Reducing water scarcity by improving water productivity in the United States

by

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Abstract

Nearly one-sixth of U.S. river basins are unable to consistently meet societal water demands while also providing sufficient water for the environment. Water scarcity is expected to intensify and spread as populations increase, new water demands emerge, and climate changes. Improving water productivity by meeting realistic benchmarks for all water users could allow U.S. communities to expand economic activity and improve environmental flows. Here we utilize a spatially detailed database of water productivity to set realistic benchmarks for over 400 industries and products. We assess unrealized water savings achievable by each industry in each river basin within the conterminous U.S. by bringing all water users up to industry- and region-specific water productivity benchmarks. Some of the most water stressed areas throughout the U.S. West and South have the greatest potential for water savings, with around half of these water savings obtained by improving water productivity in the production of corn, cotton, and alfalfa. By incorporating benchmark-meeting water savings within a national hydrological model (WaSSI), we demonstrate that depletion of river flows across Western U.S. regions can be reduced on average by 6.2-23.2%, without reducing economic production. Lastly, we employ an environmentally extended input-output model to identify the U.S. industries and locations that can make the biggest impact by working with their suppliers to reduce water use "upstream" in their supply chain. The agriculture and manufacturing sectors have the largest indirect water footprint due to their reliance on water-intensive inputs but these sectors also show the greatest capacity to reduce water consumption throughout their supply chains.

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Acknowledgments

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Chapter 1

Introduction

The U.S. Geological Survey quinquennial National Water Censuses have revealed a remarkable and counterintuitive trend in recent decades: from 1980-2015, total water withdrawals decreased 27%[1] even while the country's population grew by 42% and GDP expanded more than five-fold[2,3]. These water-use reductions have been attributed to improvements in water productivity as well as structural shifts in the U.S. economy (i.e., declines in water-intensive agriculture and manufacturing and rise in service economies)[4,5].

The multi-decadal decline in U.S. water withdrawals has not yet eliminated water scarcity risks, however. Numerous recent hydrologic assessments have revealed that in spite of lessened water withdrawals, the consumptive (lost) fraction of those withdrawals continues to deplete many natural water sources to near exhaustion, posing ongoing water shortage risks for both people and ecosystems[6,7,8]. Lacking access to additional freshwater supplies and facing rapid population growth and climate change, water managers in forty of fifty states expect water shortages in some portion of their jurisdiction by 2023[9].

Recently, water productivity benchmarks have emerged as a promising tool for improving the sustainability of water use by identifying productivity levels that can be reasonably attained by water users operating within a variety of contexts and limitations. However, the studies to date have been limited to individual sectors, countries, or products. One global analysis estimated a 7.7×10^{10} m^3 yr^{-1} water savings on irrigated croplands if the lowest water productivities were improved to the 20^{th} percentile, amounting to more than one quarter of current water consumption on these lands[10]. Another global study of crop production estimated the possibility of a 39% reduction in total water consumption (blue + green) when improving the water productivity of all crops to a 25^{th} percentile benchmark[11]. Using the same benchmark level, other work focused on crop production in Iran showed the potential for a 32% groundwater savings through water productivity improvements[12], and another study on winter wheat in China found the opportunity to reduce total water consumption by 53%[13]. To the best of our knowledge, no research has been done to assess non-agricultural sectors or to quantify the potential for improved water productivities to realize water savings in the United States. This study provides the first national multi-sectoral assessment of water productivity benchmarks and blue water savings for the U.S.. Blue water relates to surface and groundwater resources, whereas green water is available soil moisture from precipitation (unless stated otherwise, water productivity in this study refers to blue water productivity). Importantly, we also demonstrate how improvements in water productivity can reduce streamflow depletion and make supply chains more sustainable.

Efforts to lessen water withdrawals can be very important for industries or services in which the cost of water as an input, or contamination of water through use, is of material concern. However, a focus on water withdrawals alone can be a misleading indicator of changes in freshwater depletion and associated risk of water shortages[14]. For example, between 1995 and 2015, water withdrawals for thermoelectric power generation—which today accounts for 41% of all withdrawals and is the largest water withdrawing sector in the U.S.—dropped by 31%, equivalent to a savings of 8.08×10^{10} m^3 yr^{-1} [15,16]. However, the reduction in water withdrawals was largely due to technological shifts within the industry that reduced water withdrawals but increased water consumption by 27%. Thus, reductions in water withdrawals may provide very little alleviation of water scarcity in the source watersheds. For this reason, our measures of water productivity are based upon consumptive water use rather than water withdrawal. In this study we explore the potential for continued improvements in water productivity to further reduce water scarcity risks and improve economic productivity. We examine water productivity through multiple lenses, including both product output and dollars earned per unit of water consumed.

Our assessment of opportunities for improving water productivity is based upon a 'benchmarking' approach in which we first characterize the spectrum (probability distributions) of water productivity values associated with production of individual commodities or provision of services (Figure 1.1). These probability distributions are derived from a new water footprint database[17] that provides industry-level detail (over 400 industries, products, and crops) and spatially explicit direct water consumption estimates per unit of production for the U.S.. We then establish target benchmarks for each sector based on water-use productivity levels achieved by the better-than-average performers in each sector. Importantly, we cluster similar water users based on shared environmental and/or technological profiles (henceforth, referred to as water-use clusters) so as to constrain target benchmarks to realistically achievable water productivity levels within each sector (e.g., it is not possible to achieve the same water productivity when growing wheat in Arizona as in Ohio due to climatic differences). Finally, we examine the potential to reduce water consumption and water scarcity by bringing water users within each water-use sector—or all water users collectively—up to realistic benchmarks set by water users with the highest blue water productivity. Moreover, our analysis enables industries to identify whether greater water savings can be achieved by improving water productivity in their own processes or working to improve their suppliers' water productivity upstream in the supply chain. This analysis has enabled us to identify the water-use sectors and watersheds across the U.S. that may offer the greatest water savings and relief from water scarcity if water productivity gains can be realized.

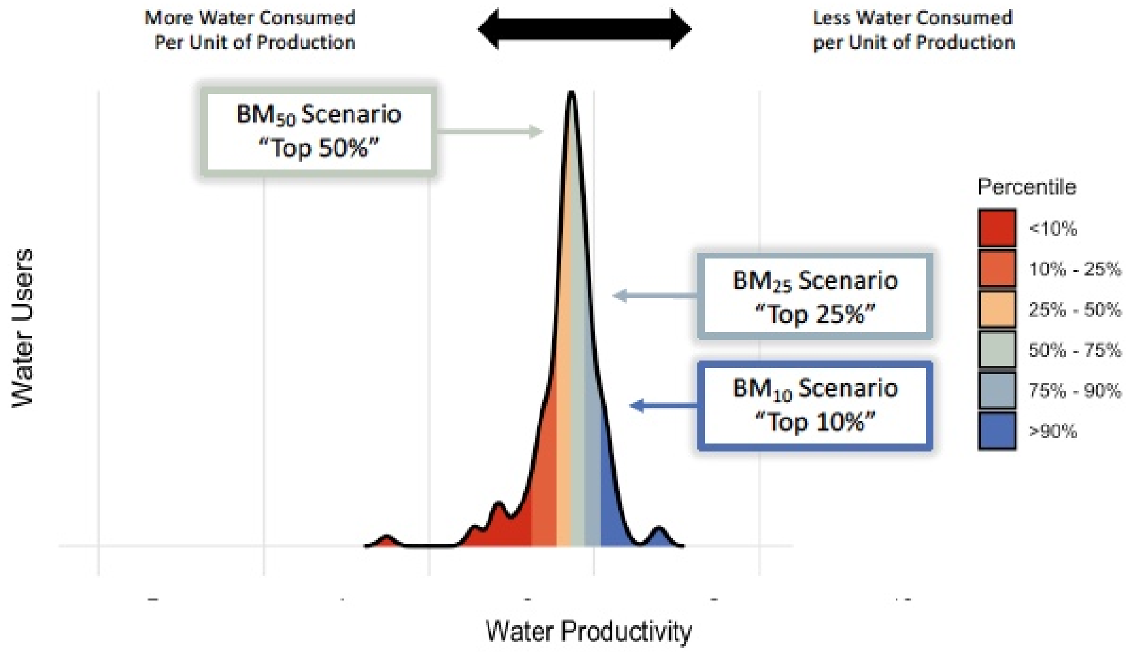

Figure 1.1: Probability distribution for water productivity and associated benchmarks. The benchmarking approach applied in this study is based upon the development of probability distributions for each water-use sector, product, or service, within each water-use cluster. The x-axis represents water productivity, measured as production or dollars earned per unit of water consumption, with water productivity improving from left to right. The y-axis represents the number of water users, such as number of factories, power plants, farms or any water user. These benchmarking relationships are built using a new water footprint database that includes >400 U.S. industries and products[17]. Labeled on the graph are three 'target benchmark' levels used in this study: $BM_{50} = 50^{th}$ percentile or median performance; $BM_{25} = 25^{th}$ percentile or high performance; and $BM_{10} = 10^{th}$ percentile or outstanding performance. Distribution plots were made using the ggplot2 Wickhan and ggridges packages[18].

One of the attractions of using a benchmarking approach is that it is not prescriptive with respect to the practices or technologies used for reducing water consumption. Instead, it enables individuals and companies to select from a portfolio of strategies, tailored to the constraints and opportunities they face in their businesses and geographic/climatic context. We simply evaluate how much water savings or how much improvement in water productivity (production or dollars earned per unit of water consumed) can be attained by improving all users' water productivity to meet a target benchmark, such as up to the 50^{th} percentile (median productivity; BM_{50}), 25^{th} percentile (high productivity; BM_{25}), or 10^{th} percentile (outstanding productivity; BM_{10}). These benchmarks represent actual water productivities achieved by a water user's regional industry peers and are therefore realistically achievable in most cases. This study provides an upper bound of potential water savings, recognizing that financial and regulatory barriers may inhibit some water users from attaining water productivities achieved by their peers.

Chapter 2

Methods

This study asks 'if water productivity is improved across the U.S. economy, how much water can be saved and in which industries and locations?'. Water productivity is defined as production obtained per unit of water consumption (i.e., uses which, through evaporation and transpiration, remove surface and groundwater from further use within a watershed). We utilize an unprecedented dataset[17] that quantifies consumptive blue water use and productivity for over 400 crops, livestock animals, thermoelectric power generation types, and commercial/industrial/institutional uses at fine spatial resolutions. Controlling for climatic conditions that may differ between geographies and constrain achievable water productivity levels, we set water productivity benchmarks for each sector in order to determine the potential to reduce water demand across the U.S. economy by improving water productivities to the benchmark level. We adopt the perspective that systems operating within the same contexts and constraints (i.e., similar industry, climate, and geographical area) have similar opportunities to improve their water productivity. We do not prescribe a particular technology or conservation practice for users to improve their water productivity because the best approach will vary depending on the limitations and opportunities faced by each individual water user. Instead, we sort water users by use type and climate region to identify what levels of water productivity have been achieved by similar water users and are reasonably attainable. After estimating the volumes of water potentially saved through benchmarking, we employ an environmentally extended input-output model to assess how water savings of production may ultimately transfer through domestic supply chains. Finally, these potential water savings are also incorporated into a national hydrological model to examine opportunities for reducing streamflow depletion across the United States.

2.1 Water productivity and benchmarking for crop production.

2.1.1 Crop blue water demand

We calculated water productivities (tonne per m^3 of blue and green water) for 23 crops that comprise 89% of irrigated harvested area, and 87% of blue water demand [17] for U.S. crop production (Appendix table A.3). Gridded crop water requirements (mm yr^{-1}) were calculated following the approach by Doll and Siebert [19]. First, state-level crop-specific planting and harvesting dates and length of growing season came from the USDA [20]. FAO data [21] were used for crops for which this information was not available. Following Allen et al. [21], we then partitioned the growing season for each crop into four crop developmental stages (initial, developmental, middle, and late), each with their corresponding crop coefficients (k_c). We then calculated daily crop-specific evapotranspiration (ET_c) as the product of potential evapotranspiration (ET_o) and k_c, where daily ET_o came from a calibrated Variable Infiltration Capacity (VIC) Model [22] and daily k_c is determined from the FAO crop coefficient curves [21]. k_c was set to zero outside of the growing season. Daily ET_c was then partitioned into green and blue crop water requirements assuming that when a crop's water demand exceeds effective precipitation, irrigation is applied to provide the crop with the water needed to avoid crop water stress (see e.g., ref. [19,23,24,25]). Effective precipitation was calculated using the USDA Soil Conservation Service method [26], with daily precipitation averaged over a moving multi-day window to account for soil moisture storage[19]. Daily precipitation data were obtained from PRISM[27]. Daily crop water requirements (CWR) were summed to the monthly scale. All data were resampled to 7.5 arcminute grid cells to ensure agreement of spatial resolution across all datasets. Finally, for each grid cell i, we calculated total water productivity ($wp_{i,c}$; tonne per m^3 of blue and green water) for crop c as the ratio of irrigated crop yield to total crop water requirement (CWR). Current (base) annual blue water demand and total water demand for a crop c in a given 7.5 arcminute grid cell i was calculated as:

$$bwd_{i,c,bl} = \sum_{day=1}^{365} bCWR_{i,day} * a * n_i * \frac{A_{irr,c,x}}{A_{tot,c,x}} \tag{2.1}$$

$$wd_{i,c,bl} = \sum_{day=1}^{365} CWR_{i,day} * a * n_i * \frac{A_{irr,c,x}}{A_{tot,c,x}} \tag{2.2}$$

where a is the area of a crop pixel[28] (30m x 30m) for year 2010 (which corresponds to the timeframe used for other water use sectors), n_i is the number of pixels representing crop c within grid cell i, $A_{irr,c,x}$ is the irrigated area of crop c in county x encompassing grid cell i, and $A_{tot,c,x}$ is the total harvested area of crop c in county x[29].

2.1.2 Constraining potential crop water productivity by climate:

When constraining crop water productivity, we first determined where each crop has been grown over the last decade. We developed high-resolution (30m) crop-specific maps of crop cover derived from the USDA National Agricultural Statistics Service Cropland Data Layer[28]. For each year between 2008 through 2017, these data report the crops cultivated in each 30m x 30m pixel across the country. For each crop c, we developed a gridded aggregated crop cover map representing the pixels in which the crop had been cultivated at any point between 2008 and 2017 and thereby controlling for interannual variability in crop planting locations due to factors such as crop rotations and fluctuations in commodity markets. We also developed corresponding maps for select climate variables averaged across 2008-2017 to match the crop layers. For each grid cell, daily PRISM precipitation data[27] were summed within each year and then averaged across the years to produce a gridded average 2008-2017 annual rainfall map (P). This information was then combined with data on open water evapotranspiration (PET_{avg})[30] to calculate the aridity index of each grid cell as:

$$I_{th} = \frac{100(P_{avg} - PET_{avg})}{PET_{avg}} \tag{2.3}$$

PRISM[27] daily temperature data ($\mathrm{T_{t,y}}$) for year y were used to calculate growing degree-days (GDD) for each grid cell as:

$$GDD_{y,c} = \sum_{t\,=\,1}^{365} (T_{t,y} - T_{base,c}) \tag{2.4}$$

where $T_{base,c}$ is the temperature below which crop c cannot grow (Appendix table A.4). If $T_{t,y}$ - $T_{base,c}$ was negative for day t, this difference was set to 0 for that day. The annual GDD maps for each year y were then averaged to produce a gridded average 2008-2017 annual GDD map for each crop c. We then masked the gridded average aridity index and GDD maps for crop c using its corresponding gridded average crop cover map. In this way, we only create climate bins based on where a crop has actually been grown. Note that the 30 m crop pixels were aggregated to match the climate grid cell resolution, such that the presence of a crop pixel within the larger grid cell would indicate that this crop had been grown somewhere within the larger grid cell. The masked average aridity index map for crop c was then split into nine Ith bins based on Thornthwaite Aridity Index categories (<-40, -40 to -20; -20 to 0, 0 to 20, 20 to 40, 40 to 60, 60 to 80, 80 to 100, and >100). Because the cultivated extent of some crops does not cover the full range of Thornthwaite categories, these crops have less than nine $\mathrm{I_{th}}$ bins. The masked average GDD map for crop c was partitioned into nine equal-area GDD bins. The $\mathrm{I_{th}}$ bin map and the GDD bin map were then overlapped to produce a map of 81 potential climate bins, similar to the approach by Mueller et al.[31] (see Figure 2.1). Thus, we controlled for the influence of agro-climatic conditions on the water use productivity of each crop. After assessing the $wp_{i,c}$ for each grid cell that had grown crop c between 2008-2017, we determined the crop water productivity for each climate bin b that represents the 25_{th} percentile $wp_{i,c}$ (i.e., 25% of pixels use less water per unit of production). Each grid cell for crop c within climate bin b that exhibited a water productivity value worse than the determined 25_{th} percentile was adjusted to match the 25_{th} percentile benchmark (henceforth, BM_{25}). Water users with water productivity levels at the BM_{25} level or better were unchanged. For each grid cell this was determined as:

$$wp_{i,c,new} = \begin{cases} wp_{i,c}, & wp_{i,c} \geq wp_{i,c,b,BM25} \\ wp_{i,c,b,BM25}, & wp_{i,c} < wp_{i,c,b,BM25} \end{cases} \tag{2.5}$$

This was repeated for all climate bins and for each crop. Total water demand within each grid cell i for crop c under benchmark conditions ($wd_{i,c,BM25}$) was then calculated as:

$$wd_{i,c,BM25} = \frac{p_{i,c}}{wp_{i,c,new}} \tag{2.6}$$

where $p_{i,c}$ is irrigated production of crop c in tonnes with grid cell i. The difference between baseline total water demand ($wd_{i,c,bl}$) and the BM_{25} water demand ($wd_{i,c,BM25}$) represent potential water savings within each grid cell. Since green water contributions are held constant, all water savings are from reduced irrigation (blue water). Blue water demand for BM_{25}, whose lower limit is zero, is calculated as the difference between baseline blue water demand and total savings.

$$bwd_{i,c,BM25} = max(bw_{i,c,bl} - (wd_{i,c,bl} - wd_{i,c,BM25}), 0) \tag{2.7}$$

In a similar way, we also calculated the 10_{th} percentile (BM_{10}) and 50_{th} percentile (BM_{50})

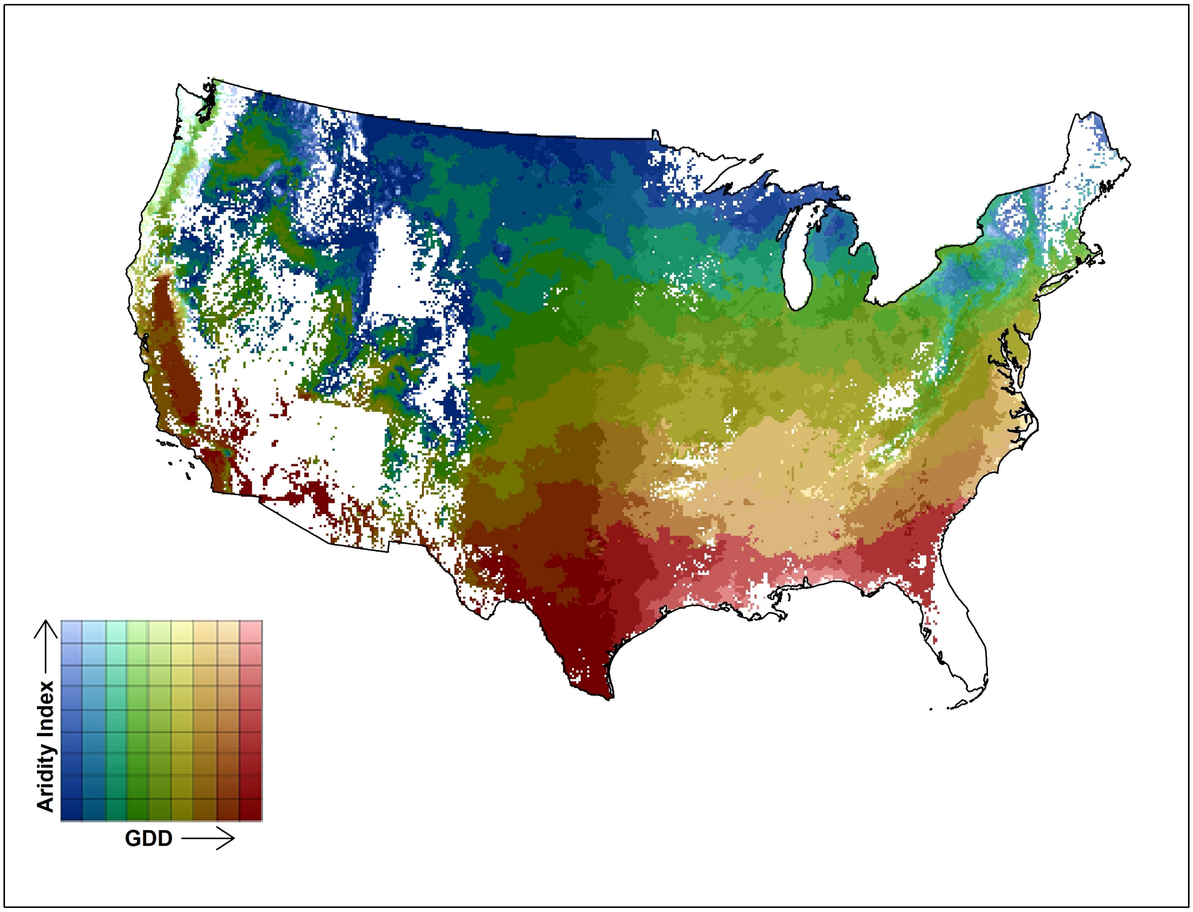

Figure 2.1: Climate bins were created for each crop (wheat shown here) so to set water productivity benchmarks among similar water users. Climate bins were set by each crop's growing degree days (GDD) and the aridity index, which is a function of precipitation and potential evapotranspiration.

bwd_c values to represent a range of stringencies in improving crop irrigation water use productivities. Potential blue water savings per unit of production for each benchmark level (BM_{10}, BM_{25}, and BM_{50}) were calculated in a similar fashion for all other sectors. For all sectors, our results reflect annual benchmarks. However, we temporally and spatially disaggregated water consumption to each month and grid cell following Richter et al.[8] so water consumption estimates were compatible with our hydrologic model (WaSSI).

2.2 Water productivity and benchmarking for other sectors.

County-level water productivity values (head per m^3 blue water) for nine livestock products came from Marston et al.[17] (Appendix table A.1) and were benchmarked based on NOAA climatic region and livestock type. County-level water productivity values for thermoelectric power water consumption came from Marston et al.[17] and were benchmarked based on fuel type, technology, and climatic region. Annual county-level public and self-supplied water consumption data came from Richter et al.[8], and were used to calculate per capita water productivities and benchmarked by climatic region. County-level water productivity values for the commercial, industrial, and institutional sectors also came from Marston et al.[17] and were benchmarked by climatic region and 2-6 digit North American Industrial Classification System (NAICS) code (see Appendix table A.2 for full listing of NAICS codes).

2.3 Water savings through the supply chain.

We employed an environmentally extended input-output (EEIO) model to assess how water savings in the production process propagated through complex supply chains. EEIO analysis is a widely used technique to connect the environmental impacts of production to economic consumption through each stage of the supply chain[32]. Our model replicates the model used by Marston et al.[17]; though in this study, we perform separate analyses using different environmental multipliers to represent current (baseline) and benchmark levels (BM_{10}, BM_{25}, BM_{50}) of water productivity for each industry. Direct and indirect water savings were calculated by taking the difference between the baseline scenario and each benchmark scenario for each industry. The EEIO model is further described in the Supplementary Materials.

2.4 National hydrology model and streamflow depletion.

Streamflow and flow depletion at the HUC8 watershed scale were estimated using the Water Supply Stress Index (WaSSI) Ecosystem Services Model. WaSSI was developed by the USDA Forest Service to assess the effects of climate, land use, and population change on terrestrial water and carbon balances, water supply stress, river flows, and aquatic ecosystems across the conterminous U.S.. WaSSI has been extensively tested using observed streamflow measurements[33,34] and has good predictive performance relative to other continental and basin scale models. Details on the model computations can be found in Sun et al. and Caldwell et al.[35,36], and modifications to WaSSI used in this study are described in Richter et al.[8]. We utilized groundwater and surface water use data from Maupin et al.[37] and Marston et al.[17] to partition blue water demands between groundwater and surface water sources before integrating these consumptive water uses within WaSSI. We evaluate water savings as they accumulate within the stream network and the associated changes in streamflow depletion (i.e., difference in predicted streamflow while accounting for water use vs. predicted streamflow with no water use) by comparing benchmark scenarios against our baseline scenario. Additional methodological details are found in the Supplementary Materials.

Chapter 3

Results

3.1 Improving water use performance by sector.

Irrigated agriculture is by far the largest consumptive water user in the conterminous U.S., representing 75% of all consumption[8]. Unsurprisingly, the greatest volumetric water savings can be attained from improving water productivity in agriculture (Figure 3.1). We note that our assessment of the potential water savings in agriculture is based upon benchmark evaluations of individual crops and other agricultural products within their individually determined water-use cluster; our results for agriculture within each climatic region (Figure 3.1) are therefore based upon an aggregation of all individual crop assessments at much finer spatial resolutions. A list of all industries/products included in this study and the broader sectors they belong to are found in Appendix table A.1 and Appendix table A.2. The total water savings potential in agriculture for the conterminous U.S. at BM_{25} amounts to 9.98×10^9 m^3 yr^{-1}—equivalent to 11.3% of all agricultural water consumption—which is about half of the total consumptive use in all other water sectors combined. Among the U.S. regions evaluated, the largest volumes can be saved in the South, with large volumetric water savings also achievable in the four Western U.S. regions. Significant water savings in the South and Western regions reflect the large baseline consumptive water use in these areas, not because these regions have greater water productivity variance than other regions. Direct blue water consumption and savings for the baseline and benchmark scenarios for each sector and climate region can also be found in Appendix table A.6.

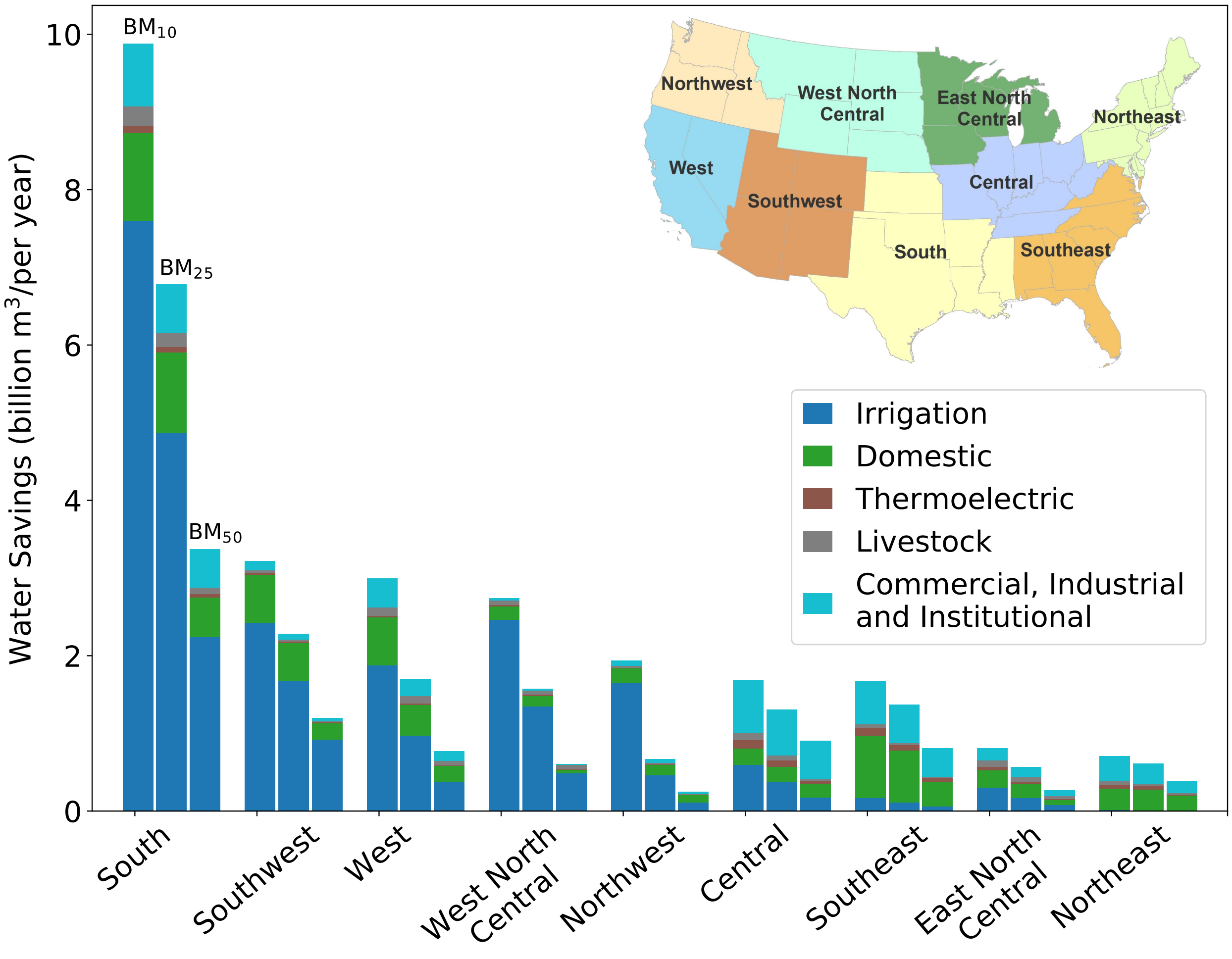

Figure 3.1: Potential direct water savings at the BM_{10}, BM_{25}, and BM_{50} levels, aggregated by climate region and sector. The greatest volumetric water savings can be realized by improving the performance of irrigated agriculture, followed by domestic water uses. The potential savings in irrigated agriculture are greatest in the South and in Western regions where agriculture relies most heavily on irrigation.

Within the agricultural sector, the greatest potential for water savings is tied to specific crops requiring the most irrigation within each region (Figure 3.2). Over half of the total potential crop water savings across the U.S. at BM_{25} are from just three crops: corn, cotton, and alfalfa. Both alfalfa and corn ($\sim$ 40% of total production) are used for animal feed;

two-fifths of corn production is also used for biofuel production, with the remaining one-fifth used for other purposes, including international export. Though these three crops represent the largest potential water savings nationally, the irrigated crops with the greatest water-saving potential vary regionally: in the South, soybeans, cotton, and winter wheat hold greatest potential, while in Western regions water savings are greatest for alfalfa.

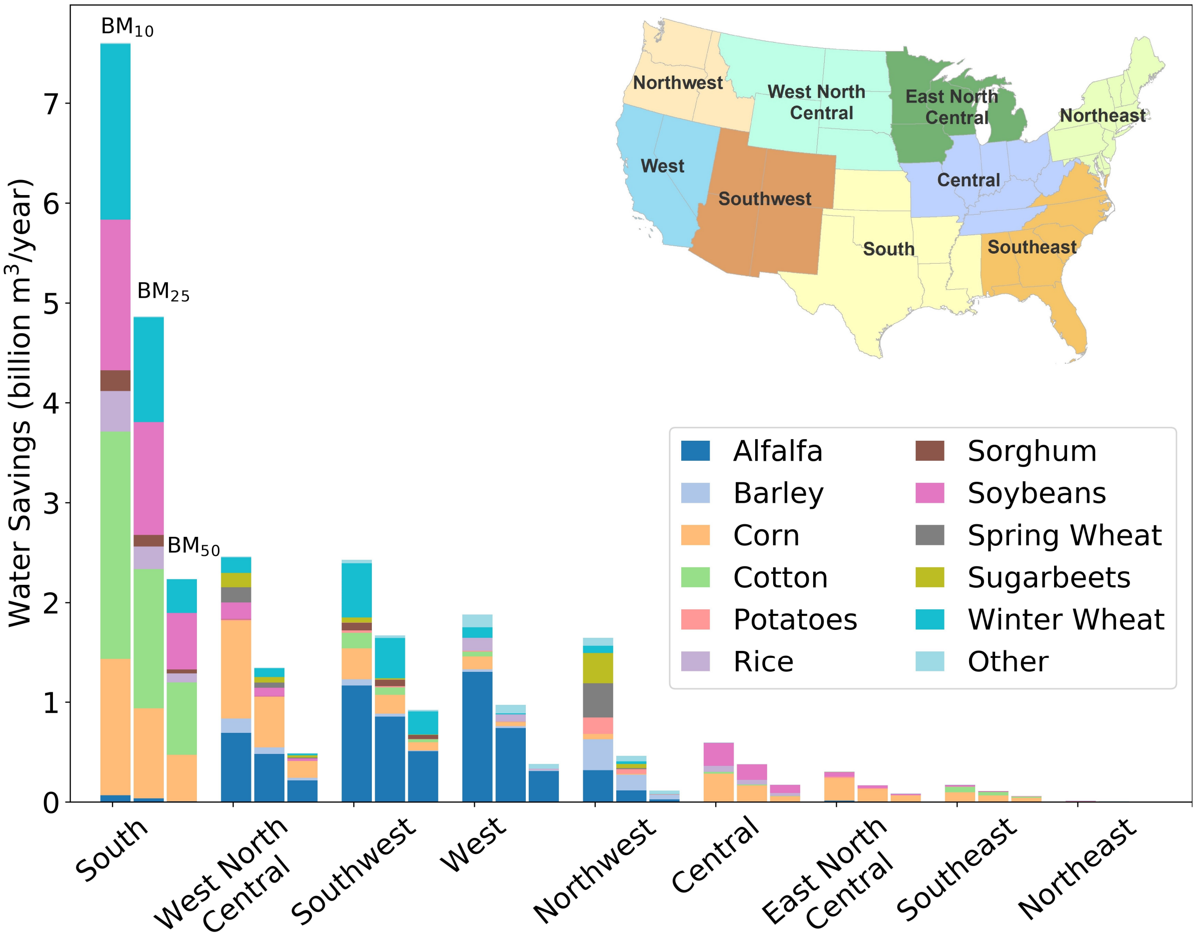

Figure 3.2: Potential direct agricultural water savings by crop at the BM_{10}, BM_{25}, and BM_{50} levels, aggregated by climate region. Within the agricultural water use sector, the greatest potential for water savings is tied to the crops requiring the most irrigation within each region.

When looking for potential water savings, distinguishing between 'direct' (i.e., water consumed in a user's own production processes) and 'indirect' (i.e., water consumed upstream in the supply chain) uses of water is also important (Figure 3.3). This way, water-saving strategies can be implemented more strategically by prioritizing the step of the supply chain consuming the most water or perhaps where the use of water is least productive economically. Nearly 95% of industries have a larger indirect water footprint than direct water footprint, indicating that the greatest potential for water savings likely occurs upstream in the supply chain of a direct water user. For example, meat production—as part of the agriculture sector—relies on feed crops; the textile industry relies on fiber crops such as cotton; and manufacturing of appliances, consumer electronics, or vehicles relies on minerals. The water consumption associated with each of these inputs must be included when evaluating overall water consumption for a product or industry. Consistent with this, the construction sector, which requires considerable inputs in production, has a much higher indirect consumptive use of water (5.17×10^9 m^3yr^{-1}) when compared to its direct use (5.77×10^7 m^3yr^{-1}), and agriculture and manufacturing both have very high direct (9.34×10^{10} m^3yr^{-1} and 2.75×10^9 m^3yr^{-1}, respectively) and indirect (6.89×10^9 m^3yr^{-1} and 4.11×10^{10} m^3yr^{-1}, respectively) water consumption (Figure 3.3). In agriculture, water is consumed directly in growing crops, and use of irrigated crops as animal feed creates a very high indirect water use in meat production. By shifting all water users within the agriculture sector to the BM_{25} level, direct water consumption decreases by 11.13%, while indirect water consumption decreases by 14.07%.

The shapes of water productivity distributions, as well comparisons between products/industries, can differ widely when water productivity is viewed through the lens of production (e.g., kg per m^3 of water consumed) versus economic outputs (USD) per unit of water consumed. Across meat categories, poultry production (turkeys, laying hens, and broilers) generates the highest meat production and economic output per unit of direct blue water consumed (i.e., not considering indirect water consumption upstream in livestock's supply chain). Dairy cows are the least productive in terms of kilograms per unit of blue water (Figure 3.4a), and beef cows are among the lowest economic producers as well (Figure 3.4b). Most industries have a Gaussian or lognormal distribution of water productivity, suggesting a central tendency of water productivity. Bimodal distributions seen in Figure 3.4c are an artefact of aggregating over 350 unique commercial/industrial/institutional water users to broader sectors. Though we aggregate these similar industries together for visualization purposes here, a unique benchmark was set for each industry.

Overall, the utilities sector produces both the most economically productive water use and the least economically productive water use (Figure 3.4c). Within the utilities sector, the transport of energy fuels like natural gas use very little water for each dollar of output, which is represented by the distribution with the higher water productivity values. Electricity generation, however, consumes significant amounts of water relative to the industry's economic production (distribution with smaller water productivity values). We highlight specific fuel types and cooling systems used to generate thermoelectric power since thermoelectric power is a key water consumer within the U.S. economy (Figure 3.4d). Natural gas is often able to produce more energy while consuming less water than other fuel types, while once-through cooling systems generally consume less water per joule of energy than recirculating cooling systems. As the energy mix continues to shift toward natural gas and renewable sources, there will be continued improvements in water productivity (joules/m^3 blue water) within this sector[39] (Figure 3.4d). Spatially explicit water productivity data on renewable energy generation are unavailable, though these energy sources generally consume very little water in their operation (hydropower and concentrating solar power technologies are exceptions)[40]. Furthermore, water consumption associated with water and sewage utilities is not represented in our study due to data limitations. Average blue water productivities per climate region and sector can be found in Appendix table A.5.

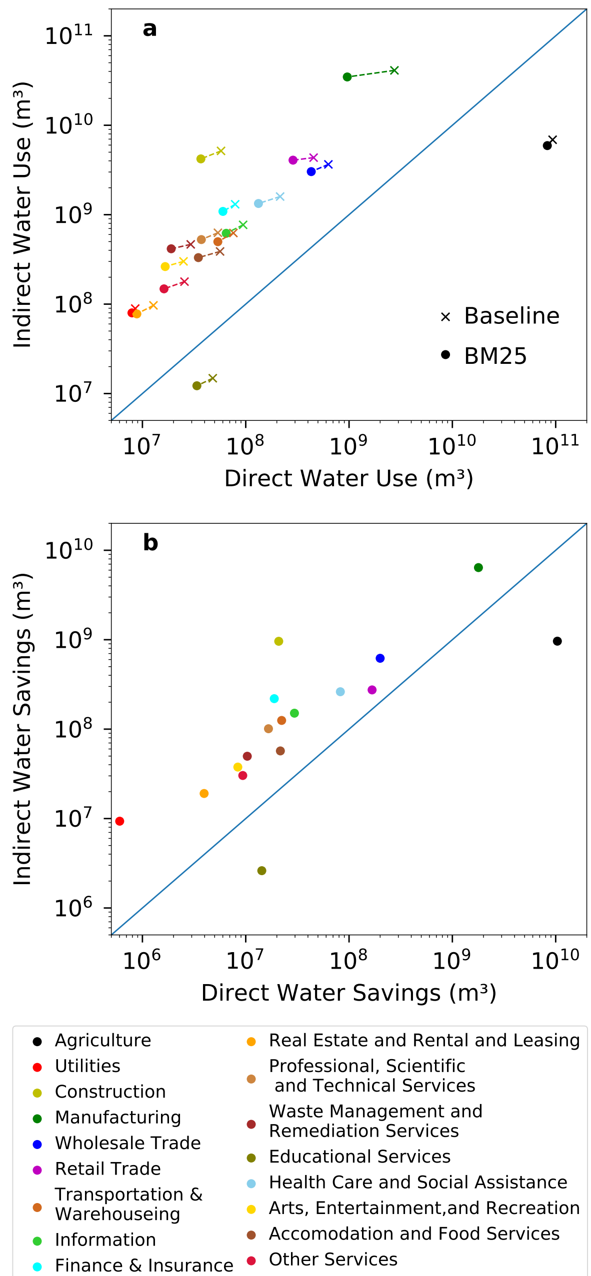

Figure 3.3: Direct and indirect water consumption (a) and savings (b) at the BM_{25} level, aggregated by sector. The total direct and indirect water requirements throughout a product's supply chain were calculated using an environmentally extended version of the Leontief Input-Output model[38]. The agricultural sector has the greatest direct and indirect water footprint but can also achieve greater water savings than all other sectors combined. The manufacturing sector has the greatest indirect water savings due to its reliance on water-intensive commodities as inputs to production.

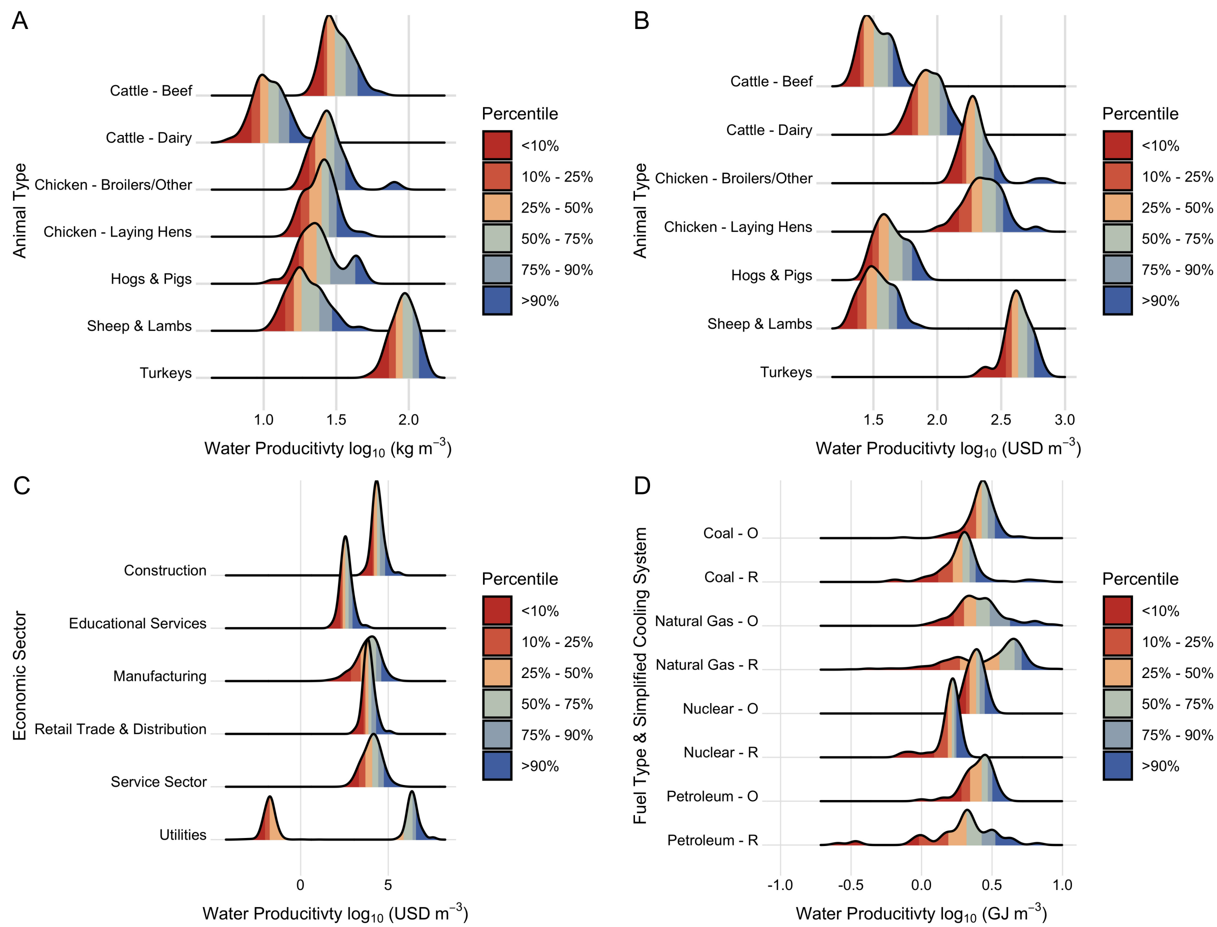

Figure 3.4: Direct blue water productivity benchmarking results expressed in terms of either production or revenue produced per unit of blue water consumed directly within their production processes. (a) Water productivity of animal production measured as weight produced (kg). (b) Water productivity of livestock production measured in terms of revenue generation. Poultry (turkeys, broilers, laying hens) generate greatest median value per unit of water. (c) Water productivity of multiple industries grouped together by sector and measured in terms of revenue generation (USD). (d) Water productivity of thermoelectric power generation measured in terms of gigajoules produced. Recirculating (R) coal and nuclear power plants are the most water intensive. For the same fuel type, once-through cooling (O) is typically more water productive, although water withdrawals are much larger for once-through cooling than recirculating cooling. Recirculating natural gas plants are the least water intensive. (Note: renewable energy sources such as solar and wind are not included due to lack of spatially explicit data)

3.2 Reductions of water scarcity through improvements in water productivity.

Ultimately, the ability of improved water productivity within and among industries to reduce water scarcity must be evaluated in the context of local water budgets[41]. Here, we define water scarcity as summer streamflow depletion relative to the mean natural summer flow (i.e., no anthropogenic water uses), with 100% depletion meaning all naturally available supplies have been consumed. We used the WaSSI Ecosystem Services Model to estimate reductions in water scarcity achieved through attainment of each water productivity benchmark (i.e., BM_{10}, BM_{25}, and BM_{50}). WaSSI operates on a monthly time step at the 8-digit Hydrologic Unit Code (HUC8) sub-watershed scale. There are 2,099 HUC8 sub-watersheds in the conterminous U.S., with a mean area of 3,750 square kilometers. The WaSSI model enables evaluation of the change in streamflow depletion associated with lessened water consumption for specific water uses such as irrigation of alfalfa or evaluating improved water use performance across all sectors in a sub-watershed.

Importantly, water scarcity reductions achievable by attaining water productivity benchmarks are greatest in Western U.S. regions (as identified in Figures 3.1 and 3.2) where baseline water scarcity is most pronounced (Figure 3.5, showing BM_{25} results versus the baseline). Geographically-averaged scarcity across these Western regions can be reduced by 23.2%, 13.6%, and 6.2% at the BM_{10}, BM_{25}, and BM_{50} levels, respectively, while maintaining similar levels of economic production. Greater levels of water scarcity reductions are attainable and could be very important in highly water-stressed basins such as the Snake River Basin (Figure 3.6). Overconsumption of available river flows in the Snake River Basin has led to recurring water shortages for both irrigation farmers and hydro-electric power producers, while severely depleting river flows and the associated warming of water temperatures continue to depress populations of imperiled salmon in the lower Snake River Basin[42,43]. In the over-appropriated Colorado River Basin, average summer water savings at the BM_{25} level equate to 1.59×10^8 m^3yr^{-1} at the U.S.-Mexico border, which amounts to an 8.3% increase in streamflow.

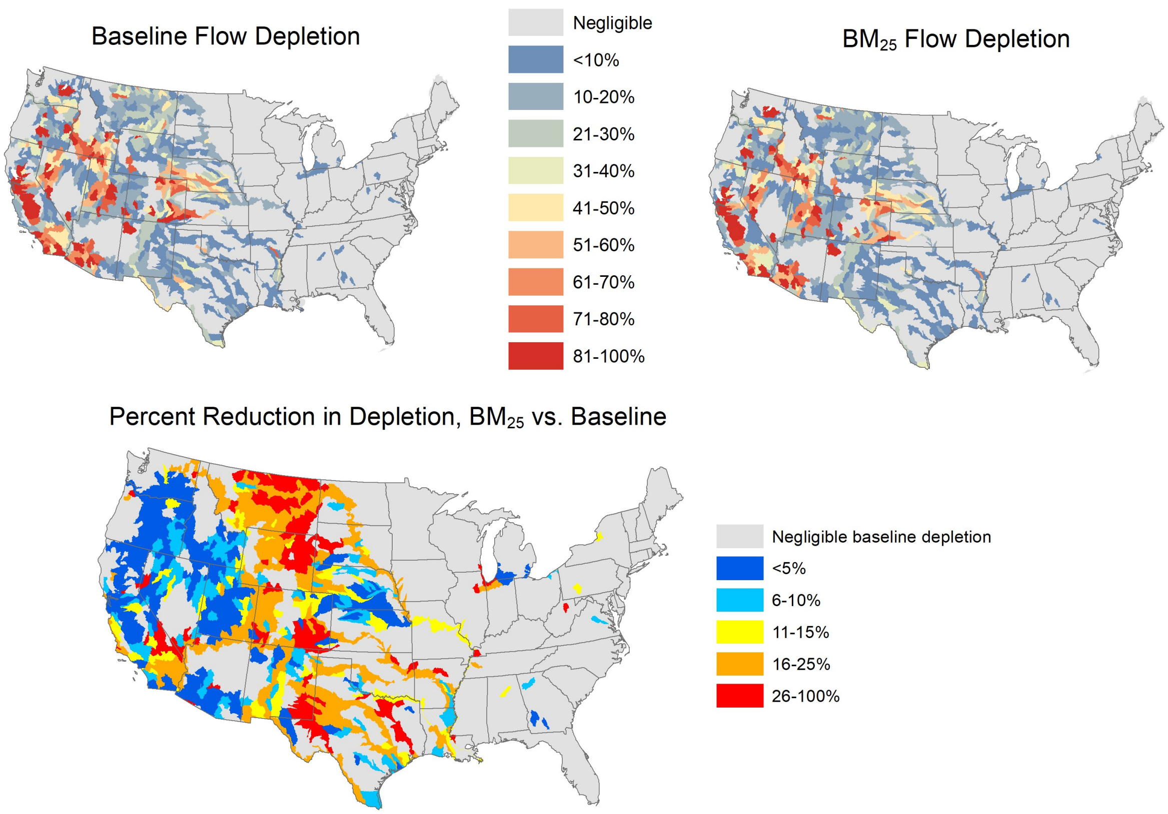

Figure 3.5: Potential change in depletion of mean river flows in summertime (July-September) during 2001-2015, based on attaining BM_{25} in all water-use sectors. The period 2001-2015 was selected because it has been identified as an extraordinary drought period for the Western U.S..

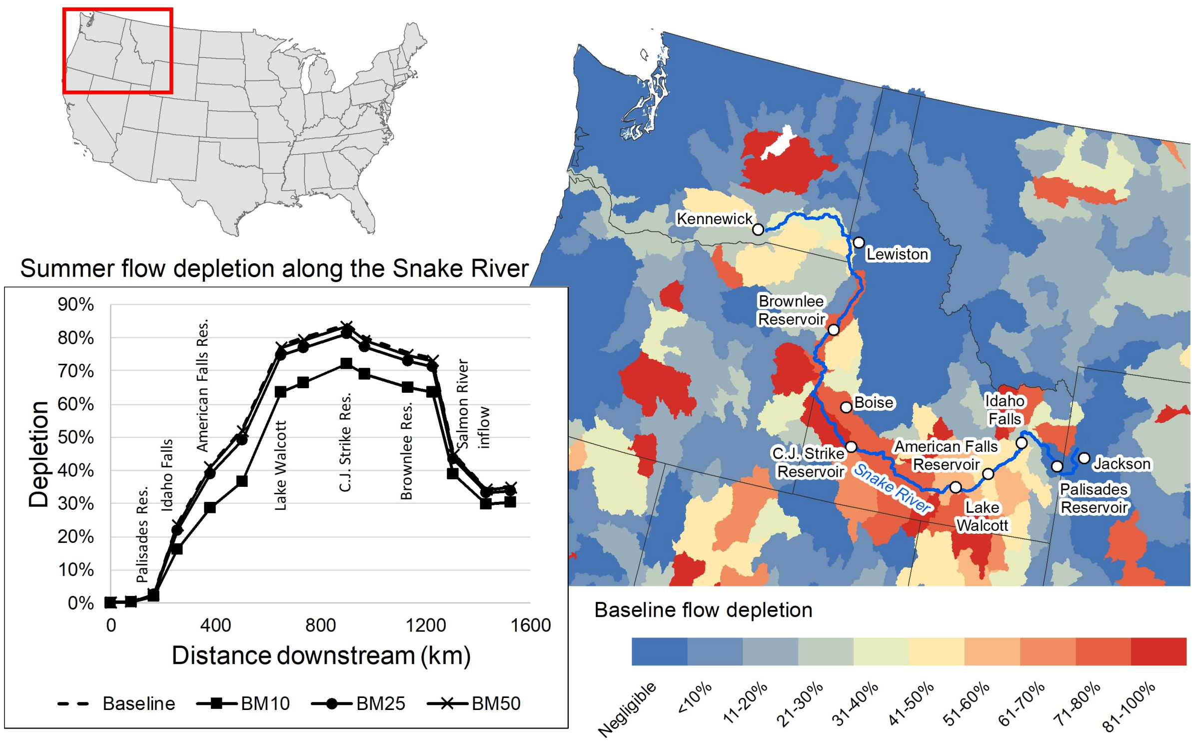

Figure 3.6: Potential reductions in river depletion along the length of the Snake River in Wyoming, Idaho and Washington. In the upper basin, increased river flows would bolster reservoir storage important to farmers and hydroelectric power producers; in the lower river, increased river flows would benefit imperiled salmon populations.

Chapter 4

Discussion

Improving water productivity through improved business practices, supply chain sourcing, policies, and water-efficient technologies is an important step towards putting water to more economically and environmentally beneficial uses. Roughly one-sixth of river basins in the United States are unable to consistently meet societal water demands while also providing sufficient water for the environment[8]. In river basins where human uses of water are satisfied but environmental flows are inadequate, leaving unused (saved) water in situ will help bolster environmental flows. However, in the instances in which neither human nor environmental needs are being fully met, any water savings from productivity improvements will most likely be consumed by users needing more water or wanting to expand production[44], unless legal or administrative rules dictate that the water savings be returned to the environment (e.g., Schwarz and Megdal ref.[45]). For example, multiple studies[46,47,48] have found public subsidies of water efficient irrigation technologies lead farmers to expand their irrigated acreage and grow more intensive crops with their water 'savings,' leading to greater production but no improvement in water conservation or environmental water scarcity. While we contend that water users are best suited to determine their own optimal strategy for improving water productivity, government programs and market forces can incentivize water users to optimize their individual practices.

Water conservation levels demonstrated at the scale of this study will require a combination of institution-level regulatory and market-based measures, along with changes in producer-level operations. Limiting new water right permits and shifting from diversionary water rights to consumptive water rights, such that return flows are considered, will help cap water use within a basin. Water use caps have been widely promoted as a means to curtail further consumptive water use within a basin[49,44]. A water market system based on formal water rights—such as the prior appropriation system that governs water use in the Western states—can be helpful in facilitating the transfer of water between users with surplus water savings and those needing more water, including the environment[50]. One advantage of such transfers is that they tend to reallocate the saved water to other users that are more economically productive[51]. They are also attractive because they financially reward users that are able to save water by allowing them to sell their water savings to other users or environmental interests, thereby creating a strong incentive for improving water productivity. Lastly, a paradigm shift is needed in irrigation management towards a focus on maximization of net benefits (which gives consideration to the opportunity costs of water), not the biological objective of yield maximization[52]. When the chief objective is to maximize yields and water is undervalued, wasted water is an expected outcome.

In the water-intensive agricultural sector, improved irrigation scheduling, switching from furrow irrigation to subsurface drip irrigation, and adopting no-till and mulching strategies that increase soil moisture retention are commonly employed approaches to reduce water consumption[53,54]. For example, a group of irrigators in western Kansas have reduced their average water use by 31% employing some of these strategies, while maintaining similar levels of profitability[55,56]. In the industrial sector, replacing "wet" evaporative cooling systems with "dry" air-cooled systems, water reuse, switching to alternative water supplies such as captured stormwater, desalinated water, or treated wastewater, regular inspection of the water system for leaks or inefficiencies, and employee education programs are common ways to reduce freshwater consumption.

Ironically, some of the areas we show as having the greatest environmental water scarcity, as well as the greatest potential for water savings, have some of the lowest municipal water prices in the U.S. and have pricing structures that charge less per unit of water with increasing water use[57]. However, many cities are not able to effectively price water so as to reduce water consumption due to state and local regulations that restrict water revenues from exceeding the cost of supplying water[57]. Cities such as Las Vegas and San Antonio support alternative approaches to reduce water demand, such as implementing water use restrictions, offering financial rebates for reduced landscape irrigation, use of analytics to identify leaks early, educational programs, and installation of low-flow appliances. Some groundwater management districts across the country have encouraged improved water productivity by taxing groundwater pumping[58] or capping groundwater withdrawals[55] to reverse aquifer overexploitation and depletion of connected streams. At the household level, federal programs such as EPA WaterSense (https://www.epa.gov/watersense) help promote sales of more water-efficient appliances and educate consumers on their water footprint.

As these select examples demonstrate, there are already myriad approaches to conserve water and increase water productivity, and their implementation at scale can achieve the potential water savings found in this study. As we demonstrate, most industries have more potential water savings in their indirect supply chains than in their direct operations, so one of the most attractive options to reduce water consumption is for industries to employ "offset" or efficiency clauses in contracts to require water-intensive suppliers to save water. Transnational companies like PepsiCo, Coca-Cola, Gap Inc., and Kellogg's have taken initial steps to promote water conservation in their own operations and also through their supply chains. Moreover, cities can achieve 'water-neutral growth' by requiring new developments offset their water consumption by retrofitting existing developments with water-efficient technology[59].

We reiterate that our study represents an upper bound on potential water savings should best practices in water conservation proliferate through each sector of the economy. Though not all producers will be able to reduce water consumption while maintaining current levels of production, numerous studies demonstrate significant (up to 76%) water savings with little to no reductions in production (e.g., Richter et al.[53] reviews over 30 studies that maintained crop yields while implementing a variety of approaches to conserve water). Importantly, the spatial detail of our analysis can help target water conservation measures at places where they are most needed and may be possible with little to no reduction in economic activity.

Chapter 5

Conclusion

Growing concerns over water shortage risks in many parts of the U.S. have stimulated interest in finding ways to lower water consumption; yet, there is a parallel objective of increasing economic activity that seems at odds with water conservation goals. Our water productivity benchmarking approach reveals a path to reduce water consumption in a manner that enhances economic productivity and is also demonstrably feasible within the unique constraints faced by each industry in each region. We find that total annual potential water savings in the U.S. economy (1.69×10^{10} m^3; BM$_{25}$ scenario) are similar to the combined consumptive water use of domestic, commercial, industrial, institutional, and thermoelectric power water users (1.92×10^{10} m^3). Many of the most water stressed river basins within the U.S. also show the greatest potential for water savings through water productivity improvements. A focus on improving water productivity and reducing environmental flow impacts of water consumption facilitates a shift from a politically untenable paradigm of restricting water rights to a more workable solution centered on getting more environmental and economic benefit out of each cubic meter of water.

Potential water savings and reductions in streamflow depletion found in this study are likely conservative due to data limitations. We use observations of individual water users when available (e.g., individual thermoelectric power plants); otherwise, water consumption by two or more water users within an industry were averaged across a county or sub-county scale within the dataset we utilize. Average water productivity values reduce water productivity variance, which likely reduces the magnitude of potential water savings achieved by attaining the benchmarks. Furthermore, our study likely underestimates both water consumption and water savings of irrigated crop production for two reasons: (1) This study does not capture conveyance losses, which can be significant. While a portion of these losses will recharge aquifers or return to rivers for other productive uses, the rest will evaporate/transpire or flow to sinks, such as inaccessible or saline aquifers and the ocean. (2) Since agricultural water use is rarely metered, we pair modeled estimates of crop irrigation with observations of crop yield to determine water productivity, and this modeling approach underrepresents low-productivity outliers that are using large amounts of water compared to their cohort. Observed crop yields allow us to capture actual variations between irrigators' water productivity[31]; however, the measure and variability of water consumption (the denominator of the water productivity term) is likely underestimated. The crop water model we use employs the common assumption[60,61,62,24] that crops are provided exactly the water needed to produce optimal yields. Irrigators often apply more water to their crops than the optimal rate[55,56], meaning the potential for water conservation is greater than we are able to represent.

Nonetheless, this study represents an important first step towards understanding locations and industries where improved water productivity shows the greatest potential to conserve water. Meeting the direct and indirect water demands of a growing population while providing sufficient water to meet local environmental flow requirements will be a key challenge in the coming decades. Improving water productivity will be critical in meeting this challenge by putting water to more economically beneficial uses, reducing unsustainable water use, and making water available for other uses, including the environment.

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Appendix A

Appendix Tables

Table A.1: List of crops, livestock, and thermoelectric power plant types evaluated in this study. The general description and NAICS 2-digit code used to aggregate individual products/production types together are provided.

	Specific Description	General Description	NAICS 2-Digit Code
1	Alfalfa	Agriculture	11
2	Barley	Agriculture	11
3	Cotton	Agriculture	11
4	Dry beans	Agriculture	11
5	Flaxseed	Agriculture	11
6	Lentils	Agriculture	11
7	Oats	Agriculture	11
8	Peas	Agriculture	11
9	Potatoes	Agriculture	11
10	Rice	Agriculture	11
11	Safflower	Agriculture	11
12	Sorghum, Grain	Agriculture	11
13	Sorghum, Silage	Agriculture	11
14	Spring Wheat	Agriculture	11
15	Sugar beets	Agriculture	11
16	Sunflower	Agriculture	11
17	Sweet Potatoes	Agriculture	11
18	Sweet Corn	Agriculture	11
19	Tomatoes	Agriculture	11
20	Winter Wheat	Agriculture	11
21	Corn, Grain	Agriculture	11

Table A.1: List of crops, livestock, and thermoelectric power plant types evaluated in this study. The general description and NAICS 2-digit code used to aggregate individual products/production types together are provided.

	Specific Description	General Description	NAICS 2-Digit Code
22	Corn, Silage	Agriculture	11
23	Soybeans	Agriculture	11
24	Cattle - Beef	Agriculture	11
25	Chicken - Broilers/Other	Agriculture	11
26	Cattle - Dairy	Agriculture	11
27	Goats	Agriculture	11
28	Hogs and pigs	Agriculture	11
29	Horses (including ponies, mules, burros & donkeys)	Agriculture	11
30	Chicken - Laying hens	Agriculture	11
31	Sheep and lambs	Agriculture	11
32	Turkeys	Agriculture	11
33	Thermoelectric - Coal, Once-Through	Utilities	22
34	Thermoelectric - Coal, Recirculating	Utilities	22
35	Thermoelectric - Natural Gas, Once-Through	Utilities	22
36	Thermoelectric - Natural Gas, Recirculating	Utilities	22
37	Thermoelectric - Nuclear, Once-Through	Utilities	22
38	Thermoelectric - Nuclear, Recirculating	Utilities	22
39	Thermoelectric - Petroleum, Once-Through	Utilities	22
40	Thermoelectric - Petroleum, Recirculating	Utilities	22

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
2212	22	Natural Gas Distribution	Utilities
23	23	Construction	Construction
311111	31	Dog and Cat Food Manufacturing	Manufacturing
311119	31	Other Animal Food Manufacturing	Manufacturing
31121	31	Flour Milling and Malt Manufacturing	Manufacturing
311221	31	Wet Corn Milling	Manufacturing
311224	31	Soybean and Other Oilseed Processing	Manufacturing
311225	31	Fats and Oils Refining and Blending	Manufacturing
31123	31	Breakfast Cereal Manufacturing	Manufacturing
3113	31	Sugar and Confectionery Product Manufacturing	Manufacturing
31141	31	Frozen Food Manufacturing	Manufacturing
31142	31	Fruit and Vegetable Canning, Pickling, and Drying	Manufacturing
311511	31	Fluid Milk Manufacturing	Manufacturing
311512	31	Creamery Butter Manufacturing	Manufacturing
311513	31	Cheese Manufacturing	Manufacturing
311514	31	Dry, Condensed, and Evaporated Dairy Product Manufacturing	Manufacturing

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
31152	31	Ice Cream and Frozen Dessert Manufacturing	Manufacturing
311611	31	Animal (except Poultry) Slaughtering	Manufacturing
311612	31	Meat Processed from Carcasses	Manufacturing
311613	31	Rendering and Meat Byproduct Processing	Manufacturing
311615	31	Poultry Processing	Manufacturing
3117	31	Seafood Product Preparation and Packaging	Manufacturing
31181	31	Bread and Bakery Product Manufacturing	Manufacturing
31182	31	Cookie, Cracker, and Pasta Manufacturing	Manufacturing
31183	31	Tortilla Manufacturing	Manufacturing
31191	31	Snack Food Manufacturing	Manufacturing
31192	31	Coffee and Tea Manufacturing	Manufacturing
31193	31	Flavoring Syrup and Concentrate Manufacturing	Manufacturing
31194	31	Seasoning and Dressing Manufacturing	Manufacturing
31199	31	All Other Food Manufacturing	Manufacturing
31211	31	Soft Drink and Ice Manufacturing	Manufacturing
31212	31	Breweries	Manufacturing
31213	31	Wineries	Manufacturing

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
31214	31	Distilleries	Manufacturing
3122	31	Tobacco Manufacturing	Manufacturing
3131	31	Fiber, Yarn, and Thread Mills	Manufacturing
3132	31	Fabric Mills	Manufacturing
3133	31	Textile and Fabric Finishing and Fabric Coating Mills	Manufacturing
31411	31	Carpet and Rug Mills	Manufacturing
31412	31	Curtain and Linen Mills	Manufacturing
3149	31	Other Textile Product Mills	Manufacturing
315	31	Apparel Manufacturing	Manufacturing
316	31	Leather and Allied Product Manufacturing	Manufacturing
3211	32	Sawmills and Wood Preservation	Manufacturing
3212	32	Veneer, Plywood, and Engineered Wood Product Manufacturing	Manufacturing
32191	32	Millwork	Manufacturing
32192	32	Wood Container and Pallet Manufacturing	Manufacturing
32199	32	All Other Wood Product Manufacturing	Manufacturing
32212	32	Paper Mills	Manufacturing
32213	32	Paperboard Mills	Manufacturing

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
32221	32	Paperboard Container Manufacturing	Manufacturing
32222	32	Paper Bag and Coated and Treated Paper Manufacturing	Manufacturing
32223	32	Stationery Product Manufacturing	Manufacturing
322291	32	Sanitary Paper Product Manufacturing	Manufacturing
322299	32	All Other Converted Paper Product Manufacturing	Manufacturing
32311	32	Printing	Manufacturing
32312	32	Support Activities for Printing	Manufacturing
32411	32	Petroleum Refineries	Manufacturing
324121	32	Asphalt Paving Mixture and Block Manufacturing	Manufacturing
324122	32	Asphalt Shingle and Coating Materials Manufacturing	Manufacturing
32419	32	Other Petroleum and Coal Products Manufacturing	Manufacturing
32511	32	Petrochemical Manufacturing	Manufacturing
32512	32	Industrial Gas Manufacturing	Manufacturing
32513	32	Synthetic Dye and Pigment Manufacturing	Manufacturing

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
32518	32	Other Basic Inorganic Chemical Manufacturing	Manufacturing
32519	32	Other Basic Organic Chemical Manufacturing	Manufacturing
325211	32	Plastics Material and Resin Manufacturing	Manufacturing
325212	32	Synthetic Rubber Manufacturing	Manufacturing
32522	32	Artificial and Synthetic Fibers and Filaments Manufacturing	Manufacturing
32531	32	Fertilizer Manufacturing	Manufacturing
32532	32	Pesticide and Other Agricultural Chemical Manufacturing	Manufacturing
325411	32	Medicinal and Botanical Manufacturing	Manufacturing
325412	32	Pharmaceutical Preparation Manufacturing	Manufacturing
325413	32	In-Vitro Diagnostic Substance Manufacturing	Manufacturing
325414	32	Biological Product (except Diagnostic) Manufacturing	Manufacturing
32551	32	Paint and Coating Manufacturing	Manufacturing
32552	32	Adhesive Manufacturing	Manufacturing

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
32561	32	Soap and Cleaning Compound Manufacturing	Manufacturing
32562	32	Toilet Preparation Manufacturing	Manufacturing
32591	32	Printing Ink Manufacturing	Manufacturing
32592	32	Explosives Manufacturing	Manufacturing
32599	32	All Other Chemical Product and Preparation Manufacturing	Manufacturing
32611	32	Plastics Packaging Materials and Unlaminated Film and Sheet Manufacturing	Manufacturing
32612	32	Plastics Pipe, Pipe Fitting, and Unlaminated Profile Shape Manufacturing	Manufacturing
32613	32	Laminated Plastics Plate, Sheet (except Packaging), and Shape Manufacturing	Manufacturing
32614	32	Polystyrene Foam Product Manufacturing	Manufacturing
32615	32	Urethane and Other Foam Product (except Polystyrene) Manufacturing	Manufacturing
32616	32	Plastics Bottle Manufacturing	Manufacturing
32619	32	Other Plastics Product Manufacturing	Manufacturing
32621	32	Tire Manufacturing	Manufacturing

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
32622	32	Rubber and Plastics Hoses and Belting Manufacturing	Manufacturing
32629	32	Other Rubber Product Manufacturing	Manufacturing
3271	32	Clay Product and Refractory Manufacturing	Manufacturing
3272	32	Glass and Glass Product Manufacturing	Manufacturing
32731	32	Cement Manufacturing	Manufacturing
32732	32	Ready-Mix Concrete Manufacturing	Manufacturing
32733	32	Concrete Pipe, Brick, and Block Manufacturing	Manufacturing
32739	32	Other Concrete Product Manufacturing	Manufacturing
3274	32	Lime and Gypsum Product Manufacturing	Manufacturing
32791	32	Abrasive Product Manufacturing	Manufacturing
327991	32	Cut Stone and Stone Product Manufacturing	Manufacturing
327992	32	Ground or Treated Mineral and Earth Manufacturing	Manufacturing
327993	32	Mineral Wool Manufacturing	Manufacturing
327999	32	All Other Miscellaneous Nonmetallic Mineral Product Manufacturing	Manufacturing

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
3311	33	Iron and Steel Mills and Ferroalloy Manufacturing	Manufacturing
3312	33	Steel Product Manufacturing from Purchased Steel	Manufacturing
331313	33	Alumina Refining and Primary Aluminum Production	Manufacturing
331314	33	Secondary Smelting and Alloying of Aluminum	Manufacturing
331315	33	Aluminum Sheet, Plate, and Foil Manufacturing	Manufacturing
331318	33	Other Aluminum Rolling, Drawing, and Extruding	Manufacturing
33141	33	Nonferrous Metal (except Aluminum) Smelting and Refining	Manufacturing
33142	33	Copper Rolling, Drawing, Extruding, and Alloying	Manufacturing
33149	33	Nonferrous Metal (except Copper and Aluminum) Rolling, Drawing, Extruding, and Alloying	Manufacturing

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
33151	33	Ferrous Metal Foundries	Manufacturing
33152	33	Nonferrous Metal Foundries	Manufacturing
332111	33	Iron and Steel Forging	Manufacturing
332112	33	Nonferrous Forging	Manufacturing
332114	33	Custom Roll Forming	Manufacturing
332117	33	Powder Metallurgy Part Manufacturing	Manufacturing
332119	33	Metal Crown, Closure, and Other Metal Stamping (except Automotive)	Manufacturing
3322	33	Cutlery and Handtool Manufacturing	Manufacturing
33231	33	Plate Work and Fabricated Structural Product Manufacturing	Manufacturing
33232	33	Ornamental and Architectural Metal Products Manufacturing	Manufacturing
33241	33	Power Boiler and Heat Exchanger Manufacturing	Manufacturing
33242	33	Metal Tank (Heavy Gauge) Manufacturing	Manufacturing
33243	33	Metal Can, Box, and Other Metal Container (Light Gauge) Manufacturing	Manufacturing
3325	33	Hardware Manufacturing	Manufacturing

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
3326	33	Spring and Wire Product Manufacturing	Manufacturing
33271	33	Machine Shops	Manufacturing
33272	33	Turned Product and Screw, Nut, and Bolt Manufacturing	Manufacturing
3328	33	Coating, Engraving, Heat Treating, and Allied Activities	Manufacturing
332911	33	Industrial Valve Manufacturing	Manufacturing
332912	33	Fluid Power Valve and Hose Fitting Manufacturing	Manufacturing
332913	33	Plumbing Fixture Fitting and Trim Manufacturing	Manufacturing
332919	33	Other Metal Valve and Pipe Fitting Manufacturing	Manufacturing
332991	33	Ball and Roller Bearing Manufacturing	Manufacturing
332992	33	Small Arms Ammunition Manufacturing	Manufacturing
332993	33	Ammunition (except Small Arms) Manufacturing	Manufacturing
332994	33	Small Arms, Ordnance, and Ordnance Accessories Manufacturing	Manufacturing

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
332996	33	Fabricated Pipe and Pipe Fitting Manufacturing	Manufacturing
332999	33	All Other Miscellaneous Fabricated Metal Product Manufacturing	Manufacturing
333111	33	Farm Machinery and Equipment Manufacturing	Manufacturing
333112	33	Lawn and Garden Tractor and Home Lawn and Garden Equipment Manufacturing	Manufacturing
33312	33	Construction Machinery Manufacturing	Manufacturing
33313	33	Mining and Oil and Gas Field Machinery Manufacturing	Manufacturing
333242	33	Semiconductor Machinery Manufacturing	Manufacturing
333249	33	Other Industrial Machinery Manufacturing	Manufacturing
333314	33	Optical Instrument and Lens Manufacturing	Manufacturing
333316	33	Photographic and Photocopying Equipment Manufacturing	Manufacturing
333318	33	Other Commercial and Service Industry Machinery Manufacturing	Manufacturing

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
333413	33	Industrial and Commercial Fan and Blower and Air Purification Equipment Manufacturing	Manufacturing
333414	33	Heating Equipment (except Warm Air Furnaces) Manufacturing	Manufacturing
333415	33	Air-Conditioning and Warm Air Heating Equipment and Commercial and Industrial Refrigeration Equipment Manufacturing	Manufacturing
333511	33	Industrial Mold Manufacturing	Manufacturing
333514	33	Special Die and Tool, Die Set, Jig, and Fixture Manufacturing	Manufacturing
333515	33	Cutting Tool and Machine Tool Accessory Manufacturing	Manufacturing
333517	33	Machine Tool Manufacturing	Manufacturing
333519	33	Rolling Mill and Other Metalworking Machinery Manufacturing	Manufacturing
333611	33	Turbine and Turbine Generator Set Units Manufacturing	Manufacturing

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
333612	33	Speed Changer, Industrial High-Speed Drive, and Gear Manufacturing	Manufacturing
333613	33	Mechanical Power Transmission Equipment Manufacturing	Manufacturing
333618	33	Other Engine Equipment Manufacturing	Manufacturing
333911	33	Pump and Pumping Equipment Manufacturing	Manufacturing
333912	33	Air and Gas Compressor Manufacturing	Manufacturing
333913	33	Measuring and Dispensing Pump Manufacturing	Manufacturing
33392	33	Material Handling Equipment Manufacturing	Manufacturing
333991	33	Power-Driven Handtool Manufacturing	Manufacturing
333992	33	Welding and Soldering Equipment Manufacturing	Manufacturing
333993	33	Packaging Machinery Manufacturing	Manufacturing
333994	33	Industrial Process Furnace and Oven Manufacturing	Manufacturing

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
333995	33	Fluid Power Cylinder and Actuator Manufacturing	Manufacturing
333996	33	Fluid Power Pump and Motor Manufacturing	Manufacturing
333999	33	All Other Miscellaneous General Purpose Machinery Manufacturing	Manufacturing
334111	33	Electronic Computer Manufacturing	Manufacturing
334112	33	Computer Storage Device Manufacturing	Manufacturing
334118	33	Computer Terminal and Other Computer Peripheral Equipment Manufacturing	Manufacturing
33421	33	Telephone Apparatus Manufacturing	Manufacturing
33422	33	Radio and Television Broadcasting and Wireless Communications Equipment Manufacturing	Manufacturing
33429	33	Other Communications Equipment Manufacturing	Manufacturing
3343	33	Audio and Video Equipment Manufacturing	Manufacturing
334412	33	Bare Printed Circuit Board Manufacturing	Manufacturing

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NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
334413	33	Semiconductor and Related Device Manufacturing	Manufacturing
334416	33	Capacitor, Resistor, Coil, Transformer, and Other Inductor Manufacturing	Manufacturing
334417	33	Electronic Connector Manufacturing	Manufacturing
334418	33	Printed Circuit Assembly (Electronic Assembly) Manufacturing	Manufacturing
334419	33	Other Electronic Component Manufacturing	Manufacturing
334510	33	Electromedical and Electrotherapeutic Apparatus Manufacturing	Manufacturing
334511	33	Search, Detection, Navigation, Guidance, Aeronautical, and Nautical System and Instrument Manufacturing	Manufacturing
334512	33	Automatic Environmental Control Manufacturing for Residential, Commercial, and Appliance Use	Manufacturing
334513	33	Instruments and Related Products Manufacturing for Measuring, Displaying, and Controlling Industrial Process Variables	Manufacturing

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
334514	33	Totalizing Fluid Meter and Counting Device Manufacturing	Manufacturing
334515	33	Instrument Manufacturing for Measuring and Testing Electricity and Electrical Signals	Manufacturing
334516	33	Analytical Laboratory Instrument Manufacturing	Manufacturing
334517	33	Irradiation Apparatus Manufacturing	Manufacturing
334519	33	Other Measuring and Controlling Device Manufacturing	Manufacturing
33461	33	Manufacturing and Reproducing Magnetic and Optical Media	Manufacturing
33511	33	Electric Lamp Bulb and Part Manufacturing	Manufacturing
33512	33	Lighting Fixture Manufacturing	Manufacturing
33521	33	Small Electrical Appliance Manufacturing	Manufacturing
33522	33	Major Appliance Manufacturing	Manufacturing
335311	33	Power, Distribution, and Specialty Transformer Manufacturing	Manufacturing
335312	33	Motor and Generator Manufacturing	Manufacturing

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NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
335313	33	Switchgear and Switchboard Apparatus Manufacturing	Manufacturing
335314	33	Relay and Industrial Control Manufacturing	Manufacturing
335911	33	Storage Battery Manufacturing	Manufacturing
335912	33	Primary Battery Manufacturing	Manufacturing
33592	33	Communication and Energy Wire and Cable Manufacturing	Manufacturing
33593	33	Wiring Device Manufacturing	Manufacturing
335991	33	Carbon and Graphite Product Manufacturing	Manufacturing
335999	33	All Other Miscellaneous Electrical Equipment and Component Manufacturing	Manufacturing
336111	33	Automobile Manufacturing	Manufacturing
336112	33	Light Truck and Utility Vehicle Manufacturing	Manufacturing
33612	33	Heavy Duty Truck Manufacturing	Manufacturing
336211	33	Motor Vehicle Body Manufacturing	Manufacturing
336212	33	Truck Trailer Manufacturing	Manufacturing
336213	33	Motor Home Manufacturing	Manufacturing

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
336214	33	Travel Trailer and Camper Manufacturing	Manufacturing
33631	33	Motor Vehicle Gasoline Engine and Engine Parts Manufacturing	Manufacturing
33632	33	Motor Vehicle Electrical and Electronic Equipment Manufacturing	Manufacturing
33633	33	Motor Vehicle Steering and Suspension Components (except Spring) Manufacturing	Manufacturing
33634	33	Motor Vehicle Brake System Manufacturing	Manufacturing
33635	33	Motor Vehicle Transmission and Power Train Parts Manufacturing	Manufacturing
33636	33	Motor Vehicle Seating and Interior Trim Manufacturing	Manufacturing
33637	33	Motor Vehicle Metal Stamping	Manufacturing
33639	33	Other Motor Vehicle Parts Manufacturing	Manufacturing
336411	33	Aircraft Manufacturing	Manufacturing
336412	33	Aircraft Engine and Engine Parts Manufacturing	Manufacturing
336413	33	Other Aircraft Parts and Auxiliary Equipment Manufacturing	Manufacturing

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NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
336414	33	Guided Missile and Space Vehicle Manufacturing	Manufacturing
336415	33	Guided Missile and Space Vehicle Propulsion Unit and Propulsion Unit Parts Manufacturing	Manufacturing
336419	33	Other Guided Missile and Space Vehicle Parts and Auxiliary Equipment Manufacturing	Manufacturing
3365	33	Railroad Rolling Stock Manufacturing	Manufacturing
336611	33	Ship Building and Repairing	Manufacturing
336612	33	Boat Building	Manufacturing
336991	33	Motorcycle, Bicycle, and Parts Manufacturing	Manufacturing
336992	33	Military Armored Vehicle, Tank, and Tank Component Manufacturing	Manufacturing
336999	33	All Other Transportation Equipment Manufacturing	Manufacturing
33711	33	Wood Kitchen Cabinet and Countertop Manufacturing	Manufacturing

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NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
337121	33	Upholstered Household Furniture Manufacturing	Manufacturing
337122	33	Nonupholstered Wood Household Furniture Manufacturing	Manufacturing
337124	33	Metal Household Furniture Manufacturing	Manufacturing
337125	33	Household Furniture (except Wood and Metal) Manufacturing	Manufacturing
337127	33	Institutional Furniture Manufacturing	Manufacturing
337211	33	Wood Office Furniture Manufacturing	Manufacturing
337212	33	Custom Architectural Woodwork and Millwork Manufacturing	Manufacturing
337214	33	Office Furniture (except Wood) Manufacturing	Manufacturing
337215	33	Showcase, Partition, Shelving, and Locker Manufacturing	Manufacturing
3379	33	Other Furniture Related Product Manufacturing	Manufacturing
339112	33	Surgical and Medical Instrument Manufacturing	Manufacturing

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NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
339113	33	Surgical Appliance and Supplies Manufacturing	Manufacturing
339114	33	Dental Equipment and Supplies Manufacturing	Manufacturing
339115	33	Ophthalmic Goods Manufacturing	Manufacturing
339116	33	Dental Laboratories	Manufacturing
33991	33	Jewelry and Silverware Manufacturing	Manufacturing
33992	33	Sporting and Athletic Goods Manufacturing	Manufacturing
33993	33	Doll, Toy, and Game Manufacturing	Manufacturing
33994	33	Office Supplies (except Paper) Manufacturing	Manufacturing
33995	33	Sign Manufacturing	Manufacturing
33999	33	All Other Miscellaneous Manufacturing	Manufacturing
42	42	Wholesale Trade	Wholesale Trade
441	44	Motor Vehicle and Parts Dealers	Retail Trade
442	44	Furniture and Home Furnishings Stores	Retail Trade
443	44	Electronics and Appliance Stores	Retail Trade
444	44	Building Material and Garden Equipment and Supplies Dealers	Retail Trade

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NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
445	44	Food and Beverage Stores	Retail Trade
446	44	Health and Personal Care Stores	Retail Trade
447	44	Gasoline Stations	Retail Trade
448	44	Clothing and Clothing Accessories Stores	Retail Trade
451	45	Sporting Goods, Hobby, Musical Instrument, and Book Stores	Retail Trade
452	45	General Merchandise Stores	Retail Trade
453	45	Miscellaneous Store Retailers	Retail Trade
454	45	Nonstore Retailers	Retail Trade
481	48	Air Transportation	Transportation & Warehousing
483	48	Water Transportation	Transportation & Warehousing
484	48	Truck Transportation	Transportation & Warehousing
485	48	Transit and Ground Passenger Transportation	Transportation & Warehousing
487	48	Scenic and Sightseeing Transportation	Transportation & Warehousing

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
488	48	Support Activities for Transportation	Transportation & Warehousing
492	49	Couriers and Messengers	Transportation & Warehousing
493	49	Warehousing and Storage	Transportation & Warehousing
51111	51	Newspaper Publishers	Information
51112	51	Periodical Publishers	Information
51113	51	Book Publishers	Information
51114	51	Directory and Mailing List Publishers	Information
51119	51	Other Publishers	Information
51121	51	Software Publishers	Information
5121	51	Motion Picture and Video Industries	Information
5122	51	Sound Recording Industries	Information
5151	51	Radio and Television Broadcasting	Information
5152	51	Cable and Other Subscription Programming	Information
5171	51	Wired Telecommunications Carriers	Information
5172	51	Wireless Telecommunications Carriers (except Satellite)	Information

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NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
5174	51	Satellite Telecommunications	Information
5179	51	Other Telecommunications	Information
5182	51	Data Processing, Hosting, and Related Services	Information
51911	51	News Syndicates	Information
51912	51	Libraries and Archives	Information
51913	51	Internet Publishing and Broadcasting and Web Search Portals	Information
51919	51	All Other Information Services	Information
521	52	Monetary Authorities-Central Bank	Finance & Insurance
5221	52	Depository Credit Intermediation	Finance & Insurance
5222	52	Nondepository Credit Intermediation	Finance & Insurance
5223	52	Activities Related to Credit Intermediation	Finance & Insurance
5231	52	Securities and Commodity Contracts Intermediation and Brokerage	Finance & Insurance
5232	52	Securities and Commodity Exchanges	Finance & Insurance
5239	52	Other Financial Investment Activities	Finance & Insurance
5241	52	Insurance Carriers	Finance & Insurance

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NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
5242	52	Agencies, Brokerages, and Other Insurance Related Activities	Finance & Insurance
5321	53	Automotive Equipment Rental and Leasing	Real Estate and Rental and Leasing
5322	53	Consumer Goods Rental	Real Estate and Rental and Leasing
5323	53	General Rental Centers	Real Estate and Rental and Leasing
5324	53	Commercial and Industrial Machinery and Equipment Rental and Leasing	Real Estate and Rental and Leasing
533	53	Lessors of Nonfinancial Intangible Assets (except Copyrighted Works)	Real Estate and Rental and Leasing
5411	54	Legal Services	Professional, Scientific, and Technical Services
5412	54	Accounting, Tax Preparation, Bookkeeping, and Payroll Services	Professional, Scientific, and Technical Services

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
5413	54	Architectural, Engineering, and Related Services	Professional, Scientific, and Technical Services
5414	54	Specialized Design Services	Professional, Scientific, and Technical Services
541511	54	Custom Computer Programming Services	Professional, Scientific, and Technical Services
541512	54	Computer Systems Design Services	Professional, Scientific, and Technical Services
541513	54	Computer Facilities Management Services	Professional, Scientific, and Technical Services
541519	54	Other Computer Related Services	Professional, Scientific, and Technical Services

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
54161	54	Management Consulting Services	Professional, Scientific, and Technical Services
54162	54	Environmental Consulting Services	Professional, Scientific, and Technical Services
54169	54	Other Scientific and Technical Consulting Services	Professional, Scientific, and Technical Services
5417	54	Scientific Research and Development Services	Professional, Scientific, and Technical Services
5418	54	Advertising, Public Relations, and Related Services	Professional, Scientific, and Technical Services
54191	54	Marketing Research and Public Opinion Polling	Professional, Scientific, and Technical Services

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
54192	54	Photographic Services	Professional, Scientific, and Technical Services
54193	54	Translation and Interpretation Services	Professional, Scientific, and Technical Services
54194	54	Veterinary Services	Professional, Scientific, and Technical Services
54199	54	All Other Professional, Scientific, and Technical Services	Professional, Scientific, and Technical Services
5611	56	Office Administrative Services	Waste Management and Remediation Services
5612	56	Facilities Support Services	Waste Management and Remediation Services

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
5613	56	Employment Services	Waste Management and Remediation Services
5614	56	Business Support Services	Waste Management and Remediation Services
5615	56	Travel Arrangement and Reservation Services	Waste Management and Remediation Services
5616	56	Investigation and Security Services	Waste Management and Remediation Services
5617	56	Services to Buildings and Dwellings	Waste Management and Remediation Services
5619	56	Other Support Services	Waste Management and Remediation Services

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
562	56	Waste Management and Remediation Services	Waste Management and Remediation Services
611	61	Educational Services	Educational Services
6211	62	Offices of Physicians	Health Care and Social Assistance
6212	62	Offices of Dentists	Health Care and Social Assistance
6213	62	Offices of Other Health Practitioners	Health Care and Social Assistance
6214	62	Outpatient Care Centers	Health Care and Social Assistance
6215	62	Medical and Diagnostic Laboratories	Health Care and Social Assistance
6216	62	Home Health Care Services	Health Care and Social Assistance
6219	62	Other Ambulatory Health Care Services	Health Care and Social Assistance

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
622	62	Hospitals	Health Care and Social Assistance
6231	62	Nursing Care Facilities (Skilled Nursing Facilities)	Health Care and Social Assistance
6232	62	Residential Intellectual and Developmental Disability, Mental Health, and Substance Abuse Facilities	Health Care and Social Assistance
6233	62	Continuing Care Retirement Communities and Assisted Living Facilities for the Elderly	Health Care and Social Assistance
6239	62	Other Residential Care Facilities	Health Care and Social Assistance
6241	62	Individual and Family Services	Health Care and Social Assistance
6242	62	Community Food and Housing, and Emergency and Other Relief Services	Health Care and Social Assistance
6243	62	Vocational Rehabilitation Services	Health Care and Social Assistance
6244	62	Child Day Care Services	Health Care and Social Assistance

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
7111	71	Performing Arts Companies	Arts, Entertainment, and Recreation
7112	71	Spectator Sports	Arts, Entertainment, and Recreation
7113	71	Promoters of Performing Arts, Sports, and Similar Events	Arts, Entertainment, and Recreation
7114	71	Agents and Managers for Artists, Athletes, Entertainers, and Other Public Figures	Arts, Entertainment, and Recreation
7115	71	Independent Artists, Writers, and Performers	Arts, Entertainment, and Recreation
712	71	Museums, Historical Sites, and Similar Institutions	Arts, Entertainment, and Recreation
7131	71	Amusement Parks and Arcades	Arts, Entertainment, and Recreation
7132	71	Gambling Industries	Arts, Entertainment, and Recreation
7139	71	Other Amusement and Recreation Industries	Arts, Entertainment, and Recreation

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
721	72	Accommodation	Accommodation and Food Services
7223	72	Special Food Services	Accommodation and Food Services
7224	72	Drinking Places (Alcoholic Beverages)	Accommodation and Food Services
8111	81	Automotive Repair and Maintenance	Other Services
8112	81	Electronic and Precision Equipment Repair and Maintenance	Other Services
8113	81	Commercial and Industrial Machinery and Equipment (except Automotive and Electronic) Repair and Maintenance	Other Services
8114	81	Personal and Household Goods Repair and Maintenance	Other Services
8121	81	Personal Care Services	Other Services
8122	81	Death Care Services	Other Services
8123	81	Drycleaning and Laundry Services	Other Services
8129	81	Other Personal Services	Other Services

Table A.2: List of commercial, industrial, and institutional (CII) water users included in this study. The full NAICS code and NAICS description are listed alongside the general description and 2-digit NAICS code used to aggregate industries to the broader sector they belong.

NAICS Code	NAICS 2-Digit Code	NAICS Description	General Description
813	81	Religious, Grantmaking, Civic, Professional, and Similar Organizations	Other Services

Table A.3: The contribution of crops included in this study to national irrigated harvested area and blue water consumption.

	Crop	Harvested irrigated area (% of U.S. total)	Blue water (% of U.S. crop total)
1	Alfalfa	18.84	29.65
2	Barley	1.59	1.30
3	Corn, Grain	25.44	17.28
4	Corn, Silage	3.09	3.02
5	Cotton	7.52	7.8
6	Dry beans	0.84	0.46
7	Flaxseed	0.00	0.00
8	Lentils	0.00	0.00
9	Oats	0.11	0.10
10	Peas	0.06	0.02
11	Potatoes	1.77	1.71
12	Rice	5.47	7.05
13	Safflower	0.05	0.05
14	Sorghum, Grain	1.25	0.76
15	Sorghum, Silage	0.32	0.21
16	Soybeans	14.31	9.81
17	Spring Wheat	1.68	0.57
18	Sugar Beets	0.83	0.91
19	Sunflower	0.17	0.25
20	Sweet Potatoes	0.08	0.05
21	Sweet Corn	0.01	0.46
22	Tomatoes	0.72	0.77
23	Wheat	4.81	4.63
	Sum	89.0	86.9

Table A.4: Base temperature below which each crop cannot grow.

	Crop	T_{base}(°Celsius)
1	Alfalfa	0
2	Barley	1
3	Corn, Grain	8
4	Corn, Silage	8
5	Cotton	8
6	Dry beans	2
7	Flaxseed	2
8	Lentils	2
9	Oats	2
10	Peas	2
11	Potatoes	2
12	Rice	5
13	Safflower	8
14	Sorghum, Grain	8
15	Sorghum, Silage	8
16	Soybeans	8
17	Spring Wheat	0
18	Sugar Beets	2
19	Sunflower	8
20	Sweet Potatoes	8
21	Sweet Corn	8
22	Tomatoes	8
23	Winter Wheat	0

Table A.5: Average blue water productivities per sector and climate region

Climate Region	Sector	Unit	Baseline	BM_{50}	BM_{25}	BM_{10}
Central	Irrigation	kg/m^3	2.0750	2.2120	2.4000	2.6350
East North Central	Irrigation	kg/m^3	4.7240	5.0440	5.4190	6.1480
Northeast	Irrigation	kg/m^3	5.2400	5.3350	5.4040	5.5690
Northwest	Irrigation	kg/m^3	3.1590	3.1970	3.3180	3.8140
South	Irrigation	kg/m^3	1.1430	1.2240	1.3360	1.4760
Southeast	Irrigation	kg/m^3	1.5330	1.6090	1.6780	1.7730
Southwest	Irrigation	kg/m^3	1.7170	1.8860	2.0500	2.2480
West	Irrigation	kg/m^3	1.5960	1.6410	1.7160	1.8460
West North Central	Irrigation	kg/m^3	2.5300	2.6130	2.7730	3.0140
Central	Domestic	$people/m^3$	0.0690	0.0910	0.0940	0.0980
East North Central	Domestic	$people/m^3$	0.0470	0.0530	0.0720	0.0840
Northeast	Domestic	$people/m^3$	0.0890	0.1220	0.1450	0.1460
Northwest	Domestic	$people/m^3$	0.0410	0.0600	0.0750	0.1150
South	Domestic	$people/m^3$	0.0160	0.0200	0.0270	0.0290
Southeast	Domestic	$people/m^3$	0.0410	0.0540	0.0820	0.1020
Southwest	Domestic	$people/m^3$	0.0130	0.0160	0.0220	0.0260
West	Domestic	$people/m^3$	0.0220	0.0250	0.0290	0.0340
West North Central	Domestic	$people/m^3$	0.0160	0.0190	0.0310	0.0400
Central	thermoelectric	GJ/m^3	2.3076	2.3904	2.4696	2.5308

Table A.5: Average blue water productivities per sector and climate region

Climate Region	Sector	Unit	Baseline	BM_{50}	BM_{25}	BM_{10}
East North Central	thermoelectric	GJ/m^3	2.5884	2.6748	2.7864	2.9700
Northeast	thermoelectric	GJ/m^3	2.3940	2.4768	2.5956	2.6604
Northwest	thermoelectric	GJ/m^3	2.7072	2.7468	2.7792	2.8404
South	thermoelectric	GJ/m^3	2.1744	2.2788	2.3364	2.3940
Southeast	thermoelectric	GJ/m^3	2.2104	2.3112	2.3688	2.4696
Southwest	thermoelectric	GJ/m^3	2.1060	2.1816	2.2212	2.2896
West	thermoelectric	GJ/m^3	2.0556	2.1924	2.3364	2.3904
West North Central	thermoelectric	GJ/m^3	2.1744	2.2536	2.3436	2.3688
Central	livestock	$head/m^3$	0.9410	0.9990	1.1980	1.3360
East North Central	livestock	$head/m^3$	0.4660	0.5140	0.5600	0.5870
Northeast	livestock	$head/m^3$	1.4730	1.7280	1.9070	2.1470
Northwest	livestock	$head/m^3$	0.2200	0.2290	0.2610	0.2840
South	livestock	$head/m^3$	0.9430	1.0900	1.3440	1.6170
Southeast	livestock	$head/m^3$	3.1720	3.4040	3.5870	3.8130
Southwest	livestock	$head/m^3$	0.1410	0.1550	0.1680	0.1740
West	livestock	$head/m^3$	0.3120	0.4140	0.4940	0.5600
West North Central	livestock	$head/m^3$	0.1260	0.1500	0.1510	0.1540

Table A.5: Average blue water productivities per sector and climate region

Climate Region	Sector	Unit	Baseline	BM_{50}	BM_{25}	BM_{10}
Central	Commercial, Industrial and Institutional	$1000/m^3	3.1610	6.1180	7.4970	9.2630
East North Central	Commercial, Industrial and Institutional	$1000/m^3	4.9930	6.3140	7.8440	8.7640
Northeast	Commercial, Industrial and Institutional	$1000/m^3	8.4810	11.9770	16.6510	21.0790
Northwest	Commercial, Industrial and Institutional	$1000/m^3	4.4240	5.2930	6.1110	6.8470
South	Commercial, Industrial and Institutional	$1000/m^3	3.4810	6.7560	9.0460	16.6480
Southeast	Commercial, Industrial and Institutional	$1000/m^3	4.2300	8.1410	12.0110	15.1120
Southwest	Commercial, Industrial and Institutional	$1000/m^3	5.3940	6.9210	9.0310	15.5770

Table A.5: Average blue water productivities per sector and climate region

Climate Region	Sector	Unit	Baseline	BM_{50}	BM_{25}	BM_{10}
West	Commercial, Industrial and Institutional	$1000/m^3	4.0110	4.8210	5.7530	8.2470
West North Central	Commercial, Industrial and Institutional	$1000/m^3	5.6380	6.5070	8.2520	10.8110

Table A.6: Baseline and benchmark annual consumptive direct blue water use and potential water savings per sector and climate region.

Climate Region	Sector	Baseline (m^3/year)	Bm_{50} (m^3/year)	Bm_{25} (m^3/year)	Bm_{10} (m^3/year)	Bm_{50} savings (m^3/year)	Bm_{25} savings (m^3/year)	Bm_{10} savings (m^3/year)
Central	Domestic	7.18e+08	5.42e+08	5.27e+08	5.05e+08	1.75e+08	1.90e+08	2.12e+08
East North Central	Domestic	5.08e+08	4.50e+08	3.32e+08	2.86e+08	5.86e+07	1.76e+08	2.22e+08
Northeast	Domestic	6.99e+08	5.07e+08	4.28e+08	4.26e+08	1.92e+08	2.71e+08	2.73e+08
Northwest	Domestic	2.99e+08	2.03e+08	1.62e+08	1.06e+08	9.59e+07	1.37e+08	1.93e+08
South	Domestic	2.60e+09	2.08e+09	1.56e+09	1.47e+09	5.15e+08	1.04e+09	1.13e+09
Southeast	Domestic	1.34e+09	1.03e+09	6.72e+08	5.45e+08	3.18e+08	6.72e+08	7.99e+08
Southwest	Domestic	1.24e+09	1.03e+09	7.46e+08	6.24e+08	2.08e+08	4.92e+08	6.14e+08
West	Domestic	1.80e+09	1.60e+09	1.40e+09	1.18e+09	1.99e+08	3.96e+08	6.12e+08
West North Central	Domestic	2.95e+08	2.50e+08	1.56e+08	1.21e+08	4.50e+07	1.39e+08	1.74e+08
Central	Thermoelectric	1.22e+09	1.17e+09	1.14e+09	1.11e+09	4.28e+07	8.03e+07	1.08e+08
East North Central	Thermoelectric	3.53e+08	3.42e+08	3.28e+08	3.08e+08	1.11e+07	2.48e+07	4.51e+07
Northeast	Thermoelectric	5.24e+08	5.05e+08	4.83e+08	4.71e+08	1.82e+07	4.10e+07	5.28e+07
Northwest	Thermoelectric	6.28e+07	6.18e+07	6.11e+07	5.98e+07	9.28e+05	1.64e+06	2.99e+06
South	Thermoelectric	9.62e+08	9.17e+08	8.94e+08	8.73e+08	4.41e+07	6.71e+07	8.87e+07

Table A.6: Baseline and benchmark annual consumptive direct blue water use and potential water savings per sector and climate region.

Climate Region	Sector	Baseline (m^3/year)	Bm_{50} (m^3/year)	Bm_{25} (m^3/year)	Bm_{10} (m^3/year)	Bm_{50} savings (m^3/year)	Bm_{25} savings (m^3/year)	Bm_{10} savings (m^3/year)
Southeast	Thermoelectric	1.00e+09	9.57e+08	9.34e+08	8.96e+08	4.40e+07	6.76e+07	1.05e+08
Southwest	Thermoelectric	3.64e+08	3.51e+08	3.45e+08	3.35e+08	1.31e+07	1.88e+07	2.93e+07
West	Thermoelectric	1.66e+08	1.55e+08	1.46e+08	1.42e+08	1.03e+07	2.01e+07	2.32e+07
West North Central	Thermoelectric	2.06e+08	1.99e+08	1.91e+08	1.89e+08	7.04e+06	1.46e+07	1.69e+07
Central	livestock	3.21e+08	3.03e+08	2.52e+08	2.26e+08	1.85e+07	6.91e+07	9.50e+07
East North Central	livestock	4.06e+08	3.68e+08	3.38e+08	3.22e+08	3.77e+07	6.75e+07	8.33e+07
Northeast	livestock	1.32e+08	1.13e+08	1.02e+08	9.07e+07	1.95e+07	3.01e+07	4.15e+07
Northwest	livestock	1.33e+08	1.28e+08	1.12e+08	1.03e+08	5.57e+06	2.09e+07	3.01e+07
South	livestock	6.17e+08	5.34e+08	4.33e+08	3.60e+08	8.28e+07	1.84e+08	2.57e+08
Southeast	livestock	2.48e+08	2.31e+08	2.19e+08	2.06e+08	1.69e+07	2.87e+07	4.17e+07
Southwest	livestock	1.51e+08	1.38e+08	1.27e+08	1.23e+08	1.29e+07	2.41e+07	2.81e+07
West	livestock	2.48e+08	1.87e+08	1.57e+08	1.38e+08	6.10e+07	9.16e+07	1.10e+08
West North Central	livestock	3.28e+08	2.75e+08	2.74e+08	2.69e+08	5.31e+07	5.47e+07	5.89e+07

Table A.6: Baseline and benchmark annual consumptive direct blue water use and potential water savings per sector and climate region.

Climate Region	Sector	Baseline (m^3/year)	Bm_{50} (m^3/year)	Bm_{25} (m^3/year)	Bm_{10} (m^3/year)	Bm_{50} savings (m^3/year)	Bm_{25} savings (m^3/year)	Bm_{10} savings (m^3/year)
Central	Commercial, Industrial & Institutional	1.02e+09	5.28e+08	4.31e+08	3.49e+08	4.94e+08	5.91e+08	6.73e+08
East North Central	Commercial, Industrial & Institutional	3.57e+08	2.82e+08	2.27e+08	2.03e+08	7.46e+07	1.30e+08	1.53e+08
Northeast	Commercial, Industrial & Institutional	5.41e+08	3.83e+08	2.76e+08	2.18e+08	1.58e+08	2.65e+08	3.23e+08
Northwest	Commercial, Industrial & Institutional	1.81e+08	1.51e+08	1.31e+08	1.17e+08	2.96e+07	4.98e+07	6.39e+07
South	Commercial, Industrial & Institutional	1.02e+09	5.24e+08	3.91e+08	2.13e+08	4.93e+08	6.26e+08	8.05e+08
Southeast	Commercial, Industrial & Institutional	7.66e+08	3.98e+08	2.70e+08	2.14e+08	3.68e+08	4.96e+08	5.52e+08
Southwest	Commercial, Industrial & Institutional	1.83e+08	1.42e+08	1.09e+08	6.33e+07	4.03e+07	7.36e+07	1.19e+08

Table A.6: Baseline and benchmark annual consumptive direct blue water use and potential water savings per sector and climate region.

Climate Region	Sector	Baseline (m^3/year)	Bm_{50} (m^3/year)	Bm_{25} (m^3/year)	Bm_{10} (m^3/year)	Bm_{50} savings (m^3/year)	Bm_{25} savings (m^3/year)	Bm_{10} savings (m^3/year)
West	Commercial, Industrial & Institutional	7.21e+08	6.00e+08	5.03e+08	3.51e+08	1.21e+08	2.18e+08	3.71e+08
West North Central	Commercial, Industrial & Institutional	6.56e+07	5.69e+07	4.48e+07	3.42e+07	8.77e+06	2.08e+07	3.14e+07
Central	Irrigation	2.79e+09	2.62e+09	2.41e+09	2.20e+09	1.73e+08	3.79e+08	5.94e+08
East North Central	Irrigation	1.31e+09	1.23e+09	1.14e+09	1.01e+09	8.34e+07	1.68e+08	3.04e+08
Northeast	Irrigation	2.46e+08	2.42e+08	2.39e+08	2.32e+08	4.36e+06	7.48e+06	1.45e+07
Northwest	Irrigation	9.58e+09	9.47e+09	9.12e+09	7.94e+09	1.15e+08	4.62e+08	1.65e+09
South	Irrigation	3.38e+10	3.15e+10	2.89e+10	2.62e+10	2.24e+09	4.86e+09	7.60e+09
Southeast	Irrigation	1.27e+09	1.21e+09	1.16e+09	1.10e+09	5.99e+07	1.10e+08	1.72e+08
Southwest	Irrigation	1.03e+10	9.37e+09	8.62e+09	7.86e+09	9.22e+08	1.67e+09	2.43e+09
West	Irrigation	1.39e+10	1.35e+10	1.30e+10	1.20e+10	3.81e+08	9.72e+08	1.88e+09
West North Central	Irrigation	1.53e+10	1.48e+10	1.40e+10	1.29e+10	4.88e+08	1.34e+09	2.46e+09
Sum	All	1.10E+11	1.02E+11	9.34E+10	8.46E+10	8.56E+09	1.69E+10	2.56E+10