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Ecological network analysis of the virtual water network within China's electric power system during 2007–2012

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HIGHLIGHTS

- Virtual water flows within China's electric power system are tracked.
- Important grids are identified through information theory.
- The impact on water stress mitigation of China's electric power system is analyzed.

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ABSTRACT

Substantial virtual water concurrent electricity is transferred among six grids in China's electric power system. An in-depth understanding of this virtual water is essential considering the increasingly severe water deficiency in China. Using ecological network analysis (ENA), we investigate the virtual water network within China's electric power system (VWNCEPS) during 2007–2012, including (1) tracking the virtual water flows from the power generators to the power consumers and analyzing the tendency of the track results, (2) identifying the important grids that largely influence both the magnitude and diversity of the VWNCEPS, and (3) evaluating the overall performance of the VWNCEPS. Additionally, a new indicator is proposed that incorporates the concept of the water stress index (WSI) to measure the impact of the VWNCEPS on national water stress mitigation. The results show that during 2007–2012, the northern and central grids were always the most important input-oriented and output-oriented grids, respectively. Furthermore, the input-oriented impacts of the six grids are similar, while the output-oriented impacts exhibit substantial variations among the different grids. Regarding the overall performance, the VWNCEPS exhibits a high level of system efficiency, whereas its flexibility is relatively low. Moreover, the VWNCEPS has a rapidly increasing positive effect on national water stress mitigation in China during 2007–2012, and the virtual water connection between the central grid and the eastern grid is found to be the main contributor to this positive effect.

1. Introduction

With rapidly growing electricity generation, the electric power industry began to pose a significant threat to the normal life of human populations due to its substantial water consumption [1–4], especially in China. China has the largest electric power system in the world [5–7], which consumed 13.18% of total water consumption in China in 2008 [8]. However, China's annual availability of renewable water resources per capita is only 25% of the world average, indicating a severe water deficiency in China. Accordingly, it is essential to examine the water issues within China's electric power system to make it more water-efficient, thereby mitigating water scarcity problems in China.

Development in China is very different between regions. Coastal areas are generally more developed, such as in eastern China, whereas inland areas have experienced much slower development, such as in the northwest. The demand for electricity in the coastal areas has increased faster than in the inland areas due to rapid development. However, the primary energy sources (i.e., coal and hydro) for power generation are located far from the coastal areas of China. Coal is primarily located in the northwest, whereas

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Nomenclature

ENA	ecological network analysis
VWNCEPS	virtual water network within China's electric power system
TEVWF	total efficient virtual water flux
TSTP	total system throughput
AMI	average mutual information
A	ascendancy
C	development capacity
O	overhead
TD	total distribution
NE	northeast
NW	northwest
N	north
E	east
C	central
S	south
T/H/W/N	thermal/hydro/wind/nuclear
L	liter
kW h	kilowatt hour
F	virtual water transmission matrix
f_{ij}	virtual water flow from the jth node to the ith node
$T_{\cdot j}$	sum of the virtual water flows flowing out from the jth grid
$T_{i\cdot}$	sum of the virtual water flows flowing into the ith grid
G_{out}	output-oriented virtual water proportion flows through direct paths
G_{in}	input-oriented virtual water proportion flows through direct paths
N_{out}	total output-oriented virtual water proportion flows
N_{in}	total input-oriented virtual water proportion flows
N_{G-D}	output-oriented track matrix
N_{D-G}	input-oriented track matrix
EIO	impacts of regional power generators on the VWNCEPS
EII	impacts of regional power consumers on the VWNCEPS
S	vector of regional water stress indexes

hydroelectric power is primarily generated in the southwest [9]. To address this problem, electricity transmission is believed to be a sensible choice because energy resource transmission by train or ship is expensive and results in excess pollution [10]. Moreover, with the rapid increase in the development of China's electric power system, the capacity of interregional electricity transmission is expected to be much larger in the future [11]. The increasing interregional electricity transmission is expected to largely enhance the interactions among regions including the virtual water interactions [12]. An in-depth understanding of these virtual water interactions is very important when researching the water issues within China's electric power system.

The term 'virtual water' was first proposed in 1994 by Allan. It is defined as the water used to produce food crops that are traded internationally [13]. Then, the concept further evolved to represent the volume of water required to produce a commodity or service [14,15]. Based on this concept, regional virtual water accounting and interregional virtual water flows are widely studied using the input–output (IO) [16,17] and multi-region input–output (MRIO) [18–21] frameworks. An advantage of these analyses is that both direct and indirect water consumption is considered. However, no indicator is provided in these analyses to evaluate the results. More specifically, the information embedded within the virtual water results is not well depicted. This gap can be filled using ecological network analysis (ENA) [22]. ENA is a useful tool to holistically analyze the structure and interactive flows in ecosystems [23–25]. Furthermore, both direct and indirect interactions are identified and quantified in ENA [26,27]. The most important feature of ENA is that many processes, such as throughflow analysis and ascendancy analysis, are represented to reveal the mutual relationships among different components [28–30].

ENA has been successfully applied to many types of systems, such as urban systems [31,32], wetlands [33], energy systems [34,35], and water systems as well [36–40]. Sustainable water use in the Yellow River Basin during 1998–2006 has been examined using ENA [41], in which total system throughput intensity (TSTI), which incorporates environmental, social and economic factors, was proposed for a more accurate sustainability analysis. Except for real water systems, virtual water systems have also been investigated using ENA. Mao et al. [42] utilized ENA to investigate the virtual water trade among different sectors in the Baiyangdian Basin in northern China. The boundary inputs and outputs and the contribution of each sector were detected using the unit environ and final contribution ratio methods, providing feasible ways to optimize the virtual water trade structure by adjusting the relationships among compartments. Moreover, global virtual water trade has also been studied using ENA [43]. The indicator called the integral control intensity was proposed, and the global food trade market was found in a competitive environment. Previous results have shown a strong guiding significance in policy making in different countries to increase the water efficiency of global virtual water trade. These successful applications have demonstrated that ENA is a suitable and powerful approach for the study of complex virtual water systems.

This paper aims to analyze the virtual water network within China's electric power system (VWNCEPS). Interregional virtual water flows are calculated according to the method proposed in [12]. It should be noted that these virtual water flows represent the embodiment of virtual water of power generation in China's electric power system; the virtual water network composed of these virtual water flows is considered to represent the VWNCEPS in this paper. Then, ENA is used to reveal the information embedded within the VWNCEPS, including (1) tracking the virtual water flows from the power generators to the power consumers and analyzing the tendency of the track results, (2) identifying the important grids that largely influence both the magnitude and diversity of the VWNCEPS, and (3) evaluating the overall performance of the VWNCEPS. Moreover, a new indicator called the total efficient virtual water flux (TEVWF), which incorporates the concept of the water stress index (WSI), is proposed to measure the impact of the VWNCEPS on national water stress mitigation.

2. Method and data

2.1. Study area

China's electricity generation increased by a factor of 11.2 from 1980 to 2009 [44]. In 2010, China became the largest source of electric power in the world. However, China's rapid development has been primarily dependent on continuous expansion at the expense of production efficiency because the focus was on quantity rather than quality, leading to many environmental impacts including vast amounts of water consumption. With the rapid development of the electric power industry, water consumption