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Key Points:

- US FEW production consumed 128 km^3 of blue water and 583 km^3 of green water in 2017, most of which was for food production
- Nearly three-fifths of FEW production occurs in regularly water-stressed watersheds
- Groundwater depletion and infrastructure degradation threatens FEW production, with risk exposure varying by FEW sector

Supporting Information:

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

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Food, Energy, and Water Production Within Watersheds of the United States

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Abstract The production of food, electricity, and treated water is often tracked and managed along political or infrastructure boundaries. Yet, water resources, a critical input in the production of these goods, are delineated along natural landscape features (i.e., watersheds). The boundary mismatch between water resources and the associated production of economic goods conceals hydrologic dependencies and vulnerabilities in the provisioning of Food-Energy-Water (FEW) resources. In this study, we pair economic, infrastructure, and hydrologic data to evaluate the production of food, electricity, and treated water within watersheds of the conterminous United States. The US FEW sectors produced 950 million tonnes of crops, 3,973 million MWh of electricity, and supplied water to 263 million people in 2017. FEW production consumed 128 km^3 of blue water (18%) and 583 km^3 of green water (82%). Watersheds in central and southern California, the Midwest, and the Southwest have the largest FEW blue water consumption and the greatest exposure to water stress. Nearly three-fifths of FEW production occurs in regularly water-stressed watersheds. FEW production in watersheds in the Great Plains and Midwest relies heavily on groundwater to buffer against intra- and inter-annual streamflow variability, while surface reservoir storage buffers against water shortages in all watersheds. We show where FEW production may be susceptible to curtailments due to ongoing groundwater depletion or known infrastructure deficiencies. This study adds to our understanding of how a nation's water resources and associated infrastructure support economic activity, as well as areas where economic activity is exposed to hydrological and infrastructure risks.

1. Introduction

The United States is a major producer of Food-Energy-Water (FEW) resources (Konar & Marston, 2020). The production of FEW products is often heavily reliant on available water supplies and is thus threatened by water shortages and stress. Most data-driven studies of FEW systems occur at geopolitical boundaries, since this is typically the scale at which the necessary information on economic activity is collected (Dang et al., 2015; FT Avelino & Dall'erba, 2020; Garcia et al., 2020; Grubert & Sanders, 2018; Marston et al., 2018; Perrone et al., 2015; Rushforth & Ruddell, 2018; Worland et al., 2018). However, it is increasingly important to understand the watersheds that support FEW production, since this is the spatial unit that determines available water supplies and at which management of water resources typically occurs (Brauman et al., 2020; Richter et al., 2020; Veettil & Mishra, 2020). Water stress and risks are prevalent in certain watersheds across the United States, and are expected to increase in several parts of the country going forward (Djehdian et al., 2019; Ruddell et al., 2014). This makes it important to determine which watersheds contribute FEW products to the national economy and the future water-related risks that they face. For this reason, the goal of this study is to map FEW production to the watersheds of the United States and assess their water dependencies and risks.

The United States' role as an important producer of FEW products (D'Odorico et al., 2019; D'Odorico et al., 2018; Vora et al., 2017) also indicates embedded risks. The US consumes much of its domestic FEW production, but also is an important exporter, especially of food products, to international markets (Dang et al., 2015; Hoekstra & Mekonnen, 2012). This means that shortages in FEW production would impact both domestic and global supplies, trade, prices, and consumption of critical FEW commodities (Keulertz & Mohtar, 2020; Lee et al., 2019). Water risks increasingly threaten FEW production within the United States, such as water stress in the arid West (Djehdian et al., 2019; Richter et al., 2020) and groundwater depletion in several key aquifers (Marston et al., 2015; Marston & Konar, 2017). Water resources infrastructure is also aging in the United States, with the quality of infrastructure posing a new and growing risk to FEW production that relies on supplies from

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dams and other water supply infrastructure (Baird, 2010). These factors make it important to evaluate the watersheds and supporting infrastructure that contribute to FEW production.

In the United States, the U.S. Geological Survey (USGS) categorizes watersheds at a variety of spatial scales. Each watershed scale is identified by a unique hydrologic unit code (HUC) consisting of two to 12 digits based on the six levels of classification in the hydrologic unit system. The coarsest level of classification is the HUC 2, which divides the United States into 21 regions (18 of which are in the conterminous US, which is our study area). These geographic areas contain either the drainage area of a major river, such as the Missouri River in the Missouri Region, or the combined drainage areas of a series of rivers. The second level of classification is the HUC 4, which further divides these 21 regions into 221 subregions, which is the level where this study assesses the water-related risks and dependencies of FEW sectors. The finest watershed scale is the HUC 12 which contains over 160,000 sub-watersheds (National Hydrography, 2022; U.S. Geological Survey, 2022).

The main novelty of this study is the quantification of FEW production within watersheds for an entire nation. This enables us to understand how watersheds contribute to economic production of critical FEW systems across the United States. Our focus on the HUC 4 subregion scale (henceforth, simply "watershed") then enables us to determine the water-related risks that threaten FEW production. Here, we focus on the long-term water-related risks that challenge the ability of watersheds to provide water supply, such as water stress, groundwater depletion, and infrastructure deterioration of dams. In this way, this study helps the scientific community and water managers to better understand the degree to which FEW sectors rely on different watersheds and where exposure to water risks may threaten FEW production in the future.

We quantify FEW production in the watersheds of the United States and assess their water risks by mapping FEW production to the HUC 4 watershed scale within the US (see Figure S1 in Supporting Information S1 for a map of HUC 2 and HUC 4 boundaries). The following research questions guide this study: (a) Which watersheds support US production of food, energy, and water for public supply? (b) Where is the FEW system most exposed to surface water stress? (c) Where does groundwater and surface water storage buffer FEW production against precipitation and streamflow variability and where are future reductions in water storage most likely? Our methodological approach to answering these questions is detailed in Section 2. In the Results and Discussion (Section 3), we reveal the degree to which FEW sectors draw upon different watersheds and where exposure to water stress may threaten FEW production. We conclude by summarizing our key findings, outlining study limitations, and charting a path for future research in Section 4.

2. Methods and Data

We estimate the food and electricity production, population served, and direct water footprint (i.e., the amount of freshwater consumed on-site) of the FEW sectors within each 4-digit HUC watershed in the conterminous United States (henceforth, US). Our analysis centers around the year 2017, which is the most recent year when all data used in our analysis is available. Our analysis estimates green water footprint (i.e., the water consumption appropriated to rainwater) for crop production and the blue water footprint, broken further into surface water and groundwater footprints, for each FEW sector. The primary datasets used to estimate economic production, population served, and the water footprint of FEW sectors is shown in Table 1. We use the USGS Watershed Boundary Dataset (National Hydrography, 2022; U.S. Geological Survey, 2022) to define hydrologic boundaries consistently throughout the US. All FEW production and water footprint data were aggregated to the corresponding HUC 4 watershed. Results at the HUC 4 level were also summarized at the HUC 2 level to drive insights at a larger spatial scale.

2.1. Food Production and Water Footprint

2.1.1. Crop Production and Water Footprint

The 135 crops included in our study account for 96% of active US croplands in 2017 (National Agricultural Statistics Service, 2019). County-level crop area and production for all crops come from the United States Department of Agriculture's 2017 Census of Agriculture. Table S1 in Supporting Information S1 provides a full crop list. Data preparation steps follow Marston et al. (2018). Subsequently, county-scale crop data were resolved to the corresponding HUC 4 watershed using a 250 m gridded irrigated cropland

Table 1
Summary of Data Sets Used to Estimate Food-Energy-Water Production and Direct Water Footprint in the United States

Sector	Study variables	Data Set description and citation	Spatial/temporal resolution	Economic coverage
Food	1. Crop production (tonnes) 2. Livestock production (head) 3. Water footprint (m^3)	MIrAD-US: irrigated area (Pervez & Brown, 2010)	250 m raster/year 2017	135 USDA crop types (see the full list in (96% of all active US cropland in 2017)
		USDA Cropland Data Layer: crop area (USDA, 2021)	30 m raster/year 2017 (crop-specific)	
		Water footprint per unit area (Mekonnen & Hoekstra, 2011)	5 arcmin raster/10-year avg.	
		Crop and livestock production (National Agricultural Statistics Service, 2019)	County/year 2017	6 livestock types: cattle (dairy and beef), chickens (broilers and layers), goats, equine (horses, ponies, mules, burros, donkeys), hogs, and turkeys
		FAO Gridded Livestock of the World (GLW 3): animal-specific density data (Gilbert et al., 2018)	5 arcmin raster/year 2010	
		Livestock water footprint per head (Marston et al., 2018)	State/2010–2012 avg.	
Energy (Electricity)	1. Net electricity generation (MWh) 2. Water footprint (m^3)	EIA form 923: Electricity generation (EIA, 2017)	Infrastructure/year 2017	All electricity sources (i.e., thermoelectric, hydroelectric, wind, solar)
		EIA thermoelectric plants water consumption dataset (EIA, 2020)	Infrastructure/year 2017	All thermoelectric power plants with generation capacity larger than 100 MW
		Hydroelectric power plants water consumption estimates (Grubert, 2020; Grubert, 2016)	Infrastructure/year 2017	1433 Hydropower facilities (97% of total generation of electricity by all hydropower plants)
		Evapotranspiration rates for hydroelectricity reservoir sites (Reitz et al., 2017)	Infrastructure/year 2013	
		Water intensities of solar and wind power (Meldrum et al., 2013)	National/year not specified	All solar and wind power facilities with generation capacity larger than 1 MW
Water (Public Supply)	1. Population served 2. Water footprint (m^3)	Public supply water withdrawal volume and population served (Dieter et al., 2018) Consumptive coefficients of public supply (Solley et al., 1998) Water utility intake location and population served (EPA, 2020a, 2020b)	County/year 2015 County/year 1995 Infrastructure/year 2019	All public water suppliers covered by USGS 2015 national inventory
Water Infrastructure and Availability	Dams: primary purpose, storage, age, location, risk assessment.	National Inventory of Dams (NID) (U.S. Army Corps of Engineers, 2022)	Infrastructure/present	All dams with a primary purpose of irrigation, hydroelectricity, or public supply
	Inter-basin transfers (IBT): location, primary purpose, transfer volume	IBT dataset online depository (Siddik et al., 2022)	Infrastructure/2017	All IBTs with a primary purpose of irrigation, electricity, or public supply

dataset (MIrAD-US) for 2017 (Pervez & Brown, 2010) and the 30 m gridded Cropland Data Layer for 2017 (USDA, 2021). The gridded datasets provide the weights for partitioning a county's crop production to the overlaying HUC 4. For instance, if the more granular gridded crop data shows that 80% of harvested corn is grown in the northwest portion of a county, then 80% of the county's reported corn production is assigned to that area and the corresponding HUC 4. Our approach allows us to leverage the greater production detail and accuracy of the Census of Agriculture data, while also taking advantage of the spatial refinement of the Cropland Data Layer and MIrAD-US data.

Green and blue water footprints of production (m^3) were calculated for each crop by multiplying crop production (tonnes) by the crop-specific green and blue water footprint intensity (m^3 of water consumption per tonne of crop production). Crop-specific water footprints (Marston et al., 2018) were updated to reflect our study period using the Fast Track method (Tuninetti et al., 2017). Briefly, the Fast Track approach utilizes the fact that most of the interannual variability in water footprints is captured by crop yield variability. The relative change in crop yields between the baseline years and the study year is used to update water footprints. Partitioning the total crop water requirement between blue and green water follows the approach used by Marston et al. (2018) and Mekonnen and Hoekstra (2011). Blue water footprints were further partitioned into surface water and groundwater using county-level data on irrigation sources (Dieter et al., 2018).

2.1.2. Livestock Production and Water Footprint

We use end-of-year county livestock inventory data from the 2017 Census of Agriculture (National Agricultural Statistics Service, 2019) to estimate livestock production and the direct water footprint of production for each animal (see Table 1 above for livestock list). County-scale livestock data was resolved to the corresponding HUC 4 watershed using sub-county (5 arcmins) gridded livestock density data (Gilbert et al., 2018). Each county's animal-specific water footprint and head counts were partitioned to the overlaying HUC 4 of each county using the relative abundance of livestock in each grid cell as weights to distribute the county-level values.

We evaluate water directly consumed during an animal's life (Marston et al., 2018). Water used to grow feed is accounted for in the water footprint of crop production and is thus not included here to avoid double counting. Our results describing food encompass both meat and crop production, while crop results describe only crop production and water footprints (we give greater emphasis to crop production since it directly consumes significantly more water than livestock). Animal-specific water footprint intensity values were partitioned into surface water footprints of production and groundwater footprints of production using the county-level livestock water withdrawals from surface water and groundwater sources (Dieter et al., 2018). Livestock inventories (in the number of heads) were multiplied by the animal-specific water footprint intensity (m^3/head/day) (Marston et al., 2018) to get an annual, animal-specific direct surface water and groundwater footprint of production for each watershed.

2.2. Electricity Production and Water Footprint

This study focuses on electricity generation, as it is the dominant water-using energy source in the United States (Grubert & Sanders, 2018). Facility-level electricity production was taken from the Energy Information Administration (EIA) (EIA, 2017). For thermoelectric power plants, the EIA data includes facility location, net electricity generation, cooling technology, fuel type, water source, water withdrawals, and water consumption. The EIA provides similar location and net electricity generation data for solar, wind power, and hydroelectric facilities. Facility-level information is aggregated to the watershed where the power plants are located.

Different data sources were used to calculate the water footprint of electricity produced by thermoelectric power plants, wind and solar power systems, and hydroelectric power plants. We use the EIA reported water consumption (i.e., blue water footprint) values for thermoelectric power plants with a generation capacity greater than 100 MW (EIA, 2020). Unlike larger thermoelectric power plants, plants with a generation capacity less than 100 MW (7% of total generation capacity) are not required to report water consumption. For plants with a generation capacity less than 100 MW, we assigned a water intensity (m^3/MWh) corresponding to the national average value of power plants of the same fuel type and cooling technology. The water intensity was then multiplied by that plant's EIA reported electricity generation (EIA, 2017) to estimate its total water consumption and water footprint (i.e., the freshwater portion of the total water consumption) (Siddik et al., 2020). Water intensities of solar and wind power (Meldrum et al., 2013) were multiplied by each facility's electricity generation to obtain the

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water footprint of each facility. The water footprint of hydroelectric power plants was calculated from location specific evaporation rates and the power plant reservoir characteristics (Grubert, 2020; Grubert, 2016; Reitz et al., 2017). The source of water (e.g., river, ocean, aquifer) is provided for most electricity generation facilities. If the facility-level data did not specify the water source, the facility's water source is assigned based on the county-level thermoelectric water sources (Dieter et al., 2018). If a county reports water deliveries from a public water utility to a thermoelectric power plant, the delivered volume is assigned to a water source using the reported water source(s) for the county public water supply (Dieter et al., 2018). Additional details describing the electricity data and its preparation can be found in Siddik et al. (2020) and Siddik et al. (2021).

2.3. Municipal Water Production and Footprint

In this study, we define water production as treated water deliveries to residential, commercial, industrial, institutional, and other users by a water supplier. This study does not assess self-supplied domestic or industrial water uses that do not depend on the public water supply sector. We use county-level data detailing total public supply withdrawal volumes, water source (groundwater or surface water), and population served for 2015 (Dieter et al., 2018). Public supply system water deliveries to thermoelectric facilities were removed from the USGS estimates since these waters were already counted when calculating the water footprint of the electricity sector. The consumptive portion of municipal water withdrawals was estimated using county-specific consumptive water use coefficients calculated from the consumption and withdrawal data provided by previous USGS Water Census reports (Solley et al., 1998).

Public supply water withdrawals and consumption within each county were attributed to a watershed based on water intake location, population served, and/or water supplies within the watershed. The USGS data we use reports the county where water was withdrawn, which aligns with our study goals. If the county is fully contained within a HUC 4 watershed, then all public supply water withdrawals and consumption are assigned to that watershed. However, if the county is within two or more watersheds, the county-level water withdrawals and consumption are divided among the underlying watersheds based on the precise water diversion location of each utility. Data on public water system intake location(s), water source (groundwater or surface water), and population served come from the Environmental Protection Agency (EPA, 2020a, 2020b). If water intake locations are not available for a county, then county water withdrawals and consumption are divided among underlying watersheds based on their relative abundance of surface water and groundwater. Average surface water and groundwater supplies come from hydrologic model simulations (Caldwell et al., 2011, 2012; McNulty & Sun, n.d.).

2.4. Water Stress and FEW Risks

The average annual water stress was calculated for each watershed using output data from the Water Supply Stress Index (WaSSI) model (Caldwell et al., 2012; McNulty & Sun, n.d.). The WaSSI model was developed by the United States Forest Service (USFS) to represent the impact of human influences (e.g., land cover change, water withdrawals, climate change) on monthly hydrologic processes and water supplies at the HUC 8 scale across the United States. The validated model has been extensively used for both governmental and research purposes (Caldwell et al., 2012; Eldardiry & Habib, 2018; Marston et al., 2020; Richter et al., 2020; Sun et al., 2008). Here, we run the model for 2011–2015 and we use the average annual streamflow and water withdrawals to estimate the Water Supply Stress Index—that is, the ratio of total water withdrawals within a watershed to total available water supplies—for each HUC 4 watershed. Following Kummu et al. (2016) and Falkenmark (1997), we categorize water stress levels as "little or no stress" (WaSSI <0.2), medium stress (WaSSI: 0.2–0.4), and "high stress" (WaSSI >0.4).

We use data on dams and inter-basin water transfer (IBT) projects in the US to understand how FEW production relies on water stored within and moved across watershed boundaries. The United States Army Corps of Engineers (USACE) National Inventory of Dams (U.S. Army Corps of Engineers, 2022) provides information on over 90,000 dams in the US, including dam location, primary purpose, average storage volume, storage capacity, year of completion, owner, and condition assessment, among other features. We evaluate a subset of these dams that have a primary purpose related to FEW (note that most dams have one or more secondary purpose(s)). We have identified 639 IBT projects in the US that primarily serve FEW sectors (Siddik et al., 2022). We define an IBT as the man-made transfer of freshwater across a HUC 4 watershed (Dickson & Dzombak, 2017; Dickson

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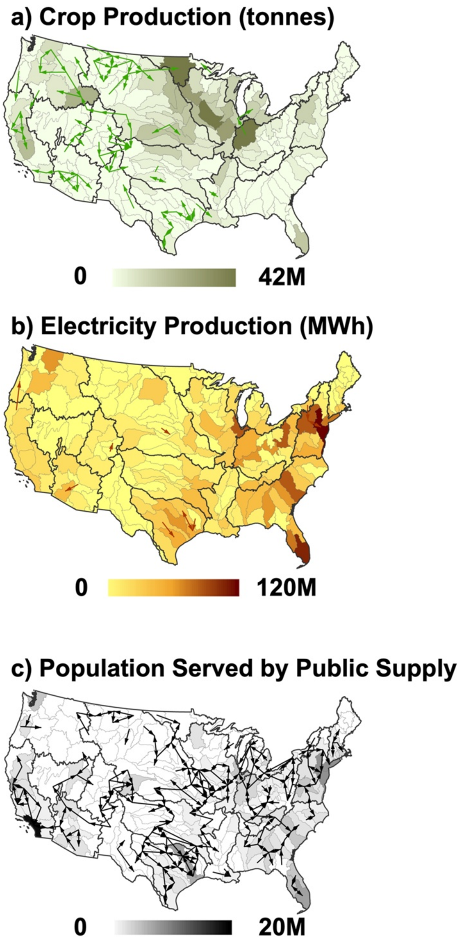

Figure 1. The (a) crop production, (b) electricity production, and (c) population served by water suppliers for watersheds across the conterminous United States. Note that watersheds (4-digit Hydrologic Unit Code) are shown with light gray borders, while larger regions (2-digit Hydrologic Unit Code) are shown with thick black lines. The arrows indicate one or more inter-basin water transfers between watersheds for each FEW primary purpose. There are records of 181 inter-basin transfers that primarily support irrigation, 11 that primarily support electricity production, and 447 for public supply.

et al., 2020; Petsch, 1985). Our IBT database includes the location, primary purpose (e.g., irrigation, water supply, energy generation), and flow data. Flow data is only available for 203 of the identified IBTs, though flow data is available for nearly all large IBT projects. Data describing the transfer of untreated (raw) water comes from Siddik et al. (2022). The transfer of treated water for public water supply across HUC 4 boundaries was determined using spatially-explicit data describing water utility intakes, treatment facilities, and distribution boundaries (EPA, 2020a, 2020b; Buchwald et al., 2022).

3. Results and Discussion

3.1. Watershed FEW Contribution

The US FEW sectors produced 950 million tonnes of crops, 3,973 million MWh of electricity, and supplied water to 263 million people in 2017. FEW production consumed 128 km^3 of blue water (18%) and 583 km^3 of green water (82%). Green water only supports rainfed and irrigated crop production, while blue water supports all FEW sectors. Food production consumes the majority of blue water, with crop production consuming 88 km^3 (69% of FEW total) of blue water and livestock production consuming 2.7 km^3 (2%). Average national corn and soybean yields - the two most widely grown crops in the US—were 12% and 19% higher, respectively, when irrigated. Local differences in crop yields and production due to irrigation can be significantly larger (e.g., irrigated corn yields in Haskell County, Kansas, one of the top corn producers, were more than double rainfed yields). Electricity generation consumes 15 km^3 of blue water (12% of FEW total), while 22 km^3 (17%) of blue water is consumed by the public water supply sector. Surface water supports at least 36% of irrigated crop production, 86% of electricity production, and 53% of the population served by water utilities.

The production of FEW varies significantly across watersheds (Figure 1). The concentration of FEW production in certain watersheds means that production risks in these watersheds could disrupt the supply chains of critical FEW goods. Water hazards—such as droughts and floods—are especially important for producers in the top-producing watersheds to consider. The Upper Mississippi River Basin (Region 7) and Missouri River Basin (Region 10) together produce 437 million tonnes of crops (46% of the national total). The Upper Snake watershed in southern Idaho, the Sacramento, Tulare-Buena Vista Lakes, and San Joaquin watersheds in central California, and the Southern Florida watershed in Florida produce 19% of the nation's fruit, nut, and vegetable crops by tonnage. The Red watershed (HUC 4) in the Souris-Red-Rainy HUC 2 region produces the greatest tonnage of food in the country. Three-fifths of the Red watershed is dedicated to cropland, including significant production of spring wheat, corn, and sugar beets. Electricity is more commonly produced in water-abundant eastern watersheds, which is also where a greater portion of the nation's population resides. Likewise, public water supplies draw from watersheds overlapping or adjacent to population centers. Just 12 watersheds (out of 204) contain 33% of the US population served by public supply water systems and provision 30% of its public water supplies. However, these watersheds are often supported by other watersheds in provisioning water supplies through the use of IBTs (Figure 1c).

Naturally available surface water supplies do not always align with where water is needed for FEW production (Figure 2; Figure S2 in Supporting Information S1). Spatial and temporal mismatches between FEW water demands and water supplies are resolved using IBTs to shift water from one watershed to another (Figures 1a–1c). The food and water sectors rely on 181 and 447 IBT projects, respectively. Projects whose primary purpose is irrigation or public supply transfer at least 24.9 km^3 of water per year across watershed boundaries each year. Only 11 IBTs' primary purpose is to supply water for electricity generation. Four IBTs support fossil-fuel power plants, two IBTs support nuclear power generation, and the remaining five IBTs are primarily for hydroelectric

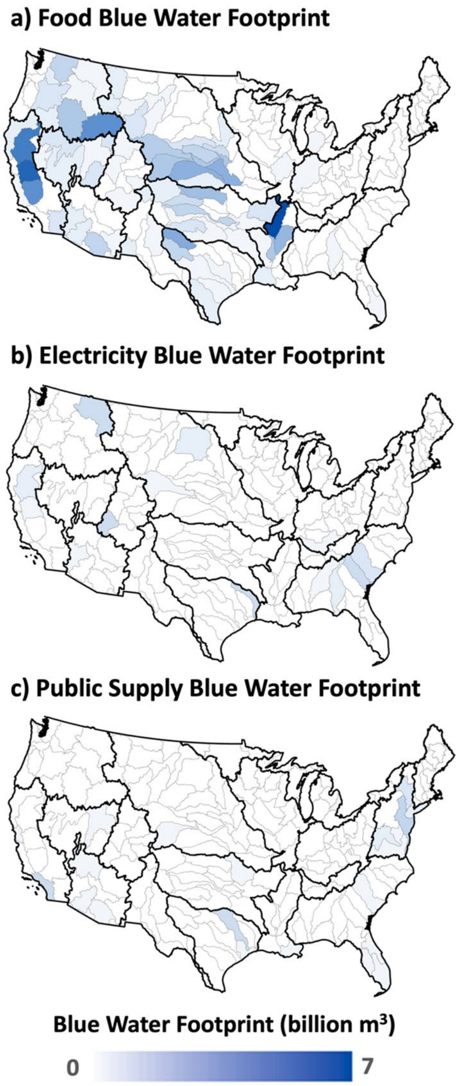

Figure 2. The blue water footprint of (a) food production, (b) electricity production, and (c) public water supply. Note that watersheds (4-digit Hydrologic Unit Code) are shown in light gray, while the larger regions (2-digit Hydrologic Unit Code) are shown with thick black lines. The blue water footprint is shown in the same scale across Food-Energy-Water production.

generation. The 11 IBTs whose primary purpose is electricity generation report a total of 3.6 km^3 of water transferred across watershed boundaries per year. Less than half of all IBTs supporting FEW production have flow rate data available (99 for irrigation IBTs, 11 for electricity, and 93 for public supply), meaning estimates of water transfers are conservative.

Blue water consumption is heavily concentrated in food production in a handful of HUC 4 watersheds. Just 25 watersheds (12%) account for half of the total blue water footprint. Food production is the dominant blue water consumer in 104 of the 204 HUC 4 watersheds (Figure 3). While these 104 watersheds represent 51% of all HUC 4s, they account for 73% of the nation's FEW blue water footprint. When green water is taken into account, the food sector is the largest water consumer in 192 watersheds and is responsible for 95% of the total (green plus blue) FEW water footprint. Energy production is the dominant blue water consumer in 24 watersheds (12%) and these watersheds account for 8% of FEW sectors' total blue water footprint. The 51 watersheds where public water supply is the dominant water consumer are primarily located in the eastern half of the US, particularly the Northeast and the South. There is greater parity among FEW sectors' blue water footprint in 25 watersheds, where no FEW sector is allocated greater than 50% of the total blue water footprint. At the HUC 2 scale, food production is the primary blue water consumer in 11 of the 18 HUC 2 regions.

The reliance on different water sources varies significantly by FEW sector and HUC 4 watershed. Food production primarily relies on green water in eastern watersheds, while surface water and groundwater are required in western watersheds to increase crop production. The production of some crops, such as lettuce, rice, grapes, almonds, and tomatoes, rely heavily on irrigation and are often produced in places where rainfall is insufficient to meet crop water requirements. Across all FEW sectors, surface water constitutes 48% of the total blue water footprint. Food production is the least dependent on surface water with at least 35% of the food sector's blue water footprint and 36% of irrigated crop tonnage reliant on surface water. In contrast, 98% of the water footprint and 86% of net electricity generation relies on surface water. Over 140 million people, or 53% of the US population served by water utilities, rely on surface water. Surface water constitutes 65% of the water footprint of the water sector.

3.2. Exposure to Water Stress

FEW production is exposed to regular water stress in 78 of the 204 HUC 4 watersheds (38%). Nearly 73 billion m^3 of blue water consumption (57% of the national FEW blue water footprint) occurs in water-stressed watersheds. Medium- and high-stress watersheds are primarily located in the South Atlantic-Gulf Region and the Great Lakes Region, as well as every HUC 2 region in the West (Figure 4). Among the 10 watersheds with the largest blue water footprint, seven experience medium- or high-water stress, suggesting FEW water demand—not just naturally limited water supplies—contributes to water stress in many watersheds. Highly stressed watersheds account for 24% of the total number of watersheds but they are responsible for 39% of the blue water footprint of US FEW production.

Exposure to water stress varies by FEW sector. Watersheds under high water stress produce 44% of the nation's irrigated crop tonnage, 24% of the net electricity generation, and supply water to 31% of the population serviced by water utilities (Figure 5). There is a strong alignment between water stress and food production. The food sector is responsible for the majority of blue water consumption in 71% of high-stress watersheds. However, the food sector is the primary blue water consumer in only 41% of watersheds with little to no water stress. In other words, if a watershed is stressed, it is likely that food production is responsible for most of the water consumption within the watershed.

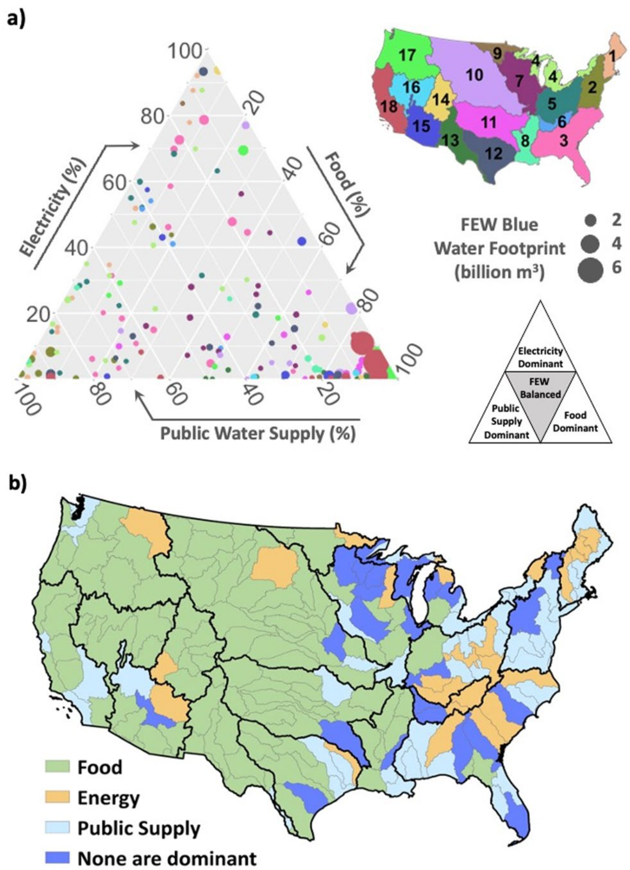

Figure 3. The blue water footprint of Food-Energy-Water (FEW) by HUC 4 watersheds across the United States. Panel (a) shows the fraction of each watershed's blue water footprint attributed to food production, electricity production, and public water supply. Each watershed is represented by a bubble whose position indicates the percentages of the total blue water footprint contributed by each of the three FEW sectors. To read the percentage values off the three axes, extend a line parallel to the corresponding arrow to each axis. Bubble size corresponds to the total FEW blue water footprint of the watershed. The bubble color indicates the HUC 2 region to which the HUC 4 belongs. Watersheds with the largest blue water footprint have the highest contribution from irrigation and are located in the bottom right corner of the triangle. Panel (b) maps the FEW sector that is the majority (>50%) blue water consumer in each watershed.

FEW production already exposed to regular surface water stress may have less buffering capacity against more severe water shortages brought on by climate change. In highly stressed watersheds, surface water accounts for 47% of the FEW blue water footprint. Over 96% of the energy sector's water footprint comes from surface water in these stressed watersheds. In high-stress watersheds, surface water contributes to over 38% of irrigated crop production, 86% of net electricity generation, and provides water to 56% of the population supplied by a water utility.

3.3. Water Storage Buffers Against Water Stress

3.3.1. Groundwater Buffers FEW Production From Water Stress

Groundwater buffers FEW production against drought and surface water shortages. Groundwater can also reduce the burden on surface water supplies or enable increased FEW production, acting as a supplement to surface water sources and/or precipitation. In highly stressed watersheds, groundwater supports around 62 million tonnes of crop production, 129 million MWh of net electricity generation, and enables water utilities to serve nearly 36 million people. When the fraction of the total blue water footprint composed of groundwater (i.e., groundwater footprint/blue water footprint) is regressed against the WaSSI stress index, we find the groundwater footprint fraction increases by 0.11% point for every percentage point increase in the stress index ($p < 0.01$). In other words, the reliance of FEW production on groundwater increases with water stress.

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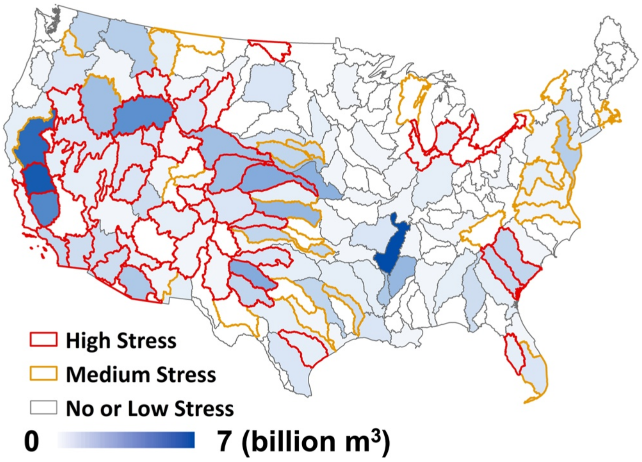

Figure 4. Total blue water footprint of Food-Energy-Water (FEW) production for watersheds across the United States with corresponding water stress levels. Here, watersheds are defined following the 4-digit Hydrologic Unit Code. Water stress is shown by the watershed boundary colors, while the blue fill shows the total blue water footprint of FEW production within the watershed.

Reliance on groundwater varies by FEW sector (Figure 6). Approximately 65% of the blue water footprint of food production comes from groundwater and around 64% of irrigated crop tonnage. Grain production in the Upper Mississippi Basin and large portions of the Missouri, Arkansas-White-Red, and Texas Gulf Regions are particularly dependent on groundwater. On the contrary, public water supplies rely heavily on surface water, with only 35% of the sector's blue water footprint from groundwater. Only 2% of the electricity sector's blue water footprint comes from groundwater.

3.3.2. Dams Buffer FEW Production From Water Stress

Surface reservoir storage buffers against intra- and inter-annual variability in precipitation and streamflow. Of the approximately 92,000 dams in the National Inventory of Dams (NID) database, over 14,000 support FEW production (i.e., their primary purpose is "irrigation", "hydroelectric", or "water supply"). Dams support FEW production in all 204 watersheds. Dams supporting FEW production collectively account for almost 281 km^3 of storage capacity (almost twice the size of Lake Tahoe), which is more than twice of the blue water footprint of FEW production, and nearly five times the surface water footprint. The average surface water storage within a watershed is positively correlated with the surface water footprint of FEW production within a watershed. However, surface water storage alone does not explain much of the variability in the surface water footprint of FEW production ($R^2 = 0.24$). Electricity production's surface water footprint is the most positively correlated with reservoir storage within a watershed ($R^2 = 0.47$), which is not surprising given the need for reservoir storage to generate most hydropower. An increase of 1,000 m^3 in surface water storage within a watershed corresponds to a 47 m^3 increase in FEW surface water footprint within the same watershed ($p < 0.001$).

Average surface water storage varies by watershed, FEW sector, and water stress status. Large reservoirs more often support FEW production in the West (Regions 13–18; Figure 7) where precipitation is generally more variable and less than in the East (Regions 01–06). The average dam size is similar among all water stress classifications but differs by FEW sector. Dams with irrigation as the primary purpose are generally the smallest and hydroelectric dams the largest. Total storage behind hydroelectric dams is an order of magnitude larger than

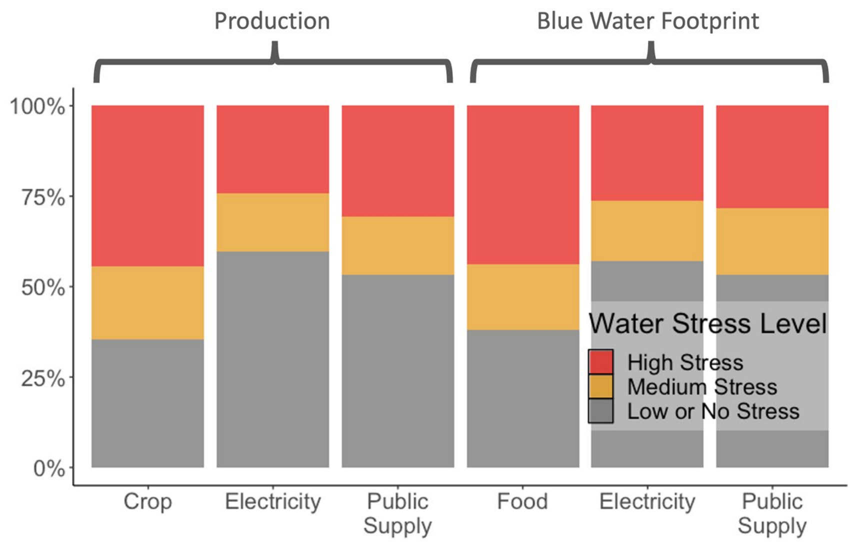

Figure 5. Percent of crop/food, electricity, and public water supply production (first three bars) and blue water footprint (last three bars) in watersheds exhibiting high, medium, or low/no water stress. The blue water footprint of food includes both livestock and crop production, whereas crop production (first bar) does not include livestock since the production units (tonnes and heads) are not comparable.

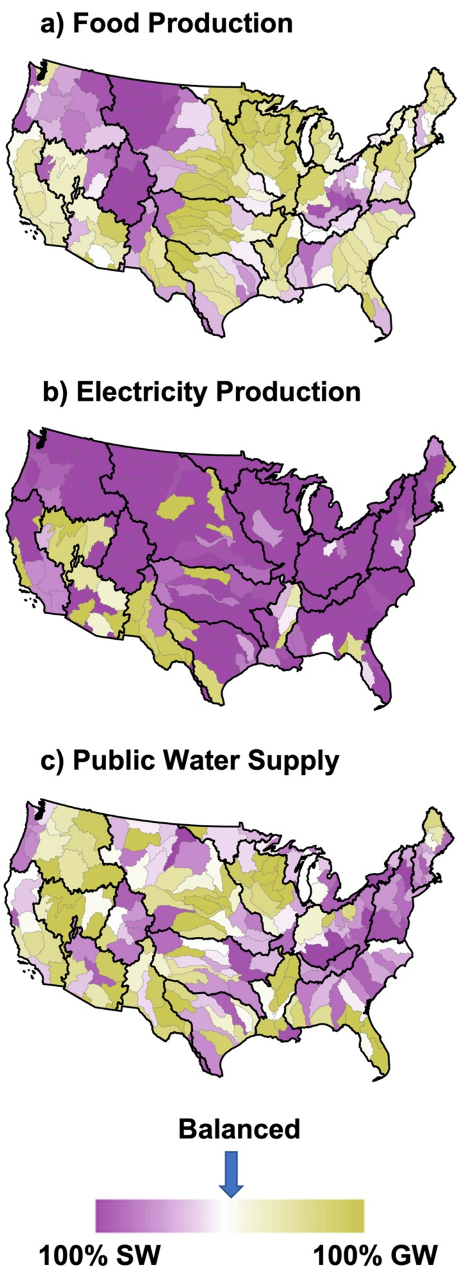

Figure 6. Contribution of groundwater and surface water to the blue water footprint of (a) food production, (b) electricity production, and (c) public water supply. Watersheds that are purple get a larger fraction of their water supplies from surface water, while those that are gold are primarily groundwater fed. Irrigated agriculture in the major growing regions of the United States is primarily groundwater fed, while electricity production tends to be surface water supplied.

dams purposed for irrigation and public water supplies. Total reservoir storage of dams whose primary purpose is related to FEW production is the greatest in western HUC 2 regions (Regions 13–18). Central HUC 2 regions (Regions 07–12) have the largest number of dams (39% of all FEW dams in CONUS, Table 2) but have the least total storage (21%), which can be attributed to numerous small irrigation reservoirs. In some watersheds in Western US, total reservoir storage primarily dedicated to food production can be several orders of magnitude larger than the surface water footprint of the food production within the watershed, suggesting that storage is used to buffer against interannual water shortages and/or to facilitate food production in downstream watersheds.

Over 65% of the FEW purposed dams and reservoir storage are in watersheds with little or no water stress, while only a fifth of the dams and water storage are in highly stressed watersheds. However, the skew of FEW purposed

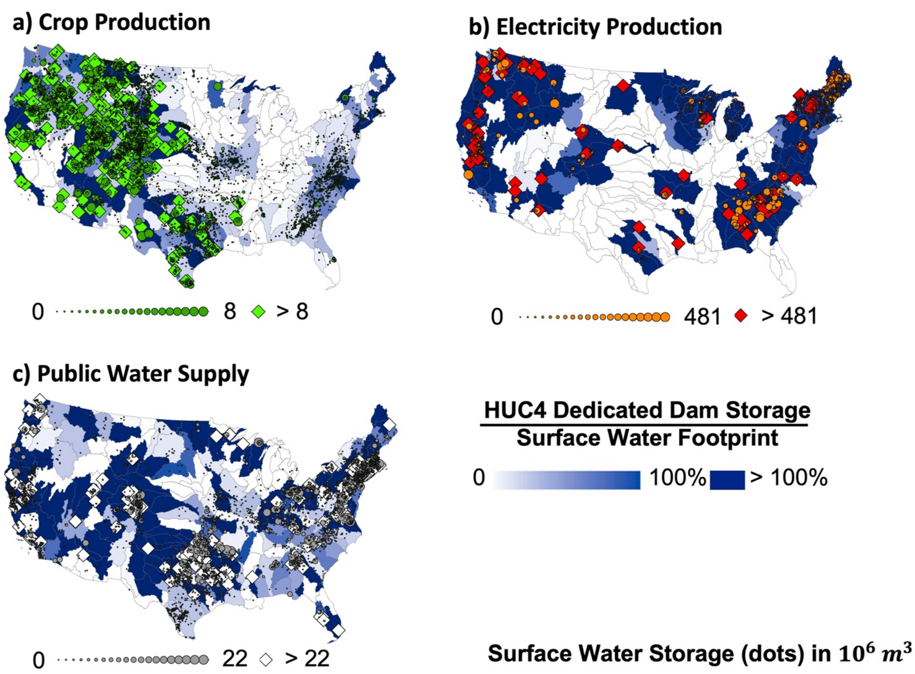

Figure 7. Reservoir surface water storage in dams whose primary purpose is (a) irrigation (crop production), (b) hydropower (electricity production), and (c) (public) water supply. The diamond-shaped points represent the top 5% of dams by typical storage for each FEW sector since these dams can be several orders of magnitude larger than smaller dams. The circles represent the dams under this threshold, whose sizes are proportional to their typical storage. Dam storage is provided in million (10^6) m^3. The blue shading of each watershed represents the total FEW reservoir storage divided by the FEW surface water footprint within the watershed (in percentage terms). Watersheds that have more FEW reservoir storage availability than their surface water footprint (i.e., storage exceeds 100% of water footprint) are shaded dark blue.

reservoir storage in watersheds with little to no water stress is driven by large reservoir storage for hydroelectricity in these watersheds. Only 29% of reservoir storage purposed for food production is in watersheds with little or no water stress, yet 43% of the food sector's storage is in high water stress watersheds. The median reservoir storage is typically around 1–2 orders of magnitude smaller than the average reservoir storage, regardless of FEW sector or water stress level, which means FEW surface water storage is driven by a small number of very large reservoirs.

3.3.3. FEW Exposure to Reduced Water Storage

The buffering capacity of groundwater infrastructure, for example, via pumps and wells, may be diminished by the overexploitation of groundwater resources, limiting the ability of groundwater to be used in future heat waves or droughts if water levels have fallen to a level that makes pumping uneconomical. Groundwater pumping enables economic production, particularly in agriculture, during short-term weather events that restrict available rainfall or surface water supplies (Marston & Konar, 2017). Yet, the long-term depletion of groundwater may restrict its long-term buffering capacity to future surface water shortages. Similarly, dams are water resources infrastructure that are used to hedge water supplies against intra- and inter-annual streamflow variability. Dams that are at the end of their design lifespan and enable the production of critical FEW goods may help to identify targeted investments in water resources infrastructure.

The dependency on surface water and groundwater storage differs by FEW sector, as does each sector's exposure to diminishing storage due to groundwater depletion and infrastructure failure/deterioration. The food and public supply sectors have the greatest exposure to groundwater depletion, particularly in watersheds overlying portions of the Central Valley Aquifer, High Plains Aquifer, and Mississippi Embayment Aquifer. Over 90% of groundwater depletion since 2000 has occurred in these three aquifer systems (Figure S3 in Supporting Information S1; Konikow, 2013) and water levels have dropped in some areas by dozens of meters. Small, rural public water suppliers and smaller, highly-leveraged farmers are particularly exposed to groundwater depletion since they often cannot afford to drill a deeper well (Ao et al., 2021; Perrone & Jasechko, 2019).

Table 2
Summary of Water Stress Status, Dam Storage as a Percent of FEW Surface Water Footprint, Count of Dams Primarily Purposed to Support FEW, and Average Dam Age by 2-Digit Hydrologic Unit Code (HUC) Region

HUC 2	HUC 2 name	Watersheds (HUC 4) in water stress category			Number of FEW dams[a]	Average age of FEW dams[a] (yrs)	Dam storage as percentage of surface water footprint
		High	Medium	Low/no			
1	New England	0	1	10	1,119	106	1775%
2	Mid Atlantic	0	4	4	1,075	96	264%
3	South Atlantic-Gulf	3	2	13	1,679	59.1	484%
4	Great Lakes	6	3	6	516	93.5	309%
5	Ohio	0	0	14	494	68.8	227%
6	Tennessee	0	1	3	107	66.1	393%
7	Upper Mississippi	1	0	13	437	77.9	186%
8	Lower Mississippi	0	0	9	148	62.9	21%
9	Souris-Red-Rainy	1	0	2	64	79.5	96%
10	Missouri	6	5	19	2,825	70.5	401%
11	Arkansas-White-Red	4	3	7	956	65.7	291%
12	Texas-Gulf	3	3	5	1,261	63.5	326%
13	Rio Grande	3	1	5	146	75.7	117%
14	Upper Colorado	3	2	3	734	78	1170%
15	Lower Colorado	5	1	2	126	78	1421%
16	Great Basin	5	0	1	436	74.6	184%
17	Pacific Northwest	2	2	8	1,177	67.5	381%
18	California	7	1	2	1,110	76.1	468%

Note. Similar statistics by HUC 4 can be found in Table S2 in Supporting Information S1.
[a]As of the year 2022.

The average age (as of 2022) of dams purposed for FEW production is 75 years (U.S. Army Corps of Engineers, 2022). Dam age does not necessarily mean it is at risk of failure, but it may indicate that a dam is approaching the end of its service life (e.g., sediment filling). While the average dam age remains consistent across water stress levels, dams whose primary purpose is hydropower (average age of 97 years) are, on average, 30 and 21 years older than irrigation and public water supply dams, respectively (Welch Two Sample t-test p-value <0.001). A public risk assessment is not available for 90% of hydropower dams, making it difficult to assess the infrastructure risk faced by the electricity sector. Condition assessments for over 40% of irrigation dams and over 60% of public supply dams are available (Figure 8). Among available dam condition assessments, 31% of irrigation dams and 17% of public supply dams are rated as either "poor" or "unsatisfactory", meaning these dams have a deficiency that may affect their operation or safety and remedial action is required. While poor and unsatisfactory dams constitute a significant fraction (26%) of overall dams, they constitute 4% and 5% of irrigation and public supply reservoir storage, respectively, since the riskiest dams typically have smaller storage volumes. Dams without risk assessments are typically privately-operated dams.

4. Conclusions

In this study, we employed a data synthesis approach to estimate the production and water footprint of FEW resources in the watersheds of the United States. Specifically, we quantified food, electricity, and public supply water production and water footprints for the HUC 4 watersheds within the conterminous United States. We then estimated the water stress and infrastructure risks that threaten FEW production across watersheds. The watersheds with the largest consumptive blue water use are in central and southern California, as well as several others scattered throughout the Midwest and Southwest with large food production sectors. These watersheds also have some of the highest levels of water stress. This study has highlighted the locations and sectors that benefit from

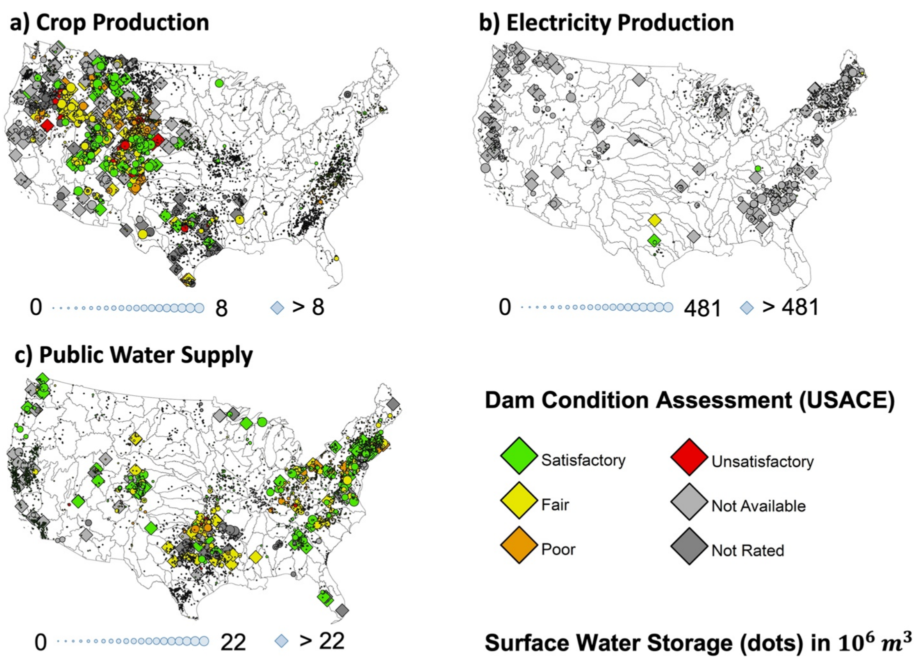

Figure 8. Dam condition assessment, sorted by size and FEW sector. Dams whose primary purpose is (a) irrigation (crop production), (b) hydropower (electricity production), and (c) (public) water supply are represented by circles or diamonds. The size of the circles represents each dam's typical storage in million m^3. Diamonds represent the top 5% largest dams in each sector by typical storage. The color of the circle or diamond indicates the category of dam condition assessment that the dam belongs to. Dam location, storage, and condition assessment come from the US Army Corps of Engineers National Inventory of Dams (U.S. Army Corps of Engineers, 2022).

groundwater and surface reservoirs that buffer water stress and potential drought, both of which are projected to occur more frequently in the future (Cayan et al., 2010; Schlosser et al., 2014; Sun et al., 2008; Wu et al., 2020). Groundwater is important for buffering intra- and inter-annual streamflow and precipitation variability (Konapala et al., 2020) for FEW production in watersheds in the Great Plains and Midwest. Similarly, dams act as a buffer to temporal variability in surface water supplies in all watersheds across the US, where aging and/or poorly maintained infrastructure may pose a risk to future FEW production in some watersheds.

There are several limitations and uncertainties in our approach to quantifying the contribution of watersheds in the production of FEW commodities. Uncertainty in the results arises from the uncertainty of the input datasets, as well as methodological assumptions. The input data used in this study are listed in Table 1, which makes it clear that various government agencies produce and provide much of the data that we rely on here. The various methods that these government agencies employ to generate the data all have their own uncertainties that will have propagated into our results. Unfortunately, uncertainty estimates are not available for the input datasets, which restricts our ability to quantify the uncertainty in our outcome variables. As detailed in our methodology, some assumptions were required to map FEW production data to watersheds. While we have high confidence in our general findings, challenges when resolving one spatial scale to another and combining multiple disparate datasets limit the precision of our estimates.

The WaSSI model - likely nearly all large-scale hydrologic models - does not fully capture flow changes due to water infrastructure operations. This model limitation may impact our assessments of water scarcity for select periods and/or locations. Furthermore, our study represents average, recent conditions. Future land use changes, economic development, and climate change may change water footprint estimates and water scarcity levels (Veettil & Mishra, 2018). While this study focuses on water as a critical input in FEW production, other factors of production such as land, labor, and capital also play an important role in FEW production and warrant additional investigation. There is also additional scope to highlight the energy consumption and carbon footprint of FEW production, such as in Zib et al. (2021) and Siddik et al. (2020).

Future research would benefit from quantifying the economic costs and benefits of infrastructure investment in FEW systems. A cost-benefit analysis of investing in the maintenance of existing water resources infrastructure, or the construction of new infrastructure, may consider the buffering capacity of such infrastructure, for example, its ability to maintain production during adverse weather conditions. This means that it is important to better evaluate the contribution of infrastructure to FEW systems in extreme circumstances, in addition to average conditions, in future work to guide decision-makers' infrastructure investments and operations. These infrastructures not only benefit local FEW producers but help bolster regional economies and support the trade and movement of water and water-intensive goods across political boundaries. While this study focuses on the production of FEW and its associated water footprint, mapping FEW consumption, as well as the associated physical and virtual movement of water from production to consumption locations and infrastructure that enables such movement, is an equally important direction for future studies.

Water has been undervalued and overutilized in many watersheds in the US, as well as globally. Poor water management has not severely hindered FEW production in many watersheds due to sufficient water availability and the buffering capacity of groundwater and water infrastructure. However, many watersheds will see more frequent and greater water scarcity in the future (Averyt et al., 2013), threatening FEW production in ways not yet seen. The ongoing drought in the Western US is already threatening reliable electricity production, requiring cuts to public water supplies, and forcing irrigated cropland to be fallowed or rely on rainfall completely. The nexus of food, energy, and water is becoming increasingly apparent. Given the importance of these resources to society, this study is a first step in beginning to assess and manage these interconnected resources along consistent spatial boundaries.

Data Availability Statement

FEW production and water footprints by HUC 4 watershed are provided in Table S2 in Supporting Information S1 and are also available on HydroShare (Ao et al., 2022). The underlying input datasets used to produce the final results are all publicly available from the sources listed in Table 1.

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