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Watersheds and Infrastructure Providing Food, Energy, and Water to US Cities

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Abstract Civil infrastructure underpins urban receipts of food, energy, and water (FEW) produced in distant watersheds. In this study, we map flows of FEW goods from watersheds of the contiguous United States to major population centers and highlight the critical infrastructure that supports FEW flows. To do this, we draw upon detailed records of agriculture, electricity, and public water supply production and couple them with commodity flow and infrastructure information. We also compare the flows of virtual water embedded in food and energy commodity flows with physical water flows in inter-basin water transfer projects around the country. We found that the virtual blue water transfers through crops and electricity to major US cities was 53 billion and 8 billion m^3 in 2017, respectively, while physical interbasin water transfers for crops, electricity, and public supply water averaged 20.8 billion m^3. Highways are the primary infrastructure used to import virtual water associated with food and fuel into cities, although waterways and railways are most utilized for long-distance transport. All of the 204 watersheds in the contiguous US support the food, energy, and/or water supplies of major US cities, with dependencies stretching far beyond each city's borders. Still, most cities source the majority of their FEW and embedded water resources from nearby watersheds. Infrastructure such as water supply dams and inland ports serve as important buffers for both local and supply-chain sourced water stress. These findings can inform efforts to reduce water resources and infrastructure risks in domestic supply chains.

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Key Points:

- Civil infrastructure enables US cities to access FEW resources from distant watersheds
- Most cities depend on nearby watersheds for FEW and embedded water
- Virtual water transfers through food and energy exceed physical water transfers

Supporting Information:

Supporting Information may be found in the online version of this article.

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1. Introduction

Cities rely on distant locations for supplies of natural resources and commodities, particularly primary goods (Seto et al., 2012). In particular, cities obtain most primary food products (and oftentimes secondary food products) from beyond their city limits (Lin et al., 2019; Rushforth & Ruddell, 2016). Similarly, the electricity consumption of cities also relies on electricity supplied from distant power plants distributed by the electricity grid (Siddik et al., 2020). Water is a critical input to both food and energy production (e.g., the Food-Energy-Water (FEW) nexus) (D'Odorico et al., 2018; Vora et al., 2017), which means that cities are linked to the distant watersheds—the physical organizing unit of hydrology and water resources—that support the production of FEW goods (Marston et al., 2015). In the United States, water supplies are projected to become more variable and scarcer under future climate and demand patterns (Brown et al., 2019). This makes it important to understand the source watersheds that support urban FEW supply chains, in order to determine exposure to water-related risks and hazards (Dolan et al., 2021). This paper determines the watersheds and civil engineering infrastructure that support urban FEW supply chains in the United States.

Information on water supply, demand, and stress is often collected and modeled at the watershed scale, as opposed to geopolitical units (e.g., county, state, city). Yet, cities and their economies are often examined along geopolitical boundaries. The spatial misalignment between information relating to critical water resources and the economic activity this resource supports hide potential risks and dependencies. Understanding urban receipts of FEW goods from watersheds will enable better tracking of their supply chain exposure to water stress. Quantifying the contribution of watersheds to urban FEW supply chains makes clear hidden dependencies and risks behind FEW production, distribution, and consumption. It is important to map out these hidden risks and dependencies to support infrastructure investment decisions to make cities more resilient to climate change and other water hazards.

Water is utilized for economic production within watersheds, which are the natural hydrological units essential for understanding the flow and storage of water. Water used to produce a product can be quantified and thought of as "virtual water" moving along with the trade or transport of the good (Allan, 1993, 1998; Konar et al., 2011;

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Marston et al., 2015). Accounting for these virtual water transfers helps us understand urban areas' reliance on watersheds. There is a large literature on virtual water flows, including within the United States (Konar and Marston, 2020), but most studies focus on flows between political units (e.g., Chini et al., 2017; Dang et al., 2015; Djehdian et al., 2019; Garcia et al., 2020; Gumidyala et al., 2020; Mahjabin et al., 2020; Rushforth and Ruddell, 2016), rather than watersheds. Human water consumption is often driven by nonlocal demands for goods and services fulfilled through virtual water transfers, and this water consumption has local hydrological impacts that can propagate downstream through the hydrologic system—the domain of hydrologic models. Tracing FEW virtual water flows from hydrological units to geopolitical units bridges the gap between water footprint accounting, with its focus on the water consumption of cities, states, and countries, and watershed hydrological modeling, which is primarily concerned with the fluxes and stores of water within and across watersheds (Konar et al., 2016).

This study examines the role of both water supply and infrastructure in the provisioning of virtual and physical water from watersheds to cities. We compare virtual water transfers with physical water transfers through inter-basin water transfer (IBT) infrastructure. Additionally, by pairing production and consumption locations with one another, we highlight critical infrastructure that supports urban FEW supplies. Accounting for water supply infrastructure, such as inter-basin canals and dams, has been shown to reduce estimates of water stress (Rising et al., 2022), particularly for cities (McDonald et al., 2014). We also bring together electrical grid and transportation infrastructure-level data to understand the various modes of transport that support FEW virtual water flows to cities. Highlighting the infrastructure that supports urban FEW supplies helps in the identification of infrastructure buffering and risks posed by infrastructure deterioration.

The goal of this study is to determine the contribution of watersheds to receipts of FEW by US cities enabled by civil infrastructure. We employ a quantitative analysis to compare indirect (virtual) water flows through supply chains and electrical grids with direct (physical) water transfers through infrastructure. We also quantify the contribution of transportation infrastructure via roadways, waterways, and rail to supply chains, as well as water resources infrastructure, including water supply dams, and inland ports. We ask and answer the following research questions: (a) Which US watersheds directly and indirectly support each US city? (b) How are US cities directly and indirectly exposed to water stress from their sourcing watersheds? (c) Where does infrastructure buffer against local and supply-chain sourced water stress? We present the data and methods employed to answer these questions in Section 2. We describe and discuss our findings in Section 3. In Section 4, we highlight our key findings, study limitations, and broader implications of our research.

2. Methods

2.1. System Boundaries and Data

We delineate our study boundary to encompass the anthropogenic transfers of FEW commodities to major cities within the contiguous United States (CONUS). We map the flows of all food products, fuels, electricity, and municipal water supplies from watersheds where they originate to the city where they are consumed or processed by urban residents or industry. When estimating virtual water flows, we limit our analysis to primary (i.e., unprocessed, raw) crop products to avoid double counting virtual water between primary and secondary crop and animal products. For example, we trace the shipment of feed crops from a watershed in central Nebraska to feedlots in Tulsa, Oklahoma but do not then connect the virtual water associated with the meat shipped from Tulsa to Houston back to the original feed production in central Nebraska. If we had done so, we would have significantly overstated the amount of water consumed in the central Nebraska watershed. This study focuses on how infrastructure, such as transportation networks, electricity grids, and interbasin water transfers, connect watersheds to cities. Therefore, we do not examine how upstream watersheds naturally deliver water to downstream watersheds that supply urban FEW consumption since these water flows are not dependent on civil infrastructure to move water between watersheds.

We define urban areas in accordance with the Freight Analysis Framework Version 5 (FAF5), which refer to these areas as urban FAF Zones. The non-urban FAF Zones (i.e., "remainder of state" FAF zones) are excluded from this study. We merge urban FAF Zones that stretch across multiple states, such as the Kansas City FAF Zones in both Kansas and Missouri (referred to as "urban FAF Zones" hereafter). Watersheds are defined using the United States Geological Survey's (USGS) Hydrologic Unit Codes (HUC) delineation. We track FEW flows from HUC4 subregions (henceforth, simply watershed), though we present some of our results at the coarser HUC2 region for

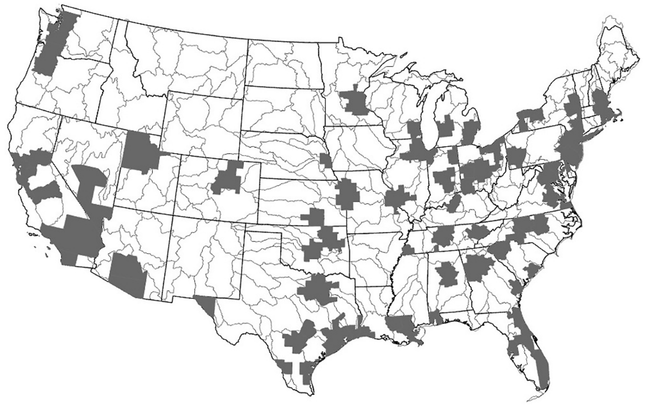

Figure 1. Boundaries of cities (urban FAF Zones; gray fill) and watersheds (HUC4; no fill) assessed in this study.

clarity. City and HUC4 watershed boundaries analyzed in this study are depicted in Figure 1. We focus on the year 2017 because that is the most recent year most datasets required for the study are available. Hydrologic, trade flow, infrastructure, FEW production, and other data used in this study are detailed in Table 1.

The main database of food and energy commodity flows is FAF5 (Oak Ridge National Laboratory, 2021), which groups and tracks different commodities in accordance with the Standard Classification of Transported Goods (SCTG). Food flows (SCTG 1–7) and energy flows (SCTG 17–18) are traced from one FAF Zone to another. The mode of transportation (i.e., truck, rail, water, air, pipeline, multimodal) used for each commodity transfer is recorded. We use this data to assess dependencies on different transportation infrastructure by commodity type. Further, we paired FAF5 data detailing commodity transfers by transport mode with spatially detailed road, rail, pipeline, and waterway/port infrastructure data (see Table 1). Pairing of these data enables us to better assess FEW dependencies on different types of infrastructure. Average national transport distances reported in this study follow the actual transport path when known; otherwise, flow lengths represent the centroid of the production watershed to the centroid of the city where FEW is consumed. Average transport distances are weighted by the amount of the goods transferred along each path.

2.2. FEW and Virtual Water Sent From Watersheds to Cities

2.2.1. Food and Associated Virtual Water Flows

We used county-to-county crop commodity flows for the year 2017 from Lin et al. (2019). Lin et al. (2019) spatially downscaled FAF commodity flows between 132 FAF Zones, which represent either major metropolitan areas or "remainder of state" (i.e., less developed areas not included within city boundaries), to the 3,143 counties in the US. There are seven SCTG categories that track the flow of agricultural and food goods assessed in this study: 01 Animals and Fish (live); 02 Cereal Grains; 03 Agricultural Products Except for Animal Feed, Cereal Grains, and Forage Products; 04 Animal Feed, Eggs, Honey, and Other Products of Animal Origin; 05 Meat, Poultry, Fish, Seafood, and Their Preparations; 06 Milled Grain Products and Preparations, and Bakery Products; and 07 Other Prepared Foodstuffs, Fats and Oils. While we assess infrastructure dependencies and flows of all agri-food products (SCTG 1–7), we only estimate the virtual water flows associated with minimally processed crops (SCTG 2–4) to account for the largest water consumers (Mekonnen & Hoekstra, 2011) and to avoid double counting of embedded water. For example, wheat (SCTG 2) is used to produce frozen pizza (SCTG 6), so tracing the virtual water flows of both products would double count the water footprint of wheat. Not accounting for water used in food manufacturing and livestock production means that our virtual water transfers likely understate the volume of the food sector's blue water used in and transferred from watersheds.

We used sub-county, sub-watershed data from Ao et al. (2023b) and described by Ao et al. (2023a) to resolve the mismatch between the county boundaries used for commodity production/flows and watershed boundaries. Briefly, we used high-resolution (30–250 m grid cells) crop area (USDA, 2021) and irrigation data (Pervez & Brown, 2010) to downscale crop production and flow data to sub-county, sub-watershed pairings. Areas where a county and watershed overlapped created a new, smaller geographic unit used for analysis. In total, there were 5,692 unique sub-county, sub-watershed pairings that connect county crop production and flow data to individual watersheds. These sub-county, sub-watershed units could be easily aggregated back to either the county or watershed level, as well as FAF Zones.

The crop-specific blue (surface and groundwater) and green water (rainwater) footprint were quantified within each sub-county, sub-watershed pairing. Blue water footprints were further partitioned into surface water and groundwater footprints. While we calculated green water footprints, our results focus on blue water footprints and virtual water flows given watersheds' role in aggregating and provisioning blue water to cities. We used existing calculations from Ao et al. (2023b), as described by Ao et al. (2023a), to estimate the water footprint of agricultural production and flows. Crop-specific water footprints and virtual water transfers were aggregated to their corresponding SCTG category. Here, we assume the composition of commodity flows reflects production

Table 1
List of Data Sets Used in This Study

Variable	Source	Description of data relevant to this study
Study boundaries		
City boundaries	Oak Ridge National Laboratory, 2021 [.shp]	The boundaries of US cities (i.e., urban FAF Zones), which are composed of counties and county equivalents and align with metropolitan statistical areas as defined by the US Office of Management and Budget
Watershed boundaries	U.S. Geological Survey, 2022 [.pdf] National Hydrography, 2022 [.shp]	US watershed boundaries by hydrologic unit code (HUC); 4-digit HUC (HUC4) and the coarser 2-digit HUC (HUC2) are the focus of this study
Food and associated virtual water flows		
Food flows	Lin et al., 2019 [.csv]	Downscaled FAF4 food flows (weight) in 2017 between US counties
Water footprint of crop products	Ao et al., 2023a, Ao et al., 2023b [.xlsx]	Sub-county water footprint coefficient for crop products by Standard Classification of Transported Goods (SCTG 2–4) for 2017
Electricity and associated virtual water flows		
Electricity water footprint coefficient	Siddik et al., 2020 [.xlsx]	Amount of water required to produce a megawatt-hour of electricity within a HUC4
Electricity consumption	Siddik et al., 2020 [.xlsx] EIA, 2022 [.xlsx] EIA, 2023a [.xlsx] EIA, 2023b [.xlsx]	Electricity production by HUC4 in 2017 State-level electricity consumption in 2017
Gross domestic product (GDP)	BEA, 2022 [.csv]	County GDP in 2017
Public water supplies		
Water service area boundaries (WSAs)	Buchwald et al., 2022 [.shp]	Public water supply system service area boundaries during 2010–2020
Public water system (PWS)	EPA, 2020a, 2020b [.xlsx]	Connections between public water supply system population served and the water source/intake watershed (as of 2019)
Infrastructure		
Food and energy flows	Oak Ridge National Laboratory, 2021 [.csv]	Flows of food products (SCTG 1–7) and fuel products (SCTG 17–18) into urban Freight Analysis Framework Version 5 (FAF) Zones in 2017 in terms of weight, weight-distance, and transport mode
Interbasin water transfers (IBT)	Siddik et al., 2023 [.xlsx] and [.shp]	Untreated water transfers across HUC4 boundaries that support FEW production. Infrastructure details, as well as flow rate values for some transfers, available for 2017
Commercially navigable waterways	USDOT, 2019 [.shp]	Commercially navigable waterways used for food and energy transport
Water supply dams and navigation dams	U.S. Army Corps of Engineers, 2022 [.xlsx]	Locks and dams used for water supply, hydropower, and commercial navigation
Highway network	USDOT FHA, 2023 [.shp]	Network of major highways used to ship food and energy goods
Railroad network	USDOT, 2021 [.shp]	Railroad network used to ship food and energy goods
Principal ports	USDOT BTS, 2023 [.shp]	Principal sea and inland port locations

patterns. For example, if a county/watershed produced 60 units of corn and 40 units of wheat (both belong to SCTG 2), then the composition of trade flows of SCTG 2 from the county/watershed is also 60/40 corn/wheat.

2.2.2. Energy and Associated Virtual Water Flows

We employ the methodology developed by Siddik et al. (2020) to determine city-level electricity flows and their associated virtual water. For every FAF zone, we identified the balancing authority responsible for providing electricity by analyzing the geographical positions of these entities. Utilizing datasets from Energy Information Administration (EIA), such as EIA 923 and EIA 930, we obtained details on power plants that supply electricity to each balancing authority, including the precise location of each plant and their water usage. Leveraging these data, we linked each FAF zone to the watersheds, as well as the power plants and their associated water consumption, that supply them with electricity and virtual water. We improved on the work of Siddik et al. by using more spatially and temporally refined data related to electricity exchanges from the grid monitoring system of the US Energy Information Administration (EIA; EIA 2022). The EIA's grid monitoring system provides hourly generation and electricity mix data by fuel type for each balancing authority, enabling us to identify the power plants supplying electricity to each FAF Zone. By incorporating electricity exchange data between balancing authorities with power plant location and operational details (EIA, 2023a), we have improved the estimate of electricity embedded water consumption intensity (m^3/MWh) and virtual water source of the FAF Zones.

Drawing from the insights of Chen and Wemhoff (2021), there's a distinct proportionality observed between a geographical area's electricity consumption and its GDP. Acknowledging this relationship, we have integrated county-specific GDP data (BEA, 2022) to disaggregate the state electricity utilization (EIA, 2023b) to each FAF Zone. By multiplying the FAF Zone-specific electricity consumption, power plant-specific electricity generation, and electricity transfers between balancing authorities with the corresponding electricity embedded water intensity factors, we derived the virtual water flows and the volumetric dependency on watersheds for each FAF Zone.

The infrastructure underpinning domestic fuel commodity flows was charted using the FAF5 records as described earlier. Tracing each city's inflows of gasoline and ethanol (SCTG 17), as well as diesel and other fuel oils (SCTG 18), provides a more comprehensive analysis of the energy flows coming into each city. While we track the flows of these commodities from their watershed of origin to the city where they are consumed, we have limited data on the water footprint of these commodities, which inhibits us from estimating the virtual water associated with these flows. Like with food virtual water flows, our estimates of energy water footprints and virtual water flows are likely conservative due to the exclusion of some commodities in our virtual water flow estimates.

2.2.3. Public Supply Water Flows

Cities are connected to watershed(s) through an array of infrastructure used to transport, treat, and distribute water to its residents, businesses, and government organizations. We mapped out the public supply water infrastructure, starting from raw water intake locations in the originating HUC4s, to the water treatment plants, sometimes through an IBT structure, to the service areas overlapping major US cities. To map the flows of water from the source watershed to the city population through the public supply water system, we joined multiple datasets to characterize different elements of the system. The raw water intake location(s) identifies the watershed(s) that provide water to a city. Water intake locations, as well as details about water source, treatment facilities, population served by each public water supply system and other details, come from the Environmental Protection Agency (EPA, 2020a, 2020b). Water service area boundaries come from the USGS (Buchwald et al., 2022). Together, these data enable us to identify the water source for each city, the population served, as well as the location and boundaries of the infrastructure that underpins the distribution of water from watershed to city.

The EPA water facility dataset does not track the volume of water withdrawn at each intake location, making it challenging to divide the total population served among the multiple watersheds supplying the city. We could assign the total population served by the city water utility to each watershed providing its water. This assumption could be justified since each watershed is critical in supplying water to the city's total population. However, such an approach would overstate the total population served and misrepresent the role of watersheds that are dominant or minor water suppliers. Instead, we use surface water and groundwater availability to partition the served population to each source watershed. Our approach follows that of Ao et al. (2023a). Briefly, we determine surface water and groundwater availability using the most recent years of publicly available data (2010–2015) from the online Water Supply Stress Index (WaSSI) model developed by the US Forest Service (Caldwell et al., 2011; Caldwell et al., 2012; McNulty, S., & Sun, G. (n.d.)). We use the relative water availability within each watershed to proportionately assign the population served by each watershed. Here, we assume that watersheds with significantly more water are more likely to provide a greater share of a city's water supply than a watershed with a relatively small amount of available water.

The amount of water each city consumed from each supplying watershed was quantified by multiplying a watershed-specific water consumption coefficient (m^3 consumed per capita; from Ao et al., 2023a; Ao et al., 2023b) by the population served by each watershed. The product of the population served and the water consumption coefficient provided the amount of a city's water consumption attributed to each supplying watershed. Due to some incomplete records within the EPA data, the city population served by each HUC4 likely represents a lower bound.

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2.3. Water Stress of City FEW

We estimate each city's exposure to local water stress and water stress through the sourcing of FEW. We build upon the water stress exposure metrics developed in Rushforth and Ruddell (2016) and used by Djehdian et al. (2019). Unlike these previous studies, which estimate direct and indirect water stress originating within political boundaries or individual grid cells, we assess water stress within each watershed, which are the natural physical unit for water stress estimates. Furthermore, we use estimates of water stress from the Water Supply Stress Index (WaSSI) model, a model specifically designed to estimate water stress within US watersheds (Caldwell et al., 2011, 2012; McNulty & Sun, n.d.). The water stress index defined in this model is the ratio of water withdrawal to available water supply, including both surface water and groundwater. We follow Kummu et al. (2016) and Falkenmark (1997) by categorizing water stress levels as "little or no stress" (WaSSI <0.2), "medium stress" (WaSSI: 0.2–0.4), and "high stress" (WaSSI >0.4). Our method stands in contrast to previous works that relied on grid-based estimates of water stress that used globally consistent parameters (Mekonnen and Hoekstra, 2016), not fully leveraging the richer data available within the US.

Each city's local water stress, LWS_c (unitless), is calculated as the area-weighted average of all watersheds that it overlaps with, as shown in Equation 1 below.

$$LWS_c = \frac{\sum_{i=1}^{k} A_{i/c} \times WS_i}{A_c} \tag{1}$$

where, c denotes the city, i is the HUC4 watershed, k is all watersheds overlapping with city i, A is the area (km^2) of the city c or the watershed/city overlap (i/c), and WS is the water stress level (unitless) within the watershed as defined by WaSSI. LWS_c is the geospatial average of WaSSI for a city, and it describes the extent of local water withdrawal compared to the locally available water supply.

We evaluated exposure to water stress for FEW sectors supplying a city by determining the average water stress of all watersheds supplying a city weighted by the amount of (virtual) water being supplied by each watershed (Equation 2). This calculation estimates a city's sourcing water stress (denoted as "sourcing water stress", or *SWS*), exposure through each of its food, energy, and public water supply receipts:

$$SWS_s = \frac{\sum_{i=1}^{k} WF_{S,i\rightarrow c} \times WS_i}{\sum_{i=1}^{k} WF_{S,i\rightarrow c}} \tag{2}$$

where WF (m^3) is the water footprint of sector s being transferred from watershed i to city c. This metric captures the spatial heterogeneity in water stress across sourcing watersheds through the assignments of a relatively higher weight for watersheds that provide a larger portion of the city's water footprint through its FEW sourcing.

A city's exposure to water stress may be evenly distributed amongst FEW sectors or it may have significant exposure in one sector but relatively little exposure in another. To assess each city's overall FEW water stress level, a water stress index value integrating the water stress across all three sectors is calculated as follows in Equation 3:

$$SWS_{FEW} = \frac{\sum_{S=F,E,W} \left(SWS_S \times \sum_{i=1}^{k} WF_{S,i\rightarrow c} \right)}{\sum_{i=1}^{k} WF_{i\rightarrow c}} \tag{3}$$

SWS_{FEW} incorporates both the spatial heterogeneity of a city's sourcing of FEW goods and the individual FEW sectors that contribute to a city's exposure to water stress. A higher value of SWS_{FEW} indicates a city's greater reliance on water-stressed watersheds for their FEW virtual blue water sourcing. Values of SWS_{FEW}, SWS_S, and LWS_c can be interpreted similarly as the Water Supply Stress Index (WaSSI), with cutoffs for little, medium, and high water stress detailed above.

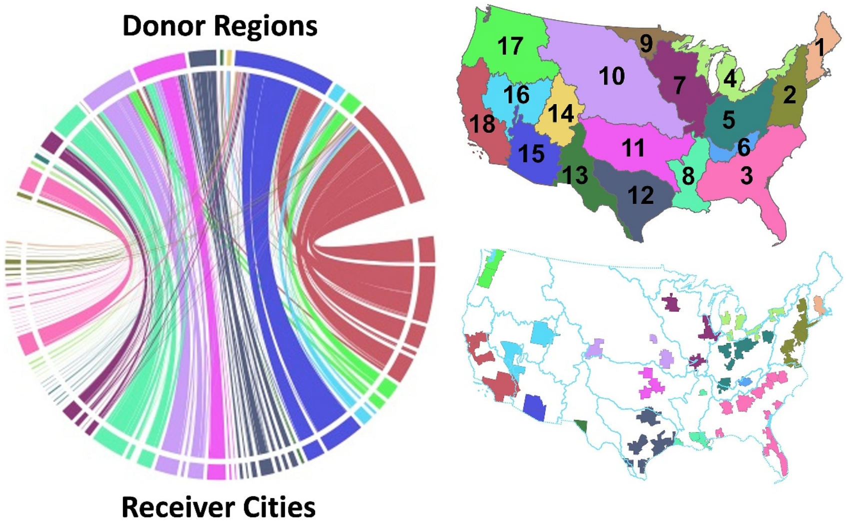

Figure 2. Transfer of virtual blue water (km^3) embedded in crop commodity flows from the originating HUC2 Region to receiving cities. The upper arcs in the Circos diagram represent the HUC2 donors of virtual blue water while the lower arcs represent the cities that receive these virtual water flows (colored by the major HUC2 where they are located). The bandwidth of the ribbons on the arc are proportional to the volume of the virtual water flow. The color of the ribbons denotes the HUC2 watershed, as shown in the upper right panel. There is a clear pattern of spatial assortativity: the virtual water transfers of crops to cities typically remain in close proximity to the source watershed. The volume of water represented in this Circos plot is 52.65 km^3.

2.4. Infrastructure Facilitating FEW and Embedded Virtual Water Flows

We assessed the waterway network (USDOT, 2019) to determine the total navigable distance inside each HUC4 watershed, and we assessed dams designed primarily for water supply to calculate their total available storage capacity for each city. We also mapped highway and railroad networks, navigation dams, inter-basin transfers intended for navigation. These steps, along with the visualization of these infrastructure networks, were essential for our qualitative analysis, enabling us to explore how infrastructure supports the adaptability in transporting food and energy commodities between land and water modes. We used ArcGIS for all data merging and mapping.

For the calculation of food commodity flow travel distance, we utilize the original FAF dataset that includes mass and mass-distance of each trade flow. We estimate the mass-weighted average travel distance by dividing the mass-distance value by the mass value. The US Bureau of Transportation Statistics routed all FAF flows through transportation network models to estimate the most likely travel distance for each shipment. Average distance traveled by virtual water associated with electricity usage was computed as the power weighted average center-to-center distance from each FAF zone to the supplying HUC4 basins.

3. Results and Discussion

3.1. Which US Watersheds Directly and Indirectly Support Each US City?

Almost all HUC4 watersheds (199 of 204) indirectly support major US cities via irrigation-dependent food supply chains. Most cities have far reaching dependencies on the nation's watersheds by sourcing their food (and, indirectly, their water) from diverse locations. However, the largest food and associated virtual blue water flows stay in close proximity to each city (Figure 2). Overall, 70% of the blue water embedded in crop products received by cities originated from the HUC2 where the city is located. Cities also import crop products from distant watersheds, drawing on their fertile land, comparative advantages, and water resources. Virtual water flows in crops are transmitted beyond HUC2 boundaries, as well as across the country. This spatial diversity in how cities source their food products is partially due to the heterogeneity of different areas' ability to produce a variety of crop products.

Cities receive 57% of all domestic processed food flows (SCTG 5–7) by mass but only 28% of the domestic unprocessed food flows (SCTG 2–4), pointing to the outsized role of hinterlands in both production and

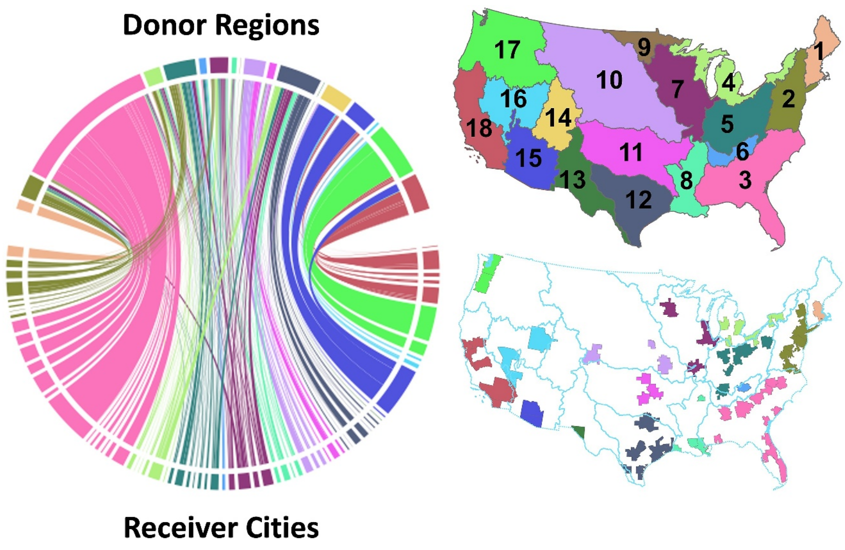

Figure 3. Transfer of virtual blue water (km^3) embedded in electricity flows from the originating HUC2 Region to receiving cities. The upper arcs in the Circos diagram represent the HUC2 donors of virtual blue water while the lower arcs represent the cities that receive these virtual water flows (colored by the major HUC2 where they are located). The bandwidth of the ribbons on the arc are proportional to the volume of the virtual water flow. The color of the ribbons denotes the HUC2 watershed, as shown in the upper right panel. Spatial assortativity is apparent but is of a different pattern from that of the blue virtual water embedded in crop flows, and the top exporters and importers change. Note that the size of the Circos here is not proportional to the food Circos in Figure 2. The total volume of virtual blue water represented by this Circos plot is 8 km^3.

processing of food goods and cities in the consumption of final food products. Western and central HUC2 regions support many of the eastern US cities through exports of food products that depend on the surface water and groundwater supplies of western and central regions. HUC2 Regions 9 (Souris-Red-Rainy) and 14 (Upper Colorado) are the only two HUC2 regions that do not have a major city (as defined by US Census/FAF) located within their boundaries and they are among the smallest virtual blue water exporters to major cities.

Most watersheds (191 of 204) support the electricity consumption of US cities by providing water used in electricity generation. Nearly two-thirds (64%) of the blue water embedded in electricity consumed by cities originates in the same HUC2 where the city is located. Blue virtual water embedded in electricity flows displays spatial assortativity, much like food flows, but with a different set of top exporters (Figure 3). Electricity generation in the South Atlantic Gulf (Region 3) consumes the highest amount of water of all HUC2 regions, but also generates the highest amount of electricity (almost 20% of total electricity generation in the US). Consequently, this hydrologic region is responsible for nearly one-third of the water embedded within electricity transfers across HUC2 boundaries, extending the dependencies on this region's water resources to outside its borders. Still, around 94% of all urban virtual water transfers associated with electricity produced within the South Atlantic Gulf HUC2 remained within the Region. All but 13 of the 204 HUC4 watersheds contributed to electricity virtual water flows into US cities. The 18 HUC2 Regions in CONUS supplied 2.5 billion MWh of electricity to major US cities in 2017, which amounts to 63% of the national total electricity generation or 68% of national total electricity consumption. Note that the volume of blue water transferred via electricity (8.01 km^3) is nearly seven times smaller than for crop transfers (52.65 km^3).

Nearly two-thirds (128 of 204) of HUC4 watersheds directly support major US cities by providing them water supplies used within local businesses, institutions, and households, among other direct uses. Cities source their public water supplies from watersheds much closer to their boundaries compared to the indirect water supplies supporting their electricity and food demands. However, water for municipal purposes is not always from the same watershed where the city is located. There are 31 cities (46% of all cities) that rely on IBT infrastructure to deliver a portion of their public supply water from a watershed that the city does not fall within. Still, the average length of these IBTs is 79 km, which is much less than the average food (700 km) and electricity (412 km) transport distance.

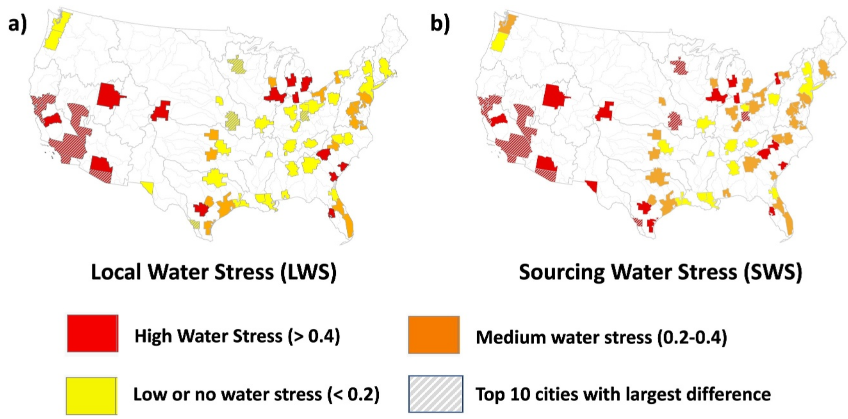

Figure 4. Local water stress (LWS) (a) and water stress embedded in the sourcing of crops, electricity, and public supply water (SWS) (b) for each US city. The top 10 cities with the largest absolute difference between local water stress and water stress exposure via sourced FEW are shown with cross hatching. All cities' SWS and LWS are listed in Table S1 in Supporting Information S1.

We find that 130.6 million people across the 68 evaluated cities depend on 128 different watersheds for their direct water supplies. Almost all (99.8%) of these 130.6 million people are served, at least in part, by HUC4 watersheds that have some overlap with their city boundaries. Another 5 million urbanites' water supplies come from the Great Lakes, which do not fall within HUC4 boundaries. Of the 68 cities assessed in this study, 67 receive their water supplies from more than one watershed, while 32 source water from four or more watersheds. Nonetheless, cities do not maintain the same level of spatial diversity in their direct water supplies as their indirect water dependencies. In 2017, cities consumed a little over 13 billion m^3 of water delivered from the nation's watersheds, delivered by an array of civil infrastructure (for reference, the public supply sector consumed approximately 22 billion m^3 in 2017 across all CONUS (Ao et al., 2023a)).

Pipelines and canals serve as critical IBT infrastructure that connect the water supplying watersheds to US cities. Of the 615 IBTs that cross a HUC4 boundary, 438 of these IBTs are primarily used to supply irrigation, municipal water, or energy (thermoelectric, mining, or hydroelectric). Of these 438 IBTs, 155 transfer water through pipelines and/or canals from 45 watersheds to 35 US cities for use in one or more of the FEW sectors. The long-term average annual volume of water transferred is known for 68 of the 155 IBTs primarily used for FEW production (including most of the largest IBTs) and they collectively transfer an average of 20.8 billion m^3 of water to US cities per year. Comparatively, the annual virtual water transfers through crops and electricity was 53 billion m^3 and eight billion m^3, respectively. Notably, physical and virtual water flows are interrelated, as physical water transfers are embedded within FEW production and then become virtual water transfers.

3.2. How Are US Cities Exposed to Local and Sourcing Water Stress?

Mapping of local water stress shows that water stress is most pronounced in the western US (Figure 4a). While this finding is consistent with multiple studies (e.g., Averyt et al., 2013; Caldwell et al., 2011; Caldwell et al., 2012; Kehl, 2020; Mekonnen & Hoekstra, 2016; Schlosser et al., 2014), our results go further in showing that over three-quarters of major US cities are exposed to medium or high water stress through the sourcing of their food and energy through supply chains and/or their public water supply (Figure 4b). Nine of the top 10 cities facing water stress through their FEW sourcing are in the arid West, reflecting the propensity for cities to source FEW from nearby sources (Figure 4b; Table S1 in Supporting Information S1). However, a little over three-quarters (52 of 68) of US cities are exposed to medium or high water stress embedded in their FEW receipts, compared to only 35 cities facing local water stress. Notably, 5 cities (i.e., Cincinnati (OH), Laredo (TX), Minneapolis-St. Paul (MN), Kansas City (KS-MO), and El Paso-Las Cruces (TX)) with low or no local water stress (LWS <0.2; due to their relatively small local surface water use compared to the surface water available), are exposed to high water stress (SWS >0.4) when water dependencies of food and energy receipts are considered. In contrast, several western cities reduce their overall exposure to water stress by sourcing FEW goods from areas less water stressed than where they are located. Still, water stress exposure in most cities is driven primarily by the water stress associated with their food imports (Figure S3 in Supporting Information S1).

Focusing on the Phoenix-Mesa-Glendale FAF Zone ("Phoenix" hereafter) shows how a city can use our findings to map their FEW water stress exposure (Figure 5; details for all cities are listed in Table S1 in Supporting Information S1). Phoenix is the second largest city in terms of blue water footprint inflow embedded in crops, electricity, and public water supply, second only to Los Angeles-Long Beach, CA. Of the 68 major US cities, Phoenix ranks seventh in terms of local water stress. However, its reliance on 130 different watersheds through their sourcing of water-intensive food and energy goods, as well as their local reliance on multiple watersheds, groundwater, and reclaimed water, helps build some diversity to their water supplies. Further, major dams and IBTs, such as the Central Arizona Project, buffer it against local and short-term water stress. Likewise, transportation infrastructure and the electrical grid reduces Phoenix's reliance on limited local water supplies. Still, Phoenix has the eighth highest FEW sourcing water stress index. The food sector of Phoenix is significantly more connected to the nation's watersheds than the city's energy and public water supplies. There were 119 HUC4 watersheds that supplied crops and embedded blue water to Phoenix, while only 33 watersheds supplied electricity and embedded blue water, and the city's public water supplies were sourced from only three watersheds. The hotspots of Phoenix's electricity water footprint supply is attributed to evaporation from reservoirs that enable hydropower at Glen Canyon dam and Hoover dam.

3.3. Where Does Infrastructure Buffer Against Local and Supply-Chain Sourced Water Stress?

Transport infrastructure enables the movement of FEW goods from hinterlands to major cities. All food categories heavily rely on the nation's highway infrastructure to transport food products to cities for consumption or processing (Figure 6). Rail and waterway infrastructure are preferred over highway transport for long-distance food transfers (Figure S2 in Supporting Information S1; Zgonc et al., 2019). The average highway distance of transported food products from watersheds to cities is 419 km, while rail food transfers travel 1,544 km on average and food shipments via waterways travel 1,690 km on average. A little under 8% of all transported food (by weight) depends on locks, dams, ports, and other infrastructure along commercially navigable waterways to move food from farm fields to cities.

The primary methods for transporting gasoline and fuel oils throughout the supply chain are via highways (58% of all fuel product mass flows into cities) and pipelines (31%). The average transport distance of fuel products to reach urban end users is 102 km for trucks, 156 km for pipelines, and 1,109 km for rail. Rail, water, and multimodal methods become increasingly important for transporting fuel over ∼300 km. Interestingly, 72% of all domestic flows of gasoline and other fuel oils are directed toward urban areas, a proportion significantly higher than that observed for the distribution of food commodities.

Commercially navigable waterways support the transfer of food and fuel into cities. There are 70,516 km of commercially navigable waterways spanning 119 HUC4 watersheds and delivering food and energy goods to 27 major cities (Figure 7). Cereal grains (SCTG 2) and other raw agricultural goods (SCTG 3) depend the most on waterways to move food from farm fields to cities. Around 43.2 million tonnes of cereal grains (55% of all food products transported by waterways) and 29.8 million tonnes of other raw agricultural products (38%) were conveyed by waterways. Waterways were used to transport 44.9 million tonnes of gasoline and ethanol (SCTG 17) and 66.8 million tonnes of diesel and other fuel oils (SCTG 18) to cities.

Inland and sea ports play a pivotal role in enhancing the resilience of the transportation system (Figure 7). Inland ports enable multi-modal transport of food and energy commodities, offering the ability to switch to less water-dependent transport (e.g., rail, truck, pipeline) when severe drought, floods, or infrastructure failure inhibit efficient transport via waterway. Even under normal operations, inland ports enable the movement of goods to cities beyond the extent of navigable waterways. Eastern seaports, even those not naturally connected to an inland waterway, serve as important node for inland water transport due to the Intracoastal Waterway - a 4,800 km constructed waterway that stretches from Massachusetts southward along the East Coast, to the southern tip of Florida, and then along the Gulf Coast to the Texas-Mexico border. There are 119 watersheds that have commercially navigable waterways, but only 63 of these watersheds have a principal sea or inland port located inside their boundaries.

There are 290 dams that directly enable commercial navigation of major waterways of the US. There are 175 additional dams that serve navigation but are not on a commercially navigable waterway. These dams either serve smaller vessels or release water during low streamflow periods to permit sufficient river depth for barge traffic. Almost half (44%, or 204) of the 465 dams with a navigation purpose are located in the Mississippi River Basin,

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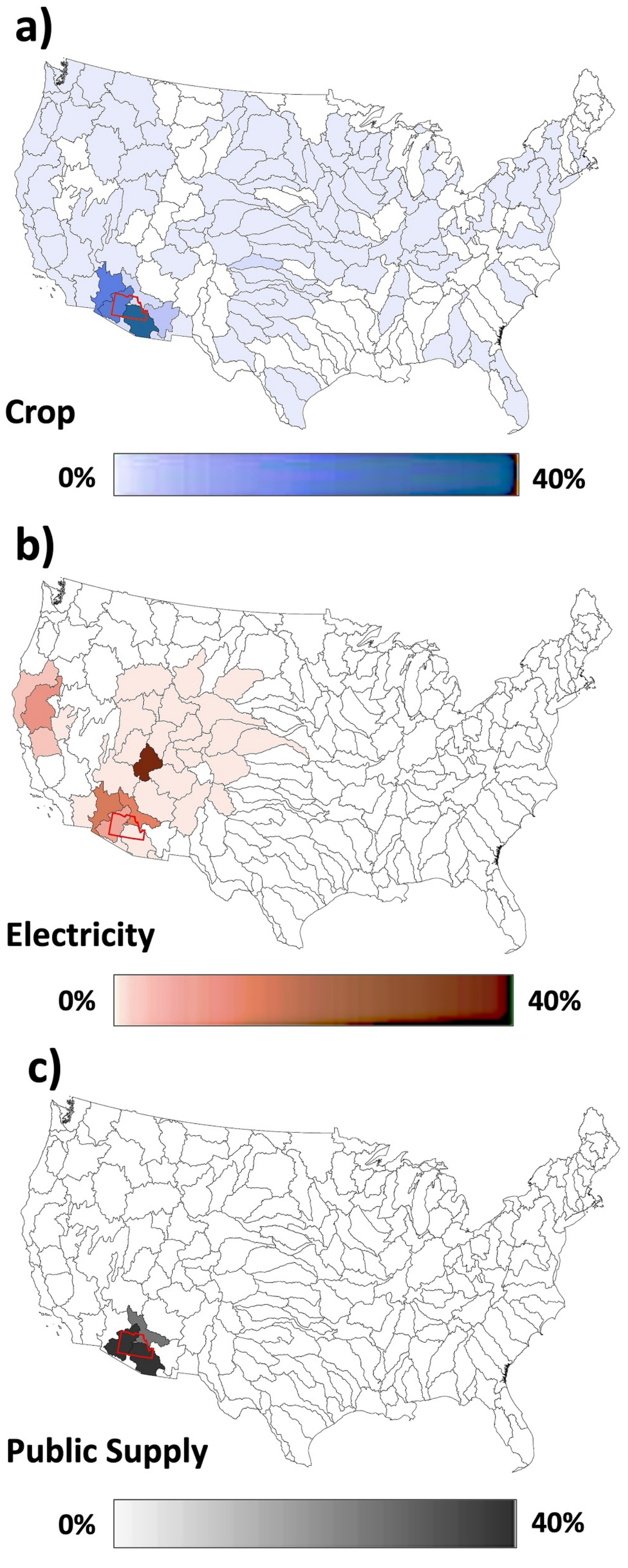

Figure 5. Watershed dependencies of the Phoenix-Mesa-Glendale FAF Zone in the sourcing of virtual blue water embedded in food, energy, and water. Watersheds in white make no contribution to the sourcing of the city.

which constitutes HUC2 Regions 5, 6, 7, 8, 10, and 11. The median age of these navigation dams is 85 years, as of 2023. Despite their age, the condition of the majority of these dams has either not been assessed (13%) or is not publicly available (79%). One-third of the navigation dams whose condition has been assessed, were rated as poor (U.S. Army Corps of Engineers, 2022).

Water supply dams help buffer cities against drought, as well as regular intra- and inter-seasonal variability in water availability. While water supply dams are ubiquitous across the US, these dams are more uniform in their spacing and storage capacity in the East compared to larger, more concentrated water supply dams in the West (Figure S4 in Supporting Information S1). Nearly 90% (60 of the 68) of the cities in our study have water supply dams located within their boundaries. Two-fifths of CONUS dams whose primary purpose is providing municipal water supplies are located inside major city boundaries. Providing public water supplies is a secondary purpose for many dams, often in conjunction with hydropower and irrigation. Dams that primarily serve food (irrigation), energy (hydropower), or water (public supplies) demands are slightly more likely (9% of all FEW dams) to be rated as being in poor condition compared to the entire population of dams (7% with poor assessment). Cities with the largest population tend to have the largest water supply dam storage capacity within their boundaries, with an additional 87 m^3 in dam storage per person, on average.

4. Conclusions

This study unveils the intertwined relationship between watersheds and cities in the United States, highlighting the vital role that civil infrastructure plays in ensuring the consistent flow of FEW resources. We showed that nearly every watershed is tapped by major US cities to provision their food, energy, and/or water supplies. The dependency of cities on watersheds far beyond their urban core may reduce their exposure to local water stress but could lead to exposure to water stress in distant watersheds from their supply chain sourcing. We showed that local water stress exposure was more pronounced in the arid West but over three-fourths of US cities, including many in the humid East, had medium to high exposure to water stress through their food and energy sourcing. We show that infrastructure, both in terms of transport (e.g., highways, railways, and waterways) and water management (e.g., dams and inland ports), plays a pivotal role in supplying FEW resources to cities. These infrastructures may serve as buffers against potential FEW resource shortages, helping to redistribute resources and maintain continuity during periods of stress (Farrell et al., 2004; Sun et al., 2023), but they can also expose cities to new forms of risks (Miller et al., 2024).

There are limitations and uncertainties in this study. The data fusion approach that we used in this study required several assumptions and approaches to bring disparate databases together, across political and watershed boundaries, with inherent mismatches. Additionally, uncertainties in the input datasets are important to consider, though they are difficult to quantify provided the limited information on data quality and uncertainty by the primary data collection agencies. Data limitations also preclude us from assessing how our findings may have changed over time or providing more recent estimates since much of the data required for this study is only available for 2017. Importantly, our approach likely provides a conservative estimate of the water embedded in FEW supply chains, since we exclude several processed goods in our virtual water calculations. This study aimed to assess the connection between US watersheds and the US cities they provide FEW resources to via

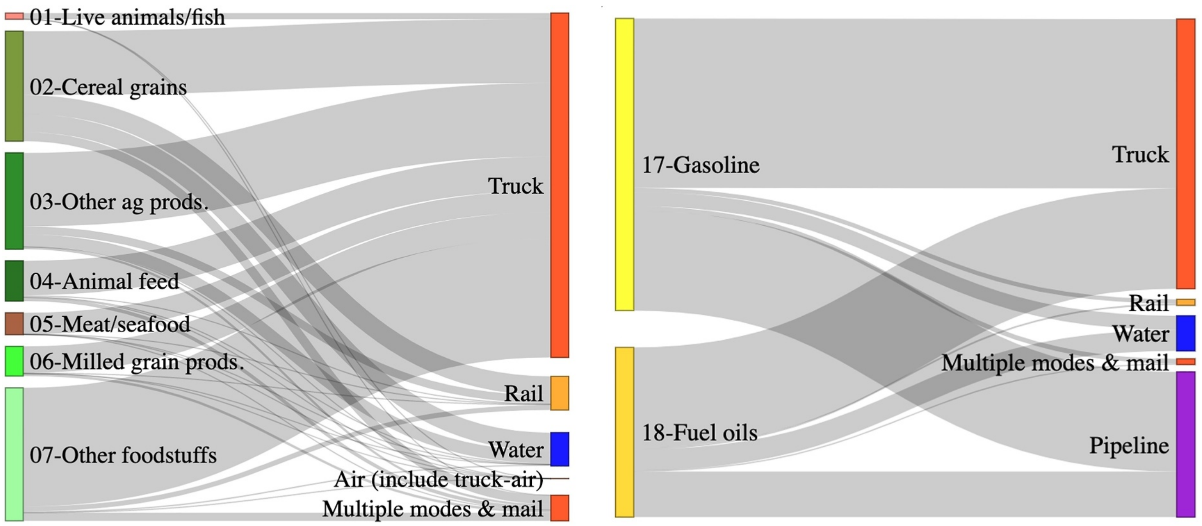

Figure 6. Commodity mass flows into major US cities, broken down by domestic transportation modes for food (left) and fuel (right) commodities. Note the two panels are not to scale to each other—the mass of food flows is roughly 30% smaller than fuel flows. The total mass of food commodity flows into major US cities in 2017 was 1,042,003,000 tonnes, while that of the fuel commodity flows was 1,471,379,000 tonnes. Mass-distance breakdown by transportation mode is shown in Figure S2 in Supporting Information S1.

an array of infrastructure. An analysis of the original FAF data indicates that about 5% of the crop product mass received by cities is of foreign origin (Oak Ridge National Laboratory, 2021). While our study did not include the inflows of foreign-origin virtual water in food products received by cities, the inclusion of foreign-origin virtual water flows remains an important area for future research and could enrich individual cities' water supply and demand analyses. Additionally, we do not account for other ways that humans shape watershed functioning other

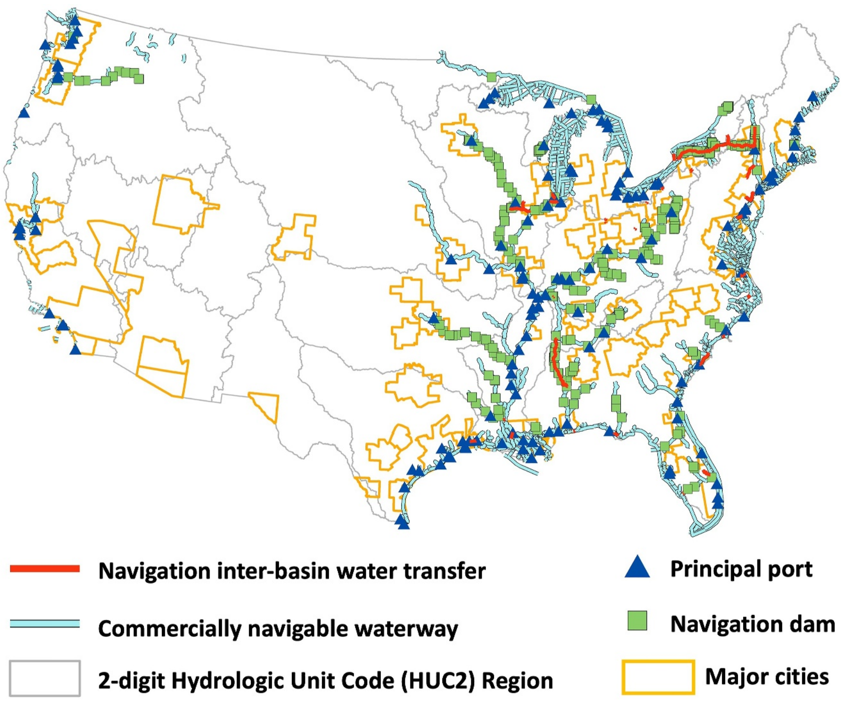

Figure 7. Waterways and related infrastructure supporting food and energy shipments to major US cities. Commercially navigable waterways, along with constructed inter-basin transfer (IBT), connect watersheds to facilitate transportation of food and energy goods. Navigation dams/locks and principal ports are important infrastructure that facilitate the movement of goods from watersheds to cities. See Figure S5 in Supporting Information S1 for railroad and federal highway networks.

than through civil infrastructure. For instance, water law, such as the Clean Water Act and water rights, can shape when, where, how much, and the quality of water used and discharged into water bodies, which may impact the source, quantity, price, and/or quality of FEW deliveries to cities.

This study demonstrates that cities, irrespective of their location, draw from multiple watersheds to meet both their direct and indirect water needs. Such a diverse sourcing strategy enhances resilience, enabling cities to weather spatially localized shocks (Gomez et al., 2021). However, such diverse sourcing is underpinned by well-functioning infrastructure. This study thus highlights that investing in the upkeep of the nation's infrastructure is important for maintaining FEW supply chains. Future research is needed to understand the vulnerabilities in our aging infrastructure, including transport, grid, and traditional water infrastructure, with the goal of preemptively addressing supply disruptions. Future studies could assess how interdependent infrastructure failure may propagate through FEW networks and disrupt their supply to cities. Future research is also needed to determine opportunities to sustainably provision FEW resources from sourcing watersheds. This understanding would be instrumental in fostering informed decision-making about national water, transport, and electrical infrastructure investments.

Data Availability Statement

The data utilized in this study are sourced from the following reputable repositories and publications: city and watershed boundaries are from Oak Ridge National Laboratory (2021), U.S. Geological Survey (2022), and National Hydrography (2022); food flows and water footprint of crop products are from Lin et al. (2019), Ao et al. (2023a), and Ao et al. (2023b); electricity water footprint coefficients and electricity consumption are from Siddik et al. (2020), EIA (2022, 2023a, 2023b), and BEA (2022); public water supply datasets are from Buchwald et al. (2022), and EPA (2020a, 2020b); infrastructure datasets are from Siddik et al. (2023), USDOT (2019), U.S. Army Corps of Engineers (2022), USDOT FHA (n.d.), USDOT (2021), and USDOT BTS (2023).

Final data products as well as selected input data tables have been deposited to CUAHSI HydroShare (Ao et al., 2024).

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