SUPPORTING INFORMATION

Water Footprint of U.S. Transportation Fuels

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Contents:

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Section 1: Background

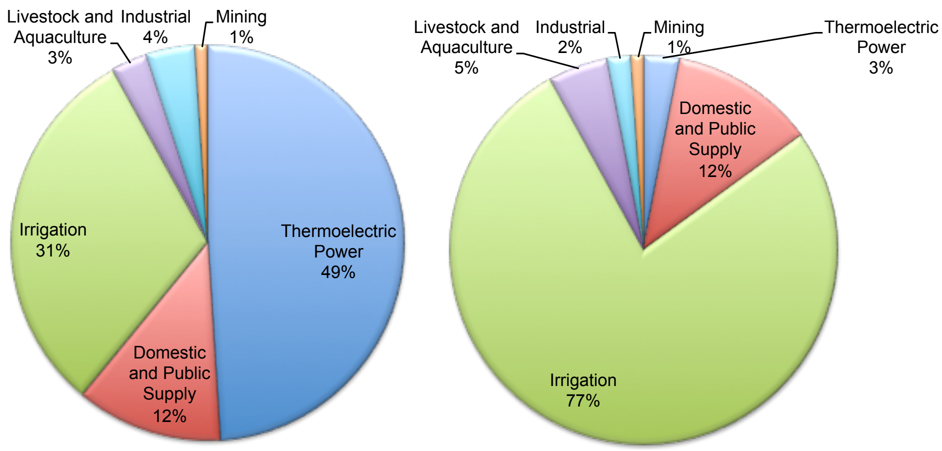

Figure S1: Estimated Freshwater Withdrawals (Left) and Consumption (Right) in the United States, 2005 (calculated using data from (*1*, *2*))

Study	Fuel				Life-Cycle Phase					Measures			
	Gasoline	Starch/ Sugar Ethanol	Cellulosic Ethanol	Electricity	Feedstock	Ref/ Prod	TS&D	Use	Indirect Effects	W	C	GHG	WSI
(1)		X			X	X					X		
(2)		X			X					X	X		
(3)				X		X				X	X		
(4)				X	X	X				X	X		
(5)	X				X					X			
(6)		X			X					X			
(7)	X			X	X	X					X	X	
(8)	X	X	X	X	X	X	X		X		X		
(9)	X	X	X	X	X	X				X	X		
(10)				X		X				X	X		
(11)		X	X		X	X					X		
(12)				X		X	X				X		
(13)	X	X	X		X	X					X		

Table S1: Water Life-Cycle Assessment Literature Review (Ref/Prod: Refining/Fuel Production; TS&D: Transportation, Storage, & Distribution; W: Withdrawals; C: Consumption; GHG: Greenhouse Gas Emissions; WSI: Water Stress Index)

Contextualizing Water Use

Water use is conceptually more complicated than fossil fuel consumption or air emissions, for example. Unlike fossil fuels, humans to not chemically destroy water; instead, human activities alter the natural water cycle and result in resource contamination. This paper focuses on the former. Researchers typically focus on two water use metrics: withdrawals, which is the total amount temporarily or permanently removed from a source, and consumption, which is the amount of water that is not directly returned to its original source. These are, however, far from perfect metrics for estimating the human impact on the water cycle.

Reference (14) described the Earth's water cycle as a giant solar-powered machine that distills ocean water, and carries the evaporated freshwater over land where it falls as precipitation and serves the freshwater needs of life on dry land. Of all the water that is evaporated from the ocean, 91% of it returns directly to the ocean via rainfall. The remaining 9% is carried to land by wind patters, where it ultimately condenses (14). This cycle is closed by surface runoff and groundwater seepage to the ocean, which replaces the ocean's 9% vapor "loss" to land. On land, an entire sub-cycle also operates, where water is returned to the atmosphere through plant evapotranspiration and evaporation from the surfaces of lakes and rivers, condensed in the form of rain or snow, at which point it is absorbed by plants, replenishes surface water resources, and percolates down to recharge groundwater resources. The global water cycle, and its sub-cycles maintain the equilibrium between oceans, groundwater, glaciers, surface lakes and rivers, soil moisture, and atmospheric vapor. However, human activities have a destabilizing effect by altering the natural water cycle, which will only become more significant as population grows and nations continue to industrialize. The question that follows is: how are humans altering this equilibrium, is it an unfavorable change, and if so, how should it be quantified?

1. Withdrawals

Fresh Surface Water Withdrawals:
For some processes, particularly industrial facilities that practice water recycling and crops that are irrigated efficiently, withdrawals are equal to consumptive use. For others, such as thermoelectric power plants with open-loop cooling systems, withdrawals are very large, but much of that water is simply cycled through the facility and immediately returned to its source, with only a small fraction lost through evaporation or other means. Aside from the ecosystem impacts associated with thermal and chemical pollution, which are not explored in this paper, this activity has essentially no impact on the availability of freshwater. Total withdrawals are nonetheless important because these facilities require that large amounts of freshwater be available, and one body of water can only withstand a limited amount of thermal pollution before the elevated ambient temperature becomes problematic. For this reason, closed-loop cooling is most common in areas with limited freshwater resources despite the fact that it actually evaporates more water per kWh of electricity produced than open-loop cooling (3).

Groundwater Withdrawals:
Fresh groundwater is a valuable resource because it is cleaner than surface water due to the natural purification that occurs as it percolates down through the soil, and it is not subject to the same fluctuations in availability (droughts, etc.). Underground aquifers can be confined, which means there is an impermeable or semi-permeable layer (rock, for example) between the aquifer and the surface that prevents the vertical infiltration of rainfall or surface water, or unconfined, in which case there is no such barrier (15). The permeability of material surrounding the aquifer plays a major role in determining its recharge rate. Many aquifers in the U.S., including the Ogallala Aquifer that underlies Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, are being depleted over time because the rate at which water is pumped out for agricultural and municipal uses exceeds the recharge rate (16). Additionally, groundwater withdrawals are rarely returned directly to the source aquifer after use unless it percolates down from irrigated crops or an artificial groundwater recharge system exists. For this reason, groundwater withdrawals are typically equated to consumption.

2. Consumptive Use

Freshwater Evaporation:
Irrigated agriculture, thermoelectric power generation, and many industrial facilities withdraw freshwater from surface or groundwater sources, some or all of which is subsequently released as vapor through evapotranspiration, cooling processes, and other evaporative losses. Predicting the fate of this vapor is difficult; will it simply increase local precipitation, thus resulting in a net zero change in freshwater resources, or will wind patterns carry it elsewhere on land before it condenses? The answer is not easily determined, and varies by location. There is, however, evidence to suggest that in drier regions, an increase in evaporative losses means a net flux of freshwater out of the area. For example, the Arroyo Seco Watershed continues to operate at a net water loss of 5600 acre-feet per year despite annual freshwater imports of 21378 acre-feet of water (17). 48% of the watershed's total water outflow is due to evapotranspiration (17). Even if all evaporated water is ultimately returned to the same area, the temporary loss in water availability has its own negative impacts. Evaporative loss of river water reduces downstream flow rates; the Colorado River serves as a prime example, in which excessive water withdrawals for use in agriculture and other applications in the U.S. decreased downstream flow. This motivated a 1944 U.S.-Mexico treaty that guaranteed at least 1.5 million acre-feet of Colorado River water reach Mexico each year (18).

Freshwater Discharges to the Ocean:
Another way that humans alter this cycle is by increasing the rate at which freshwater flows to the ocean, the likely result being an increase in ocean water volume and decrease in freshwater resources on land. A common example of this would be a municipal utility or industrial facility located near the coast that withdraws its water from a freshwater source on land, and discharges its wastewater into the ocean.

Incorporation of Freshwater into Products:
Some amount of water is often incorporated into products. For example, agricultural products contain varying moisture contents, bottled water uses water as an integral part of its product, and chemicals will frequently be diluted with water. This is considered to be consumption because much of these products will inevitably be shipped to locations outside of the watershed in which they were produced. Thus, the products result in a net flux of water out of the immediate area.

3. Other Water Use Metrics

Saline Water Use:
The total dissolved solids (TDS) in saline water makes it unfit for the majority of human uses. However, saline water can be used for open-loop cooling, or it can be desalinated (at a high energy cost) and used to supplement fresh drinking water sources. Because saline water has limited usefulness for humans, its withdrawals and evaporative losses are not included in water footprint calculations.

"Blue", "Green" and "Grey" Water:
One of the most popular schemes for categorizing water use comes from (19), in which the water footprint is split into three parts: blue water, green water, and grey water. Blue water represents water that is taken from a surface or groundwater source, green represents rainfall or soil moisture (for example, rainwater that is absorbed by crops), and grey water is the amount of

freshwater required to dilute contaminated wastewater discharges such that they meet existing environmental standards. So-called blue water is the focus of this paper. Grey water is not explored further because this paper does not deal with water quality issues. Green water consumption, although potentially a useful metric, should account for the fact that native plants would also consume rainwater and soil moisture. Therefore, in a consequential LCA, one would need to compare the relevant crop's green water consumption to that of native vegetation. This type of analysis is data-intensive and wrought with uncertainty, and is therefore not performed here.

Consequential Approach for Transportation Fuel LCAs

Consequential and attributional LCAs are distinguished from one another by the type of question being asked. As the name might suggest, consequential LCAs aim to answer the question: what are the consequences of adding or subtracting some amount (relative to the status quo) of a good or service? An attributional LCA aims to answer the question: what are the impacts of the existing production of a good or service? If one of the primary goals is to drive environmental policy, consequential LCA is a powerful approach because it can be used to predict the outcome of a particular regulation or mandate. Unfortunately, this approach is often more challenging because it requires information about expected market behavior in response to the proposed change. For example, if cellulosic ethanol production were to be scaled up, what fuel(s), if any, would it displace? If state-level or national policies require a certain amount of biofuels to be sold, and the standard is currently being met with corn ethanol, cellulosic ethanol may displace corn ethanol. If oil prices rise dramatically, cellulosic ethanol could displace gasoline from conventional crude. If a large carbon tax is put in place, accounting for the high carbon-intensity of producing gasoline from oil sands, cellulosic ethanol could displace gasoline from oil sands. Similar questions could be asked about electricity as a transportation fuel. Rather than make judgments about which scenario is most likely, this paper takes a consequential approach by comparing electricity and cellulosic ethanol to all three baseline fuels (gasoline from crude oil, gasoline from oil sands, and corn ethanol).

Water Use Metrics

Ideally, water use should be geospatially mapped, and split not only into consumptive use and withdrawals, but also by source (groundwater and surface water). For the sake of simplicity, this study only makes a distinction between total withdrawals and consumptive use. Even this simple distinction provides more information than existing water LCIs for transportation fuels, which only quantify consumptive use (*9, 10, 15*).

Section 2: Electricity & the Importance of Geospatial Analysis

It can be tempting to assume that a higher resolution for calculating emissions or other environmental impacts of electricity consumption is always favorable; for example, previous studies often use the generation mixes for individual states. Assuming that the generation mix for a particular state is equal to the consumption mix would only be appropriate if no major transmission lines crossed the state's boundaries (in other words, the state is a relatively closed system). However, this is generally not the case. Figure S2 shows that most states either import or export a significant amount of electricity, demonstrating that political boundaries are not effective for developing regional electricity consumption mixes. Further discussion of how accounting for interstate power trading can affect the state electricity consumption mixes can be found in (20). Better boundaries for estimating regional electricity mixes are developed based on the structure of the electricity grid and its major transmission lines. The map available at: http://teeic.anl.gov/er/transmission/restech/dist/index.cfm shows the electricity transmission lines in the contiguous U.S. Although it may appear to be a tangled mess at first glance, some basic characteristics do stand out. For example, the western half of the country is very interconnected, with a number of transmission lines greater than 500 kV running between states. Secondly, one may observe that Texas has no transmission lines greater than 500 kV connecting it to other states; this is consistent with the net zero electricity imports for Texas shown in Figure S2.

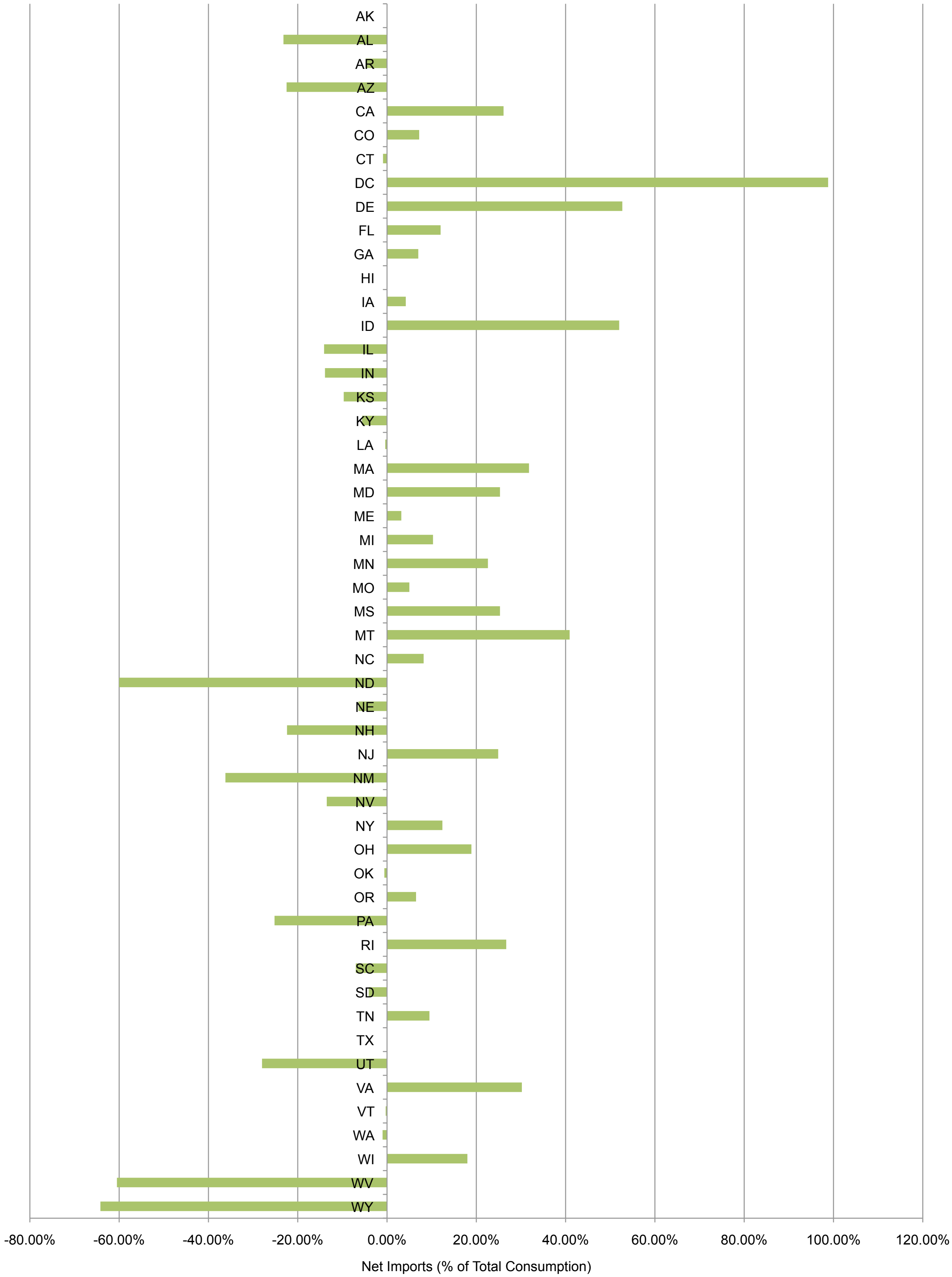

Figure S2: Net Electricity Imports by State (Based on data from (21))

There are four sets of boundaries for developing electricity mixes. The first method is to simply use the average for the continental U.S., and then separate averages for both Hawaii and Alaska. Although this minimizes possible error due to unaccounted-for power trade across boundaries, it does not reflect the regional nature of the grid. Line losses and lack of transmission infrastructure prevent the entire U.S. grid from being completely interconnected; if demand rises in Texas, for example, new power plants will likely be built in-state, even if unused capacity exists other parts of the country. To capture this regionalization of supply, the U.S. can be split into four North American Electric Reliability Corporation (NERC) Interconnections: Western Interconnection, ERCOT Interconnection, Eastern Interconnection, and the Quebec Interconnection, as shown in the standard NERC region map (available at: http://www.nerc.com/page.php?cid=1|9|119). NERC regions split the Eastern Interconnection into six subregions. Finally, the U.S. Environmental Protection agency has developed an even further disaggregated set of regions, known as eGRID subregions (map available at: http://cfpub.epa.gov/egridweb/reports.cfm). The question of which set of regions best reflects the regionalization of power supply while also serving as relatively closed systems is one that cannot be easily answered. Depending on which set of regions is chosen, the results of an environmental analysis can be quite different (22).

For the purposes of this research, the U.S. electrical grid is split into ten regions, controlled by regional entities defined by NERC. The eight regions that make up the contiguous U.S. include: Florida Reliability Coordinating Council (FRCC), Midwest Reliability Organization (MRO), Northeast Power Coordinating Council (NPCC), Reliability*First* Corporation (RFC), SERC Reliability Corporation (SERC), Southwest Power Pool (SPP), Texas Regional Entity (TRE), and the Western Electricity Coordinating Council (WECC). Additionally, the state of Alaska is contained within the Alaska Systems Coordinating Council (ASCC) and the state of Hawaii is covered by the Hawaiian Islands Coordinating Council (HICC).

Section 3: Water Use Inventory

Direct Water Use

1. Crude Oil to Gasoline

Particularly for water consumption, direct water requirements often make up the largest fraction of a fuel's overall footprint. For the crude oil-to-gasoline pathway, oil extraction and refining both require water. Extraction water use data from (*9, 25-28*), as compiled by (13) were used to develop estimates for domestic oil production by PADD, as well as imports, where Saudi Arabian extraction is assumed to be representative of U.S. imports. The breakdown used to calculate water requirements for onshore recovery, which makes up two thirds of domestic oil production, is as follows: 6.6% primary recovery, 74.7% secondary recovery (water flooding), 6.9% CO_2 injection, 8.3% steam injection, 0.4% forward combustion, and 3.2% other enhanced oil recovery techniques (13). Each of these extraction technologies requires water. When crude is extracted, it carries with it large volumes of water, known as produced water (often more than 10x the volume of crude), and some of this produced water can be used for reinjection. In this analysis, produced water is not counted as part of freshwater resources because it is highly contaminated with hydrocarbons, so total freshwater required for crude oil extraction is equal to the total, technology-weighted requirements, minus any produced water used for reinjection. Offshore oil recovery uses only produced water and seawater for injection, so its freshwater requirements are assumed to be zero. PADD-specific data from (23) and (24) are used to account for produced water use in extraction.

Once oil reaches the refinery, many processes are used to separate and upgrade its components to produce an array of products varying in function and monetary value. Water is primarily used to generate steam for process heat and cooling (25), totaling to approximately 1.5 liters of water consumed per liter of crude oil input (13). More complicated than estimating direct water withdrawals and consumption is the process of allocating this water use to individual refinery products. So far, no study has clearly and defensibly allocated water withdrawals and consumption to refinery products. In the analysis presented here, the allocation scheme is based on market value, which serves as an inherent measure of the economic factors driving production. The factors are taken from (26), in which allocation is performed on a sub-process level, further capturing the differences between products' impacts based on which processes are involved in their production. Because data on water use for individual processes within the refinery is not available, water use is assumed to correlate with energy consumption. Considering 68% of all withdrawals and 96% of consumption is associated with either cooling or process heat (25), this is a reasonable assumption. The result is a larger fraction of impacts allocated to high value products, particularly gasoline (approximately 20% higher than what most studies allocate to gasoline), and a much smaller fraction allocated to low value products such as residual oil.

The direct water requirements for both feedstock and product transportation, distribution, and storage have not yet been discussed. Crude oil and petroleum products are transported to their final destination by oil tanker, barge, pipeline, and to a lesser extent, railcar and truck. Because the many of the vessels are dedicated for transporting petroleum, water required for washing is negligible. Pipelines do not require water on a regular basis; water is only used for testing or decommissioning purposes. In the case of decommissioning, the section of pipe being taken out of service is filled with water, drained, and the wastewater is subsequently treated, which means water use is equal to the volume of the pipe section. Because vast amounts of crude/products pass through pipelines before they must be decommissioned, the water use for pipelines is assumed to be insignificant.

2. Oil Sands to Gasoline

Oil sands, also known as tar sands, are made up of a mixture of hydrocarbons called bitumen, deposited in sand or porous rock. Oil sands are attractive as a substitute for conventional crude oil because they are abundant, with a greater fraction located in North America than is the case for conventional crude (27). For example, Canada's oil-sand reserves are estimated at approximately 1.7 trillion barrels of oil equivalent. Once oil sands are converted to synthetic crude oil (SCO), the life cycle is essentially identical to that of conventional crude oil. The extraction phase is what sets oil sands apart from conventional crude.

Because oil sands are too viscous to be pumped to the surface at ambient temperature, they must either be mined along with the sand or rock and heated to separate the bitumen (known as retorting), or retorted in-situ. There are three different processes by which oil sands can be retorted in-situ: 1. Steam assisted gravity drainage (SAGD), in which two wells are bored to different depths. Steam is injected in the shallow well to liquefy the bitumen, which drains to the deeper well where it can be pumped to the surface, 2. Cyclic steam stimulation (CSS), which involves alternating steam injection with pumping, and 3. Multi-scheme, which involves various elements of CSS, SAGD, and other recovery techniques (13). In these processes, water is required to produce steam for retorting, and for raw oil sands transport if a slurry pipeline is used. Although the water withdrawals and consumption for SCO production from oil sands is higher than primary extraction of crude oil, it compares favorably to most secondary and tertiary recovery technologies.

In the refining process, the production of gasoline from SCO is assumed to be essentially the same as conventional crude oil refining. For further details on crude oil refining and the allocation procedure used in this analysis, as well as petroleum transportation, storage, and distribution, see the Crude Oil to Gasoline direct water use methodology.

3. Corn Grain to Ethanol

Corn is the only regularly irrigated biofuel crop discussed in this paper. Currently, more than 95% of ethanol produced in the U.S. is currently made from corn (1). Largely due to irrigation, the water footprint of corn ethanol is higher than any other fuel analyzed in this paper. Irrigation inputs were calculated using state-specific irrigation (28) and production (29) data to generate a weighted average for all U.S. corn production. For each L of corn ethanol ultimately produced, 282 L of water are used for corn irrigation.

Corn ethanol biorefineries employ a significantly simpler conversion process than cellulosic biorefineries, and thus require less direct freshwater. The water usage is taken from (30), who use a process model developed by the USDA for a dry milling ethanol plant. According to (13), who also pull information from the USDA model, 53% of direct water consumption for ethanol production is used for cooling, 42% is used in the dryer, and the remainder is used in the boiler (3%) and for dried distillers' grains production (DDGS). Similar to petroleum refineries, allocation issues also arise in corn ethanol plants. However, because the co-products displace existing products whose primary production pathway is not ethanol plants, system expansion can be used (31). According to GREET 1.8c (32), the DDGS co-product displaces 0.71 kg of corn, 0.22 kg of soybean meal, and 0.016 kg of N-Urea per L of ethanol produced. System expansion as an allocation method does not account for elasticity of demand, but it is a simple, reasonable estimate for the purposes of this analysis.

Together, crop irrigation and biorefining make up the total direct water footprint. Corn and ethanol are transported by a combination of barge, rail, and truck transportation. As discussed previously, the direct water use for transportation is negligible. This is particularly true for ethanol transportation because water contamination is problematic, so water washing of any equipment that comes into contact with ethanol should be avoided whenever possible.

4. Corn Stover to Ethanol

Corn stover is the most plentiful crop residue in the U.S. (33). Some of the stover must be left on the field for the purpose of maintaining soil carbon and preventing erosion, but an estimated 62% can be removed sustainably (34). Because stover is currently a waste product of corn crops (with the exception of the stover that must remain on the field to maintain soil quality), we assert that none of the energy or materials used for corn production are allocated to stover. No additional irrigation is required if stover is harvested, as opposed to being left on the field, so corn stover production results in no direct on-farm water use in the consequential LCA framework. However, in the body of the paper, corn grain and stover are combined, thus eliminating the allocation problem and avoiding what is arguably a subjective assumption.

The conversion of corn stover to ethanol is a significantly more complex process than what is required to convert corn grain. Although numerous technology options exist, this analysis uses the co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover described in detail by (35). They assume 100% water recycling, so water withdrawals at the biorefinery are equal to consumptive losses. The vast majority of water is lost through evaporation during biomass washing, vents to the atmosphere, and other evaporative losses, while 1% of water losses are contained in solid waste that is landfilled. As was the case with corn ethanol, the biomass-to-ethanol conversion process also results in co-products that must be credited to the biorefinery: gypsum and electricity. In this analysis, gypsum, although technically a co-product, is treated as a waste product (this is consistent with GREET 1.8c). The excess electricity resulting from the burning of lignin that can be exported to the grid is credited through system expansion, as described for Corn Grain to Ethanol.

As with corn grain ethanol, any freshwater used during the transportation, storage, and distribution phases is assumed to be negligible.

5. Miscanthus to Ethanol

Miscanthus x *Giganteus* is a high-yielding perennial grass that can be used as a biomass feedstock for ethanol production. If grown in the Midwestern and parts of the Eastern U.S., it can survive without irrigation, and only requires fertilizer during the establishment year, after which the crop can go 15-20 years between plantings (36). For the agriculture phase, no irrigation is assumed for this analysis, although studies have shown that irrigation, particularly paired with increased nutrient inputs, can increase yields in some climates (37).

Once the grasses are transported to the biorefinery, the pathway is very similar to that of corn stover. New results have been generated by building a process model based on (35), and adjusting the inputs to match the Miscanthus biomass composition. Again, water use during transportation, storage, and distribution of biomass and ethanol is assumed to be negligible.

A list of factors included in the liquid fuel water inventory and respective data sources is shown in Table S2.

Pathway	Phase	Element	Spatial Disaggregation	Data Source
Crude Oil to Gasoline	Extraction	Energy Use	Average	(32)
		Water Use	PADD + Saudi Arabia	(13)

		Chemical Use	Average	(*44, 45*)
	Refining	Energy Use	Average	(26)
		Steel	Average	Calculated
		Concrete	Average	Calculated
		Water Use	Average	(7, 13)
		Chemical Use	Average	(38)
	Transportation, Storage, & Distribution	Energy Use	Average	(32)
	Supply-Chain	Agriculture & Services	Average	(39)
Oil Sands to Gasoline	Extraction	Energy Use	Average	(32)
		Water Use	Average	(13)
	Refining	Energy Use	Average	(26)
		Steel	Average	Calculated
		Concrete	Average	Calculated
		Water Use	Average	(7, 13)
		Chemical Use	Average	(38)
	Transportation, Storage, & Distribution	Energy Use	Average	(32)
	Supply-Chain	Agriculture & Services	Average	(39)
Corn Stover to Ethanol	Feedstock Production	Energy Use	U.S. Average	(32)
		Steel	U.S. Average	(32)
		Rubber	U.S. Average	(32)
		Fertilizer	U.S. Average	(32)
	Fuel Production	Energy Use	U.S. Average	(35)
		Steel	U.S. Average	Calculated
		Concrete	U.S. Average	Calculated
		Water Use	U.S. Average	(35)
		Chemical Use	U.S. Average	(35)
		Electricity Co-Product	U.S. Average	(35)
	Transportation, Storage, & Distribution	Energy Use	U.S. Average	(32)
	Supply-Chain	Agriculture & Services	U.S. Average	(39)

Miscanthus to Ethanol	Feedstock Production	Energy Use	Midwest Average	(32)
		Steel	Midwest Average	(32)
		Rubber	Midwest Average	(32)
		Fertilizer	Midwest Average	(40)
		Herbicide	Midwest Average	(40)
	Fuel Production	Energy Use	U.S. Average	ASPEN® model based on (35), adjusted for Miscanthus
		Steel	U.S. Average	Calculated
		Concrete	U.S. Average	Calculated
		Water Use	U.S. Average	ASPEN® model based on (35), adjusted for Miscanthus
		Chemical Use	U.S. Average	ASPEN® model based on (35), adjusted for Miscanthus
	Transportation, Storage, & Distribution	Energy Use	U.S. Average	(32)
	Supply-Chain	Agriculture & Services	U.S. Average	(39)
Corn Grain to Ethanol	Feedstock Production	Energy Use	U.S. Average	(32)
		Water Use	State	(28)
		Steel	U.S. Average	(32)
		Rubber	U.S. Average	(32)
		Fertilizer	U.S. Average	(32)
		Pesticide	U.S. Average	(32)
	Fuel Production	Energy Use	U.S. Average	(41)
		Steel	U.S. Average	(42)
		Concrete	U.S. Average	(42)
		Water Use	U.S. Average	(13)
		Chemical Use	U.S. Average	(42)
	Transportation, Storage, & Distribution	Energy Use	U.S. Average	(42)
	Supply-Chain	Agriculture & Services	U.S. Average	(39)

Table S2: Data Sources for Liquid Fuel Pathways

6. Electricity

The majority of U.S. electricity generation is thermoelectric: coal (44%), natural gas (24%), and nuclear (20%) (43). Thermoelectric power generation requires large volumes of water for cooling, as shown in Figure S1. For once-through cooling, water is withdrawn, run through the condenser to absorb the plant's waste heat, and then discharged to its source (typically a river) at a higher temperature (see Figure S3). This warm-water discharge results in a heat plume that releases some steam before equilibrating with the ambient river temperature. The amount of water that evaporates from this heat plume is much smaller than the total volume of water that is cycled through the power plant, so withdrawals for once-through cooling systems are much larger (200x) than consumption (evaporative losses). In contrast, closed-loop cooling systems (see Figure S3) consume less than twice the amount they withdraw. Air, propelled either by a fan or the natural difference in air density at the top and bottom of the tower, enters the bottom of the cooling tower and flows upward while heated water enters near the top and flows down. The air updraft cools the heated water, evaporating some of the water, which exits the top of the tower as steam. Water that reaches the bottom of the tower in liquid form is recirculated, and fresh makeup water is withdrawn from a nearby source to replace the evaporated water. To avoid excessive mineral buildup in the recirculated cooling water, this water must be periodically discharged, known as blowdown, when it reaches between 5 and 10 times the natural mineral concentration (known as cycles of concentration) (3). It is because of blowdown that withdrawals for closed-loop cooling are slightly higher than consumption.

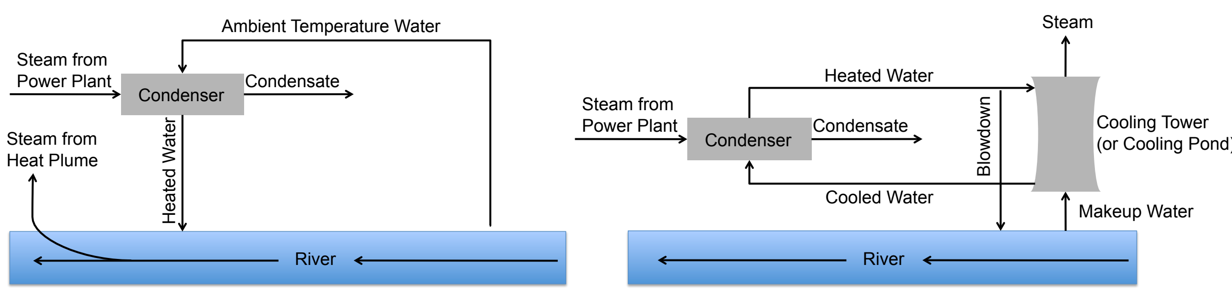

Figure S3: Power Plant Cooling Systems – Once-Through (Left) and Closed-Loop (Right) (Based on information from (3))

Total withdrawals and consumption per unit of electricity produced varies not only by system type, but also by fuel (nuclear, coal, natural gas, etc.). The fuel mix for each NERC region as well as region-specific transmission losses and GHG emission factors are shown in Table S3. Data on cooling water use for coal-fired power plants and nuclear plants are taken from (10), which inventories all coal-fired and nuclear power plants in the U.S., identifying each plant's cooling system(s). Because such an inventory does not exist for natural gas, biomass, or oil-fired power plants, each plant listed in the (44) database is assigned the national average water use for coal plants, with 38% of generation utilizing once-through with freshwater, 3% using once-through with saline, and 59% using closed-loop. Finally, water consumption at geothermal plants listed in (44) is estimated using data from (7, 45).

There is one non-thermoelectric power plant that results in significant water consumption: hydroelectric dams. When dams are built, they typically cause an increase in the surface area-to-volume ratio of a river, which in turn increases surface evaporation. If this change in evaporation is attributed exclusively to hydroelectricity production, the results are dramatic; for example, hydroelectricity in Arizona results in 245 L of consumptive water use per kWh of power produced (12), as compared to 1.8 L/kWh for a typical closed-loop coal-fired power plant. The question of whether all of the evaporative losses should be attributed to hydroelectricity is an important one; dams are also built for irrigation, public water supply, and flood control. Because most studies choose not to include hydroelectricity-related water consumption (*5, 9, 12, 54*), this analysis remains conservative and does not include hydro-related water use.

Finally, line losses between power plants and final uses must be accounted for. NERC region-specific loss factors are taken from (21). Although the electricity is lost, rather than being consumed for some functional use, line losses are treated as electricity consumption for the fuel transportation, distribution, and storage phase.

Biomass	Hydro	Nuclear	Natural Gas	Oil	Coal	T&D Loss Adjustment Factors
0.1%	22.3%	0.0%	56.6%	11.6%	9.5%	12.9%
1.5%	0.0%	13.8%	39.0%	17.9%	26.2%	9.6%
2.6%	0.8%	0.0%	0.0%	78.8%	14.2%	8.9%
1.2%	4.1%	14.0%	5.2%	0.8%	72.7%	9.6%
3.2%	11.7%	27.2%	29.2%	13.2%	14.4%	9.6%
0.7%	0.6%	26.2%	5.8%	1.4%	64.4%	9.6%
1.8%	3.3%	24.2%	11.7%	1.5%	57.1%	9.6%
1.1%	2.6%	4.1%	27.7%	0.7%	62.6%	9.6%
0.1%	0.3%	11.9%	47.5%	0.5%	37.1%	16.0%
1.3%	24.7%	10.1%	26.3%	0.5%	33.4%	8.4%
1.3%	6.5%	19.3%	18.8%	3.0%	49.6%	9.9%
(*44*)	(44)	(44)	(44)	(44)	(44)	(21)

Region	GWP (100 yr) (g CO2e)/MJ Electricity	N2O Emissions: g/MJ Electricity	CH4 Emissions: g/MJ Electricity	CO2 Emissions: g/MJ Electricity	Other/Unknown	Other Fossil	Geothermal	Solar	Wind
ASCC	1.4E+02	7.6E-04	3.1E-03	1.4E+02	0.0%	0.0%	0.0%	0.0%	0.0%
FRCC	1.7E+02	2.1E-03	5.8E-03	1.7E+02	0.8%	0.6%	0.0%	0.0%	0.0%
HICC	2.2E+02	3.8E-03	2.1E-02	2.2E+02	0.0%	1.6%	1.9%	0.0%	0.1%
MRO	2.3E+02	3.9E-03	3.5E-03	2.3E+02	0.0%	0.2%	0.0%	0.0%	1.8%
NPCC	1.1E+02	1.7E-03	7.6E-03	1.1E+02	0.0%	1.1%	0.0%	0.0%	0.0%
RFC	1.8E+02	3.0E-03	2.9E-03	1.8E+02	0.1%	0.7%	0.0%	0.0%	0.1%
SERC	1.7E+02	2.8E-03	2.9E-03	1.7E+02	0.1%	0.4%	0.0%	0.0%	0.0%
SPP	2.2E+02	3.2E-03	3.1E-03	2.2E+02	0.1%	0.2%	0.0%	0.0%	0.9%
TRE	1.7E+02	1.9E-03	2.3E-03	1.7E+02	0.2%	1.2%	0.0%	0.0%	1.2%
WECC	1.3E+02	1.9E-03	2.9E-03	1.3E+02	0.0%	0.4%	2.1%	0.1%	1.1%
U.S. Avg	1.7E+02	2.6E-03	3.4E-03	1.7E+02	0.1%	0.6%	0.4%	0.0%	0.4%
Data Source	*(44)*	*(44)*	*(44)*	*(44)*	*(44)*	*(44)*	*(44)*	*(44)*	*(44)*

Table S3: Electricity Mixes and Emission Factors

Fuel	**Cooling System**	**Boiler Type/Plant Type**	**Flue Gas Desulfurization System**	**Withdrawals (L/kWh)**	**Consumption (L/kWh)**	**Data Source**

Coal	Once-Through	Subcritical	Wet	1.0E+02	5.2E-01	(*10*)
Coal	Once-Through	Subcritical	Dry	1.0E+02	4.3E-01	(*10*)
Coal	Once-Through	Subcritical	None	1.0E+02	2.7E-01	(*10*)
Coal	Once-Through	Supercritical	Wet	8.6E+01	4.7E-01	(*10*)
Coal	Once-Through	Supercritical	Dry	8.6E+01	3.9E-01	(*10*)
Coal	Once-Through	Supercritical	None	8.5E+01	2.4E-01	(*10*)
Coal	Once-Through	AVERAGE	AVERAGE	9.8E+01	5.0E-01	Calculated
Coal	Recirculating	Subcritical	Wet	2.0E+00	1.7E+00	(*10*)
Coal	Recirculating	Subcritical	Dry	1.9E+00	1.7E+00	(*10*)
Coal	Recirculating	Subcritical	None	1.8E+00	1.5E+00	(*10*)
Coal	Recirculating	Supercritical	Wet	2.5E+00	2.0E+00	(*10*)
Coal	Recirculating	Supercritical	Dry	2.5E+00	1.9E+00	(*10*)
Coal	Recirculating	Supercritical	None	2.3E+00	1.7E+00	(*10*)
Coal	Recirculating	AVERAGE	AVERAGE	2.1E+00	1.8E+00	Calculated
Coal	Cooling Pond	Subcritical	Wet	6.8E+01	3.0E+00	(*10*)
Coal	Cooling Pond	Subcritical	Dry	6.8E+01	2.9E+00	(*10*)
Coal	Cooling Pond	Subcritical	None	6.8E+01	2.8E+00	(*10*)
Coal	Cooling Pond	Supercritical	Wet	5.7E+01	2.4E-01	(*10*)
Coal	Cooling Pond	Supercritical	Dry	5.7E+01	1.6E-01	(*10*)
Coal	Cooling Pond	Supercritical	None	5.7E+01	1.5E-02	(*10*)
Coal	Cooling Pond	AVERAGE	AVERAGE	6.5E+01	2.3E+00	Calculated
Natural Gas	Once-Through	AVERAGE	N/A	9.8E+01	5.0E-01	Calculated
Natural Gas	Recirculating	AVERAGE	N/A	2.1E+00	1.8E+00	Calculated
Biomass	AVERAGE	AVERAGE	N/A	2.7E+00	2.3E+00	(*7*)
Nuclear	Once-Through	AVERAGE	N/A	1.2E+02	5.2E-01	(*12*)
Nuclear	Recirculating	AVERAGE	N/A	4.2E+00	2.4E+00	(*12*)
Nuclear	Cooling Pond	AVERAGE	N/A	7.9E+01	5.4E+00	Calculated
Oil	Once-Through	AVERAGE	N/A	9.8E+01	5.0E-01	Assumed to be same as coal
Oil	Recirculating	AVERAGE	N/A	2.1E+00	1.8E+00	Assumed to be same as coal
Geothermal	Once-Through	Vapor Dominated	N/A	1.3E+01	1.3E+01	(*7*)
Geothermal	Recirculating	Vapor Dominated	N/A	6.8E+00	6.8E+00	(*7*)
Geothermal	Recirculating	Water Dominated	N/A	1.5E+01	1.5E+01	(*7*)

Table S4: Water Use for Thermoelectric Power Generation

	Coal: L/MJ Electricity	Oil: L/MJ Electricity	Gas: L/MJ Electricity	Nuclear: L/MJ Electricity	Hydro: L/MJ Electricity	Biomass: L/MJ Electricity	Wind: L/MJ Electricity	Solar: L/MJ Electricity	Geothermal: L/MJElectricity	Other Fossil: L/MJ Electricity	Unknown: L/MJ Electricity	Weighted Total

U.S. Average	WECC	TRE	SPP	SERC	RFC	NPCC	MRO	HICC	FRCC	ASCC
5.9E-01	7.5E-01	6.5E-01	6.8E-01	5.8E-01	5.5E-01	2.9E-01	5.6E-01	7.1E-01	5.6E-01	5.9E-01
4.8E-01	7.5E-01	7.9E-01	8.0E-01	6.8E-01	4.0E-01	1.3E+00	8.2E-01	6.7E-01	7.7E-01	6.7E-01
6.6E-01	6.5E-01	7.1E-01	6.8E-01	6.6E-01	6.2E-01	6.6E-01	7.1E-01	3.8E-01	6.5E-01	7.8E-01
5.8E-01	1.3E-01	1.1E+00	1.0E+00	5.2E-01	8.3E-01	2.7E-01	3.7E-01	8.3E-02	8.4E-02	8.6E-02
0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
7.0E-01	6.9E-01	7.4E-01	7.0E-01	7.0E-01	7.0E-01	7.0E-01	7.0E-01	7.0E-01	7.0E-01	7.2E-01
0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
3.1E-02	3.0E-02	3.2E-02	3.0E-02	3.0E-02	3.0E-02	3.0E-02	3.0E-02	3.0E-02	3.0E-02	3.1E-02
3.4E+00	3.3E+00	3.5E+00	3.3E+00	3.3E+00	3.3E+00	3.3E+00	3.3E+00	3.3E+00	3.3E+00	3.4E+00
6.6E-01	6.5E-01	7.1E-01	6.8E-01	6.6E-01	6.2E-01	6.6E-01	7.1E-01	3.8E-01	6.5E-01	7.8E-01
3.8E-01	3.8E-01	4.0E-01	3.8E-01	3.8E-01	3.8E-01	3.8E-01	3.8E-01	3.8E-01	3.8E-01	3.9E-01
5.7E-01	5.2E-01	7.2E-01	6.7E-01	5.6E-01	6.2E-01	5.0E-01	5.1E-01	7.2E-01	5.7E-01	5.8E-01

Table S5: Life-Cycle Water Consumption for U.S. Electricity Production

WECC	TRE	SPP	SERC	RFC	NPCC	MRO	HICC	FRCC	ASCC	
3.9E+00	1.9E+01	1.0E+01	1.8E+01	1.4E+01	1.6E+01	1.8E+01	8.1E-01	1.8E+00	1.5E+01	Coal: L/MJ Electricity
1.2E+01	1.3E+01	1.2E+01	1.2E+01	1.2E+01	1.3E+01	1.2E+01	1.2E+01	1.2E+01	1.2E+01	Oil: L/MJ Electricity
1.2E+01	1.3E+01	1.2E+01	1.2E+01	1.2E+01	1.2E+01	1.2E+01	1.2E+01	1.2E+01	1.3E+01	Gas: L/MJ Electricity
2.2E+00	3.1E+01	2.1E+01	1.9E+01	1.3E+01	1.6E+01	2.8E+01	8.3E-02	8.4E-02	8.6E-02	Nuclear: L/MJ Electricity
0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	Hydro: L/MJ Electricity
8.3E-01	8.8E-01	8.3E-01	8.3E-01	8.3E-01	8.3E-01	8.3E-01	8.3E-01	8.3E-01	8.6E-01	Biomass: L/MJ Electricity
0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	Wind: L/MJ Electricity
3.0E-02	3.2E-02	3.0E-02	3.0E-02	3.0E-02	3.0E-02	3.0E-02	3.0E-02	3.0E-02	3.1E-02	Solar: L/MJ Electricity
3.3E+00	3.5E+00	3.3E+00	3.3E+00	3.3E+00	3.3E+00	3.3E+00	3.3E+00	3.3E+00	3.4E+00	Geothermal: L/MJ Electricity
1.2E+01	1.3E+01	1.2E+01	1.2E+01	1.2E+01	1.2E+01	1.2E+01	1.2E+01	1.2E+01	1.3E+01	Other Fossil: L/MJ Electricity
1.2E+01	1.2E+01	1.2E+01	1.2E+01	1.2E+01	1.2E+01	1.2E+01	1.2E+01	1.2E+01	1.2E+01	Unknown: L/MJ Electricity
4.9E+00	1.7E+01	1.1E+01	1.6E+01	1.4E+01	1.2E+01	1.8E+01	9.8E+00	7.6E+00	1.0E+01	Weighted Total

U.S. Average	1.4E+01	1.2E+01	1.2E+01	1.6E+01	0.0E+00	8.4E-01	0.0E+00	3.1E-02	3.4E+00	1.2E+01	1.2E+01	1.3E+01

Table S6: Life-Cycle Water Withdrawals for U.S. Electricity Production

Electricity Consumption
See Electricity.

Primary Fuel Consumption
The production of liquid transportation fuels and electricity require coal, natural gas, various petroleum fuels, and uranium. The water use associated with extraction and refining of petroleum fuels is discussed in the *Direct Water Use* section. Natural gas is often linked with petroleum fuels because gas and oil reserves are located nearby one another. Additionally, natural gas is dissolved in oil, and can be separated out and sold; this practice is responsible for 23% of U.S. gas production (*46*). This practice presents yet another allocation problem: how should water use for oil extraction be allocated if natural gas is also present in the oil? Because 70% of domestic natural gas is extracted from dedicated gas wells (*46*), one can make the argument that the gas co-product from oil extraction is displacing gas well production, in which case system expansion can be used. According to reference (7), water used in gas wells is negligible, so system expansion dictates that all water use for oil extraction, regardless of whether natural gas is co-produced, should be allocated to oil. Reference (7) does, however, list small direct water use for natural gas processing and pipeline operation, and somewhat significant water use for other processing plant operations, such as plant service, potable water requirements, and boiler makeup water. Natural gas is also produced alongside coal in the form of coalbed methane (7% of U.S. production). As with petroleum, system expansion shows that no coal extraction-related water use should be allocated to natural gas.

The vast majority of water in coal mines is used for dust control, with other minor uses including showers, potable water, sanitary uses, and equipment maintenance (25). Data on water use for surface and underground coal mining is taken from reference (7) and the fraction of water taken from saline sources is provided by (25). Half of surface mines are assumed to require revegetation.

Uranium (U-235) mining water use data is also taken from reference (7), which includes mining (both open pit and underground), milling, UF_6 conversion, and enrichment (gaseous diffusion and gas centrifuge). The breakdown of open pit vs. underground mining was taken from GREET1.8c (32), and a 50/50 ratio was assumed for gaseous diffusion vs. gas centrifuge enrichment.

Energy use for primary fuel extraction and processing, including primary fuels as well as electricity, are taken from GREET1.8c, and the water footprint of this energy is included in the total water footprint of coal, petroleum, natural gas, and uranium.

Chemicals

Reliable water use data for chemical production are notoriously difficult to find. However, chemical use can make up a significant portion of some fuels' water footprint. (25) provides both withdrawals and consumption for the top nine chemicals produced in the U.S. (by volume), as well as the top ten per-lb water users. These lists include specific data for ammonia (used for fertilizer production and biorefining), phosphoric acid (used in fertilizer), and sulfuric acid (used in biorefining). Additionally, water use for lime production (as used in biorefining) is taken from the (*47*) LCA software. For all other chemicals average withdrawals/consumption for organic, inorganic, and agricultural chemical production is calculated by dividing total water use data from (25) by total U.S. chemical shipments estimated by reference (*48*), allocated to each category based on monetary output from the 2002 U.S. Economic Census (*58-60*). It is assumed that 28% of total withdrawals are consumed (*49*). Compared to the product-specific estimates from (25), these averages appear to be conservative. The water footprint of energy used to produce these chemicals is also included, using GREET1.8c (32) energy consumption data.

Construction & Materials

The only direct water use for construction that is quantified in this analysis is dust control. There is a large amount of uncertainty associated with these estimates because they are dependent on how much of a lot is actually undergoing construction at any given time, the total duration of construction, local rainfall and average temperatures, and whether chemical adhesives are also used to enhance dust control, thus resulting in less frequent water application. However, dust control proves to be a relatively insignificant fraction of the total transportation fuel water footprints.

The water footprint of materials used in construction of facilities and other equipment required for transportation fuel production has also been calculated. For most pathways, steel and concrete make up the bulk of the construction materials. Concrete mixes require water (approximately 175 L of water per m^3 of average, ready-mix concrete) (*50*). This water is consumed by reacting with cement through a process called hydration. In contrast, the steelmaking process does not chemically destroy water molecules, but a great deal of water is withdrawn and evaporated for material conditioning, air pollution control, and heat transfer (25). Water consumption and withdrawals are taken from reference (*51*), the breakdown of U.S. electric arc furnaces and blast furnaces, as well as steel imports are taken from (*52, 53*). Finally, energy (both electricity and primary fuels) use at steel plants is taken from the Manufacturing Energy Consumption Survey (*54*).

Material/Activity	Direct Withdrawals	Direct Consumption	Units	Source
Misc. Agricultural Chemicals	1.8E+01	5.1E+00	L/kg output	Calculated
Aluminum	6.4E+01	1.6E+01	L/kg aluminum	(*47*)
Ammonia	1.4E+02	1.1E+01	L/kg ammonia	(*55*)
Chlorine	7.5E+01	9.0E+00	L/kg chlorine	(*55*)

Copper	5.9E+01	1.1E-03	L/kg copper	(*47*)
Glass	3.0E-02	5.5E-03	L/kg glass	(*47*)
Hydrogen via Steam Reforming of Natural Gas	8.5E+00	5.6E+00	L/kg H_2	(*47*)
Misc. Industrial Inorganic Chemicals	1.7E+01	4.7E+00	L/kg output	Calculated
Misc. Industrial Organic Chemicals	2.6E+01	7.3E+00	L/kg output	Calculated
Lime	7.4E-01	9.4E-02	L/kg lime	(*47*)
Phosphoric Acid	2.8E+02	3.0E+01	L/kg P_2O_5	(*55*)
Plastics	1.7E+01	2.6E+00	L/kg PVC	(*47*)
Polyethylene	8.3E+01	6.5E+00	L/kg polyethylene	(*55*)
Ready-Mix Concrete	2.5E-01	2.5E-01	L/kg concrete	(*50*)
Silica (Sand)	2.7E-03	6.0E-04	L/kg silica sand	(*47*)
Silicon Wafers	3.1E+02	3.1E+02	L/kg silicon	(*56*)
Steelmaking: Basic Oxygen Furnace	4.4E+00	4.0E+00	L/kg steel	(*51*)
Steelmaking: Electric Arc Furnace	8.8E+00	8.3E+00	L/kg steel	(*51*)
Sulfuric Acid	6.6E+01	5.0E+00	L/kg sulfuric acid	(*55*)

Table S7: Water Embodied in Materials

Supply-Chain Agriculture and Services

Water use for both supply-chain services and agriculture are taken from the 2002 EIO-LCA model (39). Service sectors encompass domestic-type water use (toilets, sinks, etc.) at facilities involved indirectly in fuel supply chains (such as insurance offices, for example). Indirect purchases of agricultural products, while small, have the potential to be significant in some cases because of the high relative water-intensity of these products. In the water portion of the 2002 EIO-LCA model, only withdrawals are quantified, so it has limited applicability for any analysis in which consumption is also quantified. However, in the case of service sectors (which typically use publically-supplied water) and agriculture, withdrawals are roughly equal to consumption.

Additional Factors Affecting Water Footprints

One life-cycle phase that has yet to be discussed is the combustion phase (fuel use in on-road vehicles). Combustion of fuels does not consume water. H_2O molecules are actually created in the process of oxidizing the fuel, which escape from the vehicle tailpipe in the form of steam. Because evaporation falls under the current definition of water consumption, combustion chemically creates water, which is immediately physically "consumed". To illustrate the magnitude of this water creation, one can use the oxidation of octane, a major component in gasoline, as an example (see Equation S1).

$$2C_8H_{18} + 25O_2 \Rightarrow 16CO_2 + 18H_2O$$

Equation S1: Complete Combustion of Octane

Assuming carbon has a molecular mass of 12 g/mol, hydrogen of 1 g/mol, and oxygen of 16 g/mol, this balanced equation indicates that 228 g of octane yields 324 g of water, or 1 L of water produced per L of octane combusted. Interestingly, the amount of water created during combustion is significant, equal to approximately two thirds the amount of water consumed during the refining process. A simple hypothesis for why this produced water does not significantly increase freshwater resources can be developed using the Earth's water cycle. Assuming the water synthesized during fossil fuel combustion is ultimately distributed in a manner similar to existing water resources, at least 98% will become ocean water (98% is calculated using water cycle data from reference (14), excluding freshwater contained in underground aquifers not within the zone of active exchange). Reference (*57*) assumes that 100% of this water becomes seawater, contributing an estimated 0.021 mm/year to sea level rise.

Allocation

ISO 14044 recommends an approach called System Expansion (*58*). For example, dried distillers' grains (DDGS) that are produced at corn ethanol plants serve as a substitute for soybean meal and urea in animal feed; assuming demand for animal feed remains constant, the amount of soybean meal and urea production that is displaced by the DDGS co-product can be calculated, and DDGS is then assigned the avoided environmental impacts of producing its soybean meal and urea equivalent (31). In the case of corn stover and Miscanthus-to-ethanol, the cellulosic ethanol plants produce export significant amounts of electricity to the grid, and the carbon footprint of the displaced electricity is larger than the entire life-cycle carbon footprint of cellulosic ethanol, resulting in a net negative number. In contrast, those who choose to allocate the impacts by some other method, such as energy content, find the net carbon footprint of cellulosic ethanol to be a positive number (34), proving that the allocation choices can significantly influence LCI results. System expansion is only possible, however, if the co-product displaces a product generated through a different process. In the case of petroleum refineries, there is no well-established alternative method of producing residual oil, kerosene, diesel fuel, etc. For this reason, impacts from the petroleum refinery sub-processes are allocated among products by market value because, although market values have the disadvantage of fluctuation over time, they are the best measure of the inherent value of co-products. Lastly, corn stover as a co-product of corn grain production presents a unique issue: while stover has previously been a waste product, it will gain a market value of its own as cellulosic ethanol production ramps up. In the present, the price of corn grain drives corn production and, although some attempts have been made at estimating a market value for stover (*59*), it is treated as a waste product for the purposes of this research. The allocation approaches taken in this research are shown in Table S8.

System	Co-Products	Method
Petroleum Extraction	Crude Oil, Natural Gas	System Expansion
Corn Stover or Miscanthus Biorefinery	Ethanol, Electricity	System Expansion
Petroleum Refinery	Gasoline, Diesel, Residual Oil, Kerosene, LPG, Other Products	Market Value
Corn Grain Biorefinery	Ethanol, DDGS	System Expansion

Table S8: Allocation Methods Applied in this Analysis

		Feedstock Extraction/ Production	Feedstock Transportation	Fuel Transportation, Storage & Distribution	Refining/Fuel Production	Hydro Contribution
Crude Oil to Gasoline (L/km Traveled)	C	4.24E-01	1.48E-02	8.71E-03	6.34E-01	5.22E-02
	W	4.45E-01	3.23E-02	1.62E-02	1.00E+00	2.62E-02
Oil Sands to Gasoline (L/km Traveled)	C	5.03E-01	8.42E-03	8.71E-03	6.34E-01	2.03E-01
	W	6.69E-01	4.44E-02	1.62E-02	9.42E-01	2.03E-01
Miscanthus to Ethanol (L/km Traveled)	C	4.21E-02	9.99E-03	1.65E-02	1.25E+00	-6.29E-01
	W	7.29E-02	9.99E-03	3.38E-02	-1.66E+00	-6.28E-01
Avg Corn Grain & Stover to Ethanol (L/km Traveled)	C	1.28E+01	1.73E-02	1.65E-02	1.14E+00	-1.15E-01
	W	1.37E+01	1.73E-02	3.38E-02	1.19E+00	-1.14E-01
Rainfed Corn Grain & Stover to Ethanol (L/km Traveled)	C	1.36E-01	1.73E-02	1.65E-02	1.14E+00	-1.15E-01
	W	1.07E+00	1.73E-02	3.38E-02	1.19E+00	-1.14E-01
Electricity: U.S. Mix (L/km Traveled)	C	1.78E-01	4.22E-03	5.48E-02	4.13E-01	1.61E+00
	W	2.57E-01	4.22E-03	1.23E+00	1.23E+01	1.61E+00

Table S9: Life-Cycle Inventory Results by Phase

		Direct	Primary Fuel Consumption	Chemicals	Construction & Materials	Supply-Chain Agriculture	Supply-Chain Services	Electricity Consumption	Hydro Contribution
Crude Oil to Gasoline (L/km Traveled)	C	9.08E-01	5.85E-02	2.33E-03	4.49E-04	8.19E-02	1.21E-02	1.83E-02	5.22E-02
	W	9.34E-01	5.85E-02	8.32E-03	1.01E-03	8.19E-02	1.21E-02	3.99E-01	2.62E-02
Oil Sands to Gasoline (L/km Traveled)	C	9.18E-01	1.04E-01	5.45E-06	4.41E-04	8.19E-02	1.21E-02	3.79E-02	2.03E-01
	W	9.18E-01	1.04E-01	1.95E-05	9.92E-04	8.19E-02	1.21E-02	5.55E-01	2.03E-01

Miscanthus to Ethanol (L/km Traveled)	C	1.03E+00	4.12E-02	1.98E-01	8.67E-03	1.90E-01	1.57E-02	-1.66E-01	-6.29E-01
	W	1.03E+00	4.12E-02	1.72E+00	2.23E-02	1.90E-01	1.57E-02	-4.57E+00	-6.28E-01
Avg Corn Grain & Stover to Ethanol (L/km Traveled)	C	1.34E+01	1.32E-01	1.88E-01	1.92E-02	1.90E-01	1.57E-02	-2.27E-02	-1.15E-01
	W	1.34E+01	1.32E-01	1.76E+00	5.13E-02	1.90E-01	1.57E-02	-6.43E-01	-1.14E-01
Rainfed Corn Grain & Stover to Ethanol (L/km Traveled)	C	7.90E-01	1.32E-01	1.88E-01	1.92E-02	1.90E-01	1.57E-02	-2.27E-02	-1.15E-01
	W	8.02E-01	1.32E-01	1.76E+00	5.13E-02	1.90E-01	1.57E-02	-6.43E-01	-1.14E-01
Electricity: U.S. Mix (L/km Traveled)	C	5.54E-01	3.95E-03	1.46E-05	2.83E-03	2.64E-02	3.52E-03	5.90E-02	1.61E+00
	W	1.24E+01	3.95E-03	5.22E-05	7.94E-03	2.64E-02	3.52E-03	1.31E+00	1.61E+00

Table S10: Life-Cycle Inventory Results by Contributor

	Feedstock Extraction/Production	Feedstock Transportation	Refining/Fuel Production	Fuel Transportation, Storage & Distribution
Crude Oil to Gasoline	• Extraction method	N/A	• Direct water use	N/A
Oil Sands to Gasoline	• Extraction method	N/A	• Direct water use	N/A
Corn Grain & Stover to Ethanol	• Water embodied in chemicals • Irrigation	N/A	• Direct water use • Water embodied in chemicals • Electricity co-product credit	N/A
Miscanthus to Ethanol	• Irrigation • Water embodied in chemicals	N/A	• Direct water use • Water Embodied in chemicals • Electricity co-product credit	N/A
U.S. Electricity	• Variation Among NERC Regions	• Variation Among NERC Regions	• Variation Among NERC Regions	• Variation Among NERC Regions

Table S11: Factors Considered in Sensitivity Analysis

Sensitivity Results (L Water / km Traveled)			**Feedstock Extraction/ Production**	**Feedstock Transportation**	**Refining/ Fuel Production**	**Fuel Transportation, Storage & Distribution**
Crude Oil to Gasoline	C	Low	5.22E-02	8.60E-03	5.02E-01	4.24E-03
		Avg	4.24E-01	1.48E-02	6.34E-01	8.71E-03
		High	6.27E-01	1.89E-02	7.58E-01	1.16E-02
	W	Low	7.19E-02	2.60E-02	8.52E-01	1.17E-02
		Avg	4.45E-01	3.23E-02	9.75E-01	1.62E-02
		High	6.49E-01	3.63E-02	1.14E+00	1.91E-02
Oil Sands to Gasoline	C	Low	3.20E-01	6.72E-03	5.66E-01	4.24E-03
		Avg	5.03E-01	8.42E-03	6.34E-01	8.71E-03
		High	7.82E-01	9.53E-03	6.81E-01	1.16E-02
	W	Low	4.37E-01	4.27E-02	8.74E-01	1.17E-02
		Avg	6.69E-01	4.44E-02	9.42E-01	1.62E-02
		High	9.00E-01	4.56E-02	9.89E-01	1.91E-02

Miscanthus to Ethanol	C	Low	3.11E-02	6.44E-03	5.25E-01	8.17E-03
		Avg	4.21E-02	9.99E-03	1.25E+00	1.65E-02
		High	2.46E+01	1.23E-02	2.08E+00	2.18E-02
	W	Low	6.23E-02	6.44E-03	-2.36E+00	2.55E-02
		Avg	7.29E-02	9.99E-03	-1.66E+00	3.38E-02
		High	2.46E+01	1.23E-02	7.82E+00	3.92E-02
Avg Corn Grain & Stover to Ethanol	C	Low	1.23E-01	9.29E-03	7.46E-01	8.17E-03
		Avg	1.28E+01	1.73E-02	1.14E+00	1.65E-02
		High	1.83E+02	2.25E-02	1.83E+00	2.18E-02
	W	Low	1.06E+00	9.29E-03	8.09E-01	2.55E-02
		Avg	1.37E+01	1.73E-02	1.19E+00	3.38E-02
		High	1.84E+02	2.25E-02	7.57E+00	3.92E-02
Rainfed Corn Grain & Stover to Ethanol	C	Low	1.23E-01	9.29E-03	7.46E-01	8.17E-03
		Avg	1.36E-01	1.73E-02	1.14E+00	1.65E-02
		High	1.48E-01	2.25E-02	1.83E+00	2.18E-02
	W	Low	1.06E+00	9.29E-03	8.09E-01	2.55E-02
		Avg	1.07E+00	1.73E-02	1.19E+00	3.38E-02
		High	1.07E+00	2.25E-02	7.57E+00	3.92E-02
Electricity: U.S.	C	Low	1.93E-01	3.65E-03	3.39E-01	4.75E-02
		Avg	1.78E-01	4.22E-03	4.13E-01	5.48E-02
		High	3.39E-01	1.01E-02	4.76E-01	6.69E-02
	W	Low	2.12E-01	3.16E-03	4.67E+00	4.02E-01
		Avg	2.57E-01	4.22E-03	1.23E+01	1.23E+00
		High	2.79E-01	5.99E-03	1.73E+01	1.68E+00

Table S12: Sensitivity Analysis Results Broken Down by Life-Cycle Phase

Section 4: Geospatial Data

A great deal of county-level geospatial data went into weighting the water use inventory by contribution to drought and groundwater overpumping. Because county-level tables are so large, rather than printing them in the Supporting Information, they have been made available in spreadsheet form at www.energy-water-footprint.com/information--data.html. Documentation for each file is also available for download at www.energy-water-footprint.com/data-documentation.html. The list of county-level data posted online is as follows:

FIPS Code to NERC Region Mapping
http://energy-water-footprint.com/County_to_NERC.xls

County-Level Surface and Groundwater Impact Indices
http://energy-water-footprint.com/Surface_and_Groundwater_Indices.xls

County-Level Mapping of Water Use for Electricity Generation
http://energy-water-footprint.com/Power_Generation_Geospatial_Breakdown.xls

County-Level Mapping of Water Use for Coal Mining
http://energy-water-footprint.com/Coal_Mine_FIPS_Breakdown.xls

County-Level Mapping of Uranium Mines
http://energy-water-footprint.com/Uranium_Mine_Locations.xls

County-Level Mapping of Natural Gas Wells
http://energy-water-footprint.com/Natural_Gas_Extraction_Locations.xls

County-Level Mapping of U.S. Corn Grain Production
http://energy-water-footprint.com/Corn_Agriculture_Locations.xls

County Level Mapping of U.S. Ethanol Production
http://energy-water-footprint.com/Ethanol_Plant_Locations.xls

County-Level Mapping of U.S. Petroleum Refining Capacity
http://energy-water-footprint.com/Petroleum_Refinery_Locations.xls

County-Level Mapping of Steel Mills
http://energy-water-footprint.com/Steel_Mill_Locations.xls

County-Level Mapping of Chemical Manufacturing
http://energy-water-footprint.com/Chemical_Manufacturing_Locations.xls

County-Level Mapping of Glass, Clay, & Sand Production
http://energy-water-footprint.com/Glass_Clay_Sand_Locations.xls

County-Level Mapping of Plastics & Rubber Manufacturing
http://energy-water-footprint.com/Plastics_Rubber_Locations.xls

County-Level Water Use Inventory Results Broken Out by Water Source (Ground & Surface)
http://energy-water-footprint.com/Inventory_Results_by_Water_Source.xls

County-Level Greenhouse Gas-Intensity of Water Supply
http://energy-water-footprint.com/GHG_Intensity_of_Water_Supply.xls

Section 5: Surface, Groundwater, & GHG Impacts

Category	Description	Palmer Index	Possible Impacts
D0	Abnormally Dry	-1.0 to -1.9	Going into drought: short term dryness slowing planting, growth of crops,

			or pastures. Coming out of drought: some lingering water deficits; pastures or crops not fully recovered
D1	Moderate Drought	-2.0 to -2.9	Some damage to crops, pastures; streams, reservoirs, or wells low, some water shortages developing or imminent; voluntary water-use restrictions requested
D2	Severe Drought	-3.0 to -3.9	Crop and pasture losses likely; water shortages common; water restrictions imposed
D3	Extreme Drought	-4.0 to -4.9	Major crop/pasture losses; widespread water shortages or restrictions
D4	Exceptional Drought	-5.0 or less	Exceptional and widespread crop/pasture losses; shortages of water in reservoirs, streams, and wells creating water emergencies

Table S13: Palmer Drought Index Descriptions (adapted from: (*60*))

For more information about how this drought severity classification maps to other measures, such as the Standardized Precipitation Index, CPC Soil Moisture Model, etc., visit: http://www.drought.unl.edu/dm/classify.htm (Accessed June 30th, 2010)

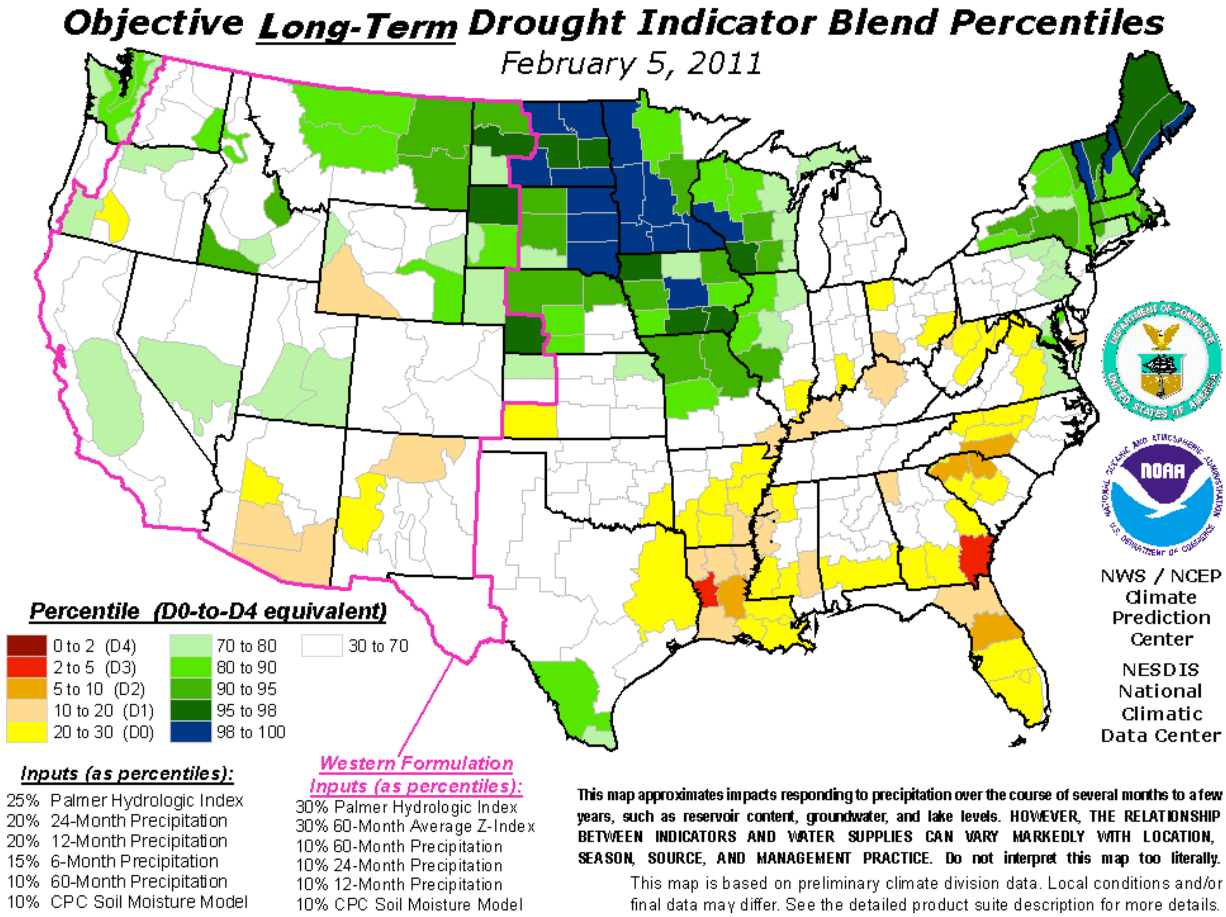

Figure S4: Alternative Drought Vulnerability Metric (Source: Reference (*61*))

State	Examples of Impacts from Groundwater Overpumping
AR	Lowered water table
AZ	Lowered water table, subsidence
CA	Lowered water table, subsidence
CO	Lowered water table, subsidence
DE	Lowered water table, subsidence
FL	Saltwater intrusion, subsidence
GA	Saltwater intrusion, subsidence
ID	Lowered water table, subsidence
IL	Lowered water table
KS	Lowered water table
KY	Lowered water table
LA	Lowered water table, saltwater intrusion
MA	Reduction in surface water flows
MS	Lowered water table
NE	Overpumping, contributing to lowered water table in KS
NJ	Saltwater intrusion, subsidence
NM	Lowered water table, subsidence
NV	Lowered water table, subsidence
NY	Lowered water table, reduction or elimination of stream base flows,

	decrease in length of perennial streams, inland movement of saline groundwater
OR	Lowered water table
SC	Saltwater intrusion
TN	Lowered water table
TX	Lowered water table, subsidence, increased susceptibility to flooding
UT	Lowered water table
VA	Lowered water table, subsidence
WA	Lowered water table
WI	Lowered water table

Table S14: Groundwater Pumping Impacts (Based on Information from (*62*), (*63*), and (*64*))

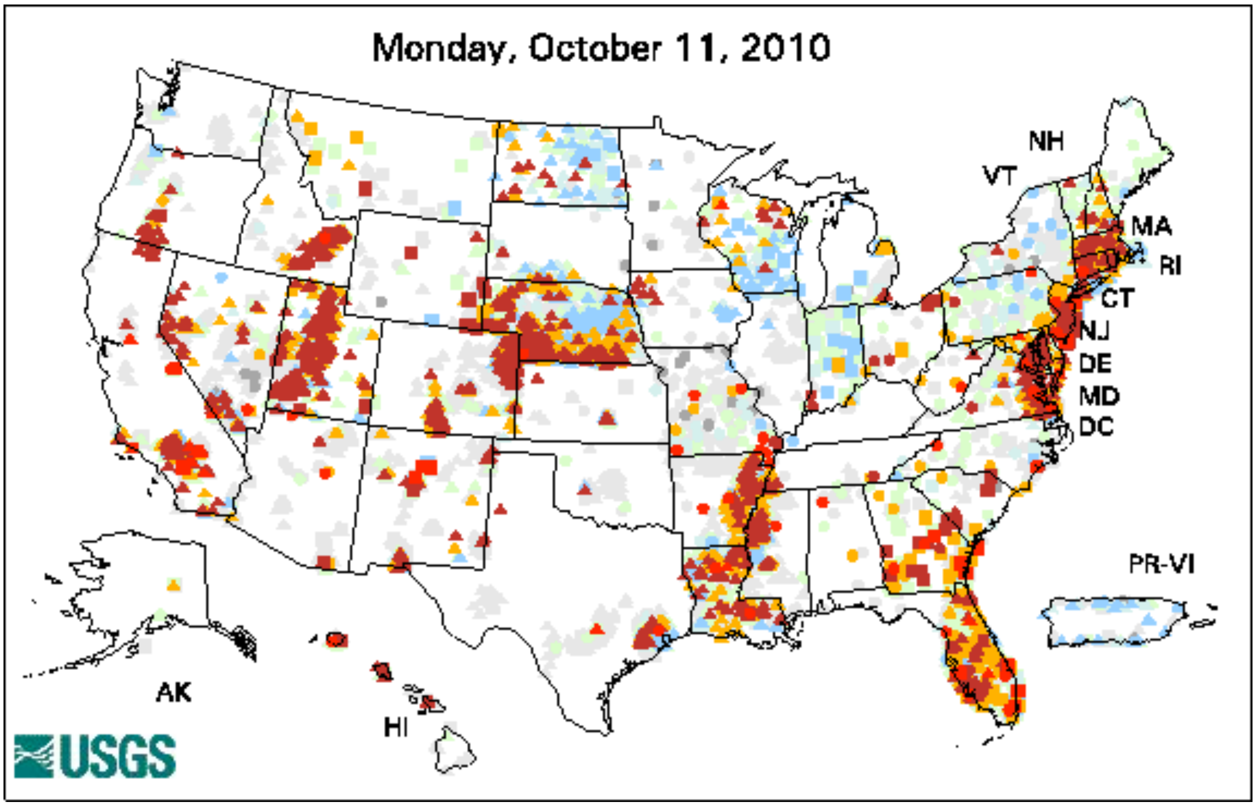

Figure S5: Groundwater Wells With Significantly Lowered Levels (Source: Reference (*65*))

Inputs	**Surface Water (g/m³)**	**Groundwater (g/m³)**	**Brackish Groundwater (g/m³)**	**Seawater (g/m³)**	**Recycled Wastewater (g/m³)**	**GWP (g/g chemical)**
Alum	3.5E-01	0.0E+00	0.0E+00	0.0E+00	5.3E+01	3.1E-01
Aqueous Ammonia	8.4E-01	0.0E+00	1.3E+01	8.0E+00	0.0E+00	2.9E+00
Calcium Carbonate	0.0E+00	0.0E+00	0.0E+00	2.6E+01	0.0E+00	1.1E-02
Caustic Soda	3.3E+00	0.0E+00	1.7E+01	0.0E+00	0.0E+00	4.3E+00
Chlorine	5.3E+00	5.3E+00	0.0E+00	0.0E+00	1.9E+01	1.4E+00
CO_2	0.0E+00	0.0E+00	0.0E+00	2.6E+01	0.0E+00	9.2E-01

Ferric Chloride	4.0E+00	0.0E+00	0.0E+00	1.8E+01	0.0E+00	2.0E-01
Sodium Hypochlorite	1.9E+00	0.0E+00	1.1E+01	6.0E+00	0.0E+00	3.0E-02
Sulfuric Acid	0.0E+00	0.0E+00	6.5E+01	8.1E+01	0.0E+00	4.5E-01
Other	2.8E+00	0.0E+00	3.0E+00	8.2E+00	4.0E+00	1.5E+00
Electricity (kWh/m^3)	7.1E-01	1.5E+00	2.9E+00	5.2E+00	2.1E+00	Depends on Location
Data Source:	*(66, 67)*	*(66)*	*(67)*	*(67)*	*(67)*	*(47)*

Table S15: Water Supply Energy and Chemical Inputs

Function	**Source**	**MJ Electricity/L**	**MJ Natural Gas/L**	**g CO_2 Embodied in Chemicals/L**	**g CH_4 Embodied in Chemicals/L**	**g N_2O Embodied in Chemicals/L**
Public Supply	Local Surface Water	2.5E-03	0.0E+00	1.8E-02	5.0E-04	0.0E+00
	Local Groundwater	2.5E-03	0.0E+00	4.4E-03	1.3E-04	0.0E+00
	Brackish Groundwater	1.0E-02	0.0E+00	8.9E-02	2.5E-03	0.0E+00
	Seawater	1.9E-02	0.0E+00	5.7E-02	1.6E-03	0.0E+00
	Recycled Wastewater	7.7E-03	0.0E+00	2.8E-02	8.0E-04	0.0E+00
Industrial	Local Surface Water	2.2E-05	0.0E+00	0.0E+00	0.0E+00	0.0E+00
	Local Groundwater	5.1E-05	0.0E+00	0.0E+00	0.0E+00	0.0E+00
	Brackish Groundwater	9.6E-03	0.0E+00	8.9E-02	2.5E-03	0.0E+00
	Seawater	1.6E-02	0.0E+00	5.7E-02	1.6E-03	0.0E+00
	Recycled Wastewater	2.3E-03	0.0E+00	2.8E-02	8.0E-04	0.0E+00
Oil Extraction	Local Surface Water	0.0E+00	7.6E-05	0.0E+00	0.0E+00	0.0E+00
	Local Groundwater	0.0E+00	1.8E-04	0.0E+00	0.0E+00	0.0E+00
	Brackish Groundwater	9.6E-03	0.0E+00	8.9E-02	2.5E-03	0.0E+00
	Seawater	1.6E-02	0.0E+00	5.7E-02	1.6E-03	0.0E+00
	Recycled Wastewater	2.3E-03	0.0E+00	2.8E-02	8.0E-04	0.0E+00
Power Generation	Local Surface Water	2.2E-05	0.0E+00	0.0E+00	0.0E+00	0.0E+00
	Local Groundwater	5.9E-05	0.0E+00	0.0E+00	0.0E+00	0.0E+00

	Brackish Groundwater	9.6E-03	0.0E+00	8.9E-02	2.5E-03	0.0E+00
	Seawater	1.6E-02	0.0E+00	5.7E-02	1.6E-03	0.0E+00
	Recycled Wastewater	2.3E-03	0.0E+00	2.8E-02	8.0E-04	0.0E+00

Table S16: Energy and GHG-Intensity of Water for Public Supply, Industrial, and Power Generation Purposes

	Surface Water (MJ/L)				Groundwater (MJ/L)			
State	**Electricity**	**NG**	**Propane/ Butane/LPG**	**Diesel**	**Electricity**	**NG**	**Propane/ Butane/ LPG**	**Diesel**
AL	2.1E-05	0.0E+00	0.0E+00	2.4E-05	4.9E-05	0.0E+00	0.0E+00	5.5E-05
AK	1.6E-05	0.0E+00	0.0E+00	2.7E-05	3.7E-05	0.0E+00	0.0E+00	6.2E-05
AZ	2.3E-05	1.5E-05	1.2E-07	6.4E-06	5.5E-05	3.5E-05	2.9E-07	1.5E-05
AR	1.2E-05	2.0E-06	8.7E-07	3.0E-05	2.7E-05	4.7E-06	2.0E-06	7.1E-05
CA	2.3E-05	5.6E-06	6.9E-07	1.6E-05	5.4E-05	1.3E-05	1.6E-06	3.7E-05
CO	3.5E-05	6.4E-06	2.8E-07	3.3E-06	8.2E-05	1.5E-05	6.6E-07	7.6E-06
CT	8.4E-06	0.0E+00	1.2E-05	2.5E-05	2.0E-05	0.0E+00	2.7E-05	5.8E-05
DE	8.0E-06	0.0E+00	0.0E+00	3.7E-05	1.9E-05	0.0E+00	0.0E+00	8.7E-05
FL	9.2E-06	0.0E+00	1.1E-07	3.6E-05	2.2E-05	0.0E+00	2.6E-07	8.4E-05
GA	1.9E-05	0.0E+00	3.9E-07	2.6E-05	4.4E-05	0.0E+00	9.0E-07	6.1E-05
HI	2.4E-05	0.0E+00	0.0E+00	2.0E-05	5.7E-05	0.0E+00	0.0E+00	4.7E-05
ID	4.3E-05	2.7E-08	9.5E-08	1.6E-06	1.0E-04	6.4E-08	2.2E-07	3.8E-06
IL	1.5E-05	0.0E+00	2.1E-06	2.8E-05	3.5E-05	0.0E+00	4.9E-06	6.5E-05
IN	2.0E-05	5.1E-07	9.5E-07	2.4E-05	4.6E-05	1.2E-06	2.2E-06	5.5E-05
IA	2.4E-05	0.0E+00	2.8E-06	1.8E-05	5.7E-05	0.0E+00	6.5E-06	4.2E-05
KS	2.7E-06	3.4E-05	5.0E-07	7.7E-06	6.4E-06	8.0E-05	1.2E-06	1.8E-05
KY	8.3E-06	0.0E+00	0.0E+00	3.0E-05	2.0E-05	0.0E+00	0.0E+00	6.9E-05
LA	4.4E-06	1.8E-06	5.6E-07	3.8E-05	1.0E-05	4.3E-06	1.3E-06	8.9E-05
ME	4.2E-06	0.0E+00	4.9E-06	3.3E-05	9.8E-06	0.0E+00	1.1E-05	7.7E-05
MD	3.8E-06	0.0E+00	3.8E-07	3.8E-05	8.9E-06	0.0E+00	8.8E-07	8.9E-05
MA	8.0E-06	0.0E+00	2.6E-05	9.2E-06	1.9E-05	0.0E+00	6.1E-05	2.1E-05
MI	2.3E-05	7.4E-07	3.5E-07	2.1E-05	5.3E-05	1.7E-06	8.1E-07	4.8E-05
MN	3.0E-05	0.0E+00	1.7E-07	1.5E-05	7.0E-05	0.0E+00	4.1E-07	3.5E-05
MS	1.3E-05	0.0E+00	0.0E+00	3.2E-05	2.9E-05	0.0E+00	0.0E+00	7.6E-05
MO	1.1E-05	5.4E-07	7.1E-06	2.5E-05	2.5E-05	1.3E-06	1.7E-05	6.0E-05
MT	3.8E-05	9.4E-07	4.1E-07	6.0E-06	8.8E-05	2.2E-06	9.7E-07	1.4E-05
NE	1.2E-05	1.4E-05	2.7E-06	1.6E-05	2.7E-05	3.3E-05	6.3E-06	3.9E-05
NV	4.0E-05	0.0E+00	0.0E+00	5.1E-06	9.4E-05	0.0E+00	0.0E+00	1.2E-05
NH	4.5E-05	0.0E+00	0.0E+00	0.0E+00	1.1E-04	0.0E+00	0.0E+00	0.0E+00
NJ	4.8E-06	0.0E+00	3.0E-08	3.7E-05	1.1E-05	0.0E+00	7.0E-08	8.7E-05
NM	3.2E-05	1.0E-05	0.0E+00	3.0E-06	7.4E-05	2.4E-05	0.0E+00	6.9E-06
NY	5.4E-06	0.0E+00	0.0E+00	3.6E-05	1.3E-05	0.0E+00	0.0E+00	8.5E-05
NC	8.9E-06	0.0E+00	3.0E-07	3.3E-05	2.1E-05	0.0E+00	7.0E-07	7.7E-05
ND	3.4E-05	1.2E-06	3.0E-07	9.4E-06	8.0E-05	2.9E-06	7.0E-07	2.2E-05
OH	1.6E-05	1.5E-05	0.0E+00	1.2E-05	3.9E-05	3.5E-05	0.0E+00	2.7E-05
OK	8.8E-06	2.9E-05	7.3E-07	6.2E-06	2.1E-05	6.8E-05	1.7E-06	1.4E-05

OR	4.2E-05	0.0E+00	0.0E+00	2.9E-06	9.9E-05	0.0E+00	0.0E+00	6.7E-06
PA	1.1E-05	0.0E+00	8.1E-08	2.5E-05	2.7E-05	0.0E+00	1.9E-07	5.8E-05
RI	1.8E-05	0.0E+00	2.7E-05	0.0E+00	4.3E-05	0.0E+00	6.3E-05	0.0E+00
SC	3.2E-05	2.1E-06	1.7E-06	8.5E-06	7.6E-05	4.9E-06	4.1E-06	2.0E-05
SD	2.9E-05	5.5E-07	5.5E-07	1.5E-05	6.9E-05	1.3E-06	1.3E-06	3.4E-05
TN	1.6E-05	0.0E+00	1.2E-06	2.5E-05	3.7E-05	0.0E+00	2.8E-06	5.9E-05
TX	1.0E-05	3.1E-05	7.8E-08	3.6E-06	2.3E-05	7.4E-05	1.8E-07	8.3E-06
UT	3.5E-05	1.9E-07	1.0E-07	9.5E-06	8.2E-05	4.4E-07	2.5E-07	2.2E-05
VT	1.1E-05	0.0E+00	0.0E+00	2.2E-05	2.6E-05	0.0E+00	0.0E+00	5.1E-05
VA	1.4E-05	0.0E+00	3.8E-07	2.6E-05	3.3E-05	0.0E+00	8.9E-07	6.0E-05
WA	4.4E-05	0.0E+00	0.0E+00	7.9E-07	1.0E-04	0.0E+00	0.0E+00	1.8E-06
WV	3.9E-05	0.0E+00	0.0E+00	6.0E-06	9.1E-05	0.0E+00	0.0E+00	1.4E-05
WI	2.4E-05	0.0E+00	1.7E-07	2.0E-05	5.7E-05	0.0E+00	4.1E-07	4.7E-05
WY	3.6E-05	1.6E-06	8.0E-07	6.7E-06	8.4E-05	3.8E-06	1.9E-06	1.6E-05

Table S17: Fuel Use for Agricultural Water Pumping (Calculated from (*28*))

FIPS	California County	Irrigation Region	Electricity for Irrigation Region (MJ/L)	Diesel for Irrigation Region (MJ/L)	MJ Electricity/L Irrigation Water	MJ Diesel/L Irrigation Water
06103	Tehama	14	3.9E-04	6.4E-04	3.9E-04	6.4E-04
06007	Butte	14	3.9E-04	6.4E-04	3.9E-04	6.4E-04
06021	Glenn	14	3.9E-04	6.4E-04	3.9E-04	6.4E-04
06115	Yuba	14	3.9E-04	6.4E-04	3.9E-04	6.4E-04
06057	Nevada	14	3.9E-04	6.4E-04	3.9E-04	6.4E-04
06061	Placer	14	3.9E-04	6.4E-04	3.9E-04	6.4E-04
06017	El Dorado	14	3.9E-04	6.4E-04	3.9E-04	6.4E-04
06067	Sacramento	14	3.9E-04	6.4E-04	3.9E-04	6.4E-04
06011	Colusa	14	3.9E-04	6.4E-04	3.9E-04	6.4E-04
06113	Yolo	14	3.9E-04	6.4E-04	3.9E-04	6.4E-04
06095	Solano	14	3.9E-04	6.4E-04	5.3E-04	4.3E-04
		8	6.7E-04	2.3E-04		
06033	Lake	8	6.7E-04	2.3E-04	6.7E-04	2.3E-04
06045	Mendocino	8	6.7E-04	2.3E-04	6.7E-04	2.3E-04
06055	Napa	8	6.7E-04	2.3E-04	5.6E-04	2.8E-04
		12a	4.5E-04	3.4E-04		
06097	Sonoma	8	6.7E-04	2.3E-04	5.6E-04	2.8E-04
		12a	4.5E-04	3.4E-04		
06041	Marin	12a	4.5E-04	3.4E-04	4.5E-04	3.4E-04
06013	Contra Costa	8	6.7E-04	2.3E-04	5.3E-04	4.3E-04
		14	3.9E-04	6.4E-04		
06009	Calaveras	12a	4.5E-04	3.4E-04	4.5E-04	3.4E-04
06109	Tuolumne	12a	4.5E-04	3.4E-04	4.5E-04	3.4E-04
06043	Mariposa	12a	4.5E-04	3.4E-04	4.5E-04	3.4E-04
06077	San Joaquin	12a	4.5E-04	3.4E-04	4.2E-04	4.9E-04
		14	3.9E-04	6.4E-04		
06099	Stanislaus	12a	4.5E-04	3.4E-04	4.2E-04	4.9E-04

		14	3.9E-04	6.4E-04	9.6E-04	1.1E-03
06047	Merced	12a	4.5E-04	3.4E-04		
		15	1.5E-03	1.9E-03		
06107	Tulare	12a	4.5E-04	3.4E-04	4.5E-04	3.4E-04
06029	Kern	15	1.5E-03	1.9E-03	1.5E-03	1.9E-03
06031	Kings	16	7.7E-04	9.9E-04	7.7E-04	9.9E-04
06025	Imperial	18	3.0E-04	1.0E-04	3.0E-04	1.0E-04
06073	San Diego	9	1.1E-03	8.6E-04	1.5E-03	7.3E-04
		3	1.8E-03	6.1E-04		
06065	Riverside	18	3.0E-04	1.0E-04	7.2E-04	4.8E-04
		9	1.1E-03	8.6E-04		
06059	Orange	9	1.1E-03	8.6E-04	1.5E-03	7.3E-04
		3	1.8E-03	6.1E-04		
06037	Los Angeles	9	1.1E-03	8.6E-04	1.5E-03	7.3E-04
		3	1.8E-03	6.1E-04		
06111	Ventura	10	1.4E-03	1.1E-03	1.5E-03	8.5E-04
		3	1.8E-03	6.1E-04		
		9	1.1E-03	8.6E-04		
06083	Santa Barbara	10	1.4E-03	1.1E-03	1.6E-03	6.6E-04
		6	1.7E-03	2.7E-04		
		3	1.8E-03	6.1E-04		
06079	San Luis Obispo	6	1.7E-03	2.7E-04	1.6E-03	6.6E-04
		10	1.4E-03	1.1E-03		
		3	1.8E-03	6.1E-04		
06053	Monterey	6	1.7E-03	2.7E-04	1.6E-03	6.6E-04
		10	1.4E-03	1.1E-03		
		3	1.8E-03	6.1E-04		
06069	San Benito	10	1.4E-03	1.1E-03	1.4E-03	1.1E-03
06019	Fresno	12b	5.2E-04	3.9E-04	9.2E-04	1.1E-03
		16	7.7E-04	9.9E-04		
		15	1.5E-03	1.9E-03		
06039	Madera	12b	5.2E-04	3.9E-04	1.0E-03	1.2E-03
		15	1.5E-03	1.9E-03		
06001	Alameda	6	1.7E-03	2.7E-04	1.1E-03	4.4E-04
		8	6.7E-04	2.3E-04		
		14	3.9E-04	6.4E-04		
		3	1.8E-03	6.1E-04		
06089	Shasta	14	3.9E-04	6.4E-04	3.9E-04	6.4E-04
06041	Marin	12a	4.5E-04	3.4E-04	4.5E-04	3.4E-04
06081	San Mateo	3	1.8E-03	6.1E-04	1.8E-03	6.1E-04
06087	Santa Cruz	3	1.8E-03	6.1E-04	1.8E-03	6.1E-04
06085	Santa Clara	8	6.7E-04	2.3E-04	5.3E-04	4.3E-04
		14	3.9E-04	6.4E-04		

Table S18: California Irrigation Water Supply Energy Requirements (Based on data from (*68*))

GHG	NG	DFO	Gasoline	LPG
CO2e (g/MJ)	5.7E+01	7.0E+01	6.1E+01	6.9E+01
CO2 (g/MJ)	4.9E+01	7.0E+01	5.9E+01	6.8E+01

CH_4 (g/MJ)	3.5E-01	3.7E-03	2.9E-02	1.0E-03
N_2O (g/MJ)	1.4E-03	1.9E-03	1.9E-03	4.6E-03

Table S19: Primary Fuel Combustion Emission Factors for Agricultural and Oil Extraction Water Pumping (Source: (*21*))

County Name	Fraction from CRA	CRA Energy Intensity (kWh/AF Water)	Fraction from SWP	SWP Energy Intensity (kWh/AF Water)	MJ Electricity/L Water	Source
Los Angeles	50%	2.0E+03	50%	2.6E+03	6.7E-03	(*69*)
Ventura	50%	2.0E+03	50%	2.6E+03	6.7E-03	(*69*)
Orange	50%	2.0E+03	50%	3.2E+03	7.6E-03	(*69*)
Riverside	50%	2.0E+03	50%	3.2E+03	7.6E-03	(*69*)
San Bernadino	50%	2.0E+03	50%	3.2E+03	7.6E-03	(*69*)
San Diego	50%	2.0E+03	50%	3.2E+03	7.6E-03	(*69*)

Table S20: Energy Intensity of California Public Water Imports

Fuel Pathway	**Water Source**	**GHG Footprint w/out Water Impacts**	**GHG Footprint of Water**	**% Change**
Crude Oil to Gasoline	Desalinated Seawater	383	1.7	0.45%
	Desalinated Brackish Groundwater	383	1.1	0.28%
	Recycled Wastewater	383	0.3	0.07%
	Imported Surface Water (CA)	383	0.7	0.19%
Oil Sands to Gasoline	Desalinated Seawater	390	1.9	0.49%
	Desalinated Brackish Groundwater	390	1.2	0.31%
	Recycled Wastewater	390	0.3	0.08%
	Imported Surface Water (CA)	390	0.8	0.19%
Corn Grain to Ethanol	Desalinated Seawater	379	6.7	1.78%
	Desalinated Brackish Groundwater	379	4.5	1.17%
	Recycled Wastewater	379	1.6	0.42%
	Imported Surface Water (CA)	379	3.0	0.79%
Corn Stover to Ethanol	Desalinated Seawater	-46	11	23.02%

	Desalinated Brackish Groundwater	-46	6.5	14.34%
	Recycled Wastewater	-46	1.6	3.52%
	Imported Surface Water (CA)	-46	4.0	8.78%
Miscanthus to Ethanol	Desalinated Seawater	-19	8.6	46.61%
	Desalinated Brackish Groundwater	-19	5.4	29.03%
	Recycled Wastewater	-19	1.3	7.12%
	Imported Surface Water (CA)	-19	3.3	17.59%
Natural Gas-Fired Electricity w/ Cooling Tower	Desalinated Seawater	143	2.0	1.43%
	Desalinated Brackish Groundwater	143	1.3	0.90%
	Recycled Wastewater	143	0.3	0.22%
	Imported Surface Water (CA)	143	0.9	0.63%
Coal-Fired Electricity w/ Cooling Tower	Desalinated Seawater	228	2.3	1.03%
	Desalinated Brackish Groundwater	228	1.5	0.64%
	Recycled Wastewater	228	0.4	0.16%
	Imported Surface Water (CA)	228	0.9	0.40%

Table S21: Results of Water GHG Footprint Analysis

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