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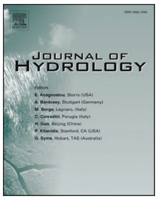

Research papers

Tracing surface water pollution in China's supply chain

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ABSTRACT

Decades of economic growth in China were enabled by rapid industrialization with insufficient water quality controls. Previous studies have traced water pollution discharges or grey water footprint using the multi-regional input–output (MRIO) model. However, there is a research gap in understanding the relation between surface water pollutant concentrations and final consumption of local and external basins. Here, we present the first national analysis to map surface water quality degradation in watersheds embedded in China's supply chains. To do this, we developed a basin-specific relationship between surface water pollution concentration and discharge, and combined it with the MRIO model to trace the water pollution of different basins through the trade of products and services. We find that ~50% chemical oxygen demand (COD) and ~46% ammonium nitrogen (NH_4^+-N) discharges from production processes can be traced to consumer demands beyond the basin where the pollution was initially released. 0.3–2.2 mg/L COD and 0.03–0.31 mg/L NH_4^+-N water quality degradation (the range indicates pollution concentration in different basins) can be attributed to final consumption of commodities from other basins in China. International consumers contributed to increased degradation of water quality (0.43 mg/L COD in Huai River Basin and 0.07 mg/L NH_4^+-N in Hai River Basin). High pollution concentrations were often concentrated in dry North China, because water scarce basins in this region are more susceptible to human pollution loadings. Basins outsourcing water pollution were mainly developed economies that outsourced production and subsequent water quality impairments to other basins. This study highlights the interactions between water quality and supply chains.

1. Introduction

Suitable water quality was laid out as a fundamental component of sustainable water and sanitation in the United Nations' Sustainable Development Goals (SDGs) (e.g. SDG #6). Water quality is also critical for many other SDGs, including those related to health, food security, and biodiversity (UNEP, 2016; UNSD, 2017). Surface water sources provide a range of ecosystem services to humans, including potable water, fisheries, aquatic habitats for biodiversity, and aesthetic and recreational opportunities (van Beek et al., 2011; Keeler et al., 2012; Hobbie et al., 2017; van Vliet et al., 2017; Viviroli et al., 2020). However, wastewater and pollution discharges from households, agricultural, and industrial sites, lead to surface water quality impairments around the world (Schwarzenbach et al., 2010; Chen et al., 2019). Developing countries are particularly prone to water pollution as a result of rapid demographic, economic, and environmental changes (UN-

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water, 2018; Obade and Moore, 2018; Chen et al., 2019).

Surface water pollution is particularly problematic in China, despite recent efforts to improve water quality through increased expenditures in water pollution abatement (Zhang et al., 2016; Tong et al., 2017; Zhou et al., 2017; Tong et al., 2020). It was reported that more than 100 billion RMB per year was spent in China for environmental restoration over the last decade (Ma et al., 2020a). However, water quality impairments continue to threaten public health, challenge water supply security, and degrade aquatic ecosystems in China, representing a major challenge to its sustainable development (Liu, 2012; Liu et al., 2012; Guan et al., 2014; Zhao et al., 2016). China's inland surface water quality presents high heterogeneity across different basins, due to regional differences in natural water endowments, anthropogenic pollution discharges and management policies (Jiang, 2015; Han et al., 2016; Ma et al., 2020a). Recent research has improved our understanding of inland surface water quality in China and its response to pollution discharges (Ma et al., 2020a).

Rapid economic growth and industrialization with insufficient environmental controls led to pollution discharges in China. Industrial production in China is the start of complex supply chains which provide end-products to domestic and international consumers. By outsourcing production to China, countries around the world contribute to water quality impairments in China. This means that the role of end consumers of pollution through supply chains should be recognized in order to understand how demand contributes to production externalities and risks in supply chains. Pollution discharges of China to water bodies were traced to final consumption in prior studies, providing a new insight of surface water pollutions from the consumption perspective (Guan et al., 2014; Hou et al., 2022). In particular, water pollution has been linked to inter-regional and international trade with grey water footprints, which is defined as the amount of water required to dilute pollution discharges to meet water quality standards (Hoekstra and Mekonnen, 2012; Mekonnen and Hoekstra, 2015). Recent grey water footprint research focused on improving grey water footprint quantification (Jamshidi, 2019; Li et al., 2021) and assessing the role of consumption patterns in impacting grey water footprint (Liao et al., 2021). Grey water footprints, although an important concept, is heavily reliant on water quality standards rather than realized in-stream water quality impairments. Notably, in-stream water quality depends on both pollution discharges and diluting capacity of natural water bodies. There is a research gap in understanding the relation between surface water concentrations and final consumption of local and external basins.

In this study, we quantify surface water pollution embedded in the full supply chain of China. Specifically, we calculate how production, domestic and international trade, and final consumption impacts surface water quality (characterized by pollution concentrations). We consider two typical surface water quality indicators, i.e. chemical oxygen demand (COD, the permanganate index) and ammonium nitrogen (NH_4^+-N) concentrations, because of their ability to indicate surface water quality and their wide in-stream measurement availability in China (Zhou et al., 2017; Ma et al., 2020b). We use a multi-regional input–output (MRIO) model coupled with spatially explicit water pollution discharge data (0.25 × 0.25 arc-degree grid data disaggregated from provincial water pollution discharges) to track pollution discharges from sectoral producers to end consumers. We develop a basin-specific relationship between surface water pollution concentration and discharge in order to attribute surface water quality degradation to production, trade, and final consumption for the ten major river basins in China and international consumers. In comparison to prior studies (Guan et al., 2014; Hou et al., 2022) that connected pollution discharges from production to final consumption, we further link pollutant concentrations in surface water to trade and final consumption.

A review article for environmental footprints highlighted the trend of using new indicators (rather than traditional indicators of water, land and materials) in footprint research (Wiedmann and Lenzen, 2018). We contribute to environmental impacts literature by integrating supply chain information with surface water quality measurements (i.e. surface water pollution concentrations). Additionally, we link supply chains to watershed basins, which is the spatial unit at which water management efforts to control pollution typically occur. Notably, a few prior MRIO studies that focused on water quantity were conducted at the basin scale (Lutter et al., 2016; Wang and Zimmerman, 2016), but most MRIO studies were conducted at the administrative unit, which is the spatial boundary at which the statistical information that underpins the MRIO tables is collected.

2. Data and methods

2.1. Surface water quality data and processing

Surface water quality data are collected from the national environmental monitoring network that covers China's major inland rivers and lakes (Ma et al., 2020b). Monthly observations of COD and NH_4^+-N concentrations are available at 2613 sampling sites by 2017 (Fig. 1). Monthly time series of COD and NH_4^+-N concentrations for each of the 10 major river basins are created as a water resource-weighted average of pollution concentrations at the sampling sites, where the water resource data at the 0.25 × 0.25 arc-degree grid level is derived by downscaling provincial-level natural water resources data (MWC, 2017) based on the Variable Infiltration Capacity (VIC) hydrologic model simulation results (Zhang et al., 2014). The 95% confidence intervals of the basin-level pollution concentrations are estimated using the weighted mean and variance of the Student's *t*-distribution. The annual COD and NH_4^+-N concentrations are obtained by averaging the monthly times series.

2.2. Multi-Region Input-Output and pollution discharge data

China's MRIO table in 2017 (Zheng et al., 2020), which is the latest available data characterizing the transaction of products and services in monetary unit among 42 sectors and 31 provinces, is used to trace water pollutions along the supply chain. The estimates of the provincial-level anthropogenic COD and NH_4^+-N discharges from four major sectors, i.e. agriculture, industry, urban residential and rural residential sectors, are referenced from the most recent Chinese pollution source census for the year of 2017 (MEEC, 2020; Ma et al., 2020a,b). Agricultural pollution discharges include those from aquaculture, livestock farming and crop farming. After subtracting pollution discharges into the sea in coastal provinces, the provincial-level industrial pollution discharges are disaggregated into discharges of 27 detailed industrial sectors (corresponding to the industrial sectors in the MRIO table). The disaggregation is made based on the estimates of pollution discharges from detailed sectors, which are calculated as the product of industrial output (data sources are listed in *Supplementary Information* Table S1) and corresponding sectoral pollution discharge coefficient from the pollution source census (MEEC, 2020). Pollution discharge data from 5 of the 27 detailed industrial sectors (i.e., Sec. 15, 21–24 in *Supplementary Information Table S2*) are not available, and are estimated by disaggregation based on sectoral economic outputs from the MRIO table. Pollution discharges from the urban residential sector are comprised of tertiary and urban domestic discharges. We assume that the share of tertiary pollution discharge is the ratio of the number of employees in the tertiary sector to the total population (NBS and MEEC, 2019). The tertiary pollution discharge is then disaggregated into 14 detailed tertiary sectors (corresponding to the sectors in China's MRIO table) according to the number of employees.

The provincial-level sectoral pollution discharges are disaggregated at the 0.25 × 0.25 arc-degree grid level based on land use (Liu et al., 2014) and urban and rural population distributions (Ma et al., 2020b) using the proportional sharing method. The agricultural pollution

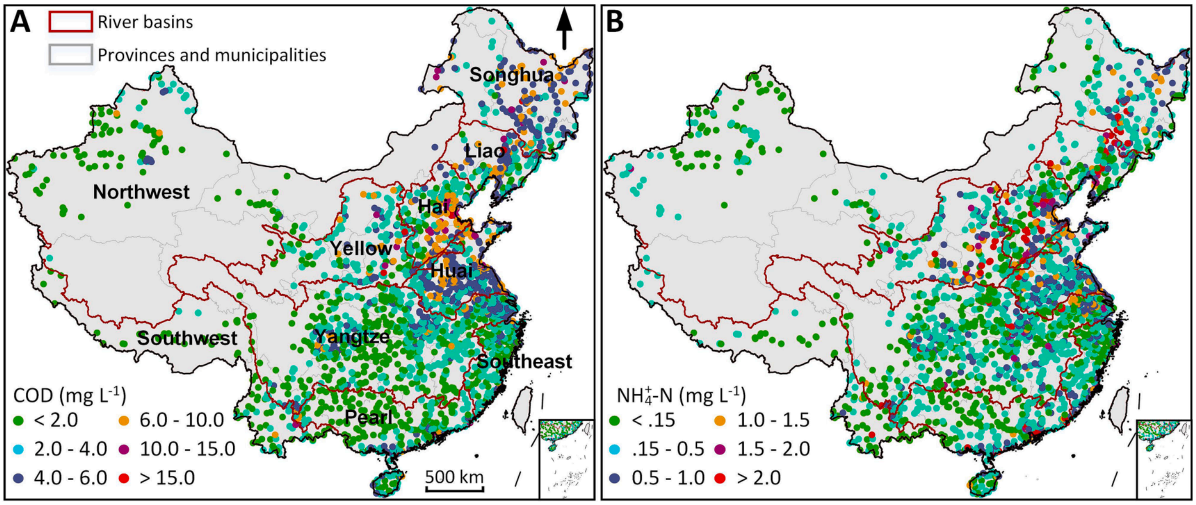

Fig. 1. Surface water quality sampling sites in the national environmental monitoring network of China. A total of 2613 sampling sites are included with monthly observations of COD (A) and NH_4^+-N (B). Annual mean concentrations of COD and NH_4^+-N in 2017 are shown.

discharge is disaggregated based on the spatial distribution of rural lands, croplands and water bodies. The industrial pollution discharge is disaggregated based on the spatial distribution of industrial lands (including factories and mines, industrial districts and oilfields). Urban and rural residential pollution discharges of provinces are respectively disaggregated based on grid-level urban and rural populations. Detailed descriptions regarding the method and datasets can be found in previous studies (Ma et al., 2020b). Main data used in this study is summarized in *Supplementary Information Table S3*. The grid-level pollution discharges are aggregated at the basin-level in order to analyze their relation with the basin-level surface water pollution concentrations.

2.3. Linking the basin level pollution concentrations to discharges

The degradation of surface freshwater quality is closely linked to pollution loadings from various sources (Tong et al., 2017; Tong et al., 2020; Ma et al., 2020a). However, the relationship between surface water pollution concentration increase and annual anthropogenic pollution discharge is nonlinear and the analytic form is unknown. It is assumed that the surface water pollution (either COD or NH_4^+-N) concentration in a basin, denoted as *C*, can be written as a function of corresponding pollution discharge (denoted as *P*) and other relevant variables (*Z*) with parameters α:

$$C = f(P, Z, \alpha) + \varepsilon \tag{1}$$

We are interested in pollution concentration increase per unit discharge, $\frac{\partial C}{\partial P}$. As f is a nonlinear function due to complex hydrological and pollution processes in rivers and lakes, $\frac{\partial C}{\partial P}$ changes with the value of *P*. We use the mean of $\frac{\partial C}{\partial P}$ over the range of *P*, i.e. $[0, p]$ (*p* is the total pollution discharge of a basin) to approximate surface water pollution concentration increase per unit discharge, because per unit pollution discharges from different sectors (attributed to end consumers of different basins) are considered to equally contribute to pollution concentration increment. This surface water pollution concentration increase per unit discharge, denoted as *b*, can be written as:

$$b = \frac{\int_0^p \frac{\partial C}{\partial P} dP}{\int_0^p dP} = \frac{f(p, Z, \alpha) - f(0, Z, \alpha)}{p} \tag{2}$$

where $f(p, Z, \alpha)$ is the observed pollution concentration of the basin of interest, and $f(0, Z, \alpha)$ is the pollution concentration if no anthropogenic pollution is discharged (i.e. in the natural condition). In this study, we use the minimum value of the observed monthly COD and NH_4^+-N concentrations at sampling sites over the period 2003–2017 to approximate $f(0, Z, \alpha)$ for each basin. The 95% confidence intervals of basin specific concentration *C* is obtained based on pollution concentrations at sampling sites using the weighted mean and variance of the Student's *t*-distribution. The 95% confidence intervals of pollution concentration per unit pollution discharge $\frac{\partial C}{\partial P}$ are then estimated based on the 95% CIs of basin specific observed concentrations.

2.4. Multi-region input–output analysis for water pollution discharge accounting

Based on the MRIO relationship, sector-level surface water pollution (either COD or NH_4^+-N) discharges can be traced along the production chains to final consumers, following the standard method in environmental footprint accounting (Zhao et al., 2015; Mi et al., 2017; Sun et al., 2017; Xu et al., 2020). In a socio-economic system with *n* regions and *m* sectors, the pollution discharge *P* (a column vector comprised of $m \times n$ water pollution discharges from *m* economic sectors in *n* regions) can be written as:

$$P = DX = D(I - A)^{-1}Y = TY \tag{3}$$

where *D* is the vector of direct pollution discharge per unit output in each economic sector, *X* is the vector of total economic output, *Y* is the vector of final consumption, *I* is the unit matrix, *A* is the matrix of technical coefficients, with its element a_{ij} indicating the intermediate input of sector *i* per unit output *j*, $(I - A)^{-1}$ is the Leontief inverse matrix, and *T* is an $mn \times mn$ matrix of total pollution discharge per unit product for final consumption.

Pollution discharge from region *r* to region *s*, represented by p^{rs}, can be calculated as:

$$p^{rs} = \sum_i t^{ri} y^{is} \tag{4}$$

where t^{ri} represents water pollution discharge in province *r* per unit product *i* (elements in matrix *T* in Eq. (1), y^{is} is the products from sector *i* finally consumed in region *s*. Final consumption *Y* in the MRIO table is provided in subcategories, i.e. consumption by urban and rural residents. This enables pollution discharges to be traced to final consumption by urban and rural residents. The consumption-based water pollution discharge of region *r*, represented by pc^r, is calculated as the sum of the local water pollution discharge p^r and inter-regional net pollution flows:

$$pc^r = p^r + \sum_{s \neq r} p^{sr} - \sum_{s \neq r} p^{rs} \tag{5}$$

where $\sum_{s\neq r} p^{sr} - \sum_{s\neq r} p^{rs}$ represents the net pollution inflow of region r through inter-provincial transfers.

2.5. *Consumption-based water pollution discharges and concentrations at the basin level*

The consumption-based water pollution discharge at the provincial level in Eq. (5) are disaggregated into grid level values based on grid-level urban and rural population distribution, differentiating the consumption of rural and urban residents. We trace consumption-based pollution discharge in each grid to different grids. The consumption-based pollution discharges at grids are aggregated at the basin level. We then link the basin-level consumption-based surface water pollution discharge to pollution concentration increases using the basin-specific parameters b in Eq. (2). The increase in pollution concentration of basin i that can be attributed to end consumers in basin s (denoted as cc^{is}) can be estimated as a function of b^i (b of basin i) and pc^{is}:

$$cc^{is} = b^i pc^{is} \tag{6}$$

3. Results

3.1. *In-situ and consumption-based water pollution discharges*

According to the latest pollution source census, 21.4 million tons COD and 0.96 million tons NH_4^+-N were released from anthropogenic sources, including agricultural, industrial, urban and rural residential discharges in 2017 (Ma et al., 2020b). We disaggregated the provincial-level COD and NH_4^+-N discharges in 2017 (*Supplementary Information*, Fig. S1) to the grid scale, based on multi-sourced high-resolution data. Anthropogenic COD and NH_4^+-N discharges are primarily concentrated in the eastern half of China (Fig. 2A and 2B), with dense human population and high industrial production. Concentrated pollution discharges are found in Huai, Hai, downstream Yangtze and Pearl River basins. Yangtze, Huai and Pearl River basins, which only comprise a quarter of

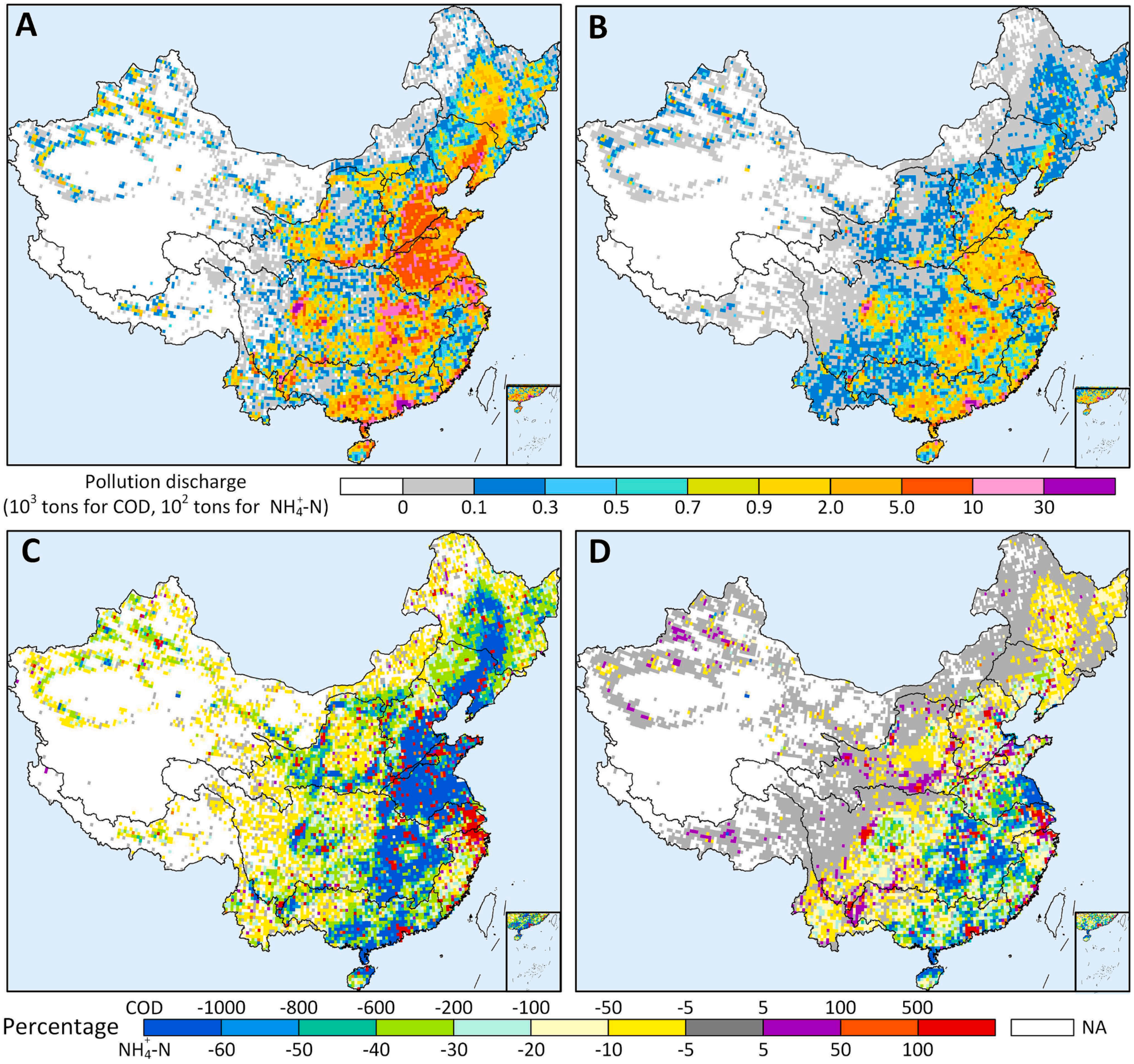

Fig. 2. Surface freshwater pollution discharges at the 0.25 × 0.25 arc-degree grid scale in China in 2017. Panels (*A*) and (*B*) show in-situ COD and NH_4^+-N discharges, respectively. Panels (*C*) and (*D*) show relative difference between consumption-based COD and NH_4^+-N and in-situ discharges, respectively, with a positive value indicating higher consumption-based discharges than in-situ discharges, and a negative value indicating lower consumption-based discharges. NA, no data available.

the national area but are home to ~ 61% of the national population, are the top three basins by pollution discharges, altogether discharging 62% COD and 70% NH_4^+-N loadings of the nation.

Though a significant share of pollution discharges are released from residential sites, pollution discharges from industry (including primary, secondary and tertiary industries) are substantial, comprising ~ 62.1% COD and ~ 43.8% NH_4^+-N of the national total. Based on the multi-region input–output (MRIO) model, we assessed pollution discharges attributed to final consumption (referred to as consumption-based pollution discharges) of 31 provincial and municipality administrative units of China (provinces for short hereafter) and exports. 11.9 million tons COD and 0.37 million tons NH_4^+-N are attributed to Chinese end consumers (including discharges from residential sites). 1.4 million tons COD and 0.05 million tons NH_4^+-N discharges are embodied in products and services exported abroad through international trade. Generally, wealthier provinces outsource pollution and have higher consumption-based pollution discharges than in-situ ones (e.g. Zhejiang, Beijing, Guangdong and Tianjin), and poorer provinces have higher local water pollution and deliver virtual pollution to other provinces through inter-provincial trade (e.g. Hebei, Guangxi, Inner Mongolia and Jiangxi).

Fig. 2 shows grid-level pollution discharges embedded in final consumption, disaggregated from provincial-level pollution discharges. This high-resolution pollution discharges highlight that large pollution discharges are most likely attributed to final consumption in urban centers with dense population. Consumption-based COD and NH_4^+-N present spatial differences to in-situ pollution discharges at the grid scale (Fig. 2C and 2D). Overall, intensive COD and NH_4^+-N embedded in final consumption remain in the east half of China. Beijing and Shanghai, the most urbanized provincial-level units in China, only representing 0.3% of the national land with 3.3% population, account for 2.4% COD and 2.6% NH_4^+-N discharges for final consumption in China. The COD and NH_4^+-N discharges embedded in finally consumed products in Beijing and Shanghai altogether are 3.7 and 1.9 times the local pollution discharges from production (excluding discharges from residential site). ~ 58% and ~ 55% of the national areas are characterized with higher in-situ COD and NH_4^+-N discharges than consumption-based discharges, respectively, whereas the areas with higher consumption-based pollution discharges distribute in a much smaller extent, i.e. ~ 5% of the national lands for COD and ~ 14% for NH_4^+-N. The distribution of COD and NH_4^+-N discharges vary in space due to the spatial distribution of sectors that produces these effluents. Because sectoral products incorporate different amounts of COD and NH_4^+-N discharges in their production processes, the relative net exchange of COD and NH_4^+-N discharges at the grid level show spatial difference (Fig. 2C and 2D). For instance, in southwest rural China where crop production dominates NH_4^+-N discharge but does not produce much COD, the relative difference between consumption- and production- based NH_4^+-N discharges is higher than that of COD.

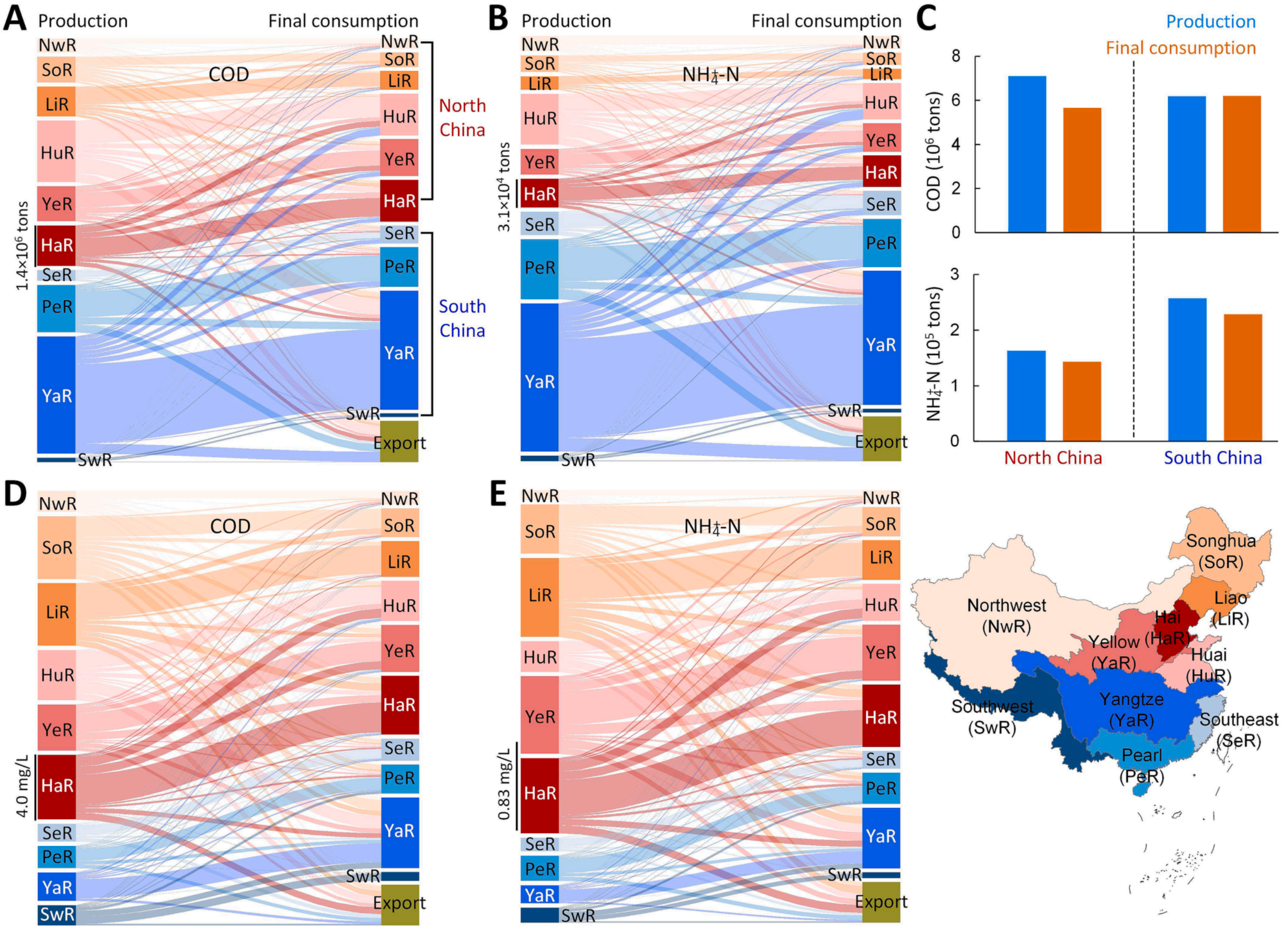

Fig. 3. Inter-basin surface water pollution transfers across 10 major river basins of China in 2012. Panels (*A*) and (*B*) exhibit COD and NH_4^+-N discharges, respectively. Panel (*C*) shows pollution discharges in North and South China. Panels (*D*) and (*E*) show COD and NH_4^+-N concentrations, respectively. The left and right columns in Panels (*A*), (*B*), (*D*), and (*E*) represent pollution discharges or concentration increases embedded in production and final consumption of sectoral products, respectively. The lower right inset indicates the geographic location of the ten basins.

3.2. Water pollution discharges embedded in domestic product transfers and exports

To assess water pollution attributed to domestic and international end consumers, we estimated pollution discharges embedded in China's domestic and international supply chain. Of all the pollution discharges generated from production processes, 50.1% COD and 46.2% NH_4^+-N discharges can be traced to end consumers in a different basin from where the pollution is initially released, indicating the importance of tracing water pollution from the consumption perspective. Approximately 89.3% COD and 88.5% NH_4^+-N are used for providing domestic final consumption of sectoral products, corresponding to a mass of 11.9 million tons COD and 0.37 million tons NH_4^+-N. Moreover, 10.7% COD and 11.5% NH_4^+-N discharges are exported abroad (Fig. 3A and 3B).

The largest pollution discharger, i.e. Yangtze River basins, also has the largest pollution discharge outflows and inflows through domestic transfer of goods, delivering about 1.3 million tons COD and 0.06 million tons NH_4^+-N to other basins, and receiving about 1.4 million tons COD and 0.04 million tons NH_4^+-N. Three basins, i.e. Southeast, Hai and Yellow River, receive net pollution discharges embodied in domestic product transfers, and thus are responsible for more consumption-based pollution discharges than production-based discharges, whereas six basins, i.e., Huai, Songhua, Liao, Northwest, Southwest and Pearl River basins, deliver net pollution discharges to other basins in China. Yangtze River basin is a net COD receiver, but a net NH_4^+-N deliverer. COD discharges in North and South China do not show much difference, for both production and final consumption of sectoral products, with the relative difference less than 15%. NH_4^+-N discharge in South China is much higher than South China, with the relative difference around 40% (Fig. 3C).

3.3. Water pollution concentration increases embedded in domestic product transfers and exports

The relationship between pollution concentration and discharge in surface water is evaluated for different basins. Estimates of $f(0, Z, \alpha)$ and b as well as their 95% confidence intervals in Eq. (2) are provided in Table 1. Based on the basin-specific relationship, the relocation of freshwater pollution discharges through supply chains is linked to surface freshwater quality degradation (i.e. pollution concentration change). We then calculated basin-level COD and NH_4^+-N concentration increases that are embedded in sectoral goods through the supply chain and the portions transferred domestically and traded abroad (Fig. 3D and 3E).

Surface water pollution attributed to inter-basin product transfer and international trade presents a different pattern than pollution discharges, because of regional differences in the response of surface water quality to pollution discharges. Generally, there is less natural water pollution diluting capacity in water scarce North China than water abundant South China, so basins in North China (with the exception of the Northwest River basin) have higher water pollution concentrations. Songhua River basin has the highest COD concentration increment attributed to end consumers in other basins and countries, i.e., ~2.4 mg/L, in comparison to its annual mean concentration of ~ 5.0 mg/L (in which ~ 3.5 mg/L can be attributed to production, see *Supplementary Information*, Table S4 with 95% confidence intervals estimated). Yellow River basin has the highest NH_4^+-N concentration increment attributed to final consumption of other basins and international end consumers, i.e., ~0.35 mg/L, in comparison to their annual mean concentration of ~ 1.32 mg/L (in which ~ 0.63 mg/L can be attributed to production, *Supplementary Information*, Table S5 with 95% confidence intervals). International consumers contribute the most COD concentration increment in Huai River basin (0.43 mg/L, in comparison to 1.5 mg/L COD concentration for supporting domestic consumption in other basins), and the highest NH_4^+-N concentration increment in Hai River basin (0.07 mg/L, in comparison to 0.26 mg/L NH_4^+-N concentration increment for supporting domestic consumption in other basins). Basins with the most water quality impairments supporting external end consumers are all in North China.

End consumers in Yangtze River basin are responsible for higher COD and NH_4^+-N concentration increments in all the other basins than pollution concentration increases of Yangtze River basin attributed to final consumption of other basins. Pearl, Hai and Southeast River basins often have higher pollution concentration increments embedded in commodity influx from other basins than commodity outflux. These basins have industrialized economies, such that high pollution concentration increments of other basins are incorporated in their supply chain. The other six basins, including Liao, Huai, Songhua, Northwest, Southwest and Yellow River basins, mostly located in North China (with an exception of Southwest River basin), usually suffer from more aggravated production-based pollution concentration increases than those embedded in their commodities for final consumption (*Supplementary Information*, Tables S4 and S5).

3.4. Water pollution discharges and concentration increases embedded in resolved sectoral products

The pollution discharges in resolved sectoral products are traced along the entire supply chain to identify sectors that are mostly relevant to water pollution (Fig. 4A and 4B). At the national level, agricultural production releases the largest share of pollution discharges in the production processes, i.e. ~ 80% COD and ~ 51% NH_4^+-N. The production of tertiary products discharges more COD (~11%) and NH_4^+-N (~14%) than industrial products (~9% for COD and ~ 7% for NH_4^+-N).

Table 1

Estimates of average pollution concentration increases per unit anthropogenic discharges for 10 major river basins in China.

	Basin	COD			NH_4^+-N		
		Observed concentration (mg/L)	Baseline concentration (mg/L)	Concentration increases per unit discharge (mg/L per million tons)	Observed concentration (mg/L)	Baseline concentration (mg/L)	Concentration increases per unit discharge (mg/L per million tons)
North China	Northwest	1.72 (1.47–1.97)	0.03	2.36 (2.01, 2.70)	0.17 (0.11–0.22)	0.01	4.86 (3.18–6.55)
	Songhua	4.98 (4.45–5.50)	0.25	4.00 (3.55–4.44)	0.81 (0.59–1.04)	0.01	23.57 (17.11–30.04)
	Liao	4.19 (3.41–4.99)	0.25	3.19 (2.56–3.83)	1.08 (0.56–1.60)	0.01	40.32 (20.65–59.98)
	Huai	4.68 (4.41–4.95)	0.12	1.40 (1.31–1.48)	0.60 (0.47–0.74)	0.01	5.05 (3.93–6.16)
	Yellow	4.02 (3.46–4.57)	0.25	2.09 (1.78–2.39)	1.32 (0.84–1.81)	0.01	22.58 (14.22–30.93)
	Hai	5.61 (4.81–6.41)	0.17	2.54 (2.17–2.91)	1.40 (0.89–1.90)	0.01	19.60 (12.47–26.74)
South China	Southeast	2.46 (2.29–2.66)	0.25	2.77 (2.56–3.01)	0.30 (0.25–0.36)	0.01	4.95 (4.10–5.92)
	Pearl	2.60 (2.42–2.91)	0.16	0.80 (0.74–0.85)	0.64 (0.49–0.79)	0.01	3.47 (2.65–4.29)
	Yangtze	3.01 (2.91–3.11)	0.06	0.43 (0.41–0.44)	0.42 (0.38–0.47)	0.01	1.12 (1.00–1.24)
	Southwest	2.00 (1.69–2.31)	0.25	7.42 (6.10–8.75)	0.21 (0.12–0.30)	0.01	19.15 (10.30–27.99)

Note: Basin-specific observed water pollution concentration is obtained based on measurements at sampling sites. Numbers in brackets represent the 95% confidence interval values.

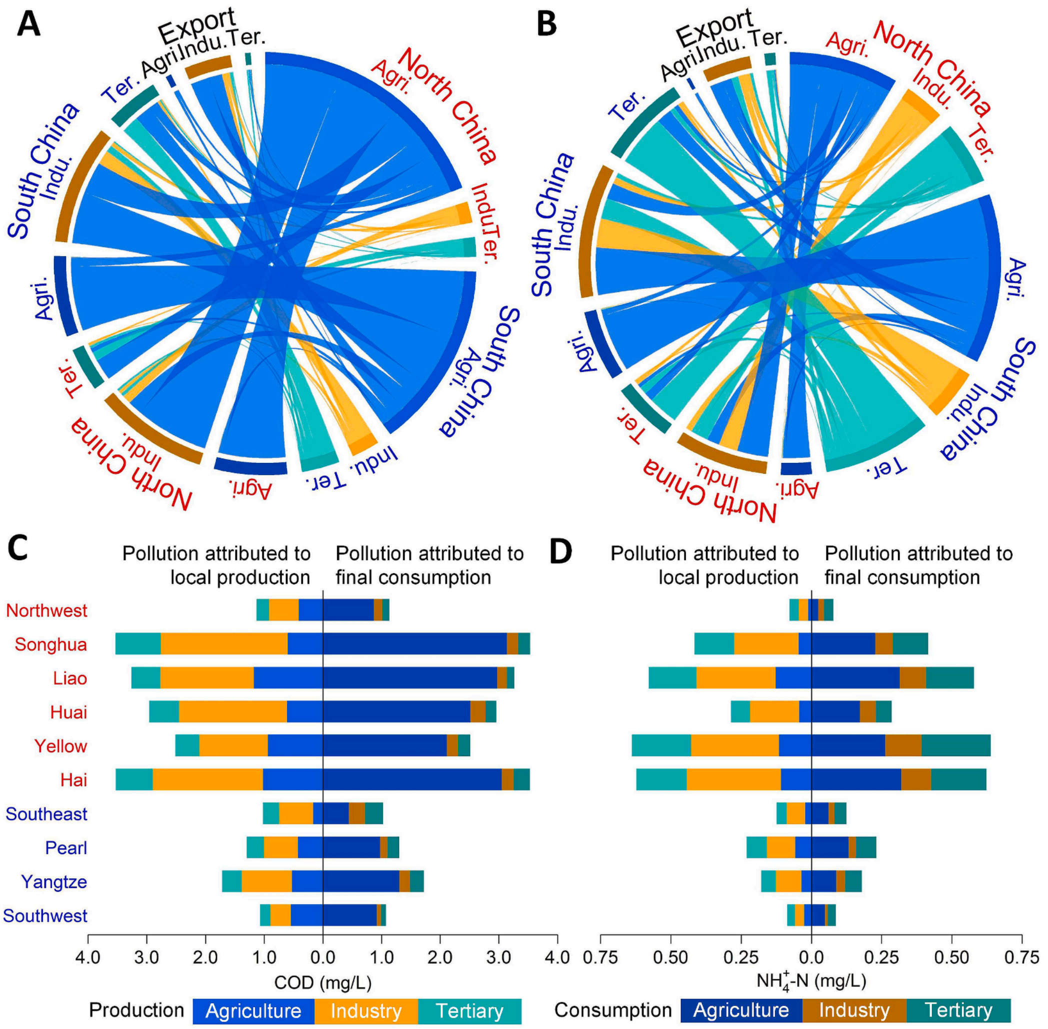

Fig. 4. Pollution discharges and concentration increases embedded in sectoral products from production to final consumption in China's river basins in 2017. Panels (*A*) and (*B*) exhibit COD and NH_4^+-N discharges for North and South China (unit: million tons yr^{-1}; for COD and NH_4^+-N, the totals are 13.3 and 0.4 million yr^{-1}, respectively). Origins of pollution discharges are indicated with links emanating from the outer bars with the same color and destinations are indicated with a white gap separating the outer bar from links with a different color. Panels (*C*) and (*D*) show surface water COD and NH_4^+-N concentration increments in different basins attributed to local production (on the left side) and final consumption (of end consumers in China and abroad, on the right side) of sectoral products. Names in red and blue indicate basins in North and South China, respectively.

A large share of agricultural products are used as intermediate inputs for industrial and tertiary products, so their corresponding pollution discharges are indirectly incorporated in industrial and tertiary products. Therefore, pollution discharges embedded in industrial and tertiary products for final consumption are much higher than the production-based accountings. ~ 52% COD and ~ 51% NH_4^+-N discharges are embedded in industrial products for final consumption. The top three sub-industrial sectors embodying the largest COD and NH_4^+-N discharges are Sec. 6- food and tobacco processing, Sec. 28- construction, and Sec. 8- garments, leather, furs, down and related products, which altogether comprise over two thirds of industrial pollution discharges for final consumption (see *Supplementary Information*, Table S2). In contrast, agricultural products for final consumption only represent ~ 29% COD and ~ 19% NH_4^+-N discharges for production processes.

Similarly, agricultural production is responsible for the largest pollution concentration increases in all the basins, whereas industrial and tertiary products for final consumption contribute higher water pollution concentration increases in most basins (Fig. 4C and 4D). Industrial products for final consumption contribute 39%-58% COD and 39%-55% NH_4^+-N concentration increments in different basins, and final consumption of tertiary products is responsible for 15%-26% COD and 29%-46% NH_4^+-N concentration increments in different basins. In particular, pollution concentration increments in Chinese basins for export are mainly linked to industrial product trade. At the sub-sectoral level, Sec.8- garments, leather, furs, down and related products, Sec. 6- food and tobacco processing, and sec. 7- textile industry are the top three industrial sub- sectors contributing the most COD discharges in international trade. Sec. 8- garments, leather, furs, down and related products, sec. 7- textile industry, and sec. 12- chemicals are the top three industrial sub- sectors embodying the most NH_4^+-N discharges in international trade (see *Supplementary Information*, Table S2).

We also differentiated pollution discharges between basins of North and South China (Fig. 4A and 4B). COD discharges embedded in the supply chains of North and South China are nearly equivalent in quantity, from both the production and consumption perspectives. However, natural water endowment leads to a large difference in surface water pollution concentrations between North and South China. In the basins of North China, pollution discharges from production activities generally lead to a greater increase of pollution concentrations due to lower surface water runoff volumes (COD concentration by ~ 2.8 mg/L and NH_4^+-N concentration by ~ 0.44 mg/L on average); in the basins of South China, production has a smaller impact on surface water quality impairment due to larger water volumes (COD concentration increased by ~ 1.3 mg/L and NH_4^+-N concentration by ~ 0.16 mg/L) (Fig. 4C and 4D).

4. Discussion

Several studies have used the grey water concept to analyze the water pollution associated with trade and consumption (Mekonnen and Hoekstra, 2015). However, grey water is a theoretical volume of water required to dilute pollution discharges to policy standards or natural background, which does not consider if that amount of water is actually available to reduce concentrations of pollutants. To improve on this approach, we link empirical data on surface water pollution concentrations to domestic product transfers and international trade. Our approach allows to attribute concentration increment of pollutants in surface water bodies to end consumers in different basins.

The Chinese government has spent much money to improve water quality, through structural and non-structural measures, e.g. wastewater treatment upgrades, watershed restoration, and the "Three Redlines" policy. Existing policies have focused on capping total pollution discharges into water bodies (e.g. China's water resources "Three Redlines" and "Water Ten Plan"), the capping volumes of which are mostly determined based on present pollution discharges. Yet, water pollution remains a challenge throughout China. Our results suggest that producers, particularly Hai, Songhua, Huai, Liao and Yellow River basins in North China, where quality-driven water scarcity is a concern (Ma et al., 2020a), need to reduce their pollution discharges. Consumers in South China generally face less water quality degradation in their own basins, but contribute to water pollution in the North through their receipt of pollution intensive goods. International consumers have an indirect impact on China's surface water quality primarily through their import of industrial products. These results highlight the importance of internalizing the cost of water pollution in China's supply chain, e.g. through including the cost of preventing/reducing water pollution into the price of commodities to send a market signal to consumers. Because basins show varied capacity in assimilating human released water pollutions due to their different natural water endowment, the cost of abating water pollution in basins should be differentiated and considered in the supply chain. This will increase prices of commodities with heavy water pollutions produced in Hai, Songhua, Huai, Liao and Yellow River basins, and this pricing signal may help consumers select environmental friendly products. Furthermore, our results show that the hotspots of pollution consumption are cities. This knowledge could be used to enhance surface water quality management by outreach and education efforts. The urban end consumers could pay more money to account for the water pollution upstream in their supply chain, helping to defray the expense of more stringent environmental regulation. A cap and trade system for water pollution could help to both minimize total pollution and reduce costs to both producers and consumers. This system should also urge water scarce Hai, Songhua, Huai, Liao and Yellow River basins to restrict water polluted industries (e.g. garments, leather, furs, down and related products, food and tobacco processing, textile industry and chemicals). Based on these findings, decision makers can evaluate how to reduce the dependence of our supply chains on water pollution and optimize spatial distribution of industries with their pollution costs considered based on natural water endowment. A broad range of options - technological, political, economic and behavioral – should be implemented to improve the surface water quality of China.

There is uncertainty in our analysis stemming from data constraints. Due to a lack of high-resolution pollution discharge data, one major source of uncertainty stems from the disaggregation of provincial-level pollution discharges to the grid level. A basin-specific relation quantifying surface water pollution concentration increase per pollution discharge neglects spatial heterogeneity of surface water quality within a basin and leads to uncertainty in pollution concentration increases attributed to end consumers. Uncertainty in the parameters of this relation through a linear regression is analyzed (Table 1). Other uncertainty sources include uncertainty in the multi-sourced data and sectoral aggregation of the MRIO data and table, the latter of which is commonly shared by all the MRIO based environmental footprint studies in China (Zhao et al., 2015; Sun et al., 2019). Pollution discharge information is not available for each of the 27 detailed industrial sectors and 14 detailed tertiary sectors (that are consistent to sectors in the MRIO table), so our disaggregation of lumped industrial and tertiary pollution discharges into high-resolution sectors represents another uncertainty source. Nevertheless, we use the best available information to reveal the general pattern of surface water pollution embedded in China's supply chain. Future efforts to improve data monitoring and collection would enhance basin-level pollution discharge accounting in China.

5. Conclusions

This study presents a quantitative assessment of basin-level surface water quality degradation related to production, trade and consumption in China, linking surface water pollution concentrations with supply chains for the first time. Nearly half of the COD discharge and one third of the NH_4^+-N discharge are released from production processes. Our results show that about a half of the pollution discharges from production processes can be traced to end consumers from a different basin where the pollution is initially released. Water quality outcomes are driven both by pollution loadings and the natural water diluting capacity of the basin, making it important to collect and integrate empirical information on water quality. The results further quantify how surface water pollution concentration increases can be linked to final consumption of various products in different basins, enabling the water pollution to be tracked based on regionally different responses of nature to anthropogenic pollutions. This provides a new perspective for surface water quality management along the supply chain.

A broad range of options - technological, political, economic and behavioral (Ouyang et al., 2016) – will be needed to improve water quality in China. In this study, we have tried to lay the foundation for thinking about local water pollution as being enmeshed in complex supply chains, with links to end consumers across the country and around the world. The analysis of water pollution embedded in resolved sectoral products allows the key sectoral products linked to high water pollution to be identified. Tracing surface water pollution in the supply chain allows us to better determine which regions and production sectors are responsible for pollution and water quality degradation. This is critical for the evaluation of demand-side policy options and supply chain management. Our results show that the hotspots of pollution consumption are cities. This knowledge could be used to enhance surface water quality management by outreach and education efforts. Funding and technology transfers can be made from affluent consumption centers to heavily polluted regions (particularly in water scarce basins in North China with a low water diluting capacity) to help improve the surface water quality. The end-consumers may play a potential role in abating surface water pollution by paying the internalized cost for water pollution in the supply chains, such as through paying the price of commodities that include the cost of preventing/reducing water pollution.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2023.129960.

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