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Developing the greatest Blue Economy: Water productivity, fresh water depletion, and virtual water trade in the Great Lakes basin

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Key Points:
- The US portion of the Great Lakes basin is a net importer of water-derived goods and services
- Commercial water uses are the most productive, with thermoelectric, mining, and agricultural uses having substantially lower water productivity
- On average, withdrawals do not create significant impacts on surface waters but local, large water uses could create environmental flow impacts

Supporting Information:
- Supporting Information S1
- Table S1
- Table S2

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Developing the greatest Blue Economy: Water productivity, fresh water depletion, and virtual water trade in the Great Lakes basin

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Abstract The Great Lakes basin hosts the world's most abundant surface fresh water reserve. Historically an industrial and natural resource powerhouse, the region has suffered economic stagnation in recent decades. Meanwhile, growing water resource scarcity around the world is creating pressure on water-intensive human activities. This situation creates the potential for the Great Lakes region to sustainably utilize its relative water wealth for economic benefit. We combine economic production and trade datasets with water consumption data and models of surface water depletion in the region. We find that, on average, the current economy does not create significant impacts on surface waters, but there is some risk that unregulated large water uses can create environmental flow impacts if they are developed in the wrong locations. Water uses drawing on deep groundwater or the Great Lakes themselves are unlikely to create a significant depletion, and discharge of groundwater withdrawals to surface waters offsets most surface water depletion. This relative abundance of surface water means that science-based management of large water uses to avoid accidentally creating "hotspots" is likely to be successful in avoiding future impacts, even if water use is significantly increased. Commercial water uses are the most productive, with thermoelectric, mining, and agricultural water uses in the lowest tier of water productivity. Surprisingly for such a water-abundant economy, the region is a net importer of water-derived goods and services. This, combined with the abundance of surface water, suggests that the region's water-based economy has room to grow in the 21st century.

1. Introduction

Regional economic and water resource policy are becoming more interrelated as the world economy globalizes and as water resources become a strategic advantage [*Hoekstra and Chapagain*, 2011; *Vörösmarty et al.*, 2010]. The concept of the "Blue Economy" is gaining popularity in the Great Lakes basin, where the region is portrayed as having water in such abundance that its water resources can provide for long-term population and economic growth, including future increases in population and in water-using industries and agriculture [*Austin*, 2010; *Marbek Consultants*, 2010]. However, water resources in the basin are stressed in localized areas, especially with respect to groundwater withdrawals. The virtual water trade framework has not been applied to analyze water use in the Great Lakes basin, except for one limited study that considered only agricultural water withdrawals and did not provide spatially distributed values of virtual water trade within the region [*Scanlan and Kehl*, 2014].

For this reason, a water-rich region like the Great Lakes is well served by developing a data-driven understanding of its water economy, including consideration of the following questions. What are the impacts of economic production and trade on the region's fresh water resources, especially the depletion of ecologically sensitive surface water flows? Where is the unused capacity for water uses, and are water uses currently distributed advantageously with respect to the abundance of regional water resources? Is the region making the most of its abundant water resources in trade with external parties? Is the region a net importer or net exporter of virtual water in water-intensive sectors of the economy?

Virtual water is the water consumed throughout the production of a good or service. Virtual water trade is a means of transferring water resources between regions via the trading of goods and services containing embedded water. According to *Hoekstra and Mekonnen* [2012], 2320 Gm^3 of virtual water was traded annually on a global basis over the period 1996–2005. The scale of virtual water trade is expected to increase as globalization intensifies trade between nations [*Hoekstra and Hung*, 2005; *Carr et al.*, 2012]. The study and management of virtual water transfers has been suggested to encourage efficiency by promoting exchanges of virtual water from highly productive countries to less productive countries [*Allan*, 2003].

The original work by *Allan* [1998] on virtual water trade has spurred a substantial body of work on the topic. Recent work has focused on improving methodologies for calculating virtual water trade [*Antonelli et al.*, 2012; *D'Odorico et al.*, 2012; *Yang et al.*, 2012; *Deng et al.*, 2015] and on the evolution of virtual water trade with time [*Zhang et al.*, 2011; *Carr et al.*, 2012; *Dalin et al.*, 2012], where it has been found that virtual water trade has intensified globally and regionally over the last few decades. Interestingly, *Konar et al.* [2013] find that future climate change is likely to result in decreased virtual water trade, because of expected decreases in crop trade because of higher crop prices.

Most regional, national, or global studies of virtual water trade have focused on the agricultural sector, since this sector is thought as the most intensive in terms of consumptive use and trade between regions [*Montesinos et al.,* 2011; *Carr et al.*, 2012; *Dalin et al.*, 2012; *D'Odorico et al.*, 2012; *Konar and Caylor*, 2013; *Konar et al.*, 2013; *Scanlan and Kehl*, 2014]. Only a few studies have considered all economically important water use sectors [*Feng et al.*, 2011; *Zhang et al.*, 2011; *Hoekstra and Mekonnen*, 2012; *Mubako et al.*, 2013a; *Deng et al.*, 2015], where it is noted that direction of virtual water trade (net importers vs. net exporters) differs substantially across water use sectors, the virtual water trade per currency of trade (value intensity) varies over orders of magnitude, and that virtual water and footprint calculations are particularly sensitive to consumptive use coefficients. *Feng et al.* [2011] point that virtual water imports, and associated water footprints, to urban areas can be substantial, because of household consumption of water-intensive goods and services. In addition to noting the importance of cross-sector analyses, *Antonelli et al.* [2012] stress the importance of distinguishing between sources of water embedded in virtual water trade in order to improve virtual water trade as a tool for informing water resource management policy.

The assessment of virtual water flows and water footprint studies is generally carried out at the national level, thus, concealing the spatial variability within regions [*Liu et al.*, 2009; *Mubako et al.*, 2013b; *Fulton et al.*, 2014]. *Fulton et al.* [2014] suggest that national level averages of water footprints may ignore important scale differences associated with "(a) the phenomenon of interest, that is the connections between consumption patterns and global water resource concerns … and (b) the decision making and ability to enact relevant policy." A finer spatial resolution may reveal where there is local diminishment associated with water use (local water footprint is greater than local water resources availability) or there is local capacity for water use (local water resources availability exceeds the local water footprint). Scale issues in the governance of water resources must also be recognized, because management may take place at several overlapping scales, most of which do not harmonize with watershed boundaries or are at scales that are irrelevant to decision-making [*Brown et al.*, 2009; *Montesinos et al.*, 2011; *Zhang and Anadon*, 2014]. Smaller scale calculations of virtual water trade and water footprints are especially critical when comparing these quantities to water availability and the potential ecological consequences of consumptive use.

In this work, we explore several important dimensions—variation across water use sectors, distinguishing between water sources, and availability of water from various sources—of virtual water trade and water footprints in US portion of the Great Lakes basin (see Figure 1). The population of the region in 2011, the study year, was 26 million [*United States Census Bureau*, 2016] and total trade exports and imports for the US portion of the Great Lakes basin were $505 billion and $921 billion, respectively [*Implan*, 2011]. Total water withdrawals over all sources were 32,400 Mm^3/year in 2011. The calculation framework and analysis of results in this work could be applied to any other region, but we have chosen to focus on the Great Lakes because of its economic importance, the apparent abundance of water in the basin, and recent policy developments that touch on economic and ecological impacts of water use.

The 2008 Great Lakes Compact [*Great Lakes-St. Lawrence River Basin Water Resources Council*, 2008] stresses that consumptive use in the basin should not cause adverse ecological impacts and mandates that states and provinces develop processes for evaluating impacts of new withdrawals. Michigan's obligations under

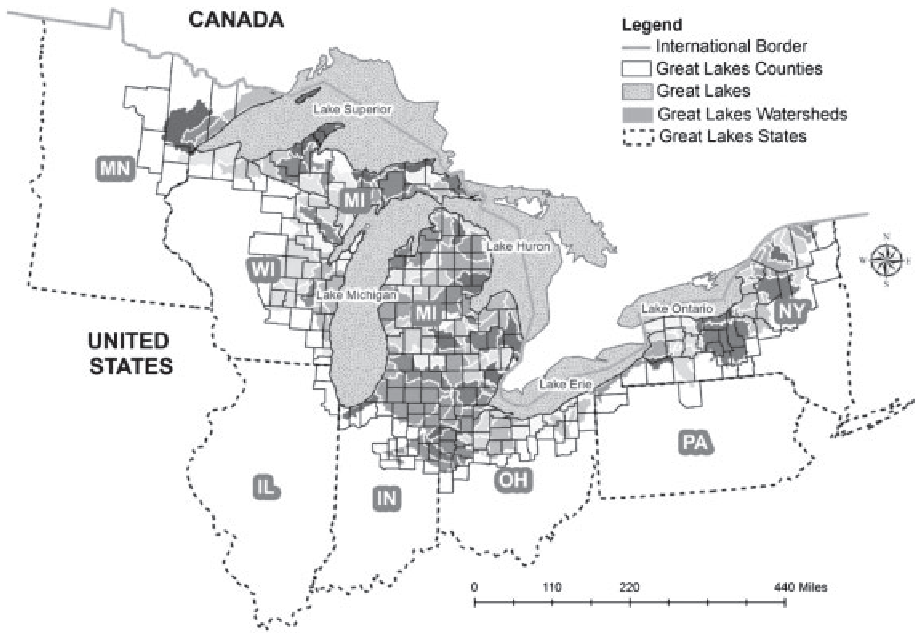

Figure 1. Study area.

the Compact have motivated the creation of a legal definition of tributary surface water (TSW) depletion thresholds through the Michigan Water Withdrawal Assessment Process [MI WWAP; *Steinman et al.*, 2011]. Other states in the basin are considering similar restrictions. While the Compact focuses primarily on protecting the Great Lakes themselves, it does address the importance of avoiding adverse impacts to terrestrial water resources, i.e., TSW and groundwater. Moreover, state-level policy developments, such as the MI WWAP, have focused on protection of TSW against low flows that could harm aquatic ecosystems. These policy developments also recognize that groundwater extractions from shallow aquifers that are hydraulically connected to streams can reduce streamflow to levels that result in impairing aquatic ecosystems. Here, we include TSW depletions associated with groundwater extractions in our virtual water trade and water footprint calculations. We also close the water balance on TSW depletions by accounting for return flows routed to TSW but originating from groundwater withdrawals.

We use input–output (IO) analysis to calculate virtual water trade and footprints by county and use sector. The IO framework defines inter-sector relationships within an economy, showing how output from one sector may become an input to another sector [*Leontief*, 1986]. Here, inter-sector trade data in the form of transactions in US dollars [*Implan*, 2011] are used to represent these economic relationships at spatial scales ranging from county-level to international. County-wide withdrawals are based on aggregating a data set of point withdrawals in the region, available in the same sectors as the trade data and categorized by water source—Great Lakes water (GLW), TSW, shallow groundwater (SGW), and deep groundwater (DGW). The IO framework couples the trade and withdrawal data. Virtual water trade and footprints are calculated for all water sources in the region, but the emphasis is on consumptive use of TSW, which is compared to surface water availability. Surface water consumptive use not only originates from surface water withdrawals but also from withdrawals from SGW. We explore the sensitivity of calculations to critical parameters and assumptions in the framework, including uncertainty in consumptive use coefficients and methods to rout return flows. Results are presented in aggregate for the study region and distributed by county. These water footprint and virtual water results are presented from the regional point of view [*Ruddell et al.*, 2014], considering the basin's watershed as the local system boundary.

Our focus here is primarily on spatial variability. However, the drivers of virtual water trade and water footprints, such as inter-sectoral trade patterns, inter-sectoral water demand, and climate, are expected to vary over a range of time scales. The time scales for aquatic ecosystem response to changes in storages and fluxes also will vary substantially. For example, at relatively short (intra-annual) scales, warmer months may have higher consumptive use, lower water availability (greater imbalances between precipitation and evapotranspiration), and greater ecosystem vulnerability to changes in fluxes and storages. At longer time scales, *Orlowsky et al.* [2014] assessed the impacts of future climate change on global water availability and the corresponding ability of nations to export virtual water, finding that reduced water availability under a range of climate change scenarios will tend to reduce virtual water exports. While we do not explicitly consider temporal variability in virtual water trade and footprints here, the framework we develop can easily accommodate temporal variations, as long as the necessary information (trade, demand, climate, and ecosystem response) is available at the relevant time scale(s).

2. Methods

Virtual water exports and imports and water footprint calculations are based on water withdrawals and corresponding consumptive uses across water use sectors and sources. The framework focuses primarily on virtual trade of TSW consumptive uses, which originate as either surface water withdrawals or SGW withdrawals, but withdrawals and consumptive use from other sources are also calculated for comparison purposes. Only blue water withdrawals and their consequent allocation to consumptive uses are included in the virtual water exports and imports and water footprint calculations, but the framework could easily be extended to include green water consumptive use associated with irrigated agriculture. Further, green water use is indirectly considered when virtual water exports and imports and water footprints are compared to water availability, which takes into account local evapotranspiration losses. Grey water requirements are excluded from our water footprint calculations, but could be included if local and sector-specific pollutant load data were available.

2.1. Water Use Data

Annual water withdrawal data for the calendar year 2011 were collected from water resources agencies in seven of the eight Great Lakes states in the United States: MN, WI, MI, OH, IN, PA, and NY. IL is excluded from the study because water withdrawals in ILs' portion of the Great Lakes basin are only from the Great Lakes [*Great Lakes Commission*, 2014] and the focus of this study is on TSW consumptive uses. The locations of withdrawals provided by the water resources agencies are spatially referenced either by latitude–longitude, township-range-section, or Hydrologic Unit Code 16 (HUC-16) watershed. In the cases of the township-range-section or HUC-16 watershed references, the centroids of these geographical units are used as approximate locations for the withdrawals. Withdrawals are assigned to the corresponding 212 counties with partial or full areas inside the US portion of the Great Lakes basin (see Figure 1 for location map).

Water withdrawals from the state agencies are classified by a number of water use categories. These categories are first harmonized into municipal, irrigation, livestock, mining, thermoelectric self-supplied, commercial self-supplied, and industrial self-supplied. Municipal withdrawals are further segregated into residential (62%), commercial (15%), and industrial (23%). Institutional use is included in commercial use. The fractions of residential, commercial, and industrial withdrawals were determined by a survey of water utilities in the basin. The segregated municipal commercial and municipal industrial withdrawals are added to the corresponding self-supplied categories, referred to as commercial and industrial withdrawals here. Residential water use is not included in virtual water trade calculations because this sector does not directly involve trades of goods. In total, there are $n_i = 7$ water withdrawal sectors: residential, irrigation, livestock, mining, thermoelectric self-supplied, commercial, and industrial.

The state agency withdrawal data are also categorized by source: Great Lakes, TSW, and groundwater. In several cases, it was found that withdrawals counted by the state agencies as TSW withdrawals are located within a few kilometers of the Great Lakes shorelines and thus are unlikely to contribute substantially to TSW consumptive use. A buffer of 5 km from the Great Lakes shoreline is used to segregate Great Lakes and TSW withdrawals based on a breakpoint analysis. Groundwater withdrawals are further segregated into SGW and DGW withdrawals using an algorithm based on the location of the withdrawals and the corresponding availability of SGW resources as described in *Watson et al.* [2014]. If surficial groundwater transmissivities, determined according to the method of *Watson et al.* [2014], exceed 10^{-4} m^2/s, the withdrawals are associated with a shallow aquifer; otherwise the withdrawals are associated with a DGW aquifer. In total, there are $n_k = 4$ sources: GLW, TSW, SGW, and DGW.

2.2. Consumptive Use and Return Flows

Consumptive uses ($CU_{i,k,l}$) and return flows ($RF_{i,k,l}$) are derived from withdrawals ($W_{i,k,l}$) based on water use category i, source k, and point location l:

$$W_{i,k,l} = CU_{i,k,l} + RF_{i,k,l} = cu_i W_{i,k,l} + \left(1 - cu_i\right) W_{i,k,l} \quad (1)$$

where cu_i is the consumptive use coefficient for water use category i. Consumptive use coefficients for the seven water withdrawal sectors are taken from *Shaffer and Runkle's* [2007a, 2007b] publication on consumptive use coefficients for the Great Lakes region. Because consumptive use coefficients can vary widely within water use sectors, virtual water trades are calculated using median, lower, and upper values identified by *Shaffer and Runkle* [2007a, 2007b].

Return flows are assumed to occur in the same county from which the withdrawals occur. Return flows associated with TSW withdrawals are implicitly accounted for because only consumptive uses from this are counted toward TSW consumptive use for this source. Return flows associated with groundwater withdrawals are considered in two cases: (a) no counting and (b) counting toward TSW consumptive use. In the first case (the Base Case), return flows associated with groundwater withdrawals are ignored. In the second case, return flows associated with shallow and DGW withdrawals are assumed to be disposed in TSWs. We ignore return flows that originate from GLW withdrawals. We assume that all of the GLW withdrawals are either routed directly to the lake, or, if they occur close to TSW, the return flows occur close to the outlet of the rivers or streams to the Great Lakes, and thus do not affect TSW flows.

2.3. Tributary Surface Water Consumptive Use

The relationship between consumptive use and TSW consumptive use ($D_{i,l}$) at a point location l depends on the source associated with the withdrawals:

$$D_{i,l} = CU_{i,\mathrm{TSW},l} + \alpha_l CU_{i,\mathrm{SGW},l} \quad (2)$$

where α_l is the local TSW consumptive use. Consumptive uses from the Great Lakes and DGW are ignored in calculating to TSW consumptive use, since withdrawals from Great Lakes are assumed to have a negligible impact on tributary streamflow and DGW withdrawals are assumed to be located in aquifers with negligible hydraulic connections to streams.

Following the methodology developed for the Michigan Water Withdrawal Assessment Tool [MIWWAT; *Reeves et al.*, 2009], which has been used to screen requests to the state of Michigan for new groundwater withdrawals since 2009, the fraction of a SGW withdrawal causing an associated streamflow depletion (α_l) for point location l is calculated using the Hunt equation [*Hunt*, 1999]:

$$\alpha_l = \left[\mathrm{erfc}\left(\sqrt{\frac{S_l d_l^2}{4T_l t}}\right) - \exp\left(\frac{\lambda_l t^2}{4S_l T_l} + \frac{\lambda_l x_l}{2T_l}\right) \mathrm{erfc}\left(\sqrt{\frac{\lambda_l t^2}{4S_l T_l}} + \sqrt{\frac{S_l d_l^2}{4T_l t_l}}\right)\right] \quad (3)$$

where S_l is the storage coefficient of the aquifer, T_l is the transmissivity of the aquifer, d_l is the distance from well to adjacent streams, t_l is the time from the start of pumping, λ_l is the streambed conductance term, $\lambda = Tw/10Bb$, w is the stream width, B_l is the aquifer thickness, and b_l is the depth to the top of the well screen. Equation 3 assumes that the aquifer is of infinite extent and constant saturated thickness and is homogeneous, isotropic, and dominated by horizontal flow. Changes in hydraulic head are assumed to be small compared to aquifer saturated thickness and the stream is assumed to remain in hydraulic connection with the aquifer, is straight, and is infinitely long [*Reeves et al.*, 2009]. Distances from wells to adjacent streams, storativities, transmissivities, and streambed conductances for each point location l are determined using the method of *Watson et al.* [2014]. Since pumping time is an unknown, we assessed the sensitivity of stream depletions to this variable by calculating stream depletions across the study area for times of $t = 1$, 5, and 20 years. We found that stream depletions for $t = 1$ year were 96% of for deletions at steady state. We use the $t = 1$ year pumping time because it also coincides with the default pumping time for the MIWWAT groundwater withdrawal request system. The fractional depletion is compared to water availability in equation 11, where water availability is determined as precipitation less evapotranspiration.

2.4. Virtual Water Exports and Imports and Sectoral Value Intensities

IO analysis is used to couple trade in currency to virtual water imports and exports by sector and by county [e.g., *Hubacek et al.*, 2009; *Wang and Wang*, 2009; *Cazcarro et al.*, 2010; *Yu et al.*, 2010; *Zhao et al.*, 2010; *Feng et al.*, 2011; *Antonelli et al.*, 2012; *Mubako et al.*, 2013a). Following the approach of *Mubako et al.* [2013a], the demand for a given product can be specified by a system of linear equations

$$x_i = \sum_{j=1}^{n} X_{ij} + y_i \tag{4}$$

where n is the number of economic sectors in an economy, x_i is the economic output of the ith sector, X_{ij} is the monetary flow from the ith sector to the jth sector, and y_i is the demand of sector i for the good. The total output of the economy for a sector is

$$x_i = \sum_{j=1}^{n} a_{ij} x_j + y_j$$

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \tag{5}$$

where a_{ij} are technical coefficients of production ($a_{ij} = X_{ij}/x_j$), $\mathbf{x}$ is the vector of total outputs, $\mathbf{A}$ is the matrix of technical coefficients, and $\mathbf{y}$ is the vector of final demands. Solving for $\mathbf{x}$, gives the final outputs required for sustaining a vector of final demands ($\mathbf{y}$):

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{y} \tag{6}$$

where $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix, which is the matrix of direct and indirect coefficients. This matrix represents the total production that every sector must generate to satisfy a unit final demand of the economy [*Velázquez*, 2006].

The relationship between the input of water and economic production is reflected through water use coefficients for each economic sector. The regional IO table for each county is extended by adding a vector of direct water use coefficients. The direct coefficient vector $\mathbf{f}$ is a vector of technical coefficients with the ith element equal to the amount of TSW consumptive use as input in the production of one unit of the good representing sector i. These coefficients represent the TSW consumptive use per unit of output expressing the direct sectoral interactions in the economy, as opposed to water consumed further upward in the supply chain to produce the good. For each county m, a multiplier vector ($\mathbf{g}_m$) is calculated by multiplying the vector of technical coefficients with the Leontief inverse matrix:

$$\mathbf{g}_m = \mathbf{f}_m\,(\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{y}_m \tag{7}$$

The ith element of the total coefficient vector $\mathbf{f}_m$ is the total amount (direct and indirect) of TSW consumptive use per unit of final use of good representing sector i. The multiplication of the ith element of $\mathbf{g}_m$ and the ith element of a $\mathbf{c}_m$ vector gives the total amount of TSW consumptive use embodied in the export of a good in sector i, so that summing over all the goods, the virtual exports of water associated with TSW consumptive use from county m gives the total virtual water exports (VWE_m) for a county:

$$VWE_m = \mathbf{g}_m \mathbf{c}_m^{\mathrm{T}} \tag{8}$$

where VWE_m, $\mathbf{g}_m$, and $\mathbf{c}_m$ have units of volume per time, volume per currency, and currency per time, respectively. The elements of $\mathbf{g}_m$ are the direct water use intensities for a sector and are specific for each county.

The data for matrix $\mathbf{A}$ was acquired from the Implan Group, Inc. (2011), which provides county-level trade data for 440 economic sectors, based on the North America Trade and Industrial Classification System (NAICS). The Implan data by NAICS sectors are aggregated to the seven water withdrawal sectors identified in the state agency water use data sets (see Table S1, Supporting Information). The data for $\mathbf{g}_m$ are derived from the TSW consumptive use calculations.

Data sources for withdrawals and consumptive uses associated with goods imported into counties are not available. To estimate county-wise virtual water imports, it is assumed that producers outside the counties produced with water intensities equal to those in the counties states. This assumption follows the logic that water consumed by the production of goods imported into a county "replaces" water that would have need to be consumed if the imports did not occur. Previous studies have used a similar approach [e.g., *Ip et al.*, 2007; *Lenzen*, 2009; *Mubako et al.*, 2013a] and demonstrated that this assumption is reasonable for quantifying virtual water imports of unknown origin. Thus, county-wise virtual water imports are calculated as

$$VWI_m = \mathbf{g}_m \mathbf{c}_I^T \tag{9}$$

where $\mathbf{c}_I$ is the equivalent $\mathbf{c}$ vector for goods imported into a county.

County-wise total *VWE* and *VWI* are aggregated into intra-county, county-to-US, and county-to-international virtual water trade. Intra-county virtual water trade is calculated by taking the difference between county-wise consumptive uses and *VWE* by sector. County-to-US and county-to-international virtual water trade are separated by multiplying monetary (dollar) exports from each county to the United States and to international destinations by the respective multiplier matrix ($\mathbf{g}_m$).

2.5. Water Footprints and Surface Water Depletion

Virtual water trades are linked to water footprints by [following *Velázquez et al.*, 2011]

$$\begin{aligned} WF &= WF_{\text{direct}} + WF_{\text{indirect}} \\ WF_{\text{direct}} &= CU = VWE + CU_{\text{local}} \\ WF_{\text{indirect}} &= VWI \end{aligned} \tag{10}$$

where WF, WF_{direct}, and WF_{indirect} are the total, direct, and indirect water footprints, respectively. The specification of WF_{direct}, and WF_{indirect} allows for separation into total direct consumptive use (*CU*) associated with all regional uses of water and indirect consumptive use associated with imports of goods and services, or total virtual water imports (*VWI*). The variable WF_{direct} is further related to the total consumptive use that is exported via trade (*VWE*) and consumptive that occurs through within-region trade (CU_{local}).

The annual, fractional surface water depletion relative to water availability, d, is calculated by county as

$$d_{a,l} = \frac{D_l - GWRF_l}{P_l - ET_l} \tag{11}$$

where the annual renewable supply to surface water is calculated as the average annual precipitation (P_l) minus the average annual evapotranspiration (ET_l) for location l, which are obtained using climate data from PRISM (http://www.prism.oregonstate.edu) and *Sanford and Selnick* [2012], and $GWRF_l$ is the groundwater return flow for location l. The fractional surface water depletion is calculated by county for two cases: (a) not accounting for groundwater return flow (Base Case) and (b) accounting for groundwater return flow. In equation 11, return flows associated with shallow and DGW withdrawals are counted as negative with respect to surface water depletion because they are additions to surface water flow.

3. Results

3.1. Virtual Water Exports and Imports and Water Footprints Aggregated Over Study Region

Figure 2 shows withdrawals and consumptive use for the study region by water source. Withdrawals from the Great Lakes are the largest, followed by surface water, and deep and SGW withdrawals. Consumptive uses follow the same pattern, but consumptive use coefficients vary substantially by source. The predominant water use sectors for each source and consumptive use coefficients associated with the sector (see the Base Case in Table 1) explain the variations in consumptive use coefficients by source. The overall GLW consumptive use coefficient is especially low because the majority of withdrawals for this source is for thermoelectric power generation. The surface water consumptive use coefficient is somewhat higher, because the majority of water withdrawn for this source is associated with the industrial and residential sectors. DGW withdrawals are a mixture of public water supplies and irrigated agriculture, whereas SGW withdrawals are typically used for irrigated agriculture.

In Figure 2, the stippled portions of the SGW bars are the fractions of SGW withdrawals and consumptive use that are associated with stream depletion. The stippled portions of the surface water bars are the

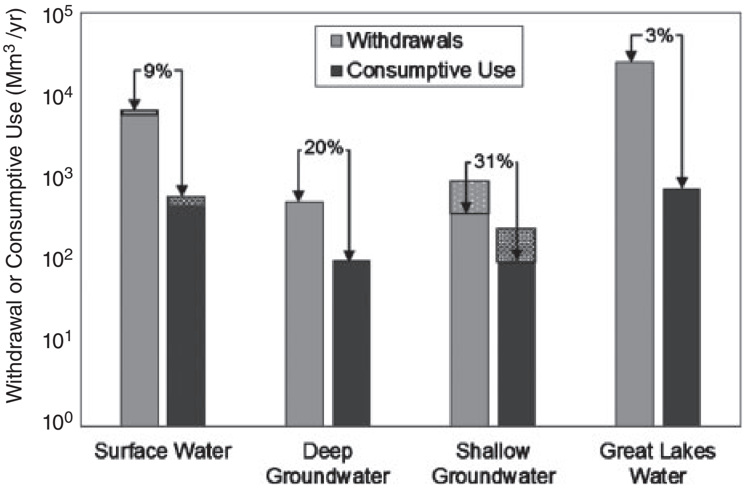

Figure 2. Withdrawals and consumptive use by source. Numbers represent overall consumptive use coefficients for each water source. The stippled portions of the shallow groundwater bars are the fractions of shallow groundwater withdrawals and consumptive use that are associated with stream depletion. The stippled portions of the surface water bars are the components of surface water withdrawals and consumptive use associated with shallow groundwater extractions.

Table 1. Consumptive Use Coefficients for Water Use Sectors

	Consumptive Use Coefficient (%)		
Category	Low Case: 25th Percentile	Base Case: Median	High Case: 75th Percentile
Public supply	10	12	15
Industrial	7	10	14
Thermoelectric power	1	2	2
Irrigation	90	90	96
Livestock	80	83	90
Commercial	8	10	15
Mining	7	10	25

Source: *Shaffer and Runkle* [2007a, 2007b].

components of surface water withdrawals and consumptive use associated with SGW extractions. The fraction of surface water withdrawals and consumptive use associated with SGW extractions is relatively small. However, it should be emphasized that these fractions are integrated over the entire study area and does not eliminate the possibility of localized regions where groundwater extractions are substantial portion of stream depletions.

Export and import trade in terms of currency is dominated by industrial and commercial trade in the US portion of the Great Lakes basin, as shown in Figure 3. Imports are higher than exports are for every sector, with mining having the largest difference between exports and imports. In Figure 4, value intensities are presented for each water use sector. As expected, commercial and industrial value intensities are highest, by more than two orders of magnitude, because these sectors comprise low consumptive water use, high value, non-food consumer products or inputs of manufactured products to higher levels of manufacturing. Irrigation, livestock, and mining sectors have low value intensities because these sectors are relatively high consumptive water users and generate low trade value. The relatively low value intensity for thermoelectric power generation indicates that this sector has an especially low trade value, given that the consumptive water use for this sector is low. The results in Figure 4 also indicate that there is substantial variation in value intensities across the counties. Further analysis (not shown here, see Table S2) indicates that variation in value intensity primarily reflects differences in the dollar values of the sectors across the counties, rather than differences in consumptive use.

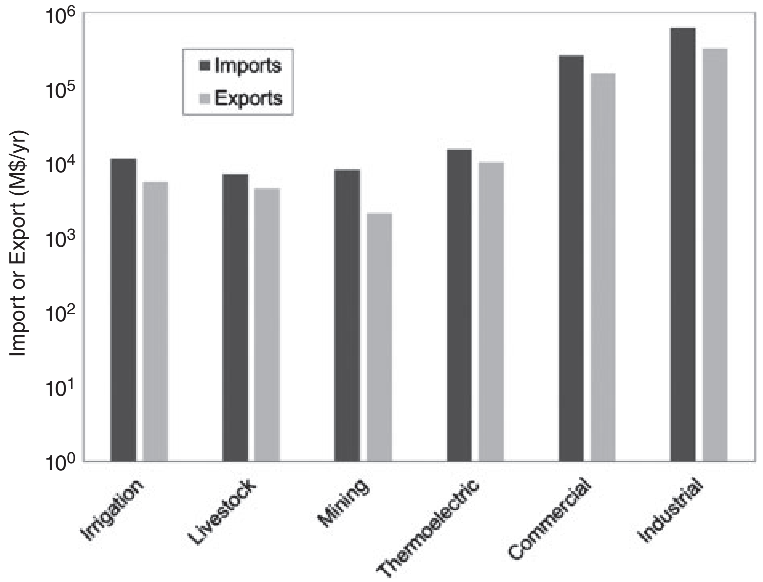

Figure 3. Export and import trade in currency (US dollars) for the US portion of the Great Lakes basin by water use sector.

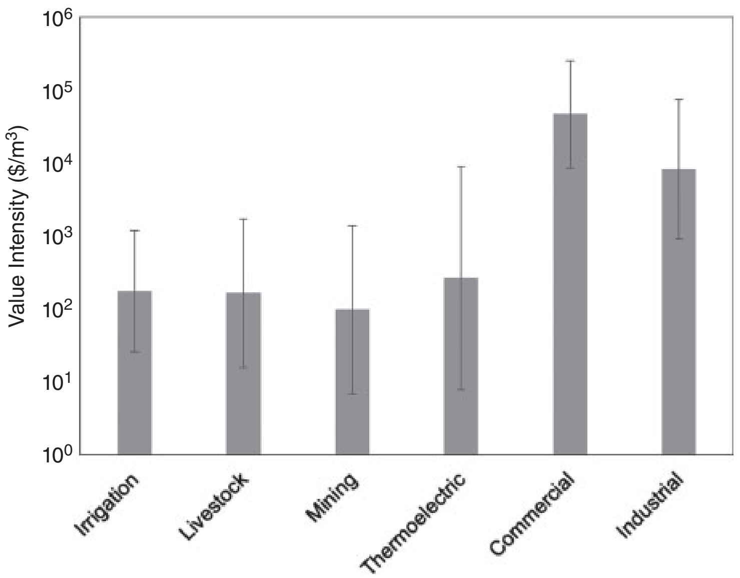

Figure 4. Median (solid bar height) and geometric standard deviation (error bars) for value intensities by water use sector over all counties.

The total virtual water exports and imports across all sectors and sources are 235 and 441 Mm^3/year, respectively. Virtual water imports are roughly double the exports, which agree with the relationship between import and export trade shown in Figure 3. The finding here that the US portion of the Great Lakes region is a net virtual water importer is in contrast to the findings of *Hoekstra and Mekonnen* [2012], where the United States as a whole was found to be a net virtual water exporter. These differences are likely due in some respect to differences in calculation methodologies. For example, our methodology does not include green water consumption. In addition, major agricultural exporting areas of the United States are not included in our study region here. *Scanlan and Kehl* [2014] found that six of the eight Great Lakes states in the United States were net exporters of virtual water associated with agricultural trade. While not shown here (see Table S2), agricultural virtual water trade was a net importer in this study. This contrast with *Scanlan and*

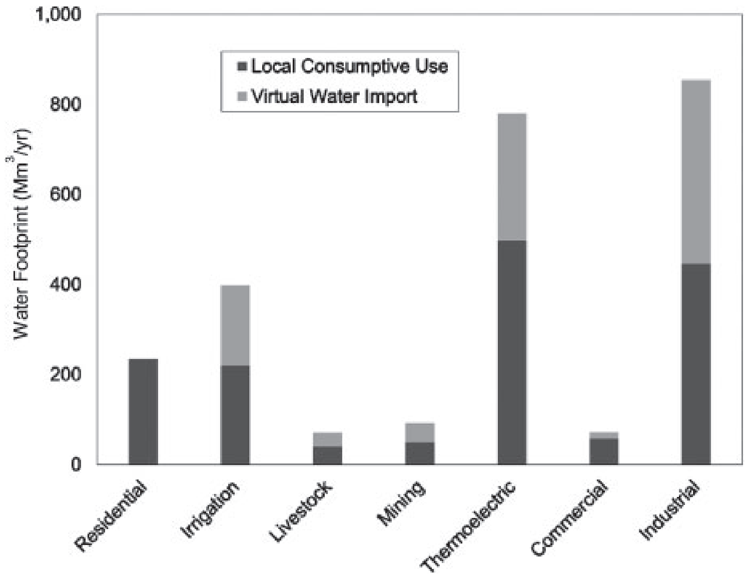

Figure 5. Water footprint for study area by sector, divided into direct (local consumptive use) and indirect (virtual water imports) fractions.

Kehl's [2014] results are likely because of differences in the study area and, again, differences in calculation methodologies.

Total water footprints (see equation 10) averaged over all sources are given by sector in Figure 5. For the largest sectors — irrigation, thermoelectric power, and industrial — the direct (local consumptive use) and indirect (virtual water imports) portions of the water footprint are roughly equal. The total water footprint is 2500 Mm^3/year, translating to a per capita water footprint of 96 m^3/year/capita. The remainder of the results is concerned with virtual trade of TSW consumptive use. Figure 6 shows virtual TSW exports and imports for the study area by water use sector for the median, high, and low set of consumptive use coefficients. Industry dominates the virtual TSW exports because of the higher quantity of water withdrawn for this sector, relative to other sectors, followed by irrigation and thermoelectric power generation. Virtual water imports of TSW follow roughly the same pattern as exports, because the ratio of exports versus import trade for each sector are distributed more or less evenly (see Figure 3). Virtual water imports of TSW are greater than exports for every use sector, which can also be explained by the patterns of export versus import trade for each sector shown in Figure 3.

The variation of consumptive use by sector over the ranges of consumptive use coefficients reflects the patterns of consumptive use coefficients in Table 1. For all values of the consumptive use coefficients, industrial exports and imports dominates. The wide range of industrial consumptive uses in Figure 6 is because of the dominance of this sector in terms of consumptive use and the wide range of consumptive use coefficients for the sector. This result indicates that values of consumptive use coefficients in the industrial sector are especially critical. The wide range of consumptive uses for the industrial sector also implies that this sector should be subdivided into finer categories of industrial use. However, it is not clear whether the underlying data and parameters will support the application of finer industrial use categories.

Overall virtual TSW exports and imports are calculated by trade boundaries in Table 2. The majority of TSW consumptive use is traded internally with the US portion of the Great Lakes basin (651 Mm^3/year). The major contributor to the internal trade is industrial to industrial trade. The domestic virtual TSW exports are dominated by industrial trade, while virtual domestic imports consist primarily of thermoelectric, industrial, and agricultural imports. For international virtual TSW trade, industrial imports and exports dominate. Table 2 also gives total exports, total imports, and net trade of virtual TSW consumptive use. Total net virtual water imports of TSW consumptive use are substantially larger than exports, attributable to the overall excess of trade imports over exports for the study area.

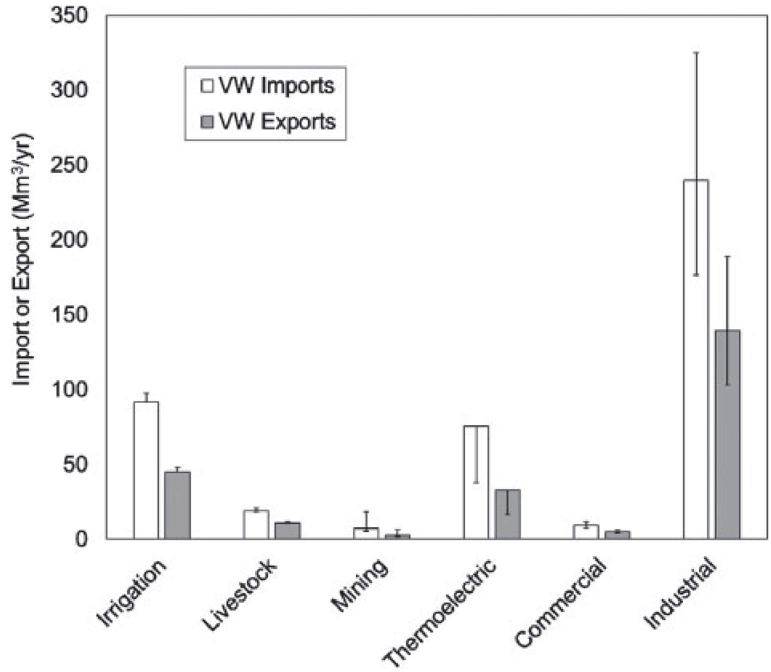

Figure 6. Surface water virtual exports and imports for the US portion of the Great Lakes basin by water use sector and sensitivity of consumptive use of tributary surface water to consumptive use coefficients. Error bars indicate surface water virtual exports and imports with high or low consumptive use coefficients.

Table 2. Exports, Imports, and Net Virtual Surface Water Flows Calculated by Trade Boundaries in Mm^3/Year

Geographic Origin	Imports	Exports	Net
Internal	651	651	0
National	376	179	197
International	65	56	9
Total external	441	235	206

3.2. Virtual Surface Water Exports and Imports and Surface Water Depletion By County

In Figure 7, virtual imports and exports of surface water consumptive use are shown for each county. The ratio of the total virtual imports and exports is given for reference, representing an average ratio of virtual imports and exports over all counties. Most counties fall near the average ratio, but a few counties are outliers. Three counties (Oswego, NY; Lake, OH; and Wayne, NY) have substantially higher ratios of imports to exports because of relatively high amounts of trade and virtual water imports associated with thermoelectric power generation. On the other hand, three other counties (Lucas, OH; Porter, IN: and Cuyahoga, OH) exhibit substantially lower import to export ratios. These counties have unusually large exports associated with thermoelectric power generation, and thus have larger virtual water exports than average.

The maps in Figure 8 indicate the net virtual water trade of surface water consumptive use by use sector and county. For most counties and water use sectors, virtual water imports exceed exports. However, a substantial number of counties are greater virtual water exporters than importers for the commercial sector. Most of these counties are in rural areas with low populations, such that production of commercial goods and associated virtual water use outweighs the imports of commercial goods for consumption by the local population. Several counties also are greater virtual water exporters than importers for the thermoelectric sector. As expected, these counties have thermoelectric power generation facilities that virtually export TSW along with the generated power. The counties that are overall exporters of virtual water associated with livestock have large animal feeding operations.

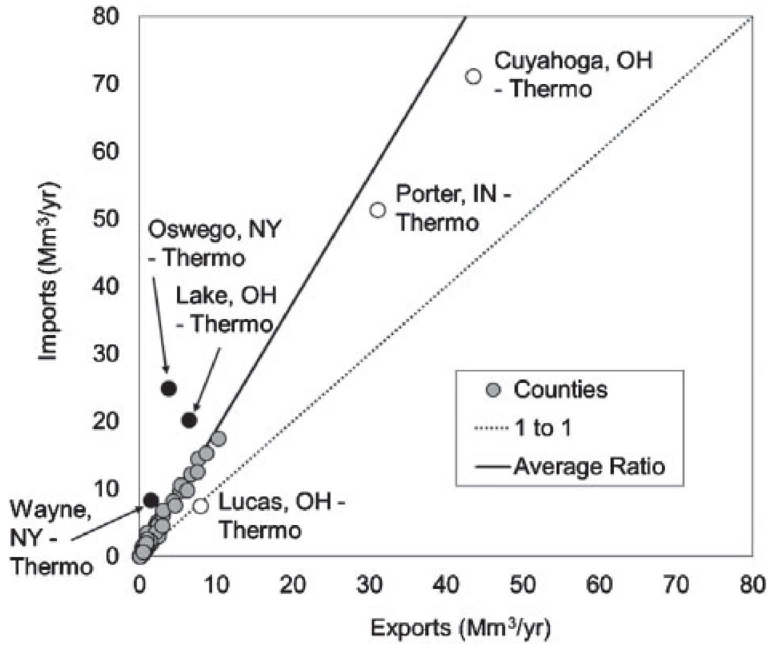

Figure 7. Virtual stream depletion exports and imports for the US portion of the Great Lakes basin by county.

The distribution of annual, fractional surface water depletion by county is illustrated in Figure 9 for two cases, not accounting for return groundwater flow (the Base Case) and accounting for return groundwater flow. For the Base Case, almost 90% of the counties have annual fractional surface water depletions of 1% or less. Only 2% of the counties have annual fractional surface water depletions of greater than 10%, which is an ecological flow depletion threshold proposed by *Richter et al.* [2011] as a realistic, general-purpose value for this type of freshwater ecosystem. When the augmentation of surface water in the form of return flows of groundwater are accounted for, most counties have negative depletions, indicating that return flows from groundwater more than offset removal of surface water via consumptive use. The small fraction of positive depletions for the return groundwater flow case occurs in counties where surface water consumptive use is relatively high and groundwater use is relatively low. Only two counties have fractional depletions of greater than 10%, when return flows from groundwater are accounted for.

These results indicate that, for the most part, consumptive use of surface water in the study region is a relatively small fraction of water available for surface water; although calculation of flow depletions on annual time scale and at the county spatial scale is likely to mask larger depletions at finer spatial and time scales. For example, *Mubako et al.* [2013b] found substantially higher depletions for Michigan's Kalamazoo River watershed for summer months. In this work, fractional depletion is the surface water consumptive use relative to a local ecological depletion threshold and are calculated for a low flow month and for each sub-watershed ($N = 126$):

$$d_{T,l,m} = \frac{D_{l,m}}{T_{l,m}} \tag{12}$$

where $T_{l,m}$ is the ecological depletion threshold at location l [*Zorn et al.*, 2008]. The ecological depletion threshold is the maximum fraction of streamflow that can be depleted, as determined in the MIWWAT system [*Reeves et al.*, 2009]. The distribution of low-flow month, fractional surface water depletion by sub-watershed is illustrated in Figure 10. While most sub-watersheds have minimal (<0.1%) depletions, 10% of the sub-watersheds have fractional depletions great than 50% and one sub-watershed exceeds the threshold ecological flow.

4. Conclusions

In summary, we have provided a high-level survey of the US Great Lakes region's water economy. This economy uses more surface water than ground water, and some of the largest water uses directly tap the Great

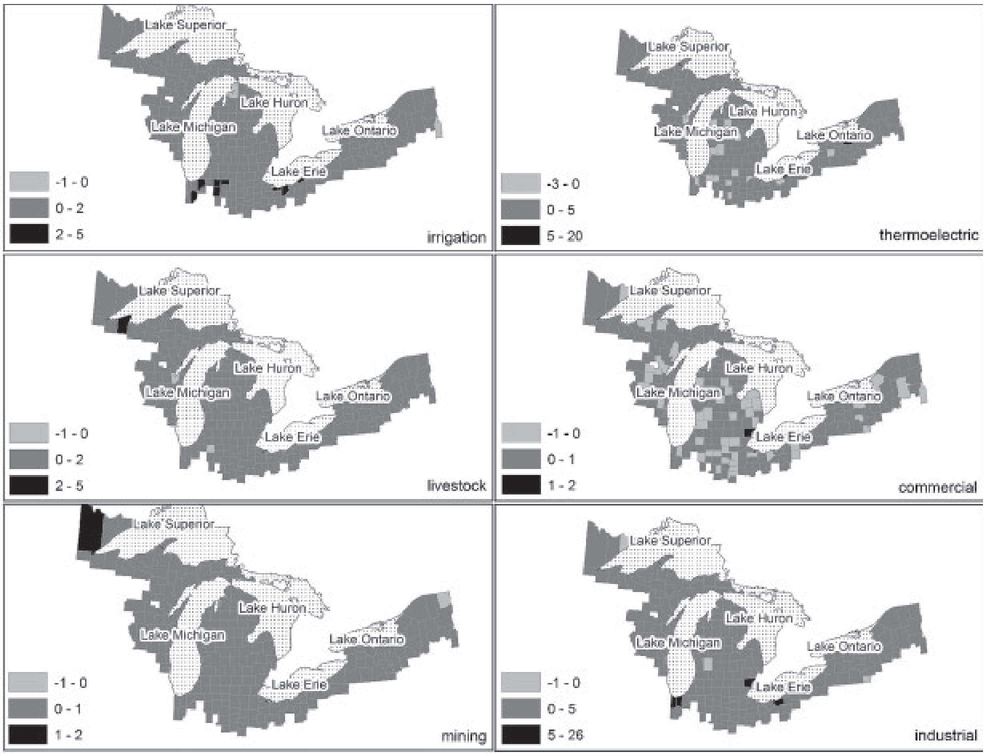

Figure 8. Net virtual surface water trade by county and by water use sector (Mm^3/year). Negative values indicate exports exceeding imports and vice versa.

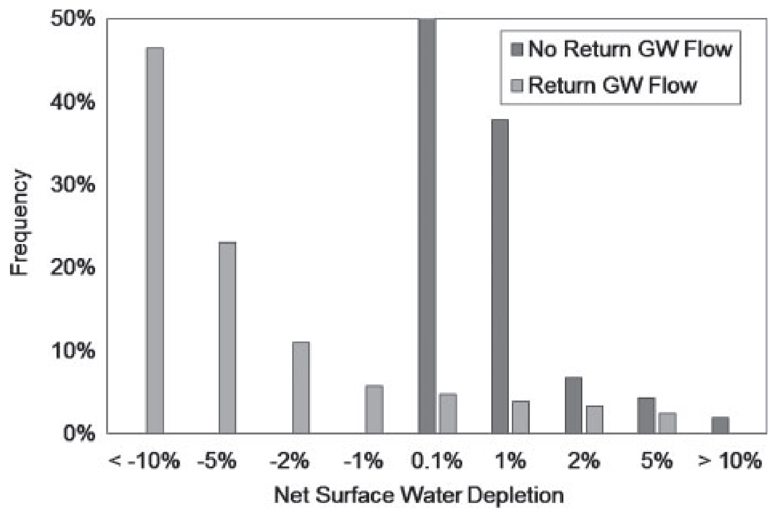

Figure 9. Frequency distribution of fractional surface water depletion (defined in equation 12) by county for the Base Case (no groundwater return flow) and the case with groundwater return flow.

Lakes and avoid stream flow depletion impacts. This is especially true of thermoelectric power plants, which tend to use huge amounts of water but are mostly drawing directly from the Great Lakes. Roughly half of water use is from inland surface waters or from shallow ground water sources, both of which have the potential to impact environmental flows, especially during summer, if enough large users of this type of water are concentrated in a small area. In several highly populated areas around the region there are high concentrations of this type of water use, and could potentially deplete surface water flows enough to cause problems with environmental flows during summertime.

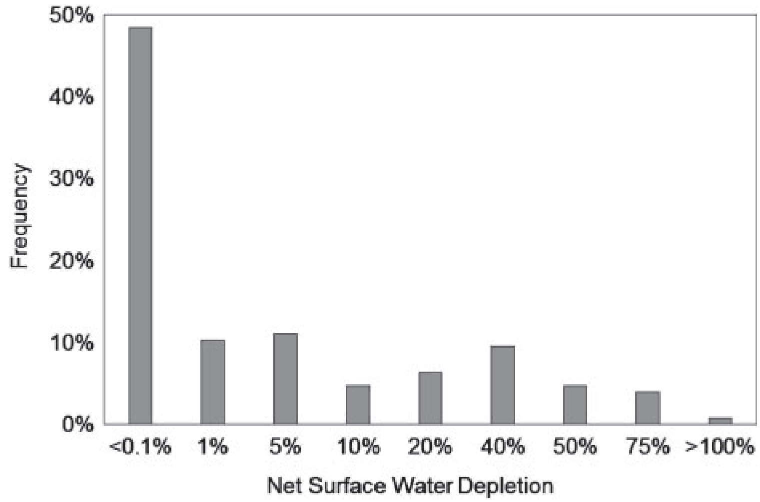

Figure 10. Frequency distribution of fractional surface water threshold depletion (defined in equation (12)) by sub-watershed for the Kalamazoo River watershed [data from *Mubako et al.*, 2013b].

However, we also show that withdrawals from groundwater are frequently discharged to surface waters, so water users in this region probably have a net positive effect on ecologically sensitive environmental flows, on average. Any particular case can depart from the average, and for this reason it makes sense for the region to carefully evaluate large water withdrawals that could affect low flow season environmental flows, especially in heavily populated areas or those with concentrations of irrigated agriculture [e.g., *Mubako et al.*, 2013b]. Because of this trend of abundant supply on average, with possible local exceptions [i.e., "hotspots," *Van Oel et al.*, 2009; *Pfister et al.*, 2011] water use regulations such as Michigan's Water Withdrawal Assessment Process [*Steinman et al.*, 2011] are likely to be an effective management tool because they can distinguish between the vast majority of cases that are free from impact from the minority that should be carefully scrutinized.

We have mapped the average value intensity for each major economic sector of the Great Lakes. This is one measure of the productivity of water, in units of dollars per cubic meter- and is not the value of the water itself. These results establish three tiers of water productivity: in the highest tier, urban commercial uses; in the middle tier, large industrial uses; and in the lowest tier agricultural, livestock, mining, and thermoelectric uses. Roughly four orders of magnitude separate the most productive from the least productive water uses. It is clear, therefore, that water is used for a wide range of valuable purposes in this region, and that stark differences exist between the water use profiles of different economic sectors. We suggest that water productivity be considered as a factor in regional or local planning for future, potentially water-intensive development. However, we recognize that, of course, water productivity is only one of many dimensions involved in decision-making with regard to development that may happen to be water-intensive.

Our findings relate specifically to surface water depletion and, more narrowly, to the blue water portion of surface water depletion. The trade patterns in Figure 3, however, indicate that, averaged over all water sources, including withdrawals from the Great Lakes and shallow and DGW storage, the US portion of the Great Lakes basin is a net virtual water importer. Further investigations of virtual water trade and water footprints could address several more points, including consideration of not only blue water, but also green water consumption and grey water requirements for diluting pollutants [see *Hoekstra and Mekonnen*, 2012 for definitions].

The results in this work focused primarily on spatial variability, but the framework developed here can be extended to consider temporal variability in climate at a range of scales, provided the necessary data are available. In the Great Lakes basin, temperatures are expected to warm over the next century, but estimates of precipitation changes are, in general, less certain [*Kunkel et al.*, 2013]. With a higher greenhouse gas emissions scenario, most models project precipitation to increase 10–20% by later in the century (2071–2099), relative to 1970–2000 [*Melillo et al.*, 2014]. However, changes in seasonal precipitation are likely to be greater, with winter and spring rain increasing and summer rain decreasing by up to 50% [*Melillo et al.*, 2014]. Increases in the frequency and intensity of extreme precipitation, wet or dry, are projected across the Great Lakes region [*Kunkel et al.*, 2013]. Stream discharges during low-flow, summer months could be substantially lower in the region; these reductions in low flows will vary widely across the basin [*LaBeau et al.*, 2015].

While projections of future climate conditions are available, obtaining predictions of withdrawals is problematic. Regional projections for future water demand in the Great Lakes basin are scarce and do not always agree [*Pentland and Mayer*, 2016]. Furthermore, it is difficult to predict the drivers of water demand, such as trade, population, irrigated farmland, and water use efficiency for more than a few years into the future. Nevertheless, it is worthwhile to at least explore spatial variability in future water availability because of climate change, in order to identify areas that may be most vulnerable or resilent to climate change in relation to local water footprints and virtual trade.

Acknowledgments
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