Journal of Cleaner Production 538 (2026) 147398

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Water loss and return flows matter for water stress mitigation in China

Dan Wang [a,b], Reetik Kumar Sahu [b], Taher Kahil [b,k], Ting Tang [b], Wei Zhang [c,d], Weili Ye [d], Guangxue Wu [e], Zhuo Chen [f], Huimei Li [g], Junxia Wang [h], Haoyuan Feng [i], Yuli Shan [a,j], Klaus Hubacek [a,b,*]

[a] *Integrated Research on Energy Environment and Society (IREES), Energy Sustainability Research Institute Groningen (ESRIG), University of Groningen, Groningen, 9747, AG, the Netherlands*
[b] *Water Security Research Group, Biodiversity and Natural Resources Program, International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361, Laxenburg, Austria*
[c] *Key Laboratory of Environmental Planning and Policy Simulation of Ministry of Ecology and Environment, Beijing, 100041 China*
[d] *The Center for Beijing-Tianjin-Hebei Regional Ecology and Environment, Chinese Academy of Environmental Planning, Beijing, 100012, China*
[e] *Civil Engineering, School of Engineering, College of Science and Engineering, University of Galway, Galway, H91 TK33, Ireland*
[f] *State Key Laboratory of Regional Environment and Sustainability, Key Laboratory of Microorganism Application and Risk Control, Ministry of Ecology and Environment, School of Environment, Tsinghua University, Beijing, 100084, China*
[g] *Industrial Ecology Group, Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, Germany*
[h] *State Environmental Protection Key Laboratory of Quality Control in Environmental Monitoring, China National Environmental Monitoring Centre, Beijing, 100012, China*
[i] *School of Ecological and Environmental Sciences, East China Normal University, Shanghai, 200241, China*
[j] *School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, B15 2TT, UK*
[k] *United Nations University Institute for Water, Environment and Health (UNU-INWEH), Hamilton, ON, Canada*

HIGHLIGHTS

- Majority provinces in China suffer from both water quantity and quality stress
- System thinking of societal water cycle is necessary for water stress assessment and mitigation
- Water loss and return flows contribute to 36–79 % of water quantity stress
- Agriculture and households' return flows contribute 61–98 % to provincial water quality stress
- The top five sectors could mitigate quantity stress by 22–75 % and quality stress by 23–76 %

ARTICLE INFO

Keywords:
Societal water cycle
Water loss
Return flows
Physical and virtual water flow
Water quantity and quality
Water stress assessment
Water stress mitigation

ABSTRACT

Water is withdrawn, lost, consumed, polluted, returned, treated, reused, and traded between regions within the societal water cycle due to human activities, contributing to regional water stress. In this research, we aim to examine the impacts of the societal water cycle on water resources and explore strategies for reducing water stress in China. The results show that most provinces in China suffer from water quantity and quality stress. However, there is a significant potential to reduce water quantity stress by 36–79 % through reducing water loss and return flows. The return flows and water loss in the virtual export forms could be avoided to reduce virtual water export-induced quantity stress by 39–89 %. Agriculture and households' return flows contribute 61–98 % to provincial water quality stress in China. The five sectors with the greatest potential to mitigate water quantity and quality stress are identified for each province, which could reduce quantity stress by 22–75 % and quality stress by 23–76 %.

* Corresponding author. Integrated Research on Energy Environment and Society (IREES), Energy Sustainability Research Institute Groningen (ESRIG), University of Groningen, Groningen, 9747, AG, the Netherlands.
E-mail address: k.hubacek@rug.nl (K. Hubacek).

https://doi.org/10.1016/j.jclepro.2025.147398
Received 25 June 2024; Received in revised form 8 November 2025; Accepted 22 December 2025
Available online 29 December 2025

1. Introduction

Water stress is a global challenge recognized as a key target in the United Nations Sustainable Development Goals (SDGs) (Bhaduri et al., 2016; Liu et al., 2017). China, with its large population and rapid economic growth, has faced increasing water shortages and pollution (Liu et al., 2019a; Zhao et al., 2015a, 2022), exacerbating already high levels of water stress and revealing pronounced regional disparities. Recent evidence shows marked improvements in inland surface water quality since 2003, largely driven by reduced point-source discharges in industrial and residential sectors, although agricultural non-point pollution and northern/northeastern hotspots remain concerns (Ma et al., 2020b). At the same time, China has relied on large inter-basin water transfer projects and substantial virtual water trade; however, transfers only modestly reduce inequality and often shift stress geographically, while efficiency-oriented policy under the Strictest Water Resources Management System (SWRMS) has reversed national water use trends without greatly lowering average stress due to constrained water availability (Sun et al., 2021; Zhang et al., 2023; Zhao et al., 2015a).

Water is withdrawn, lost, consumed, polluted, returned, treated, reused, and traded between regions within the societal water cycle, which encompasses all stages of water quantity and pollutant flows. However, numerous studies on water quantity stress, many focusing solely on the impact of water withdrawal or consumption on water resources (Liu et al., 2016; Liu and Zhao, 2020; Zeng et al., 2013; Zhao et al., 2016). Virtual water studies likewise focus primarily on withdrawal or consumption when tracking interregional flows (Feng et al., 2014; Hoekstra and Mekonnen, 2012; Wang et al., 2021), even though recent provincial scale evidence shows that virtual flows (35 % of national supply in 2007) far exceed physical transfers (around 4.5 %) and that both mechanisms provide limited relief for importing regions while exacerbating stress for exporters (Zhao et al., 2015a). At the basin scale, the capacity of inter-basin water transfer projects reached ~48.5 billion m^3 yr^{-1} by 2016 (around 8 % of national use), affecting 43 of 76 sub-basins; transfers reduced inequality only slightly (e.g., the inequality coefficient fell from 0.64 to 0.59 in 2016) and increased scarcity for 357 million people in source basins (Sun et al., 2021). Meanwhile, policy evaluation of the SWRMS using a high-resolution dataset shows that national total water use fell after 2012, with ~90 km^3 yr^{-1} savings attributed mainly to irrigation and industrial efficiency, freeing 17 prefectures from extreme stress, yet with limited impact on average national stress because availability dominates (Zhang et al., 2023). For water quality, a national monitoring analysis documents sustained improvements linked to declining point-source discharges, while warning that agricultural pollution threatens further progress and that northern/northeastern regions remain relatively severe. It is also argued that scarcity indicators explicitly combine sectoral quality requirements with local water quality (Ma et al., 2020b).

The literature reveals some important gaps. First, quantity and quality stress are typically assessed separately (Cai et al., 2023; Ma et al., 2020a; van Vliet et al., 2017) (e.g., inter-basin water transfer and virtual-water studies emphasize water volume, while water quality work emphasizes pollutant dynamics), limiting diagnosis of both stresses together and their drivers (Ma et al., 2020b; Sun et al., 2021; Zhao et al., 2015a). Second, the societal water cycle includes processes of water withdrawal, loss, consumption, wastewater treatment, return flows, pollutant discharging, and their virtual forms along supply chains. However, numerous studies on water quantity stress mainly focus on the impact of water withdrawal or consumption on water resources (Liu and Zhao, 2020; Zeng et al., 2013; Zhao et al., 2016) and ignore water loss, return flows, other processes, and their virtual forms (Feng et al., 2014; Hoekstra and Mekonnen, 2012; Wang et al., 2021). The stages of water loss, return flows, and their virtual forms (virtual water loss and virtual return flows) decrease water-use efficiency and exacerbate water quantity stress, yet their impacts on water stress are rarely considered. Thus, understanding the whole process in the societal water cycle is essential to reveal the socio-economic drivers of water stress and to provide a stronger basis for mitigation. Third, multi-sector, multi-region mitigation strategies grounded in a societal water cycle perspective remain underexplored (Ma et al., 2020b; Sun et al., 2021; Zhang et al., 2023; Zhao et al., 2015a).

In this study, we aim to understand the impacts of the societal water cycle on water resources in China and to explore the causes and potential solutions to water stress in different provinces in China. To achieve this, we (1) apply Material Flow Analysis (MFA) combined with Input-Output Analysis (IOA) to track both water quantity and pollutant flows in the societal water cycle across various economic sectors and provinces, (2) identify provinces of high water stress in terms of both quantity and quality, and the economic sectors that contribute most significantly to this stress in each province, and (3) develop strategies to alleviate water stress in each province by utilizing findings from our MFA-IOA analysis and by examining various scenarios for enhancing sectoral water use efficiency, with a focus on eliminating unnecessary water utilization within the societal water cycle. Overall, our contribution is to integrate quantity and quality within a single, sector- and province-resolved societal water cycle framework, explicitly accounting for water withdrawal, loss, consumption, wastewater treatment, return flows, and their virtual forms along supply chains, and to evaluate potential solutions to water stress.

2. Methods and data

2.1. Framework for water stress assessment and mitigation

We develop a framework for water stress assessment and mitigation, as shown in Fig. 1. The framework consists of three parts: MFA-IOA analysis, water stress assessment, and a water stress mitigation pathway. The first step is to apply an MFA-IOA approach to trace physical and virtual water quantity and pollutants flows of water use sectors (i.e., agriculture, 26 industries, construction, services, urban households, rural households, and ecosystems). The MFA-IOA analysis is based on the societal water cycle (Fig. 2). In this research, we define the societal water cycle as water and pollutant flows between economic sectors, including withdrawal, conveyance loss, consumption, pollution, return flows, wastewater treatment, wastewater use, and virtual water trade. We map physical water flows, including withdrawal, loss, consumption, return flows to wastewater treatment plants, return flows directly discharged to the environment, and wastewater reuse. Flows of physical water pollutants refer to sectoral discharges of TN (Total Nitrogen), TP (Total Phosphorus), COD (Chemical Oxygen Demand), and NH_3-N (Ammonia Nitrogen) into the environment. Virtual water pollutant flows involve tracing the movement of virtual COD, NH_3-N, TN, and TP across sectors and provinces. It is essential to track the amount of virtual water that is wasted or ineffectively used through trade, as water utilized at any stage in the supply chain results in water loss, consumption, or return flows. Therefore, virtual water embodied in trade is classified into three categories: virtual water loss (i.e., virtual agricultural water loss and virtual industrial leakage), virtual water consumption, and virtual return flows (i.e., virtual agricultural return flows, virtual return flows direct discharge to the environment, and virtual return flows to wastewater treatment plants). The physical water flows of 32 sectors (industry list see Table S1) in each province are analysed, including urban and rural households and environmental flow augmentation. Physical water pollutant flows do not include environmental flow augmentation, as it does not generate pollution. Virtual water quantity and pollutant flows do not include households and environmental flow augmentation.

Based on the MFA-IOA analysis, we evaluate water quantity stress for different stages of the societal water cycle in terms of physical water and virtual exported water to determine whether water is being used efficiently. We also assess water quantity and quality stress at the sectoral and provincial levels to identify hotspots of sectors and provinces

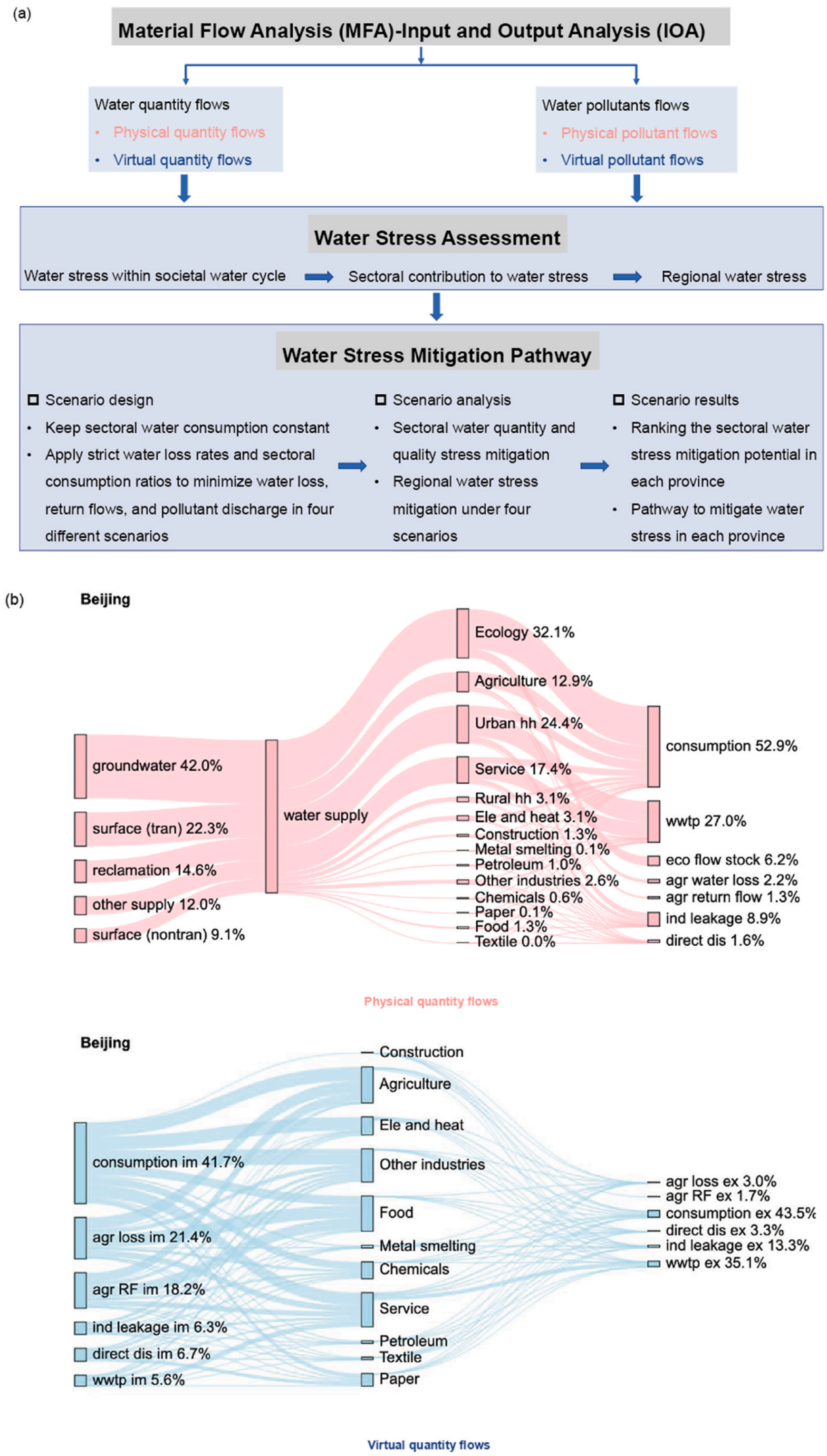

Fig. 1. Framework for water stress assessment and mitigation. (a) General Framework; (b) Physical and Virtual quantity flows in Beijing; (c) Physical and Virtual pollutant flows (COD) in Beijing. Beijing is selected as an example to show physical quantity flows (Fig. S1), virtual quantity flows (Fig. S2), physical pollutant flows for TN, TP, COD and NH_3-N (Fig. S3), and virtual pollutant flows for TN, TP, COD, and NH_3-N (Fig. S4) across 31 provinces in China. COD is used as a representative pollutant in the framework figure. Classification of aggregated water use industry in Sankey diagrams is shown in Table S2 **surface (tran):** surface water supply with first order inter-basin transfer; **surface (nontran)**: surface water supply without first order inter-basin transfer; **Ecology**: environmental flow augmentation; **Urban hh**: Urban households; **Rural hh**: Rural households; **Ele and heat**: Production and distribution of electric power and heat power; **Metal smelting**: Smelting and processing of metals; **Petroleum**: Processing of petroleum, coking, processing of nuclear fuel; **Chemicals**: Manufacture of chemical products; **Paper**: Manufacture of paper, printing and articles for culture, education, and sport activity; **Textile**: Textile industry; consumption: water consumption; **agr water loss**: agricultural water conveyance loss; **agr return flow**: agricultural return flow; **ind leakage**: industrial and households water conveyance leakage; **eco flow stock**: environmental flow augmentation that stored in rivers and lakes etc.; **wwtp**: wastewater treatment plant; **direct dis**: direct discharge.

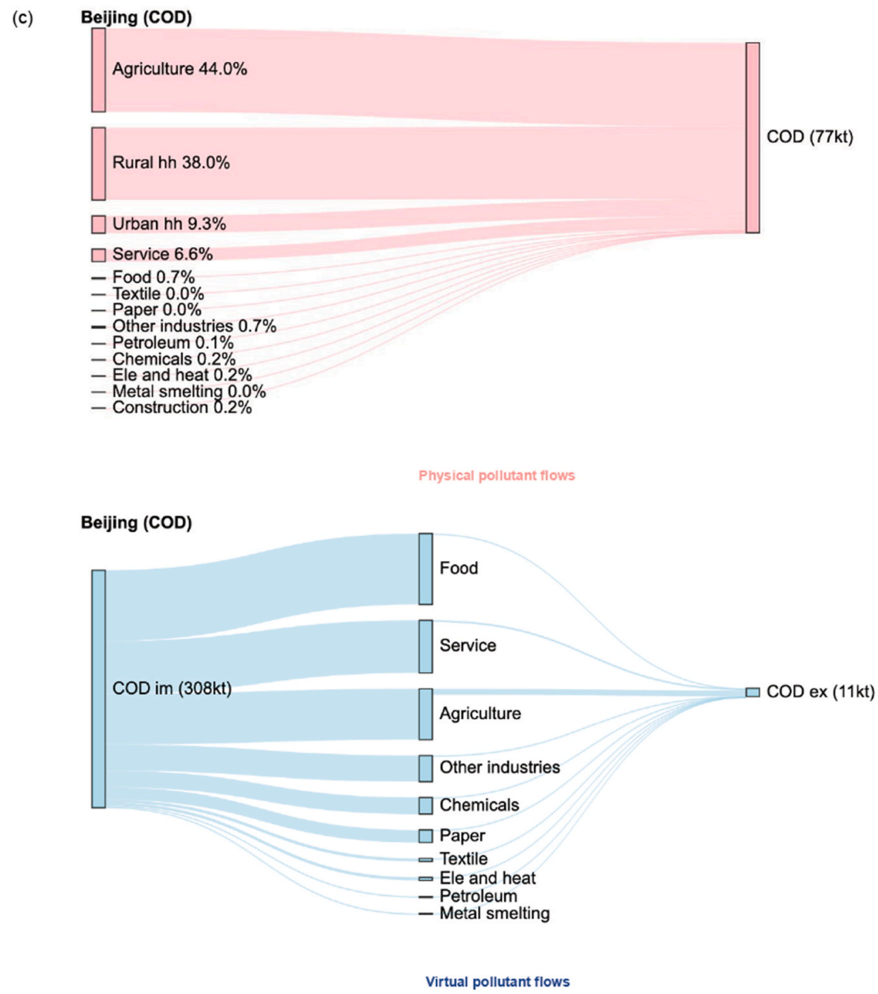

Fig. 1. (*continued*).

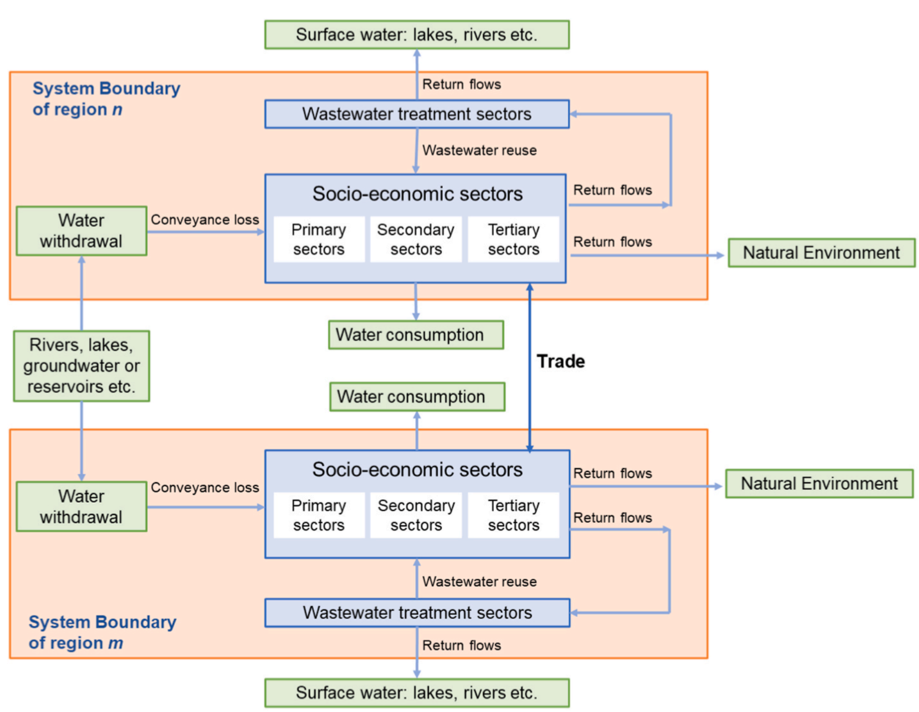

Fig. 2. Framework of the societal water cycle.

experiencing water stress. Finally, according to scenario analysis, we propose pathways to simultaneously mitigate quantity and quality stress in each province by improving the water use efficiency of each sector across 31 provinces by avoiding water conveyance loss and return flows.

2.2. Physical water quantity and pollutant flow analysis

For physical water quantity flows, we account for water conveyance loss, water consumption, return flows to wastewater treatment plants, and return flows directly discharged to the environment from the water use sectors. These sectors include agriculture, 26 industries, construction, services, urban and rural households, as well as environmental flow augmentation for each province. Our approach to accounting for physical water quantity flows relies on water balance and material flow analysis.

Regarding physical water pollutant flows, our analysis takes into account the pollutant loads of COD, NH_3-N, TN, and TP released into the environment. These pollutants originate from various sources, including agriculture, 26 industries, construction, services, urban and rural households. For a comprehensive understanding of our methodologies for both physical water quantity and pollutant flow analysis, please refer to the Supporting Information SI 1 for detailed explanations.

2.3. Virtual water quantity and virtual water pollutant flow analysis

We apply an Environmental Extended Multi-Regional Input-Output (EEMRIO) model to trace virtual water quantity (i.e., virtual water loss, virtual water consumption, virtual return flows including virtual returning flow to WWTP and virtual return flows discharging to the environment) and virtual water pollutants (i.e., virtual COD discharge, virtual NH_3-N discharge, virtual TN discharge, and virtual TP discharge) across each sector for each province in China (Feng et al., 2019; Miller and Blair, 2021; Wiedmann, 2009). The MRIO (Multi-Regional Input-Output) table in 2017 is from CEADs (China Emission Accounts and Datasets) (Zheng et al., 2020). It comprises 42 sectors, including 1 agricultural sector, 26 industrial sectors, 1 construction sector, and 14 service sectors. We merge the 14 service sectors into 1 sector to alighn with water quantity and pollutant data of the service sector. The detailed method for virtual water quantity and virtual water pollutant flow analysis is shown in Supporting Information SI 1.

2.4. Water stress assessment

Water stress assessment in this study includes two parts: water quantity stress and water quality stress. Water quantity stress is used to measure whether a province suffers from water shortage or not. Water quality stress reflects the degree of water pollution induced by discharged polluted wastewater or return flows from agriculture, industry, services, and households. By evaluating water quantity and quality stress levels, we can identify the provinces that suffer from water shortage and water pollution.

2.4.1. Water quantity stress

Water quantity stress is defined as the ratio of annual water withdrawal to water availability minus environmental flow requirements (FAOUN Water, 2021a).

$$Water\ stress_{quantity_i} = \frac{WW_i}{WA_i - EFR_i} \tag{1}$$

$$WW_i = WU_i - WS_{uncon_i} \tag{2}$$

Where, *Water quantity stress*$_i$ is water quantity stress level. WW_i is annual water withdrawal in each province. Water withdrawal means withdrawn surface water and groundwater. Water withdrawal is calculated by total water use WU_i including water loss minus unconventional water supplies WS_{uncon_i}, which are rainwater utilization, wastewater reclamation, desalinated seawater, and treated dewatering from mining sectors. WA_i is water availability from Water Resources Bulletin from each province in 2017. We used the indicator of "Environmental Flow Percentage" under "Present Day Environmental Management Class" to estimate the environmental flow requirement, which represents the "percentage of natural flow required to maintain the current condition of the river". The environmental flow requirement at the provincial level, denoted as EFR_i, is calculated by multiplying water availability by the environmental flow percentage. The environmental flow percentage was obtained from the Global Environmental Flow Information System at the provincial level (GEFIS, https://eflows.iwmi.org/). Detailed methodologies for determining the environmental flow percentage and the development of GEFIS can be found in the report "Global Environmental Flow Information for the Sustainable Development Goals" (Sood et al., 2017). Water quantity stress values are categorized into five levels: 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) (FAOUN Water, 2021a).

2.4.2. Water quality stress

Water quality stress refers to the ratio of provincial grey water footprint to water availability minus environmental flow requirements (Liu et al., 2016; Wang et al., 2025).

$$Water\ stress_{quality_i} = \frac{GWF_{total_i}}{WA_i - EFR_i} \tag{3}$$

$$GWF_{total_i} = GWF_{agr_i} + GWF_{ind_i} + GWF_{con_i} + GWF_{ser_i} + GWF_{urban,hh_i} + GWF_{rural,hh_i} \tag{4}$$

Where, *Water stress*$_{quality_i}$ is water pollution-induced stress in province *i*. GWF_{total_i} is provincial total grey water footprint. GWF_{agr_i}, GWF_{ind_i}, GWF_{con_i}, GWF_{ser_i}, GWF_{urban,hh_i} and GWF_{rural,hh_i} are grey water footprints from agriculture, industry, construction, services, and urban and rural households.

$$GWF_{agr_i} = GWF_{farm_i} + GWF_{liv_i} \tag{5}$$

$$GWF_{farm_i} = \max\left(GWF_{farm,TN_i}, GWF_{farm,TP_i}\right) \tag{6}$$

$$GWF_{liv_i} = \max\left(GWF_{liv,TN_i}, GWF_{liv,TP_i}, GWF_{liv,COD_i}, GWF_{liv,NH3-N_i}\right) \tag{7}$$

$$GWF_{farm\ or\ liv_{i,j}} = \frac{Pollutant\ load_{i,j}}{C_{maxj}} \tag{8}$$

Where, GWF_{farm_i} and GWF_{liv_i} are grey water footprint from farming and livestock in province *i*. GWF_{farm,TN_i} and GWF_{farm,TP_i} are TN and TP grey water footprint of farming. GWF_{liv,TN_i}, GWF_{liv,TP_i}, GWF_{liv,COD_i} and $GWF_{liv,NH3-N_i}$ are TN, TP, COD, NH_3-N grey water footprint of livestock. $GWF_{farm\ or\ liv_{i,j}}$ is the grey water footprint of pollutant *j* of farming and livestock in province *i*. *Pollutant load*$_{i,j}$ is pollutant load of pollutant *j* in province *i*. C_{maxj} is the maximum acceptable concentration of the ambient water quality of pollutant *j*. In this study, C_{maxj} is the third grade of China's Environmental Quality Standards for Surface Water (Ministry of Environmental Protection of the People's Republic of China (MEPPRC), 2002). The third grade indicates the water is suitable for fishing, swimming, and aquaculture. C_{maxTN}, C_{maxTP}, C_{maxCOD} and $C_{maxNH3-N}$ are 1, 0.2, 20 and 1 mg/L.

$$GWF_{ind_i} = \sum_{k=1}^{k=26} GWF_{ind_{k,i}} \tag{9}$$

$$GWF_{ind_{k,i}} = \max\left(GWF_{ind,TN_{k,i}}, GWF_{ind,TP_{k,i}}, GWF_{ind,COD_{k,i}}, GWF_{ind,NH3-N_{k,i}}\right) \tag{10}$$

$$GWF_{ind_{k,i,j}} = \begin{cases} 0 \left(\frac{Load_{ind_{k,i,j}}}{C_{maxj}} < RF_{ind_{k,i}} \right) \\ \frac{Load_{ind_{k,i,j}}}{C_{maxj}} - RF_{ind_{k,i}} \left(\frac{Load_{ind_{k,i,j}}}{C_{maxj}} > RF_{ind_{k,i}} \right) \end{cases} \quad (11)$$

Where, GWF_{ind_i} is the grey water footprint of the industry sector in province *i*. $GWF_{ind_{k,i}}$ is the grey water footprint of industry *k* in province *i*. $GWF_{ind_{k,i,j}}$ is the grey water footprint of pollutant *j* in industry *k* in province *i*. $RF_{ind_{k,i}}$ are return flows of industry *k* in province *i*.

$$GWF_{m_i} = max\left(GWF_{m_{i,j}}\right) \quad (12)$$

$$GWF_{m_{i,j}} = \begin{cases} 0 \left(\frac{Load_{m_{i,j}}}{C_{maxj}} < RF_{m_{i,j}} \right) \\ \frac{Load_{m_{i,j}}}{C_{maxj}} - RF_{m_i} \left(\frac{Load_{m_{i,j}}}{C_{maxj}} > RF_{m_{i,j}} \right) \end{cases} \quad (13)$$

Where, $GWF_{m_{i,j}}$ is the grey water footprint of pollutant *j* in sector *m*. *m* represents construction, services, and urban and rural households. RF_{m_i} are return flows from sector *m* in province *i*.

When $Water\ stress_{quality_i}$ is greater than 1, province *i* suffers from water pollution induced stress, otherwise, province *i* has no water quality stress.

2.5. Scenario analysis

Water conservation is critical in reducing water waste and boosting water use efficiency, which in turn could alleviate water stress. However, there is a lack of understanding about the water conservation potential across sectors, the key sectors that contribute to mitigating water stress, and the pathway to alleviate water stress in each province. To address these challenges, we design scenarios based on the results of MFA-IOA analysis and water stress assessment.

Firstly, we design four scenarios to compare the potential of agriculture, 26 industries, and other sectors (services and urban households) to mitigate water stress through water conservation, as shown in Table 1. In scenario 1, we only reduce water loss and return flows in agriculture and assess the resulting reduction in provincial water quantity and quality stress. In scenarios 2 and 3, 26 industries (scenario 2) and services and urban households (scenario 3) are designed to reduce water leakage and return flows, respectively. In scenario 4, all socio-economic sectors and urban households, except for rural households and environmental flow augmentation, are assumed to avoid water loss and return flows. We use this scenario to evaluate the mitigation of provincial water quantity and quality stress. Subsequently, by comparing scenarios 1–3 with scenario 4, we can identify the significant socio-economic sectors (agriculture, industry, services and urban households) that contribute to water stress mitigation and their reduction potential. Finally, based on scenario 4, we rank the top 5 subsectors with the highest potential to reduce water stress in each province, so as to propose a pathway to mitigate water stress in each province.

The core for the quantity stress scenario setting is to avoid water conveyance loss and return flows through adjusting parameters of water conveyance loss rate (i.e., the ratio of water loss to the sum of water loss, water consumption, and return flows) and water consumption ratio (i.e., the ratio of water consumption to the sum of water consumption and return flows). We set strict values for the water loss rate and water consumption ratio for our scenario analysis. The water leakage rate is set at 8 %, as it is expected to reach this level in most provinces by 2025 (National Development and Reform Commission and Ministry of Housing and Urban-Rural Development, 2022). We assume an irrigation water loss rate of 20 %, which is slightly lower than the predicted loss rate of 25 % in Beijing for 2025 (Ministry of Water Resources and National Development and Reform Commission, 2022), the lowest value among all provinces. To minimize return flows to specific sectors, we adopt the strictest sectoral water consumption ratio for return flow reduction. This ratio was derived from the maximum water consumption ratio for a specific sector in 31 provinces. Table 2 summarizes the mean, maximum, and designed water consumption ratios for each sector. We make two assumptions for the water quantity stress scenarios: (1) The value added for each economic sector is not changed. (2) To produce the same value-added, we assume that water consumption remains the same. Methods for quantifying water loss, return flows, and gross water use across scenarios are detailed in Supporting Information SI 1.

Table 1
Scenario setting for water stress mitigation.

Scenarios	Scenario setting	Parameters setting	
		Water conveyance loss rate	The ratio of water consumption to the sum of water consumption and return flows
Baseline (BL)	The original situation in 2017	• Irrigation: 26–57 % • Industry: 10–29 % • Urban households: 9–26 % • Rural households: 7–16 %	• Irrigation: 46–90 % (min-max) • Livestock: 60–96 % (min-max) • 26 industrial sectors and construction sectors: See Table 2 (ave-max) • Service sectors: 18–62 % (min-max) • Urban households: 18–50 % (min-max) • Rural households:78–97 % (min-max)
Scenario 1	Water loss and return flows of agricultural sectors are reduced	• Irrigation: 20 %	• Irrigation: 90 % • Livestock: 100 %
Scenario 2	Water leakage and return flows of 26 industrial sectors and construction sectors are reduced	• 26 industrial and construction sectors: 8 %	• See Table 2
Scenario 3	Water leakage and return flows of service sectors and urban households are reduced	• Service sectors and urban households are reduced: 8 %	• Service sectors and urban households: 70 %
Scenario 4	Water conveyance loss and return flows from agricultural, 26 industrial, service and construction sectors and urban households are reduced	• Irrigation: 20 % • 26 industrial, service and construction sectors and urban households: 8 %	• Irrigation: 90 % • Livestock: 100 % • 26 industrial sectors and construction sectors: See Table 2 • Service sectors and urban households: 70 %

Note: The water conveyance loss rate for point-source sectors is set at 8 %, as it is expected to reach this level in most provinces by 2025 (National Development and Reform CommissionMinistry of Housing and Urban-Rural Development, 2022). We assume an irrigation water loss rate of 20 %, which is slightly lower than the predicted rate of 25 % in Beijing for 2025 (Ministry of Water Resources and National Development and Reform Commission, 2022), the lowest value among all provinces. The strictest water consumption ratio for each sector is determined by either the sectoral maximum value in 2017 or a value close to the maximum.

Table 2
Parameter design of the water consumption ratio for scenario setting.

Sectors	The ratio of water consumption to the sum of water consumption and return flows (unit: %)		
	Average in 2017	Maximum in 2017	Adopted the strictest water consumption ratio for scenario analysis
Agriculture, Forestry, Animal Husbandry and Fishery-irrigation	38	87	90
Agriculture, Forestry, Animal Husbandry and Fishery-non-irrigation	79	100	100
Mining and washing of coal	31	100	100
Extraction of petroleum and natural gas	61	100	100
Mining and processing of metal ores	51	100	100
Mining and processing of nonmetal and other ores	54	100	100
Food and tobacco processing	33	51	60
Textile industry	27	63	70
Manufacture of leather, fur, feather, and related products	26	57	70
Processing of timber and furniture	58	100	100
Manufacture of paper, printing and articles for culture, education, and sport activity	33	91	95
Processing of petroleum, coking, processing of nuclear fuel	67	98	100
Manufacture of chemical products	56	91	100
Manuf. of non-metallic mineral products	86	100	100
Smelting and processing of metals	75	100	100
Manufacture of metal products	48	98	100
Manufacture of general-purpose machinery	46	100	100
Manufacture of special-purpose machinery	43	100	100
Manufacture of transport equipment	46	100	100
Manufacture of electrical machinery and equipment	47	97	100
Manufacture of communication equipment, computers and other electronic equipment	24	40	50
Manufacture of measuring instruments	39	100	100
Other manufacturing and waste resources	47	98	100
Waste resources	63	100	100
Repair of metal products, machinery, and equipment	40	100	100
Production and distribution of electric power and heat power	93	100	100
Production and distribution of gas	65	100	100
Production and distribution of tap water	–	–	–
Construction	71	95	95
Service	34	62	70
Urban households	32	50	60
Rural households	86	97	no change for each province

Note: The strictest water consumption ratio in each sector is determined by either the sectoral maximum value in 2017 or a value close to the maximum. The water consumption ratio for rural households in each province remains unchanged as it is already very high.

2.6. Limitations

We mainly consider water quantity stress at each stage of the societal water cycle, but do not consider the changes in water quality stress that occur throughout the process of withdrawal and consumption due to a lack of data. Future work should integrate water quality data by mapping the flows of water pollutants from economic activities to better capture how pollution transfers between regions and contributes to water stress (Hoekstra et al., 2011; Sun et al., 2023). In addition, it should be noted that the societal water cycle analysed in this study is based on administrative boundaries, which may not align with actual watershed boundaries, leading to an incomplete understanding of the recharge or pollution of water resources (Cohen, 2011; Davidson and de Loë, 2014). It is important to acknowledge that the examination of only four conventional water pollutants (COD, NH_3-N, TN, and TP) for each sector may lead to an underestimation of water quality stress, since industries that have a high grey water footprint for metal pollutants, which are not captured in this study, may result in an underestimation of the provincial grey water footprint and water quality stress (Feng et al., 2024; Huang et al., 2022). Ignoring sectoral and provincial heterogeneity in scenario design is also a limitation of this research. This study uses sector classification based on the sectoral structure in an input-output (IO) table, which ignores heterogeneity within sectors. This heterogeneity affects the determination of the strictest sectoral water consumption ratio in scenario analysis, as there may be significant variations in water consumption ratios within sectors (Lenzen, 2011). In addition, sectoral water consumption ratios in scenario settings may be too strict for certain provinces due to provincial heterogeneity. For example, setting the strictest water consumption ratio for irrigation at 0.9 may not be appropriate for a province where rice is the dominant crop (Mallareddy et al., 2023).

Finally, we assumed each industry's value-added and output remain unchanged under different water-saving scenarios, consistent with common simplifying assumptions in IO-based scenario analysis (Miller and Blair, 2021). In practice, however, water-saving measures may trigger a rebound effect (Grafton et al., 2018), leading to an increase in water usage. For instance, in the context of irrigation, reducing water withdrawal, which is often pursued by increasing irrigation efficiency, defined as "ratio of the volume of all irrigation water beneficially used on a farmer's field [predominantly, evapotranspiration (ET) by crops and salt removal to maintain soil productivity] to the total volume of irrigation water applied" (Grafton et al., 2018), may incentivize farmers to expand the irrigation area or shift to more water-intensive crops, ultimately resulting in higher water use for irrigation purposes. This rebound phenomenon has been documented in numerous studies of irrigation modernization and efficiency improvements (Li and Zhao, 2018; Xu et al., 2021), highlighting the need for water conservation policies to account for behavioral and economic responses (Grafton et al., 2018).

3. Results

3.1. Flows of water quantity and pollutants

Tracing the flows of physical water quantity, physical water pollutants, virtual water quantity, and virtual water pollutants in the societal water cycle of 31 provincial-level administrative regions (provinces, municipalities, and autonomous regions, hereafter referred to as the 31 provinces) is the foundation for the subsequent water stress assessment and mitigation, as shown in the framework in Fig. 1. Detailed information about the MFA-IOA results of these four types of flows for the 31 provinces in China can be found in Figure S1-Figure S4.

3.2. Water quantity stress within societal water cycle

Based on MFA-IOA results, we first analyse the water quantity stress of each stage of the societal water cycle in terms of physical water and virtual exported water (as shown in Fig. 3). The results show that, at the provincial level, water consumption contributed 20–59 % to quantity stress, while water loss and return flows contributed the remaining 36–80 %. In other words, provincial water use efficiency, the ratio of water consumption to withdrawal, ranges from 0.20 to 0.59, with 36–80 % of water withdrawal not being utilized effectively. In 19 provinces where agricultural water use is prevalent, the high share of agricultural water loss and return flows contribute to 42–71 % of quantity stress. In highly urbanized provinces, i.e., Shanghai and Beijing, where water is primarily used for industry and households, water leakages and return flows to wastewater treatment plants are major contributors to water stress, accounting for over 36 % of water withdrawal. Attention must be directed to eliminating water leakage and return flows to wastewater treatment plants as a means of mitigating water stress in regions characterized by high levels of urbanization.

Virtual water export exacerbates water stress in exporting regions, but virtual export of return flows and water loss decreases the efficiency of virtual water export (i.e., the ratio of virtual water export for consumption to virtual water withdrawal for export) and could be avoided by improving local water use efficiency. To understand efficiency of virtual water trade in each exporting province, we also quantify and compare different types of virtual water export in the societal water cycle in Fig. 3. It shows that virtual export of return flows and water loss contributes 39–89 % of virtual water withdrawal at the provincial level, indicating that virtual water export efficiency ranges from 11 to 61 %. In the highly urbanized regions of Beijing and Shanghai, virtual export of water leakage and return flows to wastewater treatment plants accounted for a much higher proportion than in other regions, with 42 % and 49 % of export-induced quantity stress, respectively. The results show that the majority of provinces in China have great potential to improve local virtual water export efficiency by reducing ineffective water use, water loss, and return flows.

3.3. Key sectors contributing to water stress

We then compare sectoral water quantity and quality stress to identify key sectors contributing to water stress in each province. The results of this comparison are presented in Fig. 4. In most provinces, agriculture is the main sector responsible for water use, accounting for 33–93 % of total water use, with the exceptions of Beijing and Shanghai. In Beijing, the largest proportion of total water use (32 %) is for environmental flow augmentation, which refers to the practice of increasing the flow of water in natural water bodies, such as lakes, rivers, wetlands, and urban environmental landscapes, through human-made measures rather than precipitation and runoff. In Shanghai, industrial water use accounts for 59 In Shanghai, industrial water use accounts for 59% of

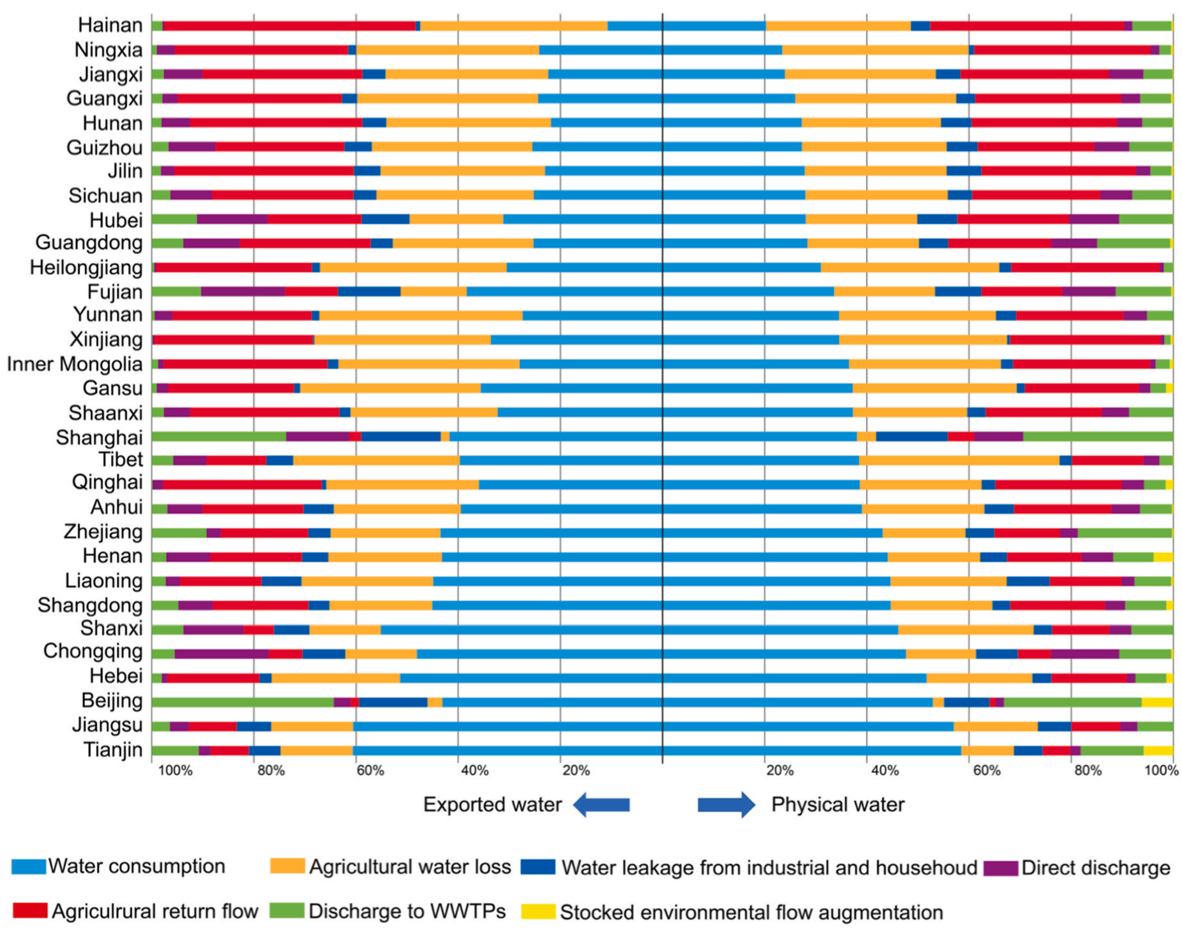

Fig. 3. Comparison of water quantity stress at different stages of the societal water cycle. The provincial ranking is arranged in ascending order based on physical water consumption percentage. **Water consumption** refers to total water consumption of all socio-economic sectors. **Agricultural water loss** is conveyance loss included by agricultural water use. **Water leakage** refers to conveyance loss due to water use of point-source sectors (i.e., industry, construction, services, households). **Direct discharge** and **Discharge to WWTPs** refer to return flows discharging to the environment directly and to WWTPs from point-source sectors. **Stocked environmental flow augmentation** refers to environmental flow augmentation that is not evaporated but is stocked in rivers and lakes.

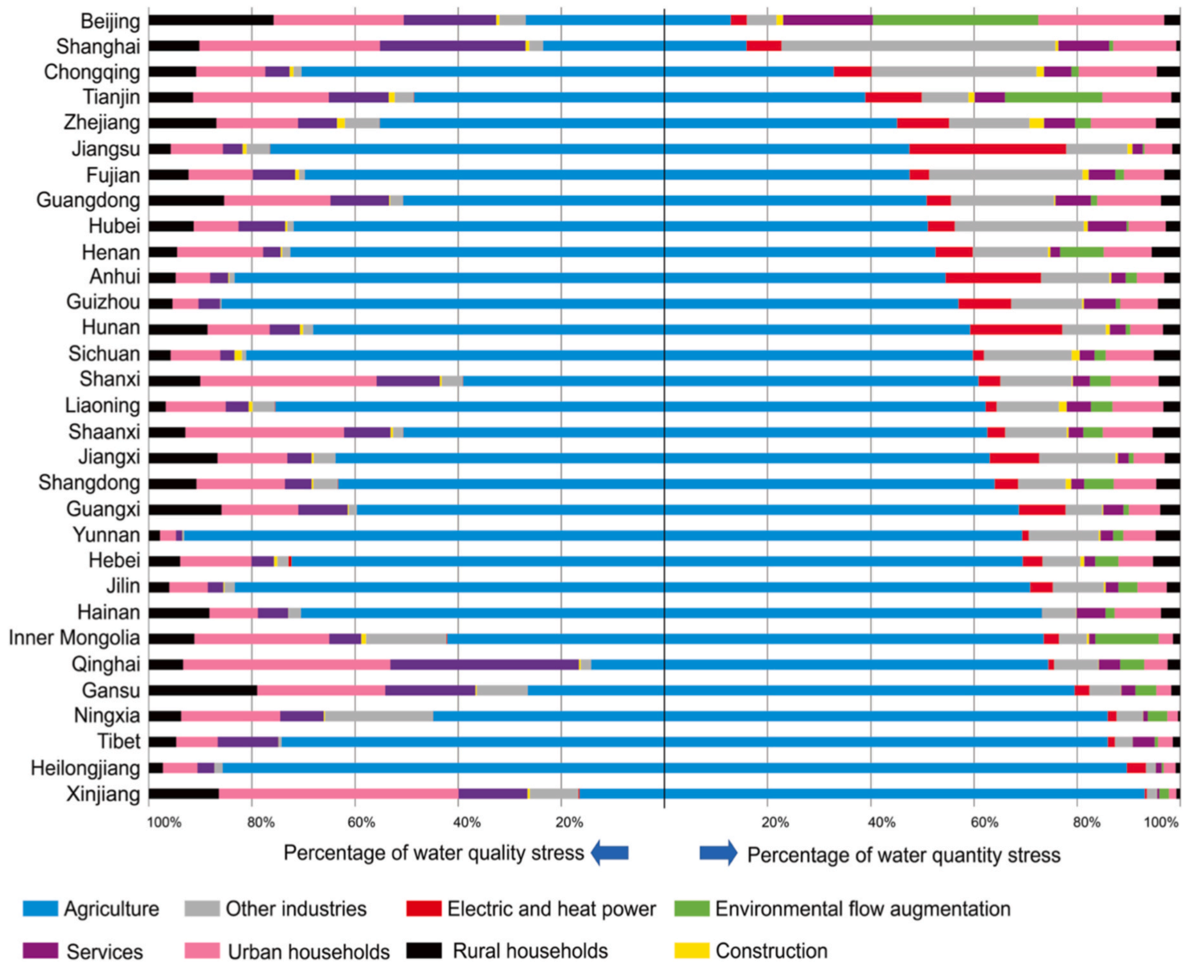

Fig. 4. Sectoral water quantity and quality stress comparison. The provincial ranking is arranged in ascending order based on the percentage of sectoral water quantity stress. In this figure, we classify industry (industry number 2–27) into Electric and heat power (industry number 25) and other industries (industry number 2–24, 26 and 27).

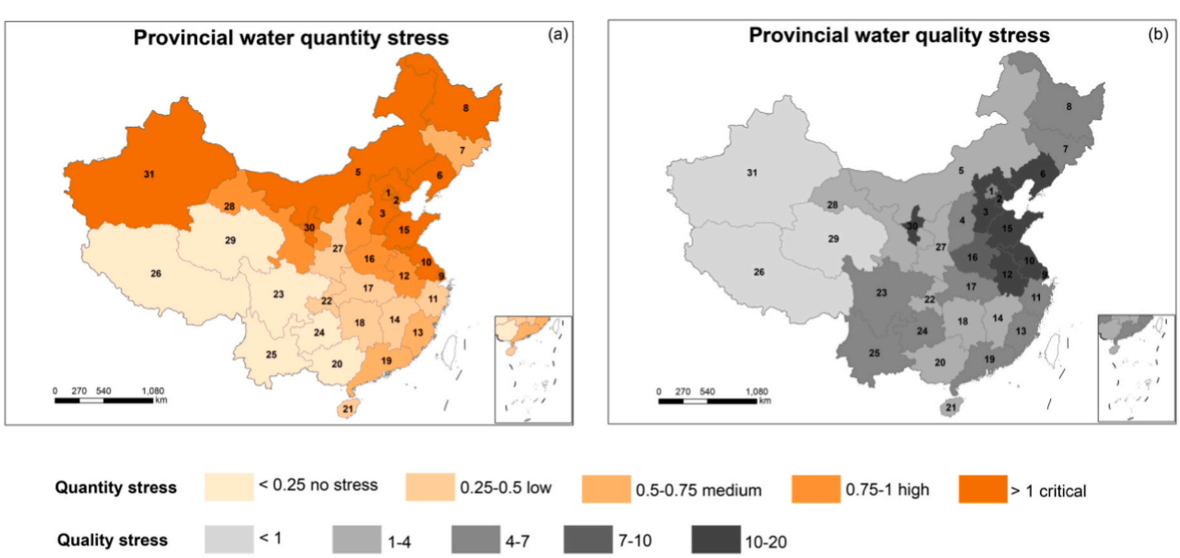

Fig. 5. Provincial water stress in China in 2017. Province IDs: 1. Beijing; 2. Tianjin; 3. Hebei; 4. Shanxi; 5. Inner Mongolia; 6. Liaoning; 7. Jilin; 8. Heilongjiang; 9. Shanghai; 10. Jiangsu; 11. Zhejiang; 12. Anhui; 13. Fujian; 14. Jiangxi; 15. Shandong; 16. Henan; 17. Hubei; 18. Hunan; 19. Guangdong; 20. Guangxi; 21. Hainan; 22. Chongqing; 23. Sichuan; 24. Guizhou; 25. Yunnan; 26. Tibet; 27. Shaanxi; 28. Gansu; 29. Qinghai; 30. Ningxia; 31. Xinjiang.

total water use. In 25 out of 31 provinces, the agricultural sector contributes to 42–93 % of water quality stress. Industrial water pollution contributes to quality stress at a low level (0.2–10 %), with the exceptions of Ningxia (20 %) and Inner Mongolia (16 %). In some provinces, households are significant sources of pollution (>45 %), such as in Xinjiang, Beijing, Qinghai, Gansu, and Shanghai. It is worth noting that high water use by a particular sector does not necessarily correspond to a high level of water pollution. For example, in Xinjiang, the contribution of agriculture to quality stress is relatively low (16.5 %), despite agricultural water use accounting for 93 % of water use. In Shanghai, the industrial sectors are the largest water consumers (59 %), but the induced quality stress is very small (2.7 %).

3.4. Provincial water stress and hotspots

Fig. 5 shows that 25 out of 31 provinces in China experience various levels of water quantity stress, with Ningxia being the most stressed province, followed by Shanghai and Jiangsu. In addition, 28 out of 31 provinces experience pollution-induced stress, as indicated by quality stress levels higher than 1, except for Xinjiang, Qinghai, and Tibet.

Given that the study employs China's provincial environmental flow requirements obtained from the Global Environmental Flow Information System (GEFIS) (FAOUN Water, 2021a) to evaluate water quantity and quality stress, the results of the estimated provincial water stress may differ from those that ignore environmental flow requirements (Mekonnen and Hoekstra, 2016; White et al., 2015; Zeng et al., 2013; Zhao et al., 2015b) or assume that 80 % of water availability is used for environmental flow requirements (Hoekstra et al., 2012; Ma et al., 2020a; Mekonnen and Hoekstra, 2016). Additionally, the latest United Nations standard for assessing water quantity stress level, which indicates a stressed region at a level higher than 0.25 (FAOUN Water, 2021), as opposed to the commonly used threshold of 0.2 in literature (EEA, 2009; Oki et al., 2001; Vörösmarty et al., 2000; Zhao et al., 2015b), may also lead to variations in the results of water quantity stress assessment. Despite these potential differences, it is widely recognized that most provinces in China face water quantity stress. For instance, it has been reported that in 2007, 23 of 30 studied provinces were affected by water quantity stress (Zhao et al., 2015b).

3.5. Water stress mitigation by avoiding sectoral water loss and return lows

The importance of socio-economic activities in contributing to regional water stress is highlighted by the need to assess the capability of various sectors to mitigate this stress. This is also reflected in the formulation of SDG target 6.4, which aims to increase water-use efficiency across all sectors and address the issue of water scarcity. In this study, we develop four scenarios to assess the ability of agriculture (scenario 1), 26 industrial sectors (scenario 2), services and urban households (scenario 3), and all sectors combined (scenario 4) to mitigate water stress by implementing stringent water conservation measures to eliminate water loss and return flows. We apply the strictest sectoral water consumption ratio and water loss rate (as shown in Tables 1 and 2) to each scenario to minimize return flows and water loss, and thus, minimize water withdrawal, while holding water consumption constant. The stringent sectoral water consumption ratios are established using the maximum sectoral water consumption ratios calculated from the dataset that we created. The results of our analysis, which include measures of quantity and quality mitigation, are presented in Fig. S5(a)–(b).

Fig. S5(a) shows that reducing water loss and return flows from the agricultural sector can significantly mitigate water quantity stress for most provinces (more than 20 %), except for the highly urbanized regions of Beijing, Shanghai, and Tianjin. In terms of water quality stress, as shown in Fig. S5(b), agriculture is a critical sector for alleviating pollution-induced stress in 22 provinces, with mitigation potential ranging from 31 % to 68 %. The results of scenario 2, which focuses on reducing water losses in the industrial sector, indicate that such measures have limited potential for decreasing water quality stress in most provinces, with less than 5 %. In certain provinces, such as Qinghai, Shanghai, and Xinjiang, reducing return flows from domestic water use (water used for construction, services, and households) is crucial for mitigating water quality stress, as these measures can lead to a reduction in water quality stress of more than 40 %.

Furthermore, based on scenario 4, we propose strategies to mitigate water stress in each province by reducing water loss and return flows in the top 5 sub-sectors (industry categories listed in Table S1) with the greatest potential for reducing water stress. Table S3–S4 list the top 5 industries that could contribute to the mitigation of quantity stress and quality stress. For most provinces, agriculture (sector 1) and urban households (sector 31) are the top two sectors for mitigating quantity stress and quality stress. Therefore, improving water use efficiency and reducing water loss and return flows in agriculture and urban households is the most effective way to reduce both quantity and quality stress in most provinces of China. The top 5 sectors listed in Table S3–S4 have the potential to reduce quantity stress by 22–75 % and quality stress by 23–76. In Supporting Information SI 2, we rank the potential to mitigate quantity and quality stress for all sectors in each province, providing a basis for policymakers to develop sector-specific strategies for water stress mitigation.

4. Discussion

Previous studies have consistently overlooked the impact of each stage of the societal water cycle on water stress and often failed to explore the relationship between water quantity and quality stress (Liu et al., 2016, 2017; Zeng et al., 2013; Zhao et al., 2016). However, our assessment of water stress based on the societal water cycle in this study shows that the impacts of water loss and return flows on water stress are significant, and water quality stress can be affected by polluted return flows. Water loss can be reduced or avoided through the update or maintenance of supplied pipelines, and return flows can be reduced through the use of advanced water-saving technologies or by restricting water use frequency and quantity. Additionally, in industrial sectors, replacing traditional water-cooling technologies with air cooling can significantly reduce water use by avoiding not only water loss and return flows, but also water consumption (Zhang et al., 2016, 2018; Zhang and Anadon, 2014). Our assessment of water stress in 2017 reveals that most provinces in China still have significant potential to mitigate water stress by reducing return flows, agricultural water loss, and water leakage from industry and households, as these account for 36–79 % of quantity stress. Meanwhile, return flows are responsible for 100 % of water quality stress, as they are always polluted. Water quality stress can be decreased if return flows are reduced, as long as pollutant concentrations to the environment remain the same due to effective treatment technologies. The results of this analysis also demonstrate that each province in China has a unique pathway through the societal water cycle, emphasizing the necessity of province-specific water stress mitigation strategies rather than a one-size-fits-all approach.

Improving water-use efficiency is a widely accepted approach to addressing water stress (Fang et al., 2010; FAOUN Water, 2021b; Hamdy et al., 2003; Zhao et al., 2015b; Zhou et al., 2020). This study differs from prior research by presenting specific ways to improve water use efficiency. Instead of just offering general recommendations to reduce total water withdrawal and implement water-saving technologies (Doeffinger and Hall, 2020; Wang et al., 2017; Zhou et al., 2020), this study specifically highlights that improving water use efficiency through the reduction of water loss and return flows while keeping consumption constant could significantly reduce water stress by 44–74 % in each province. Our analysis shows that the irrigation water conveyance loss rate in China is still high, with values ranging from 26 % to 57 %. Irrigation return flows account for 27–46 % of total irrigation water use.

Consequently, average irrigation water consumption ratios of 38 % have great potential for improvement. The water leakage rate for water supply to industry, services, and households was 10–29 % of water withdrawal in 2017, and this value is expected to decrease to less than 9 % by 2025 for each province (National Development and Reform Commission and Ministry of Housing and Urban-Rural Development, 2022), according to The Fourteenth Five-Year Plan in China. Reducing water leakage has the potential to significantly improve water use efficiency. Table 2 presents the average and maximum water consumption ratios for each sector across all provinces. These ratios were calculated using our dataset that was developed through the integration of provincial water resources bulletins and the China Environmental Statistics Database (CESD) (Ministry of Environmental Protection of the People's Republic of China (MEPPRC), 2017), highlighting that many sectors in 31 provinces still have great potential for improving water use efficiency. Some industries have particularly low average consumptive ratios, emphasizing the need to set reasonable targets for water consumption ratios in specific sectors in China to improve water use efficiency and reduce return flows.

This study provides new perspectives for understanding virtual water trade by analysing physical water flows and virtual water flows. The conventional view holds that regional water savings in virtual water trade, measured by net virtual water import, can help mitigate water stress (Liu et al., 2019b). However, numerous studies have shown that virtual water trade can both mitigate and exacerbate regional water stress (Guan and Hubacek, 2007; Zhao et al., 2015b, 2019). Thus, water savings from virtual water trade do not address water stress (Liu et al., 2019b). This study contributes to the discourse by highlighting that water savings of physical water flows by reducing water loss and return flows throughout the societal water cycle are effective ways to mitigate water stress. Virtual water quantity flows in the societal water cycle are affected by physical water quantity flows. Increasing regional water use efficiency also improves virtual water export efficiency. Our research on virtual water withdrawal extends traditional quantification by classifying it into virtual water loss, virtual water consumption, and different virtual return flows. This advance enables the measurement of virtual water export efficiency, which holds significant implications for policymakers seeking to optimize virtual water export and thereby reducing competition with local water resources usage.

The separate analysis of quantity and quality stress, as seen in the current literature, does not effectively identify factors that concurrently influence both forms of stress and develop strategies to simultaneously mitigate them. This study utilizes the MFA-IOA approach to provide novel insights into the coupled assessment and mitigation of quantity and quality-based water stress within the societal water cycle. The framework and methodology presented in the study can be applied in other countries or globally by using data from the Exiobase global MRIO dataset, which contains sectoral information on water consumption, and TN and TP pollutants.

CRediT authorship contribution statement

Dan Wang: Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Reetik Kumar Sahu:** Writing – review & editing, Methodology, Formal analysis. **Taher Kahil:** Writing – review & editing, Methodology, Formal analysis. **Ting Tang:** Methodology, Formal analysis. **Wei Zhang:** Resources, Investigation. **Weili Ye:** Resources, Methodology, Investigation. **Guangxue Wu:** Methodology. **Zhuo Chen:** Resources, Methodology, Investigation. **Huimei Li:** Resources, Investigation. **Junxia Wang:** Resources. **Haoyuan Feng:** Methodology. **Yuli Shan:** Resources, Investigation. **Klaus Hubacek:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

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

Acknowledgements

We are grateful to Jianning Chen for his insightful discussion, valuable comments, and generous data sharing. Jianning is from the Center for Water Resources and River Affairs Management in the Water Resources Department in Fujian Province, China. D.W. thanks the International Institute for Applied Systems Analysis (IIASA), as this work was partly conducted during participation at the IIASA's Young Scientist Summer Programme (YSSP). D.W. thanks the support from Sustainable Society PhD Grant at University of Groningen and the China Scholarship Council (No. 201908440332). W.Y. was funded by Major Science and Technology Program for Water Pollution Control and Treatment of China (No.2018ZX07111001). G.W. was supported by Galway University Foundation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.147398.

Data availability

I have shared the link to my data

References

Bhaduri, A., Bogardi, J., Siddiqi, A., Voigt, H., Vörösmarty, C., Pahl-Wostl, C., Bunn, S.E., Shrivastava, P., Lawford, R., Foster, S., Kremer, H., Renaud, F.G., Bruns, A., Osuna, V.R., 2016. Achieving sustainable development goals from a water perspective. Front. Environ. Sci. 4. https://doi.org/10.3389/fenvs.2016.00064.

Cai, B., Jiang, L., Liu, Y., Zhang, W., Zhang, Z., 2023. The impact of interregional trade on both quantity- and quality-related water scarcity of Beijing-Tianjin-Hebei urban agglomeration in China. Sustain. Cities Soc. 88, 104270. https://doi.org/10.1016/j.scs.2022.104270.

Cohen, D., 2011. The watershed approach: challenges, antecedents, and the transition from technical tool to governance unit. Water Altern. (WaA) 4, 1–14.

Davidson, S.L., de Loë, R.C., 2014. Watershed governance: transcending boundaries. Water Altern. (WaA) 7, 367–387.

Doeffinger, T., Hall, J.W., 2020. Water stress and productivity: an empirical analysis of trends and drivers. Water Resour. Res. 56. https://doi.org/10.1029/2019WR025925 e2019WR025925.

EEA, 2009. Water Resources Across Europe : Confronting Water Scarcity and Drought (No. EA Report No 2/2009). European Environment Agency, Copenhagen.

Fang, Q.X., Ma, L., Green, T.R., Yu, Q., Wang, T.D., Ahuja, L.R., 2010. Water resources and water use efficiency in the North China plain: current status and agronomic management options. Agricult. Water Manag. Crop water Use Effici. Multiple Scales 97, 1102–1116. https://doi.org/10.1016/j.agwat.2010.01.008.

FAO, UN Water, 2021a. Progress on the level of water stress: global status and acceleration needs for SDG indicator 6.4.2. FAO and UN Water. https://doi.org/10.4060/cb6241en. Rome.

FAO, UN Water, 2021b. Progress on change in water-use efficiency: global status and acceleration needs for SDG indicator 6.4.1. FAO and UN Water. https://doi.org/10.4060/cb6413en. Rome.

Feng, K., Hubacek, K., Pfister, S., Yu, Y., Sun, L., 2014. Virtual scarce water in China. Environ. Sci. Technol. 48, 7704–7713. https://doi.org/10.1021/es500502q.

Feng, K., Hubacek, K., Yu, Y., 2019. Local Consumption and Global Environmental Impacts: Accounting, trade-offs and Sustainability. Routledge, London. https://doi.org/10.4324/9781315739595.

Feng, Y., Na, L., Rongxiang, W., 2024. Grey water footprint model of heavy metal based on the hazard quotient. Ecol. Indic. 162, 112052. https://doi.org/10.1016/j.ecolind.2024.112052.

Grafton, R.Q., Williams, J., Perry, C.J., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S.A., Wang, Y., Garrick, D., Allen, R.G., 2018. The paradox of irrigation efficiency. Science 361, 748–750. https://doi.org/10.1126/science.aat9314.

Guan, D., Hubacek, K., 2007. Assessment of regional trade and virtual water flows in China. Ecol. Econ. 61, 159–170. https://doi.org/10.1016/j.ecolecon.2006.02.022.

Hamdy, A., Ragab, R., Scarascia-Mugnozza, E., 2003. Coping with water scarcity: water saving and increasing water productivity. Irrig. Drain. 52, 3–20. https://doi.org/10.1002/ird.73.

Hoekstra, A.Y., Chapagain, A.K., Mekonnen, M.M., Aldaya, M.M., 2011. The Water Footprint Assessment Manual: Setting the Global Standard, first ed. Earthscan, London, UK. https://doi.org/10.4324/9781849775526.

Hoekstra, A.Y., Mekonnen, M.M., 2012. The water footprint of humanity. Proc. Natl. Acad. Sci. USA 109, 3232–3237. https://doi.org/10.1073/pnas.1109936109.

Hoekstra, A.Y., Mekonnen, M.M., Chapagain, A.K., Mathews, R.E., Richter, B.D., 2012. Global monthly water scarcity: blue water footprints versus blue water availability. PLoS One 7, e32688. https://doi.org/10.1371/journal.pone.0032688.

Huang, Y., Han, R., Qi, J., Duan, H., Chen, C., Lu, X., Li, N., 2022. Health risks of industrial wastewater heavy metals based on improved grey water footprint model. J. Clean. Prod. 377, 134472. https://doi.org/10.1016/j.jclepro.2022.134472.

Lenzen, M., 2011. Aggregation versus disaggregation in input–output analysis of the environment. Econ. Syst. Res. 23, 73–89. https://doi.org/10.1080/09535314.2010.548793.

Li, H., Zhao, J., 2018. Rebound effects of new irrigation technologies: the role of water rights. Am. J. Agric. Econ. 100, 786–808. https://doi.org/10.1093/ajae/aay001.

Liu, J., Liu, Q., Yang, H., 2016. Assessing water scarcity by simultaneously considering environmental flow requirements, water quantity, and water quality. Ecol. Indic. 60, 434–441. https://doi.org/10.1016/j.ecolind.2015.07.019.

Liu, J., Yang, H., Gosling, S.N., Kummu, M., Flörke, M., Pfister, S., Hanasaki, N., Wada, Y., Zhang, X., Zheng, C., Alcamo, J., Oki, T., 2017. Water scarcity assessments in the past, present, and future: review on water scarcity assessment. Earths Future 5, 545–559. https://doi.org/10.1002/2016EF000518.

Liu, J., Zhao, D., 2020. Three-dimensional water scarcity assessment by considering water quantity, water quality, and environmental flow requirements: review and prospect. Chin. Sci. Bull. 65, 4251–4261. https://doi.org/10.1360/TB-2020-0918.

Liu, X., Tang, Q., Liu, W., Veldkamp, T.I.E., Boulange, J., Liu, J., Wada, Y., Huang, Z., Yang, H., 2019a. A spatially explicit assessment of growing water stress in China from the past to the future. Earths Future 7, 1027–1043. https://doi.org/10.1029/2019EF001181.

Liu, X., Tang, Q., Liu, W., Veldkamp, T.I.E., Boulange, J., Liu, J., Wada, Y., Huang, Z., Yang, H., 2019b. A spatially explicit assessment of growing water stress in China from the past to the future. Earths Future 7, 1027–1043. https://doi.org/10.1029/2019EF001181.

Ma, T., Sun, S., Fu, G., Hall, J.W., Ni, Y., He, L., Yi, J., Zhao, N., Du, Y., Pei, T., Cheng, W., Song, C., Fang, C., Zhou, C., 2020a. Pollution exacerbates China's water scarcity and its regional inequality. Nat. Commun. 11, 1–9. https://doi.org/10.1038/s41467-020-14532-5.

Ma, T., Zhao, N., Ni, Y., Yi, J., Wilson, J.P., He, L., Du, Y., Pei, T., Zhou, C., Song, C., Cheng, W., 2020b. China's improving inland surface water quality since 2003. Sci. Adv. 6. https://doi.org/10.1126/sciadv.aau3798 eaau3798.

Mallareddy, M., Thirumalaikumar, R., Balasubramanian, P., Naseeruddin, R., Nithya, N., Mariadoss, A., Eazhilkrishna, N., Choudhary, A.K., Deiveegan, M., Subramanian, E., Padmaja, B., Vijayakumar, S., 2023. Maximizing water use efficiency in rice farming: a comprehensive review of innovative irrigation management technologies. Water 15, 1802. https://doi.org/10.3390/w15101802.

Mekonnen, M.M., Hoekstra, A.Y., 2016. Four billion people facing severe water scarcity. Sci. Adv. 2, e1500323. https://doi.org/10.1126/sciadv.1500323.

Miller, R.E., Blair, P.D., 2021. Input-Output Analysis: Foundations and Extensions, third ed. Cambridge University Press. https://doi.org/10.1017/9781108676212.

Ministry of Environmental Protection of the People's Republic of China (MEPPRC), 2017. Annual Statistic Report on Environment in China. China Environmental Science Press, Beijing.

Ministry of Environmental Protection of the People's Republic of China (MEPPRC), 2002. Environmental Quality Standards for Surface Water.

Ministry of Water Resources, National Development and Reform Commission, 2022. Target control of total water use and water use intensity for 14th five-year plan [WWW Document]. URL. http://www.gov.cn/zhengce/zhengceku/2022-03/18/content_5679631.htm (accessed 9.30.22).

National Development and Reform Commission, Ministry of Housing and Urban-Rural Development, 2022. Organize and carry out the pilot construction of public water supply network leakage control [WWW Document]. URL. https://www.ndrc.gov.cn/xwdt/tzgg/202203/t20220315_1319313_ext.html (Accessed 30 9 22).

National Development and Reform Commission (NDRC), Ministry of Water Resources (MWR), 2021. Ministry of Housing and Urban-Rural Development (MHURD), Ministry of Industry and Information Technology (MIIT), Ministry of Agriculture and Rural Affairs (MARA). In: The 14th Five-Year Plan on Water-Saving Society Construction. National Development and Reform Commission, Beijing, China.

Oki, T., Agata, Y., Kanae, S., Saruhashi, T., Yang, D., Musiake, K., 2001. Global assessment of current water resources using total runoff integrating pathways. Hydrol. Sci. J. 46, 983–995. https://doi.org/10.1080/02626660109492890.

Sood, A., Smakhtin, V.U., Eriyagama, N., Villholth, K.G., Liyanage, N., Wada, Y., Ebrahim, G.Y., Dickens, C., 2017. Global Environmental Flow Information for the Sustainable Development Goals. International Water Management Institute. https://doi.org/10.5337/2017.201.

Sun, S., Konar, M., Tang, Q., Fu, G., Fang, C., Wang, J., Ni, Y., Ma, T., 2023. Tracing surface water pollution in China's supply chain. J. Hydrol. 624, 129960. https://doi.org/10.1016/j.jhydrol.2023.129960.

Sun, S., Zhou, X., Liu, H., Jiang, Y., Zhou, H., Zhang, C., Fu, G., 2021. Unraveling the effect of inter-basin water transfer on reducing water scarcity and its inequality in China. Water Res. 194, 116931. https://doi.org/10.1016/j.watres.2021.116931.

van Vliet, M.T.H., Flörke, M., Wada, Y., 2017. Quality matters for water scarcity. Nat. Geosci. 10, 800–802. https://doi.org/10.1038/ngeo3047.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. Science 289, 284–288. https://doi.org/10.1126/science.289.5477.284.

Wang, D., Chen, Z., Sahu, R.K., Kahil, T., Tang, T., Shan, Y., Zhang, W., Ye, W., Wu, G., Li, H., Hubacek, K., 2025. Impacts of water conservation, wastewater treatment, and reuse on water quantity and quality stress mitigation in China. J. Ind. Ecol. 29, 777–793. https://doi.org/10.1111/jiec.70006.

Wang, D., Hubacek, K., Shan, Y., Gerbens-Leenes, W., Liu, J., 2021. A review of water stress and water footprint accounting. Water 13, 201. https://doi.org/10.3390/w13020201.

Wang, T., Liu, S., Qian, X., Shimizu, T., Dente, S.M.R., Hashimoto, S., Nakajima, J., 2017. Assessment of the municipal water cycle in China. Sci. Total Environ. 607–608, 761–770. https://doi.org/10.1016/j.scitotenv.2017.07.072.

White, D.J., Feng, K., Sun, L., Hubacek, K., 2015. A hydro-economic MRIO analysis of the Haihe river Basin's water footprint and water stress. Ecol. Model. 318, 157–167. https://doi.org/10.1016/j.ecolmodel.2015.01.017.

Wiedmann, T., 2009. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. Ecological economics, special section: analyzing the global human appropriation of net primary production - processes, trajectories. Implications 69, 211–222. https://doi.org/10.1016/j.ecolecon.2009.08.026.

Xu, H., Yang, R., Song, J., 2021. Agricultural water use efficiency and rebound effect: a study for China. Int. J. Environ. Res. Publ. Health 18, 7151. https://doi.org/10.3390/ijerph18137151.

Zeng, Z., Liu, J., Savenije, H.H.G., 2013. A simple approach to assess water scarcity integrating water quantity and quality. Ecol. Indic. 34, 441–449. https://doi.org/10.1016/j.ecolind.2013.06.012.

Zhang, C., Anadon, L.D., 2014. A multi-regional input–output analysis of domestic virtual water trade and provincial water footprint in China. Ecol. Econ. 100, 159–172. https://doi.org/10.1016/j.ecolecon.2014.02.006.

Zhang, C., Zhong, L., Fu, X., Wang, J., Wu, Z., 2016. Revealing water stress by the thermal power industry in China based on a high spatial resolution water withdrawal and consumption inventory. Environ. Sci. Technol. 50, 1642–1652. https://doi.org/10.1021/acs.est.5b05374.

Zhang, C., Zhong, L., Wang, J., 2018. Decoupling between water use and thermoelectric power generation growth in China. Nat. Energy 3, 792–799. https://doi.org/10.1038/s41560-018-0236-7.

Zhang, L., Ma, Q., Zhao, Y., Chen, H., Hu, Y., Ma, H., 2023. China's strictest water policy: reversing water use trends and alleviating water stress. J. Environ. Manag. 345, 118867. https://doi.org/10.1016/j.jenvman.2023.118867.

Zhao, D., Hubacek, K., Feng, K., Sun, L., Liu, J., 2019. Explaining virtual water trade: a spatial-temporal analysis of the comparative advantage of land, labor and water in China. Water Res. 153, 304–314. https://doi.org/10.1016/j.watres.2019.01.025.

Zhao, H., Miller, T.R., Ishii, N., Kawasaki, A., 2022. Global spatio-temporal change assessment in interregional water stress footprint in China by a high resolution MRIO model. Sci. Total Environ., 156682 https://doi.org/10.1016/j.scitotenv.2022.156682.

Zhao, X., Liu, J., Liu, Q., Tillotson, M.R., Guan, D., Hubacek, K., 2015a. Physical and virtual water transfers for regional water stress alleviation in China. Proc. Natl. Acad. Sci. 112, 1031–1035. https://doi.org/10.1073/pnas.1404130112.

Zhao, X., Liu, J., Liu, Q., Tillotson, M.R., Guan, D., Hubacek, K., 2015b. Physical and virtual water transfers for regional water stress alleviation in China. Proc. Natl. Acad. Sci. USA 112, 1031–1035. https://doi.org/10.1073/pnas.1404130112.

Zhao, X., Liu, J., Yang, H., Duarte, R., Tillotson, M.R., Hubacek, K., 2016. Burden shifting of water quantity and quality stress from megacity Shanghai. Water Resour. Res. 52, 6916–6927. https://doi.org/10.1002/2016WR018595.

Zheng, H., Zhang, Z., Wei, W., Song, M., Dietzenbacher, E., Wang, X., Meng, J., Shan, Y., Ou, J., Guan, D., 2020. Regional determinants of China's consumption-based emissions in the economic transition. Environ. Res. Lett. 15, 074001. https://doi.org/10.1088/1748-9326/ab794f.

Zhou, F., Bo, Y., Ciais, P., Dumas, P., Tang, Q., Wang, X., Liu, J., Zheng, C., Polcher, J., Yin, Z., Guimberteau, M., Peng, S., Ottle, C., Zhao, X., Zhao, J., Tan, Q., Chen, L., Shen, H., Yang, H., Piao, S., Wang, H., Wada, Y., 2020. Deceleration of China's human water use and its key drivers. Proc. Natl. Acad. Sci. USA 117, 7702–7711. https://doi.org/10.1073/pnas.1909902117.