

## ARTICLE OPEN



# Spatial analysis connects excess water pollution discharge, industrial production, and consumption at the sectoral level

Siyu Hou<sup>1,2</sup>, Xu Zhao<sup>2</sup>, Yu Liu<sup>3,4</sup>, Martin R. Tillotson<sup>5</sup>, Shenglin Weng<sup>6</sup>, Hua Wang<sup>1</sup>, Yiping Li<sup>1</sup>, Baoyin Liu<sup>3</sup>, Kuishuang Feng<sup>7</sup> and Ning Zhang<sup>2</sup>

Linking of 'consumption-industrial production-surface water deterioration' is essential for industrialised economies to understand the mechanism of industrial water pollution. However, such a connection may mislead policy decisions if sectoral details are lacking. This study investigated excess pollution discharge from 11,094 industrial enterprises comprising 22 economic sectors through setting discharge thresholds on 1338 water function zones in Jiangsu Province, the most industrialised province in China. We further evaluated the contribution of final consumption in Chinese provinces to excess pollution discharge in Jiangsu via a national multi-region input–output table. Notably, despite typically heavy polluting sectors contributing the maximum excess pollution discharge, high-tech manufacturing sectors had a higher level of risk for excess pollution discharge. This was attributed to the spatial agglomeration of these sectors, with enterprises typically located in industrial parks. The increasing final consumption of specific sectors in both Jiangsu and other provinces may further drive excess pollution discharge in Jiangsu.

*npj Clean Water* (2022)5:4; <https://doi.org/10.1038/s41545-022-00152-7>

## INTRODUCTION

Industrialisation is an important driver of economic development and can be significant in alleviating poverty<sup>1,2</sup>. However, industrialisation also leads to water pollution, an unwanted byproduct, particularly prevalent in developing countries, which often lack control legislation and prevention infrastructure<sup>3–5</sup>. Water pollution discharged by industrial sectors has caused severe ecological degradation in the surface water environment and has yielded significant health problems in indigenous populations<sup>6–8</sup>. However, efforts to identify the impact that industrial sectors as pollution sources have on surface waters are usually conducted at coarse spatial resolutions<sup>9</sup>. Specifically, the discharge volume and location of enterprises affiliated with different industrial sectors are usually masked by aggregated information on industrial discharge<sup>10</sup>. Additionally, pollution discharge from industrial enterprises is virtually transported along complex industrial supply chains, which are largely outsourced by the final consumption beyond local boundaries through trade<sup>11</sup>. Neglecting investigations on the above information for industries would raise questions, such as which industrial enterprises or sectors have the largest contribution to water contamination and how the final consumption drives excess pollution discharge from industrial sectors? Answering these questions will help policymakers to understand and control surface water pollution from industrial sources based on both local and global perspectives.

A surface water network is a multipurpose system with varying designated functions in different sections of the network<sup>12,13</sup>. Classified as a point source, the impact that industrial pollution has on different surface water function zones is spatially heterogeneous and determined by complex pollution transportation mechanisms<sup>14</sup>. Many studies have evaluated the impact that pollution transportation has on surface water deterioration using a

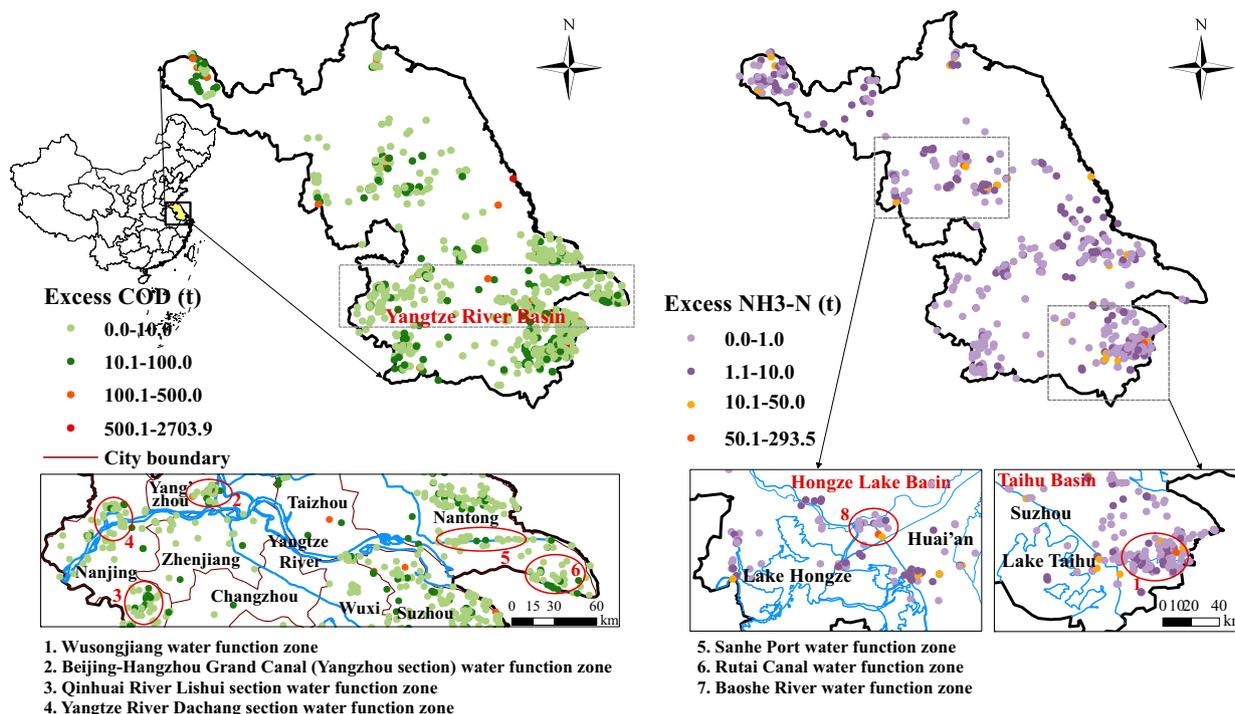
water quality model or monitoring approach<sup>15–17</sup>. However, these studies have typically accounted for pollution sources by starting from sewage outlets, thus failing to understand the origins and spatial characteristics of industrial pollution sources at the sectoral level.

Efforts have been made to further link water deterioration to anthropogenic pollution sources at regional scales. One group of studies applied statistical correlation analysis to achieve this goal<sup>18</sup>. For example, Ma et al.<sup>10</sup> applied a generalised linear model to link the changes in the surface water quality of China to anthropogenic water pollution discharge. Another group of studies have evaluated the impact that the excess discharge of water pollution has on the deterioration of the aquatic environment, which were based on efforts to build a regional safe operating space (threshold) for local water pollution management<sup>19</sup>. Liu et al.<sup>20</sup> developed a water pollution level indicator, i.e., the ratio between the grey water footprint and actual discharge of a river basin, to show the impact that nitrogen and phosphorus inputs have on global river basins. Yu et al.<sup>21</sup> quantified the excess total nitrogen discharge of China to the aquatic environment using an absolute nitrogen boundary, which was set according to water quality standards in different representative river basins. However, setting a single threshold for a river basin does not reflect the variations in the water quality conditions, water quality goals, and complex pollution transportation mechanisms in different sections of a surface water network. Hence, the water pollution discharge thresholds set in different water function zones of a surface water network are more policy relevant for controlling surface water pollution.

Until recently, studies identifying the impact that water pollution from different industrial sectors has on different sections of a surface water network were scarce. This was mainly owing to

<sup>1</sup>Key Laboratory of Integrated Regulation and Resource Development on Shallow Lakes, Ministry of Education, College of Environment, Hohai University, 210098 Nanjing, China.

<sup>2</sup>Institute of Blue and Green Development, Shandong University, 264209 Weihai, China. <sup>3</sup>Institutes of Science and Development, Chinese Academy of Sciences, 100190 Beijing, China. <sup>4</sup>School of Public Policy and Management, University of Chinese Academy of Sciences, 100049 Beijing, China. <sup>5</sup>School of Civil Engineering, University of Leeds, Leeds LS2 9JT, UK. <sup>6</sup>Research Institute for Environmental Innovation (Suzhou), Tsinghua, 215163 Suzhou, China. <sup>7</sup>Department of Geographical Sciences, University of Maryland, College Park, MD 20742, USA. ✉email: xuzhao@sdu.edu.cn; zn928@naver.com



**Fig. 1** Distribution of the industrial enterprises in Jiangsu Province with excess pollution discharge (tons/yr). **a** Excess COD and **b** excess  $\text{NH}_3\text{-N}$ . The dots in the figure show the locations of the enterprises with excess pollution discharge while the colours represent the amount of territorial-based excess industrial pollution. Three basins, where enterprises with excess pollution discharge are densely distributed, are partially enlarged, including the Yangtze River Basin, Hongze Lake Basin, and Taihu Basin. Ten hotspot water function zones, which cover most enterprises with excess pollution, are marked. The blue lines represent the main rivers.

a lack of understanding of the spatial layout of enterprises affiliated with these industrial sectors and the varying thresholds of different sections of water bodies for these spatially dispersed discharges. Additionally, failing to link water pollution discharge from different industrial sectors to the aquatic environment further impedes analyses of the impact that consumption has on water quality responses. Introducing a consumption perspective to environmental research is essential for addressing the impact that consumers and trade have on pollutant outsourcing<sup>22–24</sup>. This perspective is also key to achieving Sustainable Development Goal (SDG) 12, i.e., Sustainable Consumption and Production<sup>25,26</sup>.

In summary, existing studies linked anthropogenic pollution sourced from production to water deterioration, but did not further link the pollution to consumption, which takes place both within the production area and beyond through trade. Meanwhile, some recent studies focused on the impact of final consumption on the sectoral level pollution discharge<sup>11,27,28</sup>, but failed to link the discharge to surface water deterioration. Also, although recent studies have linked the excess use of phosphorus fertilizer on croplands, as well as excess freshwater use, to final consumption using multi-region input–output (MRIO) modelling<sup>29,30</sup>, no study has evaluated the impact that consumption has on excess pollution discharge across industrial sectors and areas.

In this study, we used spatial data to investigate excess industrial water pollution discharge to the surface water bodies in 2015 in Jiangsu Province, the most industrialised province in China (Supplementary Note 1, Supplementary Fig. 1). The chemical oxygen demand (COD) and ammonia nitrogen ( $\text{NH}_3\text{-N}$ ) were selected as water quality proxies, as these are the principal pollutants causing water deterioration in China<sup>31</sup>. We divided the surface water network of Jiangsu into 1338 surface water function zones and evaluated their response to pollution discharge from 11,094 industrial enterprises affiliated with a broad range of 22 industrial sectors. We then linked excess pollution discharge from

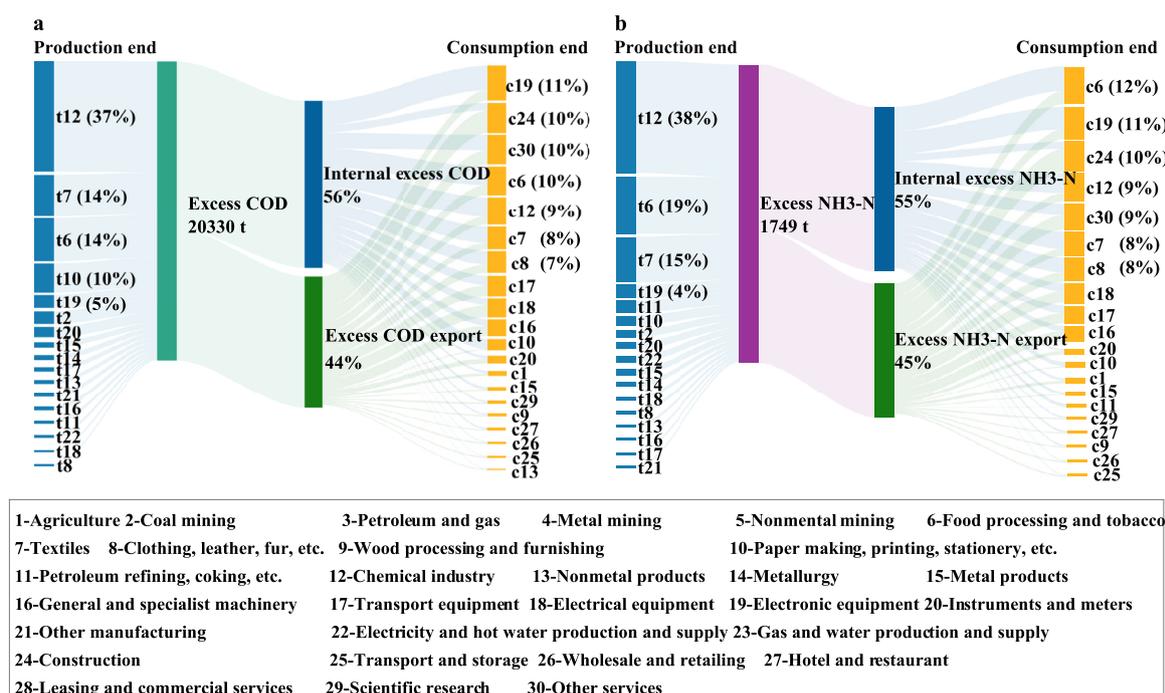
these industrial sectors to the final demand of different sectors in all Chinese provinces using the latest national MRIO table. We also proposed an indicator, i.e., the *pollution exceedance rate*, to examine industrial sectors with high levels of risk for excess water pollution discharge. Our research framework can help identify hotspots and industrial sectors with high levels of risk for excess discharge, thereby supporting the formulation of effective mitigation strategies for industrially derived water pollution.

## RESULTS

### Territorial-based excess industrial pollution (TEIP) in Jiangsu

In 2015, 174,824 tons of COD and 12,241 tons of  $\text{NH}_3\text{-N}$  were discharged by 11,094 industrial enterprises in Jiangsu. Approximately 12% of the COD discharge (20,330 tons) and 14% of the  $\text{NH}_3\text{-N}$  discharge (1749 tons) occurred in water function zones where the pollutant amount exceeded the maximum allowable pollution load (MAPL). Specifically, there were 41 water function zones receiving excess COD discharge from 1099 enterprises and 45 water function zones receiving excess  $\text{NH}_3\text{-N}$  discharge from 396 enterprises.

Geographically, enterprises with excess pollution discharge were mainly located in southern Jiangsu, where the river network is dense, and the economy is highly developed (Fig. 1). Enterprises with excess annual COD discharge were densely distributed in the Yangtze River Delta urban agglomeration, including the cities of Suzhou (8075 tons/yr), Yangzhou (2936 tons/yr), Nanjing (1542 tons/yr), and Nantong (1374 tons/yr) (refer to Supplementary Fig. 2 for city location and Supplementary Note 2 for detailed city results). As the most industrialised region in China, this urban agglomeration has built 174 industrial parks during the past 30 years and contributed ~13% (11.9 trillion yuan) to the industrial output of China in 2015 alone<sup>32</sup>. Hotspots covering most enterprises with excess COD include the Wusongjiang water



**Fig. 2** Inter-sector flows of excess pollution discharge from the production end in Jiangsu Province to the consumption end in Jiangsu and other Chinese provinces. **a** excess COD and **b** excess  $\text{NH}_3\text{-N}$ . Sectors with excess COD (from both production and consumption) of <100 tons/yr and sectors with an excess  $\text{NH}_3\text{-N}$  of <10 tons/yr are not shown in this figure. The list of 30 Chinese provinces is shown in Supplementary Table 1.

function zone in Suzhou, the Beijing-Hangzhou Grand Canal (Yangzhou section) in Yangzhou, Qinhuai River Lishui section, and Yangtze River Dachang section water function zones in Nanjing, Sanhe Port, and Rutai Canal water function zones in Nantong (Fig. 1). These water function zones each accommodated 57–341 polluting enterprises, most of which belonged to the ‘Chemical industry’, ‘Textiles’, and ‘Paper making, printing, stationery, etc.’ sectors. Enterprises with excess  $\text{NH}_3\text{-N}$  discharge were concentrated in Suzhou City (574 tons/yr), Yangzhou City (318 tons/yr), and Huai’an City (146 tons/yr). Excluding the water function zones of the Wusongjiang and Beijing-Hangzhou Grand Canal (Yangzhou section), hotspots covering most enterprises with excess  $\text{NH}_3\text{-N}$  include the Baoshe River water function zone in Yangzhou and the Qing’an River water function zone in Huai’an. Over one-third of the enterprises in the Baoshe River water function zone were food processing enterprises, whereas over one-third of those in the Qing’an River water function zone were chemical enterprises.

Eighty-six percent of the enterprises analysed in this study had an excess amount of COD of <10 tons/yr while 88% had an excess amount of  $\text{NH}_3\text{-N}$  of <1 ton/yr. The number of large polluting enterprises is small, but their contributions are substantial. For example, two enterprises in the ‘Chemical industry’ sector and one in the ‘Food processing and tobacco’ sector had an excess COD of >1000 tons/yr. These three enterprises are located in the Yangtze River Delta urban agglomeration; combined, they accounted for 18% of the total excess COD in Jiangsu. The same two chemical enterprises and an enterprise in the ‘Textiles’ sector in the Hongze Lake Basin each caused an excess  $\text{NH}_3\text{-N}$  of >50 tons/yr, contributing to 23% of the total excess  $\text{NH}_3\text{-N}$ .

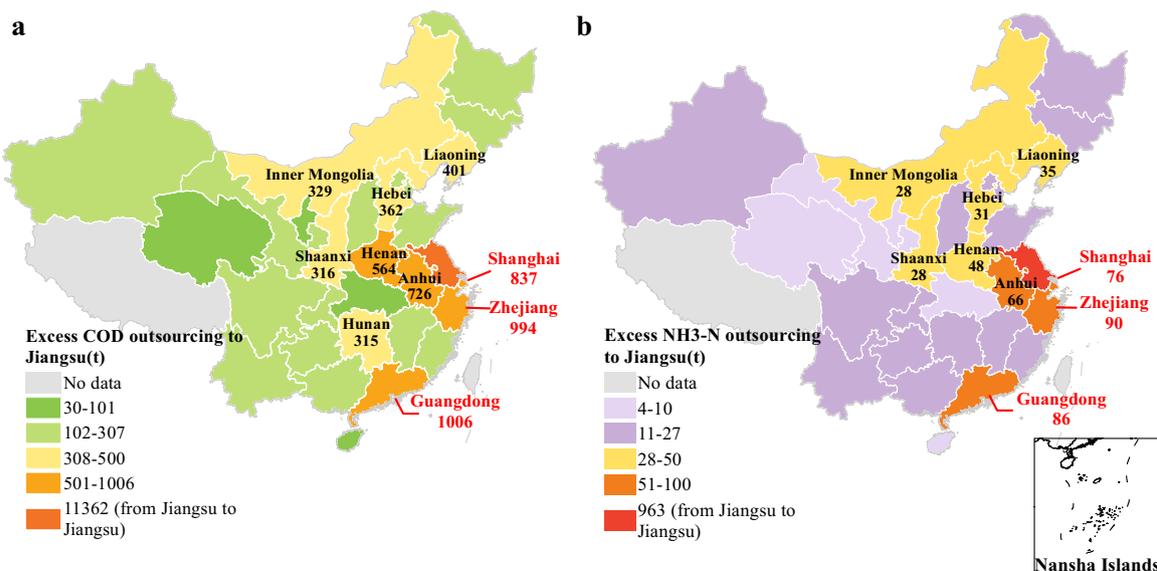
In terms of the sectoral distribution, the ‘Chemical industry’ sector had the largest TEIP (7459 tons/yr COD and 653 tons/yr  $\text{NH}_3\text{-N}$ ) in Jiangsu, followed by ‘Textiles’ (2943 tons/yr COD and 267 tons/yr  $\text{NH}_3\text{-N}$ ), and ‘Food processing and tobacco’ (2880 tons/yr COD and 337 tons/yr  $\text{NH}_3\text{-N}$ ). Approximately 65% of the excess COD and 72% of the excess  $\text{NH}_3\text{-N}$  were related to production in these three sectors. This was followed by the ‘Paper

making, printing, stationery, etc.’ which resulted in 1955 tons/yr of excess COD (Fig. 2). These sectors are widely characterised as heavy polluting sectors and are important basic industries in China<sup>33</sup>.

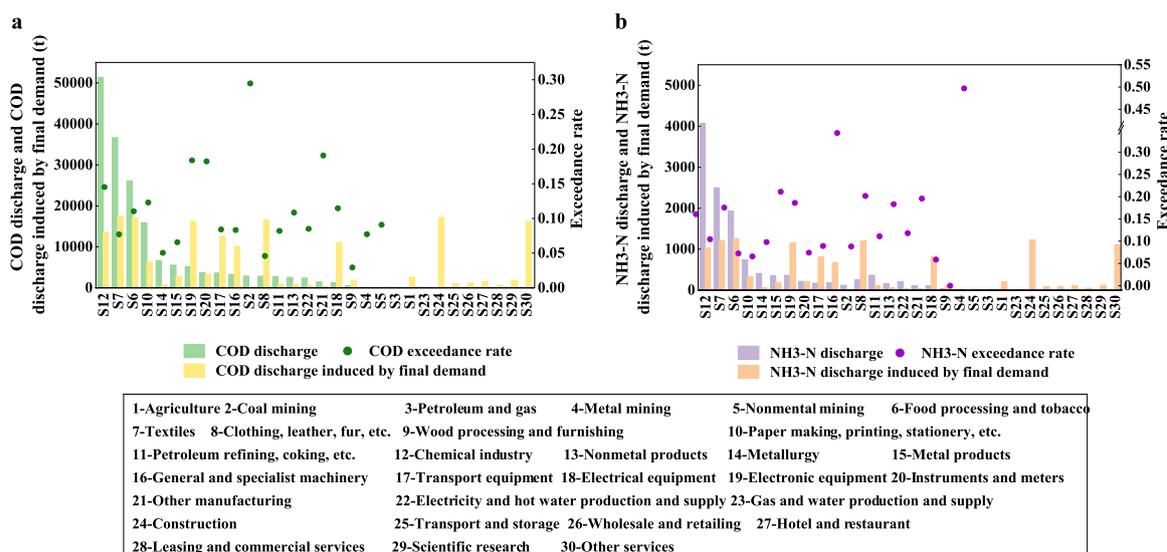
### TEIP of Jiangsu linked to final consumption

Linking the TEIP to the final consumption, our results showed the impact of consumption on excess industrial pollution discharge in Jiangsu. We found that 56% of the excess COD discharge (11,362 tons/yr) and 55% of the excess  $\text{NH}_3\text{-N}$  discharge (963 tons/yr) in Jiangsu can be linked to the final consumption within Jiangsu, whereas the remaining excess discharge was embodied in the products exported from Jiangsu to fulfil the final demand of the other 29 Chinese provinces. The contribution of the final demand from other provinces to the TEIP of Jiangsu varied, with excess COD ranging from 30 to 1006 tons/yr and excess  $\text{NH}_3\text{-N}$  ranging between 3 and 90 tons/yr (Fig. 3, Supplementary Table 1).

In terms of the sectoral distribution, the top five sectors whose final demand induced the largest excess discharge were ‘Electronic equipment’ (2328 tons/yr for COD, 190 tons/yr for  $\text{NH}_3\text{-N}$ ), ‘Construction’ (2039 tons/yr for COD, 175 tons/yr for  $\text{NH}_3\text{-N}$ ), ‘Other services’ (2015 tons/yr for COD, 154 tons/yr for  $\text{NH}_3\text{-N}$ ), ‘Food processing and tobacco’ (1939 tons/yr for COD, 215 tons/yr for  $\text{NH}_3\text{-N}$ ), and ‘Chemical industry’ (1861 tons/yr for COD, 164 tons/yr for  $\text{NH}_3\text{-N}$ ) (Fig. 2). The large impact from the consumption of these sectors may be attributed to their final demand for TEIP-intensive products. We found that 84% of the excess COD discharge and 89% of the excess  $\text{NH}_3\text{-N}$  discharge from the ‘Food processing and tobacco’ sector in Jiangsu can be linked to the final demand in the same sector while the larger excess discharge induced by the final demand of the remaining major sectors was due to the large demand for chemical products as intermediate inputs. Apart from ‘Food processing and tobacco,’ these TEIP-intensive chemical products contributed 39–83% of the excess COD discharge and 44–82% of the excess  $\text{NH}_3\text{-N}$  discharge to the top five sectors.



**Fig. 3 Excess pollution discharge in Jiangsu induced by final demand of Jiangsu and other Chinese provinces. a** Excess COD and **b** excess NH<sub>3</sub>-N. Map colours show the amount of excess pollution embodied in the exported products of Jiangsu to 30 Chinese provinces (tons/yr). The top 10 provinces outsourcing excess pollution to Jiangsu are marked on the map.



**Fig. 4 Comparison of the pollution discharge, pollution discharge induced by final demand, and pollution exceedance rate. a** COD and **b** NH<sub>3</sub>-N. The coloured bars denote the amount of pollution discharge and pollution discharge induced by final demand while the dots represent the pollution exceedance rate.

### Pollution exceedance rate

Economic sectors with high pollution exceedance rates have a high risk level for excess pollution discharge but are not necessarily those currently producing the most pollution (Fig. 4). For example, sectors such as 'Coal mining,' 'Electronic equipment,' and 'Instruments and meters' which were found to have the largest exceedance rates for both COD and NH<sub>3</sub>-N, only discharged a limited amount of pollution. Their discharge amounts were lower than the provincial average (5827 tons/yr COD, 408 tons/yr NH<sub>3</sub>-N), but their COD and NH<sub>3</sub>-N exceedance rates were between 6% and 17% and 5% and 20% higher than the provincial average (12% for COD and 14% for NH<sub>3</sub>-N), respectively (refer to LH quadrant in Supplementary Fig. 3). In contrast, some economic sectors with the largest discharge amounts had relatively lower pollution exceedance rates (Fig. 4). For example, the COD exceedance rates for 'Textiles,' 'Food processing and

tobacco,' and 'Metallurgy,' and the NH<sub>3</sub>-N exceedance rates for 'Textiles,' 'Paper making, printing, stationery, etc.' and 'Metallurgy' were all below the provincial average pollution exceedance rate.

Having a higher pollution exceedance rate may mainly be attributed to spatial agglomerations of industry. The most common form of agglomeration of industrial activities is within industrial parks<sup>34</sup>, in which enterprises within the same sector are often co-located. Water pollution arising from industrial parks is typically combined and discharged into the same water function zone. For example, the Wusongjiang water function zone (Fig. 1), which had the most severe pollution exceedance rate, was surrounded by 56 enterprises classified in the 'Electronic equipment' sector and 37 enterprises in the 'Instruments and meters' sector. Although the amount of discharge from each enterprise was limited, the combined pollution exceeded the MAPL of the water function zone. Another example of spatial agglomeration

was associated with proximity to raw materials, i.e., factories were built near these resources. As all the coal reserves of Jiangsu were located in Pei County (Xuzhou City) (Fig. 1), this county contained nine bituminous coal and anthracite coal mining enterprises; therefore, the generated water pollution was discharged to the same water function zone. On the provision that the MAPL of the water function zone was limited, the centralised discharge caused a higher pollution exceedance rate in the 'Coal mining' sector. Supplementary Table 2 lists the exceedance rates of the other sectors.

Economic sectors with high pollution exceedance rates (above average, HH and LH quadrants in Supplementary Fig. 3) may be linked to the final demand of different sectors. For sectors with high COD exceedance rates, the final demand of 'Electronic equipment' (17%), 'Chemical industry' (13%), 'Other services' (12%), and 'Construction' (11%) were the main contributors to their TEIP. For sectors with high NH<sub>3</sub>-N exceedance rates, the final demand of 'Food processing and tobacco' accounted for 16% of its TEIP, followed by 'Electronic equipment' (13%), 'Chemical industry' (12%), and 'Construction' (10%).

## DISCUSSION

We developed a novel framework to quantitatively analyse the spatial patterns of excess pollution discharge across a range of industrial sectors, further tracking the contributions of consumption leading to this discharge. The framework helped identify the industrial sectors with the largest contribution and risk level to water pollution in high spatial resolution. The results demonstrated that regional water pollution derived from industrial production is not only determined by the amount of pollution discharged but also by the spatial distribution of enterprises, industrial structure, and final consumption beyond the research area. Hence, our framework highlights the complexities associated with the effective control of industrial pollution sources. For emerging economies, it is necessary to incorporate industrial production, consumption, and the response of surface water quality into a unified assessing and management framework to achieve water pollution mitigation. Using Jiangsu as a case example thus provides an appropriate foundation for emerging economies experiencing significant industrial expansion and associated water pollution.

Notably, our results highlighted the sectors that had high risk levels for the discharge of large amounts of excess pollution, but for which limited concerns have been raised. Characterised by high pollution exceedance rates, these are mainly high-tech manufacturing sectors, including 'Electronic equipment,' 'Instruments and meters,' and 'Electrical equipment.' Although these sectors had limited amounts of pollution discharge, the excess discharge of these sectors would increase rapidly to a high level when there was an increase in the amount of the pollution discharge. Indeed, these sectors are projected to continue to expand and experience high economic growth; since 2015, these industries have experienced rapid development and an annual growth rate in their industrial output >8%<sup>35</sup>. Under such a strong development momentum, the pollution discharge from high-tech manufacturing industries may continue to increase, aggravating the excess pollution discharge. In contrast, heavy polluting sectors with large TEIP values, including the 'Chemical industry,' 'Textiles,' 'Food processing and tobacco,' and 'Paper making, printing, stationery, etc.' have received wider and well-documented concerns<sup>28,33</sup>. In 2015, the Chinese government issued an 'Action Plan for Prevention and Control of Water Pollution (Water Ten Plan)'<sup>36</sup>, with emissions reductions for heavy polluting sectors given prominent positions. In response, 4022 heavy polluting chemical enterprises in Jiangsu were placed on a rectification list, and nine chemical industrial parks, comprising 337 enterprises, were shut down<sup>37</sup>.

We found that industrial agglomeration was the main reason for the high pollution exceedance rates of high-tech manufacturing sectors. Such gathering of industrial activities into intensive zones, such as industrial parks, is a common strategy for economic growth worldwide<sup>38</sup>. More than 2500 national-level and provincial-level industrial parks exist in China, contributing to >50% of the national industrial output<sup>34</sup>. Industrial agglomeration is especially prevalent among high-tech industries, owing to their intensive requirement for specialised technology and talent<sup>5</sup>. Our results showed that 16% of 'Electronic equipment' manufacturing enterprises and 23% of 'Instruments and meters' manufacturing enterprises in Jiangsu were located in Suzhou Industrial Park and Wujiang Industrial Park, near the Wusongjiang water function zone. However, the lack of a pollution discharge control plan may create problems with pollution agglomeration<sup>39</sup>. To decouple industrial development from pollution exceedance, the Chinese government must implement greening strategies, such as the establishment of eco-industrial parks. An eco-industrial park is a business community dedicated to enhance its environmental, economic, and social performance through collaboration<sup>40</sup>. Measures may be taken to minimise pollution, such as gathering of complementary enterprises in terms of their economy and ecology, closing material cycles, and reusing 'waste' materials<sup>41</sup>.

Pollution exceedance in industrial parks also exposes problems associated with current wastewater discharge standards based on concentration. For example, for the Yuanhetang water function zone, the total pollution received exceeds its MAPL. However, the concentration of pollution discharged from each enterprise to this water function zone conforms to the wastewater discharge standards (Fig. 1, Supplementary Table 3). The regulatory focus is on the concentration of the pollution discharge from individual enterprises, but it ignores the layout of different enterprises and its cumulative impact on the MAPL of the receiving water function zone<sup>42</sup>. Therefore, load standards (the MAPL values of the water function zones) established based on the assimilative pollution capacity theory can serve as more stringent standards<sup>42</sup>.

Different load standards have been developed in different countries. The United States has prepared a complete water pollution control framework based on load standards i.e., the ATTAINS. It involves setting the total maximum daily load (TMDL) of impaired water bodies, allocating the TMDL to pollution sources, and applying pollution control practices<sup>43</sup>. The EU's Industrial Emissions Directive regulates the emission limit values for industrial enterprises based on the best available techniques associated emission levels (BAT-AELs). The BAT was applied to over 50,000 industrial enterprises comprising 31 sectors regulated by the EU in 2018. These efforts have led to the investment of at least 100 billion EUR per year<sup>44</sup>, which may not be an affordable choice for developing countries. The efforts of China to develop a load standard started in 2011, when the Chinese State Council mandated that water pollution discharge must be strictly regulated to avoid transgressing the 'water pollution redline' i.e., the MAPL in the water function zone unit<sup>45</sup>. However, the large amount and dense distribution of enterprises in China leads to difficulties in collecting pollution discharge data. In fact, pollution load control based on the MAPL and enterprise-level pollution discharge have not been efficiently conducted to date<sup>42</sup>. In this study, we identified the enterprises and water function zones with excess industrial pollution discharge, through comparing the enterprise-level pollution discharge with the corresponding MAPLs. This helps specify the enterprises and sectors needing pollution reduction actions, thereby, reducing the cost for a wide range of end-of-pipe investment. Our work, thus, provides a reference for emerging economies experiencing significant industrial expansion and consequent severe water pollution, such as India<sup>46</sup>, Brazil<sup>47</sup> and South Africa<sup>48</sup>.

Our fine-scale analysis helped in identifying the hotspots of water function zones presenting excess industrial water pollution

discharge. We found that the MAPL of a water function zone to pollution discharge was largely affected by its hydrodynamic condition. Plain river network is a typical surface water form in Jiangsu, which is a combination of dense rivers and flat terrain. Characterised as low flow velocity, a plain river network has relatively poor hydrodynamics, resulting in a lower MAPL for its water function zones<sup>49</sup>. As a result, the intensive industrial pollution discharge to these water bodies easily transgresses the MAPL. For example, excess pollution discharge in plain river networks was found in the Rutai Canal, Sanhe Port, and Qinhuai River Lishui section water function zones, owing to dense distribution of enterprises in these regions. In contrast, the Yangtze River has good hydrodynamic conditions characterised as large flow velocity, leading to a higher MAPL in its water function zones<sup>49</sup>. However, these water function zones also tend to accommodate heavy polluting enterprises. For example, the enterprises with the heaviest discharges among the 'Chemical industry' and 'Petroleum refining, coking, etc.' sectors were distributed around the Yangtze River Dachang section water function zone.

Consequently, the hydrological characteristics of water function zones and their MAPLs must be considered when planning the regional layout of industrial enterprises. First, the number of newly built enterprises and industrial parks should be strictly limited around the water function zones that have lower MAPLs. Second, clean technologies for pollution prevention and end-of-pipe treatment should be implemented for enterprises with heavy excess pollution discharge. Third, high polluting enterprises centred in the hotspot water function zones can be transferred to areas with large environmental carrying capacities<sup>50</sup>. For example, the Yangtze River Protection Law<sup>51</sup> has led to the relocation of steel and petrochemical industries along the river to coastal areas with a higher carrying capacity for water pollution<sup>35</sup>. However, during the transfer, the distribution of enterprises, the scale of centralised sewage discharge, and the MAPLs of the surrounding water function zones in the undertaking areas must be considered to prevent the transferred regions from becoming 'pollution havens'<sup>52</sup>.

From a consumption perspective, high pollution exceedance rates can be linked to the final demand for the 'Electronic equipment,' 'Other services,' 'Food processing and tobacco,' 'Chemical industry,' and 'Construction' sectors. The final consumption for these sectors may increase in the future. First, China is now entering a 'new consumption' era in which traditional consumption patterns are gradually transforming into high-tech and service-based products<sup>53,54</sup>. Hence, there is an increasing demand for products such as electronics and services<sup>55,56</sup>. Second, although the 'Chemical industry' and 'Construction' sectors face declining demands, boosting the demand for these sectors has been included in the 14th Five-Year Plan of the Chinese government<sup>57</sup>. Third, due to the growing population and the promotion of the Chinese policy for expanding domestic demand, there will be a steady increase in the final demand of China's 'Food processing and tobacco' sector<sup>58</sup>. These increasing demands together may cause the TEIP of Jiangsu to increase in industrial sectors with large exceedance rates. However, the number of chemical enterprises in Jiangsu has declined by 70%<sup>59</sup> since the release of the 'Jiangsu Province improvement plan for safety and environmental protection of the chemical industry' in 2019. Hence, the final consumption toward the 'Chemical industry' in Jiangsu may be transferred to other provinces in the future. Neighbouring provinces with high levels of industrial activity, such as Shandong, Zhejiang, and Anhui, may embrace more 'Chemical industry' enterprises to fulfil the production gap created by Jiangsu<sup>60</sup>. Such an activity transfer to other provinces may increase the TEIP in these provinces.

In this study, we aggregated the enterprise-level excess water pollution discharge into sectoral levels and attributed this sectoral

level excess discharge to the final consumption, both within and beyond the pollution discharging area. Our framework stressed on the importance of fulfilling SDG 12, i.e., Sustainable Consumption and Production, which refers to the use of services or products in a manner that minimises the use of natural resources and emission of pollutants<sup>26</sup>. Meanwhile, mitigating water pollution from the consumption perspective is also in line with the Integrated Water Resources Management (IWRM) policies of the UN<sup>61</sup> and the EU Water Framework Directive<sup>62</sup>. The linkage of final consumption and surface water deterioration is a necessary first step to raise consumer awareness towards reducing water pollution. Our enterprise-level results can facilitate the development of a mechanism that requires payments from consumers to offset their impacts on excess pollution generated in production areas<sup>11</sup>.

## METHODS

### Quantifying territorial-based excess industrial pollution

Here, we propose an indicator, i.e., the *territorial-based excess industrial pollution* (TEIP), to quantify the transgression of pollution discharge across different industrial sectors above the water pollution discharge thresholds of different water function zones. We considered the water function zone as the minimum unit to calculate the TEIP for each industrial sector. The Ministry of Water Resources of China proposed the concept of the water function zone<sup>63</sup>, which refers to an area of a water body defined according to its dominant function, e.g., fishery, agriculture, or industrial use, and applicable to a corresponding water quality standard in the 'Environmental quality standards for surface water (GB 3838-2002)'<sup>64</sup> (Supplementary Table 4). Its purpose is to control water pollution based on the natural conditions of the water body, as well as socio-economic and environmental protection requirements<sup>63</sup>. With clear functional division and protection requirements between zones, the aim is to maximise the economic, social, and environmental capacities of different surface water bodies.

The MAPL of a water function zone was selected as the water pollution discharge threshold for industrial water pollution discharge. The Chinese State Council first proposed the MAPL concept in 2011, which was set as the 'water pollution redline' that should not be exceeded in each water function zone<sup>45</sup>. The MAPL calculates the maximum allowable load discharged by point sources derived from industrial facilities and municipal wastewater treatment plants without damaging the water quality requirements of a water function zone<sup>49,65</sup>. This concept is similar to the TMDL concept proposed by the U.S. EPA, which calculates the maximum daily amount of a pollution allowed to enter a water body under certain water quality standards<sup>43</sup>. The magnitude of the MAPL in a water function zone is related to the water quality standards, spatial distribution of sewage outlets, pollution degradation coefficients, and hydrological conditions.

We calculated the TEIP of a water function zone,  $l$ , by subtracting the MAPL of  $l$  from the total discharge received by  $l$ :

$$TEIP_{l,s}(k) = \sum_n R_{n,l,s}(k) - W_{l,s}(k), \quad (1)$$

where  $TEIP_{l,s}(k)$  (tons/yr) is the amount of territorial-based excess pollutant  $k$  [COD or  $\text{NH}_3\text{-N}$ ] received by water function zone  $l$  in region  $s$ .  $TEIP_{l,s}(k)$  is set to 0 if it is  $<0$ .  $\sum_n R_{n,l,s}(k)$  (tons/yr) is the total amount of pollutant  $k$  discharged by industrial enterprise  $n$  to water function zone  $l$  in region  $s$ . Here, we assumed that domestic water pollution discharge is fully treated, such that  $R_{n,l,s}(k) = R_{n,l,s}(k) \times Re_s(k)$  can be calculated by multiplying the actual discharge amount,  $R_{n,l,s}(k)$ , by the sewage treatment residual rate,  $Re_s(k)$ .  $Re_s(k)$  is obtained by dividing the outlet concentration of pollutant  $k$  (mg/L) from the wastewater treatment plant by its inlet concentration to the wastewater treatment plant (mg/L), which indicates the proportion of pollutant  $k$  remaining in water body after treatment. For pollutants discharged directly into the water body without any treatment,  $Re_s(k) = 1$ .  $W_{l,s}(k)$  (tons/yr) is the MAPL of pollutant  $k$  in water function zone  $l$ , whose calculation and validation procedures can be found in the Supplementary Methods, Supplementary Figs. 4–6.

Next, we adopted a grandfathering approach to allocate  $TEIP_{l,s}(k)$  to each pollution discharging enterprise in water function zone  $l$ . This allocation was conducted according to the enterprises' share of the total

emissions in water function zone  $l$ :

$$TEIP_{n,l,s}^i(k) = \frac{R_{n,l,s}(k)}{\sum_n R_{n,l,s}(k)} \times TEIP_{l,s}(k), \quad (2)$$

where  $TEIP_{n,l,s}^i(k)$  (tons/yr) is the amount of territorial-based excess pollutant  $k$  caused by industrial enterprise  $n$  that enters water function zone  $l$  in region  $s$ , where superscript  $i$  represents the economic sector of the enterprise.

Subsequently,  $TEIP_{n,l,s}^i(k)$  was aggregated to different sectors to acquire the TEIP at the sector level,  $TEIP_s^i(k)$  (tons/yr):

$$TEIP_s^i(k) = \sum_l \sum_n TEIP_{n,l,s}^i(k). \quad (3)$$

The territorial-based excess industrial pollutants in region  $s$ ,  $TEIP_s(k)$  (tons/yr), were therefore summed as follows:

$$TEIP_s(k) = \sum_i TEIP_s^i(k). \quad (4)$$

To obtain the risk level of each sector for excess pollution discharge, we proposed the pollution exceedance rate. This was calculated by dividing the excess amount of pollutant  $k$  released by sector  $i$  in region  $s$ ,  $TEIP_s^i(k)$ , by its total discharge,  $R_s^i(k)$ . This indicator shows that the excess pollution discharge of a certain sector increases rapidly to a high level once there is an increase in the amount of pollution discharge. Hence, the larger the pollution exceedance rate, the greater the risk level the sector exhibits for having an impact on the water quality of a water function zone.

### Linking TEIP to the final consumption of Jiangsu and other provinces

The TEIP for Jiangsu Province can be linked to the final demand of different consumers, including Jiangsu and other Chinese provinces. This link can be investigated using the MRIO approach. With the MRIO model, the excess pollution discharge induced by the final consumption (EPF) at the sectoral level was calculated as follows:

$$\mathbf{epf} = \mathbf{epf}_s + \sum_{r \neq s} \mathbf{epf}_r = \left( \sum_l \hat{\mathbf{d}}_s (\mathbf{I} - \mathbf{A}_s)^{-1} \hat{\mathbf{y}}_s \right)' + \sum_{r \neq s} \left( \sum_l \hat{\mathbf{d}}_s (\mathbf{I} - \mathbf{A}_s)^{-1} \hat{\mathbf{e}}_{sr} \right)', \quad (5)$$

where  $\mathbf{epf}$  is the EPF in vector form ( $30 \times 1$ ), and its  $i$ th element denotes the EPF of sector  $i$ . It has two components, i.e.,  $\mathbf{epf}_s$  and  $\sum_{r \neq s} \mathbf{epf}_r$ .  $\mathbf{epf}_s$  is the TEIP in Jiangsu driven by its final demand while  $\sum_{r \neq s} \mathbf{epf}_r$  is the TEIP in Jiangsu driven by the final demand of the other 29 provinces.  $\hat{\mathbf{d}}_s$  is a diagonal matrix of the excess pollution intensity in Jiangsu;  $\hat{\mathbf{d}}_s = \mathbf{t}_s / \mathbf{x}_s$  is calculated by dividing the vector of the territorial-based excess industrial pollutant,  $\mathbf{t}_s$ , by the output,  $\mathbf{x}_s$ , of Jiangsu.  $\mathbf{L}_s = (\mathbf{I} - \mathbf{A}_s)^{-1}$  is the Leontief inverse matrix, where  $\mathbf{I}$  is the unit matrix and  $\mathbf{A}_s$  is the technical coefficient matrix of Jiangsu.  $\hat{\mathbf{y}}_s$  is a diagonal matrix of the final demand of Jiangsu and  $\hat{\mathbf{e}}_{sr}$  is the export of final products from Jiangsu to other provinces.

It should be noted that the system boundary in our study was constrained within China. Hence, international imports were neglected during EPF accounting. Meanwhile, the TEIP driven by the final demand for international exports was allocated to provinces that export products for final demand to other countries. Such boundary settings can be observed in existing studies<sup>11,66,67</sup>. Further uncertainties and limitations concerning methods and data are shown in the Supplementary Discussion and Supplementary Table 5.

### Data sources

In this study, the MAPLs of 1338 surface water function zones in Jiangsu were acquired from Fan<sup>68</sup>, whose results have been officially released as 'Opinions of Water Resources Department of Jiangsu Province and Jiangsu Development and Reform Commission on the pollutant load capacity and the MAPL of water function zones'<sup>69</sup>. The detailed procedure of MAPL calculation is presented in the Supplementary Methods. Enterprise-level data, covering 11,094 industrial enterprises in Jiangsu, included the basic situational information, i.e., the geographical position (Supplementary Fig. 1), industrial sector, and annual discharge of principal pollutants. More importantly, the data included the drainage destinations, i.e., the water function zones of different enterprises. These data were obtained from the Chinese Environmental Statistics Database and have been officially released in Jiangsu Statistical Yearbook 2016<sup>32</sup>. Established by the Ministry

of Ecology and Environment (MEE), this database contains environmental information from all major industrial pollution sources nationwide<sup>70</sup>. These data are self-reported by enterprises and compiled by the MEE. County-level ecology and environment bureaus ensure data quality through environmental monitoring and unannounced field inspections<sup>71</sup>. Raw discharge data are first compiled into a report and submitted to the ecology and environment department at the municipal or provincial level. After scrutiny, the environmental information is submitted to the MEE, where it is finally compiled into the annual environmental statistical yearbook<sup>70</sup>. Owing to the strict data inspection procedures, this database is the most reliable environmental database in China<sup>72</sup>.

The COD and  $\text{NH}_3\text{-N}$  were selected as water quality proxies because they are widely used for water quality assessments in China<sup>31</sup> and are the principal pollutants responsible for the deterioration of the water quality in Jiangsu<sup>73</sup>. The inlet and outlet concentrations of the COD and  $\text{NH}_3\text{-N}$  for 797 wastewater treatment plants in Jiangsu were used to calculate the sewage treatment residual rates and were sourced from the Chinese Environmental Statistics Database. As wastewater treatment plants in the same city shared similar residual rates, we used the average residual rates of all wastewater treatment plants in the same city to represent the situation in each city (Supplementary Table 6).

To calculate the EPF, we used the 2015 China MRIO table<sup>74</sup> which covers 30 Chinese provincial-level administrative regions (abbreviated as provinces) and 30 economic sectors. To explore consumer responsibility for the TEIP within Jiangsu, we used the TEIP of Jiangsu as input and ignored the TEIP of the other 29 Chinese provinces. As our study focused on sector-level industrial pollution, we assigned the TEIP of 11,094 industrial enterprises to 22 industrial sectors in the MRIO model. As the MAPL was set as the water pollution discharge threshold for point source discharge, agriculture sector pollution discharge originating from nonpoint sources was only considered when calculating the MAPL (see Supplementary Methods for details) and was not included as an input to the MRIO model. The TEIP associated with service sectors was included with the domestic wastewater production, which was assumed to be fully treated by municipal wastewater treatment plants, as the average domestic sewage treatment rate in Jiangsu was up to 90% in 2015<sup>75</sup>. The sectoral aggregation principle was based on the 'Industrial Classification for National Economic Activities (GB/T 4754-2017)'<sup>76</sup>.

### DATA AVAILABILITY

The data of the maximum allowable pollution load at the water function zone level, as well as the data for pollution discharge and excess pollution discharge at the enterprise level are available via a repository (<https://figshare.com/s/6f6a5dc88a4c371b7189>).

Received: 10 October 2021; Accepted: 28 January 2022;

Published online: 25 February 2022

### REFERENCES

- United Nations Industrial Development Organization. *Industrialization as the Driver of Sustained Prosperity* (United Nations Industrial Development Organization, 2020).
- United Nations Department of Economic and Social Affairs. *Description of Industry* (United Nations Department of Economic and Social Affairs, accessed 7 June 2021); <https://sdgs.un.org/topics/industry>.
- Strokal, M. et al. Urbanization: an increasing source of multiple pollutants to rivers in the 21st century. *npj Urban Sustain.* **1**, 1–24 (2021).
- Damania, R., Desbureaux, S., Rodella, A. -S., Russ, J. & Zaveri, E. *Quality Unknown: The Invisible Water Crisis* (World Bank, 2019).
- lordache, A. M. et al. Past and present anthropic environmental stress reflect high susceptibility of natural freshwater ecosystems in Romania. *Environ. Pollut.* **267**, 115505 (2020).
- Chen, W., Huang, X., Liu, Y., Luan, X. & Song, Y. The impact of high-tech industry agglomeration on green economy efficiency—evidence from the Yangtze River economic belt. *Sustainability* **11**, 5189 (2019).
- Su, G. et al. Human impacts on global freshwater fish biodiversity. *Science* **371**, 835 (2021).
- Xing, Z., Wang, J., Feng, K. & Hubacek, K. Decomposition and attribution analysis for assessing the progress in decoupling industrial development from wastewater discharge in China. *J. Clean. Prod.* **266**, 121789 (2020).

9. Liu, W., Antonelli, M., Liu, X. & Yang, H. Towards improvement of grey water footprint assessment: With an illustration for global maize cultivation. *J. Clean. Prod.* **147**, 1–9 (2017).
10. Ma, T. et al. China's improving inland surface water quality since 2003. *Sci. Adv.* **6**, eaau3798 (2020).
11. Zhao, X. et al. Burden shifting of water quantity and quality stress from megacity Shanghai. *Water Resour. Res.* **52**, 6916–6927 (2016).
12. Del Carmen Sabatini, M., Verdiell, A., Rodriguez Iglesias, R. M. & Vidal, M. A quantitative method for zoning of protected areas and its spatial ecological implications. *J. Environ. Manag.* **83**, 198–206 (2007).
13. Shen, Z., Zhong, Y., Huang, Q. & Chen, L. Identifying non-point source priority management areas in watersheds with multiple functional zones. *Water Res.* **68**, 563–71 (2015).
14. Su, S. et al. Temporal trend and source apportionment of water pollution in different functional zones of Qiantang River, China. *Water Res.* **45**, 1781–95 (2011).
15. Cox, B. A review of currently available in-stream water-quality models and their applicability for simulating dissolved oxygen in lowland rivers. *Sci. Total Environ.* **314–316**, 335–377 (2003).
16. Costa, C., Leite, I. R., Almeida, A. K. & de Almeida, I. K. Choosing an appropriate water quality model—a review. *Environ. Monit. Assess.* **193**, 38 (2021).
17. Yi, Q., Chen, Q., Hu, L. & Shi, W. Tracking nitrogen sources, transformation, and transport at a basin scale with complex plain river networks. *Environ. Sci. Technol.* **51**, 5396–5403 (2017).
18. Mokarram, M., Saber, A. & Sheykhi, V. Effects of heavy metal contamination on river water quality due to release of industrial effluents. *J. Clean. Prod.* **277**, 123380 (2020).
19. Steffen, W. et al. Sustainability. Planetary boundaries: guiding human development on a changing planet. *Science* **347**, 1259855 (2015).
20. Liu, C., Kroeze, C., Hoekstra, A. Y. & Gerbens-Leenes, W. Past and future trends in grey water footprints of anthropogenic nitrogen and phosphorus inputs to major world rivers. *Ecol. Indic.* **18**, 42–49 (2012).
21. Yu, C. et al. Managing nitrogen to restore water quality in China. *Nature* **567**, 516–520 (2019).
22. Wiedmann, T. & Lenzen, M. Environmental and social footprints of international trade. *Nat. Geosci.* **11**, 314–321 (2018).
23. Yang, Y. et al. Mapping global carbon footprint in China. *Nat. Commun.* **11**, 2237 (2020).
24. Li, Y. et al. Spatially explicit global hotspots driving China's mercury related health impacts. *Environ. Sci. Technol.* **54**, 14547–14557 (2020).
25. Hoekstra, A. & Wiedmann, T. Humanity's unsustainable environmental footprint. *Science* **344**, 1114–1117 (2014).
26. United Nations Environment Programme. *SDG 12 Issue Brief: Ensuring Sustainable Consumption And Production Patterns* (United Nations Environment Programme, accessed 25 June 2021); <https://wedocs.unep.org/handle/20.500.11822/25764>.
27. Oita, A. et al. Substantial nitrogen pollution embedded in international trade. *Nat. Geosci.* **9**, 111–115 (2016).
28. Wang, J., Li, L., Li, F., Kharrazi, A. & Bai, Y. Regional footprints and interregional interactions of chemical oxygen demand discharges in China. *Resour. Conserv. Recy.* **132**, 386–397 (2018).
29. Li, M. et al. Exploring consumption-based planetary boundary indicators: an absolute water footprinting assessment of Chinese provinces and cities. *Water Res.* **184**, 116163 (2020).
30. Li, M., Wiedmann, T. & Hadjikakou, M. Towards meaningful consumption-based planetary boundary indicators: The phosphorus exceedance footprint. *Glob. Environ. Chang.* **54**, 227–238 (2019).
31. Ministry of Water Resources of the People's Republic of China. *Water Resources Management and Protection in China* (Ministry of Water Resources of the People's Republic of China, accessed 3 March 2020); <http://www.mwr.gov.cn/english/mainsubjects/201604/P020160406507020464665.pdf>.
32. Bureau of Statistics of Jiangsu Province. *Jiangsu Statistical Yearbook 2016* (China Statistics Press, 2016).
33. Han, D., Currell, M. J. & Cao, G. Deep challenges for China's war on water pollution. *Environ. Pollut.* **218**, 1222–1233 (2016).
34. Guo, Y., Tian, J. & Chen, L. Managing energy infrastructure to decarbonize industrial parks in China. *Nat. Commun.* **11**, 981 (2020).
35. Jiangsu Development & Reform Commission. *Statistical Bulletin on National Economic and Social Development of Jiangsu Province* (Jiangsu Development & Reform Commission, 2020) (in Chinese).
36. State Council of China. *Action Plan for Prevention and Control of Water Pollution* (the People's Publishing House, 2015).
37. The General Office of Jiangsu Provincial Committee. *Jiangsu Province Chemical Industry Safety and Environmental Protection Improvement Plan* (the General Office of Jiangsu Provincial Committee, 2019) (in Chinese).
38. Genc, O., van Capelleveen, G., Erdis, E., Yildiz, O. & Yazan, D. M. A socio-ecological approach to improve industrial zones towards eco-industrial parks. *J. Environ. Manag.* **250**, 109507 (2019).
39. Dong, F., Wang, Y., Zheng, L., Li, J. & Xie, S. Can industrial agglomeration promote pollution agglomeration? Evidence from China. *J. Clean. Prod.* **246**, 118960 (2020).
40. World Bank. *International Framework for Eco-Industrial Parks v.2* (World Bank, 2021).
41. Le Tellier, M., Berrah, L., Stutz, B., Audy, J.-F. & Barnabé, S. Towards sustainable business parks: a literature review and a systemic model. *J. Clean. Prod.* **216**, 129–138 (2019).
42. Wang, H., Meng, X. & Lin, C. Key technology and practice of black-odor river regulation. *Yangtze River* **51**, 1–9+108 (2020).
43. United States Environmental Protection Agency. *ATTAINS Program Information* (United States Environmental Protection Agency, accessed 4 October 2021); <https://www.epa.gov/waterdata/attains-program-information>.
44. European Environment Agency. *Industrial Waste Water Treatment—pressures on Europe's Environment* (European Environment Agency, 2019).
45. CPC Central Committee and State Council. *The Decision on Accelerating the Reform and Development of Water Conservancy* (CPC Central Committee and State Council, 2010).
46. Stepping, K. & Never, B. Comparing urban wastewater systems in India and Brazil: options for energy efficiency and wastewater reuse. *Water Policy* **20**, 1129–1144 (2018).
47. Singh, P. et al. (Eds). Government initiative and policies on water conservation and wastewater treatment in Brazil. In *Water Conservation and Wastewater Treatment in BRICS Nations*, 215–231 (Elsevier, Oxford, UK, 2020).
48. Iloms, E., Ololade, O. O., Ogola, H. J. O. & Selvarajan, R. Investigating industrial effluent impact on municipal wastewater treatment plant in Vaal, South Africa. *Int. J. Environ. Res. Public Health* **17**, 1096 (2020).
49. Pang, Y. et al. *Calculation Theory and Application of Water Environment Capacity* (China Science Publishing & Media: 2010) (in Chinese).
50. Tian, Y. et al. Regional industrial transfer in the Jingjinji urban agglomeration, China: an analysis based on a new “transferring area-undertaking area-dynamic process” model. *J. Clean. Prod.* **235**, 751–766 (2019).
51. Ministry of Environmental Protection of China. *Ecological Environment Protection Plan of the Yangtze River Economic Belt* (Ministry of Environmental Protection of China, 2017) (in Chinese).
52. Wang, X., Zhang, C. & Zhang, Z. Pollution haven or porter? The impact of environmental regulation on location choices of pollution-intensive firms in China. *J. Environ. Manag.* **248**, 109248 (2019).
53. Niu, F. & Wang, F. How does China's new consumption era reshape residents' shopping behaviors from the perspective of community in Hohhot, China. *Sustainability* **13**, 7599 (2021).
54. State Council of China. *New Consumption Stimulates New Vitality* (State Council of China, accessed 10 August 2021); [http://www.gov.cn/shuju/2018-04/22/content\\_5284855.htm](http://www.gov.cn/shuju/2018-04/22/content_5284855.htm) (in Chinese).
55. National Development and Reform Commission. *In the First Half of the year, the Service Industry Economy Continued to be Stable and Recovered to a Good Trend* (National Development and Reform Commission, accessed 10 August 2021); [https://www.ndrc.gov.cn/fggz/cyfz/fwyfz/202107/t20210720\\_1290851\\_ext.html](https://www.ndrc.gov.cn/fggz/cyfz/fwyfz/202107/t20210720_1290851_ext.html) (in Chinese).
56. State Council of China. *Leading 'New Consumption' with High-quality Development* (State Council of China, accessed 10 August 2021); [http://www.gov.cn/xinwen/2017-12/21/content\\_5248969.htm](http://www.gov.cn/xinwen/2017-12/21/content_5248969.htm) (in Chinese).
57. State Council of China. *The Outline of the 14th Five-Year Plan (2021–2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035* (in Chinese) (the People's Publishing House, 2021).
58. Liu, C. et al. Decoupling of wastewater eco-environmental damage and China's economic development. *Sci. Total Environ.* **789**, 147980 (2021).
59. Jiangsu Provincial People's Government. *2020 Report on the Work of the Government* (Jiangsu Provincial People's Government, accessed 30 July 2021); [http://en.jiangsu.gov.cn/art/2020/1/22/art\\_54128\\_8960806.html](http://en.jiangsu.gov.cn/art/2020/1/22/art_54128_8960806.html).
60. China Water Web. *The Closure of Xiangshui Industrial Park. What Kind of Big Changes has the Chemical Industry Ushered In?* (China Water Web, accessed 30 July 2021); <https://www.h2o-china.com/news/289992.html> (in Chinese).
61. United Nations Environment Programme. *Progress on Integrated Water Resources Management. Tracking SDG 6 Series: Global Indicator 6.5.1 Updates and Acceleration Needs* (United Nations Environment Programme, 2021).
62. European Environment Agency. *European Waters Assessment of Status and Pressures 2018* (European Environment Agency, 2018).
63. Ministry of Water Resources of the People's Republic of China. *Water Function Regionalization of China* (Ministry of Water Resources of the People's Republic of China, 2002) (in Chinese).

64. Ministry of Environment Protection of China. *Environmental Quality Standards for Surface Water (GB3838-2002)* (the Standards Press of China: Beijing, 2002) (in Chinese).
65. Yan, R., Gao, Y., Li, L. & Gao, J. Estimation of water environmental capacity and pollution load reduction for urban lakeside of Lake Taihu, eastern China. *Ecol. Eng.* **139**, 105587 (2019).
66. Guan, D. & Hubacek, K. Assessment of regional trade and virtual water flows in China. *Ecol. Econ.* **61**, 159–170 (2007).
67. Zhang, C. & Anadon, L. D. A multi-regional input–output analysis of domestic virtual water trade and provincial water footprint in China. *Ecol. Econ.* **100**, 159–172 (2014).
68. Fan, L. *Study on Water Environment Capacity of Plain Area*. Ph.D thesis, Hohai University (2008).
69. Water Resources Department of Jiangsu Province. *Opinions of Jiangsu Water Resources Bureau and Jiangsu Development and Reform Commission on the Pollutant Load Capacity and the Maximum Allowable Pollutant Load of Water Function Zones* (Water Resources Department of Jiangsu Province, accessed 25 September 2019); [http://www.jiangsu.gov.cn/art/2016/9/14/art\\_46144\\_2545450.html](http://www.jiangsu.gov.cn/art/2016/9/14/art_46144_2545450.html) (in Chinese).
70. He, G., Wang, S. & Zhang, B. Watering down environmental regulation in China. *Q. J. Econ.* **135**, 2135–2185 (2020).
71. Liu, M., Shadbegian, R. & Zhang, B. Does environmental regulation affect labor demand in China? Evidence from the textile printing and dyeing industry. *J. Environ. Econ. Manag.* **86**, 277–294 (2017).
72. Fan, H., Zivin, J. S. G., Kou, Z., Liu, X. & Wang, H. Going Green in China: firms' responses to stricter environmental regulations. NBER Working Paper Series 26540 (2019).
73. Water Resources Department of Jiangsu Province. *Water Resource Bulletin in Jiangsu 2015* (China Water Power Press, 2015) (in Chinese).
74. Zheng, H. et al. Regional determinants of China's consumption-based emissions in the economic transition. *Environ. Res. Lett.* **15**, 074001 (2020).
75. Society of Chinese Urban Water Supply and Drainage. *Urban Drainage Statistic Yearbook* (China Statistics Press, 2016) (in Chinese).
76. Standardization Administration of the People's Republic of China. *Industrial Classification for National Economic Activities (GB/T 4754-2017)* (the Standards Press of China, 2017) (in Chinese).

## ACKNOWLEDGEMENTS

This study was supported by the National Natural Science Foundation of China (Nos. 72074136, 72033005, 72022009, 72125010 and 71974186), the National Social Science Foundation of China (No. 21ZDA065), the Taishan Scholars Programme of Shandong Province (Young Taishan Scholars), and Low-carbon development under the Beautiful China Initiative in 2035 and roadmap for China's Carbon Neutrality in

2060 (CEMF03). We are grateful to Professor Hong Yang at Eawag for her valuable suggestions to this study.

## AUTHOR CONTRIBUTIONS

X.Z. designed the study; Y.L. and S.H. compiled the data; S.H. and S.W. conducted the calculations; S.H., X.Z., M.R.T., and K.F. analysed the results; S.H. and B.L. created the figures; X.Z. and N.Z. provided the funding; all authors participated in the writing and revision of the paper.

## COMPETING INTERESTS

The authors declare no competing interests.

## ADDITIONAL INFORMATION

**Supplementary information** The online version contains supplementary material available at <https://doi.org/10.1038/s41545-022-00152-7>.

**Correspondence** and requests for materials should be addressed to Xu Zhao or Ning Zhang.

**Reprints and permission information** is available at <http://www.nature.com/reprints>

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2022