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Recent water quality trends in a typical semi-arid river with a sharp decrease in streamflow and construction of sewage treatment plants

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Abstract

Identification of the interactive responses of water quantity and quality to changes in nature and human stressors is important for the effective management of water resources. Many studies have been conducted to determine the influence of these stressors on river discharge and water quality. However, there is little information about whether sewage treatment plants can improve water quality in a region where river streamflow has decreased sharply. In this study, a seasonal trend decomposition method was used to analyze long-term (1996–2015) and seasonal trends in the streamflow and water quality of the Guanting Reservoir Basin, which is located in a semi-arid region of China. The results showed that the streamflow in the Guanting Reservoir Basin decreased sharply from 1996−2000 due to precipitation change and human activities (human use and reservoir regulation), while the streamflow decline over the longer period of time (1996−2015) could be attributed to human activities. During the same time, the river water quality improved significantly, having a positive relationship with the capacity of wastewater treatment facilities. The water quality in the Guanting Reservoir showed a deferred response to the reduced external loading, due to internal loading from sediments. These results implied that for rivers in which streamflow has declined sharply, the water quality could be improved significantly by actions to control water pollution control. This study not only provides useful information for water resource management in the Guanting Reservoir Basin, but also supports the implementation of water pollution control measures in other rivers with a sharp decline in streamflow.

1. Introduction

Rivers are the chief source of water supply for humans and freshwater ecosystems (Tang and Lettenmaier 2012, Vorosmarty et al 2010). The streamflow and water quality of rivers are both key for sustainable water use (Zeng et al 2013). There are many stressors, such as population, economy, land-use changes and climate change, that could lead to changes in water quantity and quality (Gleick 1998, Haddeland et al 2014, Kundzewicz and Krysanova 2010). Moreover, the impacts of these stressors on water quantity and quality are not independent but interactive (Zimmerman et al 2008). Therefore identifying the interactive responses of water quantity and quality to changes in these multiple stressors is important for the effective management of water resources (Crossman et al 2013).

A decline in streamflow has been observed in many regions due to climate change and human activities (Barnett et al 2008, Petrone et al 2010). Human activities, being particularly water-intensive, have been the main driving factors of streamflow decline in many arid and semi-arid regions (Barceló and Sabater 2010). Studies in northern China showed that streamflow in a large number of basins had a significantly

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decreasing trend during the past decades (1950s–2000s), and abrupt changes in streamflow mostly occurred between 1978 and 1985 (Bao et al 2012, Wang et al 2013, Xu et al 2014). This period corresponded to the beginning of China’s reform and opening up, when agricultural and industrial water use dramatically increased; this was considered to be the main reason for the decline in streamflow (Liu and Xia 2004, Xia et al 2014, Yang and Tian 2009). Similar conclusions were drawn for many basins located in the Mediterranean region. With no decreasing trend in precipitation, Tordera River (Spain) dried out for a longer time than that corresponding to the rainfall–runoff relationship because more than 30% of the runoff had been used for irrigation and industry (Benejam et al 2008). With increasing population and economic growth, water abstraction is likely to increase rapidly around the world (Heathwaite 2010) and streamflow decline will occur in more regions.

Population increase and economic growth, which bring more pollutant emissions, have resulted in poor water quality of rivers in many developed countries (Krysanova et al 2006, Luo et al 2013). In recent decades, with the construction and progress of sewage treatment plants (STPs), the water quality of many rivers in developed countries has improved significantly (Interlandi and Crockett 2003, Johnson et al 2009, Kundzewicz and Krysanova 2010). For example, the water quality in Japanese rivers improved significantly from 1992 to 2005, ascribed to improved wastewater treatment (Luo et al 2011). A decrease in ammonium in the lower Seine River occurred around the 1990s due to progress in wastewater treatment (Romero et al 2016). However, the streamflow, which was very important for water quality due to the dilution effect, did not change significantly in these rivers (table S1 available at stacks.iop.org/ERL/13/014026/mmedia). Given that streamflow decline will be observed in more regions, whether STPs can sustain or improve water quality in these regions is crucial for the sustainable human development. However, there is little information about how the river water quality changes with a sharp streamflow decrease and construction of STPs.

The Guanting Reservoir used to be the second largest source of drinking water for Beijing, China. In the mid-1990s, reduced inflow coupled with an increase in organic pollutants resulted in a degradation of water quality, thus the Guanting Reservoir no longer supplied drinking water for Beijing after 1997 (Liang et al 2011). The shortage of water resources in Beijing is becoming increasingly serious, and it is increasingly urgent to restore the Guanting Reservoir as a drinking water resource. The Chinese government has taken many actions, such as implementing the ‘Plan for the Sustainable Utilization of Water Resources in the Capital in the early 21st Century’. Specific measures included STP construction, soil and water conservation, and water-saving irrigation. However, there has been no consensus on whether this work has reached its goal and whether the implemented management measures have been successful. This study provides a historical analysis of streamflow and water quality for the upstream area of the Guanting Reservoir in response to changes in climate and human activities. The paper’s objective is to determine how river water quality has changed with a sharp streamflow decrease and construction of STPs.

2. Material and methods

2.1. Study area

Guanting Reservoir is located in the upper reaches of the Yongding River in northwest Beijing (figure 1). The Guanting Reservoir basin covers an area of 43,605 km² and spans four provinces, including the northeast part of Shanxi, the northwest part of Hebei, small parts of Beijing and Inner Mongolia. The regional climate is characterized as a warm temperate monsoon climate. The temperature and rainfall show large variations during the year, with annual averages of approximately 6 °C–7 °C and 397.5 mm, respectively. The main land-use types in 2010 were classified as agriculture (48.65%), forest (26.21%), grassland (20.63%), urban land (3.56%) and unused land (0.25%) (www.resdc.cn).

The major tributaries of the reservoir include the Yang River, the Sanggan River and the Guishui River. The Yang River and Sanggan River converge in Zhuguantun to form the Yongding River, which accounts for more than 90% of the total flow and total nutrient load to the Guanting Reservoir (He et al 2011). Xiangshuipu and Shixiali are two hydrometric stations, located in the Yang River and Sanggan River, respectively. Jimingyi, Baozhuang and Bahaqiao are three water quality stations, located in the Yang River, Sanggan River and Yongding River, respectively.

The Guanting Reservoir Basin has experienced rapid socio-economic growth (figure S5): the population rose from 7.55 million in 1996 to 8.06 million in 2015 and the per capita GDP showed a 10-fold increase between 1996 and 2015. During the same period, many STPs were built in the upstream area of the Guanting Reservoir Basin. In 2001 there was only one STP, but in 2015 there were 32 (figure 2).

2.2. Data sources

Monthly precipitation data from 1960 to 2015 were obtained from the China Meteorological Data Service Center (http://data.cma.cn/). Due to the difficulty in obtaining streamflow data, only two decades (from 1996 to 2015) of monthly discharge data, which were provided by Hebei Provincial Survey Bureau of Hydrology and Water Resources, were used in this study. Guanting Reservoir inflow and outflow data, and the annual volume of water for domestic use in Beijing were provided by the Beijing Water Authority. The number of STPs and their processing capacity were...
provided by the Ministry of Environmental Protection of the People’s Republic of China. Land-use data (1995, 2000, 2004 and 2010) were obtained from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (www.resdc.cn).

Water quality data at bimonthly intervals (on average) from 1996 to 2015 at the three sampling sites were obtained from two sources. Data for 1992–2008 were obtained from the Zhangjiakou Branch of the Hebei Provincial Survey Bureau of Hydrology and Water Resources. Data for 2009–2015 were obtained from the Zhangjiakou Environmental Protection Bureau. The water samples were collected in 1 l polypropylene sampling bottles, transported to the laboratory and stored at 0 °C–4 °C. The chemical measurements were taken within 24 h of sample collection using standard methods (Wei 1989, Wei 2002). Ammonia nitrogen was measured using the Nessler’s reagent.
spectrophotometry method, the permanganate index was determined by the acid potassium permanganate method and Cr$^{6+}$ was measured using the diphenylcarboxyldiazide spectrophotometric method. Arsenic was determined by the silver diethyldithiocarbamate spectrophotometric method from 1996 to 2002 and the atomic fluorescence method from 2003 onwards. The detection limits were 0.025, 0.5, 0.004 mg l$^{-1}$ for ammonia nitrogen, permanganate index and Cr$^{6+}$, respectively. The detection limit for As was 0.007 mg l$^{-1}$ from 1996 to 2002 and 0.0002 mg l$^{-1}$ from 2003 onwards. When the heavy metals were not detectable, the detection limits were used. These four water quality indices were selected because they were the principal pollutants preventing Guanting Reservoir from being used as a drinking water supply for Beijing (Liang et al. 2011).

2.3. Statistical methods
All the trend analyses of precipitation, streamflow and water quality were conducted with a generalized additive modeling approach: seasonal trend decomposition using loess (STL) (Cleveland and Cleveland 1990, Shamsudduha et al. 2009). With nonparametric regressions, the STL filtering method decomposes the time series into seasonal (cyclic), trend and remainder components. The STL approach is useful for describing nonlinear patterns and seasonal interactions that cannot be detected with traditional trend techniques (Lloyd et al. 2014). This technique has been used to analyze water quality time-series data in many rivers (Qian et al. 2000, Romero et al. 2016, Stow et al. 2015).

Two parameters were used to determine the degree of smoothing in seasonal and long-term components. Using the recommendations and diagnostic methods in previous studies (Cleveland and Cleveland 1990, Romero et al. 2016), we chose window widths of 15 months and 41 months separately for the seasonal and long-term components. Because the STL method cannot be used if there are missing values, the median polish method was used to reckon missing bimonthly concentration values in the time series (Sun and Genton 2012). All analyses were performed in R (open source statistical programming language).

3. Results

3.1. Long-term and seasonal trend of precipitation
Precipitation showed considerable yearly variability (figure 3(a) residuals), while there were no significant long-term trends in either Xiangshuipu and Shixiali (figure 3(a) trend). When resolution on the vertical scale was expanded, the fluctuation patterns were apparent in both these stations (figure 3(b)), but the magnitude of the changes was still very small. The precipitation slightly decreased in the 1970s and 1990s, and showed a slightly increasing trend after 2002.

Due to the regional monsoon climate, precipitation showed a distinct seasonal cycle. Precipitation rose steadily from January to July, reached its peak in July, then declined gradually until December. Precipitation in the rainy season accounts for approximately 75% of the annual total. The long-term seasonal trend showed that the precipitation had a decreasing trend in August and an increasing trend in May and September (figure 4). The precipitation in June and July first increased and then decreased after the mid-1990s. Precipitation in the other months showed no obvious change.

3.2. Long-term and seasonal trend of streamflow
For the long-term trend component, a significant downward trend in streamflow was observed for both stations (figure 5). Streamflow at both Xiangshuipu and Shixiali declined significantly and the turning...
Figure 4. STL of precipitation patterns depicted by month (blue curves) with corresponding long-term monthly averages (black horizontal dashed lines).

Figure 5. STL showing the three components in the streamflow trend model.
points were observed at the end of 1999 and 2002, respectively. After the turning points, the discharge at Xiangshuipu was relatively stable, while the streamflow at Shixiali showed a slight upward trend first and then remained relatively stable. The seasonality of streamflow in Xiangshuipu weakened, which could be attributed to the fact that streamflow decreased sharply and the intra-annual distribution of streamflow became gradually homogenized. The seasonality of streamflow in Shixiali was reinforced by the fact the streamflow in October declined less than in the other months. The monthly streamflow time-series showed a trend similar to the long-term trend for these two stations, and all monthly streamflows showed significant downward trends (figure 6). The seasonal streamflow patterns were relatively stable over time. The seasonal changes of streamflow were not significant at Xiangshuipu, and the streamflow in August was slightly higher than for other months. At Shixiali, the highest flow occurred in October. The seasonal distribution of discharge was not consistent with precipitation.

3.3. Long-term and seasonal trend of water quality

For the long-term trend component, due to the discharge of a large amount of industrial wastewater and domestic sewage without treatment, the pollutant concentrations in the earlier period were relatively high (figure 7). Then the decline in flow volume had an adverse influence on the dilution of effluent loads, and led to increasing trends of pollutant concentration. In 2005, concentrations of all the water quality parameters began to decrease, and the decrease was especially obvious in Jimingyi and Bahaoqiao. After 2010, the water quality in Baozhuang and Bahaoqiao remained relatively stable. In Jimingyi, concentrations of ammonia nitrogen and Cr\textsuperscript{6+} remained stable, but concentrations of permanganate index and As showed a slight increase after 2012.

The long-term seasonal trend was similar to the long-term trend for these three stations, and concentrations of all the water quality parameters showed significant downward trends after 2005 (figure S4). All the water quality indices showed distinct seasonal cycles, with higher values in the dry season for ammonia nitrogen and permanganate index and higher values in the rainy season for the two heavy metals due to the influence of diffused pollution.

The water quality at Baozhuang was superior to the other two stations at all times. Therefore, the improved water quality of the Yang River was the main contributor to the trend of improved water quality flowing into the Guanting Reservoir.

4. Discussion

4.1. The potential drivers of trends in streamflow

In this study streamflow in Xiangshuipu and Shixiali declined sharply from 1996 to 2000, which could be attributed to changes in precipitation and human activities (human use and reservoir regulation). The largest annual precipitation (between 1956 and 2000) occurred in 1995 (508 mm) (Wang et al 2010), and the inflow of Guanting Reservoir in 1995 (0.73 billion m\textsuperscript{3}) was the second largest since 1990 (figure S6). Furthermore, most of the 257 reservoirs upstream of the Guanting Reservoir reached nearly record levels in 1995, with a total storage capacity of about 1.5 billion m\textsuperscript{3} (Chen 2003). Subsequently, the relatively higher precipitation in 1996 (432.5 mm) led to more water...
being released from reservoirs located in the upstream area of Guanting Reservoir. Hence, the inflow of Guanting Reservoir in 1996 was larger than in 1995 (figure S6). Between 1997 and 2000 the decreasing precipitation, both annual and in the rainy season, not only resulted in less runoff being generated but also meant more water was drawn directly from rivers and more water was stored in reservoirs for human use. Consequently, streamflow declined sharply between 1996 and 2000.

However, human activities were the main reason for streamflow decline over the longer period of time. Previous studies showed that the streamflow in the Guanting Reservoir basin decreased significantly with no significant change in precipitation from the 1950s to the 2000s, with an abrupt change occurring in about 1980 (Liu et al. 2013, Xia et al. 2014, Yang and Tian 2009). The decreasing streamflow had been thought to be due to the increasing demand for water for human use, especially for irrigation, since 1978 when China implemented the reform and opening-up policy (Yang and Tian 2009). Hence, although the greatest annual precipitation (for 1956–2000) occurred in 1995, the inflow of the Guanting Reservoir in 1995 (0.73 billion m³) was much lower than the average inflow from 1956 to 1994 (1.25 billion m³). In the more recent record (1996–2015) of this study, the planting areas for vegetables, which consumed more water than cereal, had increased rapidly in the area upstream of Guanting Reservoir (Liu et al. 2013). However, the total irrigated area showed no obvious change over this period (table S2), suggesting that the total irrigated area could not fully capture the increased water use for agriculture. In addition, increasing population and economic growth also contributed to the decreasing streamflow: the population rose from 7.55 million in 1996 to 8.06 million in 2015; similarly, the per capita GDP increased 10-fold between 1996 and 2015 (figure S5). Due to the increasing demand for water for human use, streamflow was still low despite the increased precipitation in the subsequent years (figure 5).

The quantity of inflowing water was an important concern with regard to the reservoir’s watershed as a source of surface water (Zheng et al. 2013). With decreasing inflow, the volume of water that the Guanting Reservoir could supply also declined. Concurrently, the demand for water in Beijing increased. Beijing’s annual domestic water use increased from 0.70 billion m³ in 1990 to 1.63 billion m³ in 2013 (figure S6) due to rapid economic growth, increased urban population and a relatively higher standard of living. The outflow of the Guanting Reservoir accounted for 31% of Beijing’s

![Figure 7. The long-term trends of water quality.](image)
annual domestic water supply in 1990 but decreased to only 2.6% in 2013 (figure S6). The decreasing trend of inflow was a great challenge to the sustainability of using the Guanting Reservoir as a water source (Fry et al. 2012, Matonse et al. 2013). Hence, more attention needs to be paid to resolving the conflict between increasing water consumption and the availability of water resources. Agriculture accounted for about 56% of available water resources (Jiang et al. 2014), and was regarded as the main stressor for the decreased streamflow in the basin (Yang and Tian 2009). Integrative water-saving methods, which were successfully implemented to improve regional water productivity in northwest China (Kang et al. 2016), should be developed in the region.

4.2. The potential drivers of trends in water quality
In this study the quality of the water flowing in to the Guanting Reservoir deteriorated at first. There were two reasons for this. First, pollutant emissions increased due to increasing population and economic growth. Secondly, the flow volume declined sharply, which had an adverse influence on the dilution of effluent loads. In about 2005, concentrations of all the water quality parameters began to decrease. The main reason for this was probably the implementation of the ‘Plan for the Sustainable Utilization of Water Resources in the Capital in the Early 21st Century’, which was released by the Chinese government in 2001. The measures to control water pollution include industrial point pollution control and STP construction. By implementing the plan, the amount of industrial wastewater processed increased from virtually zero to $2.3 \times 10^5$ m$^3$ per day, and the water-reuse rate of industry increased from 52%–57%, which alleviated the impact of industrial point pollution on river water quality. Since 2001, many STPs have been built in the upstream area of the Guanting Reservoir Basin (figure 2). Energy conservation and emission reduction, which were implemented in the 11th Five-Year Plan of China (from 2006–2010), further promoted the construction of STPs. Between 2005 and 2009, the number of STPs increased from 3–22, and the amount of water processed increased by 160 million m$^3$ per year. This processing may be the reason why the water quality improved sharply in around 2005.

With the improvement in the quality of inflowing water, the concentrations of the water quality parameters in Guanting Reservoir began to decrease. Study of the trend in water quality (from 2001–2011) in the Guanting Reservoir showed that the concentrations of nutrients and permanganate index began to decrease in 2006, but the concentrations in 2011 were still higher than in 2001 (Zhang et al. 2012). Many studies have shown that internal loading, which comes from sediments, would delay recovery when the external loading was reduced (Lewis et al. 2007, Nowlin et al. 2005). For example, an analysis covering 35 lakes revealed that 10–15 years would be required for total phosphorus (TP) to reach a new equilibrium after the external loading had been reduced (Jeppesen et al. 2005). The study on the Guanting Reservoir showed that considerable amounts of nutrients and heavy metals had been stored in the sediments, such that the average sediment P concentration was 838 μg g$^{-1}$ (Zhou 2002), while the value in the Miyun Reservoir (a drinking water source for Beijing) was 687.71 μg g$^{-1}$ (Qin et al. 2016). Hence, more attention should be paid to internal loading from sediments for the Guanting Reservoir.

4.3. The relationship between the STP construction and improvement of water quality in China
China’s rapid economic development is often considered to be an economic miracle. However, this process has caused serious environmental issues. For example, 44% of the surface water in the seven key basins did not meet the environmental quality requirements for Type V water in 2001, and this means that nearly half of the surface water in these basins did not meet the demand for any use. To solve these problems, two measures were implemented in the 11th Five-Year Plan (from 2006 to 2010): end-of-pipe treatment facilities and the phasing out of backward capacity (Liu and Wang 2017). In the 12th Five-Year Plan (from 2011 to 2015), the same measures were used again (Zhang et al. 2015). As a result, the capacity of wastewater treatment facilities in China has been improved significantly. There were 224 STPs in China in 2001, but by 2014 the number of STPs had reached 4435 (figure S7); similarly, by 2014, the capacity of wastewater treatment facilities had risen to seven times the 2005 capacity. During the same period, the percentage of surface water in the seven key basins that did not meet the environmental quality requirements for Type V water decreased from 44% in 2001 to 9% in 2014. Water quality had a positive relationship with the capacity of wastewater treatment facilities.

Among the seven key basins in China (figure S8), the water quality of rivers in the south was better than those in the north, which may be attributed to the fact that North China has only 19% of the total water resources but accounts for 45% of the country’s total population (Jiang 2015). Due to the increase in water abstraction the flow of many rivers in North China has declined sharply (Liu and Xia 2004), which has decreased the ability of rivers to absorb and mitigate pollution. However, the water quality of all key basins in North China has improved due to the construction of STPs in recent years.

5. Conclusion
This study analyzed seasonal and long-term trends in the quantity and quality of water flowing into the Guanting Reservoir, and identified possible factors underlying these trends. Precipitation change and human activities (human use and reservoir regulation) were mainly responsible for the sharp decline in streamflow from 1996 to 2000, while human
activities were the main reason for streamflow decline in the Guanting Reservoir Basin over a longer period of time (1996—2015). The outflow of the Guanting Reservoir accounted for 31% of Beijing’s annual domestic water supply in 1990 but decreased to only 2.6% in 2013. Meanwhile, all the water quality parameters in the Guanting Reservoir basin improved significantly, which should be attributed to the construction of STPs. The water quality in the Guanting Reservoir showed a deferred response to the reduced external loading due to internal loading from sediments. These results imply that for rivers in which discharge has declined sharply the water quality could be improved significantly by construction of STPs. This study provides useful information for implementing water pollution control measures in other rivers with a sharp decline in streamflow.

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