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Analysis

Input–output analysis of virtual water transfers: Case study of California and Illinois

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ABSTRACT

Increasing pressures on water resources in the two economically important states of California (CA) and Illinois (IL) have created a need for critical information related to sustainable water use and management. This paper applies input–output (IO) analysis to evaluate water use and quantify virtual water transfers involving the two states. Results show that aquaculture requires the largest input of direct water per unit of economic output, followed by crops, power generation, livestock, mining, services, domestic, and industry. Low water use intensity industry and services sectors contributed the largest proportions of value added and employee compensation. In 2008, the two states were net virtual exporters, with CA exporting 1.3 times the net export volume of IL. More than 72% of virtual water exports for each state originated from the high total water use intensity but low value added crops sector, with irrigation and rainfall contributing 99% and 97% of the crop-related exports for CA and IL, respectively. Virtual water export volumes were 59% for CA and 71% for IL when compared to actual water use. These results highlight the need to consider water use efficiency and opportunity cost when managing water under scarcity conditions.

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1. Introduction

Competing water demands in the U.S. economy have left people faced with the need to make choices in the allocation of water. Should scarce resources be allocated to irrigate fields or generate electricity, support ecosystems or supply human settlements? Previous studies (Alcamo et al., 2003; Oki and Kanae, 2006; Smakhtin et al., 2004) have shown that the U.S. is partially under water stress. This is especially the case in the western region of the country where the capacity of water to support demands from urban areas, industry, ecosystems, agriculture and other sectors is nearing its limit under current management practices (Sabo et al., 2010).

According to international trade theory, regions can gain from trade if they specialize in producing goods and services for which they have a comparative advantage. Therefore, the export of water-intensive commodities from water-abundant to water-scarce regions can allow the latter to forgo high water-intensity, but low economic return activities, and reallocate water to other high value uses. Allan (2003) introduced the concept of "virtual water" to characterize the transfer or flow of water resulting from the export of water-intensive commodities. The concept is relevant in assessing water resources sustainability in locations producing water-intensive commodities for local consumption, or for trade with other regions. As observed by Novo et al. (2009), virtual water "is linked to water productivity, geographical location, and to the site-specific socioeconomic setting." Virtual water trade has been shown to conserve water in the production of crops by shifting production to areas where less water is needed per unit of output (Hoekstra and Hung, 2005). It can also reduce ecological opportunity costs, conceived as foregone ecosystem service flows, in water-scarce regions, where water withdrawals may have greater impacts than in water-abundant regions.

Globally, the majority of blue water consumption is used for food production. When green water is included, agriculture becomes the dominant water-using sector. Specific regions of the world, such as the Middle East and North Africa, parts of South Asia, and northern China, are becoming increasingly dependent upon food imports because they lack the local water resource endowment to produce sufficient food domestically (Hoekstra and Hung, 2002). Importing food is more efficient than importing water directly because it often takes 1000 kg of water to produce a single kilogram of food.

On the exporting side of this relationship, most virtual water quantification studies have identified the United States (U.S.) as the leading global virtual water exporter (for example, Hanasaki et al., 2010; Hoekstra and Chapagain, 2008). However, few studies have analyzed virtual water flows at a sub-national spatial scale. In particular, the internal virtual water flow dynamics of the world's largest virtual water exporter have not been analyzed. Such knowledge is relevant for a large country where there are wide variations in water and other natural resource endowments between regions.

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The two U.S. states of California and Illinois are significant but different economies located in natural regions of the country with contrasting water endowments. CA, the largest economy and most populous state, is located in the relatively dry Western region of the country, and most of its water for crop production comes from irrigation (blue water). In contrast, most crop production in the major agricultural Midwestern state of IL is rainfed (green water).

The objectives of this case study are (i) to calculate direct and indirect water use intensities across economic sectors in CA and IL, and (ii) to quantify the water embodied (directly and indirectly) in trade involving the states of CA and IL, other U. S. states and the rest of the world, and assess the environmental and economic significance of the current composition of trade on water resources in the two states. To accomplish these objectives, we apply input–output (IO) analysis, a method that uses monetary transactions to quantify how various sectors of a complex economic system are related (Leontief, 1986). The first contribution of this study is the generation of direct water use intensity and total water use intensity indicators for each economic sector in these two states. These critical indicators can assist in evaluating sectoral water use efficiency and identifying sources of pressure on water resources in support of policy decisions related to water allocation under scarcity conditions. Second is the quantification of both direct and indirect water use in the economies of the two states. This is important in assessing water resource impacts of commodity supply chains that use water as an input to economic production. Third is the categorization of water sources into blue, green, and saline water in the two states. Use of water from these different sources have different opportunity costs, with blue the highest and saline the lowest. In the context of this study, "water use" denotes water that is received by an economic sector through withdrawals, and not consumptive use. The case study covers the states of CA and IL, selected for economic data availability reasons at the time of conducting the study, and the year 2008, the latest year for which regional economic IO tables could be obtained for the two states.

2. Virtual Water and IO Analysis

According to Hoekstra and Mekonnen (2012), water resources experience the impacts of production and consumption activities through both consumptive use and pollution. Impacts can be local or external to the area of production, as is the case when water-intensive commodities are traded. A few studies in the last decade have explored alternative methodologies to quantify virtual water transfers (for example, Aldaya et al., 2008; Chapagain and Hoekstra, 2004; Hanasaki et al., 2010; Hoekstra and Hung, 2002; Oki and Kanae, 2004). To better understand the impacts of human water use on freshwater resources, the concept of "water footprint" has also been proposed and defined as "…a measure of humans' appropriation of freshwater resources" (Hoekstra and Chapagain, 2008). Consumption in this definition refers to the amount of water that is lost to evaporation or is incorporated into a commodity (Hoekstra and Mekonnen, 2012).

Unlike IO analysis, most of the above-mentioned methodologies are largely suitable for quantifying virtual water transfers in relation to individual commodities within economic sectors.

The IO technique is based on a transactions table that describes the flow of goods and services from producing economic sectors to all other consuming sectors over a stated accounting period (Gretton, 2005). Application of the pioneer IO analysis dates from 1936 when Wassily Leontief published an IO table of the U.S. economy (Leontief, 1986). The widely applied IO model can be used as a tool of analysis in life cycle assessment, an accounting framework that quantifies environmental impacts across the entire life cycle of a product or process (Mo et al., 2010; Pfister et al., 2009). In contrast to Europe and water scarce countries such as Israel, the incorporation of water into life cycle assessment modeling work in the U.S. is not widespread due to a relative shortage of water data that is customized for its application (Cooney, 2009).

A distinction can be made between using a multiregional IO table or a regional IO table as the foundation for IO analysis. The former table provides a more comprehensive basis for IO analysis because it contains monetary transactions of goods and services for both different sectors and different regions, in contrast to the latter table, where only transactions across different sectors of a region are provided (Zhang et al., 2011).

The earliest application of IO analysis in U.S. water policy was by Finster in the early 1970s, in a case study for the state of Arizona (Chanan et al., 2008). An IO model was used to manipulate external commodity trade patterns through allowing interbasin water transfers. The study showed that a demand-oriented water policy was the most efficient in allocating water in the state. Recent IO work in the U.S. water sector includes the study by Blackhurst et al. (2010), where the 2002 national economic IO table was used to estimate direct and indirect industrial water withdrawals. Deisenroth and Bond (2010) applied IO models to estimate the total economic contribution of the recreational fisheries industry in the western U.S., while Mo et al. (2010) applied a hybrid approach combining IO analysis and process assessment to analyze the energy use impact of the Kalamazoo public water supply system.

The IO method has also been extensively utilized in other world regions as a water accounting mechanism for guiding water policy decisions (Chanan et al., 2008). Feng et al. (2012) and Zhao et al. (2010) applied multi-regional IO models to calculate water footprints in the Yellow and Haihe River Basins in China using consumption-based approaches. Lenzen and Foran (2001) applied the technique to Australia's water sector and found that Australia was a net virtual water exporter, an outcome in agreement with results from a more recent assessment by Hoekstra and Chapagain (2008) using a different methodology.

Zhao et al. (2009) studied the national water footprint of China using an IO framework and concluded that China was a net virtual water exporter, in contrast to a partial analysis by Hoekstra and Hung (2002) that was based only on global crop trade. IO studies in Spain found the very arid Andalusia region to be a net exporter of water, in contradiction to both environmental sustainability and comparative advantage theory (Dietzenbacher and Velazquez, 2007; Velázquez, 2006), while Duarte et al. (2002) applied the technique to study the productive sectors of the Spanish economy as direct and indirect consumers of water.

Based on IO tables and factor decomposition analysis, Kondo (2005) found that Japanese industrial goods manufactures depended on virtual water imports from domestic and foreign subsidiaries to strengthen their competitiveness. Extending a regional input–output model enabled Guan and Hubacek (2007) to analyze water pollution processes, and their study found that North China received a lot of wastewater from consumption activities in other regions. Similar to separate analyses by Ip et al. (2007) and Wang et al. (2009), they also found that the region was a net virtual exporter, although water scarce. The IO approach has also been applied to predict the impacts of river rehabilitation in Switzerland (Spörri et al., 2007), and to track virtual water flows across the whole global economy (Chen et al., 2012). Rather than using monetary IO tables, Hubacek and Giljum (2003) applied physical IO tables to estimate the ecological footprints of international trade activities. Unlike monetary IO analysis, physical IO analysis was considered more appropriate in assessing environmental processes in the physical world.

Other applications of IO analysis to natural resources include the assessment of greenhouse gas emissions by American households (Weber and Matthews, 2008), land and ecological footprint studies (Ferng, 2001), CO_2 and global warming (Chen and Chen, 2010, 2011), energy use intensity comparisons between the U.S. and Canada (Norman et al., 2007), ecological cumulative energy