Water Policy 20 (2018) 490–509

Spatio-temporal relational evaluation of the Beijing water crisis and planning implementation from 1949 to 2013

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Abstract

Due to a lack of evaluation of the implementation of water planning policies, based on long-term spatio-temporal analysis, this research uses Beijing as an empirical case study to bridge this gap. We analyze the spatio-temporal evolution of water problems and water planning implementations. Content analysis, cluster analysis, and spatial interpolation analysis are used to illustrate the spatio-temporal evolution of water planning implementation. In addition, a grey relational model is developed to determine the impact of the most relevant implementation objects on each water issue. The results indicate that the Beijing water crisis evolves from the center outwards in a planar expansion. However, the water plan implementation shows linear and point characteristics. The majority of implementation categories consist of single-function infrastructure. The implemented categories 'which show a significant implementation peak' influence more than one water issue. The categories 'that were implemented at a steady rate' have a high relational grade with both surface and underground water shortage problems. Different implementation types from different planning categories may have simultaneous effects on one kind of water problem. Thus, improving water governance is the key to water security in Beijing. This study may serve as a reference for future water planning in other cities.

Keywords: Impact; Planning implementation; Relationship; Urban water planning; Water crisis

Introduction

Research into the failure of policy to protect the environment and to promote sustainable development is receiving increasing international attention (Berke & Conroy, 2000; Kabisch, 2015; Galler *et al*., 2016). Ineffective management by governments has led to a 'water governance crisis' (World Water Commission, 1999; United Nations, 2002), for example, Florida's Coastal High Hazard Area policy (Brown *et al*., 2005; Puszkin-Chevlin & Esnard, 2009), small water systems in Nova Scotia (Brown

doi: 10.2166/wp.2018.107

et al., 2005), Australian freshwater protected area networks (Nevill, 2007), and Belgium afforestation policy (Van Gossum, 2008).

Due to improved management methods for land areas, the availability of better statistics and spatial analysis methods, more emphasis has been placed on the evaluation of land use planning decisions and their implementation (Zhong *et al*., 2014; Xu *et al*., 2015). However, empirical studies are more often characterized by evaluating urban sprawl (Haase & Nuissl, 2007; Tian & Shen, 2011; Long *et al*., 2012; Yizhou *et al*., 2013) and less aimed at evaluating the implementation of environmental planning policies. Meanwhile, in the particular area of the evaluation of environmental planning implementation, there has been: (1) more emphasis on spatio-temporal static evaluation methods (Carter *et al*., 2015) and less on spatio-temporal dynamic relationships research; (2) also more focus on conformance-based methodologies (Laurian *et al*., 2004; Brody & Highfield, 2005; Brody, 2006), however high conformance does not necessarily mean good performance; (3) more emphasis on subjective experience (Daniels, 2009; De Jong *et al*., 2016) and a lack of quantitative content mechanism analysis to generate recommendations. Water planning implementation evaluation based on long-term spatio-temporal analysis has so far not been attempted; in addition, in China, the evaluation of planning implementation has yet to be carried out fully and more specifically.

Thus, this research aims to bridge the gap by dynamically evaluating and quantifying spatio-temporal water planning implementation from 1949 to 2013. We take Beijing as the empirical study area using water resources as a measure of the performance of water planning. Beijing is a typical large city that has changed rapidly and recently enough to have good data over a period of significant change. We first systematically analyze the content and spatial evolution of urban water planning implementation in Beijing. Then, we consider the spatio-temporal relationship between planning implementation and water problems. On this basis, we conclude that there is a relationship between implementation and the water crisis. We then use this conclusion to propose new approaches for future planning to rectify the negative influence on water availability and quality. This study provides an approach for other cities across the world to evaluate the effectiveness of water planning policies.

Materials and methods

Study area

Beijing has a continental climate with high temperatures and significant rainfall in the summer months. Since 1949, both the economy and the population have experienced a period of spectacular boom, which has been accompanied by the growth of urban sprawl. The urban area of Beijing increased from 100.2 km^2 in 1950 to 1,289.2 km^2 in 2013, while the urban population increased from 1.8×10^6 in 1950 to 18.3×10^6 in 2013 (Beijing Municipal Bureau of Statistics, 2013). Water-related problems, as a core issue in the current ecological and environmental crisis, are now seriously worsening to the point of becoming one of the main obstacles to the sustainable economic and social development of Beijing and many other cities.

According to the developmental progress of society and the economy, different water problem orientations and urban master planning implementations have been applied at different times. We divided the evolution of Beijing water planning implementation from 1949 to 2013 into six periods (Table 1).

Table 1. List of water planning categories and objects.

Period	Stage
1949–1957	Initial post-war restoration of the aquatic environment and the construction and development of water conservation projects
1958–1965	Large-scale construction of water diversion facilities and the associated development work
1966–1978	Recognition of the importance of water pollution and of keeping waterways flowing
1979–1989	The adjustment of imbalances between water resource supply and demand
1990–2000	Comprehensive drainage and water treatment system
2001–2013	Resource-oriented water governance adjustment

During each period, five intervention plans for the water system were implemented (Beijing Municipal Planning Committee, 2006). These are:

(a) Water diversion and transfer plan
(b) Wastewater drainage and irrigation plan
(c) Rainwater drainage and storage plan
(d) Rivers and lakes system plan
(e) Flood control plan.

Data resources

The data from 1949 to 2000 were obtained from: (1) the Beijing Local History Compilation of planning, environmental protection, water supply, water conservation, drainage, and landscaping; (2) Beijing archives on permits, project details, plans, notices, minutes of meetings, geological and geographical research data; (3) the flood and drought record books published by each district or county's water conservancy bureau and by the Chaobai, Beiyun, and Yongding River management office. Implementation data from 2001 to 2013 were obtained from the online Beijing Statistical Yearbook master plan and subject plan.

Methods

Our research consists of three parts: the spatio-temporal evolution of water problems, the spatio-temporal evolution of water planning implementation, and the relational evaluation of water problems and water planning implementations (Figure 1). Systematic analysis of changes in conditions related to water resources in Beijing since 1949 was performed. These include changes in water quantity and quality, water disasters, and water-body patterns. The spatial mapping analysis (Brody, 2006; Forest & Forest, 2012) was carried out by inputting and comparing the geographic information on the water crisis (location, year, area, and value). In addition, the six phases of land use data for water bodies (1951, 1971, 1985, 1993, 2001, and 2010) in each period were taken into consideration.

The first part of our research involves analyzing the spatio-temporal evolution of water problems using content analysis (Weber, 1990; Haasnoot & Middelkoop, 2012; Moore *et al.*, 2014; Rivera & Wamsler, 2014) as a tool to quantitatively analyze textual information of Beijing water planning

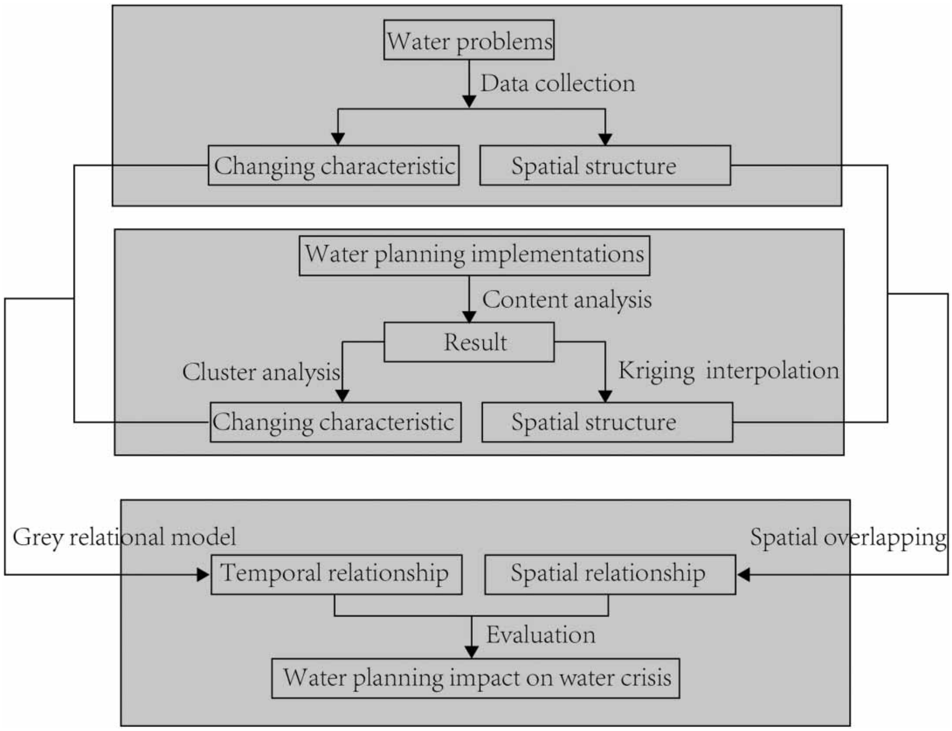

Fig. 1. Technical route.

implementation. On this basis, we summarize the content of planning implementations into 32 categories or keywords (Table 2). In the second part of our analysis, we use statistical methods to quantify the frequencies of each keyword. Based on this, we use cluster analysis (SPSS 17.0) to interpret the frequency data. In addition, we map water planning implementations (keyword frequency, location, and year) into GIS (Geographic Information System) for each of the six periods. Then, kriging interpolation (ArcGIS 10.2) is used to interpolate frequencies in the six stages of each geographic map to locate implementation hot spots.

The third and final part of our analysis consists of overlapping the spatial structure of water problems and water planning implementations. We use a grey relational grade model to analyze the frequencies of implementations and to correlate these with observations on the state of water resources (Chan & Tong, 2007; Chiang & Liang, 2013; Galvis *et al*., 2014; Sun *et al*., 2015). The grey relational model was employed in policy-oriented studies on urban planning and infrastructure (Li & Zhang, 2009; Jie *et al*., 2011; Sun *et al*., 2015). This process is described in more detail below.

First, water issues are taken as a reference sequence. They are marked as $X_0(k)$, $k = 1,2, \dots$ n, where n represents the evaluation number. There are six implementation periods, so 6 is the largest number.

Second, we compare sequence selections. The frequencies of the 32 keywords in our study are compared. They are marked $X_i(k)$, $k = 1,2,3,4,5,6$, $i = 1,2, \dots ,$m.

Third, a dimensionless analysis to both reference and compared sequences is applied. The analysis method sets the maximum of every sequence to 1; the others are divided into them.

Table 2. List of water planning categories and objects.

Number	Category	Implementation object	Number	Category	Implementation object	Number	Category	Implementation object	Number	Category	Implementation object
1	Water supply plan	Industrial water supply plant	9	Rivers and lakes system plan	River-channel shape adjustment	17	Wastewater discharge plan	Wastewater treatment plant	25	Rainwater discharge plan	Dredging channel
2		Water supply plant	10		River-channel section adjustment	18		Wastewater guidance	26		Dredging river
3		Water recycling plant	11		Floodgate and dam	19		Drainage pumping station	27	Flood control plan	Impounding reservoir
4		Reservoir for drinking water	12		Greenery	20		Sewerage pipeline	28		Dike project
5		Water conservation	13		Lake regulation	21		Wastewater irrigation system	29		Critical engineering embankment
6		Water diversion (transfer)	14		Wetland park	22		Rainwater pumping station	30		River training work
7		Emergency water source	15		Sewerage pumping station	23		Rainwater pipeline	31		Flood storage area
8		Self-drilled well	16		Sewerage interception	24		Underground cistern	32		Flood diversion and detention

Then, we calculate the correlation coefficient between all the indices of the compared sequences and reference sequences from Equation (1):

$$\xi_i(k) = \frac{min_i min_k \Delta_i(k) + \zeta max_i max_k \Delta_i(k)}{\Delta_i(k) + \zeta max_i max_k \Delta_i(k)} \tag{1}$$

Equation (2) represents the absolute difference of k

$$\Delta_i(k) = |X_0(k) - x_i(k)| \tag{2}$$

$\zeta \in [0, 1]$ is the distinguishing coefficient. The smaller the value of ζ, the better its resolving ability. Equation (3) for the relational grade is:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \tag{3}$$

Finally, we rank the outcomes according to Equation (3). The higher the grade of the relationship, the closer the relationship between the reference sequence and the comparison sequence. The score reflects which implementation category has the highest correlation with each of the water problems.

Results

The spatio-temporal evolution of Beijing's water crisis

Changes in water bodies. In terms of our six stages (Table 1), the remote sensing digital map shows that the total area of water bodies in Beijing has gradually increased, reaching a peak of 769 km^2 around 2001, followed by a decrease of 165 km^2. The river and lake area has been shrinking since 1951 (Table 3). The most obvious region with shrinking rivers is Yongding. After 2010, the section downstream of the Lugou Bridge dried up. The most obvious regions of shrinking lakes are in the north part of the Qing River and the south part of South Moat. In urban areas, lakes and rivers have shrunk from the center outwards. Water bodies disappeared conspicuously between the 2nd and 3rd urban ring roads. River-channel shape adjustment, such as curve cut-off and distributary measures, has brought obvious changes to the Qing, Wenyu, Chaobai, Beiyun and Ba Rivers.

Changes in water shortages. The supply of water resources is gradually diminishing. From the beginning of the establishment of China, the only urban source of surface water in Beijing was from the Yuquan Mountains. However, its outflow sharply decreased due to high demand in the initial stage (1949 to 1957). In 1954, Guanting Reservoir was built upstream on the Yongding River for water supply and flood control. However, since it was established, the water level continued to decrease; therefore, the Miyun Reservoir was built in 1960. Subsequently, both the inflows of the two major reservoirs reduced exponentially (Fu & Li, 2014). The runoff of surface water decreased or dried up rapidly, especially for the Chaobai River and Yongding River, which are both downstream of the respective

Table 3. The evolution of water resource issues.

Year	Total water use (10^9 m^3)	Chaobai River (Suzhuang Station) average runoff (10^9 m^3)	Yongding River (Lugouqiao Station) average runoff (10^9 m^3)	Amount of Yuquan mountain effluent (10^5 m^3)	Groundwater depth (m)	Wastewater discharge (10^9 m^3)	Area of groundwater hardness overproof (km^2)	Water pollution accident (time)	Flooding area of Beiyun River watershed (km^2)	Area of water body (km^2)	Area of waterscape (km^2)
1949–1957	23.80	23.50	976.57	3593.00	(3.09)	0.68	15.65	0	58.60	234.75	341.95
1958–1965	27.62	15.26	526.80	3033.67	(4.17)	3.25	53.90	1	13.85	377.40	450.00
1966–1978	42.92	10.19	134.22	1363.75	(7.24)	6.84	105.24	4	5.20	370.95	545.46
1979–1989	41.12	2.23	66.49	0.00	(10.62)	7.58	507.39	46	2.50	563.68	705.64
1990–2000	40.40	1.25	7.33	0.00	(15.36)	13.55	839.81	16	0.00	615.77	768.38
2001–2013	35.90	2.86	0.10	0.00	(25.33)	15.20		10	0.01	424.62	602.94

Miyun and Guanting reservoirs. The runoff from the Yongding River (at Sanjiadian Station) has fallen to a meager 25 million m^3/year since the end of the 1950s. The annual surface flow of the Chaobai River (at Suzhuang Hydrological Station) dropped from 2 billion m^3 to less than 0.2 billion m^3 (Table 3). Since 1980, only infrequent and unstable runoff has occurred during heavy rains in the rainy season.

Changes in groundwater depth. The depth of the groundwater also declined. In the 1950s, the water table was at a very shallow depth of only about 1 m on the eastern outskirts of the city. In 2010, the average depth to groundwater was more than 25 m below the surface. In order to alleviate the surface water shortage, groundwater has been pumped even more rapidly since the 1960s, causing a rapid decline in the water table. During the 1970s, the outflow of Yuquan Mountain dropped dramatically and, by 1975, the outlet was no longer flowing. A groundwater funnel was also formed around 1975. The ratio of accelerating transmission was 13–34 km^2/year. Overall, 30 mm/year of ground subsidence occurred over an area of 1,637 km^2, from west to east (Table 3).

Changes in water pollution. In terms of water quality, 97% of Beijing's waterway is currently polluted. Wastewater discharge increased linearly during the study period (Table 3). The annual increment is 23.1 million m^3, which has led to an increase from 5.1 million m^3 in 1949 to 1.5 billion m^3 in 2013, and it is still increasing. The sources of pollution have gradually become more diverse, from simple domestic wastewater in the early stages until, by the 1980s, more than 30 rivers and ditches were contaminated (Figure 2(d)). Among the five major water systems in the city, with the exception of upstream areas where water quality was relatively good, the majority of the middle and downstream rivers were increasingly polluted. In the urban areas, more than 450 km of downstream river channels were severely polluted, including over 50 km that were filled with lifeless, dark and putrid water. Water pollution events reached a peak during this time. In 2013, all drainage channels had various degrees of contamination or were simply dry (Figure 2(f)). The water quality of 967.6 km of river channels fell below grade V[1], accounting for 44% of all segments of the rivers that were evaluated (Fu & Li, 2014). The range of groundwater hardness also gradually increased in the east and south of the city.

Changes in floods. During the study period, the area of Beijing affected by flooding decreased, as is evident from Figure 2(a). The hardest-hit period was from 1949 to 1957. During this time, flood disasters occurred every summer, and the proportion of area flooded reached 66%. Major flood disasters occurred in 1956, 1959, 1963, 1964, 1976, 1994, and 2012. In addition, the ratio of cumulative area inundated by the Beiyun River, which is the largest flood-affected watershed area, reached 56% (Table 3). However, during the last 20 years, bridges and roads have become the newest urban catchment center, based on Figure 2(e). By the 21st century, over 80% of local floods occurred on roads, overpasses, and intersections (Figure 2(f)). In 2012, there were over 80 waterlogged locations (Zhao *et al.*, 2014). The water depth in the worst affected areas was 6 m.

[1] The Environmental Quality Standards of China for Surface Water: Grade I is mainly applicable to the water from sources, and the national natural reserves. Grade II is mainly applicable to the first class of protected areas for centralized sources of drinking water, the protected areas for rare fishes, and the spawning fields of fishes and shrimps. Grade III is mainly applicable to the second class of protected areas for centralized sources of drinking water, protected areas for common fishes and swimming areas. Grade IV is mainly applicable to the water areas for industrial use and entertainment, which are not directly touched by human bodies. Grade V is mainly applicable to the water bodies for agricultural use and landscape requirement.

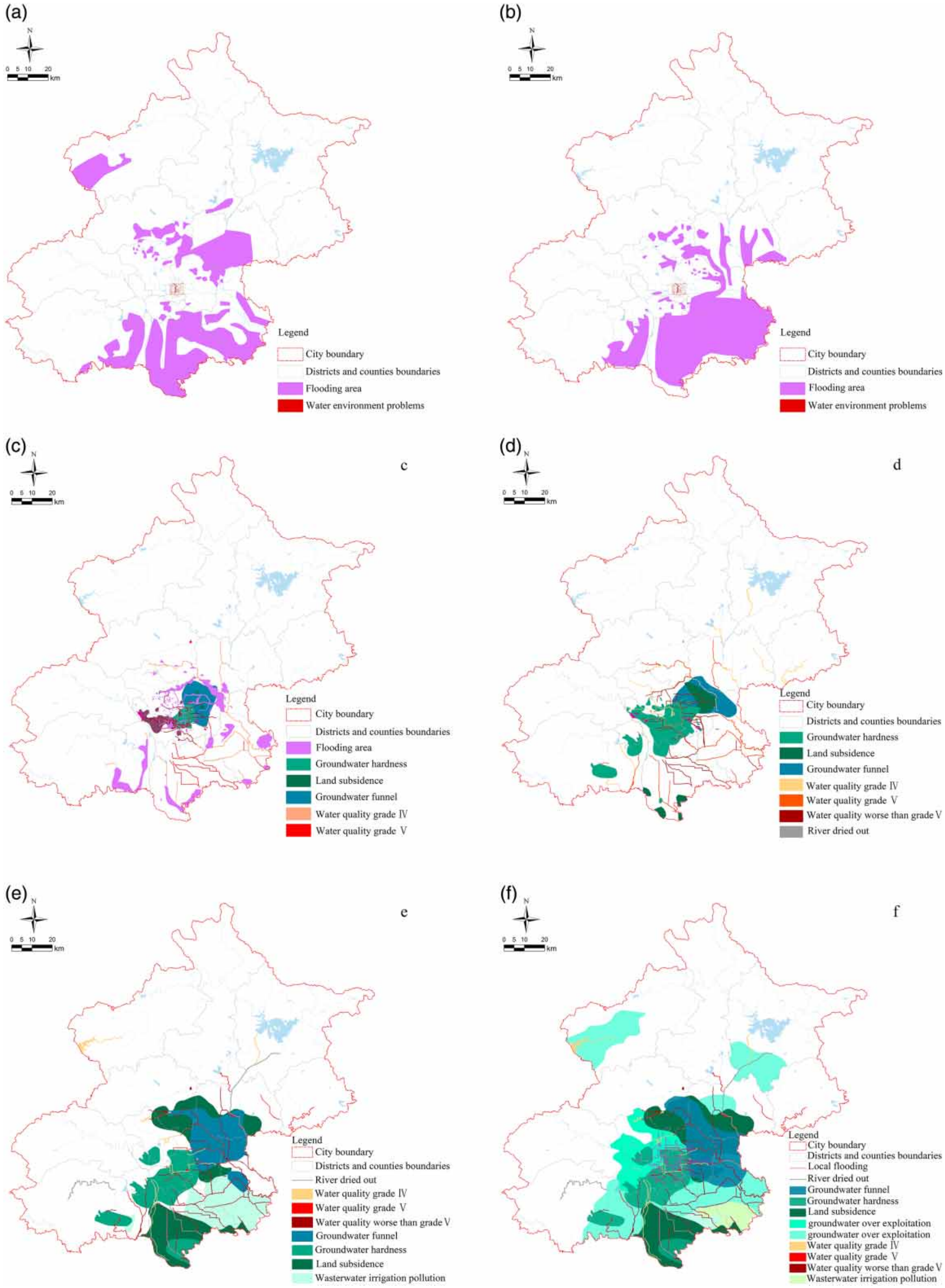

Fig. 2. (a) The spatio-temporal evolution of the Beijing water crisis from 1949 to 1957; (b) the spatio-temporal evolution of the Beijing water crisis from 1958 to 1965; (c) the spatio-temporal evolution of the Beijing water crisis from 1966 to 1978; (d) the spatio-temporal evolution of the Beijing water crisis from 1979 to 1989; (e) the spatio-temporal evolution of the Beijing water crisis from 1990 to 2000; (f) the spatio-temporal evolution of the Beijing water crisis from 2001 to 2013.

The spatio-temporal evolution of the Beijing water crisis from 1949 to 2013 is shown in Figure 2. Surface water problems and groundwater problems are represented. It can be seen that the area involved in the groundwater crisis has expanded to cover almost the whole of Beijing, whether considered from a water shortage or groundwater funnel perspective. In terms of water contamination problems, or shrinking rivers and lakes, the spatio-temporal evolution of the Beijing water crisis is expanding from the center outwards.

The spatio-temporal evolution of water planning implementation

As the result of the content analysis phase of our research, the frequency of all the 32 keywords and their significance in the five planning categories during the six temporal stages have been summarized (Figure 1). From this, we can see the following: the overall trend of each of the planning categories; the predominance of each object(s) in each planning category during the study period and during each stage; object clustering characteristics; and the spatial evolution of water planning implementations. Each of these is discussed in more detail below.

(a) The overall frequency of implementations has increased (Figure 3), especially for plans concerning rivers and lakes, and wastewater discharge. These two plans have gradually increased by multiples of 6 and 4, respectively. The water supply plan implementation remained relatively stable (1.5 times per year) during the first five stages. In the last stage, the rate jumped dramatically by a factor of about 4.8. The content trend of the rainwater discharge plan implementation follows a U-shaped curve. During the first two stages, it dropped by a factor of almost 3. However, during the last three stages, it increased by a factor of 4.5 over nearly 50 years. Conversely, the flood control

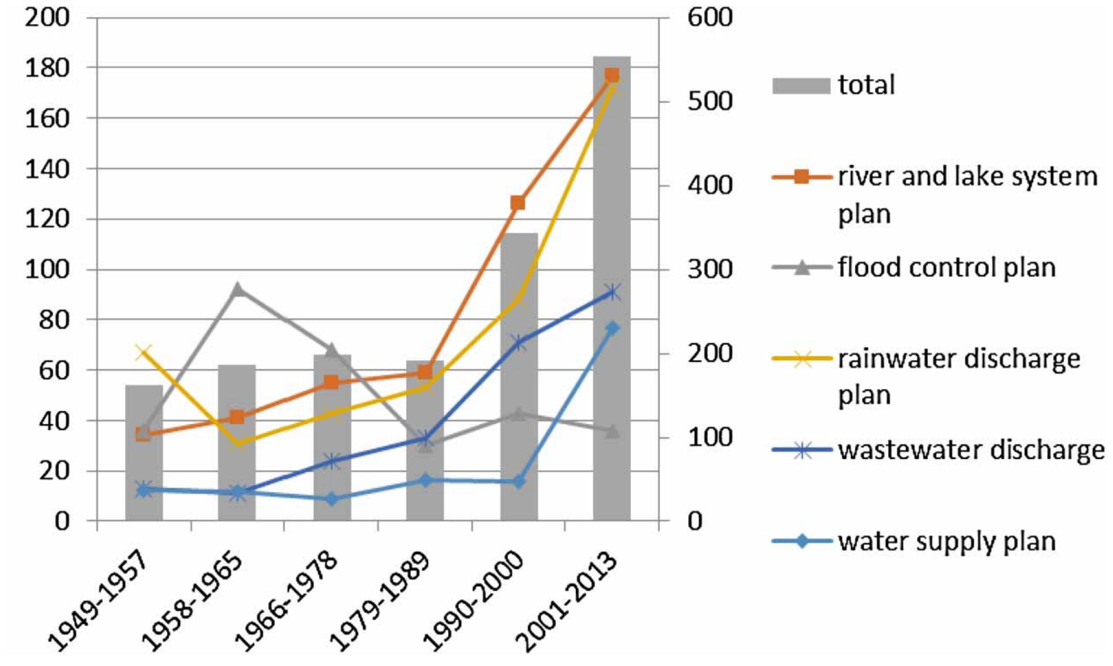

Fig. 3. Frequencies of five planning categories in six temporal stages.

plan implementation shows an inverse-U-shaped curve. During the first two stages, the frequency of implementation increased from 36 to 92, while during the last three stages, it decreased by 36.

(b) Each of the five categories of the plan implementation method had a different emphasis over the six temporal stages. Overall, hydraulic engineering was the most dominant. In terms of the water supply plan, the most frequently mentioned category was the water supply plant, i.e. 26%. However, during the first five stages, the water supply plant occupied the primary position; in the last stage, both the water recycling plant and water conservation were the most prominent.

The most frequently mentioned category of the flood control plan was reservoir and river training work. Overall, the ratio was 32%. In the first two stages (1949–1965), river training work took the top position at over 66%. During the next two stages, the leading role was reservoir construction, i.e. 62% in 1966–1978 and 42% in 1979–1989. Meanwhile, dike construction projects increased in frequency with the effect of decreasing the ratio of reservoir construction. In the last two stages, flood diversion and prevention became the primary implemented category with a ratio of over 54%.

The most frequently mentioned category of the river and lake system plan implementation was floodgate and dam, with a ratio of 21%. In the first stage, river-channel shaping and section adjustment accounted for 71% of total implementations. In the second stage, due to the high level of attention placed on lake recovery and pit and depression development, lake regulation accounted for almost half of the total implementations. Then, during the third stage, river-channel shaping and section adjustment were back in the top position with a ratio of over 65%. In the fourth stage, despite shape and section adjustment retaining a major role (29%), lake regulation, and floodgate and dam kept pace with ratios of 22% and 24%, respectively. In the meantime, the ratio of greenery started to increase. During the fifth stage, the ratios of the river-channel shape and section adjustment, floodgate and dam, and greenery were similar. During the last stage, floodgate and dam played a major role (31%).

The most frequently mentioned category of the rainwater discharge plan implementation was the rainwater pipeline. This ratio reached 77%. In Beijing, the rainwater pipeline consists of a rain–sewerage mixture pipeline and a rainwater pipeline. It retained its leading role during the study period. However, it is worth mentioning that the ratio of the underground cistern increased rapidly from zero during the last stage.

The most frequently mentioned category of the wastewater discharge plan implementation was the sewerage pipeline, with a ratio of 41%. During the first stage, the main implemented category was the sewerage pipeline, i.e. 54%. During the next two stages, the wastewater pumping station implementation played the major role for almost the next 20 years. The ratio of implementation during 1958–1965 and 1966–1978 was 64% and 54%, respectively. During 1979–1989, the sewerage pipeline became the primary category again, with a ratio of 61%. During the period 1990–2000, over 44% of implementations focused on sewerage interception, and during 2001–2013, the sewerage pipeline was back at the top. The ratio of wastewater treatment was consistently far behind the ratio of wastewater interception and transfer implementation.

(c) According to the results of the cluster analysis, there were five groups within the 32 implemented categories. (i) Those that exhibit significant implementation peaks or spikes. These include self-drilled wells (1958–1965), river training work (1958–1965), reservoirs for flood control (1966–1978), river-channel shape adjustment (1966–1978), and wastewater irrigation (1958–1989). (ii) Categories that were implemented much more frequently during the latter part of the study period. These were recycling water plants, water conservation, wetland parks, wastewater treatment plants, flood storage areas, underground cisterns, greenery, wastewater guidance, sewage pumping stations, and flood diversion and prevention. (iii) Categories that were implemented consistently over the whole study period. These were water supply projects (water supply plants, reservoirs for drinking water, and water diversion and transfer projects), wastewater pumping stations, channel dredging, flood dike and critical engineering embankments. (iv) Categories that were implemented in a gradually increasing trend were floodgates and dams, and rainwater and sewerage pipelines. (v) Categories that changed periodically were lake regulation, river dredging, and river-channel section adjustment.

In spatial terms, (i) the main implemented categories have a line and point structure. Water supply planning has changed from relying on the surface water system as the transfer pathway to relying on underground pipelines (a linear structure) to transfer water for industry and domestic water. More recently, planar structures such as water conservation areas have appeared. The main spatial characteristic of wastewater discharge planning is that the sewerage pipelines and wastewater treatment plants grew in parallel with the increasing urban sprawl. Only the wastewater irrigation area, which expanded from the west, north, south, and then to the southeast of the suburban area, is an example of a planar implementation. The spatial pattern of the flood control plan shows that the planar lakes and wetlands kept shrinking in area. Floodgate and dam implementations remained as point structures, and river-channel curve shaping kept cutting off bends in the rivers. Around 1958, green spaces and water spaces were designed together in the city center. After 2000, although water conservation space and flood storage areas have changed the spatial pattern, linear structures in the form of transfer lines, wastewater pipes, water supply, recycled water, and rainwater pipelines, and point structures like water supply, wastewater treatment, water recycling plants, and underground cisterns retained their primary position.

(ii) Spatial hot spots (Figure 4) shrank during the first three stages (1949–1978), mainly in the Beiyun River watershed and the upstream area of the Yongding River at Lugouqiao Station. In the last three stages, the hot spots began to grow. However, the former hot spot area in the Yongding River weakened. Instead, the Chaobai River and its alluvial-proluvial fan arose. In addition, the four large drainage water systems in the city center (the Qing, Ba, Liangshui, and Tonghui Rivers) remained as hot spots during the study period.

(iii) The implementations manifested an imbalance between grey infrastructure and green infrastructure. Fortunately, the proportion of area of green infrastructure gradually increased from 3% to 17%. Nevertheless, grey infrastructure still maintained an area of 77–90%. The majority of implementation categories consist of single-function infrastructure. These have poor resilience and a high level of vulnerability to environmental emergencies or disturbance. The use of 'hard' infrastructure, including reservoirs, dikes, floodgates, channelized rivers, sewers and drainage pipelines, increased dramatically as water resource plans were implemented. 'Softer' measures related to integrated water management, such as using natural processes and designing systems to accommodate runoff and other water sources, were generally abandoned.

Relational grade between implementations and the water crisis

Based on the grey relational grade analysis result, different water problems were found to have the following relationship with different implementation objects.

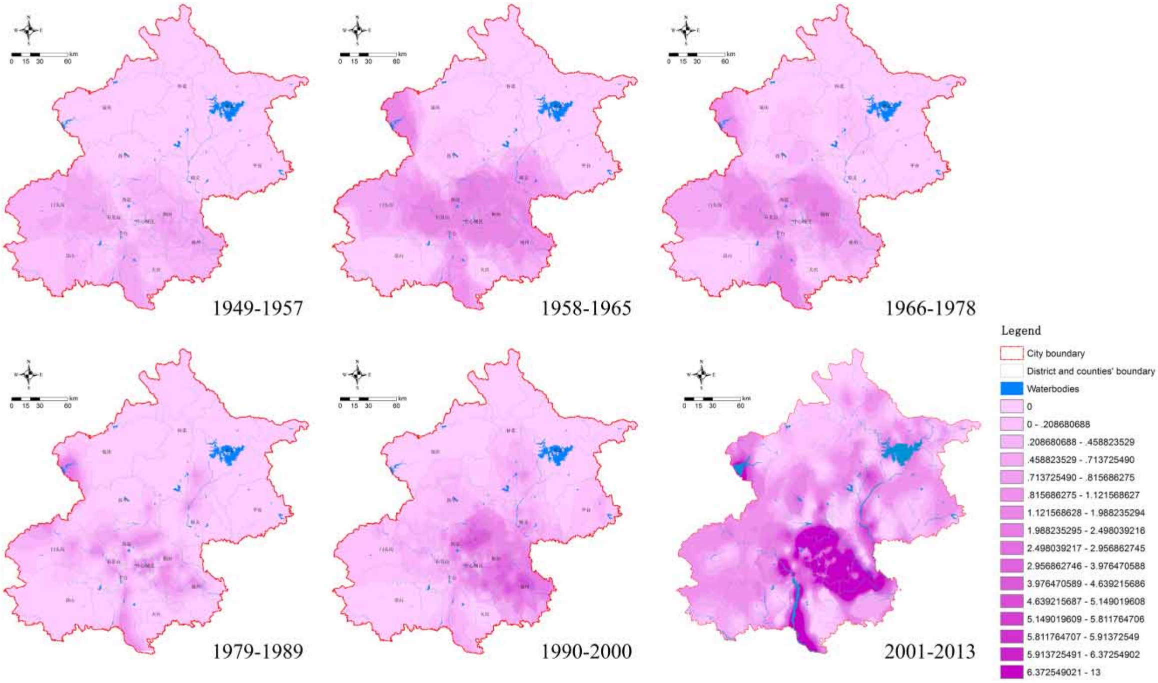

Fig. 4. The spatial evolution of water planning implementation.

The problem of the reduction or drying out of runoff from large rivers such as the Chaobai River has a high relational grade with reservoir construction, water supply plant building, and channel dredging. Further investigation, by reviewing the history of the development and the use of the water resources along the Chaobai River in the past 60 years, showed that before 1960 the river flowed continuously. The middle and downstream portions of the Chaobai River then underwent several episodes of channel dredging in this period, including river excavation in Chaobaixin, widening of the Dongyin River, and dredging of the Qinglongwan River. After 1960, when the Miyun Reservoir had been built, runoff values measured at different hydrological stations downstream of the reservoir were substantially reduced, apparently as a result of the construction of the reservoir. After the establishment of the Miyun Reservoir, the number of projects designed for water resource management and development increased. In 1960–1981, 15 medium and small reservoirs were built in the upstream reaches of the Chaobai River, allowing control of all runoff in the upstream area. These reservoirs provided almost half of Beijing's water during that time. In the 1980s, Beijing experienced rapid economic development. Increases in industrial and other water consumption exacerbated the urban water shortage. Drought occurred in two consecutive years: 1980 and 1981. In 1981, the Xiangyang Floodgate was constructed in the middle of the Chaobai River to supply water to the Beijing Eighth Water Supply Plant and the newly established Beijing Ninth Water Supply Plant. In addition, in order to supply the Second and Third Water Supply Plants of Shunyi district and the Water Supply Plant of Tongzhou district, over 200 wells were drilled around 1981 in the Chaobai River alluvial fan. It was found that the Chaobai River runoff exhibited another sharp decline after 1961 through upstream monitoring of Suzhuang Hydrological Station (Figure 5). Subsequently, drying out has continued where the drying season has

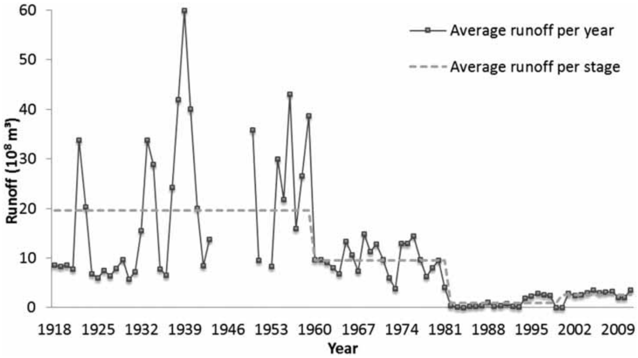

Fig. 5. The evolution of the Chaobai River runoff (Suzhuang Hydrological Station). Unit: (10^8 m^3).

begun earlier and earlier; the duration of the drying season has increased, and the portion of river that dries out has continued to expand upstream.

The decreasing volume of the Yongding River runoff has a high relationship with river training work, and reservoir and water supply plant construction. During the development and utilization of the Yongding River since 1949, the river has experienced several episodes of reservoir building and river training work, designed to control floods and to store rainwater. The Guanting Reservoir and Yongding diversion aqueducts were completed in 1957. Additionally, 101 episodes of large-scale river training work were completed in Beijing, mostly aimed at flood control of the Yongding River. This construction work reached a peak during 1958–1965. As a result, the volume of runoff shows a conspicuous decline during this period. Due to the fact that previous rounds of flood control and attempts to increase the water supply did not consider all aspects of the river training works' effect on the Yongding River, segments of the river in the plain area often dried up, exposing the riverbed and contributing to severe sandstorms. The various isolated projects that were designed for different purposes led to conflicts between the aims of flood control, water shortages, and deterioration of the environment. In the 1980s, the limited water resources of the Yongding River were almost completely depleted due to water supply plant use in the western part of Beijing. This exacerbated the drying up of the Yongding River at Sanjiadian (Figure 6).

With a relational grade of 83%, the annual rate of decline in Beijing's groundwater table has the highest relationship with self-drilled wells. The next highest level of relationship is with industrial and domestic water supply plants. Shown in Figure 7, in the first 30 years, the trend of self-drilled wells increased gradually. In the next 15 years, the trend decreased, and in the recent 10 years, it increased again. Both the groundwater exploitation volume and groundwater table decline followed the same path, i.e. increased at the beginning, then decreased, and increased again.

The evolution of the Yuquan Mountain outflow has the strongest relationship with water supply plant construction because the outflow of the Yuquan Mountain ceased in 1975 (Table 2). Outflow of the Yuquan Mountain was directly influenced by the groundwater table depth. Until 1975, Beijing had 11 water supply plants, i.e. 79% of the total number of current water supply plants. According to the data, almost all of the water supply plants prior to 1975 were underground water supply plants (Beijing Sixth Water Supply Plant is partly sourced from surface water). Water plants partly led to a decline in groundwater and this, in turn, caused the outflow of mountain wells to dry up rapidly.

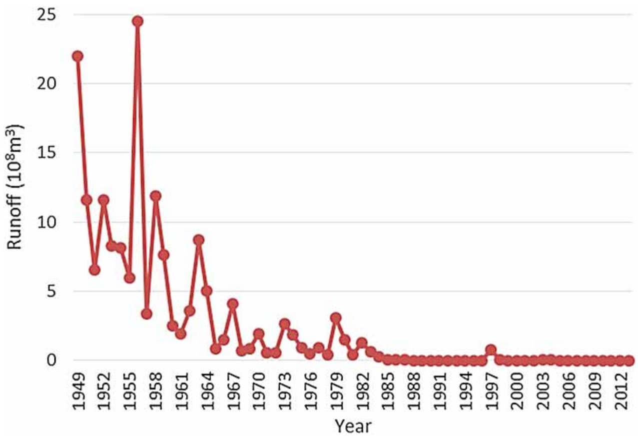

Fig. 6. The evolution of the Yongding River runoff (Sanjiadian Hydrological Station). Unit: (10^8 m^3).

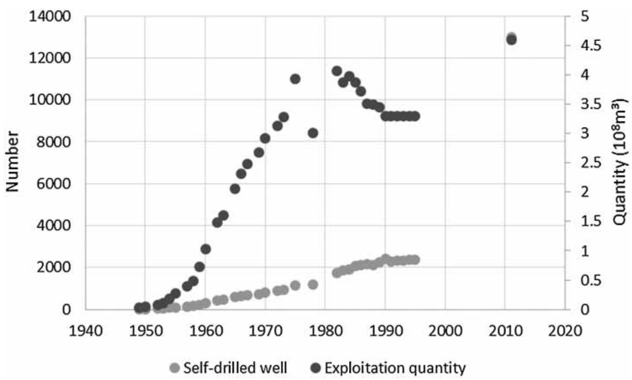

Fig. 7. Beijing self-drilled well number and annual exploitation quantity. Unit: (10^8 m^3).

The increasing volume of wastewater discharge has the highest relationship with wastewater treatment plant construction. From 1949 to 1956, no wastewater treatment plant was located in the central area; however, two sewage pumping stations were located in this area. The first wastewater treatment plant (Jiuxianqiao) was established in 1956. Figure 8 shows that the increasing trend of wastewater discharge changed slowly after the build up of the plant, but this was controlled for only 2 years, after which a rapid increasing rate occurred after 1958. Thus, the second treatment plant (Gaobeidian) came into service in 1961. The increasing trend of wastewater discharge slowed down again. However, this slowly increasing rate was maintained for only 8 years. From 1969 to 1992, the trend of wastewater discharge significantly increased. This period was also the lowest point of the wastewater treatment rate, and only one treatment plant was put into operation. From 1992 to 2000, four treatment plants were established. The overall trend of wastewater discharge exhibited a fluctuating increase. From 2001 to 2013, 34 treatment plants were placed into service. The trend of wastewater discharge decreased remarkably (Figure 8).

The evolution of water pollution incidents has the highest relationship with the evolution of groundwater hardness. Urban and industrial wastewater irrigation incidents accounted for 85% of the total

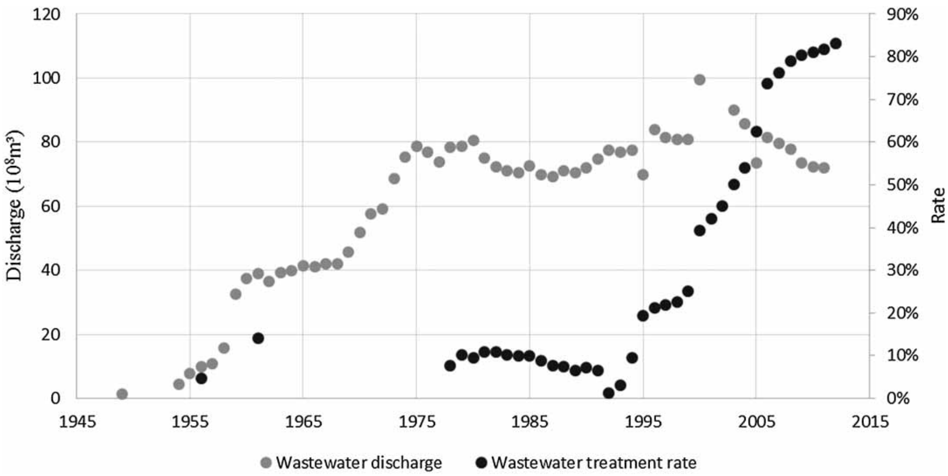

Fig. 8. Volume of Beijing wastewater discharge and treatment rate. Unit: (10^8 m^3).

water pollution incidents. The developments of water pollution incidents and sewerage irrigation have similar spatio-temporal patterns (Figure 9). In 1952, the Beijing Municipal Committee issued a document stating, 'The use of sewerage water on farmlands has increased productivity.' Thus, to make full use of sewerage, the area of sewerage irrigation was expanded to the southeast. In 1959, the area irrigated using wastewater was only 40 km^2, but it soon expanded by almost ten times to 390 km^2 by 1969 and, in 1990, it reached a peak of 840 km^2 in the study area, which represented about one-fifth of the farmland in Beijing. During this period, groundwater hardness increased exponentially. Subsequently, some problems, including pathogen contamination and soil hardening, appeared. Meanwhile, industrial development increased. An increasing amount of hazardous industrial waste was deposited in the irrigation water, leading to damaged crops, environment and groundwater. Subsequently, the area irrigated by

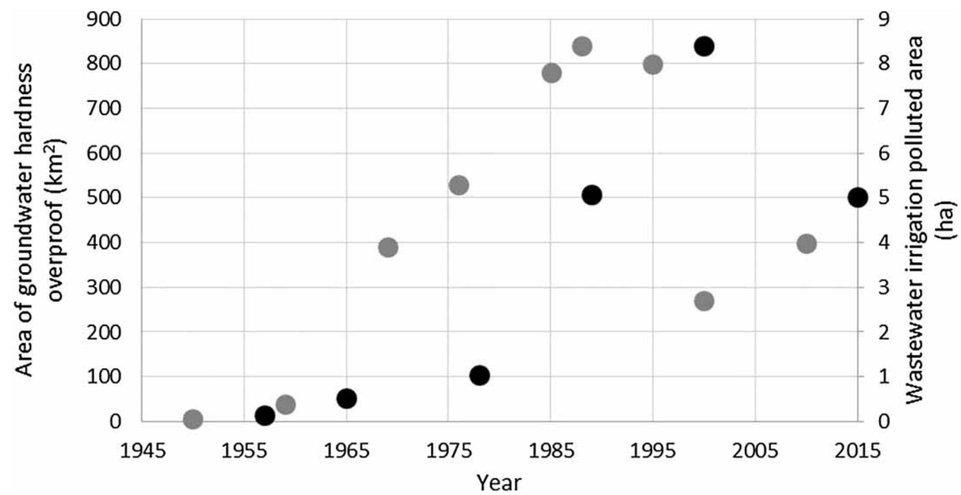

Fig. 9. The evolution of area of groundwater hardness overproof (km^2) and wastewater-irrigated, polluted area (ha).

wastewater started to shrink, and the wastewater was replaced with recycled water. At the same time, Beijing groundwater hardness started to decrease to around the year 2000.

The area affected by flooding was found to be highly correlated with river dredging and the rainwater system. The reasons for flooding are defects in the rainwater pipeline infrastructure and conflict between river drainage and storage (Zhao *et al*., 2014). The terrain around Beijing tends to slope downwards from the northwestern mountainous area to the southeastern plain. Due to the reliance on a single controlling system of floodgates and dams for river drainage, poor drainage downstream during periods of heavy rain results in the rainwater system becoming full and unable to discharge quickly enough (Beijing Water Conservancy Bureau, 2003). This leads to urban waterlogging. Since 1949, the urban drainage functions have relied more heavily on the pipeline system to connect the four main river drainage systems. In addition, both water consumption and the urban area that is impervious to water both increased, placing additional pressure on the river and pipeline system.

Conclusions and recommendations

In general, the spatio-temporal evolution of the Beijing water crisis has expanded from isolated parts to the whole basin, from single to compound issues, and every issue has a high level of complexity. The severity of water shortage, water pollution, and water-related ecological problems is now no less significant than the flood disasters of the past. This is partly due to the adverse effects of the increase in population, the associated industrial and agricultural development, and the expansion of urbanized land. However, planning implementation, as part of governance, has also exacerbated Beijing's water crisis. Our study examines that on-the-ground water resource conditions were related to water planning implementation over the past 60 years in Beijing. The study offers the following conclusions and recommendations based on the trend of each implemented category, clustering characteristics, and the spatial evolution of water planning implementations.

As to the relational grade between the trend of each implemented category and the water crisis, the runoff reduction of a large river (Chaobai) has a high relationship with reservoir construction, water supply plant building, and channel dredging. The decreasing volume of runoff in a large river (Yongding) has a high relationship with river training work, and reservoir and water supply plant construction. The groundwater table decline rate has the highest relationship with self-drilled wells. The evolution of mountain outflow has the strongest relationship with water supply plant construction. The increasing volume of wastewater discharge has the highest relationship with wastewater treatment plant construction. The evolution of water pollution incidents has the highest relationship with the evolution of groundwater hardness. The flooding area was highly correlated with river dredging and the rainwater system. Different implementation types from different planning categories may have simultaneous effects on one kind of water problem. Hence, we cannot use one planning category to deal with more than one water issue.

As to the clustering characteristics, three groups within implemented categories have a significant impact on the water crisis.

(a) We found that self-drilled wells, reservoirs, river training works, and wastewater irrigation systems influence more than one water issue and all belong to 'the categories which show a significant implementation peak'. Due to the strong relationship between the categories that show a significant implementation peak and the origins of the water crisis, we should be cautious in applying the implemented categories when they only show good effects in the short term, especially implementing grey infrastructure, which is now very common. In Beijing, spatial and temporal variability and limited knowledge of the underlying geohydrology combine with other uncertainties about the effect of these interventions. Social uncertainties also arise in part from unpredictable human responses. Therefore, it is necessary in the long term to supervise the outcome of implementations and to avoid intense and concentrated implementations.

(b) The categories that were implemented much more frequently during the latter study periods should be brought to the forefront. Recycled water has started to be widely used in the Beijing water supply system. However, since the current studies have different views on its utility, we should not expand this category too blindly into the future. Wang et al. (2012) suggested that simply relying on the strict control of wastewater drainage by adding treatment plants cannot accomplish energy conservation and reductions in emissions. In fact, the comprehensive environmental effect may be even worse. We must use the linkage effect between water recycling plants and wastewater receptors, and the source of pollution and treatment methods. Recent statistics also suggest that underground cisterns have the potential for being implemented most widely due to their rapid implementation. We should deal carefully with large-scale retention and storage facilities, which may have an adverse impact on the quality and quantity of rivers and habitats. Thus, we may not achieve the results we want by continuing to increase the standard of the water supply, water treatment, and flood control. On the contrary, this may result in other unexpected environmental problems.

(c) Our study shows that water supply plants, reservoirs for drinking water, and water diversion and transfer projects in the categories that were implemented at a steady rate during the study period have a high relational grade with both surface and underground water shortage problems. In our research, the water demand and supply have a symbiotic relationship. The more we need, the more we depend on the same sources. Hence, the original water scarcity problem remains. In fact, the traditional approach of dealing with water scarcity in Beijing has been to constantly expand the total amount of available water resources by diverting water over ever-increasing distances. Hence, water governance should stop using a single or limited approach in dealing with water problems. Water distribution should use more predictable and reasonable methods and so avoid the path-dependence and conflicts that arise when faced with the need for appropriate water management.

As to the spatial evolution of water planning implementations, the main implemented categories have a line and point of 'hard' infrastructure. The implementations manifested an imbalance between grey infrastructure and green infrastructure. With respect to spatial factors, considering the mismatch between the spatial pattern of the water crisis and of water planning implementation, water planning should add more planar infrastructure, especially green infrastructure instead of linear and point grey infrastructure (Angelstam *et al*., 2017; Ghimire & Johnston, 2017; Meerow & Newell, 2017; Mell, 2017; Sanesi *et al*., 2017). It is important to develop a comprehensive, balanced infrastructure to allow multiple ecosystems to implement water purification, flood storage, water conservation, ecological maintenance and promote the urban water culture. Considering the more complex and overlapping surface and underground water issues, the shift from seeing water as an adversary to adapting to the natural flow of water and accommodating it should not be stopped by a myopic emphasis on short-term economic benefits. This type of long-term management should be an integral part of water resource management plans. We assert that improving water governance is the key to water security in Beijing.

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Received 17 July 2016; accepted in revised form 3 December 2017. Available online 30 January 2018