Impacts of temperature and precipitation on the spatiotemporal distribution of water resources in Chinese mega cities: the case of Beijing

Pengpeng Jia, Dafang Zhuang and Yong Wang

ABSTRACT

Water shortages in China have hindered development of mega cities, especially Beijing. Assessing the impact of temperature and precipitation on water resources is important. This study analyzed spatiotemporal variations and impacts of temperature and precipitation on water resources in Beijing from 1956 to 2013, using statistical and spatial analysis. The results showed the following. (1) Temperature and precipitation affect water resources variously from region to region; their correlation in mountains is lower than in other areas. Precipitation redistribution caused by terrain reduces water resources. (2) The inter-annual variabilities of precipitation, temperature and water resources are different among five water resource divisions. Because of ‘rain-slope’, Beisanhe’s precipitation is larger than others; Yongdinghe’s precipitation is less than others due to ‘rain-shadow’; suffering from urban heat island effect, Beisihe and Daqinghe-plain’s temperature is higher than others; Beisanhe and Beisihe’s water resources are greater than others due to area differences. (3) Water resources are positively correlated with precipitation and negatively with temperature. (4) In recent years, precipitation and water resources decreased and temperature rose. Population growth, land use/land cover change, urbanization and pollution affected precipitation, temperature and water resources. Imported water cannot completely solve water shortages. With increasing water demand, precipitation and temperature will significantly influence water resources in Beijing.

Key words | impact, precipitation, spatiotemporal distribution, temperature, water resources

INTRODUCTION

Since the 1980s, global climate change predictions and their impact on water resources have become an unavoidable issue. The IPCC (Intergovernmental Panel on Climate Change) released its fifth assessment report, Climate Change 2013: The Physical Science Basis, in Paris. According to the 2013 IPCC report, from 1880 to 2012, the average land-ocean surface temperature trended linearly upward, increasing by 0.85 °C. The linear temperature rate increase in the most recent 50 years is about 0.13 °C per 10 years (IPCC 2013). The climate change trend in China is consistent with global climate change. Since 1913, the average surface temperature in China has risen by 0.91 °C and the temperature rise has been particularly evident in the last 60 years, with an average annual increase of about 0.23 °C, which is almost twice as fast as the global average (Guo et al. 2016). In addition, with abundant water resources, but lower per capita availability, China is included in the most water-stressed countries in the world. Many mega cities in China have suffered from severe water shortages, hindering the development of regional economies and sustainable development (Tian et al. 2016).
In recent decades, many scholars have studied the impact of climate change on water resources. As climate change is becoming more prominent, associated with changing precipitation (Christensen et al. 2004), analysis on the impact of precipitation on water resources has become a main direction of research (Cui & Li 2016). Using long time series data to analyze trends and cycles of precipitation and water resources is the basis for research on the impact of precipitation on water resources (Arnell et al. 2011). Water resource yield and distribution are affected as a direct result of fluctuation in intensity, frequency and distribution of precipitation (Ligaray et al. 2015). But the effect of climate change on water resources is a complex process (Rochdane et al. 2012). It is insufficient to analyze the impact of precipitation on water resources so as to have an in-depth understanding of the impacts of climate change on water resources. Moreover, the length and the accuracy of historical data limit research on changes in precipitation and water resources (Labat et al. 2004).

There is an increasing consensus that changing climatic trends, especially temperature and precipitation, can change the hydrological cycle, which influences water resources (Jordan et al. 2014). Selecting appropriate hydrological models based on specific conditions of the region to simulate water resource yield, and quantitatively assess the impact of climate change on water resources in combination with measured data, is the main method to study climate change impacts on water resources (Emam et al. 2015; Mahmood et al. 2016). The main reason for declining water resources is increasing temperature and decreasing precipitation (Kundzewicz et al. 2008). However, the impact of temperature and precipitation on water resources may vary from region to region (Emam et al. 2015; Mahmood et al. 2016). Hence, the analysis of the variable impact of climate change on water resources between regions is the focus of current research.

The hydrological cycle of a region is mainly influenced by regional terrain, climatic conditions, land use/cover and population scale (Kundzewicz et al. 2008). The speed at which temperature, precipitation and land use/cover have changed has accelerated as a direct result of population growth and human activities, thereby affecting the interception, infiltration, and evaporation process of the hydrological cycle in the spatial and temporal domain (Madhusoodhanan et al. 2016; McGrane 2016). Research has evaluated the impact of climate change on water resources, but has not been comprehensive enough (Rochdane et al. 2012; Ligaray et al. 2013). Numerous studies might not effectively reflect spatial and temporal distribution of water resources and cannot reflect spatial correlation; nevertheless, spatial attribute is the most important feature of geographical elements such as water resource divisions and basins.

Geographic information system technology is used to collect, store, manage, analyze, display and describe the geographic distribution data on the surface of the earth, using computer system support (Longley et al. 2005). It is an important method to analyze water resource differences in distribution and spatial correlation, which has the unique advantage in describing temporal and spatial variations in water resources and analysis of basin spatial differences. In this study, the cumulative departure method, linear regression analysis, correlation analysis and spatial analysis were used to analyze spatial and temporal variations. We evaluate the impact of changes in temperature and precipitation on water resources, using 1956 to 2013 as a reference period. The results of the study can provide data support and method references to ease water resource pressure in Beijing and provide management plans for future development of urban water resources.

**DATA AND METHODOLOGY**

**Study area**

Beijing is the capital of China, a typical mega city in the northern North China Plain. The city center coordinates are: 39.54°20′N, 116.25°29′E, with a total area of about 16,411 square kilometers. By the end of 2015, the resident population was about 21.7 million. Beijing is located in the transition zone between mountains and plains, mountains accounting for 62% and plains for 38%. Beijing’s precipitation varies greatly each year and the inter-annual distribution of water resources is extremely unstable. High flow years and low flow years alternated with each other and the probability of continuous occurrence was 1/3. The average time of continuous occurrence was 2–3 years, and the longest low flow period lasted for 9 years (Wu et al. 2009). Using historical records (BMB 1987), the frequency of dry years from 1271 to 2000 is shown in Table 1. Statistics
indicate that water resources have been extremely scarce in Beijing since ancient times, especially in recent years. This has become the main limiting factor for resource optimization and rational distribution in Beijing. Therefore, it is important to study the impacts of temperature and precipitation on the temporal and spatial distribution of water resources in Beijing. Because it is representative of culture, economy, and population and holds a special position in politics, choosing Beijing as the study area is significant.

Beijing covers five third-level divisions of water resource (WRD_3rd), as shown in Figure 1. Among them, Beisanhe division (BSH) accounts for 31%, Beisihe division (BSIH) accounts for 32%, Yongdinghe division (YDH) accounts for 9% and Daqinghe-Mountain division (DQH_M) accounts for 7%, Daqinghe-Plain division (DQH_P) accounts for 6% in the city of Beijing. The difference between regional areas results in disparity of water resources among the five WRD_3rd.

Data description

Basic geography data came from the Resources and Environmental Sciences of Chinese Academy of Sciences data center, terrain data was sourced from the SRTM 30 m resolution digital elevation model and administrative divisions were obtained from the Beijing 2010 administrative boundary data. Weather data is from China Meteorological Data Network (http://data.cma.cn/site/index.html). The 1956 to 2013 annual temperature and precipitation data was obtained from the Guan Xiang Tai meteorological station of Beijing. The 1956 to 2013 Beijing water resource data, surface and ground water resources came from the Beijing water resources bulletin and the Department of Water Resources of China Institute of Water Resources and Hydropower Research.

Method description

In this study, the cumulative departure curve was used to analyze inter-annual variations in precipitation; the binary standardized linear regression method was used to establish the quantitative assessment model for the impact of precipitation and temperature on water resources; the population carrying capacity of water resources was used to evaluate the interaction between population scale and water resources; the inter-annual variation and spatial variability of precipitation, temperature and water resources in WRD_3rd were studied using geographic information system (GIS) spatial analysis methods as shown in Table 2.

RESULTS AND ANALYSES

Inter-annual variability analysis

Precipitation and temperature

Analysis of 57 years of annual mean precipitation data from 1956 to 2013 in Beijing (Figure 2) shows that the maximum was 1,404.6 mm in 1959 and the minimum was 261.4 mm in 1965. Since the 1960s, precipitation has been declining, and since the 1990s the rate of decline has accelerated significantly. Linear regression show that the downward trend of precipitation in Beijing was significant, and the decreasing range was about 37.4 mm per 10 years. There were obvious cyclical changes in Beijing precipitation as the wet and dry seasons alternate (Figure 3). 1956 to 1960 was a relatively wet period in Beijing; mean annual precipitation was significantly greater than the multi-year mean precipitation. After 1960, the amount of precipitation dropped sharply, followed by continuous drought. The severe drought in the 1990s was
the continuation and development of a dry spell that began in 1960. After the 1960s, the average precipitation had a negative anomaly, which may be the main reason for the continuous Beijing water shortage (Song et al. 2003; Zhang & Xia 2011).

According to the annual mean temperature data of Beijing from 1956 to 2013 (Figure 4), the highest mean annual temperature was 14 °C in 2007, the lowest was 10.5 °C in 1956, and since the 1960s, temperature has been on the rise. Especially since the 1980s, the rate of increase has accelerated. Linear regression shows that the temperature in Beijing increased significantly, with an uptrend of about 0.4 °C per 10 years, which is higher than the recent 50 year global trend of 0.13 °C per 10 years. This shows that Beijing has a sensitive response to global warming (Gao & Fu 1992), underlying surface changes caused by urbanization, artificial waste heat, excessive greenhouse gas emissions and other human activities are the main reasons for the temperature increase in Beijing (Xu 1987; Zhang et al. 2002; Lin & Yu 2005; Mehta et al. 2011). Especially after reform and opening, Beijing has entered a period of rapid development; cultivated land is occupied by urban construction land; and large-scale land cover changes are the main reasons for the rapid temperature increase in Beijing since the 1980s.

**Water resource yield**

Water resources yield is the sum of surface streamflow and precipitation infiltration recharge. Based on water resource yield data in Beijing from 1956 to 2013 (Figures 2 and 4),
the maximum amount of water resources in Beijing was 9.653 billion m³ in 1956 and the minimum was 1.508 billion m³ in 2009. Since the 1960s, water resources have been declining. The rate of decline has accelerated significantly since the 1990s. Linear regression shows that water resources yield in Beijing decreased significantly, the

Table 2 | Main research methods of this research

<table>
<thead>
<tr>
<th>Methods description</th>
<th>Calculation formula</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative departure curve is a method to judge the trend of change from curve directly</td>
<td>$\bar{X}<em>t = \frac{1}{n} \sum</em>{i=1}^{t} (X_i - \bar{X})$</td>
<td>For time series $X_t$ the accumulated anomaly at time $t$ is $X_t$. By calculating $n$ times' cumulative departure values</td>
</tr>
<tr>
<td></td>
<td>$t = 1, 2, 3 \ldots, n$</td>
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<tr>
<td></td>
<td>$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i$</td>
<td>(Zhao et al. 2011)</td>
</tr>
<tr>
<td>Standardized regression coefficients are used in multiple regression to compare the importance of variables</td>
<td>$\hat{Y} = b_0 + b_1 \hat{X}_1 + b_2 \hat{X}_2$</td>
<td>$X_1$ and $X_2$ are the normalized independent variables of $X_1$ and $X_2$. $Y$ is the normalized dependent variable of $Y$. $b_0$ is a constant, $b_1$ and $b_2$ are regression coefficient. $\bar{X}$ is the mean of $X_t$, $\sigma_X$ is the standard deviation of $X_t$</td>
</tr>
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<td></td>
<td>$\hat{X}_i = \frac{X_i - \bar{X}}{\sigma_X}$</td>
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<td>(Gao &amp; Fu 1992)</td>
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<td>The carrying capacity of water resources depends on the total water resources, water supply capacity coefficient and per capita water consumption, three indicator variables</td>
<td>$P = \alpha \frac{W_t}{W_p}$</td>
<td>$P$ is the population carrying capacity; $W_t$ is the total amount of water resources; $W_p$ is the comprehensive water consumption per capita; $\alpha$ is the coefficient of water supply; $W_t$ is the actual annual water supply. In this study, the average per capita water consumption in 1979–2014 of Beijing was 301.8 m³/person, which was taken as the water consumption per capita</td>
</tr>
<tr>
<td></td>
<td>$\alpha = \frac{W_s}{W_t}$</td>
<td></td>
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<tr>
<td>(Chen et al. 2011)</td>
<td></td>
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</tr>
<tr>
<td>GIS spatial analysis based on spatial data of the location and shape of geographic objects</td>
<td>$P = \alpha \frac{W_t}{W_p}$</td>
<td>Overlay analysis is the operation of creating a new feature layer by superimposing two or more layers of map elements, which combines the attributes of the original two or more layers. Spatial statistical analysis is to analyze the spatial dependence, spatial correlation or spatial autocorrelation between geographic position-related data. The statistical relationship between data is established by spatial location</td>
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</table>

the maximum amount of water resources in Beijing was 9.653 billion m³ in 1956 and the minimum was 1.508 billion m³ in 2009. Since the 1960s, water resources have been declining. The rate of decline has accelerated significantly since the 1990s. Linear regression shows that water resources yield in Beijing decreased significantly, the
decrease was about 407 million m³ per 10 years. Beijing’s water resources are synchronous with precipitation. The water resource yield change is directly affected by precipitation changes. Precipitation reduction is the most important reason for decreasing water resources yield in Beijing (Christensen et al. 2004; Labat et al. 2004; Arnell et al. 2011; Rochdane et al. 2012; Jordan et al. 2014; Ligaray et al. 2015; Cui & Li 2016).

The water resource yield is the sum of surface water and groundwater generated by precipitation, after deducting the repeated calculation. Through analysis of groundwater changes, water resources in Beijing show a decreasing trend. Figure 5 shows that since 1960, groundwater depths in Beijing have been declining: about 3 meters in the 1960s, about 10 meters in the 1970s, about 15 meters in the 1980s, about 20 meters in the 1990s, and about 25 meters after 2000, the rate of decrease was 5 m per 10 years. Although the rate of decrease has lessened since 2000, groundwater depth has decreased by nearly 22 meters compared with the 1960s. As a result of

Figure 2 | Annual mean precipitation, water resource yield and linear fitting (LF) from 1956 to 2013.

Figure 3 | Cumulative departure curve of precipitation (CDP) from 1956 to 2013.
precipitation reduction and temperature rise, the water resource yield in Beijing is declining. Beijing has to use outside water resources and increase production of groundwater resources to alleviate the pressure on water resources caused by a sharp increase in population and economic growth. Excessive groundwater exploitation has become more serious. During continuous dry years and reduced precipitation, the amount of recharge is much less than that of exploitation, which makes the groundwater resource problem more serious in Beijing (Cao et al. 2015).

Difference analysis between mountain and plain areas

Precipitation and temperature

Beijing plain area and mountainous area annual mean precipitation analysis between 1989 and 2013 (Figure 6) indicates that both areas show a decreasing trend; 41 mm per 10 years in the mountains and 44 mm per 10 years in the plains. Mean annual precipitation in the mountains is generally larger than in other areas. Due to the special dust-pan-shaped terrain in Beijing, the precipitation on the
windward side of the mountains is significantly larger than that in the plains. Precipitation continues to decrease from northwest to southeast of the arc mountains (Zhu 2014). In addition, the physical properties of the ground in the mountains are different from those of the plains, which cause atmospheric thermal differences and local atmospheric thermal circulation, leading to more precipitation in the mountains (Cai et al. 2016). Thermal differences due to different land cover types between the plains and mountains are the main reason for the larger mean annual precipitation in the mountains than in the plains (Cao et al. 2013).

Mean annual temperature analysis from 1989 to 2013 (Figure 7) indicates that the temperature in the plain and mountain areas is rising, affected by global warming. In addition, the temperature increase on the plains is more significant than that in the mountains. As economic development and population growth in the plains are less constrained by terrain, urban land is expanding and the heat island effect is becoming more obvious (Lin & Yu 2005). Meanwhile, the population and industry are highly concentrated, emitting more waste heat, which leads to more significant warming effects and higher
mean annual temperature in the plains (Xu 1987; Zhang et al. 2002).

Water resource yield

Beijing mean annual water resource yield in plain (BSIH, DQH_P) and mountainous (BSH, YDH, DQH_M) areas from 1989 to 2013 were analyzed (Figure 8), using data from five WRD_3rd. Less precipitation reduced water recharge, and higher temperatures increased the evaporation rate of water resources; both the plains’ and mountains’ water resources showed a decreasing trend. The mean water resource yield of the mountains decreased by 20 million m$^3$ per 10 years and the water resources in the plains decreased by 19 million m$^3$ per 10 years. In addition, land cover types in the mountains are mainly forested, and soil retention, interception, storage and infiltration increase water resources in the mountains, so they are generally larger than in the plains (Lin & Yu 2005; Zhu 2014; Cao et al. 2015; Cai et al. 2016).

Difference analysis in the WRD_3rd

Precipitation and temperature

From 1989 to 2013, the annual mean precipitation of WRD_3rd in Beijing showed an overall downward trend (Figure 9). However, water resource yield varied from region to region. The terrain disparity caused different precipitation among divisions. Precipitation on the ‘rain-slope’ (the area located on the windward slope of the mountain) is enhanced by the terrain. In contrast, precipitation on the ‘rain-shadow’ (the area on the leeward slope of the mountain) is weakened by the terrain (Hua et al. 2013). Due to atmospheric circulation and terrain, precipitation in BSH, which is located on the ‘rain-slope’ of YanShan and XIShan, is larger than in other divisions. In contrast, precipitation in YDH is lower than in other divisions because of the influence of the ‘rain-shadow’ (Zhu 2014; Markovic & Koch 2015; Cai et al. 2016) (Figures 1 and 9). Disparity in watershed environment and hydrological processes within the WRD_3rd caused precipitation differences.

The annual mean temperature in five WRD_3rd is consistent with the mean annual temperature trend in Beijing, showing an upward trend in the period 1989–2013 (Figure 10). The mean annual temperature of BSIH and DQH_P, located in the plains, was significantly higher than the other areas (Figure 10). The urban heat island effect and the disparity in urbanization process caused by terrain constraints are the main reasons for the spatial distribution of mean annual temperature in the five WRD_3rd (Yang et al. 2009; Fujibe 2011; Zhang et al. 2011; Cao et al. 2013).

Figure 8 | Annual mean water resource yield in mountainous area (AMWIM), annual mean water resource yield in plain area (AMWIP) and linear fitting (LF) from 1989 to 2013.
Both yield and inter-annual fluctuation of water resources in BSH and BSIH are greater than other divisions during 1989–2013 (Figure 11). Water resources yield in WRD_3rd is impacted by the watershed environment; besides, it is directly related to division area. Using GIS, we compare the area of five WRD_3rd (Figure 11) and find the areas of BSH and BSIH are significantly greater than other divisions. This may be the main reason for variation in water resource yield among the five WRD_3rd.

Impact and correlation analysis

Inter-annual variability analysis

From 1956 to 2013, the mean annual precipitation and water resource yield in Beijing showed an overall downward trend (Figure 2); moreover, precipitation and water resources were positively correlated. When precipitation decreased or increased, the amount of water decreased or increased more quickly than the precipitation. Because precipitation is the only source of fresh water recharge, it has a direct impact on water resources. However, in recent years, under the impact of water shortage and over-exploitation, a general increase in precipitation is unable to satisfy the increasing demand on water resource yield (Zhang & Chen 2008; Dobler et al. 2010; Sun et al. 2012; Wu et al. 2012; Li et al. 2013; Chen & Wang 2014; Kassian et al. 2016).

Analysis of the 2006 and 2012 monthly mean precipitation in Beijing and monthly groundwater depth curve of Beijing plain areas (Figure 12) shows that compared to 2006, the groundwater depth in the Beijing plains declined severely in 2012. In addition, precipitation recharge for water resources is continuous and lagging. From January to February, groundwater depth was gradually recovering under the influence of lateral recharge. From March to June, the groundwater depth was continuously declining, affected by agricultural exploitation. In June, the depth reached the lowest point. From July to December, with the flood season onset, precipitation in July reached a maximum and groundwater depth gradually increased. However, under the influence of lower precipitation and surface water infiltration recharge, although the groundwater
Figure 11 | Water resource yield spatial distribution of five WRD_3rd for the period 1989-2013.
depth increased, it did not reach a balance and by the end of 2006 groundwater depth was not equal to its starting depth at the beginning of the year.

Variations in temperature can alter evapotranspiration rate and water consumption, which indirectly affects the amount of water resources. In Beijing, mean annual temperature from 1956 to 2013 was negatively associated with water resources (Figure 4). Correlation between mean annual temperature and water consumption per capita is shown in Figure 13. With temperatures rising, especially from 1979 to 2000, water consumption per capita increased year to year. However, since 2000, water consumption per capita gradually dropped. Precipitation reduction and temperature increase have aggravated water resource shortages in Beijing. First, the amount of water resources has decreased. Second, evapotranspiration rose. Third, the demand for water by human activities increased (Sonali & Nagesh 2016). Climate warming gave rise to water consumption (Gato et al. 2007). Since 2000, the mean annual temperature growth rate in Beijing has lowered, while the population has expanded rapidly. As a result, the total water supply reached a bottleneck and water consumption

![Figure 12](image1.png) Monthly mean precipitation (MMP) and groundwater depth in plain area in 2006 and 2012.

![Figure 13](image2.png) Annual mean temperature, per capita water consumption and quadratic polynomial fitting (QPF) from 1979 to 2013.
per capita decreased (Parandvash & Chang 2016). Given the increase in water consumption caused by urbanization, industrial development, and agriculture in the future, climate warming will have a greater effect on the demand for water resources (Cavalcante et al. 2016).

Regional variability analysis

In this study, annual precipitation, temperature and water resource variations in different regions of Beijing were analyzed and their correlation coefficients were calculated, using data from WRD_3rd. The correlation coefficient of precipitation, temperature and water resource is greater than that of precipitation and water resource (Table 3). Although precipitation is the only source of water recharge, temperature affects the evaporation rate of water resources and other consumption processes. Therefore, it is better to analyze the binary impact of precipitation and temperature on water resource yield. Influenced by land cover types and the hydrological cycle of WRD_3rd, the correlation coefficients between precipitation, temperature and water resources are different in different areas. The correlation coefficients of BSIH and BSH are 0.93 and 0.96 (p < 0.01) while the YDH correlation coefficient is only 0.54 (p = 0.2).

Overlay analysis between urban functional regions and spatial correlation of precipitation, temperature and water resources in WRD_3rd (Figure 14) shows that precipitation, temperature and water resources in the regions of new urban development and ecological conservation development are moderately correlated, while in the regions of inner city and urban expansion, they are highly correlated. In addition, in the mountainous regions of western Beijing, precipitation, temperature and water resources are moderately correlated. Spatial distribution is closely related to factors such as altitude, slope, and land cover. Despite fluctuations in precipitation and temperature in mountainous regions, redistribution of precipitation caused by terrain reduced water resources where streamflow gathered inconveniently (Xu 1987). Forest land cover in the mountains influenced infiltration, evaporation and water resources. Therefore, it led to spatiotemporal changes in water quantity and quality (Hua et al. 2015; Zhu 2014; Markovic & Koch 2015; Cai et al. 2016). Terrain and forestland in mountains changed hydrological processes and water balance, affected the amount of surface water and groundwater, and decreased the correlation between precipitation, temperature and water resources.

Quantitative evaluation model

Precipitation and temperature have a great influence on water resources. Therefore, to maximize the fitting of precipitation and temperature impact on water resources, this study established: a unitary standard linear regression Equation (7) to study the relationship between precipitation (P) and water resource yield (W); and a binary standard linear regression Equation (8) to study the correlation between precipitation (P), temperature (T) and water resource yield (W).

\[
W_P = 0.89P \quad R = 0.89 \\
W_{PT} = 0.85P - 0.18T \quad R = 0.91
\]

Analysis of the correlation coefficients (0.89, 0.91) from these two equations found that the binary linear fitting Equation (8) is better than the unitary Equation (7). Therefore, in this study, the water resource yield was used as a dependent variable and precipitation and temperature were used as independent variables to establish a quantitative evaluation model of water resources.

<table>
<thead>
<tr>
<th>WRD_3rd</th>
<th>BSIH</th>
<th>BSH</th>
<th>YDH</th>
<th>DQH_M</th>
<th>DQH_P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>0.9, p &lt; 0.01</td>
<td>0.93, p &lt; 0.01</td>
<td>0.25, p = 0.43</td>
<td>0.62, p &lt; 0.05</td>
<td>0.68, p &lt; 0.05</td>
</tr>
<tr>
<td>Precipitation and temperature</td>
<td>0.95, p &lt; 0.01</td>
<td>0.96, p &lt; 0.01</td>
<td>0.54, p = 0.2</td>
<td>0.62, p = 0.11</td>
<td>0.7, p &lt; 0.05</td>
</tr>
</tbody>
</table>
The model is used to analyze the impact of precipitation and temperature on water resources. Although both changes in temperature and precipitation will affect water resource yield, the impact of precipitation is much greater than temperature.

Model validation

In order to verify the accuracy of the quantitative evaluation model for the impact of precipitation and temperature on water resources, mean annual precipitation and temperature data from 1956 to 2013 was used to fit water resources (Figure 15). The fitted value of water resources and its trend are similar to the actual conditions, except for 1985 and 2006. The relative error over 57 years is less than 6%, except for 1984 (Table 4). Therefore, it is clear that this model has better accuracy.

DISCUSSION

Correlation differentiation under different spatial scales

In this study, urban functional regions of Beijing were used as a minimum research unit (Table 5) and results showed that under the filter effect of human activities, such as administrative boundaries, land cover types, and urbanization, water resource is highly correlated with precipitation and temperature. However, there is no significant difference among these regions. To sum up, the influence of human activities masks differences across regions. Therefore, it is illogical to use the data of urban functional regions or administrative divisions to study correlations between precipitation, temperature, and water resources in different regions and different spatial scales in Beijing. In addition, results will be accurate if natural water resources divisions or basins are used to calculate these correlations.
Influence of urbanization processes on water resources

The spatiotemporal distribution of water resources in Beijing was influenced by temperature, precipitation and urbanization. Since the 1980s, with rapid economic development in Beijing, the process of urbanization has further accelerated and the scale of urban land has expanded. The type of land cover has changed, which shows that urban construction occupies forestland and cultivated land. City development has resulted in the replacement of large areas of vegetation and soil by artificial construction, such as streets, manufacturing, and dwellings. Ground is covered with impervious concrete and asphalt, which reduces the water seepage area and disrupts the hydrological process, seriously affecting the circulation of groundwater and surface water. As a result, groundwater does not get enough recharge from surface water (Madhusoodhanan et al. 2014). Due to changes in ground retention and permeability, and reduction in ground interception, infiltration and depression detention, precipitation on impervious land leads to rapid runoff. This leads to an increase in surface streamflow and a decrease in groundwater streamflow. Most surface streamflow converges in rainspouts and is discharged by sewer, which results in a reduction in recharge to water sources by precipitation (McGrane 2016).

Table 4 | Comparing the actual and fitted values of water resource

<table>
<thead>
<tr>
<th>Year</th>
<th>Actual value</th>
<th>Fitted values</th>
<th>Relative error (%)</th>
<th>Trend assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1957</td>
<td>31.9</td>
<td>32.7</td>
<td>2.53</td>
<td>Correct</td>
</tr>
<tr>
<td>1964</td>
<td>54.9</td>
<td>51.7</td>
<td>-5.94</td>
<td>Correct</td>
</tr>
<tr>
<td>1968</td>
<td>24.1</td>
<td>24.2</td>
<td>1.08</td>
<td>Correct</td>
</tr>
<tr>
<td>1970</td>
<td>37.1</td>
<td>38.6</td>
<td>4.11</td>
<td>Correct</td>
</tr>
<tr>
<td>1975</td>
<td>21.9</td>
<td>22.7</td>
<td>3.97</td>
<td>Correct</td>
</tr>
<tr>
<td>1979</td>
<td>42.3</td>
<td>43.4</td>
<td>2.84</td>
<td>Correct</td>
</tr>
<tr>
<td>1984</td>
<td>25.0</td>
<td>27.1</td>
<td>8.78</td>
<td>Correct</td>
</tr>
<tr>
<td>1998</td>
<td>40.9</td>
<td>41.5</td>
<td>1.43</td>
<td>Correct</td>
</tr>
<tr>
<td>2011</td>
<td>26.8</td>
<td>27.6</td>
<td>3.24</td>
<td>Correct</td>
</tr>
</tbody>
</table>

Influence of water quality on water resources

In the exploitation of water resources, water quality is one of the important indexes. According to the application of water resources, water quality is divided into five categories: I, II, and III are suitable for drinking, while IV and V are suitable for industry, agriculture and ecology (ZHB 1994; ZHB 2002). By analyzing the proportion of I, II, III water yield in the evaluated water resources, we can find the change in the amount of available drinking water.
The analysis of the proportion of I, II, III water yield in the evaluated water resources of Beijing (both surface water and groundwater) from 1999 to 2014 (Figure 16) showed that I, II, III groundwater yield is less than 50% of the evaluated groundwater and the proportion has slight variation. Combined with the change of total groundwater resources in Beijing (Figure 5), it can be found that the groundwater resources reduced sharply in total amount and the groundwater resources suitable for drinking amounts to less than half of the total amount. As can be seen from Figure 16, the proportion of I, II, III surface water yield (river, lake and reservoir) in the evaluated water resources decreased year by year and the rate of decline accelerated after 2005. Combined with the change of total surface water resources in Beijing (Figures 2 and 4), it can be found that the proportion of surface water resources suitable for drinking is decreasing while the total amount of surface water resources decreases continuously. Therefore, with the decrease of total water resources, the deterioration of water quality is also an important factor that leads to the shortage of water resources in Beijing.

### Influence of population scale variations on water resources

The resident population of Beijing has increased dramatically from 1979 to 2013 (Figure 17); by the end of 2013, the resident population reached 21.148 million. Under the influence of economic development and urbanization, population growth in Beijing has directly led to an increasing demand for water consumption. In addition, with technological and industrial development, water demand is also increasing (Tong 2010). However, water resources in Beijing are decreasing and water resource shortages are becoming more serious, leading to the rapid decline in the population carrying capacity of water resources. Since the 1990s, the population carrying capacity of water resources in Beijing has been lower than the resident population and the gap...
between them has grown in the last 15 years (Figure 17). These changes indicate that compared with current population growth, water resources in Beijing have been unable to satisfy the demand from urban development and water shortages will become more severe.

**Influence of outside water transfer projects on water resources**

The South-to-North Water Transfer Project is a strategic project in China that allocated water resources of the Yangtze River basin to water shortage areas in north and northwest China to meet the needs of mega cities. From 2008 to 2014, Beijing has been in a dry spell and its water resources cannot meet the city’s development needs. As a result, the Jing-Shi Water Transfer Project, part of the South-to-North Water Transfer Project, transferred nearly 1.5 billion m$^3$ of water from Hebei and Shanxi provinces (Table 6). However, the cyclical variation of water resources and climate in these places is similar to Beijing, which limited the project’s impact. Therefore, over-exploitation of underground water resources has become the only way to alleviate water shortage pressures. The South-to-North Water Transfer Project was put into use on December 7, 2014; the project provides 1 billion m$^3$ of water to Beijing every year, equivalent to 1/3 of the multi-year mean water resources. This effectively alleviated the water shortage pressure and Beijing gradually reduced the amount of groundwater exploitation. At present, the groundwater decline has slowed and it is expected that the groundwater depth will gradually rise until 2025 (Xinhua Net 2016). In 2015, the South-to-North Water Transfer project transferred 880 million m$^3$ of water resources to Beijing (Table 6), which accounted for nearly 30% of the total water resources that year in Beijing. The project rapidly increased the water resources population carrying capacity in Beijing, but with increasing water consumption it will stop or even decline again. Therefore, the project can only temporarily solve the problem; it is difficult to completely solve the water resource problem in Beijing.

**Table 6** | Annual variability of outside water resources from 2008 to 2015

<table>
<thead>
<tr>
<th>Source</th>
<th>Shanxi Province, Hebei Province</th>
<th>Yangtze River basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Years</td>
<td>2008</td>
<td>2009</td>
</tr>
<tr>
<td>Outside water resources (hundred million m$^3$)</td>
<td>0.73</td>
<td>2.6</td>
</tr>
</tbody>
</table>
CONCLUSIONS

China is one of the most water-stressed countries in the world. The imbalance between supply and demand of water resources has restricted development of Chinese mega cities, especially Beijing. Therefore, it is of great significance to assess temperature and precipitation impacts on the water resources of China’s mega cities, which is the key to reduce pressure on urban water resources. In this study, statistical, spatial and quantitative analyses were used to analyze the spatiotemporal variations and impacts of temperature and precipitation on water resources in a mega city of China (Beijing) from 1956 to 2013. The results showed the following. (1) The impacts of temperature and precipitation on water resources vary from region to region, and the correlation of temperature, precipitation and water resources in mountainous areas is lower than that in the plains. The precipitation redistribution caused by mountain terrain reduces water resources where streamflow gathered inconveniently. Mountain land cover, based on forest and vegetation, influences the hydrological process of infiltration and evaporation. (2) The inter-annual variabilities of precipitation, temperature and water resources are different among five WRD, 5th. Because of ‘rain-slope’, precipitation in BSH is larger than other divisions; meanwhile, precipitation in YDH is less than other divisions under the influence of the ‘rain-shadow’. Suffering from the urban heat island effect and other human activities, the temperature of BSIH and DQH, located in the plains, is significantly higher than other divisions. The water resource yields of BSH and BSIH are greater than other divisions as a result of the significant differences between the division areas. (3) The water resource yield correlations are positive with precipitation and negative with temperature. Furthermore, the impact of precipitation on water resources is greater than that of temperature. (4) In the last 60 years, precipitation and water resources decreased and temperature showed a rising trend. The changes in precipitation, temperature and water resources were caused by a decrease in water resource population carrying capacity as a result of population growth, urbanization and pollution. Meanwhile, the South-to-North Water Transfer Project has not completely solved the water resource problems in Beijing. With increasing demand on water resources from urban development, the influence of precipitation and temperature on water resources in Beijing will be more significant.

ACKNOWLEDGEMENTS

This work was supported partially by the Ministry of Science and Technology of China (Grant No. 2016YFC1201301) and the High Resolution Earth Observation Systems of National Science and Technology Major Projects (10-Y30B11-9001-14/16). We thank the editors and anonymous reviewers for their helpful remarks.

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First received 24 January 2017; accepted in revised form 2 July 2017. Available online 7 August 2017