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Direct and indirect urban water footprints of the United States

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Special Section:
Socio-hydrology: Spatial and Temporal Dynamics of Coupled Human-Water Systems

Key Points:
- The total urban water footprint includes direct and indirect water inputs and opportunities for energy and water benchmarking
- Conservation opportunities exist for water and energy in direct and indirect water resources
- Water embedded in food resources dominates the total urban water footprint

Supporting Information:
- Supporting Information S1
- Table S1

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Abstract The water footprint of the urban environment is not limited to direct water consumption (i.e., municipal supplies); embedded water in imported resources, or virtual water transfers, provides an additional component of the urban water footprint. Using empirical data, our analysis extends traditional urban water footprinting analysis to quantify both direct and indirect urban resources for the United States. We determine direct water volumes and their embedded energy through open records requests of water utilities. The indirect component of the urban water footprint includes water indirectly consumed through energy and food, relating to the food-energy-water nexus. We comprehensively quantify the indirect water footprint for 74 metropolitan statistical areas through the combination of various databases, including the Commodity Flow Survey of the U.S. Census Bureau, the U.S. Department of Agriculture, the Water Footprint Network, and the Energy Information Administration. We then analyze spatial heterogeneity in both direct and indirect water footprints, determining the average urban water footprint in the United States to be 1.64 million gallons of water per person per year [6200 m^3/person/yr or 17,000 L/person/d], dominated by indirect water. Additionally, our study of the urban water cycle extends beyond considering only water resources to include embedded energy and equivalent carbon dioxide emissions. The inclusion of multiple sectors of the urban water cycle and their underlying processes provides important insights to the overall urban environment, the interdependencies of the food-energy-water nexus, and water resource sustainability. Our results provide opportunities for benchmarking the urban energy-water nexus, water footprints, and climate change potential.

1. Introduction

A growing global urban population creates national and global hot spots of resource consumption requiring large flows of water, food, and energy. Estimations by the United Nations show that sometime within the past 10 years, a majority of the world's population now resides in cities for the first time in human history [United Nations, 2014]. Cities have a relatively small geographical surface area, but they have a large ecological and economic footprint. They are critical nodes in the flows of material, handle a majority of the global gross domestic product (GDP), and are responsible for approximately 75% of total greenhouse gas emissions [*Otto-Zimmermann*, 2012; *Dobbs et al.*, 2011]. An increased urban population, in conjunction with external factors such as climate change, droughts, or pollution, stresses water resources in environments. Water resources are integral to the sustainability of an urban system [*Pamminger and Kenway*, 2008; *Kenway et al.*, 2011], with understanding human modifications to the water cycle important for determining water scarcity [*McDonald et al.*, 2014]. Water footprints measure humans' appropriation of fresh water resources to support a population [*Hoekstra and Chapagain*, 2008; *Aldaya et al.*, 2012].

This paper builds on water footprint literature by partitioning into direct and indirect water [*Paterson et al.*, 2015]. We provide a quantitative extension of the traditional water footprints of cities and incorporate concepts of indirect water to quantify the food-energy-water nexus [*Vanham*, 2016]. Existing studies identify water as a critical material flow through an urban environment, accounting for approximately 90% of mass flows [*Wolman*, 1965; *Decker et al.*, 2000; *Kenway et al.*, 2011]. However, this estimation only accounts for direct flows of physical water into an urban environment. Water enters the urban environment not just directly through drinking water; water also enters the system indirectly as an embedded resource. The direct water footprint is the physical water consumed by a population within the city boundaries, measured from the outflow of the drinking water treatment plant. The indirect water footprint is water consumed for the procurement of high flux consumer goods and resources that are then imported into the urban environment. These consumables include resources with a daily demand, such as food, electricity, and fuel. We comprehensively evaluate both direct and indirect water footprints across the United States and evaluate their spatial variability, relative contributions to the total water footprint, and statistical properties.

A component of indirect water flows, virtual water flows, account for a large volume of water embedded in the food products, fuel resources, and other processed goods that enter an urban environment [*Rushforth and Ruddell*, 2016]. The embedded water in these resources carries important implications for food and water security [*Hoekstra and Chapagain*, 2008; *Porkka et al*., 2013]. These embedded water resources in food sources provide a means to assess the water exports and imports of water stressed locations, creating opportunities for globalized redistribution of water resources. Previous work has compared countries or regions within global virtual water trade [*Mekonnen and Hoekstra*, 2011; *Hoekstra and Mekonnen*, 2012], analyzed the network properties of virtual water trade [*Konar et al*., 2011; *Carr et al*., 2013; *Dalin et al*., 2012], and quantified urban reliance on aquifers [*Marston et al*., 2015]; however, only a few studies have discussed water footprints at an urban scale [*Vanham and Bidoglio*, 2014; *Rushforth and Ruddell*, 2016; *Vanham et al*., 2016a, 2016b]. The remainder of the indirect water footprint comes from water-for-energy demands associated with electric power generation or natural gas extraction [*Solley et al*., 1998; *Stillwell et al*., 2011a; *Macknick et al*., 2012; *Maupin et al*., 2014; *Sanders*, 2014; *DeNooyer et al*., 2016; *King and Webber*, 2008; *Twomey et al*., 2010; *Grubert et al*., 2012; *Mauter et al*., 2014]. Recent work has expanded the energy-for-water literature to quantify water consumed for hydroelectric power generation [*Mekonnen and Hoekstra*, 2012; *Destouni et al*., 2013; *Jaramillo and Destouni*, 2015a, 2015b; *Grubert*, 2016]. Studying cities as a unique ecosystem, as opposed to studies at a national or subnational scale, reflects the population at a greater resolution [*Otto-Zimmermann*, 2012]. Previous studies have not examined the embedded energy or emissions as part of the urban water footprint, nor have they comprehensively analyzed all of the cities within a country. Our study fills this knowledge gap for both direct and indirect water flows entering the urban environment using the highest resolution data available to capture this spatial scale of the food-energy-water nexus.

Both direct and indirect water require some amount of energy to either directly treat water and wastewater or transport goods from their origin to the urban environment. The energy required for water footprints is an important component of the energy-water nexus and the urban water cycle. Previous research quantified energy consumption in the water sector at regional and national scales [*Stillwell et al*., 2011b; *Sanders and Webber*, 2012; *Siddiqi and de Weck*, 2013; *Bartos and Chester*, 2014], with one study estimating that direct water services (including drinking water supply, water heating, wastewater treatment, and steam services) represent an estimated 12% of the United States' primary energy consumption [*Sanders and Webber*, 2012]. Both the consumed water and its embedded energy provide important topics of discussion when comparing water footprints of urban environments. Taking the analysis one step further, the carbon emissions associated with embedded energy provide an extra layer of information about the energy-water nexus and the urban water cycle.

In this study, we offer estimates of indirect water footprints for all urban areas in the United States for the first time. Then, we determine the total water footprint of cities for urban areas with direct water utility data. This combination enables us to provide a novel comparison between the direct and indirect water footprints of cities and discuss many of the critical points of water footprinting for the food-energy-water nexus described in *Vanham* [2016]. The geographical analysis and visualization of data provide a unique opportunity for spatially evaluating variation in the urban water footprint across different cities within the United States. We first discuss methods to obtain direct and indirect water footprints in an urban environment. Then, we present our results on urban water footprints. Next, we describe the implications of the study. Quantifying and comparing water footprints of cities from both the direct and virtual water perspective provide important insights into sustainable water resources management.

2. Methods

Prior to discussing methodologies associated with computation of water footprints, it is important to declare geographical system boundaries and the methodological scope. In this study, we consider the water footprint of the city. For the purposes of this study, we define our consumptive direct water boundary as water that leaves a drinking water treatment plant and enters the public water supply. We consider this use of water as consumption as wastewater discharges often occur downstream of the drinking water intake for

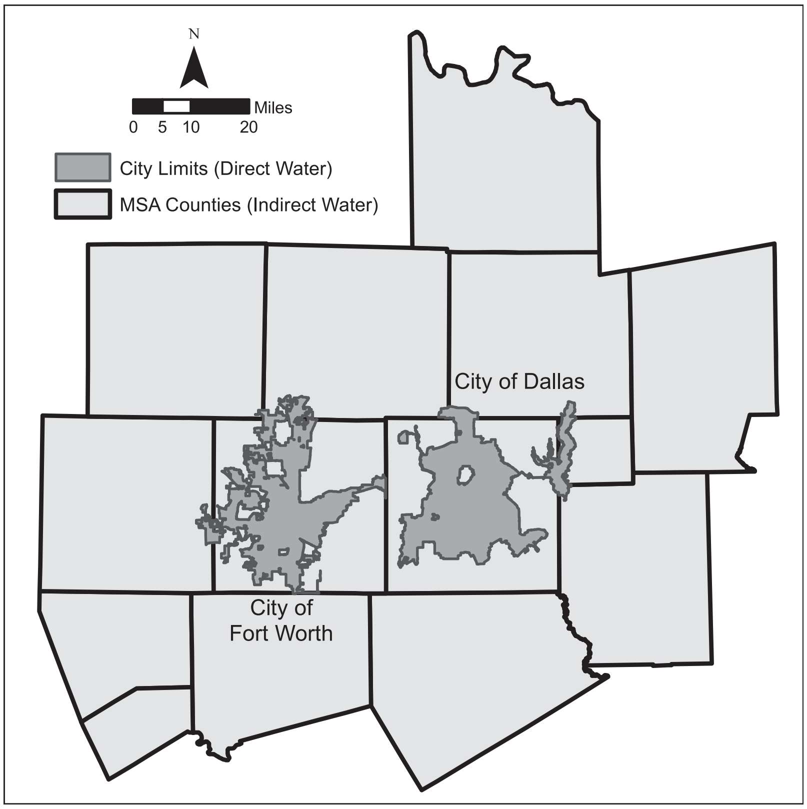

Figure 1. Example of differences in utility boundaries and metropolitan statistical areas (MSAs) for the City of Fort Worth and the City of Dallas (Texas). Note that city limits are used to obtain direct water footprints and the MSAs are used to estimate indirect water footprints. Due to discrepancies in these spatial domains, each footprint is normalized by the population of each geographical unit to facilitate comparison.

cities. The water is, therefore, removed from its original source without full replacement at the same location from the individual city perspective. We use the term "consumption" to retain language consistency between direct and indirect water footprints, especially regarding water consumption for electricity. Furthermore, this definition provides an upper bound estimate of the direct water footprint of cities. Direct water system boundaries are the service boundaries of the primary water utility provider of the municipality. Indirect water system boundaries, however, correspond to the metropolitan statistical areas (MSAs) of the U.S. Census Bureau. These discrepancies in system boundaries are unavoidable and, therefore, require mediation to make appropriate comparisons between the direct and indirect water footprints (see Figure 1). We normalize both direct and indirect water footprints by their respective service populations. For MSAs that extend across multiple states, we only consider counties in which the main city's state is located to remain closer to the boundary of utility districts. The Commodity Flow Survey [United States Census Bureau (USCB), 2012a] is the limiting factor in our work due to its pentannual publication, limiting our study to the year 2012 as a representation of recent conditions. For embedded resources accounting, we consider energy for water and emissions associated with energy. We provide a holistic framework for understanding system interdependencies, reserving detailed life-cycle assessment for smaller scale studies. Figure 2 provides an overall methodological depiction of the scope of the urban water footprint.

2.1. Direct Water Footprints

We assume that direct water in urban environments originates from water utilities with minimal contributions from other potential sources of water consumption such as rainwater capture or private well water, due to accessibility. Annual pumping and treatment data from open records requests for water utilities provide the necessary accounting for direct water. These records requests represent MSAs as defined by the U.S. Census Bureau and ask for both water volume and energy data for the treatment and distribution of potable water (see supporting information for a template records request sent to utilities). MSAs such as

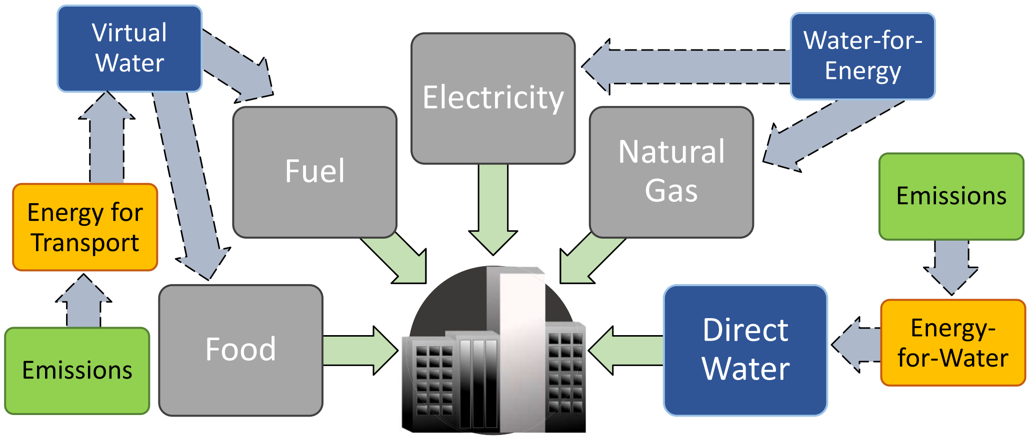

Figure 2. Schematic of water and energy resources used to quantify the total water footprint of urban areas in this study. Green arrows with solid outlines represent direct inputs to the city, and blue arrows with dashed outlines represent embedded resources. Importation of food and fuel resources leads to indirect water consumption through virtual water, while electricity and natural gas consumption require water-for-energy.

San Jose-San Francisco-Oakland or Dallas-Fort Worth received multiple requests for each of the municipalities' major drinking water distributors. The open records requests asked for data at the daily time scale with monthly data as a secondary option. For the purposes of this study, however, only annual data were necessary. Therefore, we aggregate the daily or monthly data into annual values. We then normalize the aggregated annual water consumption by provided service population.

We aggregated energy data from the open records requests to an annual total, converted electricity and natural gas consumption to equivalent killowatt-hours (kWh) of consumption, and normalized based on 10^6 U.S. gallons (Mgal) of water treated. Supporting information contains sample calculations and conversions to international units. Energy data correspond to the energy required for water extraction, purification, and pumping, where available. For the purposes of this study, we limit emissions calculations for drinking water treatment to the embedded energy within drinking water. The purpose of this study is not to perform a full life-cycle assessment on drinking water production and distribution, but to provide a framework for future high-level evaluations of the urban water cycle. Literature quantifying emissions from drinking water production and distribution varies widely depending on the type of treatment system and the quality of raw water [*Loubet et al*., 2014], with one paper estimating that energy demands account for only 33% of total emissions from treatment processes with the remainder from chemicals in the treatment process [*Bonton et al*., 2012]. We estimate energy emissions based on state level emissions data for electricity and natural gas from the Energy Information Administration [*United States Energy Information Administration*, 2012a]. Therefore, we expect our estimation of emissions for drinking water production and distribution to be highly conservative. This assumption, however, corresponds with the boundary scope of the indirect virtual water emissions that only considers emissions from transporting goods (discussed in the following section).

2.2. Indirect Water Footprints

Indirect water consists of two distinct components: virtual water and water-for-energy. The calculation of these indirect water footprints of the urban environment relies upon the combination of empirical data sets. Virtual water requires the Commodity Flow Survey and other data sets, while the water-for-energy calculation relies upon the Energy Information Adminstration's database. The Commodity Flow Survey is a collaboration between the Bureau of Transportation Statistics and the Census Bureau to provide information about the movement of commodities within the United States [USCB, 2012a]. The survey tabulates commodity transfers by origin, destination, value, weight, and mode of transportation. This pentannual survey groups transfers based on the Standard Classification of Transported Goods (SCTG) for food, fuel, manufacturing, electronics, and other goods. Table 1 shows the groups in the Commodity Flow Survey for food and fuel. These data, in conjunction with the methodology employed in *Dang et al*. [2015], provide the foundation for estimating indirect water footprints of cities. However, *Dang et al*. [2015] only included 5 of the 7 food commodity groups within the Commodity Flow Survey, excluding "agricultural products" and

Table 1. The Commodity Flow Survey Provides Information About Transfers of Goods Using the Standard Classification of Transported Goods (SCTG) Including Food and Fuel Commodities [United States Department of Transportation, 2012]

SCTG	Full Commodity Group Name
1	Animals and fish[a]
2	Cereal grains (including seed)[a]
3	Agricultural products[b]
4	Animal feed, eggs, honey, and other products of animal origin[a]
5	Meat, poultry, fish seafood, and their preparations[a]
6	Milled grain products and preparations, and bakery products[a]
7	Other prepared foodstuffs, fats, and oils[b]
15	Coal[c]
16	Crude petroleum[c]
17	Gasoline, aviation turbine fuel, and ethanol[c]
18	Fuel oils[c]
19	Other coal and petroleum products not elsewhere classified[d]

[a]"Staple" food commodity groups as defined in *Dang et al.* [2015].
[b]Additional food commodity groups not included in *Dang et al.* [2015].
[c]Fuel commodity groups included.
[d]Fuel commodity group not included.

"other prepared foodstuffs" (SCTG commodity groups 3 and 7). We expand this methodology by accounting for the remaining two food commodity groups and fuel commodity groups (SCTG commodity groups 15–18, refer to Table 1). SCTG commodity group 19 ("other coal and petroleum products") is not included due to ambiguity in assigning a virtual water content (VWC) to the products. VWC equals the crop evapotranspiration per crop yield [*Hanasaki et al.*, 2010], equivalent to the water footprint of each food commodity [*Hoekstra and Chapagain*, 2008]. Supporting information includes the VWC for each commodity group in Mgal/ton; generally, VWC for food commodity groups varies by state of origin, but VWC is on the national or regional scale for fuel products.

For these 11 commodity groups, we determine the VWC of each commodity group based on state of origin using the methodology in *Dang et al*. [2015]. This methodology assumes that the VWC of each commodity group is equal to a weighted average of individual quantities produced by the respective state. For SCTG commodity groups 1–5 and 7, we calculate the VWC based on food production amounts in each state from the United States Department of Agriculture's Census of Agriculture [2012]. We couple the agricultural census data with the individual food items' VWC described in various databases [*Mekonnen and Hoekstra*, 2011; *Mubako and Lant*, 2013; *Mubako*, 2011]. When possible, we utilize state specific values for virtual water and substitute a national average when not available. Equation (1) describes the calculation of VWC of each commodity group, adapted from *Dang et al*. [2015]

$$VWC_{c,s}=\frac{\sum_{i\epsilon c}^{I}[(\text{Green}VWC_{i,s}+\text{Blue}VWC_{i,s})*\text{Production}_s]}{\sum_{i\epsilon c}^{I}\text{Production}_s} \quad (1)$$

where c indicates commodity group, i indicates item, I indicates number of items within c, $i\epsilon c$ indicates items contained in commodity group c, and s indicates state of production. For the virtual water footprint of cities, we include both the green and blue virtual water content values. Supporting information shows the various individual agricultural items included in each commodity group. The VWC for SCTG commodity group 6 ("milled grain products") is directly from *Dang et al*. [2015] without update.

The second component of indirect water is water-for-energy. In addition to the fuel sources identified in the Commodity Flow Survey, Table 1, we include electricity and natural gas. Various literature sources provide the embedded water resources required for extraction, processing, and refining of fuel commodity groups. *Mielke et al*. [2010] estimates the water consumption of coal to be 6 gallons per MMBtu. Generalizing for 19.5 MMBtu per short ton of coal in the year 2012 [United States Department of Energy: Energy Information Administration, 2015], this conversion equates to a value of 117 gallons per ton of coal. A study by Argonne National Laboratory [*Wu et al*., 2009] estimates water intensities of crude oil and gasoline by region, with a United States average of 4.8 gal/gal of crude and 4.6 gal/gal of gasoline, equivalent to 1100 gal/ton and 7200 gal/ton, respectively. We assume that fuel oils have similar water intensities as crude petroleum.

The electricity and natural gas consumption of an urban population is difficult to estimate as electricity grids and gas distributors do not align with political jurisdictions. The smallest unit that the Energy Information Administration (EIA) estimates is at the state level. Therefore, we assume that per person averages for electricity consumption and the water consumed for electric power generation at a state level adequately represent the embedded water in electricity consumed at the urban level, as a first estimate. EIA Form 923 provides electricity generation and water consumption on a production plant level [United States Department of Energy: Energy Information Administration (EIA), 2012b]. Since water consumption for hydroelectric

Table 2. Truck Freight Traffic Requires the Greatest Energy Intensity per Ton-Mile [*Davis et al*., 2013], and the Combined Truck and Air Traffic has the Greatest Global Warming Potential

Mode of Travel	Energy Intensity Btu/ton-mile	Global Warming Potential kg CO_{2e}/ton-mile
Truck freight[a]	3711	0.1983
Train freight	294	0.0783
Barge freight	210	0.0760
Combined air and truck[b]	2003	0.9224

[a]Assumes a standard truck weight of 5.8 tons.
[b]Averages air and truck energy and emissions intensities per ton-mile.

power is reported as zero in the EIA database, we use the assembled regional values for gross water consumption through evaporation for hydropower generation in *Grubert* [2016]. Similarly, we normalized natural gas consumption on a per person level based on state level estimates from United States Department of Energy: Energy Information Administration (EIA) [2012c], with embedded water estimated at 3 gallons per MMBtu [*Grubert et al*., 2012].

The embedded energy in indirect water provides a metric to determine the geographic extent of the water footprint of a city. There are two components to embedded energy: (i) energy for virtual water and (ii) energy for water-for-energy. The embedded energy in the water-for-energy component comes from pumping cooling water at thermoelectric plants or flowback from natural gas extraction, with these values negligible and highly variable, respectively. Therefore, we only consider the embedded energy of the virtual water component (refer to Figure 2). For this study, we draw our control volume around the transportation of finished goods for the embedded energy calculation. The Commodity Flow Survey provides commodity information based on transportation type and ton-miles [USCB, 2012a]. The Center for Transportation Analysis [*Davis et al*., 2013] provides annual estimates of energy (Btu) per ton-mile equivalents for the various modes of travel for the year 2012; conversions to international units are provided in supporting information.

The modes of travel can be further used to determine the emissions of the commodities flowing into the urban system. The EcoInvent database (v3.1) implemented in SimaPro (v8.0.4; PRé Consultants; The Netherlands) provided climate change characterization factors for each mode of travel in equivalent kilograms of CO_2 per ton-mile. Characterization factors for climate change are available through the U.S. Environmental Protection Agency's (EPA) Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) [United States Environmental Protection Agency, 2016]. Table 2 presents values of Btu per ton-mile and global warming potential for each mode of travel.

3. Results and Discussion

We obtained data for direct water footprints, representing a population of approximately 47.2 million people, while our estimates of indirect water footprints account for 197.2 million people, or 15.0% and 62.8% of the 2012 population of the United States, respectively [United States Census Bureau, 2012b]. The large difference in service population is due to the inclusion of suburbs within the metropolitan statistical area for indirect water that often have separate water systems from the main city (refer to Figure 1). Additionally, there is a disparity in the number of cities represented by direct water data versus indirect water data (33 versus 74). Table 3 provides the mean, standard deviation, minimum, and maximum values for direct, indirect, and total urban water footprints.

3.1. Direct Urban Water Footprints

Direct water footprints and their embedded energy vary widely with respect to geography; see Figure 3. We present embedded energy for direct water in terms of kWh as opposed to indirect water's embedded

Table 3. Urban Water Footprints are Dominated by Indirect Water; the Population Weighted Average μ_{pop} is Lower Than the Strict Average (μ), Indicating a Lower Per Capita Consumption in Cities with a Larger Population

Urban Water Footprint	n	Water Footprint (Mgal/person/yr) μ_{pop}	μ	σ	V_{min}	V_{max}
Indirect water footprint	74	1.34	1.58	2.27	0.09 (Mobile, AL)	16.83 (New Orleans, LA)
Food virtual water	74	1.17	1.36	2.25	0.05 (Charleston, SC)	16.80 (New Orleans, LA)
Fuel virtual water	74	0.16	0.21	0.34	<0.01 (Newark, NJ)	2.46 (Tulsa, OK)
Direct water footprint	33	0.058	0.059	0.022	0.030 (Boston, MA)	0.138 (New Orleans, LA)
Total water footprint	33	1.64	1.82	2.84	0.38 (Baltimore, MD)	16.97 (New Orleans, LA)

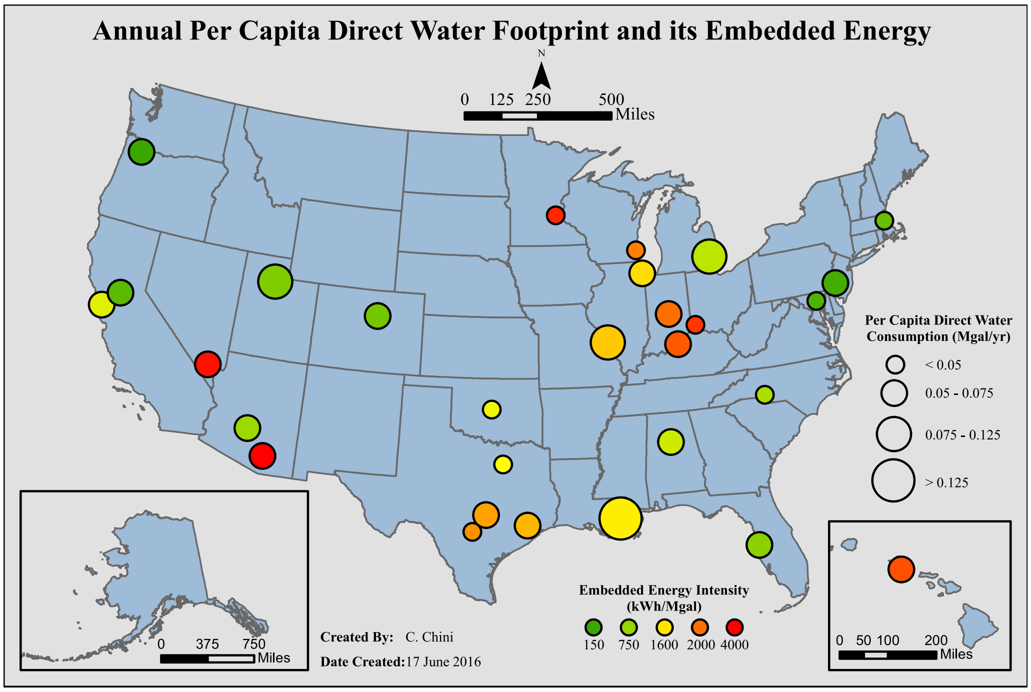

Figure 3. Map of per capita direct water footprints for urban areas of the United States. Note that the size of the circle indicates the volume of the annual per capita direct water footprint (ranging from <0.05 to >0.125 Mgal) and the color of the circle indicates the embedded energy intensity (ranging from 150 to 4000 kWh/Mgal). Direct water footprint information is restricted to 29 urban areas with both direct water footprint volume and energy information available.

energy in MMBtu. Only 29 of the 74 MSAs studied returned drinking water volume and energy through open records requests. Of these 29 cities, the population-weighted average (μ_{pop}) direct water footprint is 58,200 gallons (0.058 Mgal) per person per year, equivalent to 162 gallons per day (see Table 3). However, the direct water footprint is highly variable, ranging from 29,700 to 137,880 gallons per year (0.030 to 0.138 Mgal/yr), equating to a range of 81–378 gallons per day for the cities of Boston and New Orleans, respectively. The center of the country from Texas through Chicago tends toward higher energy intensities with lower embedded energies along the coasts. This trend has two notable exceptions of Las Vegas, NV, and Tucson, AZ, with very large embedded energies (4000 and 4700 kWh/Mgal, respectively). In contrast, the average embedded energy for the reporting cities across the country is 1425 kWh/Mgal, with a standard deviation of 1091 kWh/Mgal. Additionally, the associated emissions for embedded energy in direct water are 800 kg CO_{2e}/Mgal with a standard deviation of 625 kg CO_{2e}/Mgal. The spatial variability of the emissions are shown in supporting information. The identified trend in the direct water footprint and its embedded energy would benefit from an expanded sample size. There are opportunities for future work to expand on the study of embedded energy within direct water footprints to further explain variation and identify trends.

3.2. Indirect Urban Water Footprints

Indirect urban water footprints have water resources originating from outside the area of the city, unlike the predominantly local direct water footprints. Therefore, there are further opportunities for analysis including network and spatial variability. Figure 4 shows the per capita indirect water consumption and its embedded energy. New Orleans, LA, and Savannah, GA, both have large per capita indirect water footprints (16.8 and 10.2 Mgal/yr, respectively), much greater than the population-weighted average (μ_{pop}) indirect water footprint of 1.33 Mgal/yr (see Table 3). These are both port cities with relatively smaller populations than other port cities, such as Boston, New York, Seattle, or Los Angeles, leading to higher, per capita virtual water inflows. Additionally, relatively large indirect water footprints occur in the states of Texas and Oklahoma and in Omaha, NE, indicating inflows of goods with higher virtual water contents (i.e., meat products). Interestingly, there is some significant clustering of embedded energy within regions. The southeastern United States tends toward a greater embedded energy within indirect water resources. Additionally, the

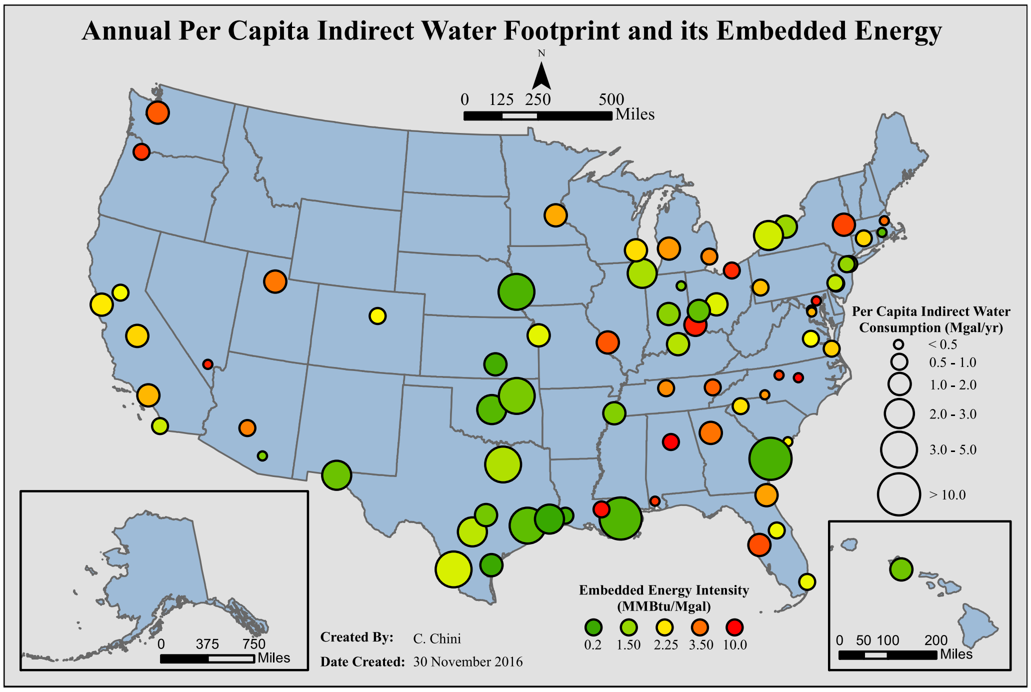

Figure 4. Map of per capita indirect water footprints for urban areas of the United States. Note that the size of the circle indicates the volume of the annual per capita indirect water footprint (ranging from <0.5 Mgal to >10 Mgal) and the color of the circle indicates the embedded energy intensity (ranging from 0.2 to 10.0 MMBtu/Mgal). Cites in the center of the United States tend to exhibit a higher indirect water footprint. Indirect water footprints are comprehensively quantified for all 74 metropolitan statistical areas of the United States.

corridor from Nebraska through Texas shows a lower than average embedded energy. This finding is due to a lower travel distance for food and fuel as well as lower intensity modes of travel through the corridor, such as trains. Nationally, embedded energy within indirect water footprints has high variability ($\mu = 2.95$ and $\sigma = 2.24$ MMBtu/Mgal). Variability in emissions of the indirect water footprint are similar to the embedded energy. The average embedded emissions from transport of goods for each unit of indirect water is 360 kg CO_{2e}/Mgal with a standard deviation of 450 kg CO_{2e}/Mgal. Supporting information includes a figure showing the spatial variability of emissions associated with the indirect water footprint of cities. Additionally, supporting information provides the indirect water footprints for all urban areas of the United States.

As previously stated, the composition of indirect water has four components: (i) food, (ii) fuel (virtual water footprints), (iii) electricity, and (iv) natural gas. Virtual water dominates the composition of the indirect water footprint of cities, which makes sense, as we only consider water consumption and not withdrawals. The food virtual water footprint constitutes 87.6% of the total indirect water footprint and that of fuel constitutes an additional 11.9% (see Table 3). The water-for-energy required for natural gas and electricity comprises, on average, less than 0.5% of the overall indirect water footprint. The water-for-electricity consumption is heavily dominated by hydroelectricity demands. In states with high evaporation rates and large contributions of hydroelectricity to the energy portfolio, such as those in the Southwest or Southeast United States, the water consumed for hydroelectricity increases. However, the contribution of hydroelectricity to the grid is less than 7% for the United States, yielding high variability of the water-for-electricity footprint. The cities of Mobile, AL, Las Vegas, NV, Tucson, AZ, and Greensboro, NC, had much greater contributions to indirect water footprints from water-for-electricity than the average at 22.2%, 11.5%, 7.8%, and 6.1%, respectively. Many of the other cities in the study have contributions of less than 1%. Using data from the EIA and *Grubert* [2016], we calculated the average, by state, embedded water in electricity to be 940 gallons per MWh. While this value only considers electricity generation and not heat generation, it is less than 25% of the global water footprint value of 4100 gal/MWh determined for net electricity and heat generation by *Mekonnen et al*. [2016]. The population-weighted averages of the food, fuel, and overall indirect water footprint are lower than that of the strict average of all cities. This trend indicates that MSAs with larger populations have lower per capita indirect water footprints.

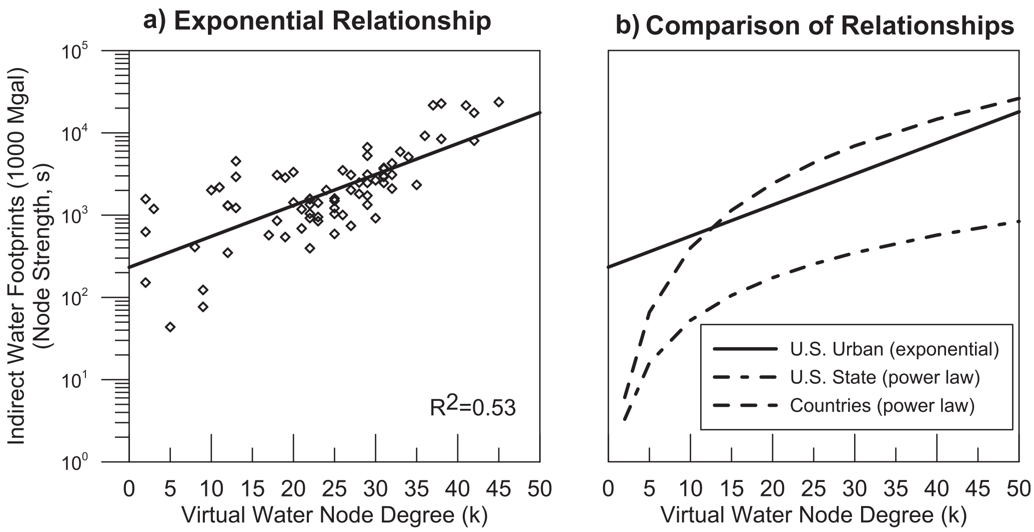

Figure 5. The relationship between node strength and node degree for virtual water of cities departs from the power law relationships previously presented in the literature [e.g., *Dang et al*., 2015; *Konar et al*., 2011]. Instead, the relationship between node strength and node degree for urban areas is best represented by an exponential distribution.

We employ network analysis to compare the node strength and node degree of the indirect water footprint for each of the 74 cities (see Figure 5). Previous virtual water studies identify a power law relationship between node strength and node degree for U.S. states [*Dang et al*., 2015] and countries [*Konar et al*., 2011]. These studies found the exponent for the U.S. states (1.72) to be smaller than the global network exponent (2.6). Our study is at a finer urban spatial resolution, and the exponent for the best-fit power law is further reduced (1.05). However, as this power law fit is nearly linear, we determine an exponential distribution to be the best approximation of the relationship between urban node degree and strength (see relationship on semilog plot in Figure 5a). Therefore, the trend of a decreasing exponent with geographically smaller nodes continues, leading the power law relationship to break down and yield an exponential fit (equation (2))

$$s=231.97 * e^{0.087k} \tag{2}$$

Figure 5b compares the functional relationships between node degree and node strength for U.S. cities, U.S. states, and countries. The exponential relationship for cities indicates that they are more efficient at obtaining virtual water resources with fewer commodity exchange partnerships (note that the exponential function produces higher node strength, *s*, values for values of node degree, *k*, less than 10 in Figure 5b). However, fewer exchange partnerships might leave urban areas more vulnerable to disruptions to their supply chains. This analysis highlights the need for further research to evaluate trade-offs between network efficiency and vulnerability, as well as the scaling properties of commodity and virtual water exchanges.

3.3. Total Urban Water Footprints

The total urban water footprint is the sum of the direct and indirect water footprints. Figure 6 shows the contributions of the indirect and direct water footprints to a city's total footprint and the values, in Mgal/yr, of the total urban water footprint. On average, the indirect water is 20 times that of direct water (see Table 3). The per capita contributions for both direct and indirect water do not sum to the total water footprint due to the differences in sample sizes. Utilizing the water footprints and associated embedded energies, we estimate that urban residents within the United States, on average, consume 1.64 million gallons of water per year, nearly 4500 gallons per person per day. The total urban water footprint provides a benchmark for urban or regional authorities to create sustainability goals and lower their total water footprint. We anticipate regional variation in policy with respect to water footprint objectives. For example, cities in water-rich environments might focus on lowering indirect water footprints and water-strained cities might focus on direct water. Supporting information provides a ranking of the top five urban areas with largest and smallest water footprint. To consume this volume of water, the required annual energy consumption is approximately 5 MMBtu per person of primary energy for transportation and 80 kWh per person of electrical

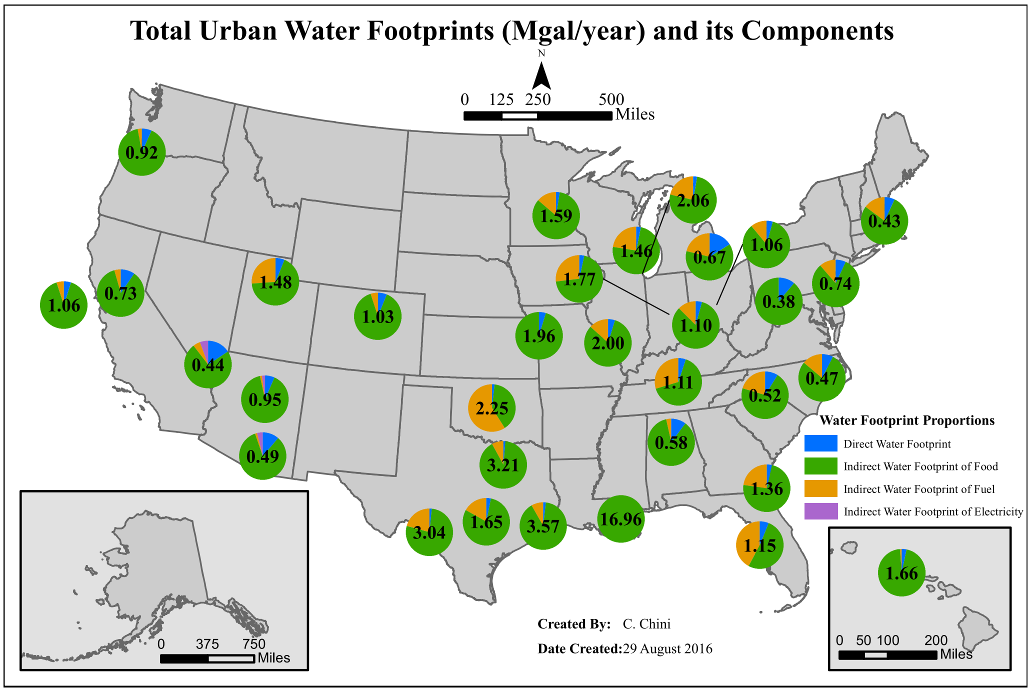

Figure 6. Map of total urban water footprint and the contributions of direct and indirect water. Indirect water dominates the water footprint of a city, with food contributing to the bulk of the water footprint. The map is restricted to 33 cities for which direct water footprint volume data are available.

energy for water treatment and distribution. While this individual energy consumption is relatively small, these values scaled to a national scale, representing a U.S. urban population of over 250 million, are a significant energy investment. The results of the total urban water footprints illustrate the significant water and energy requirements to support urban environments within the United States.

4. Conclusions

When studying the urban water footprint, quantification of both the direct and indirect virtual water components is important when considering the food-energy-water nexus. Additionally, embedded resources and emissions provide an essential layer of evaluation and understanding for the overall urban water footprint. Our study, to our knowledge, is the first to comprehensively characterize the water footprint of all cities within the United States, enabling us to draw three major conclusions: (i) indirect water dominates the total flow of water into an urban environment, (ii) reductions in energy consumption can be realized in both the direct and indirect water footprints, and (iii) benchmarking of total water footprint might inform policy and management of the urban water cycle. These conclusions provide further direction for study of the urban water cycle and its embedded energy.

Indirect water, comprised of virtual water and water-for-energy, dominates the urban water cycle on a per capita basis. On average, indirect water is an order of magnitude greater than direct water consumption. Additionally, virtual water imports associated with food and fuel dominate the indirect water footprint over the water-for-energy component of indirect water. Understanding indirect water and its sourcing is essential for detecting vulnerabilities in the urban water supply [*Suweis and D'Odorico*, 2014; *Rushforth and Ruddell*, 2016]. The results of our comprehensive study further support the need for indirect water calculations to be included in urban water accounting and policy considerations.

Our analysis provides important insights into the food-energy-water nexus at the urban scale, creating opportunities for understanding water and energy savings and efficiency. To promote policy and management of the urban water cycle and its embedded energy and emissions, an overall understanding of the intranational variations in the urban environment is necessary. The large-scale geographical comparisons of the urban water cycle presented in this analysis provide unique insights that evaluating a single city does not afford. By comprehensively analyzing many urban systems, we lay the foundation for future research to address questions of urban water resources sustainability. Evaluating multiple cities in a singular effort, with a unified methodology, enables benchmarking and other policy objectives to evaluate the urban water cycle and the urban food-energy-water nexus.

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