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July 2021

Tracking the U.S. Domestic Food Supply Chain's Freshwater Use Over Time

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Abstract

The U.S. food system uses freshwater from both surface water and groundwater sources (both blue water) throughout the domestic food supply chain, from on-farm irrigation to water used in the home kitchen. In this report, we study water use in the U.S. food system in 1997, 2002, 2007, and 2012 using the most recent benchmark economic datasets and an environmental input-output model. Our results show that blue water use has increased and decreased over the 4 time periods, but surface water is consistently the primary source of food-related water use. The U.S. food system used 34 trillion gallons of blue water in 2012, or 30 percent of the blue water used throughout the U.S. economy. We find that the majority of water use was in the crop and livestock production stages, although supply chain stages downstream from agriculture (processing and packaging, distribution and marketing, energy, and households) used 32 percent of the U.S. food system's blue water in 2012. This research also considers specific food categories. In 2012, the fresh vegetable category required the most blue water at 5.14 trillion gallons.

Keywords: Freshwater, blue water, U.S. food system, environmental input-output model, sustainability, life-cycle assessment, food supply chain.

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Contents

Abbreviations or Acronyms

BEA	Bureau of Economic Analysis
Bgal	Billion gallons (of water)
CBP	County Business Patterns
CMLE	Constrained Maximum-Likelihood Estimation
COA	Census of Agriculture
EIO	Environmental Input-Output
ERS	Economic Research Service
FAH	Food at Home
FAFH	Food Away from Home
FEDS	Food Environment Data System
FIPS	Federal Information Processing System
FRIS	Farm and Ranch Irrigation Survey
GAMS	General Algebraic Modeling System
GDP	Gross Domestic Product
GHGE	Greenhouse Gas Emissions
IO	Input-Output
LCA	Life-Cycle Assessment
Mgal	Million gallons (of water)
NAICS	North American Industry Classification System
NWISWeb	National Water Information System Web Interface
SIC	Standard Industry Classification
USDM	United States Drought Monitor
USGS	U.S. Geological Survey

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A report summary from the Economic Research Service July 2021

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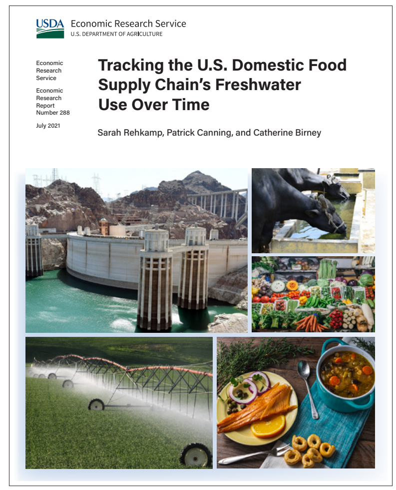
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What Is the Issue?

Although water is one of the Earth's most abundant resources, only 2.5 percent is freshwater—water that is not seawater or brackish such as rainfall or lake water. Of this 2.5 percent, more than two-thirds is not readily available for human use since it may be frozen or underground, or in other forms (DOI-USGS, 2016). Not only is freshwater a scarce resource, but it also plays a key role in food production. Water is used on-farm for irrigation and later in the supply chain to process food, clean processing plants, generate electricity, and operate home kitchens. Very little is known about these freshwater withdrawals, also called blue water, in the U.S. food system beyond what is used in agriculture, in part, because it is mostly self-supplied (DOI-USGS, 2018c).

Annual food and beverage spending in the United States surpassed $2 trillion in 2019 (USDA-ERS, 2020b) and the majority of these foods and beverages are domestically produced. This research evaluates the blue water resources used throughout the U.S. food system to meet the domestic demand for foods and beverages overtime. Therefore, this analysis excludes water used to produce food for export or to produce non-food commodities, such as fiber or ethanol; the analysis also excludes water used in the production of food and ingredients imported for U.S. domestic use.

The results will help inform how much blue water might be needed for future food demand and how our food system might adapt its use of blue water. This information could be especially helpful in discussions around food system sustainability given competing realities such as a growing population, climate change, and changing consumer preferences.

ERS is a primary source of economic research and analysis from the U.S. Department of Agriculture, providing timely information on economic and policy issues related to agriculture, food, the environment, and rural America.

What Did the Study Find?

- Over the years studied, blue water use in the U.S. food system was highest in 2002 at 43 trillion gallons, or 34 percent of total water withdrawals in the United States that year. In 2012, the most recent year included in the study, the U.S. food system required 34 trillion gallons of water for the production of U.S. food and beverages purchased (plus home kitchen operations). This would be enough water to cover the State of California at a depth of 1 foot.

- One of the primary uses for blue water in the U.S. domestic food system is for agricultural production (crops and livestock), but supply chain stages other than agriculture also use a considerable amount of blue water. In 2012, crop and livestock production used 68 percent of food-system blue water, while later stages of food production used 32 percent.

- Energy industries such as electric power and numerous petroleum products used substantial amounts of water in the supply chain. Water for energy contributed 13 percent of food-system water, emphasizing the food-energy-water nexus.

- Water used by the food system had an inverse relationship with precipitation in the four years studied. As precipitation increased, blue water withdrawals decreased, signaling that these water types may be substitutes for each other on-farm.

- Among all food-at-home (FAH) purchases in 2012, fresh vegetables accounted for the greatest water use at 5 trillion gallons of blue water, an amount sufficient to cover West Virginia in 1-foot of water, and the most blue water use by a FAH expenditure category.

How Was the Study Conducted?

This study was conducted by using an environmental input-output (EIO) model. This is a national economy-wide model in which we can track resources used throughout different industries. This modeling approach allowed us to measure embodied water, or direct and indirect water use throughout the production process through points of purchase. We employed the EIO model to measure water withdrawals linked to all domestic foods and beverage expenditures, including FAH and food away from home (FAFH). We used county-level blue water data from the U.S. Geological Survey over 4 time periods (1995, 2000, 2005, 2010) as the primary data source for this research. These 4 time periods of water data correspond with the most recent 4 time periods of benchmark input-output data. We allocated the blue water use data to the industries in the benchmark input-output data published by the Bureau of Economic Analysis (1997, 2002, 2007, 2012), using allocation metrics based on numerous other data sources.

Tracking the U.S. Domestic Food Supply Chain's Freshwater Use Over Time

Introduction

Water covers 71 percent of the Earth's surface, and oceans contain the majority of this water (DOI-USGS, 2016). Freshwater, water that is not seawater or brackish such as rainfall or lake water, constitutes 2.5 percent to the world's water resources, of which more than two-thirds is not readily available for human use; it may be frozen in ice caps or be underground in an aquifer, for example (DOI-USGS, 2016). Freshwater is essential to human survival. Human uses of freshwater come from withdrawals from surface and underground sources (or blue water) and precipitation (or green water). Freshwater (henceforth, water) is used for public health purposes such as drinking and sanitation and daily tasks such as washing clothes, washing dishes, or watering the lawn.

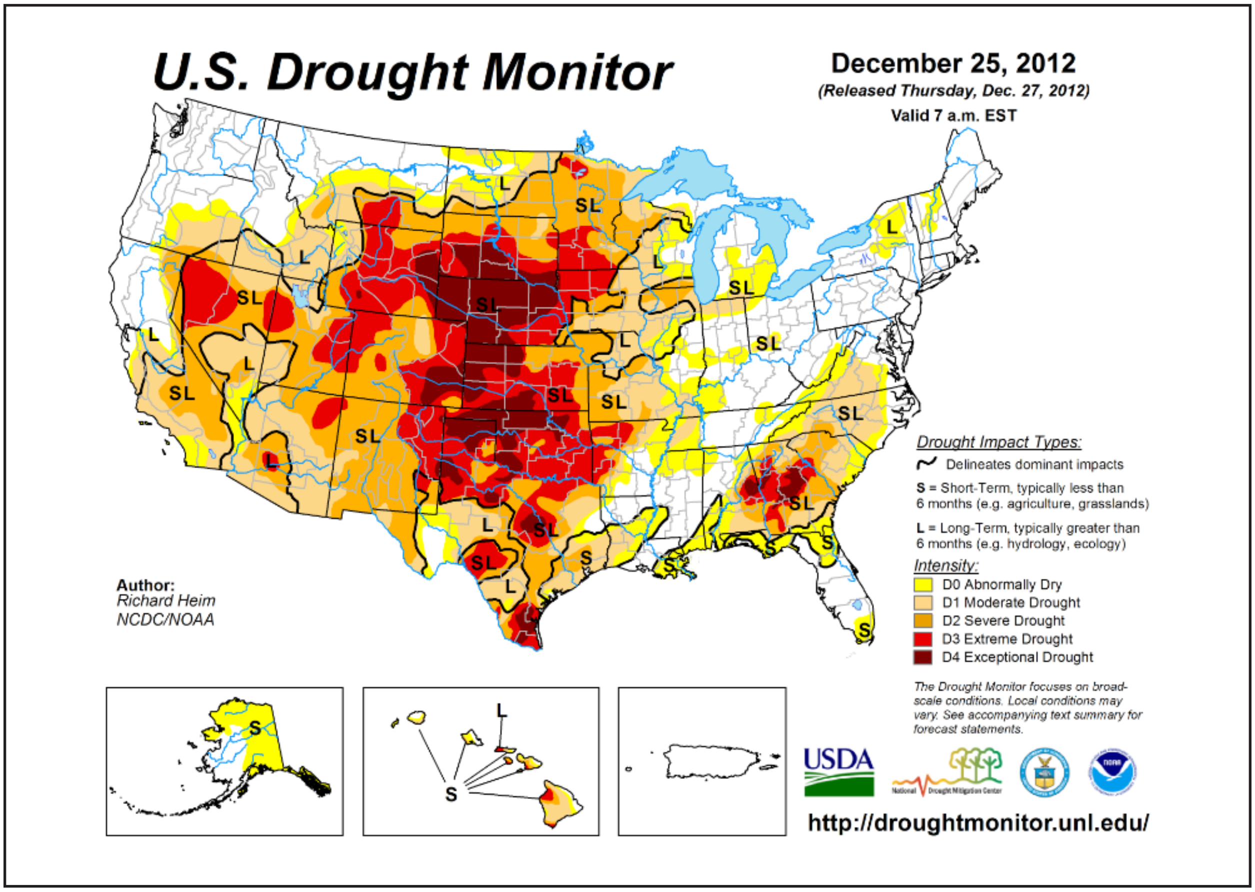
Water is also an important input in food production. In the United States, agricultural uses account for 80 percent of consumptive water use (i.e., water removed from its source but not returned). Yet, this percentage can be even higher in the western part of the country. In 2012, there were approximately 56 million acres irrigated, representing 7.6 percent of all cropland and pastureland in the United States (USDA-ERS, 2019b). In the same year, about half of the total value of crop sales came from irrigated farms (USDA-ERS, 2019b). Irrigation as a supplement to rainfall is beneficial for increasing crop yields, thus increasing land use efficiency. Irrigation efficiency has increased over time, most notably from a transition towards more efficient irrigation systems (e.g., more pressure sprinkler and drip/trickle irrigated acres), technological advancement in irrigation equipment, and improved water management by producers (USDA-ERS, 2019b). Efficiently using our natural resources maintains the supply and ability for future use.

Given its scarcity, water is often the focus of news coverage. Internationally, Cape Town, South Africa, faced Day Zero in the spring of 2018. Day Zero is when the city's taps run dry, and water rations would come into effect. Although this water crisis was ultimately averted due to water use restrictions and rainfall, the risk of Day Zero exists in other countries, including the United States (Laudicina, 2018).

The U.S. Drought Monitor (USDM) tracks U.S. drought intensity (National Drought Mitigation Center, 2019a). In 2012, the USDM showed that U.S. agricultural producers were affected by harsh drought conditions. In the latter half of July 2012, more than 80 percent of the contiguous United States was at least abnormally dry, with 63 percent categorized as having drought conditions (D1-D4). By December 2012, 6.7 percent of the United States was experiencing exceptional drought (D4), the highest intensity category that USDM measures.

More recently, in 2018, 67.1 percent of the country experienced drought conditions ranging from abnormally dry (D0) to exceptional drought (D4) between January 30 through February 5. Wallander and Crane-Droesch (2019) reported that drought is the leading cause of production risk and indemnity payments in the United States. Drought frequency and severity are exacerbated by climate change and other impacts such as heat waves, floods, cyclones, and wildfires (IPCC, 2014). These weather events and changing climate conditions affect U.S. agricultural productivity (Liang et al., 2017) and ultimately the security of our national food supply.

Figure 1
U.S. drought conditions in December 2012



Source: National Drought Migration Center. 2019b. United States Drought Monitor.
Maps: Map Archive. Accessed March 8, 2019

Because human need for water is growing and the majority of the foods and beverages in U.S. diets are domestically produced, it is important to better understand how water is used throughout the U.S. food system. This research focuses on the domestic water resource requirements to meet U.S. food demand and estimates the water requirements to produce and deliver these foods and beverages. This work builds on a 1-year analysis by Canning et al. (2020) by evaluating 3 additional years over time. We also examine where the water is used in the food supply chain and break water use down by food category. In brief, we address the following four questions:

1. How much water is used by the U.S. domestic food system to meet domestic demand?

2. Where is water used in the U.S. food system's supply chain?

3. How is food system water used by different food categories?

4. How has water use in the U.S. food system differed over time?

The results will help us understand how much domestic water might be needed to meet future U.S. food demand and domestic nutritional needs. Also, the results may help facilitate new research on how and where our food system might adapt its use of water—especially in competing realities such as a growing population, climate change, and changing consumer preferences.

Background

Trends in Total Water Withdrawals

Global water withdrawals have historically been difficult to measure. One of the primary challenges of measuring water use is that the majority of water is self-supplied. For example, in some parts of the United States, farmers may pump water from groundwater sources on their land to irrigate crops. This water is not paid for at a unit price; rather, pumping rights are included with the purchase of the land (Johansson et al., 2002). Conversely, in the energy market, electricity is generated at a power plant and then dispersed to users through a public grid system where users pay for energy based on the quantity used.

Gleick et al. (2014) complied data on total water use[1] in different countries. Table 1 ranks the top 10 water users globally, with India using the most water, followed by China and the United States. Aside from the United States and Japan, the world's top water users are all developing economies (United Nations, 2019). Of the 10 countries in table 1, the United States has the highest withdrawal rate per capita.

Table 1
Top 10 countries in total freshwater withdrawals

Rank	Country	Most recent water data	Total freshwater withdrawal	Per capita withdrawal
		(year)	(km3/year)	(meter3/year)
1	India	2010	761.00	627
2	China	2007	578.90	425
3	USA	2005	482.20	1,518
4	Pakistan	2008	183.50	993
5	Indonesia	2000	113.30	487
6	Iran	2004	93.30	1,243
7	Japan	2001	90.00	709
8	Vietnam	2005	82.00	921
9	Philippines	2009	81.60	872
10	Mexico	2009	80.40	727

Note: km^3/year: kilometers cubed per year; $meter^3$/year: meters cubed per year.

Source: Gleick et al. 2014. The World's Water: The Biennial Report on Freshwater Resources. Volume 8, Table 2. Island Press. Available at: http://worldwater.org/water-data/

The ranking changes when looking at the top 10 countries in terms of per capita water withdrawals (table 2). This ranking shows a different group of countries, with many differing characteristics that may contribute to the amount of water withdrawn. For example, half of these countries are classified as economies in transition, and there is a lower average population among the countries (Gleick et al., 2014; United Nations, 2019). These two tables emphasize the United States is a primary user of water globally. The United States comes in eighth in per capita water withdrawals but has the highest total withdrawal among the 10 countries. In fact, the United States is the only country listed in both tables.

[1]Here, total water use refers to all the freshwater withdrawn in the country, across all economic sectors.

Table 2
Top 10 countries in per capita freshwater withdrawals

Rank	Country	Most recent water data	Total freshwater withdrawal	Per capita withdrawal
		(year)	(km3/year)	(meter3/year)
1	Turkmenistan	2004	28.00	5,409
2	Australia	2010	59.84	2,782
3	Guyana	2000	1.64	2,154
4	Iraq	2000	66.00	2,097
5	Uzbekistan	2005	56.00	2,015
6	Tajikistan	2006	11.50	1,625
7	Chile	2007	26.70	1,558
8	USA	2005	482.20	1,518
9	Kyrgyzstan	2006	8.00	1,441
10	Azerbaijan	2005	12.21	1,367

Note: km^3/year: kilometers cubed per year; $meter^3$/year: meters cubed per year.

Source: Gleick et al. 2014. The World's Water: *The Biennial Report on Freshwater Resources*. Volume 8, Table 2. Island Press.

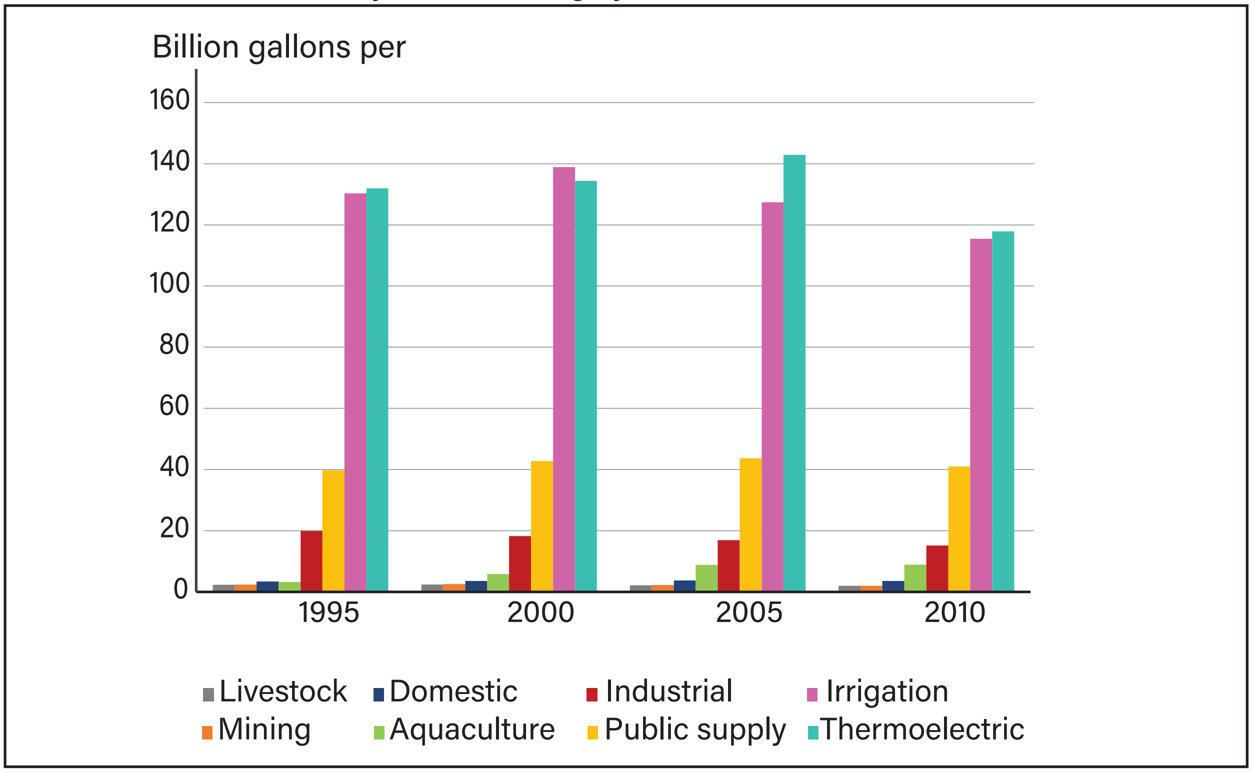
The U.S. Geological Survey (USGS) has published data on water use in the United States since 1950. The data, published in national circulars every 5 years, are available at the county level in broad water use categories and with breakouts between freshwater and saline withdrawals.

Total freshwater withdrawals in the United States have varied in the years studied from approximately 333 billion gallons per day in 1995 to 306 billion gallons per day in 2010. Total withdrawals were at their highest in 2000 and 2005 at 349 and 348 billion gallons, respectively. Figure 2 shows total water withdrawals broken out into the eight water use categories that USGS reports consistently throughout our years of analysis.[2]

Water comes from both groundwater and surface water sources. Focusing on water withdrawals in 2010, the most recent year of data considered in this report, 25 percent of withdrawals come from groundwater, while 75 percent come from surface water. These proportions stayed consistent throughout the earlier years of this study, varying by 2 percentage points or less. Figure 3 shows withdrawals by water use category and source. The data indicate that all categories rely on both groundwater and surface water, but may be much more reliant on one source. For example, thermoelectric, the water use category that used the most water in 2010, relies almost entirely on surface water withdrawals for cooling at power plants. In 2010, irrigation water was split more evenly—43 percent of water withdrawals came from groundwater, while 57 percent came from surface water.

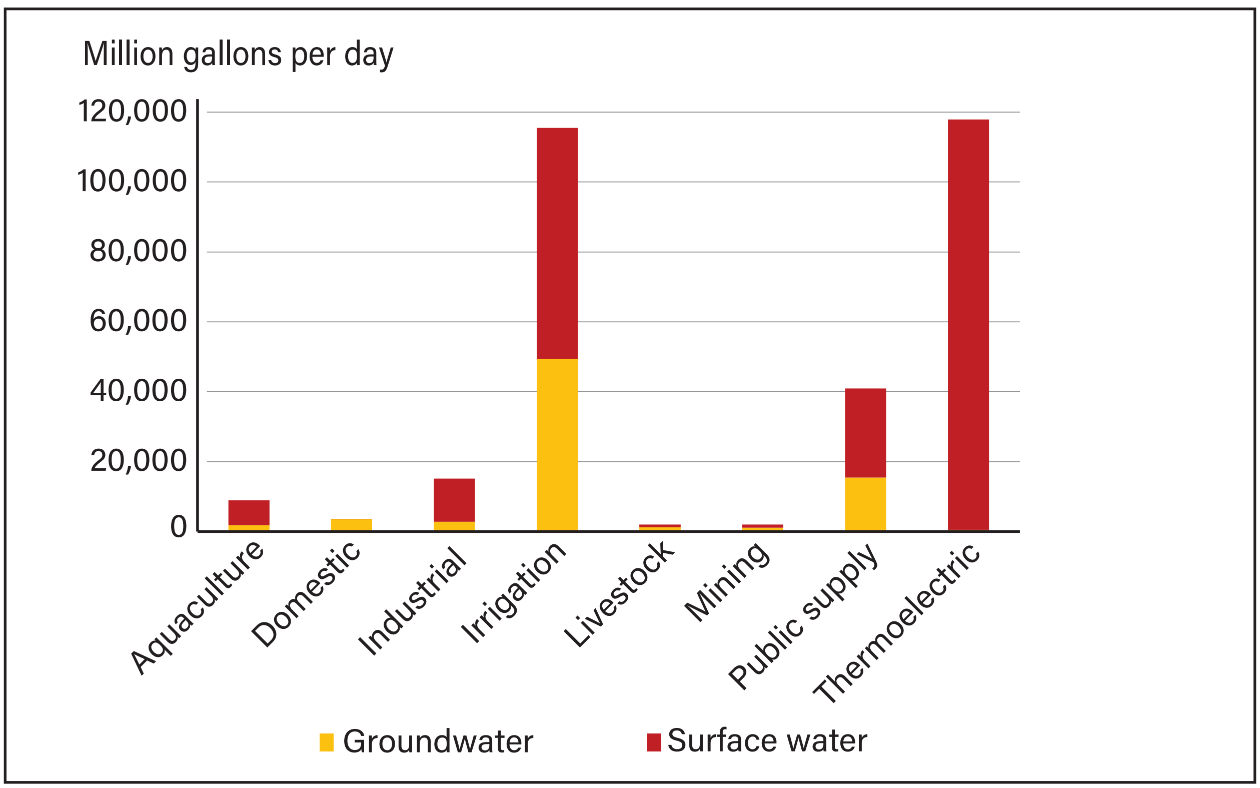
[2]Direct references to USGS water use data in this report will cite the years in which the data were enumerated, whereas references to food system water use data refer to the reference years of the environmental input-output models that input the USGS data to represent water withdrawals in the models.

Figure 2
U.S. freshwater withdrawals by water use category and source in 2010



Source: U.S. Department of the Interior, U.S. Geological Survey (DOI-USGS). 2018. *USGS Water Data for the Nation*. National Water Information System: Web Interface. Accessed November 13, 2018. Data last updated June 2018.

Figure 3
U.S. freshwater withdrawals by water use category and source in 2010



Source: U.S. Department of the Interior, U.S. Geological Survey (DOI-USGS). 2018. *USGS Water Data for the Nation*. National Water Information System: Web Interface. Accessed November 13, 2018. Data last updated June 2018.

Selected water definitions

Blue water: Fresh surface and groundwater, from freshwater lakes, rivers, aquafers, or other sources (Hoekstra et al., 2011).

Consumptive use: "The part of water withdrawn that is evaporated, transpired, or incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment" (Dieter et al., 2018). Said another way, this is the water that is used up and is a subset of water withdrawals.

Conveyance loss: Water lost in transit through leakage or evaporation (Dieter et al., 2018).

Direct water use: The water used directly by an industry. For example, the cattle industry uses water directly for livestock's drinking and servicing needs.

Embodied water: A sum of the direct and indirect water. Embodied water may also be referred to as embedded water.

Green water: Precipitation that is stored in soil, on soil, or on vegetation, as opposed to runoff or groundwater recharge, and ultimately evaporates or transpires through plants (Hoekstra et al., 2011).

Grey water: The water needed to dilute pollutants to a harmless level. Grey water is not measured in this report but may be used in water footprint studies (Hoekstra et al., 2011).

Indirect water use: Water used indirectly by an industry, which is measured using the environmental input-output model. For example, the cattle industry uses water indirectly through irrigated crops that become animal feed.

Non-consumptive use: Water that is not removed from the immediate water environment, such as depercolation or run-off.

Public-supply water use: One of the water use categories measured by the U.S. Geological Survey that represents the "water withdrawn by public or private suppliers that furnish water to at least 25 people or have a minimum of 15 connections." Water uses include domestic, commercial, industrial, thermoelectric power, irrigation, and industrial as well as public services and system losses (Dieter et al., 2018).

Self-supplied water use: One of the water use categories measured by the U.S. Geological Survey and represents water that is not public-supply water, instead the water is withdrawn from the source by a user (Dieter et al., 2018).

Water use: A synonym to water withdrawals in the U.S. Geological Survey data/documentation and in this report. It is water withdrawn for a specific purpose. "…More broadly, water use pertains to the interaction of humans with and influence on the hydrologic cycle, and includes elements such as water withdrawal, delivery, consumptive use, wastewater release, reclaimed wastewater, return flow, and instream use" (Dieter et al., 2018).

Water withdrawal: Water withdrawals are estimated by the U.S. Geological Survey for the United States and are the primary data source in this report. Water withdrawal is when water is removed from the source for another use (Dieter et al., 2018). This category represents a larger measurement of water than consumptive use, for example.

Current Understanding of Water for Food

The focus of this research is to look at total water use that can be linked to the U.S. food system, a subset of the total water withdrawals presented above in figure 3. In this report, the U.S. food system comprises all businesses operating in the United States that either directly or indirectly produce and market food products purchased by or for domestic food consumers. Additionally, we include home kitchens (including travel to and from the store for food at home (FAH) purchases).[3]

[3] See the "Scope of Analysis" section below for a more in-depth discussion.

To produce food for purchase, food businesses produce either consumer food products—such as meats, dairy, produce, or bakery products—or products they sell for use by other food system businesses—such as veterinary, electricity, packaging, and advertising services.

Data and Methods to Measure Water for Food

Water use measurement varies with water withdrawal being the largest (or parent) estimate. Water withdrawals and water use are used synonymously by USGS and in this report. Alternatively, water applied is the amount of water applied to the field from an irrigation system (excluding conveyance loss). Consumptive water (water withdrawn without return flow) is another measurement that is much less than water withdrawal. As shown in Debaere and Kurzendoerfer (2017), water withdrawals were four times the amount of water consumption in 1995, the last year data were available for each series. The relationship between these different water terms are defined in box 1, relying mostly on USGS definitions.

U.S. water withdrawal data are published by USGS (DOI-USGS, 2018c). As examples of subsets of water withdrawn, water applied on U.S. farms is estimated by the U.S. Department of Agriculture's Farm and Ranch Irrigation Survey (FRIS). USGS estimated consumptive water use between 1960 and 1995, then after a two-decade lapse, resumed the consumptive water use estimates in 2015 for the irrigation and thermoelectric power categories (DOI-USGS, 2018b). Aside from box 1, the USDA-ERS Irrigation & Water Use topics page also provides clear definitions for the different water terms and is a good reference to better understand terminology (USDA-ERS, 2019b).

Using the water data, a review of the literature indicates one of a few methods are primarily used to measure water use throughout the life cycle of food. The water footprint and process-based life-cycle assessments (LCA) are bottom-up approaches, while the environmental input-output (EIO) model is a top-down approach (Carnegie Mellon University-Green Design Institute, 2016; Pfister et al., 2018). These methods are similar in that they all estimate embodied water or the sum of water used directly and indirectly by industries, products, or processes. However, the approaches differ in some nontrivial ways, including the types of water measured and the boundary definitions of the system being studied (Daniels et al., 2011; Feng et al., 2011; Pfister et al., 2018). For example, the water footprint method in Hoekstra et al. (2011) may include consumptive water use of blue, green, and grey water (see definitions in box 1) across various spatiotemporal scales, whereas Debaere and Kurzendoerfer (2017) focus on blue water withdrawals using an EIO model in the United States. There are variations of each of these methodologies, such as a multi-regional EIO model (Deng et al., 2016; Rehkamp and Canning, 2018) and sometimes the methods are combined (Carnegie Mellon University-Green Design Institute, 2016; Wang et al., 2013).

Literature on Water for Food in the United States

Although EIO models are common within economics literature, there have been few studies combining this method and USGS water withdrawal data to measure water use in the U.S. economy (Avelino and Dall'erba, 2020; Blackhurst et al., 2010; Debaere and Kurzendoerfer, 2017; Mubako et al., 2013; Wang et al., 2014; Wang et al., 2015). To our knowledge, literature that focuses on water embodied in domestic food demand over time throughout the supply chain does not exist. We summarize the papers closest to our research below.

Sherwood et al. (2017) used a hybrid EIO-LCA approach to study the nexus of urban food, energy, and water, incorporating embedded food mass and food calories as flows in their model, in addition to the water and energy environmental flows. Their study found a strong correlation between food and water use across metropolitan statistical areas, but less of a correlation between water use and gross domestic product (GDP). They also found that crop production, electricity generation, animal production, and food manufacturing sectors use substantial water.

One paper published in 2014 focused on a specific supply chain stage of the U.S. food system. Egilmez et al. (2014) studied 33 food manufacturing sectors in the United States using an EIO-LCA model joined with a data envelopment analysis, a non-parametric mathematical optimization tool. Egilmez et al. (2014) calculated sustainability performance indices and found more than 40 percent of food manufacturing sectors performed below the U.S. average in sustainability performance. In terms of water impacts, animal (except poultry) slaughtering, rendering, and processing was the dominant sector in terms of water withdrawals—contributing 15.4 percent of water withdrawals across the food manufacturing sectors evaluated in the paper. The poultry processing sector had the largest improvement potential for water withdrawals to become more efficient (Egilmez et al., 2014).

Avelino and Dall'erba (2020) used an EIO model and USGS data to estimate the water use of agribusiness sectors in the United States between 1995 and 2010. Cereal grains and vegetables, fruits, and nuts consistently ranked as top water users during the study. Both the oilseed crops and aquaculture sectors showed large percentage increases in their water use. Aquaculture has been growing in the United States (USDA-NASS, 2019a) and the Avelino and Dall'erba (2020) point to growing demand for oilseeds on in international markets.

An EIO model is employed to measure water use in the U.S. food system in Rehkamp and Canning (2018). They found that 28 percent of the blue water withdrawn in the United States in 2007 can be attributed to the U.S. food system, and that food system stages past the farm gate contribute more than two-fifths of total water use. This report builds on Rehkamp and Canning (2018) by studying 4 time periods, rather than 1, to explore differences in water use over time.

Measuring Water Withdrawals in the U.S. Food System

Scope of Analysis

We focused this study on the relationship between food demand and the natural resources used in the food system. Our scope was influenced by the following: 1) the USDA, Economic Research Service's (ERS) emphasis on measuring domestic food acquisition, 2) data limitations, and 3) the dominance of domestically-produced food in U.S. diets.

There is a sustained focus at ERS on annual food acquisitions and expenditures of U.S. food consumers, and this report maintains that focus. The report represents the first comprehensive multiyear study of water withdrawals linked to food spending, with annual estimates in 5-year intervals spanning the current and previous 2 decades. Three premiere ERS data products—Food Availability (USDA-ERS, 2020a), Food Dollar (USDA-ERS, 2020c), and Food Expenditure (USDA-ERS, 2020b)—focus on the annual total of food acquired by U.S. consumers.[4] According to a recent ERS study, total domestic resource use dedicated to accommodating total food acquisitions in 2007 accounted for more than 1/4 of the nation's land area,[5] 28 percent of all freshwater withdrawals, 11.5 percent of fossil fuels used, 18 percent of total greenhouse gas emissions, and 7 percent of forest products used (Canning et al., 2020). This intersection of data on total food acquisitions of U.S. consumers (and the domestic resources used to accommodate this acquisition) helps inform ERS research on topics such as diet and nutrition promotion, consumer behavior, food safety, and sustainability policy.

Adopting the same study boundaries in this report as those in the ERS Food Dollar Data Product (USDA-ERS, 2020c) and recent report (Canning et al., 2020) is not meant to suggest other embodied blue water use is unimportant or unrelated. For example, embodied blue water in U.S. exports of agricultural and food commodities and the blue water embodied in products prior to entering the U.S. food supply chain are related and important users of water. Similarly, the focus on domestic food spending of U.S.-produced food in the ERS Food Dollar Series does not suggest that a global food dollar series is unimportant or unrelated or that global food acquisition and availability are either.

There are both conceptual and logistical arguments for establishing boundaries between the domestic and international components of these study areas. One of the tools used by economists is the conventional input-output (IO) model, which provides information on interindustry transactions in dollar units or monetary flows throughout the economy (Canning, 2011; Leontief, 1941; Miller and Blair, 2009). In developing the data and model for this report, the benchmark IO data compiled every 5 years by the Bureau of Economic Analysis (BEA) (DOC-BEA, 2018) are foundational.

Conceptually, consider the economic accounting concepts that underly the measure of GDP, gross domestic income (GDI), and the integrated environmental and economic accounting framework (DOC-BEA, 2017). The largest component of GDP accounts is personal consumption expenditures (PCE). These expenditures are in a separate account to the net export accounts (exports minus imports). Within PCE accounts, more

[4]Each of these data products have unique contributions, methods, and uses. For example, the Food Availability data can adjust for food loss, the Food Dollar data can disaggregate the U.S. food system into supply chain stages, and the Food Expenditure data disaggregates food at home (FAH) and food away from home (FAFH) expenditures by sales outlet. Exports are exclusively included in the Food Availability data as these data are reported at the commodity level. Some commonalities between data products exist as well, such as the inclusion of imports. Imported food and beverages are embedded in the Food Expenditure data and, depending on the readers' interest, imports of food products or commodities can be identified in both the Food Availability and Food Dollar data products.

[5]The study only measured agricultural land use, so land use by industries (both upstream and downstream from agriculture) are not measured by this study.

than 20 different food expenditure categories are included on items such as eggs, fresh vegetables, and meals at schools and colleges. Export sales of commodities compiled in the exports sub-account of GDP accounts do not have commodity breakouts used in PCE accounts. Another conceptual argument for the boundaries established in this study comes from the accounting framework behind the integrated environmental and economic satellite accounts (IEESA) outlined by BEA (Nordhaus, 1999). In the IEESA, the boundaries, or study area, for the measurement of natural resource and environmental accounting inventories are the geographic boundaries of the United States and this study follows these same boundary definitions.

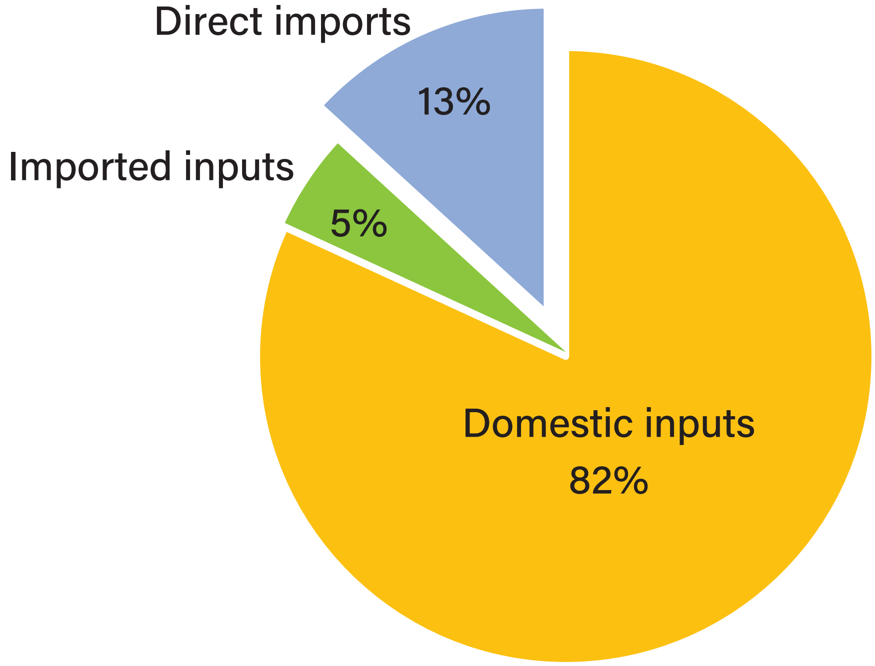
The main logistical arguments for this report's study boundary stems from the conceptual accounting framework. Specifically, the information content of BEA source data used for this analysis is not sufficiently detailed for a study with an expanded scope that includes the embodied blue water in U.S. food and beverage exports or the embodied blue water for U.S. imports.

For example, PCE accounts break food expenditures into detailed categories. With this detail, we learn that in 2012 there were $1.2 billion of personal consumption expenditures on the greenhouse, nursery, and floriculture commodity that were known to be for fresh vegetables—and about $8.8 billion of expenditures on this same commodity that were known to be for flowers, seeds, and potted plants (DOC-BEA, 2018). From the 2012 export subaccounts, reported in the 2012 Benchmark Use table (DOC-BEA, 2018), we only know that there were $681 million of greenhouse, nursery, and floriculture export sales—with no further breakout such as vegetables versus flowers. Many similar examples are prevalent in the source data for this study. Examples concerning the embodied water use data linked to imported commodities have far greater logistical issues—there is no consolidated international counterpart to the USGS water use data.

While there are other ways to access this data (such as referencing the more detailed commodity trade statistics available from the U.S. Department of Commerce, Bureau of the Census and applying U.S. estimated water use intensities to imported commodities), these approaches have significant limitations. Given the stated conceptual justification for using the study boundaries adopted in this report, it would be counterproductive to implement these workarounds and report estimates for food system embodied blue water exports and imports. These metrics are both important and relevant since food-related exports and imports also require water, and if previous studies covered these metrics, they would merit a discussion in this report. To date, no such studies exist.

In the United States, slightly more than half of agricultural production receipts are from producing foods and beverages that make up the U.S. diet. The remaining agricultural production receipts are from exports and fiber crops production, plus crops that are grown for biofuel production and not embodied in domestically marketed food commodities (Rehkamp and Canning, 2018). Furthermore, the majority of foods and beverages purchased in the United States are domestically produced.

Figure 4
Source of U.S. food and beverages expenditures, 2018



Source: U.S. Department of Agriculture, Economic Research Service (USDA-ERS). 2020. Food Dollar Series. Data product.

The foods and beverages that make up U.S. diets include both domestically-produced items (such as sweet corn grown on a Minnesotan farm with domestic inputs like seed), domestically-produced items with imported ingredients (such as cranberry juice with imported Canadian cranberries), and imports (direct imports such as Spanish wine or Mexican avocados). Even with the growth in international trade and an increasingly globalized food system, the primary market for U.S. producers are domestic consumers; most food commodities stay in the country they are produced in (D'Odorico et al., 2014). Figure 4 supports this finding, showing that 87 percent of the food and beverages marketed to and consumed in the U.S. in 2018 were domestically produced (USDA-ERS, 2020c).

In this study, we evaluated the domestic water use for U.S. food production for U.S consumption, or the water embodied in domestically-produced foods and beverages marketed and sold in the country. This includes the water used in the transportation and marketing of imported foods and beverages and imported inputs from the port of unlading to the point of purchase.

Excluded in our measurement is domestic water use for U.S. food exports, or the water embodied in foods and beverages exported to other countries as a final product or ingredient, and the international water use for U.S. food consumption of imports, or the embodied water in imported foods and beverages purchased for consumption in the United States. This water can be measured, but we are interested in the U.S. food system's ability to provide an adequate domestic food supply.

Food Environment Data System and Model

A Food Environment Data System (FEDS) is being developed at ERS across multiple environmental metrics. The modeling approach used is a national-level EIO model, which extends the conventional IO framework by incorporating physical units and measuring environmental flows throughout the economy (Leontief, 1970), such as gallons of water. We refer to this data system and modeling effort as FEDS-EIO.

In 2003, the United Nations and several other international organizations issued a joint handbook of economic accounting guidelines that recommended the EIO approach as a best practice for achieving "a consistent analysis of the contribution of the environment to the economy and of the impact of the economy on the environment" (United Nations et al., 2003). The European Commission also uses this approach with its EIPRO (Environmental Impact of PROducts) model (Mason and Lang, 2017). In 2002, the National Research Council (NRC) identified EIO analysis as an effective approach to model economy-wide water use.

EIO is our preferred method to analyze water use in the U.S. food system. This method is comprehensive and consistent since it is based on the official U.S. System of National Accounts published by the BEA. We enhanced this EIO approach to capture the key attributes of the U.S. food system, using historical and current survey-based data sources.

We relied on benchmark IO data, which provided additional detailed information on 344 industries.[6] Since the BEA benchmark data are compiled every 5 years (DOC-BEA, 2018), the years of data that correspond closest to the USGS data are 1997, 2002, 2007, and 2012.

Rehkamp and Canning (2018) explained the concise mathematics for the FEDS-EIO model. Although we performed a national-level analysis in this report, we did not consider different regions. In short, we measured the vector,[7] **w:**

Equation (1) $\mathbf{w} = \mathbf{E}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{ELy} = \mathbf{Ex}$

where

w: total water flows embodied in final demand

E: environmental direct requirements matrix

I: identity matrix

A: industry direct requirements matrix

y: final demand vector

L: total requirements matrix

x: gross industry output vector

[6]See the list of industries in supplementary table A5.

[7]Our notation for a vector is a bold, lower-case letter and our notation for a matrix is a bold, upper-case letter.

We included consumption expenditures on international imports (GDP plus imports) in **y** and added imports to domestic outputs in **x,** which is conventional practice in type I IO multiplier analysis (e.g., Canning et al., 2016). Type I IO multiplier analysis is the simplest of these types of economy-wide models in which direct and indirect effects are captured. There are no induced effects[8] since household spending is exogenous (Miller and Blair, 2009).

A key model feature that facilitates our analysis was the assumption of linear homogeneous production technologies. This feature has the effect of assuming, for example, that if it takes 100 bushels of wheat to accommodate the sale of 9,000 loaves of whole wheat bread to U.S. households, then 50 bushels are required for the 4,500 loaves sold to a subset of these households. If $\mathbf{y}^f$ itemizes the subset of elements in **y** that are food or food-related expenditures of U.S. households,[9] then by the linear homogeneity property, multiplying this vector by **EL** (see equation 1 above) would produce estimates of total water flows embodied in food-related final demand($\mathbf{w}^f$).

We used the food-related elements of the $\mathbf{y}^f$ vector to estimate embedded water for household kitchen operations (such as purchases of kitchen appliances and the energy to run them) and personal food-related transportation (such as trips to a grocery store or food establishment). Kitchen faucet water use is the third component of the household supply chain stage and is outside of the model (see the appendix and supplementary tables of this report, for additional details).

Water Data Inputs

The data we used to measure water withdrawals, or blue water, come from USGS, accessed from the National Water Information System's Web (NWISWeb) Interface (DOI-USGS, 2018a). We used these data, rather than the publication data from the circulars, since these are the current best-available estimates and the practice is advised by USGS (2018c). We focused on 4 years of data (1995, 2000, 2005, 2010) since these correspond with the input-output data.[10] By collecting and standardizing the data for the 4 years, we were able to evaluate how water use has differed over time.

The water data are published in broad water-use categories. We focused on eight water use categories that we could consistently measure over our 4 years which are aquaculture, domestic, irrigation, industrial, livestock, mining, public supply, and thermoelectric (DOI-USGS, 2018b). These categories were further broken out into groundwater and surface water sources. All the water-use categories are self-supplied water, except for public supply.

Linking Water Data with Food System-Related Economic Industries

One major challenge of this research was linking the water use categories to economic industries, especially given that most water withdrawn is self-supplied. Having water organized by economic industries (FEDS industry groups) facilitated the material flows analysis and allowed us to measure the amount of water used in the U.S. food system.

[8]Induced effects are additional captured effects from household spending due to changes in income (Miller and Blair, 2009).

[9]See supplementary table A4 for the food and food-related elements in $\mathbf{y}^f$.

[10]1997 is the first year of NAICS-based benchmark input-output data, and 2012 is the most recent benchmark data that has been released (DOC-BEA, 2018).

Our goal was to map water from the broad USGS water use categories to more specific North American Industry Classification System (NAICS) based industries and, finally, to FEDS industry groups. A complete list of the 344 FEDS industries are reported in supplementary table A5.

Data Inputs: Developing and Estimating Allocation Metrics

In addition to the USGS water data and BEA economic data, we also needed data inputs to allocate systematically the USGS water data. We relied on the data sources summarized in table 3.

There were challenges with using these data sources to allocate water data. First, the data changed over time, as described in more detail in the appendix. Second, we preferred to allocate water at the county-level when possible to account for geographical heterogeneity, but there are generally data suppressions for the county-level allocation metric. For example, there are county-level suppressions in the Census of Agriculture (COA), so individual producers cannot be identified. Therefore, we first needed to estimate these suppressions, so we could reliably allocate the water data with a complete allocation dataset. We estimated the county-level data suppressions in the COA, FRIS, and County Business Patterns (CBP) using a maximum-likelihood estimation model and General Algebraic Modeling System (GAMS) software. The model exploits the hierarchical nature of the datasets. This method has been well-documented (Canning, 2013), and we provide a generalized mathematical representation of how we estimated the county-level suppressions for COA irrigated crop data in the appendix. Estimating the suppressions allowed us to use all publicly available government data sources for this research.

Allocating Water Withdrawals to FEDS Industry Groups

Having developed allocation metrics to disaggregate the water use data, we used these data to allocate the water withdrawals to FEDS industry groups. We first disaggregated the broad water use category provided by USGS into the NAICS-based industries and then aggregated back up to the FEDS industry groupings. A spreadsheet that classifies all the 2002 NAICS industries that fall under each of the water use categories was provided to the authors by USGS. We used concordances to link the different NAICS years as necessary (DOC-BOC, n.d.b).

As an example, we disaggregated the livestock water withdrawals in each county using our allocation metric (table 3). We calculated the share by multiplying the county-level livestock inventory (USDA-NASS, 2019a) by the water use coefficient for each type of livestock (Lovelace, 2009). The water-use coefficient accounts for variations in the amount of water that animals need (e.g., dairy cattle require more water than beef cattle) and is also used by USGS to estimate livestock water withdrawals. This results in water withdrawals disaggregated into NAICS-based industries at the county level. In the livestock example, this would be water used by beef cattle, dairy cattle, other cattle, or other livestock types with inventory in that particular county. We then aggregated the water from the NAICS-based industries to FEDS industry groups, representing economic industries. The water for cattle NAICS-based industries in a county aggregates to the FEDS industry dairy and beef cattle. A mathematical example of the livestock allocation is provided in the appendix.

In a similar manner, we linked all USGS water use categories to FEDS industry groups to complete the analysis. Table 3 lists our allocation metrics.

Finally, we aggregated the FEDS industries water data to the national level. These input data are used in the FEDS_EIO model, which we used to calculate total water withdrawals in the U.S. food system in 4 recent time periods, keeping track of surface water and groundwater sources. The results of the EIO analysis tell us how much total blue water is being used throughout the U.S. food system, both directly and indirectly to accommodate all food-related expenditures by or for all U.S. households.

Table 3

Summary of U.S. Geological Survey (USGS) water use categories and allocation metrics

USGS water use cateogries		Our variable convention	Withdrawal type	Allocation metric	Geographical level of allocation	Data source of allocation metric
Category	Subcategory					
Aquaculture		AQ-WFrTo	Self-supplied	Assigned to one FEDS industry	N/A	N/A
Domestic		DO-TOTAL	Self-supplied+ Publicly-supplied	Assigned to final demand vector		
	Self-supplied domestic	DO-WFrTo	Self-supplied		N/A	N/A
	Domestic deliveries from public supply	DO-PSDel	Publicly-supplied		N/A	N/A
Industrial		IN-WFrTo	Self-supplied	Employment by county and NAICS industry	State	U.S. Department of Commerce, Bureau of the Census, County Business Patterns (1998, 2002, 2007, and 2012)
Irrigation		IR-WFrTo	Self-supplied	Disaggregated into crop and/or golf irrigation by using shares in nearest year to data suppression, if share existed. If share didn't exist, assigning 100% to crop.		
	Crop irrigation	IC-WFrTo	Self-supplied	Irrigated harvested cropland by county and crop; water application rate by state and crop	County	U.S. Department of Agriculture (USDA), Census of Agriculture (1997, 2002, 2007, 2012); USDA, Farm and Ranch Irrigation Survey (1998, 2003, 2008, 2013)
	Golf irrigation	IG-WFrTo	Self-supplied	Assigned to one NAICS industry and FEDS industry	N/A	N/A
Livestock		LI-WFrTo	Self-supplied	Inventory by county and livestock; National median water intake rates by livestock	County	USDA, Census of Agriculture (1997, 2002, 2007, 2012); Lovelace (2009)
Mining		MI-WFrTo	Self-supplied	Employment by county and NAICS industry	State	U.S. Department of Commerce, Bureau of the Census, County Business Patterns (1998, 2002, 2007, and 2012)
Public supply		PS-WFrTo	Publicly-supplied			
	Net public supply (non-domestic)	NetPS-WFrTo	Publicly-supplied	Dollar value of direct requirements by industry for NAICS 221310 from FEDS_EIO	National	U.S. Department of Commerce, Bureau of Economic Analysis (1997, 2002, 2007, 2012)
Thermoelectric		PT-WFrTo	Self-supplied	Assigned to one NAICS industry and FEDS industry	N/A	N/A

Notes: Acronyms defined: North American Industry Classification System (NAICS), Food Environment Data System (FEDS), and Food Environment Data System and Environmental Input-Output Model (FEDS-EIO).
Data are U.S. county-level water withdrawals (excluding territories and the District of Columbia) for years 1995, 2000, 2005, and 2010.
Water is further broken out into groundwater and surface water for each water use category.
The rows highlighted in grey are those allocated to FEDS economic industries and used in the FEDS_EIO model.
Our convention is based on USGS variable names, but kept consistent throughout the years.
See appendix table A1 for additional details.

Source: USDA, Economic Research Service calculations using data from U.S. Department of the Interior, U.S. Geological Survey (DOI-USGS). 2018. USGS Water Data for the Nation. National Water Information System: Web Interface. Accessed November 13, 2018. Data last updated June 2018.

Supply Chain Decomposition

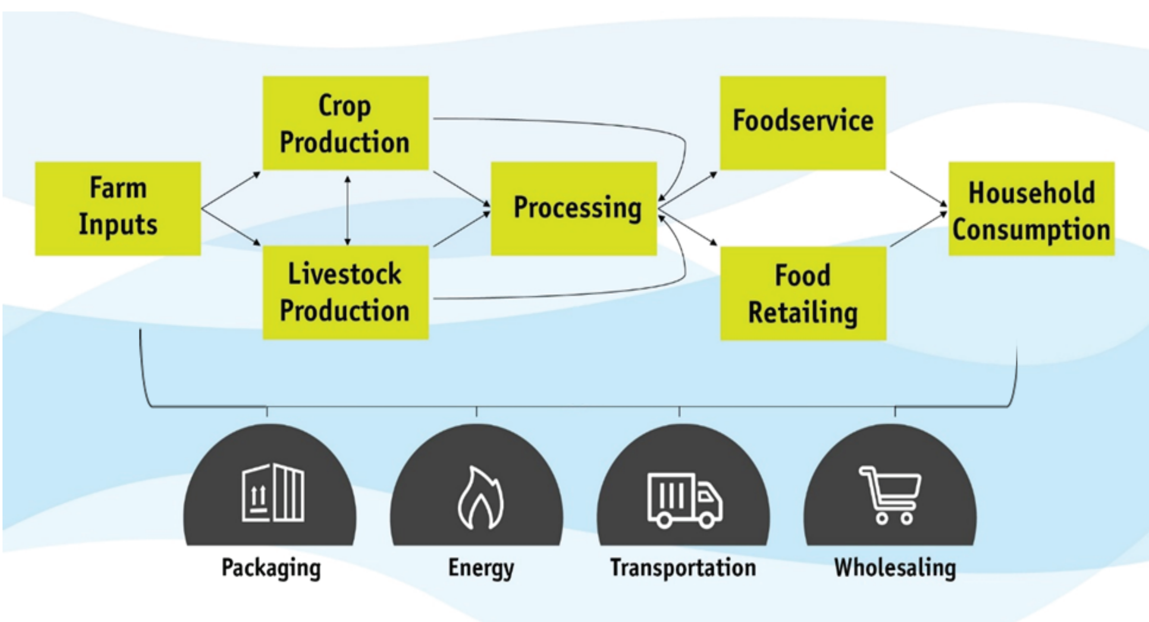
After measuring total water withdrawals in the U.S. food system with FEDS-EIO, we further characterized how water is used by conducting a supply chain analysis. This analysis decomposed total water used into the different supply chain stages throughout the food system. Water is used on-farm for irrigation, but also by supply chain stages downstream. We considered water for various uses—such as packaging, energy, transportation, and wholesaling—which are not distinct, linear stages but touch many points getting the food from farm to fork. For example, seeds are transported to the farm for planting and the crops are then transported to the processing plants after harvest. The resulting food item is then transported to the retailer. Finally, the consumer drives to the grocery store to purchase the food item.

Figure 5 shows the boundaries of our analysis, which begin with embodied water in farm inputs through household consumption, or "cradle-to-table." Our analysis did not include post-consumption water use, such as recycling and disposal. The lines in the figure show the basic structure of the food system and the flow of water. Packaging, energy, transportation, and wholesaling are shown at the bottom of the figure since they are used throughout the other stages shown.

Our analysis of supply chain decomposition applies only to food and food-related final demand ($\mathbf{y}^f$). For final food demand, we used a reduced-dimension matrix supply chain model. For food-related final demand, we used the full, unreduced IO model and then parsed the home kitchen's share.

The supply chain analysis shows where water is being used in the U.S. food system. Rehkamp and Canning (2018) fully documents the mathematics of the decomposition methodology.

Figure 5
Supply chain stages in the U.S. food system



Source: USDA, Economic Research Service.

Food Category Decomposition

The total water embodied in the U.S. food system includes both food-at-home (FAH) and food-away-from-home (FAFH) food and beverage subsets.[11] We decomposed FAH water withdrawals into specific food categories; these same food categories are represented in the ERS Food Dollar Data Product (USDA-ERS, 2019a). The categories are based on the U.S. National Income and Product Accounts (NIPA) line items of PCE related to food and beverages (DOC-BEA, 2017). Collectively, we examined 19 different types of annual food and beverage spending: total FAH and FAFH, total FAFH, total FAH, and 16 distinct (non-overlapping) food category breakouts of FAH spending.[12]

For the total FAH spending breakouts, a final demand vector, $\mathbf{y}^{f1}$ to $\mathbf{y}^{f19}$, is developed to translate total spending into individual purchases of a specific food category (plus transportation and either retail or food-service spending). For example, in 2012, the final demand vector for FAH fresh milk contained $13.74 billion in expenditure entries for the FEDS fluid milk and butter manufacturing industry, $7.53 billion to trade merchants (wholesalers and retailers), plus $260 million for various transportation services. All other elements in the final demand vector are $0.

From equation 1 above, if we replace the overall expenditure vector, $\mathbf{y}$, with $\mathbf{y}^{f\#}$ for # = 1 to 19, our measure of overall water withdrawals for that food expenditure category is measured as:

Equation (2)= $\mathbf{w}^{f\#} = \mathbf{E}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}^{f\#} = \mathbf{ELy}^{f\#} = \mathbf{Ex}^{f\#}$, for # = 1 to 19

Water use by supply chain stage, s = 1 to 11 (see figure 5), is measured as:

Equation (3)→ $\mathbf{w}^{f\#(s)} = \mathbf{E}^{s}(\mathbf{I} - \mathbf{A}^{s})^{-1}\mathbf{y}^{f\#} = \mathbf{E}^{s}\mathbf{L}^{s}\mathbf{y}^{f\#} = \mathbf{E}^{s}\mathbf{x}^{f\#}$, for # = 1 to 19, s = 1 to 11

This part of the analysis helps us better understand how water is being used for different food categories.

[11]FAH includes food purchases from grocery stores and other retailers. Conversely, FAFH includes food purchases from sit-down restaurants, fast-casual chains, sandwich shops, etc.

[12]These expenditure categories include cereal products, bakery products, beef/pork/other meats, poultry meats, fish and seafood, fresh milk, processed dairy products, eggs, fats and oils, fresh fruits, fresh vegetables, processed fruits and vegetables, sugar and sweets, other foods, and nonalcoholic and alcoholic beverages.

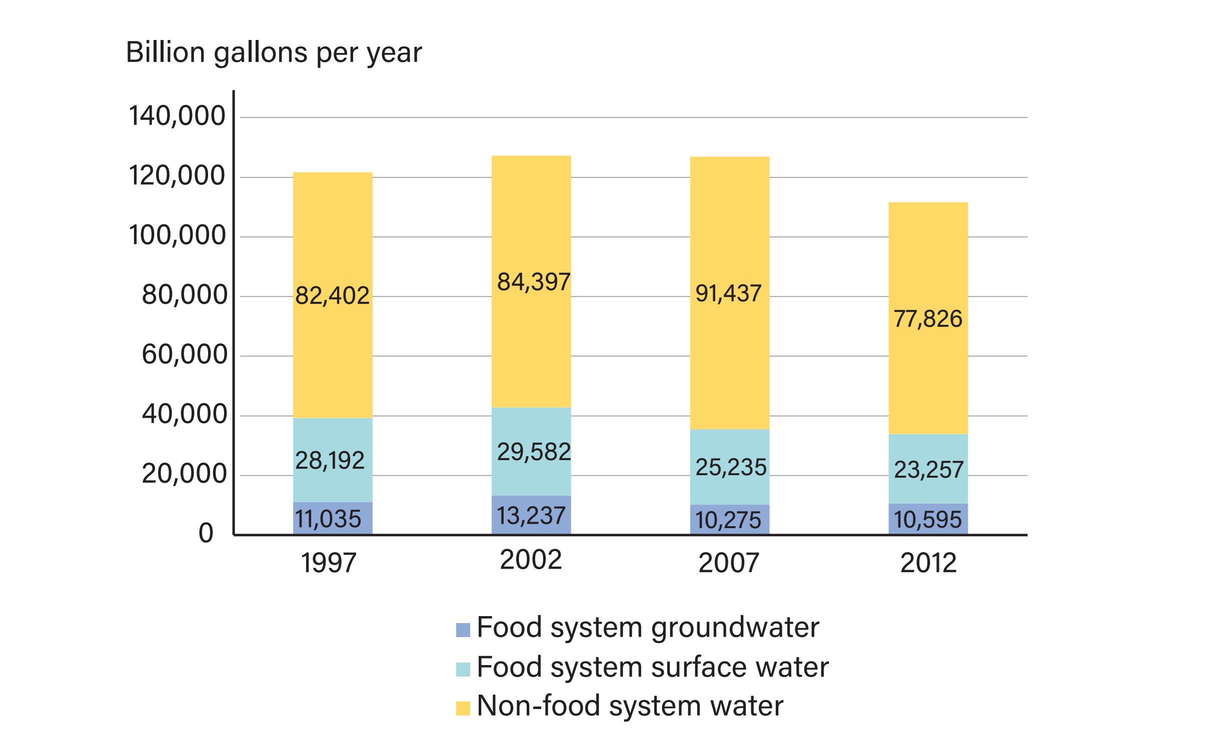
Results

How Much Water is Used for the U.S. Food System and How Does It Differ over Time?

Water is used throughout the U.S. food system's supply chain stages and is embodied in the foods and beverages purchased by domestic consumers. We present the results annually and by benchmark year (1997, 2002, 2007, and 2012) from the economic data (DOC-BEA, 2018). The benchmark year estimates are based on USGS water withdrawal data compiled 2 years prior to the corresponding benchmark year (e.g., 1995, 2000, 2005, and 2010). Changes in water use levels for each use category over the 2 years between the two data sources are not reflected in these estimates.[13] Also, the results are subject to the caveat that temporal comparisons should be made with caution, given the data quality issues described in the limitations section. The data presented can be considered a snapshot for each particular year.

Annual domestic food system water use was 39 trillion gallons in 1997, rose to 43 trillion gallons in 2002, and decreased in 2007 (36 trillion gallons) and 2012 (34 trillion gallons). The U.S. food system's share of domestic water use ranges from 28 percent in 2007 to 34 percent in 2002, meaning the annual amount of food system water use is approximately the same volume as Lake Tahoe or enough water to fill 54 million Olympic swimming pools. Shown in figure 6, the food system is more reliant on surface water than groundwater withdrawals.

Figure 6
U.S. food system freshwater withdrawals by groundwater and surface water source



Source: USDA, Economic Research Service calculations.

[13]The decision to report the results as benchmark-year measures was made to align related research that measures benchmark-year energy use.

Comparing water use in the U.S. food system to worldwide total water use (table 1) shows water use in the U.S. food system is on par with Indonesia's total water use throughout the Indonesian economy. If put in rank order, the U.S. food system would be a top-five water user worldwide.

Where is Water Used in the U.S. Food System's Supply Chain?

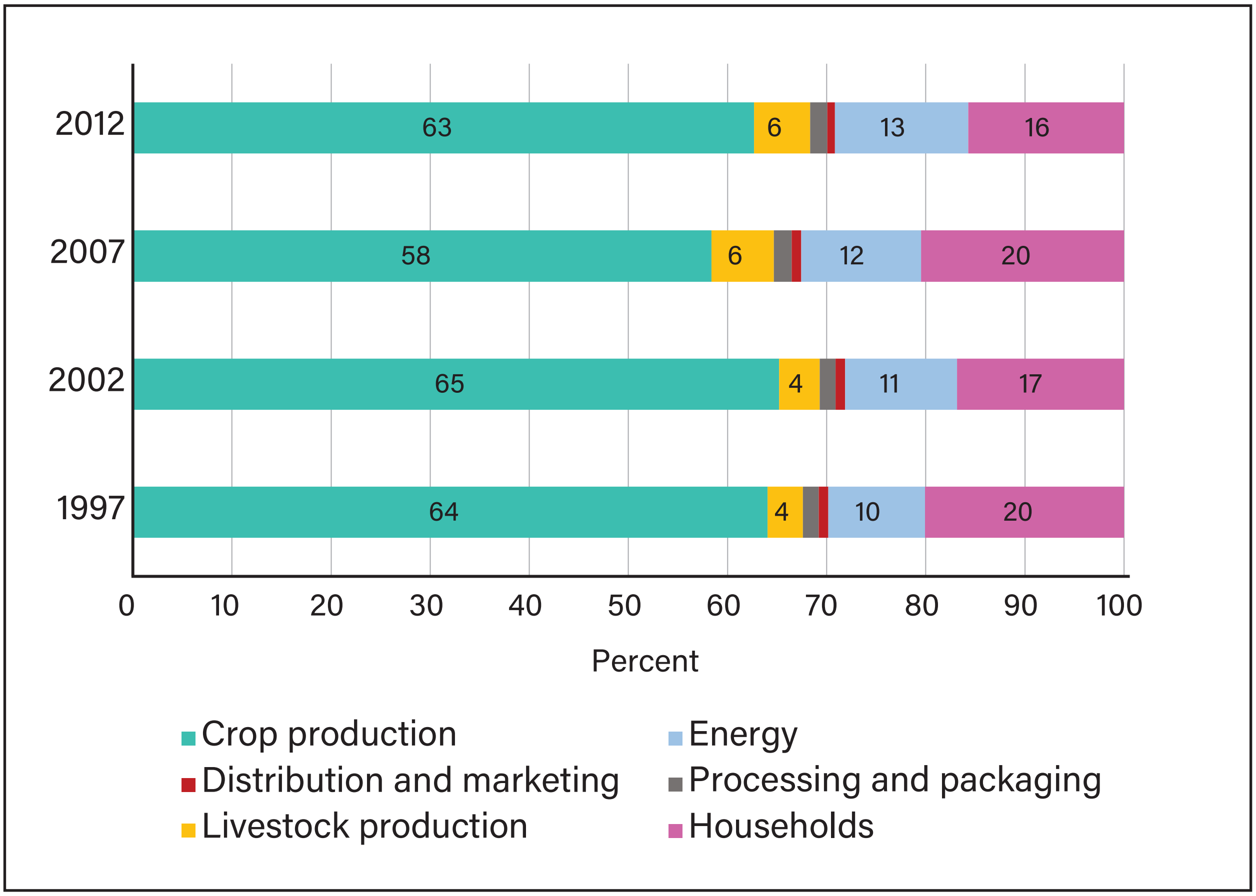
Figure 7 shows the six supply chain stages for each year of our analysis. The data behind this figure can be found in the appendix (table A3). Crop production groups farm inputs for crops and crop production. Livestock production groups farm inputs for livestock and livestock production.[14] Food processing and packaging groups the stages of food processing and packaging. Distribution and marketing groups the transportation, wholesale trade, retail trade, and foodservice stages. These groupings provide better organization by combining smaller individual shares into larger groups.

As expected, crop production used the most water along the supply chain. Crop production showed a mostly steady proportion of water use and was 63 percent of food system water use in 2012. The livestock production and energy stages showed a growing trend between 1997 and 2012, whereas both the processing and packaging stage and distribution and marketing stage remained flat in their percentage of food system water use. Processing, packaging, distribution, and marketing were a very small share of food system water use at 2 and 1 percent, respectively, in all years studied. Therefore, even with the transition to more processed food on the shelves in grocery stores in recent years (e.g., triple-washed boxed salads, peeled and cut fruits, grab-and-go items), processing water was minor compared to other supply chain stages.

Our results show that household water use is an important contributor to the food system's total water use. This stage is often not measured in the literature due to estimation limitations, particularly for studies using process-based LCA methods. Household water use includes the water embodied in home kitchen operations (e.g., the water for energy to operate a blender used in food preparation), household food-related transportation (e.g., the water for gasoline production used in vehicles for grocery shopping trips), and kitchen faucet water use (e.g., water used to rinse fresh produce or wash dirty dishes). Among these components, home kitchen operations contributed the most water, followed by the kitchen faucet. In each year of our analysis, household water use ranked second behind crop production, ranging from 16 percent (2012) to 20 percent (1997 and 2007).

[14]Irrigation for food or feed crops is the only water use connected to the food system determined by the supply chain decomposition. Irrigation does not include non-food system uses of irrigation such as fiber crops, biofuel feedstock, or irrigation used in the production of exported food or feed crops. Because non-food system uses of irrigation or exported crops are not included, the water withdrawals assigned to our crop production stage is lower than the irrigation water withdrawals reported by DOI-USGS (2018a). Non-irrigated crops are included in this analysis to the extent that they are an ingredient, input, or final food item purchased in the United States. Yet, because these crops are not irrigated, the water embodied in their production is primarily accounted for in the supply chain stages upstream from the crop production stage.

Figure 7
Share of U.S. food system freshwater withdrawals by supply chain stage



Source: USDA, Economic Research Service calculations.

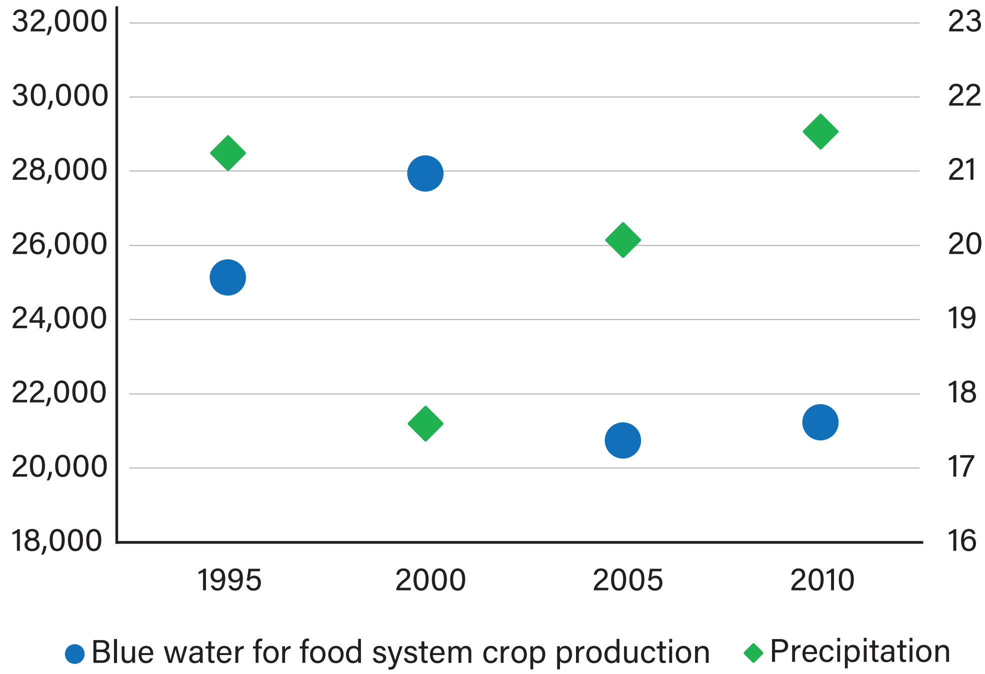
Energy is an important user of food system water, and through our research, we observed a food-energy-water nexus. This supply chain stage represents energy throughout the entire U.S. food system, which is used from farm to points of purchase—such as diesel fuel for tractors on the farm to the electricity used by grocery stores to run their refrigerators or freezers. Not included in this measure is the energy used by households—this measure is included in the household stage. Water use for food system energy reached its lowest point in 1997 at 10 percent and gradually increased in each time period to 13 percent in 2012.

The changes in supply chain stage water use are due to changes in quantity and/or types of products produced and/or production practices. We did not examine what drives the changes by stage, but that could be an interesting area of future research. However, to provide context, we performed some basic calculations to explore the relationship between blue water and precipitation, which are shown in figure 8.

Precipitation, in general, is highly variable and based on micro-geography and seasonality. In the food system, precipitation changes primarily affect farm-level production and water withdrawals for crop irrigation. Furthermore, water for crop production accounts for more than half of food system water use in each year studied.

Figure 8

Comparison of blue water for crop production in the U.S. food system and weighted average annual precipitation in the United States



Source: USDA, Economic Research Service calculations and Parameter-elevation Regressions on Independent Slopes Model Climate Group (2019).

A weighted average of annual precipitation in the United States was compared in this study to our blue water results at the crop production stage. Annual, county-level crop density-weighted average precipitation comes from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Group (2019). These precipitation data were further weighted by the county's share of national crop irrigation water. This means the counties that used a substantial amount of crop irrigation water received a higher weight since we were interested in precipitation on irrigated cropland. These weighted precipitation data were summed at the county-level and combined to reach a national data total.

A negative correlation exists between blue water and precipitation, even at national and annual scales, that admittedly obscures the differences observed at smaller scales (figure 9). As precipitation increased, blue water withdrawals decreased, signaling that these water types may be substituted for each other. Therefore, climate change's impact on precipitation may also impact the blue water use in the U.S. food system.

A more refined approach could further explore this relationship between water types and drivers of food system water use. There are complex relationships in the hydrologic cycle, such as groundwater recharge from precipitation, that could be more informed by hydrologists in future research.

How is Food System Water Used for Different Food Categories?

This section explores how FAH water use is distributed among food categories, focusing first on 2012, our most recent year of analysis. We grouped 14 food categories and 2 beverage categories, for a total of 16 groupings. Household water use cannot be attributed to these specific categories, so that supply chain stage is excluded in this section.

Table 4

Food at home (FAH) freshwater withdrawals by food category and supply chain stage in 2012

	Food system supply chain stages					
	Crop production	Livestock production	Processing and packaging	Distribution and marketing	Energy	Total
	Billion gallons/year					
Cereals	1,348	13	27	4	153	1,544
Bakery products	1,106	19	79	7	281	1,492
Beef, pork and other meats	1,002	1,195	50	9	278	2,534
Poultry	609	115	77	5	159	964
Fish and seafood	9	40	5	1	24	79
Fresh milk	218	37	13	2	70	339
Processed dairy products	444	73	22	4	137	681
Eggs	248	28	4	1	33	314
Fats and oils	704	10	9	2	60	784
Fresh fruits	1,813	2	1	3	66	1,885
Fresh vegetables	5,049	3	2	3	88	5,145
Processed fruits and vegetables	595	15	16	2	76	704
Sugar and sweets	922	8	28	3	114	1,075
Other foods	3,933	93	82	12	393	4,512
Nonalcoholic beverages	969	11	61	8	306	1,355
Alcoholic beverages	898	6	41	12	287	1,243
Total	19,866	1,667	517	78	2,523	24,650

Note: The "Other foods" category includes a number of different food products such as nuts, seeds, other snacks, and ready-to-eat or ready-to-heat foods.

Source: USDA, Economic Research Service calculations.

Fresh vegetables used the most water across all supply chain stages (5.1 trillion gallons annually), compared to all other food categories in 2012. The 5.1 trillion gallons used would be enough to cover the State of West Virginia in 1 foot of water. Other foods, which include a number of different food products such as nuts, seeds, other snacks, and ready-to-eat or ready-to-heat foods, came in second for total water use while beef, pork, and other meats ranked third—using 4.5 and 2.5 trillion gallons per year, respectively. The results are based on U.S. household purchasing decisions in 2012, so the result that the most water was embodied in the fresh vegetables category incorporates the quantity and types of vegetables purchased. This does not necessarily mean that a fresh vegetable, such as a carrot, is more water-intensive when compared on an equal mass basis to an individual item in a different category, say cheese in the processed dairy category. Both the quantity and composition of food items purchased within these categories matter for the attributed water use, in addition to production practices and water use efficiency throughout the supply chain.

Fresh vegetables also used the most water at the crop production stage, compared to other food categories in 2012, at 5.1 trillion gallons per year. The livestock production stage is next, with beef, pork, and other meats using 1.2 trillion gallons of water annually, accounting for 72 percent of water used by all food categories in this stage. For the remaining supply chain stages (processing and packaging, distribution and marketing, energy), other foods used the most water in each of these, although these stages use relatively minor amounts of water compared to crop and livestock production.

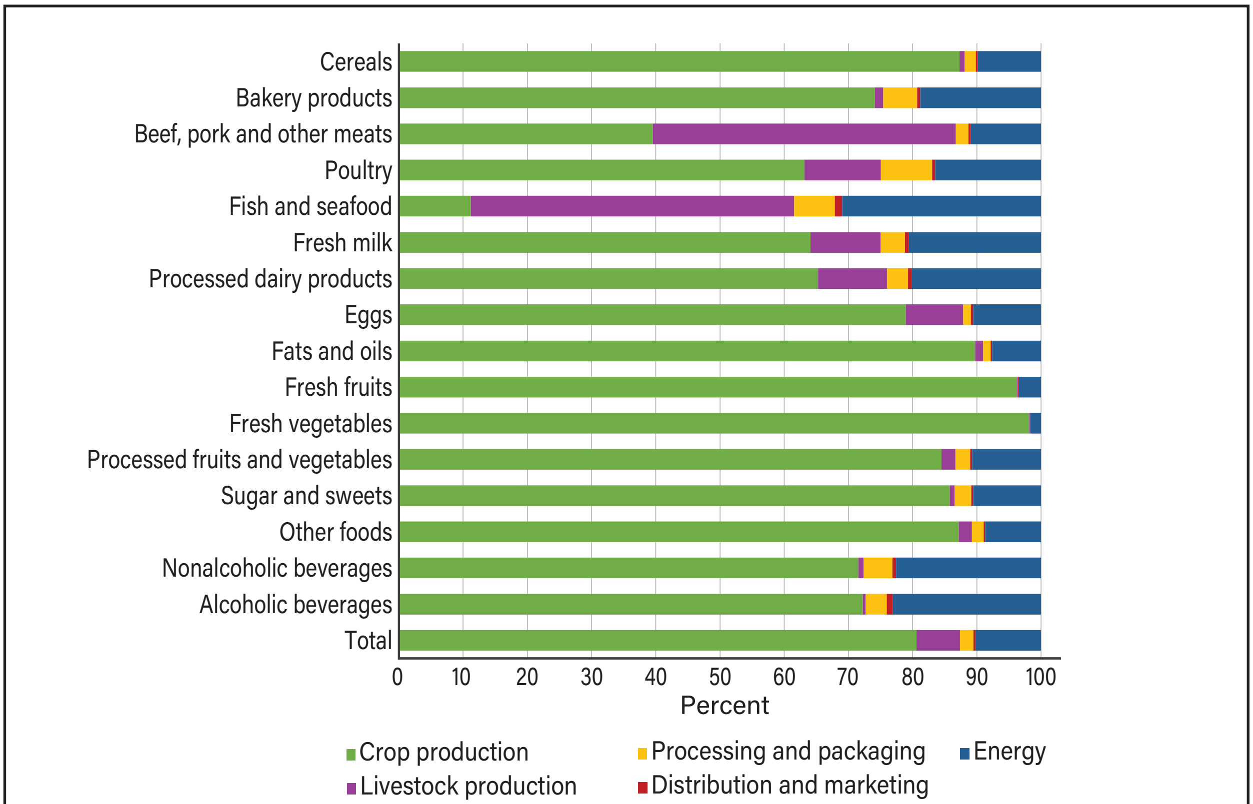
Looking deeper into the results by food category and supply chain stage, an interesting result was found in the beef, pork, and other meats food category. In this category in 2012, the water used at the crop and livestock production stages were about equal. Livestock production requires on-farm water for animal drinking and servicing. Yet, almost as much water was needed at the crop production stage to grow animal feed. In the poultry category, crop production water use was more than five times more than the water used at the livestock production stage. Therefore, we observed substantial amounts of water are needed to produce animal feed to ultimately deliver the end meat or poultry food items purchased.

Figure 9 focuses on shares of water use across the supply chain stages, rather than amounts. The crop production stage accounted for 81 percent of water use in 2012 across all food categories. Livestock production, processing and packaging, distribution and marketing, and energy used 7, 2, 0, and 10 percent of overall water, respectively. However, the shares of water use varied somewhat, based on the food category. For example, fish and seafood accounted for 50 percent of water usage at the livestock production stage and 31 percent of water use for energy, both higher-than-average shares in that year.

Table 5 shows water withdrawals for FAH by food category and year. Water in the U.S. food system is dependent on the types and quantities of foods and beverages purchased by U.S. consumers and production practices related to water efficiency. For example, fresh milk used 1.1 trillion gallons of water in 1997. The water for fresh milk production decreased in each study year, ending at 339 billion gallons in 2012, which is only one-third of the 1997 water use in this category. This decrease in water use for fresh milk production is due, in part, to domestic consumers' declining fluid milk consumption (Stewart et al., 2013). A 13 percent increase in milk production per cow in the United States in the past 10 years also contributed to this decrease (USDA-NASS, 2019b). Additionally, another key driver of our results, supported by USDA's National

Figure 9

Share of food-at-home freshwater withdrawals by food category and supply chain stage in 2012



Note: The "Other foods" category includes a number of different food products, including nuts, seeds, other snacks, and ready-to-eat or ready-to-heat foods.

Source: USDA, Economic Research Service calculations.

Agricultural Statistics Service's (NASS) data, is that vegetables are grown on irrigated land more so than other crops. For example, vegetables have one of the highest irrigated acres harvested to total acres harvested proportions compared to other crops. In 2012, 74 percent of vegetables acres harvested were irrigated (USDA-NASS, 2019a). Wheat, for comparison, was grown mostly on dryland and only 7 percent of acres harvested were irrigated (USDA-NASS, 2019a). Looking at FRIS, another NASS data series, shows that vegetables has one of the highest average irrigation rates by crop (USDA-NASS, 2018). Furthermore, of crops grown on irrigated land in the United States, vegetables are almost exclusively going into the food system whereas other crops, such as mint, can be used for oil. Further analysis is needed to determine which factors drive the changes in water withdrawals and each factor's contribution to the total change.

In each of the years studied, beef, pork, and other meats, fresh vegetables, and other foods have been the top three water users, but their order changes. In 1997, beef, poultry, and other meats ranked first, other foods ranked second, and fresh vegetables ranked third in water use across food categories. The top three water-using categories in 2012 were fresh vegetables, other foods, and beef, pork, and other meats. Again, these changes could result from a variety of factors not explored systematically in this study, such as changes in quantities, prices, production technologies, or a combination.

Table 5

Food-at-home freshwater withdrawals by food category and year

	1997	2002	2007	2012
	Billion gallons per year			
Cereals	1,391	1,516	1,416	1,544
Bakery products	997	1,729	1,459	1,492
Beef, pork, and other meats	5,749	5,252	3,012	2,534
Poultry	1,132	1,744	1,103	964
Fish and seafood	106	120	99	79
Fresh milk	1,137	1,041	538	339
Processed dairy products	1,957	1,744	897	681
Eggs	292	476	362	314
Fats and oils	375	717	720	784
Fresh fruits	1,970	2,649	1,968	1,885
Fresh vegetables	2,406	2,846	2,542	5,145
Processed fruits and egetables	713	828	742	704
Sugar and sweets	1,334	2,075	1,878	1,075
Other foods	2,657	4,428	4,422	4,512
Nonalcoholic beverages	1,180	1,240	1,252	1,355
Alcoholic beverages	730	1,275	1,078	1,243
Total	24,126	29,680	23,487	24,650

Source: USDA, Economic Research Service calculations.

Based on the results, it's evident there is variation among the 16 FAH food and beverage categories in terms of total water use, wateruse at different supply chain stages, and water use over time.

Discussion and Conclusions

Summary of Findings

This research measured domestic water resource requirements of food demand in the United States, informing the issue of the U.S. food system's ability to produce and distribute an adequate food supply given resource constraints. We considered water use in the U.S. food system over four different time periods, and we sought to understand how water for food has changed over time. Our analysis asks how much water is used in the U.S. food system, where it is used along the supply chain, and how water is distributed among different food categories.

We found total food system water use has varied over time, from 34 trillion gallons in 2012 to 43 trillion gallons in 2002. As a share of total water use in the United States, food system water use was approximately 1/3, ranging from 34 percent in 2002 to 28 percent in 2007. We find that the food system is more reliant on surface water, than groundwater but less reliant on surface water than economywide water use.

In our supply chain analysis, we confirmed the majority of water use in the U.S. food system is for crop production through irrigation. Other primary water-using stages are energy and households. In 2012, crop production, energy, and households contributed 63, 13, and 16 percent to water use in the food system, respectively. Livestock production's share of water use has been growing over time and reached 6 percent of water use in 2012. Although the magnitude of water use by the distribution and marketing stage is small at 1 percent of food system water use in each year of analysis, water use by this stage showed a 31 percent decrease between 1997 and 2012.

The finding that fresh vegetables use the most water is not surprising, as vegetables require a substantial amount of water at critical times in their production. Additionally, vegetables have one of the highest proportions of irrigated production and water application rates that support this finding.

Discussion

Our results on water for food as a proportion of total water are similar to the results in Lenzen and Foran (2001). These authors studied water in Australia and used an EIO model to find that domestic food production accounts for 30 percent of Australia's water requirement.

Water is one of the natural resources necessary for food production, and its use varies compared to other resources or environmental metrics. Because of this, it is prudent to consider different environmental metrics when thinking about food system sustainability. In comparison to a work by Canning et al. (2020) that considers U.S. food system resource use in 2007 by supply chain stage along multiple environmental dimensions, the authors found that the stage responsible for the most use varied based on environmental impact studied. For example, the farm production stage contributed the most greenhouse gas emissions (GHGE), land use, and water use—while households used more fossil fuels than supply chain stages further upstream, and most of our forest products were used in processing and packaging. Households' contribution to water and fossil fuel energy for food are important shares along the supply chain—indicating that at home, individual choices and behaviors could be impactful.

Furthermore, similar research on sustainability in the food system indicates animal-based products are relatively more resource intensive, particularly in land and GHGE (Birney et al., 2017; Boehm et al., 2018; Hitaj et al., 2019; Peters et al., 2016; Tichenor Blackstone et al., 2018). Our research results on water use show this is not necessarily the case based on domestic food and beverage purchases; fish and seafood, eggs, and fresh milk were the food categories lowest in water use needs.

Although there has been some research on water use related to the U.S. food system, this is the first study we are aware of that considers water use throughout the U.S. food system, across time periods and supply chain stages, using an EIO modeling approach. Other studies have looked at the water embodied in U.S. dietary patterns, but our results are not directly comparable. For example, Birney et al. (2017) and Tom et al. (2016) both used a footprinting methodology, relying on consumptive water data by Hoekstra et al. (2011). Birney et al. (2017) found that meats, poultry, and eggs currently consumed domestically used the most water while vegetables rank second in blue water use. Again, these authors used different methods and data than our study; recall that water footprinting is a bottom-up approach and consumptive water, their measurement unit, is a much smaller volume than water withdrawals. Food category groupings also differ. Using methods more similar to our work, Avelino and Dall'erba (2020) found that the vegetables, fruit, and nuts sectors are major water users.

Overall, trends in domestic food system water use differ from trends in total water use across all economic sectors. For example, total freshwater withdrawals were approximately constant in 2000 and 2005 and higher than the other years studied. Water use by U.S. food system was highest in 2002 (using 2000 water use data) yet decreased considerably in 2007 (using 2005 water data), such that it was ranked behind 1997 (using 1995 water use data). We hypothesized and presented key factors that may have driven water use change in earlier sections. Such factors include the relationship between precipitation and blue water for food system crop production (figure 9), the changing preferences of U.S. consumers, production characteristics as in the high proportion of irrigated acres for vegetables, and production efficiencies as in the case of fresh milk. Additionally, there are a number of competing factors that may influence water requirements, such as changes in population, changing food purchasing behavior and production of different types of crops/animals, temperature fluctuations, and the adoption of more efficient water conveyance and use technologies, among others. Three papers stand out in providing insight on factors driving U.S. water withdrawals using structural decomposition analysis (Avelino and Dall'erba, 2020; Wang et al., 2014; and Wang et al., 2015). Similarities between these papers and our work are 1) the primary water data source was USGS, 2) we evaluated comparable time periods, and 3) an EIO model was used.

Wang et al. (2014) focused on industrial sector water withdrawal use in the United States between 1997 to 2002. The authors considered 136 sectors, including food-related sectors such as crop production and food manufacturing, but used a broader scope than in our work. The results of the study were economywide, not focused on the U.S. domestic food system. The authors found net water withdrawals increased between 1997 and 2002, with water use intensity, GDP per capita, and population driving this increase, in rank order. Expanding on this work to compare water withdrawals by U.S. industrial sectors between 2005 and 2010, Wang et al. (2015) found water withdrawals decreased by 14 percent overall, and the primary factor driving this decrease was water use efficiency.

Avelino and Dall'erba (2020) did a commendable job expanding on the work of Wang et al. (2014 and 2015) by focusing specifically on agribusiness sectors and by including both domestic and international drivers of water use (e.g., international trade, foreign population) in these two sectors. Their results showed that water efficiency (i.e., a decrease in water intensity) mostly drove the decrease in water withdrawals for the agricultural sector, followed by technology effects. Looking forward, the authors wrote, "given that the U.S. population and per capita GDP is expected to increase over the next 5 decades, water management strategies will have to support changes in food consumption and dietary patterns" (Avelino and Dall'erba, 2020).

Our research results may help inform policymakers concerned about the viability of the Nation's food system, which currently provides most of our food and beverages and will need to meet future domestic food demands. Water is an essential human need and a required input in the production of food and beverages purchased by U.S. consumers. These results may contribute to discussions around food system sustainability and the synergies or tradeoffs that may exist. Sustainable production and consumption are intrinsically linked. Changing consumer preferences in types and quantities of foods and beverages purchased affects production upstream, and ultimately the water required throughout the U.S. food system. Impactful work has been done looking at healthy diets from sustainable food systems (Willett et al., 2019).

Limitations

There are some additional limitations of our study to note, specifically relating to the data used. First, water use data are measured in 5-year intervals (years ending in a 5 or 0) (DOI-USGS, 2018a). Our benchmark data on economic transactions are also available every 5 years, but for years ending in 2 or 7 (DOC-BEA, 2018), so they do not match exactly. Other data sources used for allocation are also for years that are inconsistent with the water data (e.g., the COA is for years ending in 2 or 7 as the economic survey data).

Furthermore, the water data used in this research can inform water use in the U.S. food system over time, but the data are not a time series. This is a limitation, as other resources used throughout the food system are measured annually (e.g., State Energy Data System (SEDS) published by DOE-EIA, 2018).

USGS is the main source of water use data for the Nation (National Research Council, 2002) and provides the best-available estimates for our purposes. As with all studies, the quality of the input data determines the quality of the output data, and we acknowledge that the limitations of the input data may lead to uncertainty in our results. As an example, USGS stopped estimating commercial and hydroelectric power withdrawals starting in 2000 (DOI-USGS, 2018b). Commercial water use includes "water for motels, hotels, restaurants, office buildings, other commercial facilities, military and nonmilitary institutions, and (for 1990 and 1995) off stream fish hatcheries" (DOI-USGS, n.d.). If these data existed for all the years studied in this report, we would have included these withdrawals, and the quantity of water we attributed to the food system would increase. In this study, water use by commercial industries represents their indirect self-supply water use (for example, through their use of industrial inputs) and their water use from the public supply. The National Research Council (2002) outlined inconsistencies and uncertainty in the USGS water data. The council made several recommendations to standardize and improve the water use estimates, which would, in turn, improve our results.

A more detailed and technical discussion around the reliability of the National input-output accounts and water estimates are presented in the appendix section "Reliability of National Accounts and Water Estimates."

Future Directions

To build on this work in the future, precipitation data could be collected and added to estimates measuring how water is used throughout the U.S. food system. Although it is briefly touched on in this report, the addition of precipitation data that accounts for availability during the growing season would improve our accounting for food system water use at the farm stages. The relationship between precipitation and water withdrawals for irrigation could be studied, as well as the drivers of the intertemporal changes in U.S. food system water withdrawals.

The water data were built up to the national level, but a more refined geographical component could be added. Water embodied in U.S. foods and beverages could be shared back down to the State or county level to see which regions the food system is most reliant on for water. Then, one could identify where water stress may be a problem given the water resources available in those regions. This research is best facilitated by compiling a multiregional environmental input-output model or MEIO (Rehkamp and Canning, 2018).

Another area of water research considers virtual water trade, or how water embodied in goods moves geographically through trade (Hoekstra and Hung, 2002). Mubako et al. (2013) compared the virtual water transfers of California and Illinois, finding that both states are net exporters of virtual water. Research also finds domestic virtual water transfers to be much larger than international transfers. Regional virtual water transfers throughout the United States could be analyzed with an MEIO model as well. Other research focuses on international virtual water trade (Chen and Chen, 2013; Lenzen et al., 2013).

Lee et al. (2019) developed an innovative, county-level water scarcity index for the United States. The authors estimated the available water remaining using high-spatial resolution data and incorporated measured runoff and human water use data to provide a geographical context for locations more vulnerable to climate change. Linking the water scarcity index with water withdrawals in the U.S. food system could better inform where adaptation measures are most urgent, especially as projected changes in the climate system indicate increasing risks (IPCC, 2014). Existing published work in this area links water-use and water-scarcity measures for Australia and the rest of the world (Ridoutt et al., 2018).

The 2015 water use data are available from USGS, so the analysis could be expanded to more recent years as the benchmark input-output data and other supplementary data sources become available. Finally, the FEDS-EIO framework is structured and versatile, so other natural resources deemed important to food production could be analyzed.

Furthermore, water withdrawals in the U.S. food system could be linked to dietary choices, and future food demand scenarios could be modeled. This modeling could contribute to the burgeoning body of sustainable nutrition literature and expand on the work of Rehkamp and Canning (2018).

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Appendix

Water Use Data

Relevant technical notes about the data or analysis are organized by water use category below. Table A1 summarizes the U.S. Geological Survey (USGS) variables used in the analysis across the 4 years and provides additional detail when necessary.

Aquaculture

In 1995, aquaculture water use was reported in animal specialties (fish farming) and commercial (fish hatcheries) (DOI-USGS, n.d.). We considered animal specialties as aquaculture water use in 1995 and assigned the water to Food Environment Data System (FEDS) industry category animal production except for cattle and poultry. Aquaculture water use in 2000 and later years was also assigned to the FEDS industry category animal production except for cattle and poultry. We did not measure commercial water use in this analysis because water use categories change over time (DOI-USGS, 2018b). Commercial water use was last measured in 1995 by USGS.

Domestic

Domestic water use is a sum of self-supplied domestic water use and publicly supplied domestic deliveries. Domestic deliveries from public supply water use were not reported in 2000, so we imputed these data. We calculated an average of per-capita publicly supplied domestic water use in 1995 and 2005 and multiplied this average by the 2000 reported population for each county. See notes under public supply for details on publicly-supplied domestic deliveries.

Water use in the home is varied and dependent on dwelling size and lifestyle preferences, among other factors. Research is sparse on looking specifically at kitchen water use as a proportion of total household water use in the United States – the water used in the home that is food-related and relevant to our study. Typically, faucets are grouped into one category, and the dishwasher is a minor contributor to household water use (Water Research Foundation, 2016). Kitchen faucet water use was calculated as 15 percent of domestic water use, informed by a literature review and following Rehkamp and Canning (2018), and is only relevant for food at home (FAH). We used this proportion consistently across all years studied.

Kitchen faucet water use is a subset of household water use, a supply chain stage in our analysis. The other components of household water use are estimated as part of the final demand vector for food as described in the text.

Industrial and Mining

County Business Patterns (CBP) 1998 data (DOC-BOC, n.d.a.) are used instead of the 1997 CBP data since the 1998 data are the first year where industries were classified by North American Industry Classification System (NAICS) codes, rather than the older Standard Industry Classification (SIC) codes.

We allocated the industrial and mining water use at the state level. First, in the CBP data, there is a catch-all county-level Federal Information Processing System (FIPS) code ending in -999 which represents all other counties that do not individually report employment data. We did not have a method to share employment to the counties that fall under FIPS XX-999, and the prevalence of employment by NAICS industries to -999 FIPS was too large to ignore. Second, there were data inconsistencies between the counties that report industrial and/or mining water withdrawals in the USGS data and the counties that report employment data by industry in the CBP data. Allocating at a State level reduced the uncertainty around using employment shares to disaggregate these industrial water use categories. Furthermore, allocating at the State level was acceptable to us since the industrial and mining water was not as critical as other water use categories (e.g., irrigation) when studying the U.S. food system.

Irrigation

In addition to crop irrigation, irrigation water is estimated to be used for golf courses, parks, nurseries, turf farms, cemeteries, other self-supplied landscape watering, and other related processes (Dieter et al., 2018). In 2000, 2005, and 2010, the irrigation water use category contained two subcategories: irrigation-crop and irrigation-golf. This breakout of the irrigation water category into crop and golf subcategories was used in 1995, and not all counties in 2000, 2005, and 2010 reported the disaggregation. Therefore, we imputed irrigation-crop and irrigation-golf for all years since crop irrigation is an important input into the U.S. food system. We imputed these data using the share of total irrigation water in that county from the most recent year the subcategories were reported—or in the case where the disaggregation into subcategories was never reported—we assigned 100 percent of irrigation water to irrigation-crop. For example, in 1995, we used the share from 2000 to disaggregate total irrigation water; if the share did not exist, we used the share in 2005; if the share did not exist, we used the share in 2010; if the share did not exist in any year, we assigned the water to irrigation-crop. For 2005, the nearest year of disaggregation could be 2000 or 2010. If the disaggregation existed in both 2000 and 2010, we used an average share.

Livestock

From 1995, data in the livestock water use category had two subcategories: animal specialties and stock. In our analysis, the stock subcategory was allocated to different types of livestock based on our allocation metrics, as in all later years. The subcategory of animal specialties includes horses and fish farming (DOI-USGS, n.d) and was ultimately assigned to FEDS industry category animal production, except cattle and poultry in our analysis. Starting in 2000, data for animal specialties are reported in livestock (horses) and aquaculture (fish hatcheries and fish farms) water use categories.

Public supply

USGS reports cover total publicly supplied water data, to include a subcategory of domestic deliveries from the public supply. USDA, Economic Research Service (ERS) calculated net public supply by subtracting the domestic deliveries from total publicly supplied water to allocate using the IO model. There were inconsistencies in the county-level data. For example, there were cases where domestic deliveries from the public supply in a county were greater than the total publicly supplied water. This difference can occur since delivery is to a particular county but could be sourced from another, nearby county. To remedy this difference, we calculated net public supply and allocated it to our FEDS industries at the national level.

Thermoelectric

Thermoelectric water use includes different subcategories (e.g., once-through and recirculation water use in 2005), but we used total thermoelectric water withdrawals for consistency throughout the years.

Table A1
Summary of U.S. Geological Survey (USGS) data used in analysis

USGS water use cateogries			USGS variables			
Category	Subcategory	Withdrawal type	1995	2000	2005	2010
Aquaculture		Self-supplied	LA-WFrTo	LA-WFrTo	LA-WFrTo	AQ-WFrTo
Domestic		Self-supplied+Publicly-supplied	Calculated by authors			
	Self-supplied domestic	Self-supplied	DO-WFrTo	DO-WFrTo	DO-WFrTo	DO-WFrTo
	Domestic deliveries from public supply	Publicly-supplied	DO-PSDel	I	DO-PSDel	DO-PSDel
Industrial		Self-supplied	IN-WFrTo	IN-WFrTo	IN-WFrTo	IN-WFrTo
Irrigation		Self-supplied	IR-WFrTo	IT-WFrTo	IR-WFrTo	IR-WFrTo
	Crop irrigation	Self-supplied	I	IC-WFrTo	IC-WFrTo	IC-WFrTo
	Golf irrigation	Self-supplied	I	IG-WFrTo	IG-WFrTo	IG-WFrTo
Livestock		Self-supplied	LS-WFrTo	LS-WFrTo	LS-WFrTo	LI-WFrTo
Mining		Self-supplied	MI-WFrTo	MI-WFrTo	MI-WFrTo	MI-WFrTo
Public supply		Publicly-supplied	PS-WFrTo	PS-WFrTo	PS-WFrTo	PS-WFrTo
	Net public supply (non-domestic)	Publicly-supplied	Calculated by authors			
Thermoelectric		Self-supplied	PT-WFrTo	PT-WFrTo	PT-WFrTo	PT-WFrTo

Notes: Data are U.S. county-level water withdrawals (excluding territories and the District of Columbia) for years 1995, 2000, 2005, and 2010.
I = imputed data, not reported in DOI-USGS (2018a) data.
The rows highlighted in grey are those we allocated to Food Environment Data System (FEDS) economic industries and used in the Food Environment Data System's Environmental Input-Output model.
Net public supply (NetPS-WFrTo) was calculated by subtracting domestic deliveries from public supply (DO-PSDel) from public supply (PS-WFrTo) since this is the water withdrawn for domestic use and how it is best accounted for in our model.
Total domestic (DO-TOTAL) was calculated by summing the self-supplied domestic water use (DO-WFrTo) and domestic deliveries from public supply (DO-PSDel).

Source: USDA, Economic Research Service calculations using data from U.S. Department of the Interior, U.S. Geological Survey (DOI-USGS). 2018. USGS Water Data for the Nation. National Water Information System: Web Interface. Accessed November 13, 2018. Data last updated June 2018.

Estimating Allocation Metric Suppressions

The example below describes an example of estimating data suppressions in the Census of Agriculture (COA). We used an identical approach for estimating suppressions in the FRIS and the CBP but adapted to these datasets.

Example Estimating Census of Agriculture Data Suppressions

The following describes the mathematical model we used to estimate the data suppressions, drawing on Canning (2013) and an example of crops in the COA.

In general, COA data related to crop and animal product production metrics (e.g., harvested acreage, the value of production, quantity sales, etc.) are reported with up to three statistical hierarchies:

1. N (commodity hierarchy) with subsets NP and NC denoting "parent" and "child" subsets[15]
2. G (geographic hierarchy) with subsets GP and GC

[15]A statistic for a "parent" subset is typically equal to the sum of statistics for all "children" subsets linked to that parent. In rare exceptions, the parent statistic is ≥ the sum of its children.

3. R (row, in lieu of an all-encompassing descriptive term) with subsets RP and RC[16]

For any statistic reported in the COA, $\mathbf{x}_{g,n,r}$, data suppressions exist in the publicly-available reports. Denote vn,g,r the estimated variance of $\mathbf{x}_{g,n,r}$ such that a published statistic has a zero variance and a suppressed statistic has a non-zero variance associated with an initial mean estimate, $\mathbf{x}^{0}_{g,n,r}$. The following model is a constrained maximum likelihood estimator (CMLE) of the true unobserved suppressed statistics (see Canning, 2013):

Equation **(A1)** $$\min_{x^1_{g,n,r}} \sum_{g} \sum_{n} \sum_{r} \left(\frac{x^1_{g,n,r} - x^0_{g,n,r}}{v^0_{g,n,r}} \right)^2$$

subject to

Equation **(A2)** $$\sum_{gc \in gp} x^1_{gc,n,r} = x^1_{gp,n,r}, \quad \forall\, gp \in g,n,r$$

Equation **(A3)** $$\sum_{nc \in np} x^1_{g,nc,r} = x^1_{g,np,r}, \quad \forall\, np \in, g,n,r$$

Equation **(A4)** $$\sum_{rc \in rp} x^1_{g,n,rc} = x^1_{g,n,rp}, \quad \forall\, rp \in, g,n,r$$

Equation **(A5)** $$x^1_{g,n,r} = x^0_{g,n,r} \ \forall\, v^0_{g,n,r} = 0$$

The objective function (equation A1) is minimized subject to constraints (equations A2-A5). This functional form is often called a quadratic penalty function (Preckel, 2001) because any deviation of the endogenous variables from their priors is penalized in inverse proportion to the prior variance statistic. Provided constraints (equations A2-A5) are valid, and the prior estimates are unbiased with errors normally distributed around the true unobserved statistic, the expression in brackets in equation A1 is both a standard normal and chi-square statistic. Treated as the log-ratio test for the CMLE, confidence intervals can be assigned to all variable estimates.

Among the constraints, equation A3 indicates that for any geography/row pair, all children commodity statistics, $x^1_{nc \in np}$, must sum to their associated commodity parent statistic, x^1_{np}. For example, estimates of wild and cultivated blueberry harvested acreage must equal total blueberry harvested acreage. Equations A2 and A4 have the same interpretations but apply to geography and row hierarchies, respectively. For example, the sum of harvested wild blueberry acreage across all Maine counties equals harvested wild blueberry acreage for the State of Maine, whereas the sum of bearing and non-bearing grape acreage in Sonoma County, California, equals total grape acreage in that county. Equation A5 fixes estimates for all published statistics since not doing so produces an infinite penalty (equation A1) due to the zero-variance assumption assigned to published statistics. Some row hierarchies in the COA are inequality constraints. In those cases, the equality in constraints (A2) to (A4) change to inequality (≤) constraints.

[16]Examples include [total/bearing/nonbearing] and [total/fresh-market/processing-market].

Allocating Water Withdrawals to NAICS-Based Industries

As described in the previous section, we estimated suppressions to comprise complete datasets we then used to allocate the water withdrawals.

Example Allocating Livestock Water Withdrawals

We show mathematically how we allocated livestock water withdrawals, as an example.

Equation (A6) $$h_{u,s,t,g,n} = w_{u,s,t,g} \times \frac{[i_{t,g,n} \times c_n]}{\sum_n [i_{t,g,n} \times c_n]}, \forall n \in u$$

where h: water use allocation from USGS to NAICS industry

u: USGS water use category (livestock, for this example)

s: source (groundwater or surface water)

t: time (year)

g: geography (county FIPS code)

n: NAICS-based identifier (animal type, for this example)

$w_{u,s,t,g}$ is freshwater withdrawals from USGS and is multiplied by $\frac{[i_{t,g,n} \times c_n]}{\sum_n [i_{t,g,n} \times c_n]}$, the share based on our allocation metric. In the numerator of the share term $i_{t,g,n}$, is the livestock inventory (estimated using USDA-NASS, 2019a) multiplied by c_n, the water use coefficient (Lovelace, 2009). This results in $h_{u,s,t,g,n}$, the water allocated in a particular year, in a particular county to a particular animal and is a subset of $w_{u,s,t,g}$. We estimated the suppressions using the maximum-likelihood model described in the previous section for the term $i_{t,g,n}$, so that we would have a complete dataset.

For example, consider Kent County, Delaware. There was an inventory of 2,099 milk cows reported in the 2012 COA. The number 2,099 was multiplied by the median water-use coefficient of 35 gallons per animal per day (Lovelace, 2009), making the numerator of the share 73,465 gallons per day attributed to milk cows in that county. This same method was applied across all livestock inventories and respective water-use coefficients in Kent County in 2012. Then, the denominator is a sum of the gallons per day across all animals to develop the share of water withdrawals we attribute to milk cows. This denominator is multiplied by the groundwater withdrawals of 0.39 million gallons daily from USGS (there is no surface water withdrawn for livestock in Kent County in 2012, but when there is, we keep track of both sources assigning the water use by animal to a groundwater and surface water in proportion to the shares in total freshwater in the county). The result gives us the amount of USGS water withdrawals we attribute to milk cows in the county in that particular year. This water is ultimately summed across counties to the national level and then summed to the FEDS industry group dairy and beef cattle.

Reliability of National Accounts and Water Use Estimates

This report provides annual U.S. economywide estimates, in 5-year intervals from 1997 to 2012, for the total domestic freshwater withdrawals embodied in all foods and beverages purchased and prepared by or for all domestic food consumers. Estimates are from the application of environmental input-output (EIO) models, compiled from annual official U.S. Government statistics. These estimates include both the national income and product accounts and the benchmark input-output accounts published by the Bureau of Economic Analysis (DOC-BEA, 2017; DOC-BEA, 2018). The estimates also include the data product, Water Use in the United States, published by USGS (DOI-USGS, 2018c). The EIO approach to measuring economic uses of freshwater withdrawals in the United States follows the recommendations of the U.S. National Academy of Science (National Research Council, 2002).

Measuring the accuracy of BEA national account estimates is challenging because the estimates are constructed from survey, non-survey, and administrative data. Since "true" values behind the data in these accounts can never be observed, conventional measures of accuracy cannot be assessed. Therefore, the concept of reliability is used. BEA's principal standard of reliability is based on the revisions from its early estimates to its "latest" estimates, most of which have been through at least one comprehensive revision. According to this approach, BEA data used to compile our EIO model are reliable (Fixler et al., 2018).

In 2002, the National Research Council of the U.S. National Academy of Science published a comprehensive assessment of the USGS water use data products (National Research Council, 2002). Their assessment noted that accuracy and confidence limits of water use estimates were not being quantified. The report points to two approaches for the development of such measures—stratified random sampling and multiple regression analysis—as a basis for a recommendation that USGS identify techniques to determine the standard error for every water use estimate (see page 7 in National Research Council, 2002). Through their Water-Use Data Research program, USGS seeks to develop improved water-use data through agreements with State water-resources agencies. To date, the emphasis of this research program focusing on data collection methods and implementation of methodologies for measuring standard errors have not materialized.

Academic research exploring methods of estimating the reliability of a system of national accounts (SNA) data focuses on three methodologies—theoretical statistics, information theory, and Bayesian econometrics. Byron (1996) examines the performance of several standard tests for estimator bias using a constrained maximum likelihood estimation (MLE) model to estimate a national social accounting matrix (SAM) from the official SNA data of Great Britain. Conducting Monte Carlo simulations (1,000 replications) that generate normally distributed SAM data priors, with a bias sequentially introduced into otherwise unbiased random initial data, Byron (1996) found that a likelihood ratio (LR) test based on the ratio of the difference between constrained and initial estimates to the standard errors of data priors effectively identified initial estimate bias and "offered powerful support for the use of formal testing procedures…" (page 144). Canning (2013) demonstrated an application of this LR test using U.S. data on consumer expenditures and found the approach had an impressive capacity to recover underlying statistics being withheld from the analysis. Like the LR test, the information theoretic entropy ratio (ER) is computed as the normalized difference between constrained and prior cross-entropy (CE) estimates and has a chi-square distribution that facilitates hypothesis testing (Jaynes, 1979). Golan and Vogel (2000) demonstrated the use of ER statistics to evaluate the contribution of several categories of data to the estimation of stationary and non-stationary U.S. SAM accounts. Preckel (2001) demonstrated a unified interpretation of hypothesis testing under both the MLE and CE frameworks, based on a notion of both the quadratic minimum and CE functions as penalty functions that provide parallel interpretations of the general linear model. Aruoba et al. (2016) applied optimal signal-extraction techniques to assess measurement error of historical U.S. gross domestic product (GDP) growth. This technique, like current BEA methodologies, is based on measures of statistical discrepancies over time and across measurement methods, for example, expenditure versus income-based measures of GDP.

To date, these promising research findings inform and improve the estimation methodologies of Country SNA data programs worldwide. But the findings have not yet produced widespread publications of standard errors or confidence intervals for any of the key economic indicators published by the SNA. A key barrier for this has been the necessity of imposing distribution error assumptions to statistics drawn from non-survey and administrative data or from "legacy" statistics. Legacy statistics refer to the imposing of assumptions about data structure based on historical measures—oftentimes dating back many years. A powerful workaround for this problem is the application of Bayesian methodologies. This approach explicitly incorporates existing information and permits revision of our knowledge regarding the distribution of the unknown model parameters as additional information becomes available, which facilitates the statistical measurement of the underlying parameters (Baldos et al., 2020).

It is important to note the application in this report of a type I IO multiplier model is designed to provide a retrospective look at historical data in order to decompose the components of U.S. food GDP. In this case, we have developed an environmentally-extended model based on the metric of embodied blue water. Contrast this type of analysis with a forward-looking analysis based on assumptions of some exogenous change to the economic setting, such as a new average U.S. diet or an income induced change to consumer food expenditures. In this latter type of forward-looking analysis, it is common practice to consider different degrees of change, often based on statistical forecasts in which low, medium, and high change occur, usually with a two-tailed normal probability distribution around the medium outcome (see, for example, table 9 in Canning and Stacy, 2019). In this report, we conducted a retrospective analysis and did not consider alternative food GDP scenarios. For each annual EIO model between 1997 and 2012, our food GDP scenarios were the official point estimates published by BEA (DOC-BEA, 2018).

In summary, our approach to reporting model reliability measures from multiplier model analysis was to carry forward the reliability measures provided by the custodial agencies for the model datasets we used and those that we generated for our scenario analysis. In the case of this report, we generated no scenario analysis, and the two custodial agencies for the model datasets we used—BEA and USGS—currently produced reliable and validated point estimates.

Comparison to Previously Published Results

A similar methodology was used by Rehkamp and Canning (2018) to study freshwater in the U.S. food system. In addition to extending the analysis over 4 time periods, we improved on our past research in several ways:

- Updated source data on water withdrawals (DOI-USGS, 2018a)
- Improved suppression estimation for livestock water withdrawals
- Accounted for county water withdrawals that did not have an allocation metric
- Improved the disaggregation method for crop irrigation and golf irrigation

Table A2 compares the results from Rehkamp and Canning (2018) and the results presented in this report over the time period (2005 water use data corresponding with the 2007 benchmark IO data). Overall, the total water withdrawals attributed to the U.S. food system decreased by 101 billion gallons per day, or essentially remaining unchanged for earlier results. When looking at food system stages presented in Rehkamp and Canning (2018), the largest percentage change was a decrease of 3 percent in the distribution and marketing stage or a magnitude of 9 billion gallons per day.

Table A2
Comparison between 2007 water results

	Rehkamp and Canning (2018)	Current report		
	Billion gallons per year (2007)		Difference	Percentage change
Crop production	20,916	20,732	184	-1
Livestock production	2,215	2,237	-21	1
Processing and packaging	622	630	-9	1
Distribution and marketing	359	350	9	-3
Energy services	4,270	4,287	-17	0
Households	7,228	7,272	-45	1
Total	35,611	35,510	101	0

Source: USDA, Economic Research Service calculations in 2020 as compared to Rehkamp and Canning (2018).

Supplemental Data Tables

Table A3
U.S. food system water withdrawals by supply chain stage

	1997	2002	2007	2012
	Billion gallons per year			
Crop production	25,123	27,926	20,732	21,220
Livestock production	1,401	1,741	2,237	1,912
Processing and packaging	615	690	630	582
Distribution and marketing	385	410	350	267
Energy	3,827	4,834	4,287	4,554
Households	7,876	7,217	7,273	5,316
Total	39,226	42,819	35,510	33,851

Source: USDA, Economic Research Service calculations.

Table A4
Benchmark year and annual food-related final demand categories

FEDS final demand benchmark series code	Representative products in category	FEDS final demand annual series code
01	Rice and packaged rice products	07
02	Flour, cornmeal, malt, dry and refrigerated/frozen flour mixes (biscuits pancakes, cakes, etc.) Made in mill	07
03	Breakfast cereals and oatmeal	07
04	Macaroni and noodle products with other ingredients and nationality foods (not canned or frozen)	10
05	Noodle pasta and dry soup mixes with other ingredients, plus fresh pasta and packaged unpopped popcorn	04
06	Popcorn and wild rice (not canned or processed)	01
07	Grits and soy flour	07
08	Dry pasta, dry noodles, and flour mixes from purchased flour	08
09	Bread, rolls, cakes, pies, pastries (including frozen)	08
10	Cookies, crackers, biscuits, wafers, tortillas (except frozen)	08
11	Beef and veal (fresh or frozen/not processed canned or sausage)	12
12	Pork (fresh or frozen/not canned or sausage)	12
13	Boxed cooked and processed (lunch) meats plus lamb & other meats (including game)	03
13	Boxed cooked and processed (lunch) meats plus lamb & other meats (including game)	12
14	Fresh frozen or processed poultry (except soups)	12
15	Fresh frozen or prepared fish & shellfish (incl. Canned and soups)	02
15	Fresh frozen or prepared fish & shellfish (incl. Canned and soups)	03
15	Fresh frozen or prepared fish & shellfish (incl. Canned and soups)	13
16	Fresh milk	11
17	Natural and processed cheese	11
18	Dry condensed and evaporated dairy	11
19	Ice-cream, custards, frozen yogurt, sherbets, frozen pudding	11
20	Cottage cheese, yogurt, milk substitutes, sour cream, butter, milk, eggnog	11
21	Shell eggs	02
22	Dried frozen or liquid eggs	04
23	Corn oils	07
24	Margarine, shortening, oilseed, oils	07
25	Peanut butter	04
26	Mayonnaise, salad dressings, sandwich spreads	04
27	Oilseed, oils, and other oilseed products	07
28	Butter and butter oils	11
29	Lard and other animal oils	12
30	Fresh fruits	01
31	Fresh vegetables	01

Table A4

Benchmark year and annual food-related final demand categories

FEDS final demand benchmark series code	Representative products in category	FEDS final demand annual series code
32	Mushrooms and other vegetables grown under cover	01
33	Fresh herbs and spices	01
34	Fruit flours made in grain mills	07
35	Frozen fruits and vegetables	10
36	Canned or dried & dehydrated fruits or vegetables	10
37	Processed vegetables and fruits packaged with other products (e.G., Noodles)	04
38	Dry beans and peas (not canned)	01
39	Corn sweeteners (e.G., Karo syrup & sugar substitutes)	07
40	Sugar and chocolate products, non-chocolate bars, gums, and candies	09
41	Jams, jellies, and preserves	10
42	Dessert mixes, sweetening, syrups, frostings	04
43	Almonds and other fresh tree nuts	01
44	Fresh peanuts	01
45	Granola	07
46	Frozen dinners, nationality foods, other frozen specialties (excl. Seafood)	10
47	Catsup and other tomato sauces (e.G., Spaghetti sauce)	10
48	Pickles and pickled products	10
49	Canned soups and stews (excl. Frozen or seafood) and dry soup mixes	10
50	Dry and canned milk plus dairy substitutes	11
51	Nuts and seeds	04
52	Chips and pretzels	04
53	Vinegar, condiments, sauces (excl. Tomato-based), semi-solid dressings, and spices	04
54	Baking powder and yeast	04
55	Refrigerated lunches	04
56	Refrigerated pizza (fresh, not frozen)	04
57	Bagged salads	04
58	Value added fresh vegetables	04
59	Fresh-cut fruits	04
60	Fresh tofu	04
61	Coffee, tea, and related beverage materials	14
62	Soft drinks and ice	14
63	Bottled water	14
64	Frozen and canned fruit drinks	10
65	Frozen and canned vegetable drinks	10
66	Spirits, flavorings, and cocktail mixes	04
67	Wine and brandy	14
68	Beer	14

Table A4

Benchmark year and annual food-related final demand categories

FEDS final demand benchmark series code	Representative products in category	FEDS final demand annual series code
69	Food on farm, vegetables	01
70	Food on farm, fruits and tree nuts	01
71	Food on farm, dairy	02
72	Food on farm, beef	02
73	Food on farm, meats except beef and poultry	02
74	Salt, fatty acids, and organic chemical food flavorings	05
74	Salt, fatty acids, and organic chemical food flavorings	06
75	Household: natural gas	15
76	Household: electricity	16
77	Household: petro for cooking	17
78	Household: appliances	18
79	Household: kitchen equipment	19
80	Household: motor vehicles and parts	20
81	Household: auto repair and leasing	20
82	Household: auto insurance	20
83	Household: auto fuels, lubricants, and fluids	21
84	All other final demand	22

Table A5

FEDS Benchmark Commodities with concordances to FEDS Annual Commodities

Feds final demand benchmark series code	Feds Commodity description	FEDS final demand annual series code
001	Oilseed farming	1
002	Grain farming	1
003	Vegetable and melon farming	1
004	Fruit and tree nut farming	1
005	Greenhouse nursery and floriculture production	1
006	Other crop farming	1
007	Dairy and beef cattle	2
008	Poultry and egg production	2
009	Animal production except cattle and poultry and eggs	2
010	Forestry and logging	3
011	Fishing hunting and trapping	5
012	Support activities for agriculture and forestry	6
013	Oil and gas extraction	7
014	Coal mining	8
015	Fossil fuels for electric power generation	193
016	Copper nickel lead and zinc mining	9
017	Iron gold silver and other metal ore mining	9
018	Stone mining and quarrying	10
019	Other nonmetallic mineral mining and quarrying	10
020	Drilling oil and gas wells	11
021	Other support activities for mining	11
022	Electric power generation transmission and distribution	12
023	Natural gas distribution	13
024	Water sewage and other systems	14
025	Maintenance and repair	15
026	Residential structures	15
027	Nonresidential structures	15
028	Dog and cat food manufacturing	16
029	Other animal food manufacturing	16
030	Flour milling and malt manufacturing	17
031	Wet corn milling	17
032	Fats and oils refining and blending	17
033	Soybean and other oilseed processing	17
034	Breakfast cereal manufacturing	17
035	Sugar and confectionery product manufacturing	18
036	Frozen food manufacturing	19
037	Fruit and vegetable canning pickling and drying	19

Table A5

FEDS Benchmark Commodities with concordances to FEDS Annual Commodities

Feds final demand benchmark series code	Feds Commodity description	FEDS final demand annual series code
038	Cheese manufacturing	20
039	Dry condensed and evaporated dairy product manufacturing	20
040	Fluid milk and butter manufacturing	20
041	Ice cream and frozen dessert manufacturing	20
042	Poultry processing	21
043	Animal (except poultry) slaughtering rendering and processing	21
044	Seafood product preparation and packaging	22
045	Bread and bakery product manufacturing	23
046	Cookie cracker pasta and tortilla manufacturing	23
047	Snack food manufacturing	24
048	Coffee and tea manufacturing	24
049	Flavoring syrup and concentrate manufacturing	24
050	Seasoning and dressing manufacturing	24
051	All other food manufacturing	24
052	Soft drink and ice manufacturing	25
053	Breweries	25
054	Wineries	25
055	Distilleries	25
056	Tobacco product manufacturing	26
057	Fiber yarn and thread mills	27
058	Fabric mills	27
059	Textile and fabric finishing and fabric coating mills	27
060	Carpet and rug mills	27
061	Curtain and linen mills	27
062	Other textile product mills	27
063	Apparel manufacturing	28
064	Leather and allied product manufacturing	29
065	Sawmills and wood preservation	30
066	Veneer plywood and engineered wood product manufacturing	31
067	Millwork	32
068	All other wood product manufacturing	32
069	Pulp mills	33
070	Paperboard mills and container manufacturing	33
071	Paperboard container manufacturing	34
072	Paper bag and coated and treated paper manufacturing	34
073	Stationery product manufacturing	34

Table A5

FEDS Benchmark Commodities with concordances to FEDS Annual Commodities

Feds final demand benchmark series code	Feds Commodity description	FEDS final demand annual series code
074	Sanitary paper product manufacturing	34
075	All other converted paper product manufacturing	34
076	Printing	35
077	Support activities for printing	35
078	Petroleum refineries	36
079	Asphalt paving mixture and block manufacturing	36
080	Asphalt shingle and coating materials manufacturing	36
081	Other petroleum and coal products manufacturing	36
082	Petrochemical manufacturing	37
083	Industrial gas manufacturing	37
084	Synthetic dye and pigment manufacturing	37
085	Other basic inorganic chemical manufacturing	37
086	Other basic organic chemical manufacturing	37
087	Plastics material and resin manufacturing	38
088	Synthetic rubber and artificial and synthetic fibers and filaments manufacturing	38
089	Fertilizer manufacturing	39
090	Pesticide and other agricultural chemical manufacturing	39
091	Pharmaceutical and medicine manufacturing	40
092	Paint and coating manufacturing	41
093	Adhesive manufacturing	41
094	Soap and cleaning compound manufacturing	42
095	Toilet preparation manufacturing	42
096	Printing ink manufacturing	43
097	All other chemical product and preparation manufacturing	43
098	Plastics packaging materials and unlaminated film and sheet manufacturing	44
099	Plastics pipe pipe fitting and unlaminated profile shape manufacturing	44
100	Laminated plastics plate sheet (except packaging) and shape manufacturing	44
101	Plastics bottle manufacturing	44
102	Other plastics product manufacturing	44
103	Polystyrene urethane and other foam manufacturing	44
104	Tire manufacturing	45
105	Rubber and plastics hoses and belting manufacturing	45
106	Other rubber product manufacturing	45
107	Clay product and refractory manufacturing	46
108	Glass and glass product manufacturing	47
109	Cement manufacturing	48

Table A5

FEDS Benchmark Commodities with concordances to FEDS Annual Commodities

Feds final demand benchmark series code	Feds Commodity description	FEDS final demand annual series code
110	Ready mix concrete manufacturing	48
111	Concrete pipe brick and block manufacturing	48
112	Other concrete product manufacturing	48
113	Lime and gypsum product manufacturing	49
114	Abrasive product manufacturing	49
115	Cut stone and stone product manufacturing	49
116	Ground or treated mineral and earth manufacturing	49
117	Mineral wool manufacturing	49
118	Miscellaneous nonmetallic mineral products	49
119	Iron and steel mills and ferroalloy manufacturing	50
120	Steel product manufacturing from purchased steel	51
121	Alumina and aluminum production and processing	52
122	Primary smelting and refining of copper	53
123	Primary smelting and refining of nonferrous metal (except copper and aluminum)	53
124	Copper rolling drawing extruding and alloying	53
125	Nonferrous metal (except copper and aluminum) rolling drawing extruding and alloying	53
126	Ferrous metal foundries	54
127	Nonferrous metal foundries	54
128	Custom roll forming	55
129	All other forging stamping and sintering	55
130	Crown and closure manufacturing and metal stamping	55
131	Cutlery and handtool manufacturing	56
132	Plate work and fabricated structural product manufacturing	57
133	Ornamental and architectural metal products manufacturing	57
134	Power boiler and heat exchanger manufacturing	58
135	Metal tank (heavy gauge) manufacturing	58
136	Metal can box and other metal container (light gauge) manufacturing	58
137	Hardware manufacturing	59
138	Spring and wire product manufacturing	60
139	Machine shops	61
140	Turned product and screw nut and bolt manufacturing	61
141	Coating engraving heat treating and allied activities	62
142	Fixture fitting valve and trim (plumbing and other) manufacturing	63
143	Ball and roller bearing manufacturing	63
144	Fabricated pipe and pipe fitting manufacturing	63
145	Ammunition arms ordnance and accessories manufacturing	63

Table A5

FEDS Benchmark Commodities with concordances to FEDS Annual Commodities

Feds final demand benchmark series code	Feds Commodity description	FEDS final demand annual series code
146	Other fabricated metal manufacturing	63
147	Farm machinery and equipment manufacturing	64
148	Lawn and garden equipment manufacturing	64
149	Construction machinery manufacturing	64
150	Mining and oil and gas field machinery manufacturing	64
151	Plastics and rubber industry machinery manufacturing	65
152	Semiconductor machinery manufacturing	65
153	Other industrial machinery manufacturing	65
154	Optical instrument and lens manufacturing	66
155	Photographic and photocopying equipment manufacturing	66
156	Office vending laundry and other commercial service industry machinery manufacturing	66
157	Heating equipment (except warm air furnaces) manufacturing	67
158	Air conditioning refrigeration and warm air heating equipment manufacturing	67
159	Air purification and ventilation equipment manufacturing	67
160	Industrial mold manufacturing	68
161	Special tool die jig and fixture manufacturing	68
162	Metal cutting and forming machine tool and accessory rolling mill and other metal work machinery manufacturing	68
163	Turbine and turbine generator set units manufacturing	69
164	Other engine equipment manufacturing	69
165	Speed changer industrial high-speed drive and gear, plus power transmission equipment manufacturing	69
166	Pump and pumping equipment manufacturing	70
167	Air and gas compressor manufacturing	70
168	Material handling equipment manufacturing	70
169	Power driven hand tool manufacturing	70
170	Packaging machinery manufacturing	70
171	Industrial process furnace and oven manufacturing	70
172	Other general purpose and fluid power process machinery manufacturing	70
173	Electronic computer manufacturing	71
174	Computer storage device manufacturing	71
175	Computer terminals and other computer peripheral equipment manufacturing	71
176	Telephone apparatus manufacturing	72
177	Broadcast and wireless communications equipment	72
178	Other communications equipment manufacturing	72
179	Audio and video equipment manufacturing	73
180	Semiconductor and related device manufacturing	74

Table A5

FEDS Benchmark Commodities with concordances to FEDS Annual Commodities

Feds final demand benchmark series code	Feds Commodity description	FEDS final demand annual series code
181	Printed circuit assembly and other electronic component manufacturing	74
182	Electromedical and electrotherapeutic apparatus manufacturing	75
183	Search detection and navigation instruments manufacturing	75
184	Automatic environmental control manufacturing	75
185	Industrial process variable instruments manufacturing	75
186	Totalizing fluid meter and counting device manufacturing	75
187	Electricity and signal testing instruments manufacturing	75
188	Analytical laboratory instrument manufacturing	75
189	Irradiation apparatus manufacturing	75
190	Watch clock and other measuring and controlling device manufacturing	75
191	Manufacturing and reproducing magnetic and optical media	76
192	Electric lamp bulb and part manufacturing	77
193	Lighting fixture manufacturing	77
194	Small electrical appliance manufacturing	78
195	Household cooking appliance manufacturing	78
196	Household refrigerator and home freezer manufacturing	78
197	Household laundry equipment manufacturing	78
198	Other major household appliance manufacturing	78
199	Power distribution and specialty transformer manufacturing	79
200	Motor and generator manufacturing	79
201	Switchgear and switchboard apparatus manufacturing	79
202	Relay and industrial control manufacturing	79
203	Storage battery manufacturing	80
204	Primary battery manufacturing	80
205	Communication and energy wire and cable manufacturing	80
206	Wiring device manufacturing	80
207	Carbon and graphite product manufacturing	80
208	All other miscellaneous electrical equipment and component manufacturing	80
209	Automobile and light truck and utility vehicle manufacturing	81
210	Heavy duty truck manufacturing	81
211	Motor vehicle body manufacturing	82
212	Truck trailer manufacturing	82
213	Motor home manufacturing	82
214	Travel trailer and camper manufacturing	82
215	Motor vehicle parts manufacturing	83
216	Aircraft manufacturing	84
217	Aircraft engine and engine parts manufacturing	84
218	Other aircraft parts and auxiliary equipment manufacturing	84

Table A5

FEDS Benchmark Commodities with concordances to FEDS Annual Commodities

Feds final demand benchmark series code	Feds Commodity description	FEDS final demand annual series code
219	Guided missile and space vehicle manufacturing	84
220	Propulsion units and parts for space vehicles and guided missiles	84
221	Railroad rolling stock manufacturing	85
222	Ship building and repairing	86
223	Boat building	86
224	Motorcycle bicycle and parts manufacturing	87
225	Military armored vehicle tank and tank component manufacturing	87
226	All other transportation equipment manufacturing	87
227	Wood kitchen cabinet and countertop manufacturing	88
228	Upholstered household furniture manufacturing	88
229	Non upholstered wood household furniture manufacturing	88
230	Institutional furniture manufacturing	88
231	Other household no upholstered furniture	88
232	Office furniture and custom architectural woodwork and millwork manufacturing	88
233	Showcase partition shelving and locker manufacturing	88
234	Other furniture related product manufacturing	90
235	Surgical and medical instrument manufacturing	91
236	Surgical appliance and supplies manufacturing	91
237	Dental equipment and supplies manufacturing	91
238	Ophthalmic goods manufacturing	91
239	Dental laboratories	91
240	Jewelry and silverware manufacturing	92
241	Sporting and athletic goods manufacturing	92
242	Doll toy and game manufacturing	92
243	Office supplies (except paper) manufacturing	92
244	Sign manufacturing	92
245	All other miscellaneous manufacturing	92
246	Wholesale trade	93
247	Air transportation	95
248	Rail transportation	96
249	Water transportation	97
250	Truck transportation	98
251	Transit and ground passenger transportation	99
252	Pipeline transportation	100
253	Scenic and sightseeing transportation and support activities for transportation	101
254	Postal service	170
255	Couriers and messengers	102

Table A5

FEDS Benchmark Commodities with concordances to FEDS Annual Commodities

Feds final demand benchmark series code	Feds Commodity description	FEDS final demand annual series code
256	Warehousing and storage	103
257	Retail trade	94
258	Trade electric utilities	201
259	Trade natural gas utilities	202
260	Newspaper publishers	104
261	Periodical publishers	104
262	Book publishers	104
263	Directory mailing list and other publishers	104
264	Software publishers	105
265	Motion picture and video industries	106
266	Sound recording industries	106
267	Other information services	109
268	Radio and television broadcasting	107
269	Cable and other subscription programming	107
270	Telecommunications	108
271	Data processing hosting and related services	109
272	Non depository credit intermediation and related activities	110
273	Securities commodity contracts and other financial investments	111
274	Insurance carriers	112
275	Insurance agencies brokerages and related activities	113
276	Funds trusts and other financial vehicles	114
277	Monetary authorities and depository credit intermediation	110
278	Real estate	115
279	Automotive equipment rental and leasing	116
280	Commercial and industrial machinery and equipment rental and leasing	118
281	Consumer goods and general rental centers	117
282	Lessors of nonfinancial intangible assets	119
283	Legal services	120
284	Accounting tax preparation bookkeeping and payroll services	121
285	Architectural engineering and related services	122
286	Specialized design services	123
287	Custom computer programming services	124
288	Computer systems design services	124
289	Other computer related services including facilities management	124
290	Management consulting services	125
291	Environmental and other technical consulting services	125
292	Scientific research and development services	126

Table A5

FEDS Benchmark Commodities with concordances to FEDS Annual Commodities

Feds final demand benchmark series code	Feds Commodity description	FEDS final demand annual series code
293	Advertising public relations and related services	127
294	Photographic services	128
295	Veterinary services	128
296	Marketing research and all other miscellaneous professional scientific and technical services	128
297	Management of companies and enterprises	129
298	Office administrative services	130
299	Facilities support services	131
300	Employment services	132
301	Business support services	133
302	Travel arrangement and reservation services	134
303	Investigation and security services	135
304	Services to buildings and dwellings	136
305	Other support services	137
306	Waste management and remediation services	138
307	Elementary and secondary schools	139
308	Junior colleges, colleges, universities and professional schools	140
309	Other educational services	141
310	Home health care services	143
311	Physician dentist and other health practitioner offices	142
312	Outpatient care centers medical and diagnostic laboratories	144
313	Hospitals	145
314	Nursing and residential care facilities	146
315	Child day care services	149
316	Social assistance	147
317	Performing arts companies	150
318	Spectator sports	151
319	Independent artists writers and performers	153
320	Promoters of performing arts and sports and agents for public figures	152
321	Museums historical sites zoos and parks	154
322	Amusement gambling and recreation industries	155
323	Accommodation	156
324	Food services and drinking places	157
325	Food services (service only)	200
326	Automotive repair and maintenance	158
327	Electronic and precision equipment repair and maintenance	159
328	Commercial and industrial machinery and equipment repair and maintenance	160
329	Personal and household goods repair and maintenance	161

Table A5

FEDS Benchmark Commodities with concordances to FEDS Annual Commodities

Feds final demand benchmark series code	Feds Commodity description	FEDS final demand annual series code
330	Personal care services	162
331	Death care services	163
332	Dry cleaning and laundry services	164
333	Other personal services	165
334	Religious organizations	166
335	Grantmaking giving and social advocacy organizations	167
336	Civic social professional and similar organizations	168
337	Private households	169
338	Other federal government enterprises	172
339	Other state and local government enterprises	180
340	Miscellaneous special industries	171
341	Scrap used and secondhand goods	192
342	Federal general government (defense)	173
343	State and local general government	181
344	Owner occupied dwellings	190