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RESEARCH ARTICLE

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Impacts of water conservation, wastewater treatment, and reuse on water quantity and quality stress mitigation in China

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Abstract

Wastewater treatment plays a crucial role in removing pollutants. Water conservation and reuse of wastewater help to reduce freshwater use and to alleviate water stress. However, the extent to which water conservation, wastewater treatment, and reuse can contribute to water stress mitigation is not clear. This study aims to investigate the impact of water conservation, wastewater treatment, and reuse on both water quantity and quality stress mitigation in China. The investigation is based on a dataset mapping water quantity and pollutant flows across 32 sectors in 31 provinces in 2017 and a dataset of 7411 wastewater treatment plants containing information on wastewater quantity and quality. The findings show that wastewater reuse can reduce provincial water quantity stress by less than 10% and alleviate water stress in 4 out of 25 water-stressed provinces. In contrast, water conservation can contribute to water quantity stress reduction by 31% on average. When water conservation measures and reuse are jointly implemented, quantity stress levels can significantly be alleviated in 19 out of 25 water-stressed provinces, with quantity stress reductions ranging from 25% to 74%. The contribution of wastewater treatment to water quality stress

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mitigation varies between 6% and 86%, with an average of 29%. Nevertheless, wastewater treatment cannot sufficiently safeguard most regions against water quality stress. This is evident as 25 out of 29 water quality-stressed provinces continue to suffer from quality stress despite implementing wastewater treatment and water conservation practices. Additional measures such as non-point-source pollution control should be implemented alongside wastewater treatment to eliminate provincial quality stress.

KEYWORDS
societal water cycle, wastewater reuse, wastewater treatment, water conservation, water quantity and quality stress, water stress mitigation

1 | INTRODUCTION

Water stress due to insufficient water availability (water quantity stress) and water contamination (water quality stress) due to stressors such as population growth, urbanization, economic growth, and climate change have been receiving increasing attention globally (Kummu et al., 2016; Liu et al., 2017; Vanham et al., 2018; Wang et al., 2021). To address this issue, water conservation, wastewater treatment, and reuse could play a vital role in mitigating regional water pollution, addressing water shortages, and improving reliability of water supply and enhancing the overall quality of the aquatic environment and ecosystems (Chen et al., 2022; Fatta-Kassinos et al., 2016; Kesari et al., 2021; Lyu et al., 2016).

The primary objective of wastewater treatment is to remove pollutants, and efforts have been committed to improve the efficiency of pollutant removal through developing advanced technologies (Obotey Ezugbe & Rathilal, 2020; Qu et al., 2019; Rout et al., 2021; Wu et al., 2020). In addition, the reuse of treated wastewater has emerged as a strategic approach to combat water shortage in regions that face water stress, leading to an increasing focus on a safe and sustainable supply from reclaimed water (Almuktar et al. 2018; Fernandes & Cunha Marques, 2023; Nan et al., 2020; Shingare et al., 2019). Wastewater treatment and reuse are intuitively acknowledged as effective ways to remove pollutants and reduce freshwater use (Tortajada, 2020; Tzanakakis et al., 2020). Recognized as a component of the circular economy, wastewater reuse enhances resource efficiency and sustainability. For instance, Kenway et al. provided an urban metabolism framework to quantify all anthropogenic and natural flows in four Australian cities, revealing a variability in wastewater reuse potential ranging from 26% to 86% (Kenway et al., 2011). Similarly, Hong and Park (2023) applied this framework to assess circular water options in Paju City, South Korea, and suggested that wastewater recycling together with other water resource management such as rainwater harvesting and water loss reduction could meet projected water supply increases by 2040. Arora et al. (2022) assessed water circularity in Singapore based on the framework of the anthropogenic water cycle and concluded that recycled wastewater could fulfill 24.9% of gross water use. Despite these insights, the impact of wastewater treatment and reuse on mitigating water stress remains uncertain.

Although systematic frameworks like the urban metabolism framework (Kenway et al., 2011; Renouf et al., 2018) and the anthropogenic water cycle (Arora et al., 2022) have been proposed to analyze the water mass balance and trace water flows within anthropogenic and natural systems, three crucial aspects require further attention: (1) Water consumption induced by economic sectors, though vital for the water mass balance, has not been clearly defined and quantified in previous studies. The term “water consumption” is often used interchangeably with “water withdrawal” or “water use,” but it specifically refers to water that is (temporarily) lost from local hydrological systems due to evaporation or being incorporated into a product (CEO Water Mandate, 2014; Wang et al., 2021). (2) Dynamic changes and interactions between different water flows are important but are often ignored. For instance, wastewater generation, including agricultural return flow, wastewater collected by wastewater treatment facilities, and wastewater directly discharged to the environment, is usually considered separately and neglects the influence of other water cycle processes. Wastewater generation is influenced by water withdrawal, conveyance loss, and consumption. Water conservation efforts that reduce water withdrawal and losses may lower wastewater generation. Therefore, it is essential to consider these connections within the broader water cycle. (3) Previous water cycle research has focused only on water quantity mass flows, neglecting water pollutants. To fill the gaps in the applied water flow framework in previous research, we utilize the societal water cycle framework to map physical water and pollutant flows across economic sectors, which includes processes of sectoral water withdrawal, conveyance loss, consumption, wastewater generation, pollution, wastewater treatment, wastewater use, and return flow (Wang, 2022) (return flow refers to flows from the technosphere directly to the ecosphere, including sectoral wastewater direct discharging to the environment and treated wastewater discharged from wastewater treatment sectors to the environment). Any change in a single flow within the societal water cycle framework can influence other water flows, subsequently impacting overall water use, water pollution levels, and ultimately, water stress mitigation. Water conservation efforts that focus on reducing conveyance losses and minimizing wastewater generation are considered effective strategies for alleviating water stress. These water-saving measures influence the entire societal water cycle and affect wastewater treatment and reuse. Consequently, it is essential to consider the broader impacts of water conservation on the societal water cycle and its role in mitigating water stress.

The quality of treated wastewater is a critical factor for reclaimed water, as it must meet specific requirements for its intended reuse (Administration of Quality Supervision, Inspection and Quarantine (AQSIQ), 2005a, 2005b, 2020, 2019; ISO 20761, 2018). To fully explore the impact of wastewater treatment and reuse on water stress, a comprehensive dataset on wastewater treatment and reuse is necessary, including information on quantity, quality, and intended reuse applications of treated wastewater. However, due to the lack of available data on water quality of reclaimed water, recent research on the impact of wastewater reuse on quantity stress reduction only considers the quantity aspect of reused wastewater (Herrera-León et al., 2022). Thus, consideration of the supply–demand balance for different economic sectors together with sectoral quality requirements is necessary for optimal allocation of reused wastewater.

In this study, we aim to examine the impact of water conservation, wastewater treatment, and reuse on water quantity and quality stress mitigation in China. This study is conducted under the framework of the societal water cycle, which considers processes of water withdrawal, conveyance loss, consumption, wastewater generation, pollution, wastewater treatment, wastewater use, and return flow. We trace water flows based on water mass balance analysis and develop a dataset mapping physical water quantity and pollutant flows within the societal water cycle in 2017 in China. We further apply scenario analysis and water stress assessment based on the developed water quantity and pollutant flow dataset and an extensive firm level dataset of 7411 wastewater treatment plants (WWTPs). We address the following four research questions: (1) What is the maximum potential for wastewater reclamation in different provinces of China? (2) What are the impacts of water conservation and wastewater reuse on mitigating water quantity stress? (3) What are the impacts of wastewater treatment and water conservation on mitigating water quality stress? and (4) What policy interventions can mitigate water stress through water conservation, wastewater treatment, and reuse?

2 | METHODS AND DATA

Water within the economic system undergoes a series of interconnected processes, including withdrawal, loss, consumption, wastewater generation, wastewater treatment, reuse, and return flow, forming the societal water cycle. Based on the system analysis of the societal water cycle, we propose a framework in Figure 1 to study the impact of water conservation, wastewater treatment, and reuse on water stress mitigation. We first quantify the physical water quantity and pollutant flows in 2017, mapping water withdrawal, water conveyance loss, water consumption, wastewater generation, collected wastewater to wastewater treatment facilities, and wastewater directly discharged to the environment containing chemical oxygen demand (COD), ammonia nitrogen (NH_4^+-N), total nitrogen (TN), total phosphorus (TP), and wastewater reuse for 32 sectors (Table A.1) and 31 provinces of China (Table A.2). The detailed description of the method for quantifying physical water quantity and water pollutant flows within the societal water cycle is derived from Wang (2022) and is summarized in “Methods for physical water quantity and pollutants flows analysis” of Supporting information S1. Subsequently, based on the societal water cycle in 2017, we stimulate 80 scenarios ($4 \times 4 \times 5 = 80$) comprising 4 scenarios of wastewater generation from each sector, 4 scenarios of reuse rates, and 5 scenarios of reuse applications for each WWTP. Based on the scenario analysis, we evaluate the impact of water conservation, wastewater reuse, and treatment on quantity and quality stress mitigation.

2.1 | Scenario analysis

2.1.1 | Scenario setting

We set a baseline scenario, which assumes a condition that there is no water conservation, wastewater treatment, or reuse across regions in China. Then, based on the societal water cycle of 2017, we design scenarios to explore the impact of water conservation, wastewater treatment, and reuse on water stress mitigation. We set scenarios by considering three factors, which are (1) water conservation reduces wastewater generation, treated wastewater, and discharged pollutant loads (assuming that discharged concentration is the same); (2) reused wastewater differs under different reuse rates; (3) water quantity stress mitigation can be affected under different reuse applications. The detailed scenario setting is shown in Table 1. There are two types of water conservation in this study: reduction of water conveyance loss and reduction of wastewater generation. For all scenarios, we adopted a stringent water loss rate of 8% for point-source sectors to reduce conveyance loss, which includes industry, services, and households. This approach is in response to the Chinese government’s initiative to decrease the national water loss rate to below 9% by the year 2025 (National Development and Reform Commission (NDRC) et al. 2021). Regarding the three steps of scenarios analysis shown in Table 1, the first step for each scenario is to determine sectoral wastewater generation through adopting strict sectoral water consumption rates in Table A.3 to minimize sectoral wastewater generation (water consumption rate is the ratio of water consumption to the sum of water consumption and wastewater generation). We assume that sectoral water consumption remains constant across scenarios, as it represents the specific amount of water required for production or consumption, whether it evaporates or is integrated into a product. Then, a higher or stricter water consumption rate corresponds to lower wastewater generation. We set four scenarios of sectoral wastewater generation according to water savings of different

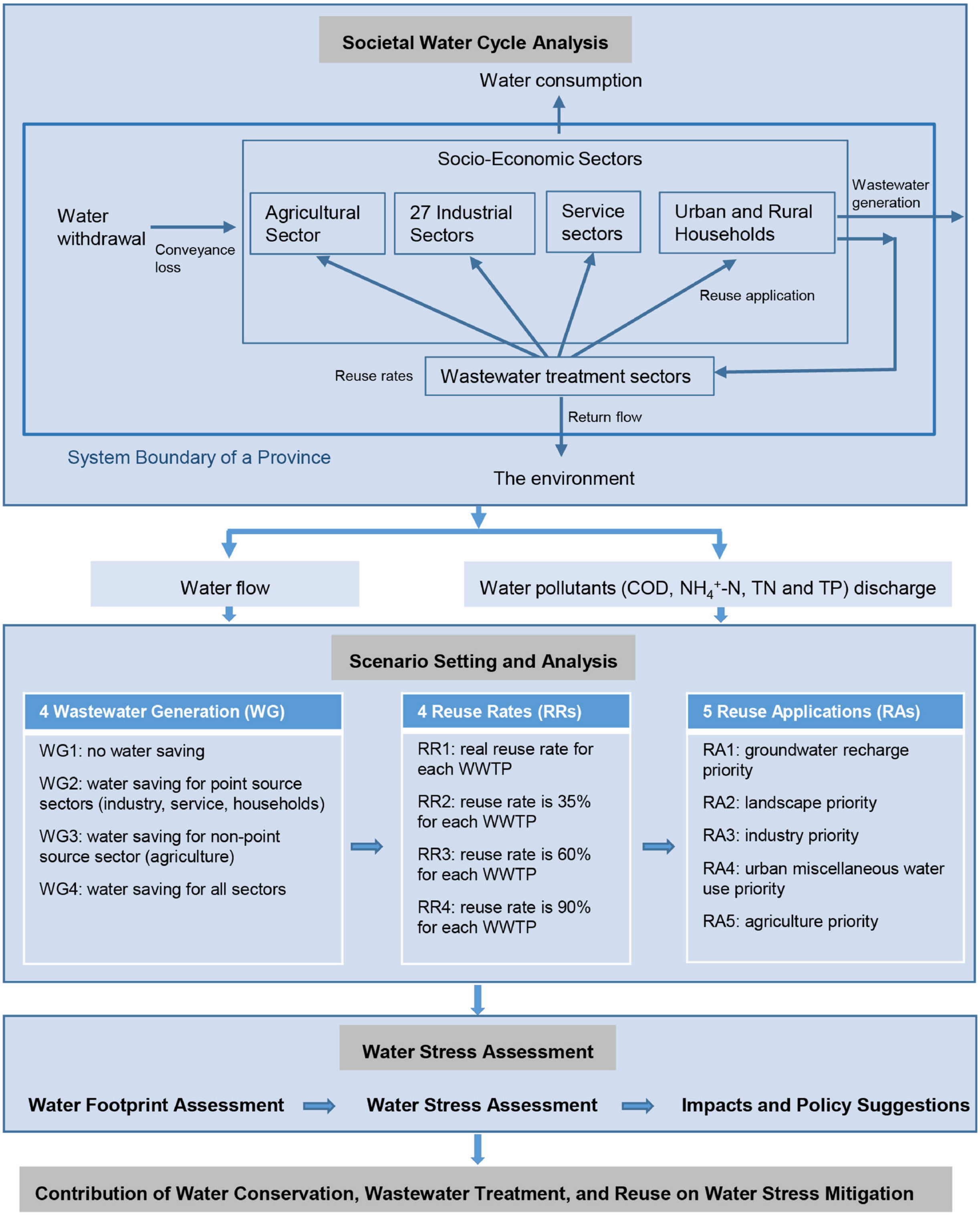

FIGURE 1 ReFramework of this study.

sectors: real wastewater generation, wastewater generation after consideration of water savings for point-source sectors only, non-point-source sector only, and all sectors. The second step is to consider four scenarios of reuse rates. We assume that sectoral wastewater treatment rate is constant, which is defined as the ratio of wastewater treated by wastewater treatment sectors to wastewater generation. Then, we simulate four different reuse rates for each WWTP based on firm level real reuse rates, as well as reuse rates of 35%, 60%, and 90% for all WWTPs. Thirty-five percent is the reuse rate target for the Beijing–Tianjin–Hebei region in 2025 (National Development and Reform Commission (NDRC) and Ministry

TABLE 1 Scenario setting for studying impacts of water conservation, wastewater treatment, and reuse on water stress reduction.

Baseline scenario	Current situation	Different scenarios on water conservation, wastewater generation, reuse rates, and reuse applications		
		The first step: Determine water conservation and wastewater generation (WGs)	**The second step: Determine reuse rate (RR)**	**The third step: Determine reuse application (RA)**
• A scenario with no water conservation, wastewater treatment, or reuse	• The real wastewater treatment and reuse situation in 2017	1. WG 1: Real wastewater generation 2. WG 2: Wastewater generation after consideration of water saving for **point-source** sectors (industry, services, and households) 3. WG 3: Wastewater generation after consideration of water saving for **non-point-source** sector (agriculture) 4. WG 4: Wastewater generation after consideration of water saving for **all** sectors	1. RR 1: **Real reuse rate** for each WWTP 2. RR 2: Reuse rate is **35%** for each WWTP 3. RR 3: Reuse rate is **60%** for each WWTP 4. RR 4: Reuse rate is **90%** for each WWTP	1. RA 1: **Groundwater recharge priority** 2. RA 2: **Scenic environment priority** 3. RA 3: **Industry priority** 4. RA 4: **Urban miscellaneous water use priority** 5. RA 5: **Agriculture priority**

TABLE 2 Water quality standard for different water reuse applications in this study.

	Wastewater reuse applications	COD (mg/L)	NH_4^+-N (mg/L)	TP (mg/L)	TN (mg/L)
1	Groundwater recharge	<40	<1	<1	<15
2	Scenic environment	<40	<5	<1	<15
3	Industry	<60	<10	<1	–
4	Urban miscellaneous water use	<80	<20	–	–
5	Agricultural irrigation	<200	–	–	–

Note: Water quality standards for different wastewater reuse applications in this study are derived from a series of Chinese water quality standards of wastewater reuse for urban miscellaneous water use (Table A.4), scenic environment use (Table A.5), industrial water use (Table A.6), groundwater recharge (Table A.7), and farmland irrigation (Table A.8). Table 2 is based on the principle that the concentration of COD, NH_4^+-N, TN, and TP are the highest in Tables A.4–A.8 for a specific reuse application, as it would be easy to meet the requirement of reuse applications.

of Housing and Urban-Rural Development (MHURD) 2021), but in the scenarios, we apply it to each WWTP in China. Additionally, we consider the reuse rates of 60% in Europe and 90% in Israel as comparison (Hydrotech, 2021). Finally, as the quality of treated wastewater may impact its potential applications, we design five reuse application scenarios, namely priority reuse for groundwater recharge, scenic environment, industry, urban miscellaneous water use, and agriculture. Water quality standard for different water reuse applications in this study is shown in Table 2. In total, we simulated 80 scenarios including 4 scenarios of wastewater generation, 4 scenarios of reuse rates, and 5 scenarios of reuse applications ($4 \times 4 \times 5 = 80$).

2.1.2 | Maximum potential for wastewater reuse under different water conservation scenarios

Measuring the maximum potential for wastewater reuse helps to understand to what extent wastewater reuse can alleviate water quantity stress. In this study, we use the relative value of point-source wastewater generation to gross water use (the sum of water loss, consumption, and wastewater generation) to define the maximum potential for wastewater reuse. The maximum potential assumes that all point-source wastewater generation can be channeled to WWTPs and can used reused, even though in 2017, up to 63% of industrial wastewater generation goes to WWTPs (Table B.1) (industrial wastewater are usually pre-treated by internal treatment facilities first before being discharged to the environment or WWTPs), and between 61 and 97% of household wastewater go to WWTPs (Table B.2). However, point-source wastewater generation is influenced by sectoral water withdrawal, loss, and consumption within the societal water cycle. Under various water conservation scenarios, particularly those involving reductions in sectoral water conveyance loss and wastewater generation while maintaining consistent water consumption, both water withdrawal and gross water use are expected to decrease. This study examines four scenarios for wastewater generation (see Table 1), with the maximum potential for wastewater reclamation assessed for each water conservation scenario as follows:

$$\text{Potential reuse}_{i,j} = \frac{\sum_{k \neq agr} \text{WGtoEnv}_{i,j,k} + \sum_{k \neq agr} \text{WGtoWWTP}_{i,j,k}}{\text{Gross water use}_{i,j}}$$

$$\text{Gross water use}_{i,j} = \sum \text{Loss}_{i,j,k} + \sum \text{Consumption}_{i,j,k} + \sum \text{WGtoEnv}_{i,j,k} + \sum \text{WGtoWWTP}_{i,j,k}$$

$$\text{WG}_{i,j,k} = \frac{\text{Consumption}_{i,k}}{\text{Max consumption rate}_k} - \text{Consumption}_{i,k}\ (\text{Max consumption rate}_k \neq 0)$$

$$\text{WGtoWWTP}_{i,j,k} = \text{WG}_{i,j,k} * \text{Treatment rate}_{i,k}$$

$$\text{WGtoEnv}_{i,j,k} = \text{WG}_{i,j,k} - \text{WGtoWWTP}_{i,j,k}$$

$$\text{Loss}_{i,j,k} = \frac{(\text{Consumption}_{i,k} + \text{WG}_{i,j,k}) * \text{Loss rate}_{i,k}}{1 - \text{Loss rate}_{i,k}}\ (0 \leq \text{Loss rate}_{i,k} < 1)$$

where, Potential reuse$_{i,j}$ refers to the maximum potential for wastewater reclamation of province i ($i = 1 \cdots 31$) in wastewater generation scenario j ($j = 1 \cdots 4$). WGtoEnv$_{i,j,k}$ and WGtoWWTP$_{i,j,k}$ are generated wastewater discharging to the environment directly and generated wastewater flowing to WWTPs of industry k ($k = 1 \cdots 32$) in province i in wastewater generation scenario j. $k \neq agr$ ($k \neq 1$) indicates that agriculture is not included in the formula because agricultural wastewater is not collected by wastewater treatment sectors. Gross water use$_{i,j}$ refers to total water use of all sectors for each province. Loss$_{i,j,k}$ is sectoral water loss in different scenarios, and Consumption$_{i,k}$ is real sectoral water consumption in different provinces. We assume that sectoral water consumption keeps constant across scenarios, as it represents the specific amount of water required for production or consumption, whether it evaporates or is integrated into a product (Wang et al., 2021). Max consumption rate$_k$ refers to the strict sectoral water consumption rate to minimize wastewater generation (Table A.3). Consumption rate is measured by the ratio of water consumption to the sum of water consumption and wastewater generation. WG$_{i,j,k}$ are wastewater generation in industry k in province i of four different scenarios. Treatment rate$_{i,k}$ is the ratio of real collected wastewater to WWTPs WGtoWWTP$_{i,1,k}$ to real sectoral wastewater generation WG$_{i,1,k}$. Treatment rate$_{i,k}$ is derived from China Environmental Statistics Database (CESD) (Ministry of Environmental Protection of the People's Republic of China [MEPPRC], 2017). Loss rate$_{i,k}$ is the strict sectoral water conveyance loss rate for each province. Loss rate$_{i,k}$ for point-source sector is projected to be 8% (National Development and Reform Commission (NDRC) et al. 2021), while for agriculture sector, this value is set at 20%, slightly below the predicted 25% loss rate in Beijing for 2025 (Ministry of Water Resources and National Development and Reform Commission, 2022).

2.1.3 | Scenario analysis of sectoral freshwater use and pollutant discharge

Sectoral freshwater use and pollutant discharge are key parameters for water quantity and quality stress assessment. In each scenario, the sectoral freshwater use is evaluated by:

$$\text{Freshwater use}_{i,j,m,n,k} = \text{Gross water use}_{i,j,k} - \text{Wastewater reuse}_{i,j,m,n,k} - \text{Water use}_{\text{unconventional},i,k}$$

$$\text{Gross water use}_{i,j,k} = \text{Loss}_{i,j,k} + \text{Consumption}_{i,j,k} + \text{WGtoEnv}_{i,j,k} + \text{WGtoWWTP}_{i,j,k}$$

$$\text{Water use}_{\text{unconventional},i,k} = \text{Water use}_{\text{unconventional},i} * \frac{\text{Consumption}_{i,k}}{\sum_k \text{Consumption}_{i,k}} (k = 2 \cdots 28)$$

$$\text{Wastewater reuse}_{i,j,m,n,k} = \text{Wastewater reuse}_{i,j,m,n,ind} * \frac{\text{Consumption}_{i,k}}{\sum_k \text{Consumption}_{i,k}} (k = 2 \cdots 28)$$

where, Freshwater use$_{i,j,m,n,k}$ indicates freshwater use in industry k in province i in wastewater generation scenario j ($j = 1 \cdots 4$), with reuse rate scenario of m ($m = 1 \cdots 4$) and reuse application scenario of n ($n = 1 \cdots 5$). Wastewater reuse$_{i,j,m,n,k}$ is sectoral wastewater reuse in each province in different scenarios. Wastewater reuse$_{i,j,m,n,ind}$ refers to total reclaimed water for industry in each scenario, and it is obtained by the decision tree (Figure 2) that determines wastewater reuse application. The firm level information on treated wastewater volume, influent, and effluent concentration of 7411 WWTPs is from CESD (MEPPRC, 2017). Gross water use$_{i,j,k}$ is sectoral total water use in four different wastewater generation scenarios in each province. Water use$_{\text{unconventional},i,k}$ refers to the estimated unconventional water use (i.e., rainwater utilization, desalinated seawater, and treated dewatering from mining sector) in industry k in province i. The unconventional water use of Water use$_{\text{unconventional},i}$ in each province is collected from the Water Resources Bulletin in 2017 (Ministry of Water Resources, 2017). However, since the sectoral data on

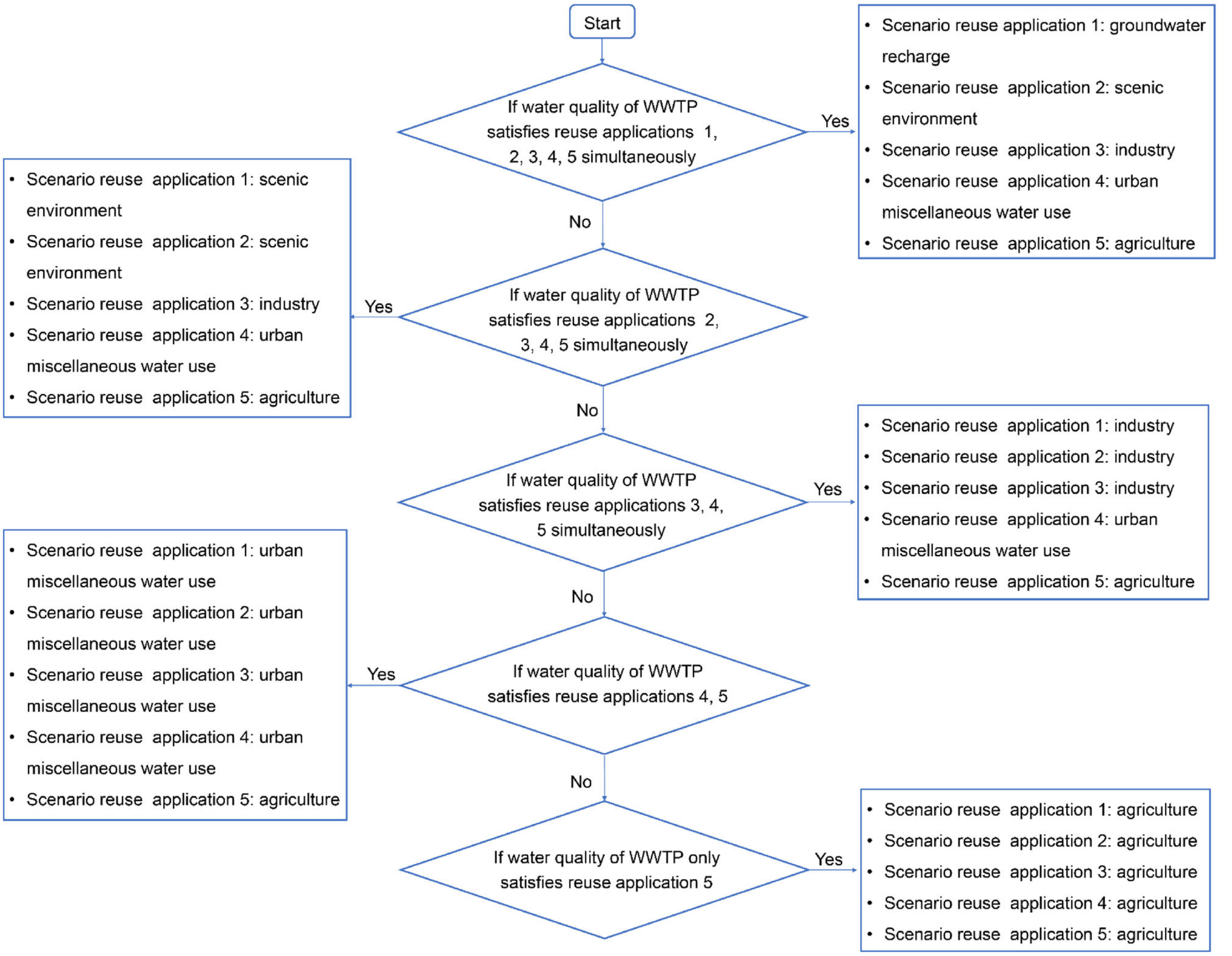

FIGURE 2 Decision tree for determining wastewater reuse applications of each wastewater treatment plant (7411 WWTPs in total) under different scenarios.

unconventional water use were unavailable, we estimate them by allocating provincial unconventional water use Water use$_{\text{unconventional}, i}$ based on the ratio of sectoral industrial water consumption to provincial industrial water consumption ($k = 2 \cdots 28$).

Regarding sectoral pollutant discharge, we have two assumptions for the assessments. For farming, we assume that leaching-runoff fractions of different pollutants vary linearly with generated wastewater. For point-source pollution sources, we assume the concentration of discharged pollutants to the environment remains the same for different scenarios. The corresponding change in pollutant loading is therefore proportional to the change in quantity of generated wastewater. This assumption is considered reasonable because of advanced wastewater treatment technologies and regulatory requirements for meeting discharge standards (Wang, 2022). Thus, for four different wastewater generation scenarios, pollutant loads discharging to the environment are assessed by:

$$\text{Pollutant load}_{i,j,k,s} = \text{WG change ratio}_{i,j,k} * \text{Real pollutant load}_{i,k,s}$$

$$\text{WG change ratio}_{i,j,k} = \frac{\text{WG}_{i,\,j,\,k}}{\text{WG}_{i,k}}$$

where, Pollutant load$_{i,j,k,s}$ refers to discharged pollutant loads of s (s= COD, NH_4^+-N, TN, and TP) of industry k in province i in wastewater generation scenario j. Real pollutant load$_{i,k,s}$ means real sectoral discharged loads of pollutant s in province i, Real pollutant load$_{i,k,s}$ is obtained from CESD (MEPPRC, 2017). WG$_{i,\,j,\,k}$ indicates sectoral wastewater generation in wastewater generation scenario j, and WG$_{i,k}$ refers to real wastewater generation of industry k in province i.

2.1.4 | Water stress assessment

Water quantity stress is defined as the ratio of provincial water withdrawal (freshwater use) to available water resources, while water quality stress refers to the ratio of provincial grey water footprint to available water resources. Available water resources are calculated as water availability minus environmental flow requirements.

$$\text{Quantity stress}_{i,j,m,n} = \frac{\sum_k \text{Freshwater use}_{i,j,m,n,k}}{\text{WA}_i - \text{EFR}_i}$$

where, $\text{Quantity stress}_{i,j,m,n}$ is water quantity stress level of province i in wastewater generation scenario j, with reuse rate scenario of m and reuse application scenario of n. WA_i is water availability from Water Resources Bulletin from each province in 2017 (Ministry of Water Resources, 2017). EFR_i are provincial level environmental flow requirements, which are obtained from FAO and UN Water (FAO and UN Water, 2021). $\sum_k \text{Freshwater use}_{i,j,m,n,k}$ is the provincial water withdrawal in each scenario. Five water quantity stress levels are categorized, namely: no stress (<0.25), low stress (0.25–0.5), medium stress (0.5–0.75), high stress (0.75–1), and critical stress (>1) (FAO and UN Water, 2021).

$$\text{Quality stress}_{i,j} = \frac{\text{GWF}_{\text{total}_{i,j}}}{\text{WA}_i - \text{EFR}_i}$$

$$\text{GWF}_{\text{total}_{i,j}} = \text{GWF}_{\text{agr}_{i,j}} + \sum_{k=2}^{k=28} \text{GWF}_{\text{ind}_{i,j,k}} + \text{GWF}_{\text{ser}_{i,j}} + \text{GWF}_{\text{urban},hh_{i,j}} + \text{GWF}_{\text{rural},hh_{i,j}}$$

$$\text{GWF}_{\text{agr}_{i,j}} = \text{GWF}_{\text{farm}_{i,j}} + \text{GWF}_{\text{liv}_{i,j}}$$

$$\text{GWF}_{\text{farm}_{i,j}} = max\left(\text{GWF}_{\text{farm,TN}_{i,j}}, \text{GWF}_{\text{farm,TP}_{i,j}}\right)$$

$$\text{GWF}_{\text{liv}_{i,j}} = \max\left(\text{GWF}_{\text{liv}_{i,j,s}}\right)\left(s = \text{COD}, \text{NH}_4{}^{+} - \text{N}, \text{TN}, \text{TP}\right)$$

$\text{GWF}_{\text{point-source}_{i,j,k}} = \max\left(\text{GWF}_{\text{point-source}_{i,j,k,s}}\right)$ (s = COD, NH_4^+-N, TN, and TP; point-source refers to industry, services, and urban and rural households).

$$\begin{cases} \text{GWF}_{\text{point-source}_{i,j,k,s}} = 0 & \left(\frac{\text{Pollutant load}_{i,j,k,s}}{C_{\max_s}} < \text{RF}_{\text{point-source}_{i,j,k}};\ k = 2 \cdots 32\right) \\ \text{GWF}_{\text{point-source}_{i,j,k,s}} = \frac{\text{Pollutant load}_{i,j,k,s}}{C_{\max_s}} - \text{RF}_{\text{point-source}_{i,j,k}} & \left(\frac{\text{Pollutant load}_{i,j,k,s}}{C_{\max_s}} > \text{RF}_{\text{point-source}_{i,j,k}};\ k = 2 \cdots 32\right) \end{cases}$$

where, $\text{Quality stress}_{i,j}$ and $\text{GWF}_{\text{total}_{i,j}}$ are water quality stress and grey water footprint of province i in wastewater generation scenario j. $\text{GWF}_{\text{agr}_{i,j}}$, $\text{GWF}_{\text{ser}_{i,j}}$, $\text{GWF}_{\text{urban},hh_{i,j}}$, $\text{GWF}_{\text{rural},hh_{i,j}}$, $\text{GWF}_{\text{farm}_{i,j}}$, $\text{GWF}_{\text{liv}_{i,j}}$, and $\text{GWF}_{\text{ind}_{i,j,k}}$ represent grey water footprint of agriculture, services, urban households, rural households, farming, livestock, and industry. $\text{GWF}_{\text{point-source}_{i,j,k}}$ is point-source grey water footprint, which includes industry, services, and urban and rural households. $\text{Pollutant load}_{i,j,k,s}$ is obtained from CESD (MEPPRC, 2017). If water quality stress level is greater than 1, it means province i under wastewater generation scenario j suffers from water pollution induced stress, otherwise, there is no water quality stress (Aldaya et al., 2012).

Additionally, in the baseline scenario, water quantity stress is measured by:

$$\text{Quantity stress}_{\text{baseline},i} = \frac{\text{Freshwater use}_{\text{baseline},i}}{\text{WA}_i - \text{EFR}_i}$$

$$\text{Freshwater use}_{\text{baseline},i} = \sum_k \text{Gross water use}_{i,1,k} - \sum_k \text{Water use}_{\text{unconventional},i,k}$$

While water quality stress in baseline scenario is estimated by:

$$\text{Quality stress}_{\text{baseline},i} = \text{Quality stress}_{i,1} + \frac{\Delta\,\text{GWF}_{\text{WWTP reduced},i}}{\text{WA}_i - \text{EFR}_i}$$

$$\Delta\ \mathrm{GWF}_{\mathrm{WWTP\ reduced},i} = \mathrm{GWF}_{\mathrm{WWTP\ in},i} - \mathrm{GWF}_{\mathrm{WWTP\ out},i}$$

$$\mathrm{GWF}_{\mathrm{WWTP\ in},i} = \sum_{w} \mathrm{GWF}_{\mathrm{WWTP\ in},i,w}$$

$$\mathrm{GWF}_{\mathrm{WWTP\ in},i,w} = \max\left(\mathrm{GWF}_{\mathrm{WWTP\ in},i,w,s}\right)\left(s = \mathrm{COD}, \mathrm{NH_4}^{+} - \mathrm{N}, \mathrm{TN}, \mathrm{and TP}\right).$$

$$\begin{cases} \mathrm{GWF}_{\mathrm{WWTP\ in},i,w,s} = 0 & \left(\dfrac{\mathrm{WWTP\ mass\ in}_{i,w,s}}{C_{\max_s}} < \mathrm{Volume}_{\mathrm{WWTP}_{i,w}}\right) \\ \mathrm{GWF}_{\mathrm{WWTP\ in},i,w,s} = \dfrac{\mathrm{WWTP\ mass\ in}_{i,w,s}}{C_{\max_s}} - \mathrm{Volume}_{\mathrm{WWTP}_{i,w}} & \left(\dfrac{\mathrm{WWTP\ mass\ in}_{i,w,s}}{C_{\max_s}} > \mathrm{Volume}_{\mathrm{WWTP}_{i,w}}\right) \end{cases}$$

$$\mathrm{GWF}_{\mathrm{WWTP\ out},i} = \sum_{w} \mathrm{GWF}_{\mathrm{WWTP\ out},i,w}$$

$$\mathrm{GWF}_{\mathrm{WWTP\ out},i,w} = \max\left(\mathrm{GWF}_{\mathrm{WWTP\ out},i,w,s}\right)\left(s = \mathrm{COD}, \mathrm{NH_4}^{+} - \mathrm{N}, \mathrm{TN}, \mathrm{and TP}\right)$$

$$\begin{cases} \mathrm{GWF}_{\mathrm{WWTP\ out},i,w,s} = 0 & \left(\dfrac{\mathrm{WWTP\ mass\ out}_{i,w,s}}{C_{\max_s}} < \mathrm{Volume}_{\mathrm{WWTP}_{i,w}}\right) \\ \mathrm{GWF}_{\mathrm{WWTP\ out},i,w,s} = \dfrac{\mathrm{WWTP\ mass\ out}_{i,w,s}}{C_{\max_s}} - \mathrm{Volume}_{\mathrm{WWTP}_{i,w}} & \left(\dfrac{\mathrm{WWTP\ mass\ out}_{i,w,s}}{C_{\max_s}} > \mathrm{Volume}_{\mathrm{WWTP}_{i,w}}\right) \end{cases}$$

where, Quality $\mathrm{stress}_{i,\,1}$ is the real water quality stress in the real wastewater generation situation (WG1) in province *i*. $\Delta\ \mathrm{GWF}_{\mathrm{WWTP\ reduced},i}$ is the grey water footprint mitigated by WWTPs for each province. $\mathrm{GWF}_{\mathrm{WWTP\ in},i}$ and $\mathrm{GWF}_{\mathrm{WWTP\ out},i}$ are grey water footprint of influent and effluent of wastewater treatment sector for each province. $\mathrm{GWF}_{\mathrm{WWTP\ in},i,w}$ and $\mathrm{GWF}_{\mathrm{WWTP\ out},i,w}$ refer to grey water footprint of influent and effluent of w_{th} WWTP in province *i*. WWTP mass $\mathrm{in}_{i,w,s}$ and WWTP mass $\mathrm{out}_{i,w,s}$ are pollutant loads of pollutant *s* in the w_{th} WWTP in province *i*. The data of influent and effluent concentration, volume of treated wastewater, and removed water pollutant loads for each WWTP is derived from CESD (MEPPRC, 2017). $C_{\max_s}$ is the third grade of China's Environmental Quality Standards for Surface Water (MEPPRC, 2002). The third grade indicates the water is suitable for fishing, swimming, and aquaculture. $C_{\max_{TN}}$, $C_{\max_{TP}}$, $C_{\max_{COD}}$, and $C_{\max_{NH3-N}}$ are 1, 0.2, 20, and 1 mg/L. $\mathrm{Volume}_{\mathrm{WWTP}_{i,w}}$ is volume of treated wastewater of the w_{th} WWTP in province *i*.

2.2 | Limitations

The framework and methodology employed in this study have several limitations: (1) The reclaimed wastewater could be achieved by hierarchical application in the economic system. However, the hierarchical application of water reuse is suitable for the same industry and requires knowledge of the purpose and water quality standard of hierarchical application of the same industry. In this study, it is difficult to consider the purpose and water quality standard of hierarchical application for all 32 water use sectors. Thus, we mainly consider one-time wastewater reuse for different reuse application scenarios in the societal water cycle. (2) We evaluate the water quality of treated wastewater with four conventional pollutant indicators to determine its suitability for a specific reuse application. However, to determine if water quality satisfies different reuse applications, indicators such as metal pollutants, fecal coliform bacteria, inorganic pollutants (such as sulfide and chlorine), organic pollutants (such as petrol and pesticides), turbidity, and pH should also be considered. Due to data limitations, we primarily consider COD, NH_4^+-N, TN, and TP, which may lead to an underestimation of the grey water footprint and water quality stress for each region. (3) In each scenario, we focus solely on the potential for mitigating water stress. We do not consider whether the necessary infrastructure exists for a particular reuse application, nor the required financial investments are in place to achieve the reuse applications. However, these factors are critical for the actual implementation of wastewater reuse. (4) The factor of upgrading treatment facilities to improve quality of wastewater is not considered, since it is difficult to predict effluent concentration of wastewater after application of advanced treatment technologies. Operating conditions of temperature, pH, dissolved oxygen, sludge retention time, hydraulic retention time, influent COD to total nitrogen ratio, influent COD to total phosphorus ratio, etc. are also factors to influence treatment effects. (5) The resolution of this study is limited to the provincial level. However, it is worth noting that the framework and methodology in this study can be applied to analyze the same topic at a higher spatial resolution.

3 | RESULTS AND DISCUSSION

3.1 | The potential for wastewater reuse is limited under different water conservation scenarios

To analyze the varying potential for wastewater reuse across different scenarios of water conservation, we conduct comparative assessments to elucidate their distinctions. Four wastewater generation (WG) scenarios (or water conservation scenarios), including WG 1 (wastewater generation in actual situation), WG 2 (wastewater generation scenario considering point-source water saving of industry, services, and households), WG 3 (wastewater generation scenario considering agricultural water saving), and WG 4 (wastewater generation scenario considering water saving in all sectors), have different potential for reuse, with wide-ranging values: WG 1 (2%–39%, mean 13%), WG 2 (0.5%–9%, mean 3%), WG 3 (4%–41%, mean 20%), and WG 4 (1%–12%, mean 5%). These percentages indicate that the provincial water quantity stress could be reduced by no more than 10% on average through wastewater reuse.

For different provinces, the maximum potential for wastewater reuse varies considerably in the four water conservation scenarios. Provinces characterized by agricultural water use, such as Xinjiang (1%–4%), Heilongjiang (1%–5%), Tibet (1%–8%), Inner Mongolia (1%–7%), and Ningxia (1%–10%), consistently exhibit the lowest potential for wastewater reuse across all scenarios. Conversely, highly urbanized regions such as Shanghai (8%–41%), Beijing (9%–29%), and Guangdong (6%–38%), where industrial and services water use predominate, consistently rank among the top five in mitigating quantity stress through wastewater reuse.

3.2 | Wastewater reuse combined with water conservation can reduce water quantity stress to a lower level for most provinces

Figure 4 shows the impact of water conservation and wastewater reuse on mitigating water quantity stress. In the baseline scenario, which assumes no wastewater reuse, only 6 out of 31 provinces (Tibet, Qinghai, Yunnan, Sichuan, Guangxi, and Guizhou) have no water quantity stress (<0.25), while the other 25 provinces experience varying levels of quantity stress (0.26–7.68). Under the current situation, provincial wastewater reuse rates are less than 10% on average. The current provincial water quantity stress in 2017 is similar to the baseline scenario (without wastewater reuse) except for Beijing, because of its high reuse rate of 60%. However, even if the reuse rates are improved to 35%, 60%, or 90% for each WWTP under the real wastewater generation condition, quantity stress levels remain largely unchanged for the majority of provinces across regions (see Figure 4, orange violin plot), with some exceptions such as a reduction in Heilongjiang from critical to high, in Henan and Shanxi from high to medium, and in Chongqing from low to no water stress. Therefore, under the current situation in 2017, wastewater reuse alone is insufficient to reduce quantity stress to lower levels for most provinces, despite observed decreases in quantity stress values.

For each water conservation scenario (or wastewater generation scenario) (see Figure 4, depicting green, purple, and yellow violin plots), it is apparent that quantity stress levels across most regions remain relatively stable, regardless of the extent to which reuse rates are increased. Only Anhui (purple plot), Guangdong (yellow plot), and Hubei (purple plot) show a decrease in quantity stress levels. This trend can be attributed primarily to the limited potential for wastewater reuse, as treated wastewater is less than 10% of gross water use (Figure 3). Thus, under various water conservation scenarios, relying solely on wastewater reuse to mitigate water quantity stress is limited and insufficient to significantly reduce the quantity stress to a lower level.

Compared to the real situation without water conservation measures for water loss and wastewater generation, water saving can contribute to reductions in water quantity stress as follows: 2%–41% quantity stress reduction (mean: 12%) when conserving water in point-source sectors (industry, services, and households), 1%–64% reduction (mean: 34%) when conserving water in non-point-source sectors (agriculture), and 16%–72% reduction (mean: 46%) when implementing water-saving measures across all sectors (see data in Table B.3). These percentages present that water conservation can contribute to water quantity stress reduction by 31% on average, ranging from 1% to 72%. Wastewater reuse combined with water conservation results in notably lower levels of water quantity stress compared to both current and baseline values. Agricultural water-saving initiatives in the scenario WG3-RRs-RAs (Figure 4, purple violin plot) have a greater impact on reducing quantity stress than point-source water-saving initiatives in WG2-RRs-RAs (Figure 4, violin plot with green) for most regions. The inclusion of wastewater reuse and agricultural water conservation in WG3-RRs-RAs (agricultural water conservation only) and WG 4-RRs-RAs (agricultural and industrial water conservation) scenarios would result in a remarkable reduction in quantity stress, far greater than that the ones observed in WG1-RRs-RAs (no water saving) and WG2-RRs-RAs (point-source water saving of industry, services, and households) scenarios, thus alleviating water quantity stress levels for most provinces. Prioritizing water conservation measures, especially agricultural water saving, complemented by wastewater reuse, has great potential to reduce quantity stress level for most provinces characterized by agricultural water use in China. However, it is important to note that Shanghai, Tianjin, Beijing, and Chongqing are exceptions to this trend, as these regions heavily rely on point-source water use. Consequently, in highly industrialized regions, scenarios emphasizing point-source water conservation (WG2-RRs-RAs and WG4-RRs-RAs) demonstrate lower levels of water quantity stress compared to scenarios emphasizing agricultural water conservation (WG3-RRs-RAs).

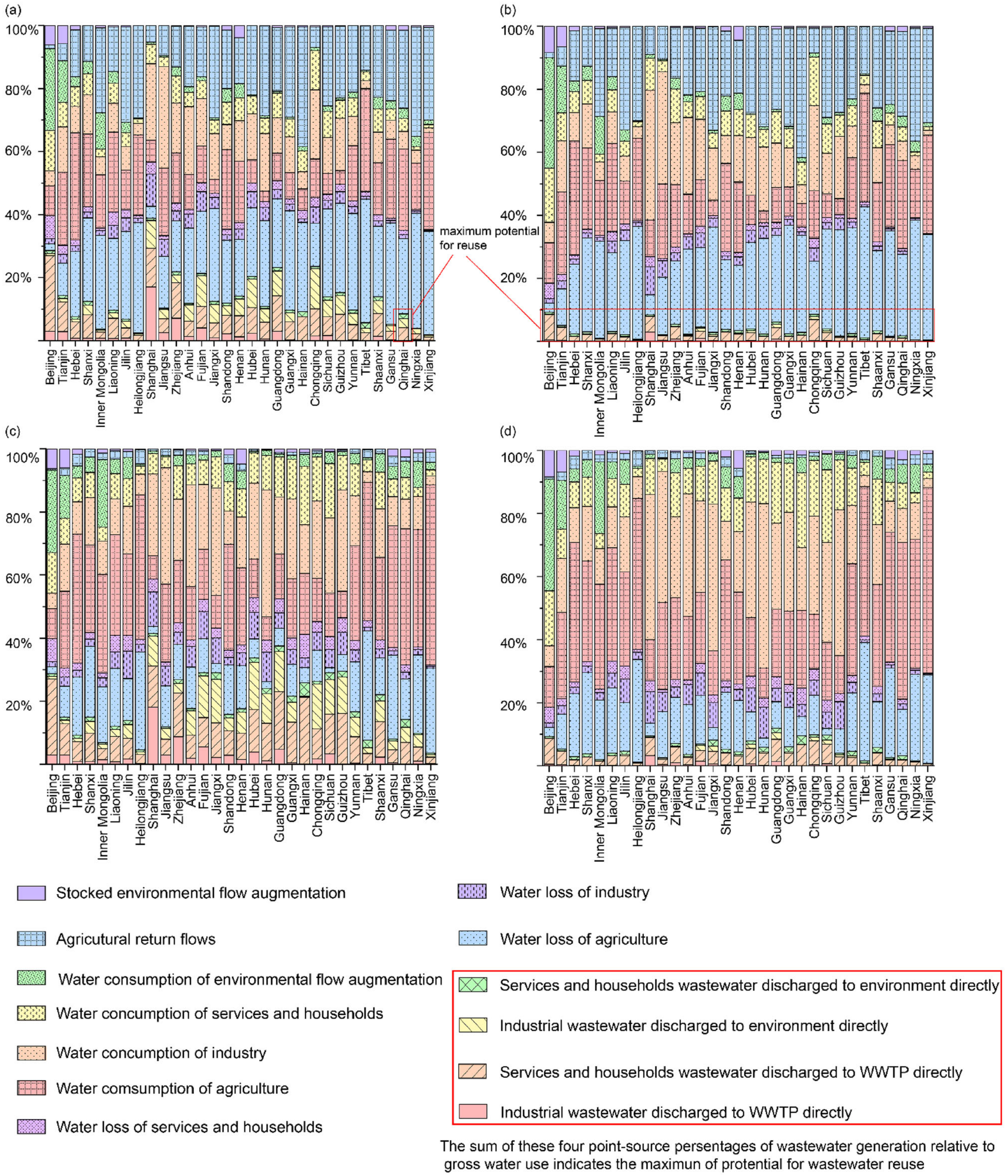

FIGURE 3 Maximum potential for wastewater reuse in four wastewater generation scenarios (in %). This figure shows the percentage of water flow from each process in the societal water cycle relative to gross water use across various water conservation scenarios. Maximum potential for wastewater reuse is the ratio of wastewater generated by point-source sectors (industry, services, and households) to gross water use. (a) Real wastewater generation in 2017. (b) Wastewater generation scenario after consideration of water saving for point-source sectors. (c) Wastewater generation scenario after consideration of water saving for non-point-source sector (agriculture). (d) Wastewater generation scenario after consideration of water saving for all sectors. The underlying data for Figure 3 are available in spreadsheets named Figure 3a-3d in Supporting information S2.

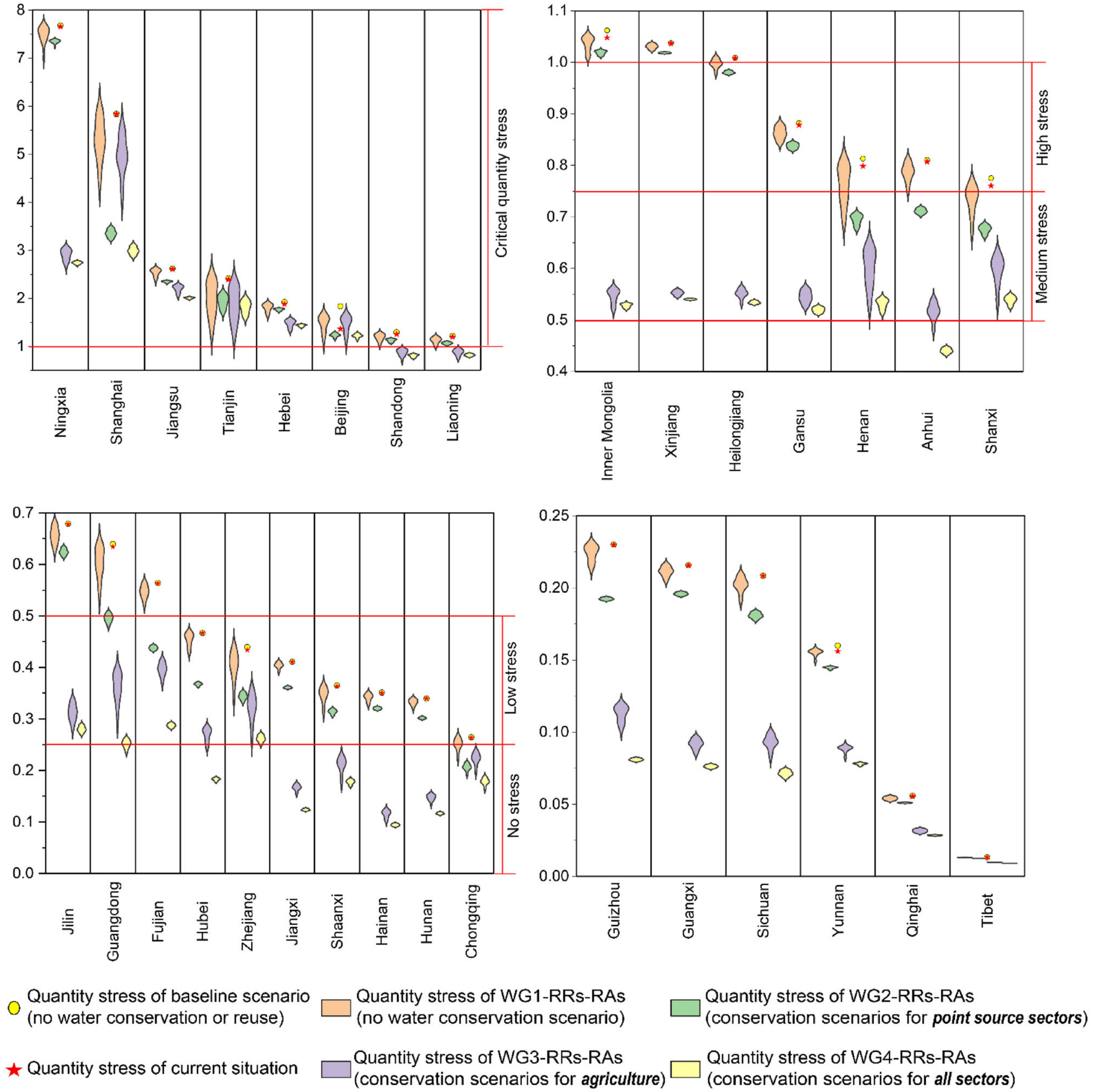

FIGURE 4 Impacts of water conservation and wastewater reuse on water quantity stress mitigation. This figure presents water quantity stress values for the situation in 2017 and different water conservation scenarios across different provinces in China. Compared to the baseline scenario (yellow dot, no wastewater reuse), a decrease in water quantity stress level, such as shifting from high to medium stress, indicates that water conservation and wastewater reuse can significantly alleviate water quantity stress. Each violin plot displays the distribution of quantity stress values across 20 scenarios, encompassing 4 reuse rate scenarios and 5 reuse application scenarios (4 × 5 = 20) under a specific water conservation scenario. Water quantity stress level is classified as: no stress (<0.25); low (0.25–0.5); medium (0.5–0.75); high (0.75–1); and critical (>1). RAs, reuse applications; RRs, reuse rates; WG, wastewater generation; WG1-RRs-RAs, scenarios that have four types of reuse rates and five types of reuse applications in the situation of real wastewater generation; WG2-RRs-RAs, WG3-RRs-RAs, and WG4-RRs-RAs refer to scenarios that have four types of reuse rates and five types of reuse applications in the situation that consider water saving for point-source sectors (WG2-RRs-RAs), non-point-source sector (WG3-RRs-RAs), and all sectors (WG4-RRs-RAs). Underlying data for Figure 4 are available in spreadsheets named Figure 4a-Fig 4d in Supporting information S2.

To optimize the allocation of reused wastewater, it is crucial to carefully assess the supply–demand balance and sector-specific quality requirements across economic sectors. However, the impact of different wastewater reuse supplies on quantity stress is rarely considered, which takes into account the quality of treated wastewater and sector-specific water quality requirements (Herrera-León et al., 2022). This study addresses this issue through the following steps: assessing the water quality of each WWTP; judging reuse application under different scenarios based on the quality of treated wastewater; comparing differences between water use and sectoral wastewater reuse supply; and evaluating freshwater withdrawal and water quantity stress. The scenario results reveal that even with the same amount of wastewater reuse, the water quantity stress varies depending on the specific reuse applications. For example, under the scenario of water-saving measures for all sectors and a 90% reuse rate for each WWTP, Beijing's water quantity stress differs among five reuse application scenarios: 1.13 (groundwater recharge priority), 1.16 (scenic environment priority), 1.22 (industry priority), 1.20 (urban miscellaneous water use priority), and 1.16 (agriculture priority). These variations stem from an imbalance between sectoral water quality requirement and water quality of treated wastewater, as well as a discrepancy between the preferences for reuse applications and the water demand of various sectors. Therefore, we recommend distributing treated wastewater according to sector-specific water quality requirements and the water demand of each sector to minimize water quantity stress.

Water conservation and wastewater reuse are two ways to reduce freshwater use (Agarwal et al., 2022; Chen et al., 2022; Hamdy et al., 2003; He et al., 2021). To address water stress, China has set forth a goal for wastewater reuse rates to surpass 25% at the city level by 2025. Particularly within the Beijing–Tianjin–Hebei region, this target is elevated to over 35%. Moreover, in water-stressed cities located in the middle and lower reaches of the Yellow River Basin, this value should reach a minimum of 30% (National Development and Reform Commission (NDRC) and Ministry of Housing and Urban-Rural Development (MHURD) 2021). This study shows that only considering wastewater reuse (even with reuse rates at 90%), provincial quantity stress values will be reduced by up to 10% on average, but quantity stress level keeps constant and would not change to a lower level for 21 out of 25 provinces that suffer from quantity stress. However, China has great potential for water conservation, especially for provincial agricultural sectors. Scenario analysis shows that 19 out of 25 provinces that suffer from water shortage will reduce their quantity stress levels if each sector adopts water conservation by improving water consumption rates to the strictest level (shown in Table A.3) to reduce wastewater generation, together with wastewater reuse. Thus, to mitigate provincial water quantity stress in China, we suggest that water conservation should be a priority, followed by wastewater reuse. This paper also offers theoretical groundwork and methodological direction for higher spatial resolution studies at city and county levels.

3.3 | Wastewater treatment and water conservation contribute to quality stress mitigation but cannot fully eliminate quality stress

Figure 5 illustrates the contribution of water conservation and wastewater treatment to mitigating water quality stress. In 2017, the baseline scenario without water conservation and wastewater treatment indicates that only two provinces, Tibet and Qinghai, did not suffer from quality stress (quality stress level <1), while the remaining 29 provinces all experience various levels of quality stress (1.11–74.16). Compared to the baseline scenario, the current situation of wastewater treatment reduces water quality stress by 6%–86% (average 29%). The values show that the contribution of wastewater treatment to quality stress mitigation varied considerably across regions. Wastewater treatment contributes only 6%–8% to water quality stress reduction in agriculture-dominated provinces such as Yunnan, Tibet, Guizhou, and Guangxi. However, in urbanized regions such as Shanghai (62%), Tianjin (75%), and Beijing (86%), these percentages are significantly higher. The primary reason could be the variation in the structure of water use and pollution. In China, agriculture is the main source for water pollution for most provinces in 2017, accounting for over 50% of quality stress in 22 out of 31 provinces (see Table B.4). However, in developed regions such as Beijing (16%) and Tianjin (26%), where the economy is predominantly non-agricultural, these values are comparatively lower. Consequently, wastewater treatment plays a critical role in alleviating quality stress, particularly in regions dominated by industrial and service sectors.

Water conservation also benefits water pollution reduction, especially decreasing wastewater generation may reduce discharged pollutant loads if effluent water quality standards are kept constant. When considering both water saving and wastewater treatment under different scenarios, quality stress can be reduced by 9%–91% (average: 43%) for WG2-RRs-RAs, 12%–87% (average: 58%) for WG3-RRs-RAs and 27%–92% (average: 72%) for WG4-RRs-RAs. This highlights that water quality stress can be significantly mitigated if water conservation and wastewater treatment are adopted concurrently.

However, it should be noted that neither wastewater treatment nor strict water conservation measures can adequately protect most regions from water quality stress, since only four regions (Xinjiang, Inner Mongolia, Gansu, and Guangxi) are able to eliminate water quality stress (reduce quality stress levels to less than 1) in the scenario that considers water conservation for all sectors. Thus, we recommend paying attention simultaneously to the mitigation of quality stress by non-point-source pollution control and point-source pollutant removal through wastewater treatment, while non-point-source pollution control should be a priority for agriculture-dominated provinces. Implementing measures outlined in China's Water Pollution Prevention and Control Law (Ministry of Ecology and Environment of the People's Republic of China [MEEPRC], 2017), which advocate to use fertilizers and pesticides in a scientific and rational manner and control the excessive use of fertilizers and pesticides, can prevent agricultural water pollution.

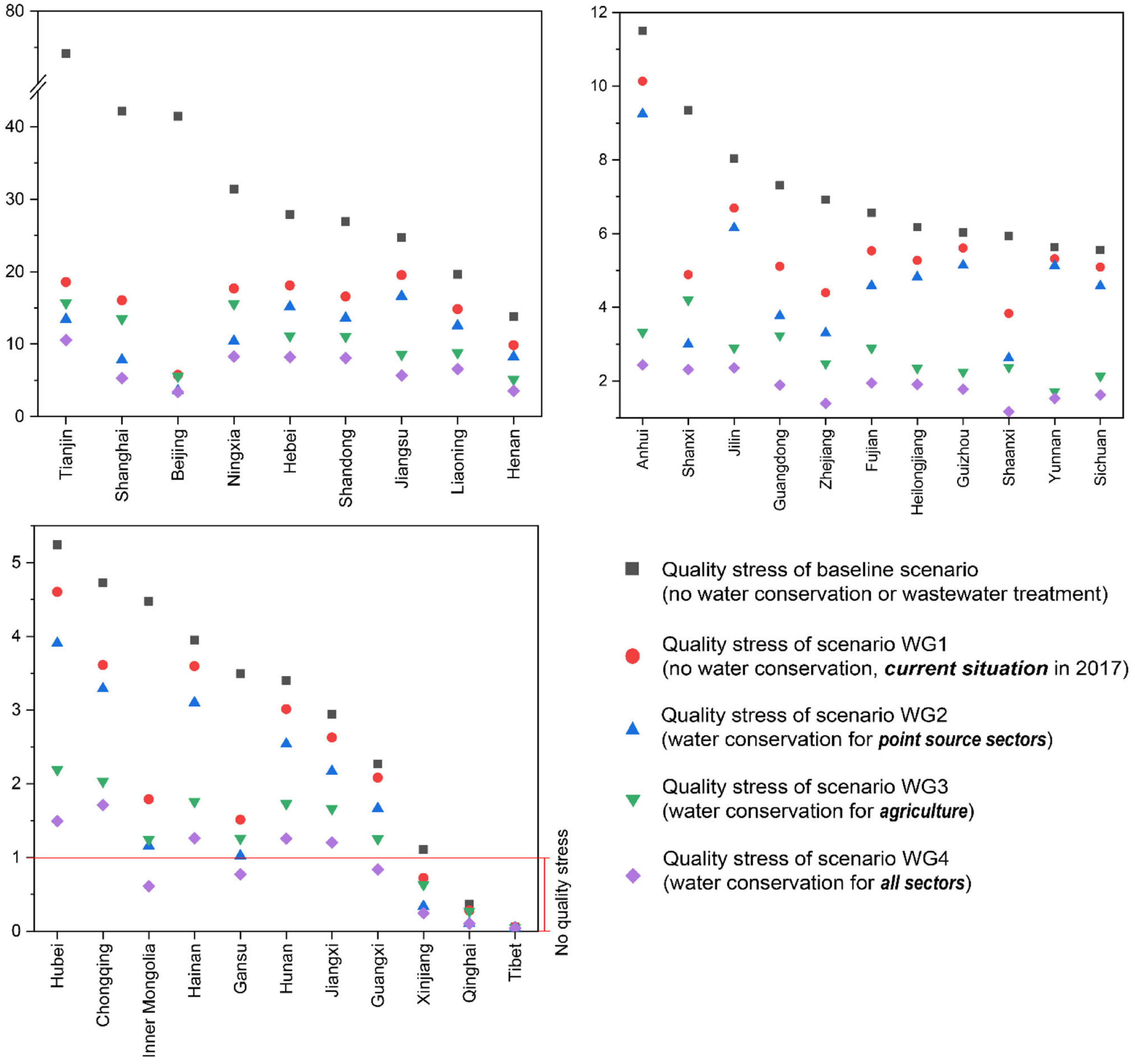

FIGURE 5 Impacts of water conservation and wastewater treatment on water quality stress mitigation. If the water quality stress level is greater than 1, it means a province suffers from water pollution induced stress, otherwise, there is no water quality stress. The underlying data for Figure 5 are available in spreadsheets named Figure 5a-5c in Supporting information S2.

4 | CONCLUSION

This study quantifies the impact of water conservation, wastewater treatment, and reuse on provincial water stress mitigation in China. We obtain the following practical and policy-relevant findings:

- Sectoral water withdrawal, conveyance loss, consumption, wastewater generation, pollution, wastewater treatment, wastewater use, and return flow are interconnected within the societal water cycle. Water conservation efforts, such as reducing conveyance loss and wastewater generation, influence both water and pollutant flows. A system thinking approach to the societal water cycle is essential to assess the impacts of water conservation, wastewater treatment, and reuse on mitigating provincial water stress.
- Wastewater reuse can reduce provincial water quantity stress by less than 10% and alleviate water stress in 4 out of 25 water-stressed provinces. In contrast, water conservation can contribute to water quantity stress reduction by 31% on average, ranging from 1% to72%. Considerable reductions in quantity stress levels can be achieved in 19 out of 25 quantity-stressed provinces by simultaneously considering sectoral

water-saving measures and wastewater treatment. It is recommended to prioritize water conservation efforts, followed by the implementation of wastewater reuse strategies.

- Wastewater treatment plays a pivotal role in removing point-source pollutants and reducing water quality stress by an average of 29%, with reductions ranging from 6% to 86% in the current situation. However, despite the adoption of wastewater treatment and water conservation measures at the same time, quality stress (quality stress level >1) persists in the majority of regions. Specifically, 25 out of 29 quality-stressed provinces continue to face challenges related to water quality, since their quality stress levels are all larger than 1. It is necessary to implement additional measures to combat water pollution in conjunction with wastewater treatment and water-saving practices, such as non-point-source pollution control.

AUTHOR CONTRIBUTIONS

Dan Wang: Conceptualization; resources; investigation; methodology; software; calculation; analysis; visualization; writing—original draft; writing—review and editing. **Zhuo Chen**: Methodology; resources; investigation; writing—review and editing. **Reetik Kumar Sahu**: Methodology; writing—review and editing. **Taher Kahil**: Methodology; writing—review and editing. **Ting Tang**: Methodology; writing—review and editing. **Yuli Shan**: Resources; investigation. **Wei Zhang**: Resources; investigation; **Weili Ye**: Resources; investigation. **Guangxue Wu**: Methodology; writing—review and editing. **Huimei Li**: Resources; investigation. **Klaus Hubacek**: Conceptualization; supervision; methodology; analysis; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data used in this research can be accessed through https://doi.org/10.6084/m9.figshare.25997896.v1

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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