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Network environ analysis for socio-economic water system

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ABSTRACT

Embodied water in a socio-economic system refers to the hidden water contained in products traded from one region or one sector to another and has been the center of concern for water management in recent years. However, most models developed for water system analysis ignore cycling and indirect flows, making it difficult to explain the effects of structure on these factors among sectors. Therefore, those models fail to examine the water utilization efficiency from an integral view. In this study, we investigate an embodied socio-economic water system using network analysis developed originally for ecological systems. In this manner, we identify structural and throughflow indicators, such as Finn Cycling Index, Indirect effects ratio, and aggradation, to show the efficiency of water utilization. The three indicators show different perspectives of the system's efficiency change over time, indicating that only the combination of these three indicators can provide a holistic portray about efficiency. Results showed that the structure influenced the cycling and indirect flows, and from a throughflow perspective, the system depends on large boundary inputs of fresh water. Furthermore, the values of Cycling Index and Indirect effect ratio are much lower than for natural food webs, implying that the policies that led to the structural change and reduction of boundary fresh water inputs do not lead to positive water utilization seen in natural systems. This study provides a novel perspective and methodology for assessing the structure and efficiency of water utilization system with a whole perspective.

1. Introduction

Stemming from increasing population and rapid urbanization, environmental resources are highly utilized as input materials and resources for economic production and consumption. High use efficiency of scarce resources has become an increasingly important objective in resources management, especially for water resources (Ridoutt et al., 2009). Water use processes involve multiple activities; therefore, it is important to consider the social, economic, and environmental aspects of the concerned system to analyze the regulation of water consumption (Li and Yang, 2011). Due to the utilization of freshwater within various sectors, only a comparatively small volume of water streams from sector-to-sector. However, the water, imported into a certain socio-economic system, can still flow among economic sectors through production transactions in the form of embodied water, which was initially proposed by Fishelson (1994) for agricultural production. Later, the concept of 'embodied water'—also known as virtual water—has been further introduced to other fields to reflect the fresh water consumed during the conversion process (Mudd, 2008; Chiu et al., 2009; Chen et al., 2010), e.g., the investigation into the water consumption relationship among different regions and sectors of a system (Allan, 1994, 1998, Dietzenbacher and Velázquez, 2007; Guan and Hubacek, 2007; Feng et al., 2012; Huang et al., 2013). Regarding such applications, the production exchanges among different sectors can be evaluated via input–output model with monetary currency, based on which the embodied water is calculated by timing consumption ratio with output value. Therefore, the social connection between different economic sectors determines the basic production trading structure, and the economic demand development contributes to the intensity of production transactions, thereby providing an effective tool for water resources management in the context of social, economic, and environmental factors.

Most research on embodied water is focused on the water resources tradeoffs or allocations on interregional or intersectoral scales (e.g., Guan and Hubacek, 2007; Dietzenbacher and Velázquez, 2007; Yang et al., 2012). Despite the achievements in

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terms of tradeoffs and allocations, the efficiency of embodied water circulation in a certain system remains to be investigated (Zhao et al., 2009). For embodied water systems, it is necessary to carefully consider the direct and indirect influence among economic sectors, and their inter linkages (Singh et al., 2009), because the conclusions from direct observation may provide an incorrect impression of the system flows, which in turn might mislead the process of policy making (Fath, 2007). Thus, a systems approach is required to integrate social, economic, and environmental aspects that consider both direct and indirect flows within embodied water systems (Li and Yang, 2011). Input–output analysis, which was initially created by Leontief (1941) to represent the transactions of goods and services among different economic sectors, is a recognized method to analyze the economic direct and indirect influence on resources driven by inputs. Environmental input–output models are commonly used to analyze water consumption relationships or water resources tradeoff in interregional or intersectoral scale (Duarte et al., 2002; Velázquez, 2006; Guan and Hubacek, 2007; Zhao et al., 2010; Zhang et al., 2011; Ewing et al., 2012). However, the structural interdependency among different sectors and integral throughflow evaluation still cannot be sufficiently explained by traditional input–output analysis (Mao and Yang, 2012).

Derived from input–output analysis, Network Environ Analysis (NEA), as a system-oriented technique, provides a unique perspective to investigate the embodied water system in a mutual and integral way. It is an environmental application to investigate the interdependence of sectors to determine the total flows that directly and indirectly link the component to its environ from the perspective of the overall system (Hannon, 1973; Patten et al., 1976; Fath and Patten, 1999; Fath, 2007), and as such adds important features to the original input–output analysis. The structure and direct and indirect flows in a system have been important considerations for the analysis of flows in networks and the interrelationships between sectors, represented as nodes in the network. These not only include studies of ecological systems (Baird and Ulanowicz, 1989; Scharler and Baird, 2005; Schramski et al., 2006, 2007), but have also been extended to other realms, such as resources cycling (Christian and Thomas, 2003; Schramski et al., 2006; Chen and Chen, 2012; Kharrazi et al., 2013), socio-economic systems (Zhang et al., 2009; Chen and Chen, 2012; Chen et al., 2011, 2013), and water use systems. Bodini and Bondavalli (2002) using network analysis depicted water exchanges and sustainability of water use by evaluating the reciprocal dependence of flows in Sarmato, Italy. Li et al. (2009), and Li and Yang (2011) analyzed sustainability of water use system in Huanghe, and Haihe Basins respectively, by incorporating the conventional network indices into the sustainable water resources management, with consideration of environmental, social, and economic factors. Zhang et al. (2010) applied network analysis to the evaluation of water fluxes of urban metabolic system, and analyzed the network structure and ecological relationships of different water sectors. For embodied water system, Yang et al. (2012) used network analysis to shed light into the issues of the indirect effects of water trade, the mutual relationships in trade system through the global economic circulation. Mao and Yang (2012) adopt this method to show the independence and interaction between different trade sectors in Baiyangdian Basin in Northern China. Most of the above cited research, specifically dealing with water resource research, is focused on the mutual relationship between different sectors in a certain water use systems. However, the study about integral efficiency of the embodied water system is still inadequate, and will be dealt with in this study by considering flow analyses as applied to other systems (Borrett and Freeze, 2011; Ma and Kazanci, 2013). Thus, in our study we introduce structural and throughflow indicators of NEA to the socio-economic research for embodied water systems, which have been successfully applied to ecosystems.

The structure of embodied water flows in a certain socio-economic system reflects the interconnections of economic sectors. A time series study can probe into the influence of structure alteration on water throughflow. Higher total throughflow, i.e., including both direct and indirect flows, gives an indication of the overall embodied water flow intensity, which is efficient for local water utilization with limited boundary fresh water inputs. This research investigates the embodied water utilization structure and throughflow in the socio-economic system of the Ganzhou District to provide a scientific basis for the water development, utilization, management, and protection.

2. Methods

2.1. Study area and system boundary

Heihe River Basin is the second largest inland river basin in the arid region of Northwest China. It flows about 821 km from the northern Gansu side of the Qilian Mountains north-northeast into the Endorheic Ejin Basin in the Gobi Desert. The basin covers an area of about 128,300 km^2. Heihe River Basin has become a commodity grain base in Northwest China because of its relatively abundant water resource. With the rapid socioeconomic development and increasing population density, extensive exploitation of water resources in the upper and middle reaches of Heihe River Basin has occurred, resulting in an uneven distribution of water resources for lower reaches of Heihe River. The study area, Ganzhou District, is situated in the middle reach of Heihe River Basin, which is one of its most economically developed regions. Agriculture is the main economic sector for this region, including farming, livestock and other agricultural activities. The agricultural sectors are the main water consumption sectors and therefore the government has changed certain policies with respect to its water consumption structure, in order to control the total amount of water resources, or standard allocation of water resources in different regions (Cheng et al., 2006). In 2000, the government implemented the water distribution plan in Heihe River, that the middle region must transport higher quantities of water resources to the downstream region in order to improve the ecological environment (Zhang et al., 2004). Because agricultural development will consume large amounts of water, the government changed the strategy of the then current water utilization structure, and tried to realize water conservation target through reducing water consumption of the agricultural sector (Cheng et al., 2006).

The system boundary of the socio-economic water system is equivalent to the economic boundary of Ganzhou District. The Ganzhou District economy is divided into six sectors, i.e. farming (1), livestock (2), other agricultural (3), industry (4), construction (5), and services (6). Considering that the agricultural sectors are the main economic sectors in Ganzhou District, there are three economic sectors related to agriculture.

2.2. NEA model for socio-economic water system

The data of socio-economic water systems of the Ganzhou district from 2002 to 2010 are based on the results of Zhang's (2013) research, which are constructed on the basis of input–output table of water resources. The method converting monetary flows to embodied water flows is described in Velázquez (2006) and Huang et al. (2010).

Our research converts the models from Zhang (2013) into network models to study the structure, integral flow and resources utilization efficiency from a holistic view. The basic network environ model, initiated by Barber et al. (1979) and developed by