlogging events have frequently occurred in Beijing urban areas. For example, on 21 July 2012, Beijing experienced a most severe storm event with 150 mm of rainfall, which was one of the heaviest storm events in Beijing in the past 60 years (Grumm 2012). The flooding claimed 77 lives, affected about 1.6 million people and caused a direct economic loss of about 11.6 billion yuan. Besides the 2012 '7.21' event, Beijing has experienced 17 heavy storms during the recent 10-year period (Li 2012). Therefore, for this important city, it remains a great challenge to mitigate severe flooding and waterlogging problems caused by such storm events.

Water pollution and water environmental deterioration

Water pollution reduces the supply of potable water, which in turn can cause water shortage, and ultimately lead to water crisis (Gleick 2000). Due to a huge amount of wastewater and pollutant discharge, river water in the study region has gradually been polluted since the 1980s (Hu & Cheng 2013). Because of the deterioration of water quality, the Guanting Reservoir has not been used as a source of potable water for Beijing since 1997 (Xue *et al.* 2006). In recent decades, surface water pollution has increasingly been expanded and aggravated. According to the standards of the Environment Quality Standard for Surface Water (GB 3838–2002) (SEPA 2002), the river water quality of the Beijing region was assessed and classified. Figure 5 indicates that the proportion of river water quality classified as Grade II–III was about 65.1% (~592.9 km river course length) in 2002, which decreased to about 48.8% (~1,147.3 km) in 2014. In contrast, the water quality of river course classified as Grade V was worse by about 26.7% (~286.6 km) in 2002, which increased to about 41.6% (~979.0 km) in 2014 (BWA 2002, 2015). For the shallow groundwater aquifer, around 48% (~3,058 km^2) of the plains area was classified as Grade IV–V in 2014, which meant that this water was only suitable for industrial and agricultural uses, respectively. In contrast, the quality of deep groundwater was in fact better. Importantly, only 761 km^2 of deep groundwater, accounting for about 22% of the monitored area, was classified as Grade IV–V in 2014 (BWA 2015). The expansion of water pollution thus decreased the available water resource and therefore, has aggravated the water crisis in the Beijing region.

Proportion of wastewater treatment and reclaimed water reuse

Wastewater associated with discharged pollutants appears to have put a great pressure on Beijing's overall water environment (Ma 2011). In 13 years, the amount of

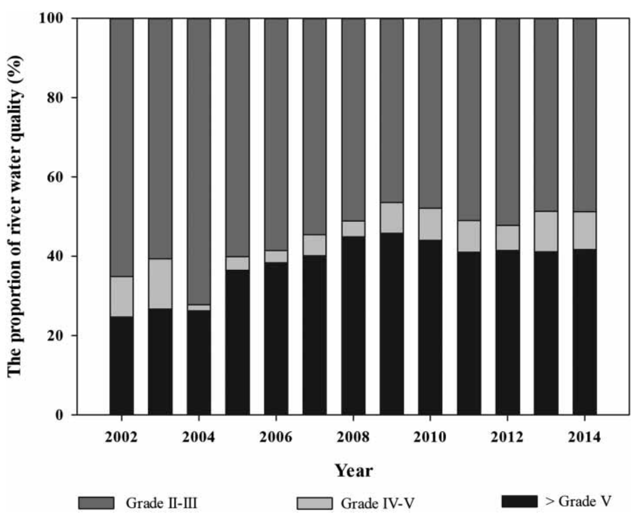

Figure 5 | River water quality of the Beijing region from 2002 to 2014.

wastewater discharge has exhibited an important increase of 18.6%, namely from about 1.362 Gm^3 in 2001 to 1.615 Gm^3 in 2014 (BWA 2002, 2015). With an increasing awareness of public health risk arising from the polluted water, the construction of wastewater treatment plants has been on the agenda of the government authorities of Beijing. Nowadays, Beijing has 15 central municipal wastewater treatment plants, and more than 300 small decentralized plants (Yi *et al.* 2011). By 2014, about 86% of Beijing wastewater was being treated and about 14% of that wastewater was discharged into rivers without any treatment (BWA 2015).

As the urban water shortage increases and water purification technologies become more advanced, wastewater reuse has been increasing for a variety of purposes, such as toilet flushing and grassland irrigation (Chen *et al.* 2013). Subsequently, the Beijing authorities are attempting to generate reclaimed water as an important component of the urban water management scheme. Wastewater reclamation has been actively promoted by the BWA since the beginning of this century (Yi *et al.* 2011), which has led the annual reclaimed water reuse in Beijing to rise rapidly from about 210 Mm^3 in 2003 to 860 Mm^3 in 2014. Importantly, this has accounted for about 23% of the total water supplies in 2014 (BWA 2004, 2015) and consequently, the reclaimed water has become an important substituted water supply source for non-potable water consumption purposes in the city of Beijing.

CURRENT PROBLEMS AND CHALLENGES OF WATER MANAGEMENT IN BEIJING

The rapid urbanization of the city in recent years has brought new challenges to Beijing's water management. Urban residents no doubt need a safe supply of sufficient clean drinking water, which has led to an increase in water demand on one hand, but the other hand, surface water has decreased, urban groundwater has been subjected to contamination and the wastewater needs to be treated, while stormwater has to be managed in a proper way (Schirmer *et al.* 2013). Considering these pertinent issues, some of the major problems and challenges existing in Beijing's water resources management sectors include the following:

(1) BWA is the key agency for integrated water resource management in Beijing. There are different departments under the management of BWA, each of them with their own functions such as water supply, water drainage, water-saving, project construction and so on. After its foundation, every district of Beijing also correspondingly set their District Water Authorities (DWAs) to manage water-related issues. Although several attempts have been made to implement water management plans, the precise duties of urban water management are implemented by several different departments, such as the water bureau, municipal department and the environmental protection bureau. Therefore, there exists no special mechanism to guide different departments responsible for water administration in cooperation and coordination, which may lead to a weakening of government management functions, structures and the underlying processes in terms of management efficiencies (Howe *et al.* 2012).

(2) With rapid urbanization and climate change in action, the main water supply sources of Beijing have decreased gradually, thus the sustainable management of water supply has continued to face challenges in recent years. Importantly, the available water resources such as surface water and groundwater continue to decrease and get polluted, leading to increasingly severe water scarcity and supply–demand contradictions (Sun *et al.* 2014). Simultaneous with this issue are the urban flooding and waterlogging problems that frequently occur due to a large amount of stormwater runoff without reasonable regulation (i.e., the measures for stormwater infiltration and retention) and rainwater harvesting. Consequently, this threatens the life-safety of residents and causes significant property damage in the city (Jia *et al.* 2013).

(3) Analysis of historical data shows that the price of water in Beijing was only about 0.12 RMB (0.018 USD) from 1981 to 1991, while it increased quite significantly from 2000 then onwards, reaching 3.7 RMB (0.559 USD) in 2004. This low price of water has resulted in waste of scarce water resources. It is also true that for a long period of time, the government did not fully realize the scarcity of water resources, and as such, did not have a suitable concept for full cost pricing. The water resources fee was introduced in Beijing in 2002 such

that there was a significant increment in the water price, which reached 5.0 RMB (0.756 USD) in 2014. However, the water price was still lower than in the other megacities in the world (Chen & Yang 2009).

(4) The degree of water scarcity especially for the local residents is not clear and wastewater and rainwater have been considered unusable, and thus returned as discharge to the streams out of the city. As such, sufficient reuse and harvest mechanisms have not been implemented as substitutes for potable water. In fact, the results obtained from questionnaires by Fan *et al.* (2015) indicated that about half of the citizens in Beijing were not in the habit of utilizing water-saving measures, and that they did not have much access to specific measures for water-savings, leading to their failing to undertake actions for the reuse of water in the city.

(5) The current Water Resources Management Regulations in Beijing were in fact issued originally in 2004 (BWA 2004), and the regulations are not expected to meet the precise needs of the Strictest Administration of Water Resources (which put emphasis on allocation, conservation and protection of water resources, and stringently enforced controlling total water consumption, improving water-use efficiency and limiting pollutant discharge) in the current period (Fan *et al.* 2015). To counteract this challenge, more stringent regulations including river and lake management, guidelines for water supply in urban areas, water-related environmental protection, and sewage treatment should also be incorporated in the legislation in force in order to establish new legislation that can effectively govern water resource management in Beijing. In addition to such measures, more effective policies for incentivizing wastewater and rainwater reuse practices should be implemented including subsidies, incentives and penalties.

EFFECTIVE STRATEGIES AND POTENTIAL SOLUTIONS FOR BEIJING'S URBAN WATER MANAGEMENT

In practice, current urban water management is strongly related to three pivotal aspects: prevention of floods, ensuring the balance between water supply and water demand and protecting the water-related environment. In light of this viewpoint, Beijing's water resource administration needs to focus more effectively on coordinating different administrations of water resource management strategies, including the adjustment of the water price systems, improving the water use efficiency and water-saving practices, mitigating potential flooding and non-point-source pollution, stimulating wastewater reuse and rainwater harvesting, and strengthening the institutional systems and construction of policies for water management.

Developing the framework for SUWM

Based on the current water management system, water resource administrations need to promote the efficiency level of water resource management systems through SUWM strategies. According to the framework for SUWM proposed by Bai & Imura (2001), four useful strategies (i.e., supply management, demand management, efficiency management and emission management) can be better adopted to achieve sustainable management of the water resources of a certain city (Figure 6). Each management strategy is expected to target the maximization of water resource inputs, keeping water demand within the scope of water supply capacity, maximization of the water use efficiency and limiting the discharge of water and related pollutants in the water environment (Bai & Imura 2001).

Coordinating different administrations of water resource management

There are different departments in BWA that have the duty to implement Beijing's water management plans, with each of them having their own functions such as water supply, water drainage, water environment protection, water-saving management, water project construction and so on (Howe *et al.* 2012). For this reason, water resources should be under unified management on the basis of a legislation framework (Fan *et al.* 2015). To concur with this view, it is recommended that BWA needs to form a coordination department as the bridge between the other related departments in respect of water resource management. Such coordinated efforts should also incorporate the competence

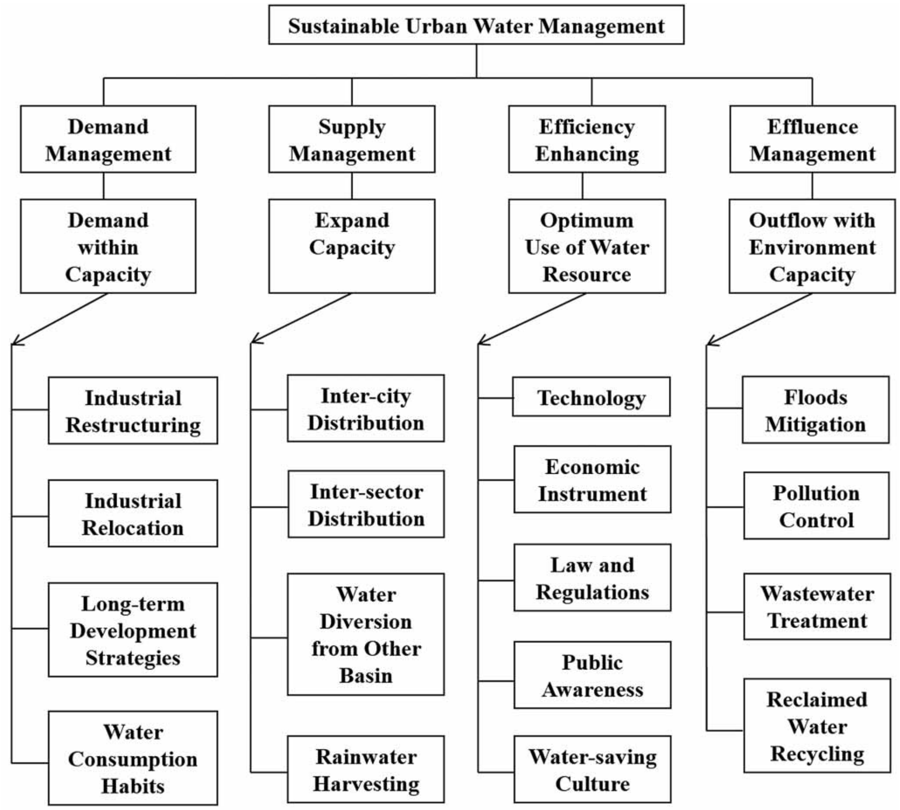

Figure 6 | A framework for sustainable urban water resources management (adapted from Bai & Imura 2001).

of supervising and accessing the works completed by the other departments. With such a coordinating department that not only connects with the other departments but also oversees the whole process being implemented, the entire system of Beijing water resource management can perform more efficiently. Also, an environmental department in BWA needs to convey information from Beijing Municipal Environmental Protection Bureau (BMEPB) to BWA to achieve the combined management of water quantity and water quality.

Adjusting the water pricing system

A scientific and rational water pricing system can be considered as a great way to adjust the water demand and water supply issues, with optional water allocation and water-saving (Convery 2013). As for the city of Beijing, natural water charges are part of the pricing system, which means that Beijing does not have as much in terms of natural water resources compared with other mega-cities (Chen & Yang 2009). Compared with the other mega-cities in the world, the annual expenditure on water and unilateral household water prices in Beijing are the lowest, while the ratio of the average annual household expenditure on water to the average household disposable income is the highest (Zhang & Brown 2005). Therefore, it is recommended that Beijing's water resource administrations should adjust the water pricing system to rationalize the utilization of water and to raise the awareness of water-saving and water resource protection.

Improving water use efficiency and water-saving practices

Faced with increasing water scarcity, it is important to note that future urban development should shift towards more water-efficient cities (Wang *et al.* 2005). Indeed, water consumption patterns can vary significantly from house to house, depending on household occupancy and social and cultural conditions as well as on the type of water-consuming appliances installed in the respective houses (Butler & Davies 2004). Approximately, 15–20% of indoor water demand is actually utilized for drinking, cooking and washing the dishes (Makropoulos *et al.* 2008). In fact, the city of Beijing's residential water use is about 140 L per capita per day, which compares with about 115 L in Germany, suggesting that there is still room for improving water use efficiency in the city of Beijing.

The construction of a water-saving culture requires greater strengthening and popularization. This is because the Beijing government and the Beijing Water-saving Office have the responsibility to increase the density and intensity of water-saving publicity and promote water-saving awareness. This can help to guide industrial, domestic and agricultural water users to form the habit of water-saving, and hence to increase water use efficiency. In terms of the implementation, water resource administrations should look for volunteers to promote water-saving knowledge, a basic water use condition in Beijing, laws and regulations about water and water-saving plans in different communities (Fan *et al.* 2015).

Widespread utilization of advanced water-saving technologies can further increase water use efficiency (Evans & Sadler 2008). For domestic water, measures such as users changing their ordinary toilets and showers into water-saving ones is a step forward. In the process of manufacturing, factories should also spend money on researching and developing new water-saving technologies, especially avoiding pipeline leaks and applying water consumption quotas. For gardening irrigation, advanced water-saving irrigation techniques such as the use of sprinkling and drip irrigation should also be implemented widely. Moreover, alternative water sources have to be used including graywater, rainwater harvesting, stormwater harvesting, building-scale treated wastewater, etc.

Mitigating urban flooding and non-point-source pollution

Historically, stormwater was viewed as a hazard in urban areas with complex networks of drainage infrastructure implemented to remove surface water and transport it away from the urban area (McGrane 2016). Traditionally, to avoid loss of life and damage to property, higher drainage standards and larger-scale engineered drainage systems need to be constructed and maintained to quickly and effectively convey increased stormwater runoff from urban areas to downstream receiving water bodies, such as rivers, lakes, etc. (Jia *et al.* 2013). However, it is difficult to design and construct proper stormwater drainage systems under uncertain climate change and urbanization effects (Giugni & De Paola 2015). Water drainage departments should thus consider incorporating natural ecosystems into flood mitigation and implementing new strategies such as low impact development (LID) and green infrastructure (GI). Similarly, hydraulic invariance principles are a good concept for flood mitigation, namely the condition for peak flow release from transformed areas to remain unvaried before and after land transformation (Pappalardo *et al.* 2017).

As an effective measure of flood mitigation, LID refers to practices that use or mimic natural processes that result in the infiltration, evapotranspiration or use of stormwater in order to reduce stormwater volume, control the movement of pollutants, and protect water quality and associated aquatic habitat (Coffman 2002). GI, on the other hand, has emerged to be the primary term used in the context of LID, particularly to describe the types of systems that can be used to manage stormwater in a more natural way (Benedict & McMahon 2012). There are many LID and GI facilities (e.g., green rooftops, rain gardens, infiltration trenches, and permeable pavements) (Coffman 2002). Importantly, GI practices applied on a broad scale can help maintain or restore a watershed's hydrologic functions, and as such, they have been utilized to mitigate the hydrology and water quality impacts of urbanization (Benedict & McMahon 2012).

Stimulating wastewater reuse and rainwater harvesting

It has been long recognized that integrated wastewater reuse and rainwater harvesting can serve as a more efficient and valuable way to cope with the scarcity of water resources and the severity of water pollution (Dixon *et al.* 1999). In this context, graywater, which is the wastewater generated in household activities such as washing clothes, showering and kitchen washing, but excluding toilet wastewater, has lower levels of pollution. As a result, graywater is easier to purify and reuse than the water from sewage (Makropoulos *et al.* 2008). Graywater systems can thus be used for toilet flushing and lawn irrigation with individual buildings and even used by larger neighborhoods or at community scales (Nolde 2000).

Due to rainwater being relatively lightly polluted water, filtration is usually the only necessary process prior to storage for non-potable uses (Zhang *et al.* 2009). Rainwater harvesting is one of the effective ways of supplementing scarce potable water consumption in urban areas (Aladenola & Adeboye 2010). Because the temporal and spatial distribution of rainfall in Beijing is uneven and too centralized, heavy rains increase the flood risk. Therefore, the Beijing government should highly emphasize utilization of rainwater.

Strengthening institutional systems and policy construction for water management

Poor policy design no doubt contributes to a wastage of scarce water resources which can lead to exacerbated water problems (Jiang 2009). In terms of institutional systems, the government of Beijing needs to legally enforce water rights, and strive to establish institutional systems that clearly define and regulate water withdrawal and use. Also, the government must build basin-level decision support systems that are designed to integrate urban hydrological processes and the socio-economic dynamics of the water demand issue. Moreover, the related laws and regulations and economic incentive policies for wastewater reuse, rainwater harvesting and water-saving also need to be quickly promulgated to facilitate and regulate these practices in a more effective manner.

Advancing urban hydrology research to provide a fundamental framework for water management

Urban hydrology has evolved to improve the way in which urban runoff is managed for flood protection, public health and environmental protection (Fletcher *et al.* 2013). Findings from a number of urban hydrological studies based on the collection of urban hydrological data, calculations and modeling constitute a necessary foundation for a meaningful way of water management in urban areas (Niemczynowicz 1999; McGrane 2016). In practice, scientific studies on urban hydrology are vital for appropriate design of urban landscapes and civil infrastructure works (Sarma *et al.* 2016). Despite many advances in this front, there remains a great degree of uncertainty surrounding the urban water cycle, rainfall-runoff response, and the impacts of climate change, land use change and economic–social activities on spatial–temporal structures of rainfall, natural hydrological processes, water quality and ecosystem processes (McGrane 2016). New monitoring technologies, more comprehensive data and integrated modelling strategies are urgently needed to extend our detailed understanding of urban hydrological processes at the plot or sub-catchment scale to the wider urban catchment scale (Fletcher *et al.* 2013).

CONCLUSION

In congruence with the present analyses on situations, challenges and strategies of urban water management in Beijing (a city which has undergone rapid urbanization), scarcity of water resources, urban flooding and water pollution have become more severe in recent years. Faced with new circumstances and the underlying challenges, the water resource administrations in the city of Beijing must empower themselves to coordinate and implement actions that integrate the concept of water management, mechanisms, technology, economy and culture to improve water resource management outcomes. Water resource protection should thus be regarded as the primary task to support the sustainable development of the economy and society. At the same time, both the government and the water resource administrations should ensure in a comprehensive manner water supply safety and that the water environment remains healthy, and that measures are put in place to build a water-saving society. This can assist with the promotion of rainwater harvesting and wastewater reuse measures, including the control of flooding and water pollution, construction of effective water institutional systems and water policies, and the advance of urban hydrology research to emulate SUWM in this important city in China.

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REFERENCES

Aheeyar, M. M. M., Nanayakkara, K. & Bandara, M. A. C. S. 2008 *Allocation of Water among Different Water-Use Sectors in Sri Lanka: Lessons of Experience*. Hector Kobbekaduwa Agrarian Research and Training Institute, Colombo, Sri Lanka.

Aladenola, O. O. & Adeboye, O. B. 2010 Assessing the potential for rainwater harvesting. *Water Resources Management* **24** (10), 2129–2137. doi:10.1007/s11269-009-9542-y.

Alwi, S. R. W., Manan, Z. A., Samingin, M. H. & Misran, N. 2008 A holistic framework for design of cost-effective minimum water utilization network. *Journal of Environmental Management* **88** (2), 219–252. doi:10.1016/j.jenvman.2007.02.011.

Apel, H., Aronica, G. T., Kreibich, H. & Thieken, A. H. 2009 Flood risk analyses: how detailed do we need to be? *Natural Hazards* **49** (1), 79–98. doi:10.1007/s11069-008-9277-8.

Bai, X. & Imura, H. 2001 Towards sustainable urban water resource management: a case study in Tianjin, China. *Sustainable Development* **9** (1), 24–35. doi:10.1002/sd.149.

Bao, C. & Fang, C. L. 2012 Water resources flows related to urbanization in China: challenges and perspectives for water management and urban development. *Water Resources Management* **26** (2), 531–552. doi:10.1007/s11269-011-9930-y.

Benedict, M. A. & McMahon, E. T. 2012 *Green Infrastructure: Linking Landscapes and Communities*. Island Press, Washington, DC, USA.

Bonta, J. V. 2004 Development and utility of Huff curves for disaggregating precipitation amounts. *Applied Engineering in Agriculture* **20** (5), 641–653. doi:10.13031/2013.17467.

Butler, D. & Davies, J. 2004 *Urban Drainage*. CRC Press, Boca Raton, FL, USA.

BWA (Beijing Water Authority) 2002 *Beijing Water Resources Bulletin*. Standards Press of China, Beijing, China (in Chinese).

BWA (Beijing Water Authority) 2004 *Beijing Water Resources Management Regulations*. http://www.bjwater.gov.cn/bjwater/300747/300754/300759/614136/index.html.

BWA (Beijing Water Authority) 2015 *Beijing Water Resources Bulletin*. Standards Press of China, Beijing, China (in Chinese).

Chen, H. & Yang, Z. F. 2009 Residential water demand model under block rate pricing: a case study of Beijing, China. *Communications in Nonlinear Science and Numerical Simulation* **14** (5), 2462–2468. doi:10.1016/j.cnsns.2007.12.013.

Chen, W., Lu, S., Jiao, W., Wang, M. & Chang, A. C. 2013 Reclaimed water: a safe irrigation water source? *Environmental Development* **8**, 74–83. doi:10.1016/j.envdev.2013.04.003.

Chithra, S. V., Harindranathan Nair, M. V., Amarnath, A. & Anjana, N. S. 2015 Impacts of impervious surfaces on the environment. *International Journal of Engineering and Science Invention* **4** (5), 27–31. Accessed from: http://www.ijesi.org/papers/Vol(4)5/E045027031.pdf.

Coffman, L. S. 2002 Low impact development: smart technology for clean water definitions, issues, roadblocks, and next steps. In: *Global Solutions for Urban Drainage, Proceedings of the 9th International Conference on Urban Drainage* (E. W. Strecker & W. C. Huber, eds), ASCE, Portland, OR, USA.

Convery, F. J. 2013 Reflections–shaping water policy: what does economics have to offer? *Review of Environmental Economics and Policy* **7** (1), 156–174. doi:10.1093/reep/res017.

Dixon, A., Butler, D. & Fewkes, A. 1999 Water saving potential of domestic water reuse systems using greywater and rainwater in combination. *Water Science and Technology* **39** (5), 25–32.

Du, J., Qian, L., Rui, H., Zuo, T., Zheng, D., Xu, Y. & Xu, C.-Y. 2012 Assessing the effects of urbanization on annual runoff and flood events using an integrated hydrological modeling system for Qinhuai River basin, China. *Journal of Hydrology* **464–465**, 127–139. doi:10.1016/j.jhydrol.2012.06.057.

Evans, R. G. & Sadler, E. J. 2008 Methods and technologies to improve efficiency of water use. *Water Resources Research* **44** (7), W00E04. doi:10.1029/2007WR006200.

Falkenmark, M., Lundqvist, J. & Widstrand, C. 1989 Macro-scale water scarcity requires micro-scale approaches. *Natural Resources Forum* **13** (4), 258–267. doi:10.1111/j.1477-8947.1989.tb00348.x.

Fan, L., Wang, H., Lai, W. & Wang, C. 2015 Administration of water resources in Beijing: problems and countermeasures. *Water Policy* **17** (4), 563–580. doi:10.2166/wp.2014.407.

Fletcher, T. D., Andrieu, H. & Hamel, P. 2013 Understanding, management and modelling of urban hydrology and its consequences for receiving waters: a state of the art. *Advances in Water Resources* **51**, 261–279. doi:10.1016/j.advwatres.2012.09.001.

Giugni, M. & De Paola, F. 2015 Urban stormwater drainage management by low impact development practices. *Sustainable Mediterranean Construction Magazine* **2**, 093–098.

Gleick, P. H. 2000 A look at twenty-first century water resources development. *Water International* **25** (1), 127–138. doi:10.1080/02508060008686804.

Grumm, R. H. 2012 *Beijing Flood of 21 July 2012*. http://cms.met.psu.edu/sref/severe/2012/21Jul2012.pdf (accessed 21 July 2012).

Heaney, J. P., Wright, L. & Sample, D. 2000 Sustainable urban water management. In: *Innovative Urban Wet-Weather Flow Management Systems* (R. Field, J. P. Heaney & R. Pitt, eds), Technomic Publishing Company, Lancaster, PA, USA, pp. 75–120.

Howe, C., Vairavamoorthy, K. & van der Steen, N. P. 2012 *Sustainable Water Management in the City of the Future*. UNESCO-IHE, Delft, The Netherlands.

Hu, Y. & Cheng, H. 2013 Water pollution during China's industrial transition. *Environmental Development* **8**, 57–73. doi:10.1016/j.envdev.2013.06.001.

IPCC (Intergovernmental Panel on Climate Change) 2012 *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* (C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor & P. M. Midgley, eds). Cambridge University Press, New York, USA.

Jenerette, G. D. & Larsen, L. 2006 A global perspective on changing sustainable urban water supplies. *Global and Planetary Change* **50** (3–4), 202–211. doi:10.1016/j.gloplacha.2006.01.004.

Jha, A. K., Bloch, R. & Lamond, J. 2012 *Cities and Flooding: A Guide to Integrated Urban Flood Risk Management for the 21st Century*. World Bank Publications, Washington, DC, USA.

Jia, H., Yao, H. & Yu, S. L. 2013 Advances in LID BMPs research and practice for urban runoff control in China. *Frontiers of Environmental Science & Engineering* **7** (5), 709–720. doi:10.1007/s11783-013-0557-5.

Jiang, Y. 2009 China's water scarcity. *Journal of Environmental Management* **90** (11), 3185–3196. doi:10.1016/j.jenvman.2009.04.016.

Li, C. 2012 Ecohydrology and good urban design for urban storm water-logging in Beijing, China. *Ecohydrology & Hydrobiology* **12** (4), 287–300. doi:10.2478/v10104-012-0029-8.

Liang, X. 2011 *The Economics of Sustainable Urban Water Management: The Case of Beijing*. PhD thesis, UNESCO-IHE, Delft, The Netherlands.

Liu, B. & Speed, R. 2009 Water resources management in the People's Republic of China. *Water Resources Development* **25** (2), 193–208. doi:10.1080/07900620902868596.

Liu, W., Chen, W., Peng, C., Wu, L. & Qian, Y. 2015 A water balance approach to assess rainwater availability potential in urban areas: the case of Beijing, China. *Water Science and Technology: Water Supply* **15** (3), 490–498. doi:10.2166/ws.2014.134.

Ma, J. 2011 *Confronting the Water Crisis of Beijing Municipality in a Systems Perspective: Focusing on Water Quantity and Quality Changes*. Master of Science thesis, Industrial Ecology, KTH, Stockholm, Sweden. http://www.diva-portal.org/smash/get/diva2:578116/FULLTEXT01.pdf (accessed 19 February 2013).

Makropoulos, C. K., Natsis, K., Liu, S., Mittas, K. & Butler, D. 2008 Decision support for sustainable option selection in integrated urban water management. *Environmental Modelling & Software* **23** (12), 1448–1460. doi:10.1016/j.envsoft.2008.04.010.

Marlow, D. R., Moglia, M., Cook, S. & Beale, D. J. 2013 Towards sustainable urban water management: a critical reassessment. *Water Research* **47** (20), 7150–7161. doi:10.1016/j.watres.2013.07.046.

McGrane, S. J. 2016 Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. *Hydrological Sciences Journal* **61** (13), 2295–2311. doi:10.1080/02626667.2015.1128084.

Mitchell, V. G. 2006 Applying integrated urban water management concepts: a review of Australian experience. *Environmental Management* **37** (5), 589–605. doi:10.1007/s00267-004-0252-1.

Mitchell, V. G., Mein, R. G. & McMahon, T. A. 2001 Modelling the urban water cycle. *Environmental Modelling & Software* **16** (7), 615–629. doi:10.1016/S1364-8152(01)00029-9.

Nie, L. & Schilling, W. 2000 Development of sustainable water management in Beijing, China. In: *Proceedings from the Symposium 'Frontiers in Urban Water Management: Deadlock or Hope'* (J. A. Tejada-Guibert & Č. Maksimović, eds), UNESCO, Marseille, France, pp. 279–284.

Niemczynowicz, J. 1999 Urban hydrology and water management: present and future challenges. *Urban Water* **1**, 1–14. doi:10.1016/S1462-0758(99)00009-6.

Nolde, E. 2000 Greywater reuse systems for toilet flushing in multi-storey buildings: over ten years experience in Berlin. *Urban Water* **1** (4), 275–284. doi:10.1016/S1462-0758(00)00023-6.

O'Hara, J. K. & Georgakakos, K. P. 2008 Quantifying the urban water supply impacts of climate change. *Water Resources Management* **22** (10), 1477–1497. doi:10.1007/s11269-008-9238-8.

Pappalardo, V., Campisano, A., Martinico, F., Modica, C. & Barbarossa, L. 2017 A hydraulic invariance-based methodology for the implementation of storm-water release restrictions in urban land use master plans. *Hydrological Processes* **31** (23), 4046–4055. doi:10.1002/hyp.11318.

Sarma, A. K., Singh, V. P., Kartha, S. A. & Bhattacharjya, R. K. 2016 *Urban Hydrology, Watershed Management and Socio-Economic Aspects*, Vol. 73. Water Science and Technology Library Springer, Switzerland.

SEPA (State Environmental Protection Administration of China) 2002 *Environmental Quality Standard for Surface Water (GB 3838-2002)*. China Environmental Science Press, Beijing, China (in Chinese). http://kjs.mep.gov.cn/hjbhbz/bzwb/shjbh/shjzlbz/200206/t20020601_66497.shtml.

Schirmer, M., Leschik, S. & Musolff, A. 2013 Current research in urban hydrogeology: a review. *Advances in Water Resources* **51**, 280–291. doi:10.1016/j.advwatres.2012.06.015.

Sun, F., Yang, Z. & Huang, Z. 2014 Challenges and solutions of urban hydrology in Beijing. *Water Resources Management* **28** (11), 3377–3389. doi:10.1007/s11269-014-0697-9.

Suriya, S. & Mudgal, B. V. 2012 Impact of urbanization on flooding: the Thirusoolam sub watershed – a case study. *Journal of Hydrology* **412**, 210–219. doi:10.1016/j.jhydrol.2011.05.008.

Tisherman, R. 2013 *Beijing's Water Crisis: A Historical Analysis of Beijing's Waterways Using Geographic Information Systems*. PhD thesis, Connecticut College, New London, CT, USA.

Tong, T. H. D. 2009 *Application of a Total Urban Water Cycle Model to Develop Urban Water Management Strategies for Tel Aviv, Israel, Water Balance and Energy Consequences*. PhD thesis, UNESCO-IHE, Delft, The Netherlands.

US EPA (US Environmental Protection Agency) 2005 *Stormwater Phase II Final Rule, Fact Sheet 1.0, Report No. EPA 833-F-00-001*. Office of Water, US EPA, Washington, DC, USA.

Wang, Y. & Wang, H. 2005 Sustainable use of water resources in agriculture in Beijing: problems and countermeasures. *Water Policy* **7** (4), 345–357.

Wang, L., MacLean, H. L. & Adams, B. J. 2005 Water resources management in Beijing using economic input–output modeling. *Canadian Journal of Civil Engineering* **32** (4), 753–764. doi:10.1139/l05-031.

Wang, Y., Sheng, L. X., Li, K. & Sun, H. Y. 2008 Analysis of present situation of water resources and countermeasures for sustainable development in China. *Journal of Water Resources & Water Engineering* **19** (3), 10–14 (in Chinese).

Wei, D. 2005 Beijing water resources and the south to north water diversion project. *Canadian Journal of Civil Engineering* **32** (1), 159–163. doi:10.1139/l04-113.

Wilcox, J., Nasiri, F., Bell, S. & Rahaman, M. S. 2016 Urban water reuse: a triple bottom line assessment framework and review. *Sustainable Cities and Society* **27**, 448–456. doi:10.1016/j.scs.2016.06.021.

Xue, N., Zhang, D. & Xu, X. 2006 Organochlorinated pesticide multiresidues in surface sediments from Beijing Guanting reservoir. *Water Research* **40** (2), 183–194. doi:10.1016/j.watres.2005.07.044.

Yang, H. & Abbaspour, K. C. 2007 Analysis of wastewater reuse potential in Beijing. *Desalination* **212** (1–3), 238–250. doi:10.1016/j.desal.2006.10.012.

Yi, L., Jiao, W., Chen, X. & Chen, W. 2011 An overview of reclaimed water reuse in China. *Journal of Environmental Sciences* **23** (10), 1585–1593. doi:10.1016/j.ecolecon.2011.08.011.

Zhai, Y., Wang, J., Teng, Y. & Zuo, R. 2012 Water demand forecasting of Beijing using the time series forecasting method. *Journal of Geographical Sciences* **22** (5), 919–932. doi:10.1007/s11442-012-0973-7.

Zhang, H. H. & Brown, D. F. 2005 Understanding urban residential water use in Beijing and Tianjin, China. *Habitat International* **29** (3), 469–491. doi:10.1016/j.habitatint.2004.04.002.

Zhang, D., Gersberg, R. M., Wilhelm, C. & Voigt, M. 2009 Decentralized water management: rainwater harvesting and greywater reuse in an urban area of Beijing, China. *Urban Water Journal* **6** (5), 375–385. doi:10.1080/15730620902934827.

Zhong, L., Mol, A. P. J. & Fu, T. 2008 Public-private partnerships in China's urban water sector. *Environmental Management* **41** (6), 863–877. doi:10.1007/s00267-008-9070-1.

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