

PAPER • OPEN ACCESS

## Ecological Network-based Input-output Model for Virtual Water Analysis in China

To cite this article: X J Wu *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **435** 012010

View the [article online](#) for updates and enhancements.

You may also like

- [Measuring scarce water saving from interregional virtual water flows in China](#)  
X Zhao, Y P Li, H Yang et al.
- [Sustainability assessment of virtual water flows through cereal and milled grain trade among US counties](#)  
Lokendra S Rathore, Danyal Aziz, Betelhem W Demeke et al.
- [Assessing international virtual water trade of crops in Yellow River Basin, China](#)  
Rong Cai, Mengting Hu, Huiting Guo et al.



**ECS**  
The  
Electrochemical  
Society  
Advancing solid state &  
electrochemical science & technology

**DISCOVER**  
how sustainability  
intersects with  
electrochemistry & solid  
state science research

# Ecological Network-based Input-output Model for Virtual Water Analysis in China

X J Wu<sup>1</sup>, J Sun<sup>1\*</sup>, J Liu<sup>1</sup>, Y K Ding<sup>2</sup>, G H Huang<sup>1,2</sup> and Y P Li<sup>1</sup>

<sup>1</sup> Department of Environmental Engineering, Xiamen University of Technology, Xiamen 361024, China

<sup>2</sup> School of Environment, Beijing Normal University; Beijing 100875, China

\*Corresponding author E-mail: sunj@xmut.edu.cn

**Abstract.** In this study, an ecological network-based input-output model (ENIOM) is developed for assessing the virtual water in China. Direct/indirect water consumption efficiency and virtual water flow directions among different sectors are quantified by input-output model, and the relationship (e.g., exploitation, competition and mutualism) among different sectors are identified by network utility analysis. Based on China's input-output table in 2017, results show that (i) agriculture sector has the highest direct water consumption coefficient, and manufacturing sector has the highest indirect water consumption coefficient; (ii) manufacturing sector is the largest virtual water input and output sector, with a total net input of  $93.6 \times 10^9 \text{ m}^3$  from the remaining seven sectors; and (iii) exploitation is the main relationship existed in the water network system. These findings suggest that more attentions should be paid on agricultural and manufacturing sectors in terms of water resources management.

## 1. Introduction

Rapid economy development and speedy urbanization expansion in China have imposed increasing water demand, threatening regional water security and socioeconomic development. Effective identification of water-insensitive sectors and water-resources flow directions can help alleviate water crisis. The proposal of virtual water concept provides new ideas and methods for analyzing the challenges of water crisis [1]. Many research studies have been conducted for assessing virtual water among regions and sectors. For example, Zhuo et al. (2016) estimated water footprints of 22 crops based on a bottom-up method, and identified crop trade reversed the net virtual water flow since 2000 in China [2]. Zhang et al. (2019) used an input-output (IO) model for establishing a water ecological network among 16 sectors of Guangdong Province [3]. The most popular method for assessing virtual water is IO-dominated “top-down” approach, which can effectively quantify the amount of water between sectors and confirm the orientation of the flow [4]. Though massive researches have been conducted with IO model, the interactions among sectors within the socioeconomic system were neglected [5,6]. Network utility analysis (NUA), a flow-based method of ecological network analysis (ENA), can quantify the interrelationships (e.g., exploitation, competition and mutualism) among different departments of the water system. In NUA, The hidden ecological relationships and the mutualism status of the sectors can be discovered.

Therefore, this study is aimed at establishing an ecological network-based based input-output model (ENIOM) to analysis virtual water in China. IO model is used to quantify the virtual water and flow directions within an economic system. NUA method is used to identify the interactions among



sectors in terms of virtual water flows. Then, the developed method is applied to China's IO table in 2017. Results are expected to provide reliable information for water resources management.

## 2. Methodology

IO model is a quantitative economic technology, representing the interdependence among different economic sectors [7], which can be expressed as:

$$X_i = \sum_{j=1}^n X_{ij} + Y_i \quad (1)$$

where  $X_i$  is the total output of sector  $i$ ;  $Y_i$  is the final demand of sector  $i$ ;  $X_{ij}$  is the inputs from sector  $i$  to sector  $j$ . Then, the model can be solved by a direct consumption matrix and a inverse Leontief matrix. Based on China's IO table of 2017 and water use data, a row of water consumption ( $W_{ij}$ ) is added to the original IO table. Then, a direct water consumption coefficient ( $DWC$ ) matrix can be calculated as:

$$DWC = [DWC_i], \quad DWC_j = DWF_i / X_i \quad (2)$$

where  $DWC_i$  is the direct virtual water coefficient of sector  $i$ , known as the amount of direct water input to increment one monetary unit output in sector  $j$ ;  $DWF_i$  is the freshwater input directly by sector  $i$ ,  $X_i$  is the gross output of sector  $i$  [8]. Then, the total water consumption coefficient matrix  $TWC$  can be defined as:

$$TWC = [TWC_i], \quad TWC_i = \sum DWC_i \times b_{ij} \quad (3)$$

where  $b_{ij}$  is an element of inverse Leontief matrix.  $TWC$  means the final demand of a product with both direct and indirect water consumption. Thus, the indirect water use coefficient ( $IWC$ ) can be subtracted by  $DWC$  from  $TWC$  as:

$$IWC = TWC - DWC = [IWC_i] \quad (4)$$

Network utility analysis is used to describe the correlation between consumption and benefits in a network [9, 10]. In this study, this approach is used to analyze the net flow  $d_{ij}$  between sector  $i$  and sector  $j$ . Then, an integral utility Matrix  $U$  is defined with  $d_{ij}$  for identifying the interactions among sectors [11].

$$d_{ij} = (f_{ij} - f_{ji}) / T_i \quad (5)$$

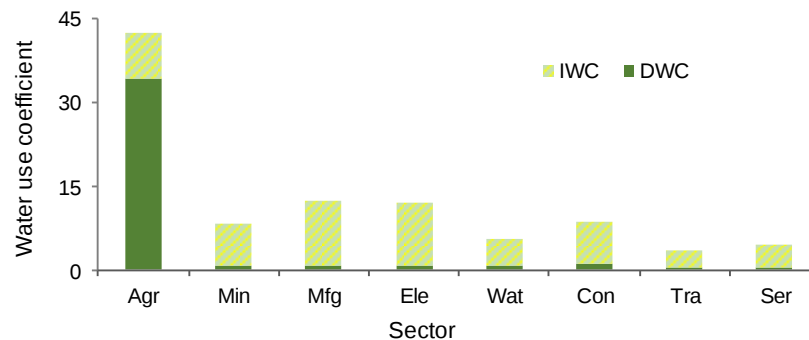
$$U = (u_{ij}) = D^0 + D^1 + D^2 + D^3 + \dots + D^\infty = (I - D)^{-1} \quad (6)$$

where  $T_i$  is the throughflow of sector  $i$ . In the matrix, the element's values " + " and " - " can help analyze the relationship between pair-wise of sectors. Assuming the sign of the utility of any element in  $U$  as  $su$ , the subscript  $ij$  means that the flow of utility is from sector  $j$  to sector  $i$ . In the utility matrix, four types of pairwise relationship exist: (1) exploitation relationship [i.e.,  $(su_{ij}, su_{ji}) = (+, -)$  or  $(su_{ij}, su_{ji}) = (-, +)$ ], meaning that one sector receives more resources from other sectors; (2) mutualism relationship [i.e.,  $(su_{ij}, su_{ji}) = (+, +)$ ], where sector  $i$  and sector  $j$  are both benefited from their interactions; (3) competition relationship [i.e.,  $(su_{ij}, su_{ji}) = (-, -)$ ], where negative effects work on the two sectors; and (4) neutralism [i.e.,  $(su_{ij}, su_{ji}) = (0, 0)$ ], meaning that the two sectors have no impact on each other.

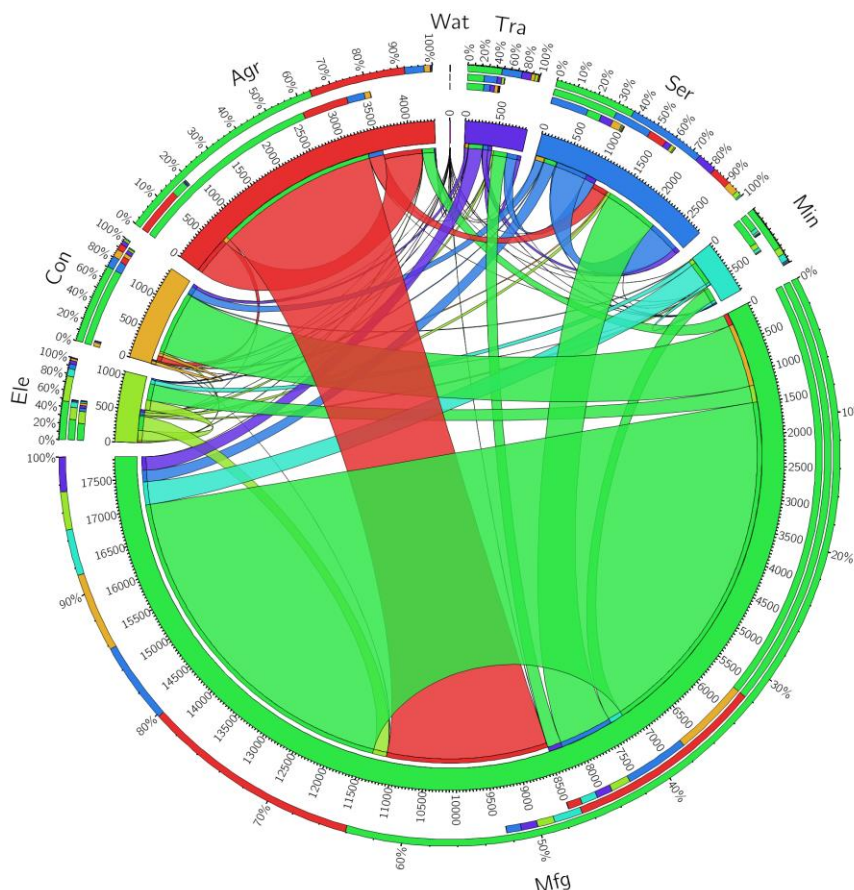
The main data sources in this study are the latest China IO table and water uses data in 2017. China IO table characterizes exchanges of products and services between 150 sectors, which are merged into eight sectors: Agricultural (Agr), Mining (Min), Manufacturing (Mfg), Electricity and gas supply (Ele), Water supply (Wat), Construction (Con), Transport (Tra), and Services (Ser). Data for water uses are collected from government reports, statistic yearbooks and surveys. For example, water use data for agricultural and secondary industry are attained from China Environmental Year Book 2017. Water use data for services sector and transport sector are obtained from the Bulletin of the first national water conservancy census in 2011, which are modified based on the difference of gross domestic products between 2011 and 2017.

### 3. Result and discussion

Figure 1 presents virtual water consumption coefficient of the eight sectors in China. Agriculture sector (Agr) has the maximum water coefficient, whose  $DWC$  is  $34.2 \text{ m}^3/10^3\text{RMB}$  and  $IWC$  is  $8.4 \text{ m}^3/10^3\text{RMB}$ . Low water use efficiency in the agricultural sector is obvious. Therefore, agriculture should be taken as the key water-saving sector. The manufacturing (Mfg) sector has the highest indirect water coefficient ( $IWC$ ), which reaches  $11.5 \text{ m}^3/10^3\text{RMB}$  in 2017. Except for agricultural, the  $IWC$  values of the remaining seven sectors are far greater than the  $DWC$  values, illustrating that most sectors utilize more indirect virtual water consumption than direct virtual water consumption.



**Figure 1.** Water use coefficient of each sector ( $\text{m}^3/10^3\text{RMB}$ )

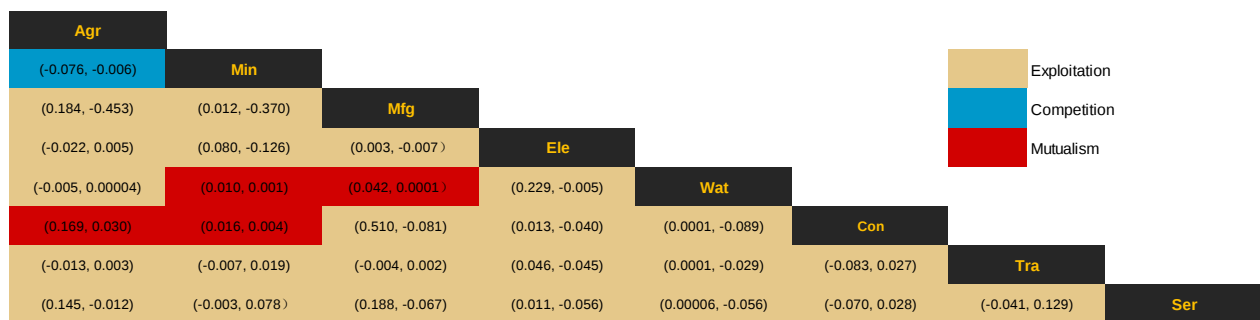


**Figure 2.** Inter-sector virtual water flows ( $10^8\text{m}^3$ ) in 2017

Figure 2 shows the virtual flow of water among different sectors in 2017. The width of the flow can present the proportion of virtual water flow amount of each sector. The manufacturing sector is the largest virtual water input and output sector, with a total net input of  $93.6 \times 10^9 \text{ m}^3$  from the remaining

seven sectors. In addition, the manufacturing sector imports a number of virtual water (28.1%) from agriculture. The construction sector mainly relies on the input of virtual water from other sectors (mainly from the transportation industry and the manufacturing industry). This phenomenon is closely related to the rapid development of urbanization in China. Besides, inter-sectoral water flows also include agriculture-manufacturing, manufacturing-construction, agriculture-services, and construction-transport. Identification of these inter-sectoral linkages can help design water conservation measures to promote the efficiency of the virtual water flow terminal department.

Figure 3 presents the relationships between pairs-wise of different sectors. Three types of ecological relationships (i.e., exploitation, competition and mutualism) are identified among the eight sectors. In short, the counts of exploitation, mutualism, and competition account for 63.9%, 33.3% and 2.8%, respectively. The main relationship between sectors in the entire virtual water network is exploitation. In detail, the agricultural sector which exploits electricity and gas supply, Water supply and transport sectors (i.e., the agricultural sector benefits from virtual water flows with Ele, Wat and Tra sectors). At the same time, it is worth noting that the agricultural sector is in a competitive relationship with the Mining sector (that is, increasing the virtual water inflow of the agricultural sector will indirectly reduce the virtual water of the mining sector), while the agricultural sector is in a mutualism relationship with the construction sector (that is, when increasing the virtual water of the agricultural, the virtual water of the construction sector will also be indirectly increased). Therefore, more attentions should be paid on agricultural sector for water saving and protecting.



**Figure 3.** Integral mutual relationship for the virtual water network

#### 4. Conclusions

In this study, an ecological network-based input-output model (ENIOM) is developed. Through integrating input-output table, indirect/direct water coefficient and network utility analysis approach into a framework, ENIOM can (1) reflect the relationship between virtual water resources and economic system; (2) quantify the flow directions of virtual water among different sectors; and (3) identify the interactions and interdependency among sectors. China's IO table in 2017 is forced into ENIOM, and eight sectors are merged for exploring their virtual water uses. Results show that agriculture sector has the highest direct water coefficient of  $34.2 \text{ m}^3/10^3\text{RMB}$ . The manufacturing sector has the highest indirect water coefficient (IWC), which reaches  $11.5 \text{ m}^3/10^3\text{RMB}$  in 2017. The manufacturing sector is the largest virtual water input and output sector, with 28.1% of virtual water imported from agricultural sector. A total net input of  $93.6 \times 10^9 \text{ m}^3$  from the remaining seven sectors. The leading relationship among sectors is exploitation. Both direct and indirect water consume must be considered, improving water efficiency in the sectors, which would reduce DWI and IWI synchronously.

## Acknowledgements

This research is supported by the China National Key Research and Development Plan Project (2016YFC0502803) and the Strategic Priority Research Program of Chinese Academy of Sciences (XDA20060302)

## References

- [1] Allan J A 1998 Virtual water: a strategic resources Global solutions to the regional deficits *Ground Water* **36** 545–546.
- [2] Zhang G, Huang G H, Liu L R, Niu G, Li J Z and Edward McBean 2019 Ecological network analysis of an urban water metabolic system based on input-output model: A case study of Guangdong, China *Science of the Total Environment* **468** 642-653.
- [3] Zhuo L, Mekonnen M M and Hoekstra A Y 2016 The effect of inter-annual variability of consumption, production, trade and climate on crop-related green and blue water footprints and inter-regional virtual water trade: A study for China (1978-2008) *Water Research* **94** 73-85.
- [4] Feng K, Chapagain A, Suh S, Pfister S and Hubacek K 2011 Comparison of bottom-up and top-down approaches to calculating the water footprints of nations *Economic Systems Research* **23** 371-385
- [5] Zhou Y, Yang B, Han J C and Huang Y F 2019 Robust linear programming and its application to water and environmental decision-making under uncertainty *Sustainability* **11** 1-12.
- [6] Zhang C, Zhong L J, Liang S, Sanders K T, Wang J and Xu M 2017 Virtual scarce water embodied in inter-provincial electricity transmission in China *Applied Energy* **187** 438-448
- [7] Ten Raa T 2010 Input-Output Economics: theory and applications-featuring Asian economies *Social Science Electronic Publishing* **19(1)** 568
- [8] Guan D B and Hubacek K 2007 Assessment of regional trade and virtual water flows in China. *Ecological Economics* **61** 159–170
- [9] Lobanova G, Fath B D and Rovenskaya E 2009 Exploring simple structural configurations for optimal network mutualism *Commun Nonlinear Science* **14** 1461–1485
- [10] Scharler U and Fath B D 2009 Comparing network analysis methodologies for consumer-resource relations at species and ecosystems scales *Ecological Modelling* **220** 3210-3218
- [11] Fang D L and Chen B 2015 Ecological network analysis for a virtual water network *J.Environmental Science & Technology* **49** 6722-6730