Engineering 21 (2023) 135–142

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Environmental Engineering—Article

Improvement of the Yangtze River's Water Quality with Substantial Implementation of Wastewater Services Infrastructure Since 2013

Weixiao Qi [a], Xu Wang [b,c,*], Jin Kang [d], Yaohui Bai [e], Rui Bian [a], Hongtao Xue [a], Li Chen [a], Aomei Guan [e], Yi-Rong Pan [b,e], Huijuan Liu [a], Jiuhui Qu [a,e,*]

[a] Center for Water and Ecology, State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, China
[b] State Key Laboratory of Urban Water Resource and Environment, School of Civil and Environmental Engineering, Harbin Institute of Technology, Shenzhen, Shenzhen 518055, China
[c] Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter EX4 4QF, UK
[d] Hubei Provincial Research Institute of Environmental Science, Wuhan 430072, China
[e] Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

ARTICLE INFO

Article history:
Received 15 November 2021
Revised 17 January 2022
Accepted 2 March 2022
Available online 26 April 2022

Keywords:
Yangtze River Basin
Wastewater services infrastructure
Water quality variation trajectory
Key affecting drivers
Decoupling
Balance

ABSTRACT

Meeting the ever-growing demands of humans while ensuring sustainability is one of the great challenges of this century. China has made significant economic progress in recent decades and is increasingly engaged in international activities. This economic prosperity, however, has resulted in substantial contaminant discharge and damage to domestic aquatic ecosystems. Considerable efforts have been made to address these issues through developments in wastewater services infrastructure. Here, we provide an overview of wastewater infrastructure development in the Yangtze River Economic Zone during 2007–2017 and analyze diverse long-term monitoring data. These analyses trace and capture the key drivers affecting the restoration of water quality and determine how such restoration may be sustained or even accelerated in future. We find that there has been a decoupling trend between the economy and environmental variables since 2013, which coincides with the substantial implementation of improved wastewater treatment systems. While further developments in sewerage facilities and phosphorus discharge reduction may continue restoration, a paradigm shift toward a circular economy remains necessary to integrate these developments with wastewater resources management. Overall, this study advances the current understanding of the impact of wastewater services facilities on the balance between economic development and environmental protection.

1. Introduction

Improving human well-being without further undermining the integrity of the Earth's environmental systems is one of humanity's greatest challenges [1,2]. China plays an essential role in global manufacturing and economic prosperity. Nevertheless, its economic growth has led to many severe environmental problems, such as domestic water pollution and biodiversity loss [3,4]. For example, increasing socioeconomic activities have resulted in anthropogenic pollutant discharge, leading to unprecedented algal blooms and the rapid extinction of rare species in the Yangtze River. The subsequent decline in aquatic ecosystems has attracted global concern [5–7].

The Yangtze River Basin (YRB) is the main wastewater-generating economic zone in China, with domestic discharge accounting for approximately 35% of the national annual total in recent years [4]. For this reason, domestic efforts to reduce China's aquatic pollutants depend heavily on the trajectory of wastewater discharge relative to the YRB. The country's pledge to reduce its annual pollutant discharges has been widely implemented since the 10th Five-Year Work Plan for National Economic and Social Development [8]. China may now have achieved this commitment through significant investments in wastewater services infrastructure and by restricting the discharge of waterborne pollutants. An analysis of historical water quality records for lakes in four geographical regions of China indicates that the monthly and annual average concentrations of pollutants have been declining in the

* Corresponding authors.
E-mail addresses: wangxu2021@hit.edu.cn (X. Wang), jhqu@mail.tsinghua.edu.cn (J. Qu).

https://doi.org/10.1016/j.eng.2022.03.014
2095-8099/

YRB's four largest freshwater lakes (Chaohu Lake, Poyang Lake, Dongting Lake, and Taihu Lake) since 2006, due to rapid improvements in sanitation [9]. Although these declines clearly demarcate a key shift, the remaining high concentrations of pollutants in the lakes (and probably also in the main stream) raise significant questions about the factors driving the current decrease and their relative importance, whether these declines are ubiquitous in the basin, and whether the declines can be sustained or even accelerated. If pollutant concentrations in the Yangtze River have fallen primarily as a result of improving wastewater service practices, then a balance between increasing economic activity and ensuring environmental sustainability may be achieved through further improvements in wastewater management services.

Here, we present an overview of developments in the municipal wastewater services infrastructure for the YRB from 2007 to 2017. Details of the analytical approach and data sources are provided in Section 2 and the Appendix A. To summarize, the values and information associated with parameters such as population, urbanization, gross domestic product (GDP), water quality and quantity, sanitation, and wastewater services status were examined from more than 100 cities in the YRB using the most recently published and revised statistics from the Chinese Government's Yearbooks. We analyzed the pollutant trajectory using water quality data from 2003 to 2018 in the mainstream Yangtze River to assess the pollutant footprint from discharges and sanitation improvement. We also identified factors that may play key roles in driving changes in pollutant fluxes in the Yangtze River and visualized the extent to which improvements could be made. Subsequently, we performed a cumulative sum analysis to investigate whether there has been any spatial heterogeneity in recent discharge patterns in the YRB. Finally, we conducted virtual regime analyses to explore the potential of alternative improvements in wastewater services management for reducing wastewater-derived pollutants. We also projected the investment space in future wastewater services infrastructure that would be capable of achieving such improvements by 2035.

2. Material and methods

2.1. Socioeconomic factors of the study area

The YRB covers an area of 1.8×10^6 km^2—20% of China's land area—and hosts about 30% of the nation's population. Our study divided the basin into the upstream (before Yichang), midstream (between Yichang and Hukou), and downstream (after Hukou) sub-basins, as was done in other studies [10,11]. The populations and GDP of each city were obtained from the China and provincial statistical yearbook (2007–2017) [12]. The town area and drainage pipeline length of each city were obtained from the *Statistical Yearbook of Urban and Rural Construction* (2007–2017) [13]. The density of the drainage pipelines was calculated by dividing the length of drainage pipelines by the area of the town.

2.2. Wastewater services infrastructure development in the YRB

We obtained the number of wastewater treatment plants (WWTPs), their designed capacity, the amounts of wastewater treated annually, the investment in wastewater infrastructure (including WWTPs and drainage pipelines), the annual reduction in pollutants (chemical oxygen demand (COD), total phosphorus (TP), total nitrogen (TN), and ammonium nitrogen), and the quantities discharged from all WWTPs during 2007–2017 in each city in the basin from the Ministry of Housing and Urban–Rural Development of the People's Republic of China (PRC).

2.3. Pollutant concentrations and loads in the Yangtze River

Historical water flow and water quality data (i.e., TP, ammonium nitrogen, and permanganate index) at the five main hydrological stations in the Yangtze River (Cuntan, Yichang, Wuhan, Hukou, and Datong) were collected from the Changjiang Water Resources Commission of the Ministry of Water Resources of PRC and from published reports and literature [3,10,14–30]. The longitudes and latitudes of the Cuntan, Yichang, Wuhan, Hukou, and Datong hydrological stations are (29°37′22.0″N, 106°36′09.0″E), (30°41′36.0″N, 111°16′53.0″E), (30°36′36.0″N, 114°18′54.0″E), (29°44′41.0″N, 115°59′55.0″E), and (30°46′41.0″N, 117°38′06.0″E), respectively. Cuntan and Yichang are the key hydrological control stations upstream and downstream of the Three Gorges Dam, respectively. Wuhan is the key hydrological control station in the midstream of the Yangtze River, and the Hukou hydrological control station is located in the boundary between midstream and downstream. Datong is a cross-section at the lowermost hydrological station of the Yangtze River and is not influenced by the tide. We based our calculations of pollutant loads at each station on the monthly flow and the corresponding monthly pollutant concentrations at the stations.

2.4. Correlation analysis among pollutant fluxes in the Yangtze River, socioeconomic and infrastructure factors, and wastewater discharge

A correlation matrix was established by calculating all possible pairwise Spearman rank correlations among socioeconomic factors including population, GDP, infrastructure investment of each city, infrastructure factors (i.e., density of drainage pipelines and number of WWTPs in each city), pollutant discharges from WWTPs (i.e., COD, TP, TN, and ammonia in each city), and pollutant fluxes in the Yangtze River (i.e., TP, ammonia, and permanganate index at the Cuntan, Yichang, Wuhan, Hukou, and Datong stations). The database period was from 2007 to 2017. Each two parameters was considered to be statistically correlative if the Spearman correlation coefficient was higher than 0.7 and the p value was lower than 0.01. A network diagram was produced based on the results derived from the Spearman rank-order correlation analysis and was prepared in Adobe Illustrator CS6. Furthermore, a redundancy analysis (RDA) was conducted in RStudio to determine whether the extent of the changes in the pollutant fluxes in the Yangtze River could be attributed to the considered variables.

2.5. Regime analysis

In order to evaluate the potential benefits of alternative improvements in wastewater services management, in terms of reductions in aquatic pollutants by 2035, we modeled several different regimes to analyze the financial balance and distribution throughout the implementation of wastewater management infrastructure in the YRB. Previous values derived from the official databases [3,10,14–30] were used to generate the related parameters under the 2007 and 2017 regimes. Furthermore, we assume that the coverage density of drainage pipelines would reach 30 km^{-2} in 2035 in order to project the quantity of wastewater phosphorus (P) collected for further handling under the remaining regimes (i.e., the back-to-2017 regime, back-to-2007 regime, zero-P regime, and P-recovery regime). More specifically, the back-to-2017 and back-to-2007 regimes assumed that further investment undertaken to achieve improved wastewater treatment and phosphorus discharge could reduce the phosphorus level to reach the 2017 level (7.5 Gg·a^{-1}) and the 2007 level (6.0 Gg·a^{-1}). The zero-P regime assumed, optimistically, that all wastewater-derived phosphorus could be treated appropriately with sophisticated wastewater treatment practices. Building on this, the phosphorus content in excess sludge was further assumed to be recycled in agricultural practices under the P-recovery regime. It should be further noted that the prediction of socioeconomic factors was conducted based on linear extrapolation, and the statistical uncertainties in the results were captured via Monte–Carlo analysis by random sampling (10 000 trials) from the underlying probability distributions obtained from the public databases and/or our previous work [31,32].

3. Results and discussion

3.1. Development trends in wastewater infrastructure and related indicators

In the last decade, the wastewater infrastructure—including the number of WWTPs and density of drainage pipelines in the YRB—has increased by 355% and 39% (Fig. 1(a)), respectively, with an accumulative investment growth of 158% (Fig. 1(b)). The 1752 WWTPs in the YRB in 2017 treated 1.97 $\times$ 10^{10} m^3 of wastewater (i.e., 38.07 m^3 per capita), which was threefold the volume treated in 2007 (Fig. S1 in Appendix A). This increase clearly reflects the effective implementation of the 11th (2006–2010), 12th (2011–2015), and 13th (2016–2020) Five-Year Plans for Urban Wastewater Treatment and Recycling Facilities Construction [33], which respectively specified that the municipal wastewater treatment rate should be increased to 70%, 85%, and 95%.

Before 2007, investment and improvement in wastewater infrastructure mainly concentrated on the coastal areas and the Yangtze River Delta (Fig. 1(b)), China's most important economic center. This resulted in the construction of more than 50% of the WWTPs in the downstream sub-basin, which occupies less than 10% of the YRB (Fig. S2 in Appendix A). This concentration may also be reflected in the spatiotemporal inequality in the sub-basin discharges, which is discussed in the subsequent section. After ten years of rapid development, the amount of wastewater treated per capita doubled in three sub-basins, but was still highest in the downstream (Fig. S1). This gap was attributed to larger wastewater emission factors (Table S1 in the Appendix A), as well as a higher wastewater collection rate and treatment capacity in the downstream sub-basin.

Compared with the rapid growth in the number of WWTPs, the density of drainage pipelines increased slowly from 9.2 km·km^{-2} in 2007 to 12.8 km·km^{-2} in 2017. This density level was only half of that in Japan (20–30 km·km^{-2}), suggesting that the construction of drainage works was not in accordance with the rapid urbanization occurring in the YRB [34]. Although the rate of wastewater treatment in the YRB increased from 54% in 2007 to 94% in 2017, the collection rate remained unclear, as about 30% of the drainage pipeline of China is combined sewer system [35]. The average load rate of WWTPs in the basin was 85% in 2017; therefore, further improvements in wastewater treatment capacity are more conditional on an increase in the density of drainage pipelines than on the number of WWTPs. This is particularly the case for the upstream and midstream sub-basins of the Yangtze River, as the density in 2017 was about 10 km·km^{-2}—half of that in the downstream sub-basin.

Since the beginning of the 10th Five-Year Plan (2001–2005), China has been investing heavily in protecting and restoring the quality of the environment. By 2017, the cumulative total investment in environmental pollution control was 953.9 billion CNY, of which 608.6 billion CNY was invested in the construction of urban environmental infrastructure [12]. The total investment in wastewater services infrastructure in the basin was 158.4 billion CNY (Fig. 1(b)), which accounted for 24.8% of national investment

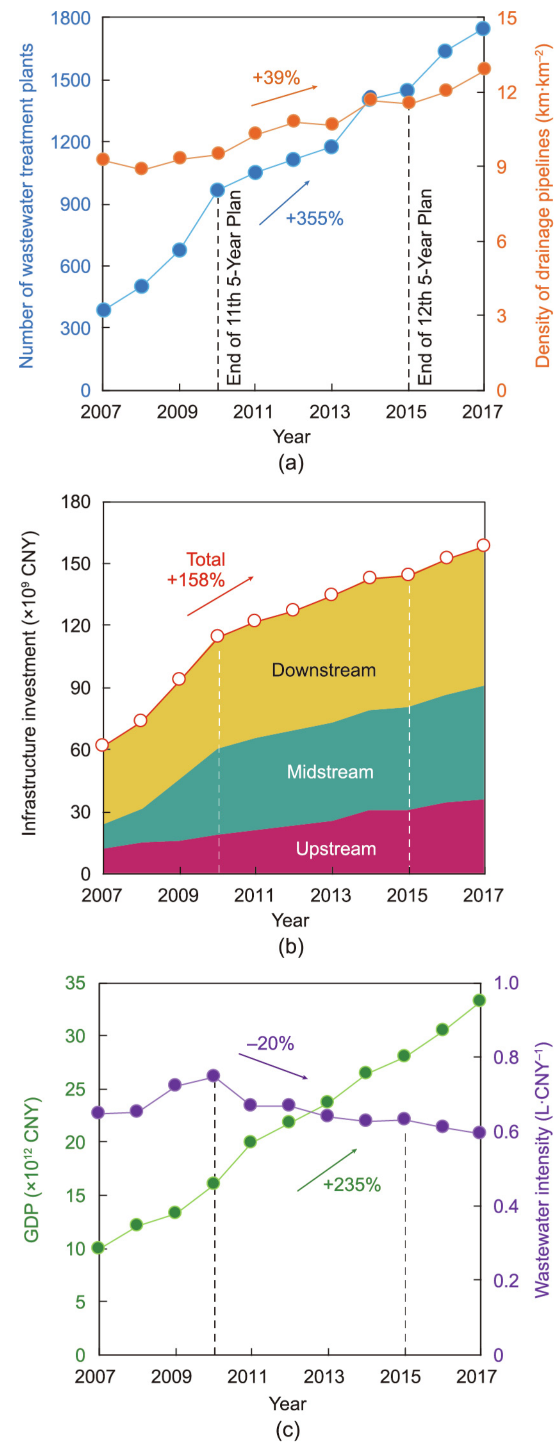

Fig. 1. Temporal change in wastewater infrastructure development and related indicators in the YRB from 2007 to 2017. (a) Number of WWTPs in operation and coverage density of drainage pipelines. (b) Total wastewater infrastructure investment, segmented by YRB regions. (c) GDP and wastewater production intensity.

and 0.48% of the GDP in the basin. This was higher than the ratio of GDP (0.2%) used in the whole country to address wastewater services infrastructure [3]. The wastewater treatment normalized by GDP increased during the 11th Five-Year Plan but has been on a downward trajectory since 2011 (Fig. 1(c)) due to a lower increase rate of wastewater infrastructure investment costs than that of GDP in the basin.

In 2007, the WWTPs in the basin removed 1584 Gg of COD, 53 Gg of TN, and 21 Gg of TP (Fig. S3 in Appendix A). The reductions in the amounts of TN and TP were 4% and 34% of the pollutant flux [26], respectively, from the Yangtze River into the sea. After 10 years, the reductions increased by 159% for COD, 620% for TN, and 170% for TP. The ratio of the reduction amount to the flux increased to 18% for TN and 50% for TP. These increases suggested a relatively more significant role for wastewater services infrastructure in phosphorus reduction than in nitrogen reduction, in view of the contribution ratio to the river.

3.2. Trajectory of the variation of concentrations of river pollutants

It has been reported that monthly and annual mean TP concentrations have declined significantly since 2006 in the Chaohu Lake, Poyang Lake, Dongting Lake, and Taihu Lake because of rapid improvements in sanitation [9]. We analyzed the concentration trajectory in 2003–2018 in the main stream of the Yangtze River (at the Cuntan, Yichang, Wuhan, Hukou, and Datong hydrological stations). The mean permanganate index (COD_{Mn}) concentrations in the river have declined slowly during this period (Fig. 2(a)): The mean COD_{Mn} concentrations decreased from 3.0 $mg{\cdot}L^{-1}$ in 2003 to 2.0 $mg{\cdot}L^{-1}$ in 2018. Since 2014, few monitoring sites have had COD concentrations higher than 6 $mg{\cdot}L^{-1}$ (the Grade III limit according to China's water quality standards). The mean concentrations of ammonium nitrogen and TP increased steadily before 2013 and then decreased (Figs. 2(b) and (c)). The peak mean ammonium nitrogen and TP concentrations occurred in 2013, at 0.30 and 0.15 $mg{\cdot}L^{-1}$, respectively. These then decreased by 57% and 33%, respectively, to 0.13 and 0.10 $mg{\cdot}L^{-1}$ by 2018. The reduction in these concentrations in the main stream probably reflects improvements in both the basin wastewater infrastructure and the nutrient removal efficiency (Figs. 1 and S1). A recent analysis also reported that China's inland surface water quality has been markedly improved or has been maintained at favorable levels across the country due to reduced discharges from the industrial, rural, and urban residential sectors [36]. However, there appears to have been a delay in the reduction of TP concentrations in the main stream compared with the lake, probably because of loading with "legacy" phosphorus [9,10,37].

3.3. Relationship among wastewater infrastructure development, socioeconomic factors, and pollutant flux in the Yangtze River

Improvements in surface water quality are conditional not only on a reduction in pollutant discharge from point and non-point sources but also on socioeconomic and infrastructure factors, and the latter are poorly understood. There have been different levels of growth in the population, GDP, infrastructure investment costs, number of WWTPs, density of drainage pipelines, and aquatic pollutants treated or discharged in the last decade. Variations in all these factors are reflected more or less in the presence of pollutants in the river. To isolate and illuminate the crucial drivers of water quality improvement, we conducted Spearman rank-order correlations among socioeconomic factors, infrastructure factors, wastewater collection and treatment factors in 117 YRB cities, and pollutant fluxes in the mainstream Yangtze River (Fig. 3). Furthermore, an RDA was conducted to determine the contribution of the considered drivers to the pollutant flux changes in the Yangtze River (Fig. S4 in Appendix A).

The results derived from Fig. 3 indicate that pollutant fluxes in the river are mainly related to wastewater infrastructure investment, GDP, the density of drainage pipelines, the number of WWTPs, and the pollutant discharge from WWTPs. In particular, the most significant apparent impact of these factors, other than on organic matter and ammonia, was on TP fluxes in the river. Population had a slight correlation with pollutant fluxes in the river. Moreover, the RDA results showed that drainage density, GDP per capita, and wastewater infrastructure investment contributed more to the pollutant flux changes in the Yangtze River than the number of WWTPs and the population did. These three driving factors explained approximately 17% of the pollutant flux changes in the river, with a greater degree of explanation in the midstream and downstream than in the upstream of the Yangtze river (Fig. S4). We then explored how these drivers contributed to pollutant fluxes in the river.

Coupling between the economy and environmental variables existed in China between 1978 and 2014, although the country's desire to achieve "ecological civilization" has resulted in a decoupling trend for major pollutants since 2015 [38]. The long period of coupling may explain the more significant correlation between pollutant fluxes and GDP and infrastructure investment, in comparison with that between pollutant fluxes and population (Fig. 3). The ammonia and phosphorus peaks (Fig. 2) mean that the concentrations in the Yangtze River around 2013 were

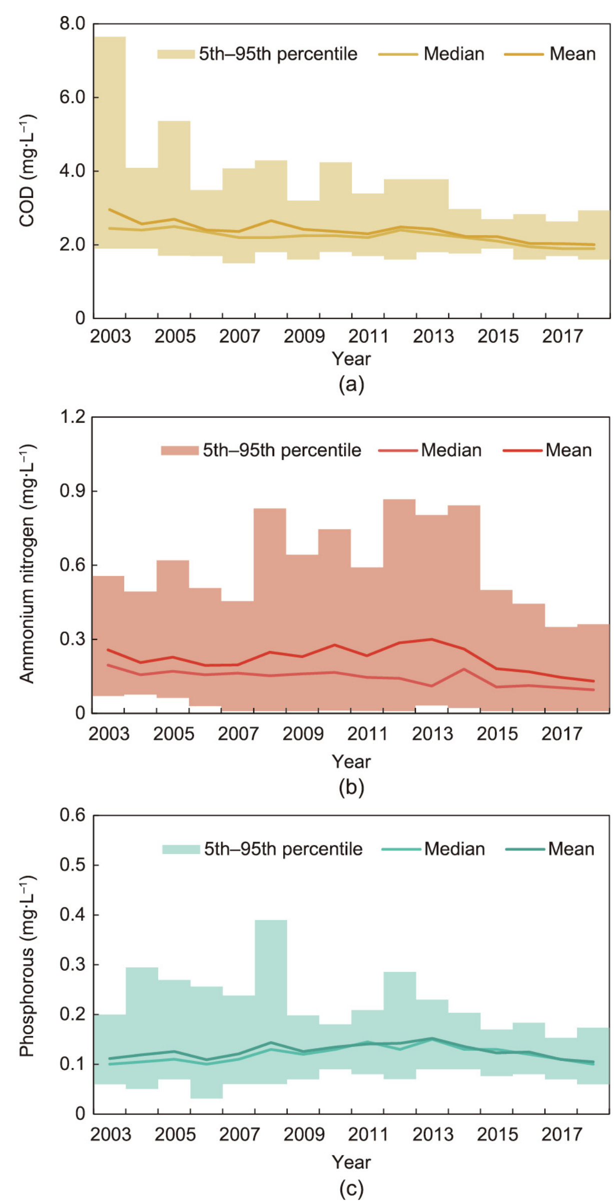

Fig. 2. Temporal changes in (a) COD, (b) ammonium nitrogen, and (c) TP concentrations in the Yangtze River.

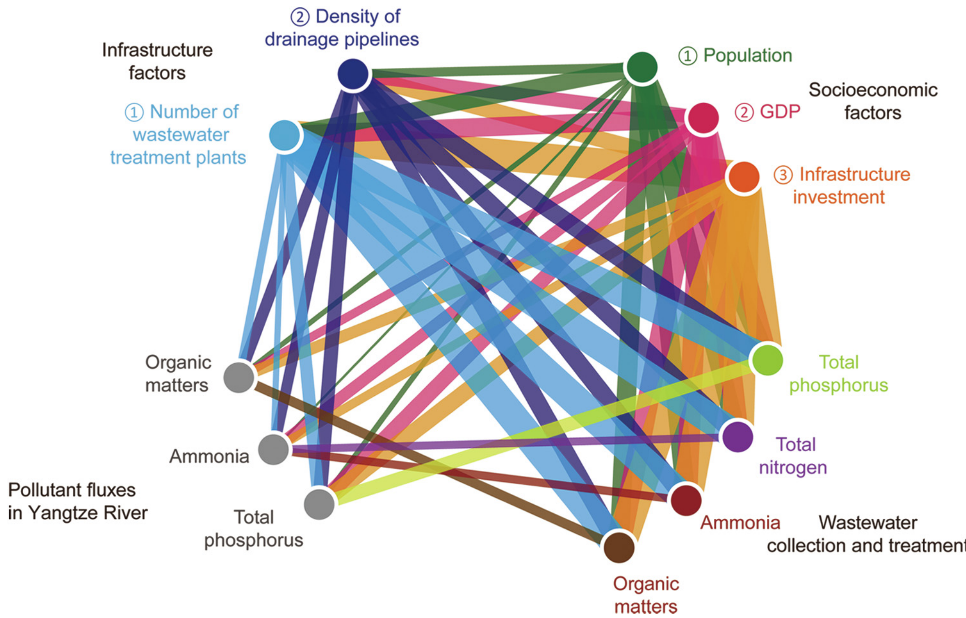

Fig. 3. Network diagram tracing the correlations among socioeconomic factors, infrastructure status indicators, wastewater collection and treatment efficiency, and pollutant fluxes in the Yangtze River. The line width is proportional to the correlation coefficient in terms of Spearman rank-order correlation analysis (p < 0.01). The larger the line width is, the higher the correlation is between the two factors.

probably the turning point for pollutant discharge from point sources such as WWTPs. It has also been reported that the increment in the Chinese GDP over the past decade was not achieved at the expense of a decline in the inland water ecosystems [39]. Along with the sustainable decoupling between GDP increase and environmental quality decline, a weaker correlation between GDP and pollutant fluxes in the river can be expected.

Moreover, the density of drainage pipelines had a stronger correlation with pollutant fluxes in the river than the number of WWTPs did (Fig. 3). This was probably because part of the combined sewerage system in the basin drained runoff into the basin and the river, as well as sewage [40]. Thus, the construction (or reconstruction) of drainage pipelines is crucial to further improvements in wastewater treatment.

In addition, the strongest correlation between phosphorus discharge loads from WWTPs and the TP flux among nutrients and organic matter in the YRB implied the significant contribution of wastewater phosphorus delivery to the basin. It has been reported that, since the mid-1990s, wastewater has been the second most dominant source of phosphorus in the upstream and midstream sub-basins, while agricultural phosphorus delivery is the dominant source [10]. In the downstream sub-basin, wastewater has been the dominant source of phosphorus since the 1980s [10]. The rapid improvement in wastewater infrastructure in the last decade may, therefore, have resulted in a gradual decline in TP concentrations in the river (Fig. 2). Similarly, the swift reduction in urban domestic phosphorus loadings accounted for about 40% of the variance in TP concentrations in the lakes [9]. In addition to the Five-Year Work Plans for Urban Wastewater Treatment and Recycling Facilities Construction, China has made considerable efforts to control point sources. In 2015, Action Plans for the Prevention and Control of Water were implemented [41]. These state that seven major basins in China, including the YRB, should have excellent water quality, with more than 70% and 75% of the watershed achieving Grade III or better (according to China's water quality standards) by 2020 and 2030, respectively. The first item of the 10 mitigation measures in the Action Plan is pollutant discharge control, which includes both domestic point source and diffuse sources from agriculture, livestock, and aquaculture. It may be imagined that diffuse sources will become increasingly important sources of nutrients, in addition to domestic nutrients [9].

The contribution of sewage TN delivery to the basin was not assessed in this study (TN is not included in China's water quality standard for river surface water, but is included in that for lake surface water), but agricultural nitrogen sources have been reported to be dominant in many studies (59%–83%) [3,15].

3.4. Variation in annual discharge of wastewater-derived phosphorus, 2007–2017

Regional inequality in pollutant discharge in the YRB exists, as does regional inequality in GDP growth [38,42]. An analysis of spatial and temporal discrepancies in the basin's phosphorus discharge (Fig. 4) examined wastewater infrastructure performance evolution in different sub-basins, differentiated according to economic activity; this is of paramount importance to future policymaking on phosphorus control.

The phosphorus load in the influent of all WWTPs in the basin increased more than twofold, from 26.7 to 63.4 Gg, in 2007–2017 as the annual amount of wastewater collected increased. However, the annual phosphorus discharge from WWTPs to the basin declined from 2012, after an earlier increase from 6.0 Gg in 2007 to a maximum of 9.1 Gg in 2011 (Fig. 4). The annual discharges decreased to 7.5 Gg in 2017. This decrease was consistent with the temporal variance in TP concentrations in the Yangtze River (Fig. 2(a)), confirming the contribution of wastewater discharge to TP loads in the Yangtze River and the positive effect of wastewater pollutant reduction on improvement in river water quality. The decline in phosphorus discharge also indicated that phosphorus removal in WWTPs was generally effective, especially after 2012. According to the statistics, anaerobic–anoxic–oxic (A^2/O), oxidation ditch, and sequencing batch reactor (SBR) accounted for about 80% of the quantity and treatment capacity in China [43]. These processes usually result in the efficient removal of phosphorus [44].

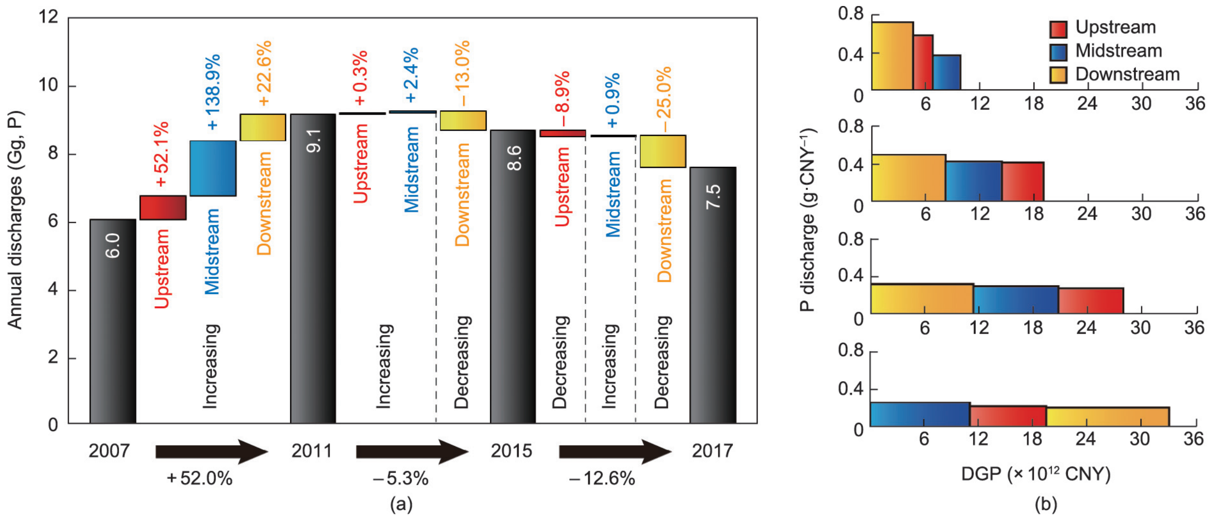

Fig. 4. Contribution of each YRB region to the change in annual discharge of wastewater-derived phosphorus in the periods 2007–2011, 2011–2015, and 2015–2017. (a) The length of each bar reflects the contribution of each region per year. (b) Column heights represent per CNY GDP phosphorus discharge, and column areas denote total phosphorus discharge from their respective regions.

In 2007, the 5.97 Gg of phosphorus discharge from WWTPs comprised 1.32 Gg from the sparsely populated upstream, 1.17 Gg from the midstream, and 3.48 Gg from the densely populated downstream. Downstream WWTPs contributed almost 60% of the phosphorus discharge to the entire basin. Even when phosphorus discharge was considered per unit of GDP, the downstream level remained the highest, at about 0.7 g·CNY^{-1}.

During 2007–2011, the annual TP discharge from WWTPs in the upstream, midstream, and downstream sub-basins increased by 52.1%, 138.9%, and 22.6%, respectively. Of the 3.1 Gg increase in phosphorus discharge in the entire basin between 2007 and 2011, more than 50% originated from the midstream sub-basin, due to the rapid construction of WWTPs in this area. The annual TP discharge from WWTPs in the basin decreased after 2011, especially in the downstream sub-basin, indicating an improvement in phosphorus removal. This improvement was probably due to the enactment of the Plan for Prevention and Control of Water Pollution in the Middle and Lower Reaches of the Yangtze River (2011–2015), which stressed nitrogen and phosphorus removal in WWTPs. In 2017, the phosphorus discharge from upstream, midstream, and downstream was 1.83, 2.89, and 2.78 Gg, respectively (Figs. 4 and S5 in Appendix A). The midstream TP discharge levels per unit GDP were the highest. However, all levels were less than 50% of those from 10 years before (Fig. 4(b)); the same was true for the phosphorous concentrations in the effluent from WWTPs (Fig. S6 in Appendix A). The main area of pollution discharge in relation to the tracking of wastewater infrastructure development and phosphorus discharge per unit GDP (Figs. 1(b), 4, and S1) has probably been shifting from downstream to the midstream sub-basin. Cities with more WWTPs or higher wastewater treatment capacity have been able to limit pollutant discharge further. However, these cities also discharge more effluents and, therefore, probably discharge more pollutants to the river through point sources (Figs. S3 and S5). Assuming that nearly 100% of sewage can be treated in all cities in the basin, the WWTPs in cities with a higher population density and GDP should engage in more sophisticated wastewater treatment processes, such as tertiary treatment or multi-stage treatment processes, to achieve lower pollutant discharge. More flexible regional water strategies are needed to cope with the different trends and sources of pollutant loadings to the upstream, midstream, and downstream sub-basins [9].

The Three Gorges Project and other dams upstream have led to a 91% decrease in the sediment load to the middle and lower Yangtze River [11]. Sediment sequestration by reservoirs upstream has resulted in clear streams in the midstream and downstream, and thus the buffering effect of sediment in regulating phosphorus concentration has been lost. Phosphorus from wastewater discharge (usually with > 50% P as a dissolved species [45]) probably remains, mainly in a dissolved phase, after entering the water body. This would have particularly occurred in the dry season, due to significant decreases in sediment. It has been estimated that the dissolved phosphorus export in the Yangtze River increased by a factor of 10 between 1970 and 2010 [7,37]. The effect of an increase of dissolved phosphorus in the river on primary aquatic productivity, as well as the potential increase in soluble reactive phosphate (SOP), merits systematic research.

3.5. Financial balance and distribution by 2035 under different regimes

To determine what would sustain or even accelerate the decline in pollutant concentrations in the basin, we conducted virtual regime analyses (Fig. 5). These analyses explored the alternative improvement potential for pollutant reduction in wastewater management and projected the investment space in future wastewater services infrastructure capable of achieving such improvement by 2035. Although only minor potential for further phosphorus reduction through end-of-pipe measures currently exists [9], there is a considerable amount of future potential in improved wastewater pipeline collection efficiency. The pipeline construction goal in the national 13th 5-Year-Plan will add 1.259×10^5 to 4.224×10^5 km in 2020—an increase of 42% compared with the 2015 figures [33]. Pipeline (re)construction is the limiting factor in further improvements in phosphorus reduction. Accordingly, we have evaluated the costs of different regimes to achieve different quantities of phosphorus reduction in 2035, assuming that the coverage density of drainage pipelines reaches 30 km·km^{-2} in the YRB.

The total accumulative investment in future wastewater services infrastructure is estimated to be (520.8 ± 136.1) billion CNY, including 214.4, 267.8, 13.8, and 24.8 billion CNY on pipeline construction, WWTP construction, energy consumption, and sludge disposal, respectively (Fig. 5). In this case, the phosphorus collected from WWTPs throughout the basin would increase to

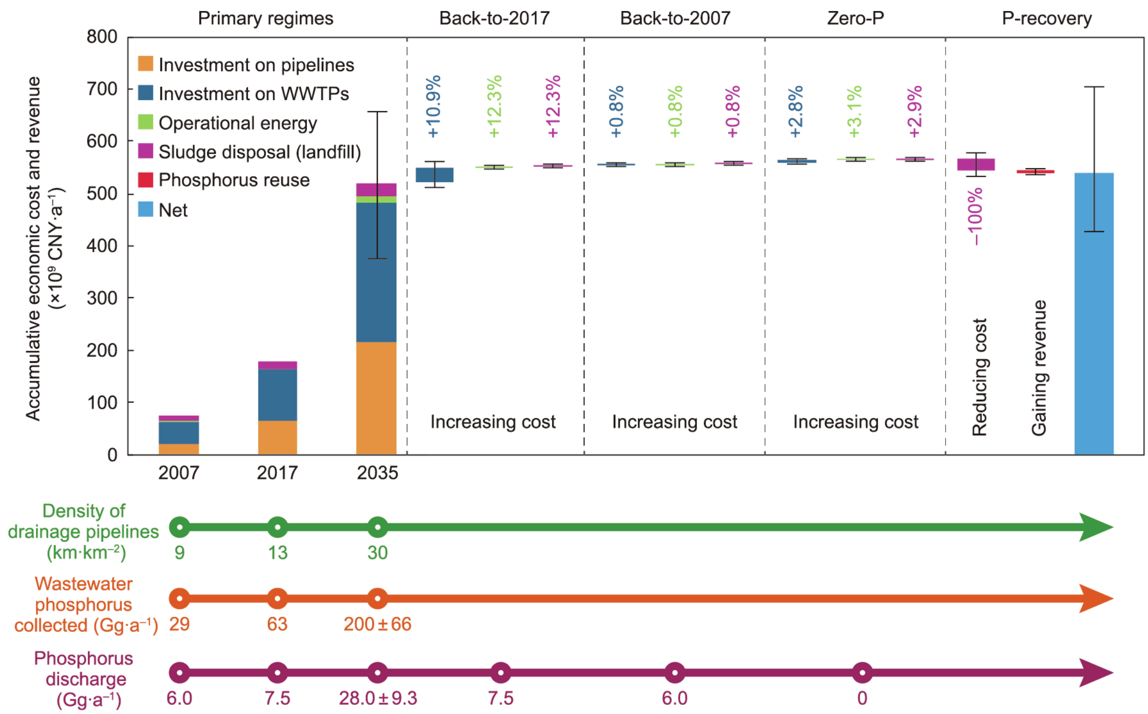

Fig. 5. Financial balance and distribution throughout the implementation of wastewater management infrastructure in the YRB under different regimes. Historical values were used to generate the related indicators under the 2007 and 2017 regimes. An estimate was made about the coverage density of drainage pipelines in 2035 (reaching 30 km^{-2}) and was used to project the quantity of wastewater phosphorus collected for further handling under the remaining regimes. The back-to-2017 and back-to-2007 regimes assumed that further investment to achieve improved wastewater treatment and phosphorus discharge could reduce the phosphorus to reach the 2017 level (7.5 Gg·a^{-1}) and the 2007 level (6.0 Gg·a^{-1}). The zero-P regime assumed, optimistically, that all wastewater-derived phosphorus could be treated appropriately with sophisticated wastewater treatment practices. Building on this, the phosphorus content in excess sludge was further assumed to be recycled in agricultural practices under the P-recovery regime. Error bars for each column, where available, are based on model results from 10 000 Monte–Carlo simulations.

(200 ± 66) Gg, and the amount discharged to the basin would be (28.0 ± 9.3) Gg—fourfold that in 2017. Simultaneously, the amounts of nitrogen collected and discharged were simulated to be (2077 ± 719) and (837 ± 289) Gg, respectively (Table S2 in Appendix A). If more phosphorus was to be collected to reduce the phosphorus discharge to the level in 2017 (7.5 Gg) or to the level in 2007 (6.0 Gg), a further investment of 33.9 billion or 36.7 billion CNY would be needed, respectively. This would mainly involve investment in the upgrading of WWTP treatment processes. In the most optimistic case of zero-P discharge and recycling in agricultural practices—which would require sophisticated wastewater treatment processes, such as tertiary or multi-stage treatment configurations—the cost would be 537.7 billion CNY, while estimations of the annual revenue from phosphorus recycling suggest a figure of (0.6 ± 0.2) billion CNY.

4. Implications and conclusions

Promoting the prosperity of human society and restoring and maintaining the health of aquatic ecosystems are both among the United Nations' Millennium Development Goals and Sustainable Development Goals; thus, many countries and regions are devoting great efforts to improving their existing wastewater services infrastructure and enabling the end-use of recoverable products from wastewater [2]. China has achieved this commitment through substantial investments in wastewater services facilities and by restricting the discharge of waterborne contaminants in the Yangtze River Economic Zone over the past two decades. Nonetheless, factors that may play key roles in driving variations in pollutant fluxes in the Yangtze River and the extent to which improvements can be achieved have not yet been unraveled.

In the present work, wastewater management improvement was assessed, with its impact on pollutant footprints during the period 2007–2017 in the Yangtze River. The main forces that may drive changes in pollutant fluxes in the Yangtze River were identified and visualized. Regime analyses were also conducted to explore the potential of alternative improvements in wastewater service management on reductions in wastewater-derived pollutants. We found that the Yangtze River's water quality has been improving since 2013, which is supported by the observation that pollutant concentrations in the Yangtze River have fallen as a result of improved wastewater service practices. Furthermore, the long period of coupling that occurred between the economy and environmental variables may explain the more significant correlation that was found between pollutant fluxes—particularly TP fluxes—and GDP and infrastructure investment, in comparison with the correlation between pollutant fluxes and population. The substantial implementation of wastewater services facilities promoted the decoupling of economic and environmental variables that occurred after 2013. During 2007–2017, the area in which most TP discharge collects has probably been shifting from downstream to the midstream sub-basin due to regional development inequality. While not explicitly investigated in the present study, the results from the regime analyses suggested that an accumulative investment of (520.8 ± 136.1) billion CNY would be needed, assuming that the coverage density of drainage pipelines reaches 30 km·km^{-2} in the YRB in 2035. Moreover, another investment of 33.9 or 36.7 billion CNY, respectively, would be needed in order to maintain a phosphorus discharge amount equivalent to that in 2017 or in 2007. In addition, since the inflation rate and other actual economic conditions were not considered in the projection of the investment space in future wastewater services infrastructure, it was not surprising that the comparison of the marginal cost of different wastewater management regimes would be meaningless. Therefore, further research efforts should be devoted to more holistic analyses of the broad effects associated with the transformation of wastewater management services, while taking into account the temporal and spatial variations in real contexts.

Overall, this study advances the current understanding of the impact of wastewater services facilities on achieving a balance between economic development and environmental protection.

Acknowledgments

We acknowledge support from the Consulting Research Project of the Chinese Academy of Engineering (2019-ZD-33), the National Natural Science Foundation of China (51922013 and 51838013), and the Shenzhen Science and Technology Program (KQTD20190929172630447).

Compliance with ethics guidelines

Weixiao Qi, Xu Wang, Jin Kang, Yaohui Bai, Rui Bian, Hongtao Xue, Li Chen, Aomei Guan, Yi-Rong Pan, Huijuan Liu, and Jiuhui Qu declare that they have no conflict of interest or financial conflicts to disclose.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2022.03.014.

References

[1] Ouyang Z, Zheng H, Xiao Yi, Polasky S, Liu J, Xu W, et al. Improvements in ecosystem services from investments in natural capital. Science 2016;352(6292):1455–9.
[2] Wang X, Daigger G, Lee DJ, Liu J, Ren NQ, Qu J, et al. Evolving wastewater infrastructure paradigm to enhance harmony with nature. Sci Adv 2018;4(8):aaq0210.
[3] Yu C, Huang X, Chen H, Godfray HCJ, Wright JS, Hall JW, et al. Managing nitrogen to restore water quality in China. Nature 2019;567(7749):516–20.
[4] Changjiang Water Resources Commission of the Ministry of Water Resources. Yangtze River yearbook. Report. Wuhan: Changjiang Water Resources Commission of the Ministry of Water Resources; 2007–2017. Chinese.
[5] Yang H, Xie P, Ni L, Flower RJ. Pollution in the Yangtze. Science 2012;337(6093):410–1.
[6] Wang B. Cultural eutrophication in the Changjiang (Yangtze River) plume: history and perspective. Estuar Coast Shelf Sci 2006;69(3–4):471–7.
[7] Dai Z, Du J, Zhang X, Su N, Li J. Variation of riverine material loads and environmental consequences on the Changjiang (Yangtze) estuary in recent decades (1955–2008). Environ Sci Technol 2011;45(1):223–7.
[8] State Council of the People's Republic of China. Outline of the Tenth Five-Year Plan for national economic and social development of the people's republic of China. Report. Beijing: State Council of the People's Republic of China; 2001 March. Chinese.
[9] Tong Y, Zhang W, Wang X, Couture RM, Larssen T, Zhao Y, et al. Decline in Chinese lake phosphorus concentration accompanied by shift in sources since 2006. Nat Geosci 2017;10(7):507–11.
[10] Liu X, Beusen AHW, Van Beek LPH, Mogollón JM, Ran X, Bouwman AF. Exploring spatiotemporal changes of the Yangtze River (Changjiang) nitrogen and phosphorus sources, retention and export to the East China Sea and Yellow Sea. Water Res 2018;142:246–55.
[11] Zhou J, Zhang M, Lu P. The effect of dams on phosphorus in the middle and lower Yangtze River. Water Resour Res 2013;49(6):3659–69.
[12] National Bureau of Statistics of China. China statistical yearbook. Report. Beijing: National Bureau of Statistics of China; 2007–2017. Chinese.
[13] Ministry of Housing and Urban-Rural Development of China. Statistical yearbook of urban and rural construction. Report. Beijing: Ministry of Housing and Urban-Rural Development of China; 2007–2017. Chinese.
[14] Yang P, Lu L, Xiang C, Wang J, Chen H. Analysis of variation trend of nitrogen and phosphorus concentrations in the main stream of the Yangtze River. Environ Eng 2019;37(2):175.
[15] Tong Y, Bu X, Chen J, Zhou F, Chen L, Liu M, et al. Estimation of nutrient discharge from the Yangtze River to the East China Sea and the identification of nutrient sources. J Hazard Mater 2017;321:728–36.
[16] Dong L, Lin L, Zhao L, Liu M. Features of phosphorus distribution along middle and lower reaches of mainstream Yangtze River. J Yangtze River Sci Res Inst 2015;32(6):70–5. Chinese.
[17] Sun C, Shen Z, Liu R, Xiong M, Ma F, Zhang O, et al. Historical trend of nitrogen and phosphorus loads from the upper Yangtze River basin and their responses to the Three Gorges Dam. Environ Sci Pollut Res Int 2013;20(12):8871–80.
[18] Müller B, Berg M, Pernet-Coudrier B, Qi W, Liu H. The geochemistry of the Yangtze River: seasonality of concentrations and temporal trends of chemical loads. Global Biogeochem Cycles 2012;26(2):1–14.
[19] Gao L, Li D, Zhang Y. Nutrients and particulate organic matter discharged by the Changjiang (Yangtze River): seasonal variations and temporal trends. J Geophys Res Biogeosci 2012;117(G4):1–16.
[20] Yao Q, Yu Z, Chen H, Liu P, Mi T. Phosphorus transport and speciation in the Changjiang (Yangtze River) system. Appl Geochem 2009;24(11):2186–94.
[21] Müller B, Berg M, Yao ZP, Zhang XF, Wang D, Pfluger A. How polluted is the Yangtze River? Water quality downstream from the Three Gorges Dam. Sci Total Environ 2008;402(2–3):232–47.
[22] Duan S, Liang T, Zhang S, Wang L, Zhang X, Chen X. Seasonal changes in nitrogen and phosphorus transport in the lower Changjiang River before the construction of the Three Gorges Dam. Estuar Coast Shelf Sci 2008;79(2):239–50.
[23] Wang F, Wang Y, Zhang J. A decade of variation of cod in the Changjiang River (Yangtze River) and its variation trend analysis. Chin J Geochem 2007;26(4):366–73.
[24] Li M, Xu K, Watanabe M, Chen Z. Long-term variations in dissolved silicate, nitrogen, and phosphorus flux from the Yangtze River into the East China Sea and impacts on estuarine ecosystem. Estuar Coast Shelf Sci 2007;71(1–2):3–12.
[25] Qin Y, Ma Y, Wang L, Zheng B, Ren C, Tong H, et al. Pollution of the total phosphorus in the Yangtze River basin: distribution characteristics, source and control strategy. Res Environ Sci 2018;31(1):9–14. Chinese.
[26] Cheng X, Xu X, Yin H. Analysis of water quality change and the pollutant fluxes into the sea at Xuliujing section in recent years. J Changjiang Inst Technol 2018;35(4):5–15. Chinese.
[27] Guo F, Li Z, Shi J, Qin Y. Mutative trend of water quality at Xuliujing monitoring intersect on Yangtze River and the pollutants flux flowing into the sea during 2005–2012. Resources Environ Yangtze Basin 2015;24(2):227–32. Chinese.
[28] Hu G, Bian J. Analysis of water quality change in Hankou station before and after Three Gorges Reservoir impoundment. Yangtze River 2013;44:89–91. Chinese.
[29] Qiao F, Meng W, Zhang B, Lei K, Zhang H. Pollution load accounting and source analysis at Cuntan section in main stream of Yangtze River. Res Environ Sci 2010;23(8):979–86. Chinese.
[30] Wang J, Bian J, Chen X. Analysis of water quality change trend of the Yangtze River since 2000. Hubei Water Power 2009;2(2):1–3. Chinese.
[31] Wang X, Daigger G, de Vries W, Kroeze C, Yang M, Ren NQ, et al. Impact hotspots of reduced nutrient discharge shift across the globe with population and dietary changes. Nat Commun 2019;10(1):2627.
[32] Pan YR, Wang X, Ren ZJ, Hu C, Liu J, Butler D. Characterization of implementation limits and identification of optimization strategies for sustainable water resource recovery through life cycle impact analysis. Environ Int 2019;133(Pt B):105266.
[33] National Development and Reform Commission, Ministry of Housing and Urban-Rural Development. Thirteenth Five-Year Plan for urban wastewater treatment and recycling facilities construction. Report. Beijing: National Development and Reform Commission, Ministry of Housing and Urban-Rural Development; 2017. Chinese.
[34] Ning Y, Dong W, Lin L, Zhang Q. Analyzing the causes of urban waterlogging and sponge city technology in China. IOP Conf Ser Earth Environ Sci 2017;59:012047.
[35] Chen W, Cheng C, Xu H, Gao W, Zhao Y. Analysis on the effect of combined sewer system on the treatment efficiency of municipal sewage treatment plants. Water Wastewater Eng 2017;43(10):36–40. Chinese.
[36] Ma T, Zhao N, Ni Y, Yi J, Wilson JP, He L, et al. China's improving inland surface water quality since 2003. Sci Adv 2020;6(1):eaau3798.
[37] Powers SM, Bruulsema TW, Burt TP, Chan NI, Elser JJ, Haygarth PM, et al. Long-term accumulation and transport of anthropogenic phosphorus in Three River basins. Nat Geosci 2016;9(5):353–6.
[38] Lu Y, Zhang Y, Cao X, Wang C, Wang Y, Zhang M, et al. Forty years of reform and opening up: China's progress toward a sustainable path. Sci Adv 2019;5(8):aau9413.
[39] Zhou Y, Ma J, Zhang Y, Qin B, Jeppesen E, Shi K, et al. Improving water quality in China: environmental investment pays dividends. Water Res 2017;118:152–9.
[40] Li LQ, Yin CQ. Transport and sources of runoff pollution from urban area with combined sewer system. Environ Sci 2009;30(2):368–75. Chinese.
[41] Zhang B. Five-Year Plan: supervise Chinese environment policy. Nature 2016;534(7606):179.
[42] Zhao H, Jiang X. Evolution of economic and industrial pollution gravity centers and the decoupling mechanism in Yangtze River. China Environ Sci 2013;33(10):1911–9. Chinese.
[43] Jin L, Zhang G, Tian H. Current state of sewage treatment in China. Water Res 2014;66:85–98.
[44] Wu Y, Wang H, Sun J, Zhang W. Analysis of nitrogen and phosphorus removal capacity of municipal sewage treatment facilities in China and countermeasures. Water Wastewater Eng 2014;40:118–22. Chinese.