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Energy-pollutant nexus for wastewater treatment in China based on multi-regional input-output analysis

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ABSTRACT

The pollutant removal of wastewater treatment has been facing the challenge of increasing energy consumption and varying spatial heterogeneity in China. This paper first employed an input-output (IO) model to calculate the sectoral wastewater pollutant (COD) discharge coefficients and a multi-regional input-output (MRIO) model was employed to explore the provincial virtual wastewater pollutant (COD) flows in China. Then, the energy efficiencies of wastewater treatment plants (WWTPs) in different provinces were inventoried. This study developed an assessment framework combining the multi-regional input-output model, virtual pollutant, and embodied energy. The critical pollutant discharge sectors (Service, Agriculture, Textile industry, Food and tobacco processing, Manufacture of chemical products, Production and distribution of tap water) and provinces (Shandong, Jiangsu, Guangdong, Henan, Zhejiang, Hubei, Sichuan) were identified. It was found that the pattern of virtual wastewater pollutant flows in China was efficient in energy saving. Majority of virtual wastewater COD (wwCOD) was transferred from higher energy efficient provinces to lower energy efficient provinces for saving 1.6×10^7 kW.h electricity. The study may help optimize the spatial regulation of national energy conservation and pollution reduction.

Keywords: Pollutant transfer, energy saving, COD, multi-regional input-output analysis

NONMENCLATURE

Abbreviations	
wwCOD	wastewater COD
WWTPs	wastewater treatment plants
MRIO	multi-regional input-output

1. INTRODUCTION

Urban expansion and economic development in China have led to large amount of wastewater discharge and severely damaged the water environment. Increasing WWTPs that undertake important task of improving the water environment were built to remove the pollutants such as SS, COD, BOD, TN, TP, NH_3-N. WWTPs as energy-intensive enterprises require massive energy to remove wastewater pollutants. What makes it even more challenging is that wastewater pollutants and energy flows are often highly interwoven in the complex networks of economic systems. The resources consumption and environmental impacts in one region can be transferred via economic trade and then transcend geographical borders, leading to potential impacts in other distant regions.

Different approaches have been used to address flow transfers in economy, such as life-cycle analysis and input-output (IO) model. Based on the IO model reflecting the intrinsic relationships between intersectoral economic inputs and outputs, multi-regional IO (MRIO) analysis can further quantify the interregional trade volumes of different products and characterize the economic relationships among sectors and regions in detail. MRIO analysis has been widely used to analyze the flows transfers of embodied products in all production and consumption stages. In addition, the flows of environmental indicators mostly examined are water resources [1-3], energy resources [4], and carbon emissions [5], while pollutant (like COD [6], NH_3-N [7], SO_2 [8], solid waste [9]) transfers embodied in interprovincial trade have not been well addressed.

Quantifying the resource savings implied in trade has been a recent research hotspot, focusing on issues of water [10], energy [2], land [11] embodied in the export trade, while very few research covered the energy pressure and corresponding energy saving / excess consumption on pollution transfer. The energy consumption of WWTPs refers mainly to electricity consumption that accounts for 70%-90% of the total energy consumption [12]. Electricity efficiency is defined by the ratio of electricity used and COD removal [13]. It is widely believed that water is saved when products transferred from a country or region with low virtual water content to a country or region with high virtual water content, while energy is also saved when products from a country or region with relatively higher energy efficiency of pollutants removal transferred to a country or region with relatively lower energy efficiency of pollutants removal. An unified framework of energy-pollutant nexus is necessary to be explored to analyze virtual pollutant flow system among sectors and provinces and pollutant removal pressure transfers among provinces. Such energy-pollutant nexus can not only improve the understanding of potential dependencies between them but also optimize the spatial regulation of national energy conservation since it is often intense and exhibits spatial heterogeneity in China Therefore, energy-pollutant nexus investigation at the provincial scale is of great significance for achieving the dual goals of pollutant discharge reduction and corresponding energy saving.

Given this, we first calculated the sectoral wwCOD discharge coefficients. Then, the coefficients were introduced into the province level MRIO tables to calculate the virtual wwCOD transfer flows. An assessment framework based on the environmentally extended MRIO model for analyzing the energy-pollutant nexus and measuring the transfer volume, energy saving and final demand-driven effect of virtual wwCOD was developed.

The remainder of the paper is organized as follows. Section 2 explains the data sources. Section 3 describes the MRIO methods and energy-pollutant nexus construction of energy saving networks. Section 4 presents the case study results of China. Further discussions and conclusions are presented in section 5.

2. DATA AND SECTORS

The IO data for China in 2017 were obtained from the National Bureau of Statistics. The province-level MRIO table for China in 2017 was collected from CEADS. The wwCOD discharge data of various Industrial sectors of China in 2017 were obtained from China Statistical Yearbook on Environment-2019, which also contained national COD discharge of agricultural, industrial and domestic wastewater. It should be noted that domestic wastewater did not distinguish wastewater COD discharge between household and service. In this study, the proportion of wwCOD discharge of various service sectors is calculated using household consumption data from the China Urban Water Supply Bulletin [14]. Various service sectors were Integrated into a single sector (see Table 1). The energy efficiencies in different regions were obtained from the operational data analysis of 4,130 WWTPs.

Table 1 Sectors and codes.

Sector	Code	Sector	Code
Agriculture, Forestry, Animal Husbandry and Fishery	AGR	Manufacture of communication equipment, computers and other electronic equipment	AM-CCE
Mining and washing of coal	M-Coa	Manufacture of general purpose machinery	AM-GPM
Extraction of petroleum and natural gas	E-PNG	Manufacture of special purpose machinery	AM-SPM
Mining and processing of metal ores	M-MET	Manufacture of transport equipment	AM-Tra
Mining and processing of nonmetal and other ores	M-Oth	Manufacture of electrical machinery and equipment	AM-EME
Food and tobacco processing	PM-FT	Manufacture of metal products	AM-Met
Textile industry	PM-Tex	Manufacture of measuring instruments	AM-Mea
Manufacture of leather, fur, feather and products	PM-LFF	Other manufacturing	AM-Oth
Processing of timber and furniture	PM-TF	Comprehensive use of waste resources	AM-Was
Manufacture of paper, printing and articles for culture, education and sport activity	PM-PES	Repair of metal products, machinery and equipment	AM-MME
Processing of petroleum, coking, processing of nuclear fuel	AM-PCF	Production and distribution of electric power and heat power	PS-EH
Manufacture of chemical products	AM-Che	Production and distribution of gas	PS-Gas
Manufacture of non -metallic mineral products	AM-NOM	Production and distribution of tap water	PS-TW
Smelting and processing of metals	AM-SME	Service	SER

3. MATERIAL AND METHODS

An IO table demonstrates a detailed flow of goods and services between producers and consumers and the intermediate linkages (inter-sector analysis) between all producing sectors in a given year.

$$x_i^{rs} = \sum_{s=1}^{n}\sum_{j=1}^{n} x_{ij}^{rs} + \sum_{s=1}^{n} y_i^{rs} \quad (1)$$

where x_i^{rs} denotes the total economic output of sector i in region r; x_{ij}^{rs} represents the input from sector i in region r to sector j in region s to meet the intermediate demand of sector j in region s; y_i^{rs} represents the input from sector i in region r to region s to meet the final demand of region s.

$$A = [A^{rs}] = [a^{rs}{}_{ij}]_{n\times n} \quad (2)$$

where A^{rs} represents the direct consumption coefficient matrix from region r to region s, and *A* represents the direct consumption coefficient matrix (of the entire region). The direct consumption coefficient a_{ij}^{rs}, which represents the amount of input from sector i directly consumed by sector j per unit of economic output, is introduced. This coefficient is calculated as follows:

$$a_{ij}^{rs} = \frac{x_{ij}^{rs}}{x_j^{s}} \quad (3)$$

Where a_{ij}^{rs} represents the amount of input from sector i directly consumed by sector j per unit of economic output; x_{ij}^{rs} represents the input from sector i in region r to sector j in region s to meet the intermediate demand of sector j in region s; x_j^s denotes the total economic input of sector j in region s.

$$Z = (I-A)^{-1}Y \quad (4)$$

$$Z = A\times Z + Y \quad (5)$$

$$L = (I-A)^{-1} \quad (6)$$

where *Z* denotes the total economic output column vector; *A* represents the direct consumption coefficient matrix; *Y* denotes the final demand matrix; *L* denotes the Leontief inverse matrix.

Based on the environmentally extended MRIO model, we accounted the virtual wwCOD of China in 2017 from three perspectives: the key wwCOD discharge sectors, the province-level wwCOD transfer volume and corresponding energy saving, the responsibility of finial demand.

3.1 Direct and indirect wwCOD discharge

The discharge coefficient can be estimated by the total discharge coefficient of wwCOD discharge. The total coefficient represents the total wwCOD per unit of economic output of each sector, reflecting the virtual wwCOD discharge of each sector. The row vector of the total coefficient of water or energy consumption T^P can be expressed as:

$$T^{P} = D^{P}L \quad (7)$$

where D^P denotes the row vector of the direct coefficient (d^p) of wwCOD discharge. The direct coefficient represents the direct wwCOD discharge per unit of economic output of each sector, which can convert the economic output into the corresponding wwCOD discharge levels. We use wwCOD discharge per unit output value to express the direct coefficient.

$$d^{p} = \frac{p_j}{X_j} \quad (8)$$

where d^p denotes the direct coefficient of wwCOD discharge for sector j; p_j denotes direct wwCOD discharge of sector j; x_j denotes the total economic input of sector j.

3.2 The province-level wwCOD transfer volume

Virtual wwCOD transfer describes the directions and volumes of wwCOD movements across regions and sectors, as well as the roles of different sectors in the wwCOD flow system of China. The formula is as follows:

$$TU = U - U^{T} \quad (9)$$

where *TU* denotes the intersectoral transfer matrix of wwCOD; *TU* is an antisymmetric matrix in which the main diagonal elements are equal to 0. The element tu_{ij} in the matrix represents the virtual wwCOD transferred between sector i and sector j; *U* denotes the wwCOD demand matrix, the calculation formula of which is as follows:

$$U^{rs} = \hat{D}^{r} \times L^{rs} \times \hat{Y}^{rs} \quad (10)$$

where U^{rs} represents the total input of virtual wwCOD from region r to region s to meet the final demand of region s; $D^{\wedge r}$ represents the diagonal matrix corresponding to the column vector of the direct wwCOD discharge coefficient in region r; L^{rs} represents the Leontief inverse matrix from region r to region s; and $Y^{\wedge rs}$ represents the diagonal matrix corresponding to the final demand column vector from region r to region s.

3.3 Energy saving

The energy saving of different provinces [15] and energy efficiency of wwCOD removal of WWTPs of 31 provinces can be calculated as follows:

$$es_{rs} = (f_r - f_s)tu_{rs} \quad (11)$$

$$f = \frac{d_m}{e_m} \quad (12)$$

$$d = \sum_{m=1}^{n} d_m \quad (13)$$

$$e = \sum_{m=1}^{n} e_m \quad (14)$$

where es_{rs} denotes the relative energy saving of wwCOD from province r to region s; f denotes the regional average value of Energy efficiency of wwCOD removal; tu_{rs} represents the virtual wwCOD transferred between region r and region s. d denotes the value of the total wwCOD removal for n WWTPs. e denotes the value of the total energy consumption for n WWTPs. m denotes the regional WWTPs.

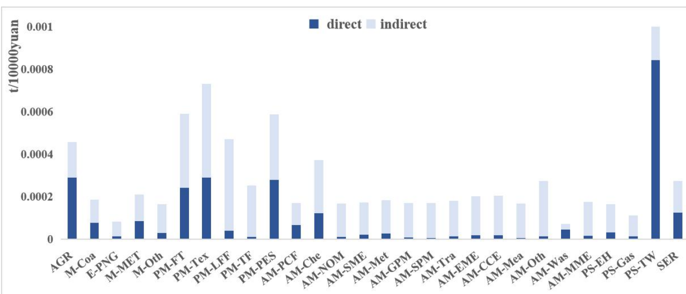

Fig 1 Sectoral direct and indirect wwCOD discharge coefficients.

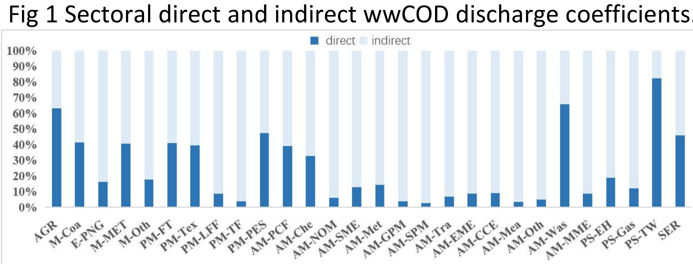

Fig 2 Proportion of direct and indirect wwCOD discharge coefficients.

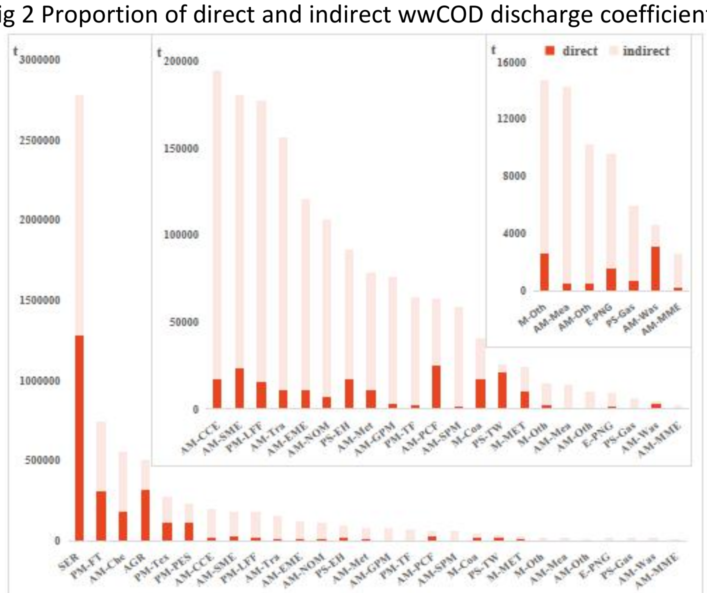

Fig 3 Volume of sectoral direct and indirect wwCOD discharge.

4. RESULTS

4.1 Vitual wwCOD discharge accounting

Fig. 1 showed the Direct and indirect wastewater COD discharges of various industries. The top five sectors of direct wwCOD emission coefficient were PS-TW, PM-Tex, AGR, PM-PES, PM-FT. The top five sectors of the indirect wwCOD discharge coefficient were PM-Tex, PM-LFF, PM-FT, PM-PES. It could be seen that only 3 sectors including PS-TW, AGR, AM-Was's direct wwCOD discharge coefficients were larger than the indirect wwCOD emission coefficients, accounting for 63.19%, 65.70% and 82.41%, respectively (Fig. 2). Fig. 3 depicted the direct and indirect volume of wwCOD discharges in sectors. SER was the largest direct wwCOD discharge sector in China, which accounted for over 50% of China's annual direct wwCOD discharge. Industrial sectors were the sector with largest virtual COD discharge accounting for 50.38%. The key sectors including PM-FT (742665 t, 11.23%), AM-Che (555447 t,

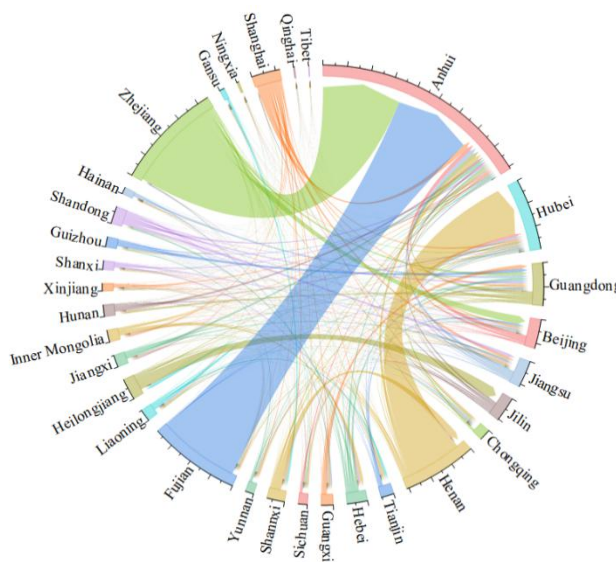

Fig 4 Virtual wwCOD flows in 31 provinces (t).

8.40%), PM-Tex (276862 t, 4.19%), PM-PES (230954 t, 3.49%) were the industrial sectors with huge wastewater discharges.

4.1 Transfer volume analysis of wwCOD

With the interprovincial goods and services trade, virtual wwCOD flows from the goods and services export provinces to the input provinces. As seen in Fig. 4, Anhui, Hubei, Guangdong, Beijing, Chongqing, Jiangsu were the main export sectors of goods and services. Here we defined sectors like those as virtual wwCOD consumption province. Anhui whose net virtual wwCOD inflow reached 9.1×10^4 t was the largest virtual wwCOD consumption province, mainly from Fujian (35190 t), Zhejiang (35393 t). Zhejiang was the largest virtual wwCOD production province, with virtual wwCOD outflow of 4.3×10^4 t, mainly to Anhui (35832 t). The virtual wwCOD flow from Henan to Hubei achieved 21283 t. Urban household consumption and fixed capital formation reached over 75% of the wwCOD discharge. Shandong was the largest virtual wwCOD discharge province accounting for over 10% of total discharge in China in 2017. Besides, Shandong, Jiangsu, Guangdong, Henan, Zhejiang, Hubei, Sichuan also faced higher virtual wwCOD discharge.

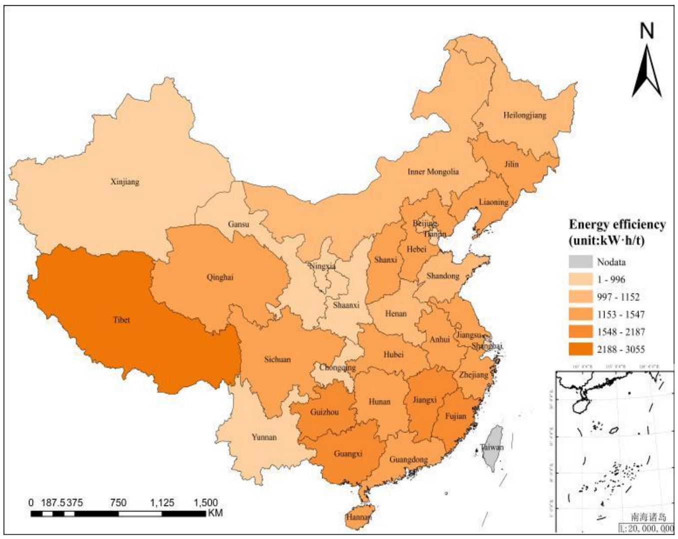

Fig 5 Energy efficiency of COD removal of WWTPs.

4.2 *Energy-pollutant nexus for wastewater treatment*

Fig 5 showed provincial average energy efficiency of COD removal of WWTPs. The average energy efficiency of China's WWTPs was 1234 kW.h/t in 2017. Xinjiang, Gansu, Yunnan, Shanghai, Tianjin, Ningxia, Shaanxi, Chongqing had relatively lower energy efficiency of wwCOD removal, while Tibet, Guangxi, Guizhou, Jiangxi, Fujian, Sichuan, Hainan's energy efficiencies of wwCOD removal were relatively higher.

Trade relationship contributes to energy savings if flow is directed from a relatively more efficient province to a relatively less efficient province. By comparing and analyzing the electricity efficiency of wwCOD removal of WWTPs between the production provinces and consumption provinces, the difference between them and how the flow influenced the energy consumption in province-level were identified comparing with an autarky situation. It was found that China's interprovincial trade led to 1.6×10^7 kW.h energy saving accounting about 1% of Chinese electricity use of wwCOD removal in 2017. In total, trade activities led to energy saving effect in 23 provinces except Tianjin, Liaoning, Fujian, Jiangxi, Guangdong, Chongqing, Guizhou, Ningxia. Anhui, Hubei, Guangdong, Beijing, Jiangsu were the main consumption provinces that led to corresponding production provinces' pollutant discharge and removal pressure. For example, Anhui as the consumption province input huge wwCOD from Zhejiang (35393 t) with a higher electricity efficiency of wwCOD removal leading to 4.4×10^6 kW.h energy saving. Anhui input 35393 t wwCOD from Fujian with a lower electricity efficiency of wwCOD removal which led to 7.6×10^6 kW.h excess energy consumption. Hubei also input 21101 t wwCOD from Henan with a higher electricity efficiency of wwCOD removal that led to 8.6×10^6 kW.h energy saving.

5. DISCUSSION AND CONCLUSION

PM-Tex, PM-LFF, PM-FT, PM-PES, AM-Oth, AM-Che, PM-TF with relatively higher indirect wwCOD discharge coefficient indicated that these sectors consumed a lot of wwCOD-intensive raw materials. These sectors had extensive product exchanges with other sectors. Meanwhile, the indirect wastewater discharges of PM-LFF, PM-TF, AM-NOM, AM-GPM, AM-SPM, AM-Tra, AM-EME, AM-CCE, AM-Mea, AM-Oth, AM-MME were much higher than direct. When indirect wastewater discharge was larger than direct, indicating that the sector consumed much wwCOD-intensive raw materials. But pollution emissions only occurred in the production sectors which were posted wwCOD removal pressure. Otherwise, sectors like basic industries and primary manufacturing were production-driven. The production structure should be improved with cleaner technology. Intersectoral associations should be taken into account when developing wwCOD discharge reduction measures. Regulating the wwCOD discharge volume and treatment efficiency of the flow starting point sector and adjusting the consumption structure in flow end point sector could be effective in wwCOD discharge reduction. In term of energy-pollutant nexus, it was found that China's interprovincial trade led to benefit effect of energy saving. Majority of virtual wastewater pollutants were transferred from higher energy efficient provinces to lower energy efficient provinces for saving 1.6×10^7 kW.h electricity. However, Anhui, Guangdong, Guizhou, Chongqing, Guizhou, Tianjin as consumer-type province with high purchasing power and large investment in buildings and equipment input large wwCOD-intensive goods from province with lower electricity efficiency of wwCOD removal, which caused both wwCOD transfer and adverse energy saving effect. Urban household consumption and fixed capital formation drove over 75% of the wwCOD discharge that should be focused in wwCOD discharge reduction. The results may help optimize the spatial regulation of national energy conservation and pollution reduction in China.

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