Evaluation of river restoration efforts and a sharp decrease in surface runoff for water quality improvement in North China

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Abstract
Rapid urbanization, population growth, and other intensive human activities have greatly altered natural hydrological conditions and matter cycling, which are the main causes of water quality deterioration in North China’s rivers. With the help of a 15-year (2005–2019) dataset of river water quality (1043 records from nine sites), this study investigated the spatiotemporal water quality patterns in the Yongding River Basin (YRB) in North China using a new water quality index (WQI-DET), which has been customized for China’s water quality classification scheme. Our results showed that the river water quality of the YRB has significantly improved due to the decreased surface runoff and an abrupt change of WQI-DET was observed in 2011. The elimination of anoxic conditions and the mitigation of nitrogen and phosphorus resulting from the construction of wastewater treatment plants and the improvement of treatment capacity are the main reasons for the improvement in river water quality. We also found that eutrophication is still not completely eradicated because of the high concentrations of NH₄⁺ and total phosphorus. Our study suggests that for rivers in which runoff has decreased sharply, the water quality could be improved significantly by wastewater treatment facilities. At present, for the YRB, more effort is needed to eliminate eutrophication and dried-up river sections and thereby finally improve the river ecosystem. We concluded that more attention and effort should be given to river hydrological conditions, specific river ecological characteristics, and the increasingly important non-point source pollutants during the design of river restoration measures in North China.

1. Introduction

Following the the ‘reform and opening-up’ policy implemented by the national government in 1978 to vigorously develop the economy, China’s extensive socioeconomic development over the past several decades has taken place at the expense of the natural environment (Liu and Yang 2012, Liu et al 2013, Zhou et al 2017, Ma et al 2020b). The general deterioration of river water quality has become one of the most serious environmental threats to human health and ecosystem services nationwide (Zhou et al 2017, Ma et al 2020b, Huang et al 2021). This situation is more serious in North China, where deficient water resources increasingly impede the control of water pollution and the improvement of water quality (Wang et al 2019, Ma et al 2020a, Huang et al 2021, Sun et al 2021), leading to water-pollution-induced severe water scarcity, for which this area has become a hot spot on a worldwide scale (Liu and Raven 2010, Guan et al 2014, Zhao et al 2015, Sun et al 2021). The increased demand for water to support irrigation, industry, and domestic life has nearly dried up all the natural runoff of the Hai River Basin (HRB) in North China, an area that accounts for 10% and 12% of the national population and the GDP, respectively (Liu et al 2010, Xia et al 2012), and failed to eliminate the accumulated water pollutants (Guan et al 2014). In the HRB, the degradation of water quality has the important impact of exacerbating water
scarcity (Ma et al 2020a). To control water pollution in the the HRB, the national government has made a high level of investment in environmental water remediation. Since 2006, the major national science and technology project for water pollution control and treatment has set up many restoration projects to improve water quality. For example, from 2006 to 2010, more than 500 water pollution control projects were built, and in 2015 (MEE 2008), the water pollution control action plan (10-point water plan) demanded increased investment to ensure acceptable water quality and a reclaimed water utilization rate of up to 30% in the HRB by 2020 (TSC 2015). Although these efforts have yielded notable results (Liu and Yang 2012, Tong et al 2017, Huang et al 2021), the current water pollution situation is relatively severe compared to that in other regions due to a chronic water shortage (Zhou et al 2017, Wang et al 2019, Ma et al 2020b). Considering that inadequate water quality can cause significant limitations to water availability (van Vliet et al 2017, Ma et al 2020a), the HRB is still facing increasing pressures on water security due to the scarcity of the available water resources (Zhang et al 2016, Sun et al 2021). Unfortunately, hardly any work has been done to evaluate the effectiveness of water quality improvement measures under the conditions of the decreased water resources in the HRB.

To this end, we selected the Yongding River (YR) in the HRB as an example with which to observe the trends of river water quality in North China based on 13 water quality indicators. The YR is one of the largest tributaries of the Hai River in North China and is the main source of domestic water supply for the capital city Beijing via the Guanting Reservoir (Lei et al 2010). Due to the dry climate over the past 30 years, increased dam construction and water abstraction have greatly altered the hydrology of the YR, causing rivers to dry up (Jiang et al 2014). To date, nearly 300 small and large reservoirs have been constructed in the upper YR Basin (YRB) to meet the increased upstream water demands of regional agriculture, industry, and domestic water use, and these reservoirs have controlled the spatiotemporal distribution of water resources (Feng 2005), resulting in poor hydrological connectivity between the upstream and downstream areas (Jiang et al 2014), which further worsens the problems of water resource allocation and water quality recovery (Peng et al 2020). The continuous shortage of water resources increasingly restricts water pollution control and water quality improvement, while, at the same time, water pollution and water quality deterioration have exacerbated water shortages (Wang et al 2019, Dai et al 2020). For instance, in 1997, due to the drainage of untreated wastewater from housing and industry, coupled with a growing and large demand for water resources which directly caused water pollution, the government banned the use of Guanting Reservoir for domestic water supply because the water was seriously polluted (Xia et al 2007). Currently, most research has concentrated on the water shortage and water quality trends of the YR (Yu et al 2017, Peng et al 2018, Dai et al 2020). Such research, however, has usually focused on temporal changes in pollutant concentrations and the lack of direct links to river restoration efforts, with the result that there has been no consensus on whether the restoration work for water quality control has achieved its original goal, especially given the continuous decrease in surface runoff.

This work mainly focuses on two aspects: (a) an investigation of the spatiotemporal patterns of water quality and the critical variables of the YR impairment in the HRB in North China, based on a 15-year (2005–2019) dataset of river water quality, long-term surface runoff (1935–2016), and the treatment capacity of regional wastewater treatment plants (WWTPs), and (b) elucidation of how the environmental water restoration efforts introduced by the Chinese government have impacted the water quality of the YR. This piece of information aims to provide a basis for identifying the key factors and critical moments that lead to river water quality improvement and improving the designs of river restoration projects in water shortage areas in the face of continued intensive human activity.

2. Materials and methods

2.1. Study area and data collection

2.1.1. Study area

The YR is located in the HRB in northern China. It originates from the Sanggan River in Shanxi Province and the Yang River in Inner Mongolia. These two rivers converge to form the YR, which has a basin area of 47 000 km². Our study area is the part of the river basin that belongs to Zhangjiakou City in Hebei Province, which has an area of 17 355 km² (figure 1). The mean annual precipitation in this area is 406 mm, the climate is semi-arid, and 75%–85% of the precipitation occurs in the flood season between June and September. This area is a water conservation area and the ecological corridor of Beijing City as it is the ‘Mother Water of Beijing’. As one of the most rapidly developing and water-scarce regions in North China, this region has consumed a disproportionate amount of water for decades due to its small water resources (203 m³ per capita a⁻¹). Many studies have shown that water quality deterioration, groundwater depletion, and natural runoff decrease are very common in this region (Xia et al 2012, Guan et al 2014, Jiang et al 2014, Dai et al 2020), and that water consumption is expected to continue to rise due to the fast-growing population and economy.

2.1.2. Data collection

To capture the dynamic trend of YR water quality, monthly river water quality data for nine sampling sites from 2005 to 2019 (figure 1) were obtained
from the Zhangjiakou Environmental Protection Bureau. The river water quality dataset used in this work includes 1043 monthly samples covering 15 years with 13 key variables: dissolved oxygen (DO, mg l\(^{-1}\)), ammonium (NH\(_4^+\), mg l\(^{-1}\)), total phosphorus (TP, mg l\(^{-1}\)), chemical oxygen demand (COD, mg l\(^{-1}\)), fluoride (F\(^-\), mg l\(^{-1}\)) (as fluoride in this area occasionally exceeds the water quality standard), and eight heavy metals (HMs) including mercury (Hg, mg l\(^{-1}\)), lead (Pb, mg l\(^{-1}\)), copper (Cu, mg l\(^{-1}\)), zinc (Zn, mg l\(^{-1}\)), selenium (Se, mg l\(^{-1}\)), arsenic (As, mg l\(^{-1}\)), cadmium (Cd, mg l\(^{-1}\)), and chromium (Cr, mg l\(^{-1}\)). The historical data for surface runoff (1935–2016) were obtained from the National Hydrological Yearbook of the HRB. The numbers of urban WWTPs and their treatment capacities were provided by the Ministry of Ecological Environment Protection of the People’s Republic of China. The amount of wastewater discharge and the effluent water quality were obtained from the Environmental Statistical Yearbooks of Zhangjiakou City.

2.2. River water quality index (WQI)

To analyse the collected YR water quality dataset, we used the WQI (WQI-DET) developed by Huang et al (2019) to determine the key variables that lead to the deterioration of YR water quality. WQI-DET is an adaptation of the traditional WQI to the five water quality classes of China’s environmental quality standards for surface water (GB3838-2002) (MEP 2002) (table S1 available online at stacks.iop.org/ERL/17/044028/mmedia). WQI-DET < 20, 20 < WQI-DET < 40, 40 < WQI-DET < 60, 60 < WQI-DET < 80, and WQI-DET > 80 mean bad, poor, moderate, good, and excellent water quality, respectively.

2.3. Trend analysis of the WQI-DET and surface runoff conditions

In this study, the Mann–Kendall method was applied for trend analysis (Gocic and Trajkovic 2013) and the Pettitt test (equations (3)–(7)) was applied for abrupt change analysis of the river water’s WQI-DET and the surface runoff of the YR. All analyses were performed using Matlab R2018b:

\[
U_{t,n} = U_{t-1,n} + \sum_{i=1}^{n} \text{sgn}(X_t - X_i) 1 \leq t \leq n
\]
The most probable change point $t$ is found when its value satisfies

$$K_t = \max_{1 \leq i \leq n} |U_{t,n}|.$$  

The significance probability associated with the value $K_t$ is approximately calculated using:

$$p = 2 \exp \left\{ -6k_t^2 / \left( n^2 + n^3 \right) \right\},$$

where $X_t$ and $X_i$ are the sequential data values of the time series in years $t$ and $i$, respectively; $n$ is the length of the time series and $U_{t,n}$ is the statistical index.

3. Results

3.1. Changes of natural surface runoff of YR

Using the Mann–Kendall method, we examined the surface runoff from the 1930s to 2016 in the YRB. Generally, surface water runoff in the selected area of the YRB exhibited a downward trend over the past eight decades ($p < 0.01$) (table S2 and figure 2). The Sanggan River’s flow (site Shixial, figure 2) was 8.0 times lower than in the 1940s and the Yang River’s flow (site Xiangshui, figure 2) was 2.0 times lower than in the 1930s, respectively (figure 2). Both of these rivers exhibited abrupt changes in runoff in 1984, as verified by the Pettitt test (figure 2). It is interesting to note that the abrupt change time of the runoff is consistent with the implementation time of China’s economic ‘reform and opening-up’ policy (after 1978), indicating that intensive human activity and socioeconomic-induced water withdrawal are the main reasons for the decreased river flow, as precipitation did not significantly decrease (Jiang et al. 2014).

3.2. Spatiotemporal characteristics of river water quality

Our results showed that significant spatial variation with poorer water quality was observed in the Qingshui River at different periods (figure 3 and table S3), although the mean WQI-DET fluctuated greatly due to lower sampling size during the period from 2005 to 2007 (table S3). The frequency of the Qingshui River’s poor water quality (WQI-DET < 40) was consistently higher before 2016 (2005–2007: 92.6%, 2008–2011: 29.3%, 2012–2015: 17.7%), even for extremely bad water quality (figure 3(a)). Specifically, for the Qingshui River, 92.6% of the sampling sites had poor river water quality, compared with 87.9% in the Yang River and 12.1% in the Sanggan River during the survey period of 2005–2007.

This is mainly because it flows through an urban area, where a large amount of wastewater was directly discharged into the river. For recent years (2016–2019), no river sections with poor water quality (WQI-DET < 40) were identified in the selected area of the YRB on an annual scale (orange scatter diagrams in figure 3(d)), indicating significant water quality improvement in the YRB.

Both the monthly and annual WQI-DET figures showed a clear improving trend of YRB water quality in the long-term records (figure 4). The annual WQI-DET showed an increasing trend during the period of 2005–2019 ($p < 0.001$), suggesting a significant improvement in river water quality. Overall, an abrupt change in river water quality was detected in 2011 (figure 4). The annual mean WQI-DET values increased from −550.11 to 48.67 and polluted water (WQI-DET < 0) in the rivers accounted for 32.5% of all results during the period from 2005 to 2009 but decreased to 0.6% during the period from 2012 to 2019.

Among the four rivers, the Sanggan River has the best water quality, achieving a mean WQI-DET value of 64.02 during 2005–2019 (figure 5(a)), but the rest of the rivers had the mean WQI-DET values of less than 20. The water quality of the Yang River, the Qingshui River, and the Yongding River showed significant improvement during our survey period (figures 5(b)–(d)). This indicates that the long-term reduction in river flow (figure 2), does not accelerate the decrease in river water quality, as the decrease of natural runoff would result in insufficient self-purification and dilution capacities of rivers. The abrupt changes in the water quality of the Yang River and Qingshui River were both detected in 2009, while that of the Yongding River was detected in 2011. Poor water quality occurred in the Qingshui River. Specifically, the mean WQI-DET value in the Qingshui River increased from −1504.16 to 53.50 between 2005 and 2009 and between 2010 and 2019. Similarly, the Yang River had a mean WQI-DET value that increased from −90.93 to 55.68 between 2005–2009 and 2010–2019, while the YR had a mean WQI-DET value which increased from −72.67 to 52.30 between 2005–2011 and 2012–2019.

3.3. Critical variables associated with the deterioration of river water quality

To find the most critical indicators associated with the impairment of river water quality in the YRB between 2005 and 2019, we calculated the relative frequency of those variables that caused the WQI-DET value to become negative. The number of water samples with water quality impairment (WQI-DET < 0) decreased sharply from 2005 to 2011, but slightly increased from 2018 (figure 6). The impairment of the river water quality in the YRB was due to nutrient pollution (i.e. high $\text{NH}_4^+$, TP), COD, fluoride ($F^-$), and HM pollution (i.e. Pb, and Cd). We also find a decreasing
Figure 2. Surface water runoff before and after abrupt change points in the selected part of the YRB. Blue and orange scatter diagrams represent annual runoff before and after the abrupt change year (1984), respectively, and the larger red points represent runoff in 1984. The upper right image inset in each figure shows the abrupt change point calculated by the Pettitt test.

Figure 3. Spatial patterns of the mean WQI-DET in the selected part of the YRB during 2005–2007, 2008–2011, 2012–2015, and 2016–2019; n is the number of data records. Gray scatter points represent an absence of monitoring data.
contribution of NH$_4^+$, F$^-$ and the variable that reflects anoxic conditions (i.e. DO), an increasing contribution of COD and TP to river water quality impairment, and a very small percentage of HM pollution (figure 6). Decreasing proportions of NH$_3^+$ and DO are observed, from 42.62% (NH$_4^+$) and 13.11% (DO) in 2005 to 33.33% (NH$_3^+$) and 0.00% (DO) in 2019. Increasing proportions of COD and TP are observed, from 22.95% (COD) and 21.31% (TP) in 2005 to 33.33% (COD) and 33.33% (TP) in 2019.
Figure 6. Critical variables associated with water quality impairment of the YR in Zhangjiakou City, Hebei Province during 2005–2019. The contribution of each variable was calculated according to $n_i/\sum_{i=1}^{j} n_i$, where $n_i$ is the number of river water samples with a negative WQI-DET value for the variable $i$, and $j$ ($j = 7$) is the total number of water quality variables considered.

Figure 7. Critical variables responsible for the impaired water quality of each river in the selected part of the YRB in Zhangjiakou City, Hebei Province during 2005–2019. Except for 2015, almost 70% of the impaired river water was caused by NH$_4^+$ and TP during the period from 2005 to 2019, and the contributions of both of TP and NH$_4^+$ appeared to have increased from 2007 to 2011 (figure 6). The decreased number of water samples with negative WQI-DET and the critical variables associated with water quality impairment in the YRB suggest that although the water pollution has been alleviated, it has not been fully eliminated. NH$_4^+$ and TP were the main causes of the deterioration of water quality in the YR and the Yang River (figure 7). In general, all the rivers showed a decreasing nutrient pollution trend; in particular, no impairment to the water quality was found in the Sanggan River after 2007 (figure 7).

4. Discussion

4.1. Evidence of the restoration efforts for water quality improvement in North China

Our analysis suggests that significant progress has been made in improving water quality in the selected part of the YRB in Zhangjiakou City, Hebei Province, especially in nutrient pollution output (figure S2). This considerable improvement was mainly owing to China’s ambitious series of plans for water pollution
control, especially after the drinking water crisis in the Taihu Lake Basin (Guo 2007). In 2006, the national major science and technology program for water pollution control and treatment was established to protect freshwater quality. Since 2008, many plans, guidelines, laws, regulations, and policies have been established to guarantee that restoration measures were taken to improve freshwater quality, e.g. the action plan for water pollution controls in 2015, the guidelines for the major river system in 2017, and the national strategic water resources management plan set by the central government in 2011, which elaborated a focus on the three stringent controlling ‘red lines’ concerning water use quantity, water use efficiency, and water pollution. In particular, for the YR, in 2009, 17 billion RMB Yuan were invested to construct a green ecological river corridor to secure water ecosystem services and at the end of 2016, the Chinese government planned to invest 37 billion RMB Yuan in the comprehensive restoration of the YRB to recover river ecosystem services. Many of these significant effects were summarized in Ma et al (2020b) and Huang et al (2021), which showed that water quality in the HRB has significantly improved due to the decrease in NH$_4^+$ and TP.

Notwithstanding a recent clear trend towards improved water quality, water quality is still an important issue in achieving water safety in YRB. Given that many studies have pointed out that there is an urgent need to improve water quality in North China (Jiang 2009, Zhou et al 2017, Yu et al 2019), for the YRB, the excessive NH$_4^+$ and TP inputs from the YR could induce the eutrophication of Guanting Reservoir, which would further affect the survival of aquatic organisms and the recovery of drinking water quality. Therefore, great efforts are still needed to focus on ecological river restoration, such as water pollution control, water conservation, and water transfer to alleviate the water pollution and water shortage in the YRB. These measures are essential to reduce pollution-induced water shortages and support sustainable socioeconomic development, as river ecological restoration and nutrient reduction are currently the most widely used strategies for water quality improvement (Richardson et al 2011, Horppila 2019).

4.2. Relationship between water quality and river restoration efforts

There are two reasons for the water quality impairment in the YRB, that is, the increased pollutant emissions due to the increasing population and economic growth, and the sharply reduced surface run-off, which limits the ability of rivers to dilute the effluents from WWTPs, as rivers in the YRB are largely supplied by the effluents of WWTPs (Busi et al 2017, Peng et al 2018). Therefore, the construction of WWTPs is the most effective way to control water pollution, as they can significantly reduce the quantities of COD, nitrogen, phosphorus, and other pollutants in wastewater (Zhang et al 2016). In the selected part of the YRB, both the number of WWTPs and the annual wastewater treatment capacity of the WWTPs have continued to increase since 2005 from 1 and 3.65 $\times$ 10$^7$ t a$^{-1}$ to 16 and 1.57 $\times$ 10$^8$ t a$^{-1}$, respectively, in 2019 (figure 8(a)). During 2005–2009, the amount of wastewater discharged far exceeded the treatment capacity of the WWTPs. The directly discharged domestic sewage and industrial wastewater had very adverse effects on the river water, especially in the Qingshui River (figure 5(b)). After 2009, the treatment capacity of the WWTPs gradually met the wastewater discharge demand. With the increased treatment capacity of the WWTPs and the improvement in effluent water quality (i.e. the COD, NH$_4^+$ and TP) of the WWTPs (figure 8(b)), the concentrations of river pollutants began to decrease. This explains the significant abrupt change in the improvement of river water quality in 2011 (figure 5). The significant positive correlation between the treatment
Figure 9. Relationship between WQI-DET, the wastewater treatment capacity of WWTPs, and the pollution load discharged from WWTPs in the selected part of the YRB. The gray area represents the 95% confidence interval. The total pollutant load discharged by the WWTPs is calculated by taking the sum of the COD, NH$_4^+$ and TP loads.

capacity of the WWTPs and the WQI-DET and the significant negative correlation between the major pollution loads discharged from the WWTPs and the WQI-DET (figure 9) also shows that the investment in WWTPs has contributed to a marked increase in the WQI-DET. This result indicates that WWTPs' treatment capacity and treatment rate are the main critical variables that can be used to recreate the recent river water quality trends in the YRB. This further proves the effectiveness of environmental investment in reducing anthropogenic water pollution emissions, especially in North China, where degraded water quality has had a significant role in exacerbating water scarcity.

4.3. Challenges and continued efforts to improve water safety in North China

Previous studies have highlighted that in water shortage regions, pollution was more prominent than in regions with abundant water resources (Wang et al 2019, Ma et al 2020a, 2020b). In North China, the ability of rivers with decreased surface runoff to dilute and mitigate pollution is decreased at the same time; in this case, the improvement of the treatment efficiency of WWTPs is the key factor in improving river water quality (Pernet-Coudrier et al 2012, Peng et al 2018). However, in our study area, there is still a big gap between urban and rural areas in terms of design principles and the operational performance of wastewater treatment facilities, owing to the delayed development of the sewage collection system and regional disparities in effluent discharge standards and water environmental protection targets (Liu et al 2020, Xie et al 2021). In this case, the existing treatment capacity of the urban WWTPs alone is not enough to maintain better water quality. Further efforts to reduce water pollution discharge are still needed to reduce human pressures on river water quality.

Apart from the mitigation of point source pollutants eliminated by the WWTPs, agricultural non-point source pollutants have been recognized as an important source of nutrient pollutants in rivers due to intensive fertilization in the YRB (Guo et al 2014). For example, the YRB’s crop production has maintained an average nitrogen fertilization rate of 195 kg ha$^{-1}$ (Guo et al 2014), almost twice as much as the crops can take up (Liu et al 2013), and the total nitrogen and phosphorus losses from the soil in the rainy season are 96 and 9 kg hm$^{-2}$, respectively (Guo et al 2014). In this case, considering that the current dominant land use type in this study area is farmland (figure S3), which accounts for 41% of the total land use, the input of pollutants from agricultural non-point sources cannot be ignored, especially in rural areas where farmland is distributed along river banks, although the precipitation that generates runoff is limited (Ongley et al 2010, Pernet-Coudrier et al 2012). Furthermore, in terms of the proportions of pollutants, the input of non-point source pollutants including agriculture, livestock and poultry breeding, and rural life almost accounted for 44%-76% of the total pollutants in the YR in Zhangjiangkou City (Zhao et al 2020). Given that best management practices (BMPs) are a new and effective method to prevent or reduce non-point source pollutants (Liu et al 2018, Huang et al 2019, 2021), especially after the point source pollutants have been well controlled, in this case, BMPs are a good choice that allows decision-makers to mitigate non-point source pollutants and further restore river ecosystems in the YRB’s agricultural region. It is also imperative to adjust the local economic structure and develop low-pollution and water-saving industries.

More importantly, since river water pollution exacerbates water scarcity and river ecosystem degradation and further increases water stress (Liu and Yang 2012, Xia et al 2012), alongside water...
pollution controls, we advocate the conservation of water resources using state-of-the-art high-efficiency water-saving technologies during river restoration efforts. Specifically, the restoration of rivers in North China needs to focus on both river water quality and quantity, and the restoration efforts of rivers in North China will be remarkably enhanced by establishing a strict framework to ensure river baseflow that is better for the biota (Poff et al. 1997, Hester and Little 2013) and that quantifies the economic benefits derived from investing in restoration works (Dai et al. 2021). It is worth noting that even though our description of the WQI-DET trends based on the annual average drew a favorable picture of river water quality in the selected area of the YRB as mentioned above, the truth is that high pollutant concentrations were occasionally observed that exceeded the standards for water quality, even in rivers that have shown significant water quality improvement (figure S2). For example, 8.9% and 9.9% of the collected water samples in YRB in 2019 registered COD and TP concentrations greater than 20.0 and 0.2 mg l\(^{-1}\), respectively. Although the levels of NH\(_4^+\) and TP have been alleviated in recent years, considering that NH\(_4^+\) and TP are still predominant factors in water quality impairment, their trends still need more attention, due to their harmful environmental impacts (Maavara et al. 2015, Chen et al. 2019, Kuwayama et al. 2020). In conclusion, we believe that improvements in North China's river water quality are both possible and desirable if great attention continues to be paid to addressing the complicated interactions between humans and nature to prevent eutrophication risks and to guarantee the baseloads of rivers in the context of reduced surface runoff.

5. Conclusion

Taking the YR as an example, North China's spatiotemporal pattern of river water quality was analyzed to evaluate the recent river restoration efforts and ongoing challenges in water safety using a 15-year (2005–2019) water quality dataset containing 1043 records. Our results revealed that river water quality has been successfully improved under conditions of decreased surface runoff owing to the mitigation of anoxic conditions and nutrient input. Although remarkable success has been achieved in water quality restoration in the YRB as a result of the unremitting efforts of the national government, NH\(_4^+\) and TP are still predominant factors in water quality impairment. It is still difficult to increase the water quantity to eradicate the dried-up river sections and achieve acceptable ecological river conditions in the YRB. The design of river restoration measures in North China must secure the baseflow of rivers, water conservation conditions, and river ecosystem services and should also consider the increasing non-point source pollutants, especially after better control of the point sources has been achieved. To our knowledge, this is the first time that restoration efforts for river water quality recovery have been assessed under the conditions of decreased surface runoff in a typical water shortage area in North China. This study provides useful information for the implementation of river restoration measures in other regions with severe water shortages.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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