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

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Analysis

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

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A B S T R A C T

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 socio-economic 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 Velázquez, 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 (Spörrli 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 house holds (Weber and Matthews, 2008), land and ecological footprint studies (Feng, 2001), CO2 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...
3. Socio-Economic Characteristics and Water Resources Endowments in CA and IL

The states of CA and IL are important contributors to the U.S. economy. A selection of key socio-economic indicators for the year 2008 shows that CA’s economy is much larger than Illinois with respect to population, GDP, value added, and employee compensation (Table 1). Table 2 gives the current level of water resource utilization in the two states. A rough index of utilization can be obtained by comparing the renewable supply to total withdrawals, and especially the ratio of consumptive use to renewable supply. This ratio is calculated as the sum of precipitation and water imports minus natural evapotranspiration and water exports (U.S. Geological Survey, online).

IL, which lies largely in the Upper Mississippi and partly in the Ohio watershed, is part of a natural water resources region where consumption (Ukidwe and Bakshi, 2007), and spatial assessment of environmental pressures due to consumption activities (Munksgaard et al., 2005). For a comprehensive review of recent studies where multi-region input-output models are applied in consumption-based environmental accounting see Wiedmann (2009).

IO analysis is very useful because of its versatility, making it applicable to various spatial scales, in addition to varying degrees of complexities in economic linkages (Leontief, 1986). It can also be used for measuring environmental impacts of economic production (Wang et al., 2009) and clearly distinguishes between direct and indirect water use, linking the real final consumption of households and the embodied water in the products they consumed.

Using IO analysis avoids the risk of double counting in quantifying virtual water trade because of the technique’s ability to distinguish between intermediate and final products (Zhao et al., 2009). As argued by Lenzen (2009), the use of other alternative virtual water quantification methodologies can result in lower estimates of virtual water volumes due to “systemic and unquantifiable truncation errors.” However, application of the IO technique can be severely restricted by a lack of primary data that better characterizes the physical structure of a system. For example, it is important to have reliable water use statistics and ensure a correct formulation of IO interrelations between economic sectors (Ip et al., 2007). Major imperfections of the IO analytical technique are provided in Miller and Blair (2009).

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CA</th>
<th>IL</th>
<th>Ranking among U.S. states</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total population</td>
<td>36 million</td>
<td>13 million</td>
<td>1st 5th</td>
</tr>
<tr>
<td>Gross Domestic Product (GDP)</td>
<td>$2 trillion</td>
<td>$644 billion</td>
<td>1st 5th</td>
</tr>
<tr>
<td>Value added (all sectors)</td>
<td>$2.183 billion</td>
<td>$813 billion</td>
<td>1st 5th</td>
</tr>
<tr>
<td>Employee compensation (all sectors)</td>
<td>$1,037 billion</td>
<td>$366 billion</td>
<td>1st 5th</td>
</tr>
</tbody>
</table>

Sources: U.S. Census Bureau (online); U.S. Department of Commerce, (online); Minnesota Implant Group, Inc. (2008).

4. Methodology

Our application of the IO methodology involves extending regional IO tables for the states of CA and IL to incorporate sectoral water use. This technique has been applied widely in previous studies such as Lenzen (2009), Wang et al. (2009), Zhao et al. (2009), and Blackhurst et al. (2010). In the first part, we estimate and compare direct and indirect water use intensities using 2008 regional IO tables. Second, we use available interstate and international trade data to calculate virtual water transfers (embedded water in goods and services) between the two states, with other U.S. states (domestic trade), and with the rest of the world (international or foreign trade). In comparing direct and indirect water use and virtual water transfers, we also distinguish between blue and green water use in the production of crops because they differ in sensitivity to climate variability and opportunity costs (Novo et al., 2009).

4.1. General IO Model of Production

The general IO model of production (Leontief, 1986) is the foundation upon which the water IO model is developed. The model portraying how the production of an economy is dependent upon interactions between different sectors and final demand can be specified by a system of linear equations (Eq. 1), summarized as in Eq. (2):

\[
x_i = X_{i1} + X_{i2} + \cdots + X_{in} + y_i
\]

\[
x_0 = X_{01} + X_{02} + \cdots + X_{0n} + y_0
\]

\[
x_i = \sum_{j=1}^{n} X_{ij} + y_i
\]

where

- \( n \) represents the number of economic sectors of an economy,
- \( x \) is the total economic output of the \( i \)th sector.

### Table 2
Regional differences in water availability and use in the California, Upper Mississippi and Ohio water resources regions.

<table>
<thead>
<tr>
<th>Water resources region</th>
<th>Renewable supply (Mm³/day)</th>
<th>Total withdrawals (Mm³/day)</th>
<th>Consumptive use (Mm³/day)</th>
<th>Ratio of withdrawals-to-renewable supply (%)</th>
<th>Ratio of consumptive use-to-renewable supply (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>282.38</td>
<td>174.50</td>
<td>95.77</td>
<td>61.8</td>
<td>33.9</td>
</tr>
<tr>
<td>*Upper Mississippi</td>
<td>273.30</td>
<td>88.20</td>
<td>6.44</td>
<td>32.3</td>
<td>2.4</td>
</tr>
<tr>
<td>*Ohio</td>
<td>528.43</td>
<td>113.04</td>
<td>7.19</td>
<td>21.6</td>
<td>1.4</td>
</tr>
</tbody>
</table>

A large portion of the state of Illinois lies in the Upper Mississippi region, with a small part falling into the Ohio region, where consumptive use to renewable supply ratios are very low at 2.4 and 1.4 percent respectively.

Source: Adopted from U.S. Geological Survey, (online).
\[ X_{ij} \] represents the monetary flow relations from the \( i \)th sector to the \( j \)th sector, and 
\[ y_i \] is the final demand of sector \( i \).

From a transactions table, technical coefficients of production \( (a_{ij}) \) can be derived by dividing the inter-sectoral flows from sector \( i \) to \( j \) \( (X_{ij}) \) by total input of sector \( j \) \( (x_j) \) (Eq. (3)).

\[
a_{ij} = \frac{X_{ij}}{x_j}
\]

Substituting for \( X_{ij} \) in Eqs. (2) and (3) yields Eq. (4), representing the economy as a whole and written in matrix notation as Eq. (5).

\[
x_i = \sum_{j=1}^{n} a_{ij}x_j + y_i
\]

\[
x = Ax + y
\]

where
\( x \) is the vector of total outputs, 
\( A \) the matrix of technical coefficients, and 
\( y \) the vector of final demands.

When solved for \( x \), Eq. (5) reduces to the total production delivered to final demand, or the vector of outputs required for sustaining a given vector of final demands (Eq. (6)).

\[
x = (I-A)^{-1}y
\]

\((I - A)^{-1}\) is the Leontief inverse matrix, defined as the direct plus indirect coefficients or total requirements matrix, representing the total production every sector must generate to satisfy one unit final demand of the economy (Velázquez, 2006).

### 4.2. Water IO Model

Water is a primary input in economic production, and this relationship is reflected through freshwater use coefficients for each economic sector. Our methodology extends the regional IO table for each state by adding a row vector of direct water use coefficients, measured in physical units. The coupling of water data to IO tables in order to quantify the impacts of sectoral demands throughout the supply chain is not new, and has been widely applied in previous studies (Feng et al., 2012; Guan and Hubacek, 2007; Wiedmann et al., 2007).

#### 4.3. Direct and Total Water Use

The direct coefficient \( f_i \) is a vector of technical coefficients and its \( i \)th element is the amount of water consumed as input in the production of one unit of the good in sector \( i \). This is not virtual but actual (from local sources). This share of water use per unit of output expresses the direct or first round effects of the sectoral interaction in the economy. For each state, a weighted multiplier matrix \( (f_i) \) was calculated by post-multiplying the vector of technical coefficients \( (f_i) \) with the Leontief inverse matrix \( (I - A)^{-1} \) (Eq. (7)).

\[
f_i = f_i(I-A)^{-1}y
\]

The \( i \)th element of the total coefficient vector \( f_i \) is the total amount (direct and indirect) of water per unit of final use of good \( i \). Since net export is a final use of a good, the multiplication of the \( i \)th element of \( f_i \) and the \( i \)th element of \( C \) gives the total amount of water embodied in the exports of good \( i \), i.e., summing these over all the goods (all \( i \)’s) we get virtual (net) exports of water from a region (Eq. (8)).

\[
V_{vw} = f_iC
\]

where
\( C \) is a term representing interstate (bilateral), domestic, or foreign trade in monetary terms.
5. Results

5.1. Interstate Trade Balances and Actual Water Use

An overview of interstate trade balances between the states of CA and IL and water withdrawals per sector for the year 2008 is shown in Table 4. CA was a net exporter (gross exports greater than gross imports) in all but the mining and industrial sectors, and withdrawals from the power generation sector was largest, followed by services and crops sectors for both states. According to the U.S. Energy Information Administration (personal communication), indirect transactions for the power generation sector include economic activities such as energy credits. The crops sector is the main water user, accounting for 53% and 55% of water use in CA and IL respectively, followed by power generation in both states (28% and 38%, respectively) (Table 4). Less than 1% of about 34,000 Mm³ water use in CA’s crops sector came from rainfall, compared to more than 97% of around 25,000 Mm³ for the same sector in IL.

5.2. Direct Water Use Intensity

Indicators on water use efficiency are useful in assessing the efficient allocation of water resources. A direct water use coefficient is an indicator that reveals water use intensity, or the amount of water directly used to produce a dollar worth of output for each sector. The aquaculture sector in CA requires the largest input of direct water per unit output, followed by crops, power generation, livestock, mining, services, domestic, and industry. There is a similar trend in the ranking of similar sectors in the state of IL (Fig. 1).

Taking crops and aquaculture sectors as examples, the results show that crops will use 0.91 m³ and 1.65 m³ of direct water to generate $1 worth of output in CA and IL respectively, compared to 3.40 m³ and 2.84 m³ per dollar worth of output for aquaculture for the two states respectively. Sectoral direct water coefficients are larger for CA in the following five economic sectors: aquaculture, livestock, mining, services, domestic, and industry, indicating that to produce a dollar worth of output, water use in these economic sectors in CA is generally higher than the equivalent sectors in IL. Further exploration of the direct water use intensities also revealed that it is crucial to consider sources of water in the two states. CA’s direct water use intensity for the crops sector may be lower than that of IL (Fig. 1), but only less than one percent of nearly 34,000 Mm³ per year of actual water use comes from rainfall, as highlighted in Table 4. The rest is irrigation water that comes at a higher opportunity cost than in IL, where about 24,000 Mm³ (or 97%) of total actual water use for the crops sector is natural rainfall (Table 4). Similar to the relatively abundant rainfall in IL, CA, bordering the Pacific Ocean, has abundant saline water for its power generation, industry, and mining sectors. In fact, recent USGS figures show that more than 99 percent of CA’s nearly 14 billion m³ water withdrawals for the power generation sector were saline water, compared to 100 percent freshwater use in IL. (Kenny et al., 2009).

Table 3

<table>
<thead>
<tr>
<th>USGS sector name</th>
<th>USGS aggregate sector description</th>
<th>New sector name in aggregation scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public supply</td>
<td>Water withdrawn by public and private water suppliers that provide water to at least 25 people or have a minimum of 15 connections. Delivered to users for domestic, commercial, and industrial purposes, and also is used for public services and system losses.</td>
<td>Services</td>
</tr>
<tr>
<td>Domestic</td>
<td>Domestic water use includes indoor (drinking, and food preparation, washing clothes and dishes, and flushing toilets), and outdoor (watering lawns and gardens and washing cars) uses at residences.</td>
<td>Domestic</td>
</tr>
<tr>
<td>Irrigation</td>
<td>Includes water that is applied by sprinkler, microirrigation, and surface (flood) systems; to sustain plant growth in all agricultural and horticultural practices. Includes self-supplied withdrawals and deliveries from irrigation companies, irrigation districts, cooperatives, or governmental entities.</td>
<td>Crops</td>
</tr>
<tr>
<td>Livestock</td>
<td>Associated with livestock watering, feedlots, milk operations, and other on-farm needs. Livestock includes milk cows and heifers, beef cattle and calves, sheep and lambs, goats, hogs and pigs, horses, and poultry. Excludes on-farm domestic use, lawn and garden watering, and irrigation water use.</td>
<td>Livestock</td>
</tr>
<tr>
<td>Aquaculture</td>
<td>Aquaculture water use is water associated with raising organisms that live in water—such as finfish and shellfish for food, restoration, conservation, or sport. Aquaculture production occurs under controlled feeding, sanitation, and harvesting procedures.</td>
<td>Aquaculture</td>
</tr>
<tr>
<td>Industrial</td>
<td>Includes water used for such purposes as fabricating, processing, washing, diluting, cooling, or transporting a product; incorporating water into a product; or for sanitation needs within the manufacturing facility.</td>
<td>Industry</td>
</tr>
<tr>
<td>Thermaelectric-power generation</td>
<td>Water for thermoelectric power is used in generating electricity with steam-driven turbine generators.</td>
<td>Power generation</td>
</tr>
<tr>
<td>Mining</td>
<td>Mining water use is water used for the extraction of minerals that may be in the form of solids, such as coal, iron, sand, and gravel; liquids, such as crude petroleum; and gases, such as natural gas. Includes operations associated with mining activities.</td>
<td>Mining</td>
</tr>
</tbody>
</table>

Sources: Modified from Kenny et al. (2009) and Olson and Lindall (2004).

Table 4

<table>
<thead>
<tr>
<th>Economic sector</th>
<th>Imports from CA (M$)</th>
<th>Exports to CA (M$)</th>
<th>Water use (Mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crops</td>
<td>447.45</td>
<td>912.17</td>
<td>33,719.45</td>
</tr>
<tr>
<td>Livestock</td>
<td>27.01</td>
<td>193.50</td>
<td>271.26</td>
</tr>
<tr>
<td>Aquaculture</td>
<td>0.00</td>
<td>0.09</td>
<td>892.69</td>
</tr>
<tr>
<td>Mining</td>
<td>580.93</td>
<td>68.48</td>
<td>426.12</td>
</tr>
<tr>
<td>Power generation</td>
<td>0.11</td>
<td>365.01</td>
<td>17,453.85</td>
</tr>
<tr>
<td>Domestic</td>
<td>0.00</td>
<td>21.10</td>
<td>671.98</td>
</tr>
<tr>
<td>Industry</td>
<td>8,901.46</td>
<td>8,795.94</td>
<td>132.30</td>
</tr>
<tr>
<td>Services</td>
<td>3,936.26</td>
<td>8,923.79</td>
<td>9,654.39</td>
</tr>
<tr>
<td>IL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crops</td>
<td>912.17</td>
<td>447.45</td>
<td>24,755.39</td>
</tr>
<tr>
<td>Livestock</td>
<td>193.50</td>
<td>27.01</td>
<td>52.40</td>
</tr>
<tr>
<td>Aquaculture</td>
<td>0.09</td>
<td>0.00</td>
<td>13.07</td>
</tr>
<tr>
<td>Mining</td>
<td>68.48</td>
<td>580.93</td>
<td>155.11</td>
</tr>
<tr>
<td>Power generation</td>
<td>365.01</td>
<td>0.11</td>
<td>17,015.40</td>
</tr>
<tr>
<td>Domestic</td>
<td>21.10</td>
<td>0.00</td>
<td>140.56</td>
</tr>
<tr>
<td>Industry</td>
<td>8,795.94</td>
<td>8,901.46</td>
<td>503.06</td>
</tr>
<tr>
<td>Services</td>
<td>3,936.26</td>
<td>8,923.79</td>
<td>2,353.03</td>
</tr>
</tbody>
</table>

Sources: Water consumption data modified from USGS (Kenny et al., 2009); Interstate trade data obtained from Minnesota Implan Group, Inc. (2008).

* Crops water consumption data includes 58.55 Mm³ and 24,058.74 Mm³ annual estimates of total evapotranspiration of rainfall by major crops in CA and IL respectively (Mubako, 2011). 

b Sectors include the following annual volumes of saline water: 26 Mm³, 286 Mm³, and 14,100 Mm³ for Industry, Mining and Power generation respectively for CA, and 29 Mm³ for the Mining sector in IL. (Kenny et al., 2009).
that rely on direct water-intensive primary sectors such as crops for raw materials used as inputs in production processes.

An interesting picture emerges in both states when total water use intensity of each sector is compared to its economic contribution in terms of value addition and employee compensation (total payroll cost of the employees paid by the employers, such as wages salaries, benefits and employer paid payroll taxes). From Table 5, we observe that despite being responsible for the largest total water use intensity in CA ($3405 \text{m}^3/\text{\$1000}$), the aquaculture sector had one of the lowest value added and employee compensation contributions (less than half a billion dollars for each). The crops sector in CA (1000 \text{m}^3/\text{\$1000} water use intensity) also contributed relatively low proportions of value added and employment compensation ($24 \text{ billion} and $11 \text{ billion}$, respectively). This is in contrast to economic contributions of sectors such as industry ($433 \text{ billion} and $180 \text{ billion}$ value added and employee compensation, respectively) and services ($1548 \text{ billion} and $835 \text{ billion}$ value added and employee compensation, respectively) that had some of the lowest total water use intensities (30 \text{ m}^3/\text{\$1000}, and 13 \text{ m}^3/\text{\$1000} respectively) in the same state. A similar pattern can be observed in the state of IL (Table 5). For example, the crops sector in that state accounted for 1,787 \text{ m}^3/\text{\$1000} total water use intensity but only $10 \text{ billion}$ and half-a-billion dollars value added and employee compensation respectively. The services sector of IL contributed $531 \text{ billion}$ and $291 \text{ billion}$ to value added and employee compensation respectively with only 3 \text{ m}^3/\text{\$1000} total water intensity.

Overall consideration of supply chain effects in the state of CA showed that aquaculture, crops, power generation, and livestock sectors had the largest total water use coefficients, with the least water-intensive domestic sector ranking last (Table 5). A similar ranking of sectors was also observed for the state of IL.

### 5.3. Total Water Use and Virtual Water Content

In addition to direct use of water, production activities in each economic sector also use water indirectly. For example, the livestock sector not only uses water for animals to drink, but also uses a large component of water indirectly to grow crops used to feed the livestock. The sum of the direct and indirect water use coefficients gives the total water demand multipliers, equivalent to virtual water content in \text{m}^3/\$\text{1000}. The total water demand multipliers are an indicator of total water use that takes into account supply chain effects, in contrast to the direct water coefficient that focuses only on water use intensity from local production activities using local water resources.

In both states, aquaculture, crops, and power generation sectors have total water multipliers that are not very big in magnitude when compared to the corresponding direct water coefficients, showing that these sectors are not associated with a lot of water-intensive indirect water uses. Indeed, the proportion of indirect water intensity to total water intensity \((T-D)/T\) is less than 10\% for these three sectors in both states (Table 5). The remaining five sectors are mainly composed of indirect water-intensive secondary or tertiary industries.

### 5.4. Virtual Water Transfers

Analyzed in 2008 were virtual water transfers from (1) water embedded in goods and services traded between CA and IL; (2) trade between the two individual states and the remaining U.S. states (domestic trade); and (3) trade between each of the two states with the international community (foreign trade). Overall, both states were net virtual water exporters, with CA’s net export volume 1.3 times that of IL. This overall net virtual water picture shows that likely water resource impacts attributable to production activities in the two states are to a large extent a consequence of consumption activities outside the borders of the two states. Through the transfer of water embedded in traded goods and services, the two important economies are exporting large volumes of virtual water to other U.S. states and to the rest of the world. The largest components of virtual water transfers were a result of domestic trade (with other U.S. states), followed by international. The large component of virtual water volumes transferred to other U.S. states is interesting in the sense that it indicates a preference or prioritization of domestic over international water resources.

### Table 5

<table>
<thead>
<tr>
<th>Sector</th>
<th>CA (T-D)/T</th>
<th>IL (T-D)/T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic</td>
<td>0.15</td>
<td>0.52</td>
</tr>
<tr>
<td>Industry</td>
<td>0.21</td>
<td>0.17</td>
</tr>
<tr>
<td>Mining</td>
<td>0.20</td>
<td>0.01</td>
</tr>
<tr>
<td>Power generation</td>
<td>0.24</td>
<td>0.14</td>
</tr>
<tr>
<td>Livestock</td>
<td>0.25</td>
<td>0.13</td>
</tr>
<tr>
<td>Crops</td>
<td>0.18</td>
<td>0.09</td>
</tr>
<tr>
<td>Aquaculture</td>
<td>0.17</td>
<td>0.07</td>
</tr>
<tr>
<td>Services</td>
<td>0.19</td>
<td>0.09</td>
</tr>
<tr>
<td>Total</td>
<td>0.18</td>
<td>0.09</td>
</tr>
</tbody>
</table>
foreign virtual water transfer, and is also an indicator of the important contribution made by water resources from the two states to the rest of the U.S. economy.

In 2008, IL exported 32% of its total 32,284 Mm$^3$ net virtual water export volume to the rest of the world, and 68% to other U.S. states including CA. However, CA transferred 22% of its total 39,860 Mm$^3$ net virtual water export volume to the rest of the world, and 78% to other U.S. states including IL. Large proportions of virtual water exports from IL originate from green water, while CA's export volumes are dominated by blue water and a substantial portion of saline water.

CA was a net virtual water exporter to IL for the following six economic sectors: crops, livestock, aquaculture, power generation, domestic, and services, while IL was a net virtual water exporter to CA for the mining and industry sectors (Fig. 2). If production decisions were only based on water endowment situations in the two states, it would be preferable for IL to produce and export to CA, especially in the water-intensive sectors. The direct water use coefficients (Table 5) also suggest that it makes more economic sense to intensify production and exports from the more water-abundant IL, where the opportunity cost of water would be lower for economic sectors such as crops. However, the fact that CA is a net exporter of virtual water to IL clearly demonstrates the counter-intuitive nature of interstate virtual water flows between the two states, although it should also be noted that CA also enjoys an advantage in the form of abundant saline water, which is especially important in the electricity sector.

6. Discussion and Limitations of the Study

6.1. Discussion

Inadequate water resources are becoming a major challenge for economic welfare and sustainable regional development, especially in the water-constrained economies of the western U.S. states. Competition between economic sectors requires appropriate strategies to manage water resources in a sustainable way, taking into account the socioeconomic and environmental consequences of such strategies.

This study reveals the direct and indirect water use intensities in two economically important states of CA and IL. By taking into account inter-sectoral supply chain linkages in calculating the volume of water used for each dollar worth of economic output, we determined direct water intensity and total water use intensity indicators in the two major economies. These two important indicators are useful for guiding sustainability decisions by considering water use efficiency, and supporting water allocation that maximizes economic outputs for each unit volume of water used. Although it has been clearly demonstrated that CA and IL have contrasting water endowment situations, the magnitudes of the direct water use intensity indicators calculated for the year 2008 were to a large extent comparable. Our study showed that the two states have major differences related to the sources of water that drive the respective direct water use coefficients. Sectors such as industry, mining, and power generation in CA, as well as mining in IL are partially dependent on saline water withdrawals. As explained in this study, the power generation sector in the coastal state of CA is almost entirely reliant on saline water withdrawals. Blue water inputs for irrigation are responsible for the large direct water use coefficients for the crops sector in CA, in contrast to green water inputs for crop production in the relatively more rainfall-abundant IL. Saline and green water can play a crucial role as alternative sources, especially in areas where the opportunity costs associated with blue water sources are likely to be higher. In evaluating water quantity and quality impacts of production and consumption activities, it is also important to note that the crops sector is the most water-consumptive of the three top direct water-intensive sectors, although the large withdrawal volumes for aquaculture and power generation will also significantly impact freshwater resources through return flows to the environment.

Water is an input in the production of most goods and services, and this study demonstrated how it is transferred virtually through trade. This virtual redistribution of water has undeniable quantity and quality impacts on freshwater resources in both producing and consuming locations.

So how significant are the virtual water transfer volumes in the two states, in comparison to actual water use? Consider the virtual water transfer proportions in Table 6, derived from all import and export volumes of each and actual water use volumes. It is clear that virtual water import and export volumes are very substantial, equivalent to 28% and 59% of total actual water use in CA, and 36% and 71% of total actual water use in IL. Thus, through virtual water transfers, these two states are using their local water resources to support production of goods and services that are consumed in other locations.

Illinois is in a very favorable position to be a major virtual water exporter. Complementing its abundant rainfall are broad areas of fertile soil for the production of crops far in excess of local demand. Less understandable is California’s position as a virtual water importer. Despite hosting 38 million residents, California is an enormous exporter of crops, especially winter produce. Yet the state must import water from the over-allocated Colorado River to supply its southern cities and the Imperial Valley irrigation district, leaving no discharge to the Gulf of California in most years. In this way California is exporting agricultural products at the expense of the once-vibrant ecosystem of the Colorado Delta. Engineering of rivers emanating from the Sierra Nevada range to facilitate irrigation in the Central Valley is resulting in numerous ecological problems in the Sacramento Delta (Mongan and Miller, 1992). The marginal ecological opportunity costs of allocating water for the export of crops from California is thus very high, probably higher than if these crops were grown elsewhere. While the logic runs against recent emphases on local food production, a greater reliance on virtual water flows would likely reduce the overall...
ecological impact of food production, just as it does for water consumption.

6.2. Limitations of the Study

There were several constraints to this study. The data used were mainly from secondary sources such as the USGS, and contain estimation errors that are articulated in the various sources. The economic data used to build IO tables for the two states also have weaknesses as detailed by their producers. For example, creating a state-level IO model requires a tremendous amount of data and time for activities such as surveying industries to produce production functions for each state. In addition, the tables are developed using data that were processed by other sources such as the Federal agencies, meaning there is potential to propagate any data processing errors made along the chain. Proper representation of the economy is required if all the direct and indirect water uses within an economy are to be correctly captured. Another inherent weaknesses of the IO methodology as used in our study is related to the use of monetary IO tables to calculate flows of water that represent the physical world. Ideally, the physical world would be better represented by physical IO tables, but they are not readily available. Use of multiple years of data instead of just the year 2008 could have improved our estimates substantially, but this was not feasible within the scope of this study. Due to data collection constraints, we did not quantify wastewater impacts in our IO formulation, an important water use that reduces available freshwater through pollution. The utilization of consumptive use data instead of water withdrawals would have improved the outcome of this study, but this was not possible due to a lack of reliable consumptive use coefficients by state and economic sector basis. Our results are also subject to a certain amount of uncertainty from using USGS water withdrawal data that is only estimated every 5 years, and loss of information through aggregation of economic sectors, although the extent of such effects cannot be estimated from available data. The error induced by aggregation can be eliminated by aggregating the impact results, instead of aggregating before the generation of multipliers, but this was not feasible for this case study because the US Geological Survey water use data did not contain specific detail disaggregated data for the crops, livestock, aquaculture, mining, power generation, domestic, industry, and services sectors.

7. Conclusion

Our study evaluated water use by different economic sectors and quantified virtual water flows in relation to two economically important U.S. states of CA and IL that have contrasting water resource endowments. Economic sectors such as aquaculture and crops were shown to be direct water use intensive, while accounting for relatively small proportions of value added and employment compensation in the two states. This was in contrast to high indirect water intensive but high value-adding sectors such as industry and services. Water use efficiency indicators like total water use intensity, that take into account supply chain effects between primary, secondary, and tertiary industries can play an important role in identifying economic sectors where water use inefficiencies are high for each unit of economic output.

According to this study, substantial volumes of water are being redistributed as a result of trade in water intensive goods and services involving the states of CA and IL, other U.S. states, and with the rest of the world. Water volumes exported virtually are more than 50 percent of actual water use for each of the two states, showing that each is using local water resources as an input in economic production to support consumption activities outside its own borders. The quantification of virtual water volumes transferred through trade is vital, given the large variations in water resource endowments between the humid eastern and arid western U.S. The very substantial virtual water transfer volumes demonstrated in this study call for increased attention to the water use intensity of economic activities, improved water efficiency measures, and prioritization of water use sectors that provide the largest economic output per unit of water, especially during water scarcity conditions.

Our study also highlighted the fact that virtual water flow patterns and volumes cannot be explained in terms of water endowments alone. This study is a first step in quantifying the important role played by water through trade in goods and services in two states. Future research also needs to focus on the following questions: What are the underlying reasons behind the observed virtual water flow patterns and volumes? What is the role played by the underlying economic structures in the producing regions, including other factors of production such as land, labor, capital, and production technologies?

Finally, this study was based on water withdrawal data. Estimation of consumptive use coefficients, especially at local level, is still very much a work in progress in the U.S. water sector. An analysis that considers actual measurements of consumptive use coefficients of water across different economic sectors would be a topic for future study.

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