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Consistent Terminology and Reporting are Needed to Describe Water Quantity Use

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Abstract

The value of water use quantification assessments is hindered by the use of inconsistent terminology and reporting standards. Challenges associated with data collection and maintenance are made unnecessarily worse by the community's lack of agreement on definitions and reporting standards. Three major problems stand out: terminology conflicts, imprecise units, and data integrity. This paper illustrates the impact of these problems using recent work on water use in the US energy system as a case study. Relatively minor changes to the definition of "water consumption" can change reported water consumption by -50% to +270%, with no change to underlying data. Quantitative impacts of imprecise units and data integrity are more difficult to estimate, but this paper demonstrates that minor changes to reporting standards in these realms can substantially improve certainty. This article identifies major terminology conflicts and recommends a mass flow-based approach to definitions, with the goal of clearly separating conversations about water quantity versus quality. Regardless of chosen approach, standardizing terminology and reporting within the research community can improve data quality at no to low cost.

Introduction

Evaluations and comparative assessments of the water sustainability of various processes, products, and systems are increasingly common (Boulay et al., 2018; Grubert & Sanders, 2018; Leão et al., 2018; Marston et al., 2018; Mekonnen et al., 2015; Pfister et al., 2009, 2015; Wang et al., 2019). Research that catalogs and analyzes water flows for human uses is found under headings like water nexus studies, integrated water resources management, life cycle and other environmental assessment methods, water footprinting (including of virtual water), coupled human-water systems, sociohydrology and hydrosociology, and others (Cai et al. 2018; Chini et al. 2018; Hoekstra et al. 2011; Loucks 2015; Marston et al. 2015; Pfister et al. 2009; Quinteiro et al. 2018; Scanlon et al. 2017; Sivakumar 2012; Sivapalan et al. 2012).

In part due to this diversity and related differences in analysis goals, substantial debate continues about the most appropriate way to evaluate water sustainability (Hoekstra 2016; Pfister et al. 2017). For example, users might be more interested in volumetric water consumption if the goal is to compare the water efficiency of two companies, but an impact assessment might be more appropriate when the goal is to evaluate the effect of water use on ecosystems. Similarly, different analyses might include or exclude a variety of water quality metrics. Given the range of analyses that water sustainability assessments support, ensuring that data are useful and compatible across analyses is important for maximizing the value of scarce data about water use (Abdallah and Rosenberg 2019; Stagge et al. 2019). Actually implementing guidelines remains very challenging (Gil et al. 2016).

Detailed data on volumetric water usage in any form are unusual. In the United States (US), for example, few water users are required to report their volumetric water usage (Chini & Stillwell, 2017; Grubert & Sanders, 2018), and many users do not know or record these figures even internally. One major source of data on water use in the US is a database compiled by the US Geological Survey (USGS) every five years (Dieter et al. 2018; Maupin et al. 2014). This database has relatively low temporal and process resolution, however, with a five year release cycle and a focus on eight sectors of the US economy. Many of the data are derived from estimates rather than measurements. Further, this database currently focuses on water withdrawals, rather than consumption and discharge volumes. Complete estimates of national water consumption have not been published since a 1998 report detailing 1995 water use (Solley et al. 1998; USGS 2018). Although some consumption data were included in the USGS’s 2015 report (Dieter et al. 2018), namely for thermoelectric power plants and irrigation, the lack of consistently available and comprehensive consumption data constrains the database's value for assessing human impacts on water availability and stress. The USGS database is not the only resource challenged by these constraints: life cycle assessment (LCA) databases like ecoinvent (ecoinvent 2017) and the United States Life Cycle Inventory (National Renewable Energy Laboratory 2012) lack complete water data, and US Department of Agriculture (USDA) water use reports address agriculture only. In general, water use reports are not based on direct measurements.

Given challenges with data availability, the quantity-oriented water resources research community has incentives to rigorously characterize available data and associated uncertainty to maximize the value of what is known. To do so, it is critical to use consistent and robust standards for reporting data so that results are not misinterpreted. Currently, this consistency and robustness is not present in the literature, which presents challenges for comparing studies, using published data, and other tasks that facilitate water resources research. Despite diverse goals, some concerns about water sustainability metrics are common to most, if not all, assessments. For example, questions about how to treat interbasin transfers (Chini et al. 2018; Duan et al. 2019), human-induced changes to evapotranspiration (Grubert, 2016; Quinteiro et al., 2018), nonfreshwater use (Grubert & Sanders, 2018), rainwater use (Fereres et al. 2017; Hoekstra and Mekonnen 2012), or water quality changes (Hoekstra and Mekonnen 2012; Pradinaud et al. 2018) in volumetric accounting are definitional. Similarly, standards about reporting specificity and clarity on data age and applicability are relevant for both inventorying and impact assessment applications. Many of these problems can be substantially addressed within the research community, without major investments in data collection or other costly activities.

This work draws on two of the authors' recent experience of creating a database of water withdrawals and consumption for US energy systems (Grubert & Sanders, 2018), a task that involved new data collection, interpretation of published data, estimation, and publication of absolute volumes and specific intensity metrics for 126 unit processes, stratified not just by withdrawal and consumption, but also by water source and water quality. Using the lessons from that effort for analysis, this paper frames three challenges and proposed solutions for the water resources research community, focusing on issues that are solvable without the need for new data collection:

1) Terminology conflicts: Definitions for basic water quantity use terms like "water consumption," "water withdrawal," and even "water" itself are inconsistent. Assumptions made in different studies often rely on implicit definitions. Even when definitions are explicit, they can be interpreted unevenly.
2) Imprecise units: Notation can be difficult to interpret across studies when it is not described precisely. One common issue arises when intensities are reported (e.g., X m^3 of water consumed per Y units of output): ambiguity about the physical meaning of the units used can exacerbate the risk of misinterpretation.
3) Data integrity: Data are frequently re-cited, and uncertainty is introduced when data age, origin, underlying assumptions, and transformations (e.g., through conversion factors) are not reported. Re-citations can persist for long periods of time without validation, which can amplify decision-relevant errors, inappropriate data use, and mischaracterizations.

The remainder of this paper first describes the analytical approach of using prior work to characterize these three challenges, then addresses each challenge in turn, drawing on examples to illustrate their impact on water quantity assessment. The paper concludes by describing why these issues matter and proposing solutions, with the intent of contributing to a serious conversation about definitions and reporting standards (e.g., Horsburgh et al. 2014).

Analytical Approach

Recommendations are rooted in and tested by the authors' firsthand experience working through data issues in the context of quantifying volumetric water use for energy (Grubert & Sanders, 2018). This article presents reanalyses of that reference work with different definitions and reporting standards to illustrate the impact of different choices that could have been made and to support this paper's recommendations, noting that definitional ambiguities make quantitative analysis challenging. Most analysis is carried out by adding to or substituting values within the Supplementary Data File S1 published in Grubert and Sanders (2018). The present article is accompanied by a Supplementary Data File that enables readers to view and replicate these steps by linking to the reference study's Data File S1. To do so, download this study's Supplementary Data File and select "Don't Update" in Excel when prompted to update values. The cover sheet includes instructions on how to link the file to the reference data file, including links to both paywalled and free versions that will enable readers to proceed.

A major advantage of using this energy-focused work to evaluate the implications of using different approaches to quantifying water volumes is that the recommendations have been tested in a context of enormous diversity in water-using processes, irregular and complex units used to describe outputs, high variability of water sources and discharge points, and strong interest in differentiating withdrawals from consumption. The energy sector includes processes from agriculture, industry, mining, and thermoelectric power, drawing on both public and self-supplied resources, demanding water ranging from extremely pure to extremely saline, and engaging questions about water "production" in the chemical (e.g., through combustion), geological (e.g., during resource extraction), and legal senses (e.g., through state declarations that pumped and discharged water is a net contribution to water resources). Questions about seasonality, environmental flows, precipitation and soil moisture inputs, and instream versus offstream uses are relevant for resources like hydroelectricity and biomass production. Similarly, issues of contamination (thermal, chemical, and otherwise) and purification (e.g., through incidental or intentional evaporative distillation) and their relevance for measuring water "use" are frequently encountered in energy.

Terminology conflicts in water use reporting

Terminology conflicts are perhaps the most significant challenges to address as the community moves toward more rigorous practice in water use reporting. Based on the authors' own work and on the literature, two major issues drive terminology conflicts. First, authors sometimes do not realize that their definition is ambiguous. Unintentional ambiguity frequently arises when authors use the word "use" to describe a specific water quantity, not realizing that "consumption," "withdrawal," and other terms are more precise, or when authors use terms like "consumption" and "withdrawal" without recognizing that readers might expect a given flow to be included or excluded. For example, particularly within specific communities with consistent norms, authors might not clarify that their use of "consumption" refers only to freshwater. The second major issue leading to terminology conflict is that different authors have different goals for data use, which influences interpretation of definitions and occasionally leads to explicit choices to change a definition. For example, an author only concerned with competition for freshwater resources might intentionally exclude nonfreshwater resources from consideration.

More rigidly, legislative mandates sometimes drive explicitly different definitions for USGS and Bureau of Reclamation use of specific terms (Bruce et al. 2018). Regardless of goal or intent, though, words often assumed to have universal definitions (e.g., “water,” “consumption,” “withdrawal,” “discharge”) can refer to a wide range of physical outcomes that can be difficult to distinguish without very explicit guidance as to the interpretation of these terms.

This section discusses the need for precision in reporting water use by focusing in turn on the terms “water” and “use,” then making recommendations for definitions grounded in the ISO 14046 standard (ISO 2014). The water resource research community would benefit from more specificity in stating water’s quality and origin and from using a mass flow-based approach to definitions for use metrics. Here, a mass flow-based approach refers to a set of definitions focused primarily on where water physically starts and ends rather than on questions of future accessibility, user availability, and other context-specific questions.

Defining “Water” Perhaps the most fundamental term associated with water resources assessment is “water” itself. Although the word might seem clear, there are several nuances to the definition of “water” that can substantially change the results of water quantity estimates. This work addresses two specific categorical modifiers, acknowledging that others might also be relevant in some contexts: 1) water quality and 2) water’s position in the hydrologic cycle. Typically, reference to “fresh” versus “nonfresh” water resources refers to distinctions drawn based on salinity, often measured as total dissolved solids (TDS). Water quality might also be distinguished based on non-salt contamination levels or temperature (particularly when the water under consideration is steam), but these characterizations are unusual in the water quantity assessment literature. Understanding the distinction between freshwater and nonfreshwater use can be relevant in contexts where a water user is not competing for high quality resources or where an atypical water source is used, as with brackish groundwater for irrigation, industrial use of saline water for drilling, district cooling and heating or power plant use of ocean water, or brackish groundwater as a desalination target (Aminfard et al., 2019; Grubert & Webber, 2015; Peer & Sanders, 2018; Scanlon et al., 2014; Zhen et al., 2007).

Historically, management- and decision maker-oriented water resource use assessments have focused on freshwater due to a perception that freshwater use is more relevant for management (Averyt et al. 2013), but nontraditional water resources are increasingly management-relevant as potential users explore opportunities to secure scarce resources (Dolan et al., 2018; Grubert & Sanders, 2018). The relevance of nonfreshwater to water use estimates varies widely by sector. For example, use of saline waters for agriculture is limited given plant and soil sensitivities, but ocean water is a relatively common cooling source for power plants (Grubert & Sanders, 2018). Overall, if the authors had only considered freshwater in our recent assessment of water-for-energy, the estimate of the energy sector's water use would be lower by 19% (consumption) or 18% (withdrawal) (Grubert & Sanders, 2018, and see sheet "Figs 1, 2 support data" in the Supplementary Data File). Similarly, the USGS nationwide estimate of water withdrawals would be lower by 13% if only freshwater were considered (Dieter et al. 2018).

In addition to quality, "water" is also commonly distinguished based on its position in the hydrologic cycle, namely its status as precipitation, soil moisture, surface water, groundwater, or increasingly, water held in anthropogenic storage for reuse. Although distinguishing among surface water, groundwater, and reused water is relevant for management decisions, particularly because of implications for resource sustainability, procurement costs, and treatment requirements, the quantitatively most impactful definition in this arena is whether "water" refers to "blue," "green," or all water, where "blue" water is fresh surface and groundwater and "green" water is precipitation that does not become runoff (Hoekstra et al. 2011). Green water is most relevant for agriculture, given that agricultural production often takes advantage of the availability of rainfall and soil moisture (Marston et al. 2018). Many water resource use assessments, including the authors' own energy-focused work (Grubert & Sanders, 2018), exclude green water consumption in part because green water resources have lower opportunity costs for procurement and application (Chapagain et al. 2006) and are thus not directly comparable to blue water from an impact, application efficiency, or replacement requirement perspective. Some life cycle assessment scholarship argues that green water has limited water-related environmental relevance and might be more appropriately considered as a land use metric than a water use metric (Núñez et al. 2013), but this decision introduces some inconsistencies in defining "water" that require clear definitional statements.

The choice to include green water in water resource use assessments is highly impactful for agricultural and agroforestry contexts, with limited impact otherwise. For example, Marston et al. find that 83% of all economically productive US water consumption is green water associated with agriculture (2018). The authors' recent overall estimate of water consumption for the US energy system would have roughly quadrupled had it included green water for energy crops, energy-oriented agroforestry, and surface coal mine reclamation (Figure 1, and see sheet "Figs 1, 2 support data" in the Supplementary Data File) (Grubert and Sanders 2018; Marston et al. 2018). Green water consumption not related to plant growth is effectively zero, and green water withdrawal is not a concept used in the literature.

A further note on the definition of “water” from a volumetric perspective is that water footprinting also includes a pollution metric that is expressed volumetrically: a concept called “grey” water that describes the volume of water required to assimilate a given pollutant load (Hoekstra et al. 2011). As such, grey water is an impact metric tracking pollutant flows into water rather than a consumption metric tracking mass flows of water itself. For context, however, grey water footprints can be substantial. Figure 1 illustratively shows the contribution of the thermal grey water footprint associated with power plant cooling discharges on the estimate of the US energy system’s water consumption (Grubert & Sanders, 2018), assuming a 10°C average temperature increase (Madden et al. 2013) and a 3°C assimilative capacity (Hoekstra et al. 2011). A full analysis of the energy system’s grey water footprint would likely result in a higher value due to nonthermal contamination, thermal contamination from sources other than power plants, and other pollution.

Defining “Use” Referring to water “use” is ambiguous. When water quantities are being reported, the word “use” should almost always be replaced by reference to water consumption, water withdrawals, or something else more specific in order to communicate what is actually occurring. One challenge, particularly across sectors, is that even “consumption” and “withdrawal” are often ambiguous despite being conceptually well understood. One driver of this ambiguity is that with few exceptions, water is not destroyed when it is “consumed,” so the common interpretation of consumption as “using water and not returning it” versus withdrawal as “using water and possibly returning it” is challenged by imprecision about what it means to return water. This lack of clarity is relevant beyond the environmental assessment and scientific communities. In US legal settings, water rights can be based on historic consumptive use that might be defined differently based on location (Taussig 2014), and transfers between and among surface water basins and aquifers can be crucial to determining legal rights (Culp et al. 2014). Given the real management implications of understanding water flows, this work advocates for definitions of water use that are ultimately based on information about mass flows at the highest level of detail authors can provide, with the goal of enabling adaptation of published data for a variety of purposes. This section describes various definitions commonly in use and illustrates the related ambiguities.

Defining "Consumption" Water consumption is a common water use metric that is often perceived as having a straightforward, clear technical definition related to types of water use that essentially prevent alternative use of some quantity of water (Harte and El-Gasseir 1978). In practice, "consumption" is not an unambiguous metric. Water is rarely actually destroyed: the nature of the hydrologic cycle is such that, except in some types of chemical conversion, "consuming" water usually means moving it from one source to another and/or changing its phase. Fundamentally, this means that the "consumed" water will almost always eventually be available for another use, though perhaps not in the same area in the same time frame. In the immediate aftermath of "consumption," however, the vast majority of consumed water does still exist as water. A question thus arises: which changes count as "consumption"? A related question arises when a human use leads to the introduction of water to a system where it did not previously exist, such as water formation via hydrocarbon combustion. What activities, if any, can be considered negative water consumption (or water "production"), and if water production occurs, how should it be inventoried?

To frame a discussion of which processes can be considered consumptive, Figure 1 shows the fate of water considered "consumed" by Grubert and Sanders (2018). These fates are categorized as evaporation, evapotranspiration, transfer, deep sequestration, and unknown, where "unknown" is generally assumed to be evaporation or transfer. For example, the fate of water used to wash solar panels is not certain, but the water very likely either evaporates or percolates into the ground. It is uncontroversial to classify evaporation and evapotranspiration of water as consumptive, likely because the mass of water that is evaporated or evapotranspired becomes precipitation that cannot be clearly and directly associated with a water source. Similarly, deep sequestration is a relatively uncontroversial consumptive category, as it involves the injection of water into deep aquifers that are not expected to be accessible in the future (e.g., Mauter & Palmer, 2014). Transfers among accessible water sources are more ambiguous, with uneven interpretation in the literature. These activities represent the movement of water outside its immediate environment, rendering it unavailable for future use in that immediate environment, but the water remains liquid and might be readily available for users in other basins.

Based on proximate water source, there are four basic types of transfers: surface water to groundwater, groundwater to surface water, groundwater to groundwater, and surface water to surface water. Here, a mass flow of water is considered to be a transfer only if it is moving as a liquid from one basin to another, non-hydrologically connected basin. That is, water abstracted from an aquifer and returned to the same aquifer is not a transfer, but water abstracted from an aquifer and discharged into a different aquifer is. Some examples of transfers include river water percolation into a nonconnected groundwater aquifer during agricultural irrigation (surface to ground), groundwater used for municipal supply and then treated as wastewater and discharged to a river (ground to surface), groundwater from a different aquifer used for enhanced oil recovery (ground to ground), and water removed from one river system being discharged across a divide (surface to surface). Such transfers can also include quality changes, as when river water is discharged to the ocean.

Whether these transfers are considered consumptive or not is often ambiguous. For example, Flörke et al. write that water not being consumed means that it is “discharged back into freshwater bodies” (2013), but they also define consumption as water that is “...removed from an immediate water environment (water body, surface- or ground-water source, basin)” by citation of Shaffer & Runkle (2007). From these statements, it is not clear whether water removed from an immediate water environment and discharged into a different freshwater environment would be considered to be consumed, or whether such mass flows were carefully tracked. One contributor to ambiguity is that different reputable sources define consumption differently. For example, the USGS definition before about April 2013 was:

> “consumptive use---that part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment. Also referred to as water consumed” (Archived copy of https://water.usgs.gov/watuse/wuglossary.html).

This definition implies that discharges or transfers are indeed consumptive uses, in the sense that they represent removal from the immediate water environment. It is also consistent with other common definitions of consumption, including that used by the International Organization for Standardization’s ISO 14046:

> “The term “water consumption” is often used to describe water removed from, but not returned to, the same drainage basin. Water consumption can be because of evaporation, transpiration, integration into a product, or release into a different drainage basin or the sea. Change in evaporation caused by land-use change is considered water consumption (e.g. reservoir)” (ISO 2014).

ISO 14046 further clarifies that a drainage basin can be a surface water basin or a groundwater basin and that they might not coincide spatially (ISO 2014), implying that a discharge of groundwater to a surface water basin or of surface water to a groundwater basin is consumptive.

The Water Footprint Network (WFN)'s definition of consumption is similar, with the added implication that flow between connected surface and groundwater bodies is nonconsumptive:

> "'Consumption' refers to loss of water from the available ground-surface water body in a catchment area. Losses occur when water evaporates, returns to another catchment area or the sea or is incorporated into a product." (Hoekstra et al. 2011).

Despite relatively consistent guidance across communities that transfers are consumptive, however, Wayback Machine records show that the USGS definition of water consumption was changed between 1 April and 15 May 2013 to read:

> "consumptive use–the part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise not available for immediate use. Water returned to a different watershed than the point of withdrawal (interbasin transfer) is ***not*** considered a consumptive use." (USGS, 2018, bolding original).

It is unclear whether that change clarified existing practice or changed existing practice, though the need to clarify indicates that different individuals and teams likely interpreted the previous definition inconsistently. This current USGS definition of interbasin transfer also implies that such transfers only apply to river basins, which creates additional ambiguity about surface-to-ground or ground-to-surface transfers.

How relevant are transfers to overall estimates of water consumption? As Figure 1 shows, about 17% of total and 18% of fresh energy-related water consumption estimated by Grubert & Sanders (2018) is due to transfers. Figure 2 illustrates the nature of these transfers (see sheet "Figs 1, 2 support data" in the Supplementary Data File for details). The largest transfers in the energy system are related to dewatering coal mines (removing water from the coal-bearing aquifer and discharging it to rivers, a practice that is sometimes legally considered to be a production of water, Smith, 2016); seepage from hydroelectric reservoirs into the ground; and conveyance losses from irrigation for energy-related agriculture.

This work recommends that any out-of-basin transfer, where basins can be surface water, groundwater, or a hydrologically connected surface-groundwater system, should be treated as a consumptive use to minimize ambiguity. This recommendation is grounded in the ISO 14046 standard (ISO 2014). Particularly when accompanied by careful distinction between (and reporting of) both "discharge" (any water released from an anthropogenic use in liquid form) and "return flow" (water returned to its proximate origin in liquid form), treating out-of-basin transfers as consumptive more readily supports location-based water scarcity and ecosystem stress assessments. Although water productivity benchmarking exercises might choose to exclude all discharges from the benchmark, reporting discharge and return flow allows for such a choice and encourages a more precise definition of intensity for such exercises. In general, reporting both water origin and water fate, when known, can reduce accounting conflicts (Quinteiro et al. 2018).

Another area of ambiguity in definitions of "consumption" concerns the possibility of negative water consumption, or water production. Water is rarely actually produced, despite naming conventions for nondiscretionary water byproducts from resource extraction that refer to water removed from, e.g., an oil well as "produced water." The major mechanism for true production of water is combustion of hydrocarbons, where hydrogen and oxygen combine to form water. Water production from combustion can be large: the volume of water (measured as a liquid) produced via combustion is equal to about 17% of total US energy system water consumption (Grubert & Sanders, 2018). As Figure 2 shows, crediting the energy sector with this water production would thus reduce the overall water consumption of the energy sector by 17% (total) or 36% (fresh), if combustion water (released as a vapor) is considered a freshwater input to the system. Although this water input certainly exists (see also Belmont et al., 2017), the authors recommend that it not be treated as negative consumption because of uncertainty about the water's ultimate fate. Combustion water effectively behaves like precipitation or evaporated water once released, so even though it is a net input to the global water system, it cannot be definitively characterized as a "return flow" to a specific water source and thus should not be treated as negative consumption unless it is somehow captured and deployed. Note that production of water via combustion is a nuance specific to hydrocarbon-combusting processes (including biomass combustion), limiting its overall impact on the water resources quantification community.

Another issue related to the concept of negative water consumption arises when anthropogenic land use change alters the amount of evapotranspiration from a given land area. For example, reservoirs replace native land cover with a water surface. In some cases, this change increases water consumption through evaporation, but it can also reduce water consumption. For example, if a high evapotranspiration land cover (e.g., a forest) is replaced by a reservoir, total water loss can actually decline. Considering net consumption (i.e., consumption after the anthropogenic land use intervention less pre-intervention evapotranspiration) is increasingly common in the hydroelectricity context (see, e.g., Grubert, 2016 for further discussion). This choice is consistent with the ISO 14046 definition of water consumption, which states explicitly that "Change in evaporation caused by land-use change is considered water consumption (e.g. reservoir)" (ISO 2014). This work recommends consistency with the ISO definition.

Defining "Withdrawal" Water withdrawal is commonly defined as the removal of water from an originating source, regardless of whether it is returned. In general, withdrawals are well understood and relatively consistently defined. This work draws attention to two nuances related to instream use of surface water, which occurs within the water channel, and one caution about multiple uses of withdrawn volumes. First, the common choice to exclude water flows through hydroelectricity generating facilities from withdrawal estimates is tenuous from a mass flow perspective. Although water used for hydropower generation nominally remains in the river, it is usually diverted into pipes and other anthropogenic structures so as to be directed through turbines. One rationale for excluding hydropower flows from withdrawal estimates is that they overwhelm other withdrawals: the volume of water diverted into pipes for hydroelectricity generation is estimated at about two orders of magnitude higher than withdrawal volumes for the rest of the energy system, combined (Grubert & Sanders, 2018). Note, though, that depending on the layout of the dam, water might be diverted as far or farther out of the natural channel as water diverted for thermoelectric power plant cooling. From a mass flow perspective, it is difficult to justify excluding hydropower water withdrawals from the definition on any basis other than it being simpler to exclude them.

A related instream use issue is whether legal restrictions on further diversion should ever be considered withdrawals. For example, if a specific volume of water is reserved for environmental use and cannot legally be diverted from the river, the water has been diverted from alternative uses. This work does not recommend defining such use as withdrawal because it has no mass flow implications, but alternative language and terminology to describe water volumes that are allocated to instream uses might be helpful for water managers.

A final point related to defining withdrawals is that when water is used more than once in a process, as when water is cycled for cooling or other industrial processes, the relationship between withdrawals from a water source versus withdrawals from an on-site vessel can be ambiguous (Mudd 2010). For example, if a unit of water is transferred from a river to a storage tank, then removed and returned to the storage tank six times during some process, the withdrawal volume should most appropriately be reported as one unit, but might be reported as six units. Clearly stating whether water is used multiple times in a given process, and clarifying whether reference to withdrawal is a withdrawal from a source (important for water resource management) or withdrawal from some vessel internal to the process (important for proxy variables, like energy use for water pumping) can alleviate this ambiguity.

Terminology Recommendations Ideally, to promote clear, intercompatible research, definitions should accommodate diverse research questions and data uses (Hoekstra, 2017) while also being usable when limited information is available (Pradinaud et al., 2018). Aside from actual volumes, reporting as much detail as possible on the source, location, and quality of water appears to be particularly useful for water sustainability assessments, as volumetric water use assessments are increasingly relevant to work addressing water use in the context of scarcity and quality degradation (Borsato et al., 2019; Boulay et al., 2018; Lee et al., 2019; Núñez et al., 2014; Ridoutt & Pfister, 2010). As Figures 1 and 2 show, seemingly minor changes in terminology definitions would have changed the authors' own estimate of total water consumption for the US energy system (Grubert & Sanders, 2018) by -50% (assuming freshwater only, assuming transfers are nonconsumptive, and assuming that combustion water is a consumptive offset) to +270% (including green water), or even to +4000% (including volumes needed to assimilate thermal pollution, as grey water).

Grounded in recognition that water quality and water source are decision-relevant water characteristics, and following ISO 14046 (ISO 2014), Table 1 lists proposed definitions for water quality, water source, and water use terminology. The authors also join ISO 14046 in recommending that water source and discharge destination are explicitly reported when known, at least at the level of surface or groundwater, to facilitate a variety of analyses that water use data can support. When such information is not available, this work recommends that source and discharge are explicitly reported as “unknown” or “unspecified” for clarity, as appropriate. In general, these definitions aim to reduce ambiguity by linking water use terms to physical characteristics and mass flow. Preserving water quantity metrics as mass flow-based and developing additional terminology and reporting standards to capture additional decision-relevant characteristics, like thermal, chemical, temporal, and other quality transformations, can promote more targeted management decisions.

Imprecise units

Even when terminology is unambiguously defined, the use of imprecise units can reduce the value of volumetric water data. As with terminology, one common problem is that authors believe their units to be less ambiguous than they are, which can be a difficult problem to solve. This section describes some common ambiguities to consider when reporting water use data and uses examples from the water-for-energy literature to illustrate the scope of these challenges.

Reporting Water Volumes Consistent with the recommendation that terminology about water use focus on water quantities specifically, while distinguishing among decision-relevant water categories (e.g., by quality, source, and fate), units chosen for water reporting should clearly reflect actual volumes. In many types of water resource analysis, the ultimate goal of using water volume data is to conduct an impact assessment that communicates the water volumes in context, for example relative to overall water availability or pollutant assimilation capacity (Boulay et al.

2018; Hoekstra et al. 2011; Pfister et al. 2015). As with similar issues related to carbon footprinting (Grubert & Brandt, 2019), however, the use of mass or volume units for outputs that have undergone some kind of weighting or impact characterization can be confusing (Hoekstra 2016). This work recommends being explicit about the meaning of units and reporting untransformed inventory data alongside any weighted outputs, both to reduce confusion and to increase the value of the underlying data for alternative (e.g., updated) transformations.

Reporting Water Intensities Many water quantity analyses publish water intensities rather than absolute volumes, which can be useful in enabling scenario analysis and similar work. A challenge arises when water use intensity factors are reported without sufficient information about the denominator. That is, when water use is normalized by another unit of measurement (e.g. per unit of electricity generation, per quantity of irrigated crop, per customer, etc.), the normalizing unit is often ambiguous. Typically, ambiguities arise when 1) the unit is not sufficiently contextualized relative to its supply chain and 2) relevant conversion factors are unstated. This section uses examples from the water-for-energy literature to explain.

Failure to fully contextualize a given unit within its value chain is a very common issue. Essentially, the problem is that the number of physical units (e.g., a gigajoule (GJ) or megawatt-hour (MWh) in energy, a bushel in agriculture, or a cubic meter of water itself) associated with some process varies based on what transformations and losses have been considered. For example, does a GJ refer to the amount of energy embodied in the entire supply chain, the heat content of energy entering a power plant, the heat content of energy exiting a power plant after conversion to electricity, the heat content of the electricity when it arrives at a home after losses from transmission and distribution, or something else? Figure 3 (details in sheet "Fig 3 & support data" in the Supplementary Data File) uses the example of US natural gas to show that referring to a GJ of natural gas-fired electricity could refer to a number between 100% and over 330% of the heat content of the energy a consumer actually purchases (Grubert & Brandt, 2019; Grubert & Sanders, 2018). Ambiguous use of energy units can easily introduce errors on the order of 10% to 300%, given typical line losses and conversion efficiencies (Grubert & Sanders, 2018). This issue is not specific to energy or water quantity reporting: ambiguous units pose challenges in many settings where the reported metric is an intensity value (Hall et al. 2014).

An example of these ambiguities is illustrated in a highly-cited review paper by Meldrum et al. (2013), referencing water consumption for natural gas processing:

> "After extraction, natural gas is processed to bring it to pipeline quality. Although three older references (DOE 1983, Tolba 1985, Gleick 1994) agree upon a relatively high water usage of 11 gal MWh^{-1} for this processing, we defer…" (Meldrum et al. 2013).

This statement refers, in part, to data published in Gleick (1994) stating that natural gas processing consumes 6 m^3/TJ(th). Here, although the designation "th" (thermal) clarifies that water consumption is being normalized by the energy content of natural gas as a primary energy source, it is unclear which losses have been accounted for in that quantity of natural gas.

A second categorical issue with reporting intensity values is that relevant assumptions about conversion factors are frequently not reported. This issue is more pronounced in settings where different groups use different units to describe a specific resource. For example, coal production quantities are commonly reported in mass units (e.g., tons or tonnes), while consumption quantities are commonly reported in energy units (e.g., mmbtu or GJ). Heterogeneity in energy density means that if the conversion factors are not reported, data users will not be able to accurately translate between communities. Similarly, when monetary units are used, data become less usable when authors do not provide data on base years (for inflation) or how much something is worth during the study period (for conversion to physical units).

Unit Reporting Recommendations Table 2 summarizes recommendations for units common in water use intensity assessments, with the goal of ensuring that reported data are not only unambiguous but easy to convert to other metrics. For example, reporting the price of a commodity alongside a water intensity per unit mass allows other users to convert to water intensity per unit of currency. Being able to perform these conversions makes data more useful for more kinds of research. This list is not exhaustive. Given that data sometimes do not allow for complete reporting, these recommendations can also be used to check for sources of uncertainty. In general, this work recommends that the date and location of original data collection be noted whenever possible.

Data integrity

The final major water use data challenge this work addresses is that given the limited amount of water volume data that do exist, data integrity challenges arise through processes of re-citation and transformation (e.g., unit conversions). Over time, the provenance and applicability of data can become unclear without obvious indicators that researchers should confirm their relevance. One particularly problematic outcome is that as data are re-cited over time, the age of the data is obscured, and re-publication dates give particular numerical values the appearance of being of more recent vintage. Publications frequently cite quantitative data used in other contemporary works as opposed to the original source of the data, in part because of practices that emphasize citing the most recent literature. Relatedly, unit conversions, rounding, and other data transformations in tandem with re-citation can lead to drift in the reported value and amplification of uncertainty that might go unnoticed.

As described in Grubert & Sanders (2018), one of the most illustrative examples of the data re-citation problem is the case of consumptive water intensity of natural gas processing. One 2016 source (Ali and Kumar 2016) references four slightly varying values from the literature, with the implication that independent estimates converge on a central value—a situation that implies high confidence in the value. In fact, the original source data for each estimate is a 1979 single significant figure estimate associated with unusual operating conditions at an unusual processing facility (White and Morgan 1979). Rather than being a recent, accurate value with wide applicability, as review of recent publications might suggest, the most common estimate for consumptive water intensity of natural gas processing in the literature is a single, inappropriately generalized value that has been converted beyond its original units with higher implied precision than is justified. Using estimates based on physical relationships and interviews with regulators and an operator, the authors found that a modern, generalizable estimate for the consumptive intensity of natural gas processing in the US is about 30% of the widely reported literature value (Grubert & Sanders, 2018). Although this example refers to a process with limited overall impact (about 4% of total natural gas-related water consumption with the updated value, or 12% with the prior literature value), the mechanisms that led to the widespread adoption of a narrowly applicable back-of-the-envelope estimate as a generalizable, precise data point are also relevant to most water volume data associated with processes that do not attract consistent re-evaluation.

As a broader illustration of the data integrity challenge, the authors reanalyze our 2014 work (Grubert & Sanders, 2018) using perhaps the best-known compilation of water-for-energy data, from Gleick's *Water and Energy* (1994). That resource, itself heavily based on a 1980

Department of Energy compilation (US DOE 1980), is a main source for many more recent compilations (Lampert et al. 2016; Mielke et al. 2010; US DOE 2006). Although the original resource was highly influential, it is concerning that the values have been assumed to be valid through time. As Mekonnen et al. write, "The data provided by Gleick are still cited, often through a string of citations, but one may doubt whether they are still valid, since practices of water use have changed over the past decades" (2015). Notably, these data are themselves substantially older than they appear, with many of the original data sources only available in print and thus challenging to trace. Figure 4 illustrates the data age to the best of the authors' knowledge, showing some transformative changes to the energy industry alongside the data age for context (see sheet "Fig 4 with refs" in the Supplementary Data File for data source references).

To specifically illustrate the issues with using older data based on availability, Figure 5 shows estimated water consumption by life cycle stage associated with the 2014 US energy economy based on the updated parameters published in Grubert & Sanders (2018), consumptive intensities published in Tables 4 and 5 of Gleick (1994), and consumptive intensities from Tables 4 and 5 in addition to an estimate of water consumption from reservoir seepage in the text of Gleick (1994). This reanalysis was performed by inserting available midpoint estimate consumptive water intensities from Gleick (1994) into the appropriate places in the Supplementary Data File of Grubert & Sanders (2018). That is, the reanalysis uses original values from Grubert & Sanders (2018) for every process not included in Gleick (1994), applies Gleick (1994) values only to processes relevant in 2014 (e.g., not including slurry pipelines for coal), and applies Gleick (1994) intensities only to the amount of energy involved in a given process as determined by Grubert & Sanders (2018). For example, water flooding water intensity is applied only to the amount of oil that experienced water flooding in 2014, not to all oil. See sheets “Introduction” and “Fig 5 & support data” in the Supplementary Data File for specific instructions to replicate this reanalysis.

As Figure 5 shows, using older data increases the overall estimate of water consumption for energy substantially, even though only about 25% of the water consumption intensity estimates in Grubert & Sanders (2018) were replaced by values from Gleick (1994). There are multiple drivers of the changes. The largest discrepancy is associated with the assumption that an average of 5% of hydropower reservoir volume is lost to seepage per year, which would increase the estimate of total energy-related water consumption by over 300%. Gleick excludes this estimate from data tables and notes that it is based on unpublished work and is qualitatively different from other consumption given exchange between shallow groundwater and reservoirs. This estimate is included in the top bar of Figure 5 to illustrate that seemingly insignificant estimates can be highly influential when they are not critically evaluated in the literature. (Note that the reference bottom bar of Figure 5 includes seepage as described in Grubert & Sanders (2018), based on observations at Lake Powell and assumptions about soil saturation for US reservoirs, described in detail on pages S108-S109 of the Supplementary Information of Grubert & Sanders (2018)). Other discrepancies likely reveal real trends, reflecting that technological change between the collection of data cited in Gleick (1994) and the estimation of 2014 water use by Grubert & Sanders (2018) has tended to bring increased water efficiency. For example, some of the largest discrepancies in consumptive water intensity are associated with oil refining and power plant cooling. Based on the original data collection dates for these processes (Figure 4), Grubert & Sanders (2018) reflects between 20 and 60 years of development and change.

Although some water resource consumption data remain accurate over time, many do not—both within and beyond the energy industry. Data based on physical relationships are more likely to remain relevant than data based on geology or some other highly variable parameter, but even data based on physical relationships will become outdated with technological changes. As the above exercise demonstrates, for example, evaporation from power plant and refinery cooling changes with new fuels, new turbine designs, and improved efficiency. In agriculture, using drip versus flood irrigation dramatically reduces water consumption. For municipalities, changing behaviors, densities, and home appliances change relationships between population and water consumption. As best practice, this work recommends that researchers carefully assess the original source of their data, consider its applicability to their work, and report as much information about the date and applicability of the value as possible.

Conclusions

Standardizing terminology and reporting standards related to water quantity assessment is critical to successful data sharing and use in an often data-limited context. This work recommends that the water quantity research community adopts practices like explicitly defining terms (suggested definitions in Table 1); precisely specifying units (i.e., with system boundaries; guidelines in Table 2); and citing original data sources to avoid observed challenges with terminology conflicts, imprecise units, and data integrity. Reanalyses of a recent study of US water for energy show that all three issues investigated here – terminology conflicts, imprecise units, and data integrity – can change top-line results by a factor of 3 or more (Figures 1-3, 5).

In general, providing as much information as available is best practice: noting water source, quality, location, and discharge point, and including relevant conversion factors for units, can dramatically improve interoperability with other analyses in the future. These practices do not require investment in new data collection, but history suggests that community-wide adoption will be challenging. As long as some requirements regarding usability and intuitiveness are met, having unambiguous standards is more important than the exact nature of the standards.

This work does not address numerous specific situations where the appropriate accounting approach is unclear, whether because the authors are not aware of them or because they represent sufficiently challenging situations that they merit additional debate within the water resource use community. For example: is there such a thing as a green water withdrawal that can exceed green water consumption? Is the water in the higher humidity air resulting from anthropogenic climate change a human-induced consumption of some combination of saline and fresh water? This work suggests that decisions about these types of issues consider relying on mass flows to guide choices, but in general, the water resources quantity community should focus on clear, explicit reporting to improve the value and usability of the limited data that are available.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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Supplemental Data

The Supplementary Data File, an Excel workbook with seven worksheets including Figures 1-5 and the data underlying the figures, is available online in the ASCE Library ([https://ascelibrary.org).]https://ascelibrary.org).

References

Abdallah, A. M., and Rosenberg, D. E. (2019). "A data model to manage data for water resources systems modeling." *Environmental Modelling & Software*, 115, 113–127.

Ali, B., and Kumar, A. (2016). "Development of life cycle water footprints for gas-fired power generation technologies." *Energy Conversion and Management*, 110, 386–396.

Aminfard, S., Davidson, F. T., and Webber, M. E. (2019). "Multi-layered spatial methodology for assessing the technical and economic viability of using renewable energy to power brackish groundwater desalination." *Desalination*, 450, 12–20.

Averyt, K., Macknick, J., Rogers, J., Madden, N., Fisher, J., Meldrum, J., and Newmark, R. (2013). "Water use for electricity in the United States: an analysis of reported and calculated water use information for 2008." *Environmental Research Letters*, 8(1), 015001.

Belmont, E. L., Davidson, F. T., Glazer, Y. R., Beagle, E. A., and Webber, M. E. (2017). "Accounting for water formation from hydrocarbon fuel combustion in life cycle analyses." *Environmental Research Letters*, 12(9), 094019.

Boulay, A.-M., Bare, J., Benini, L., Berger, M., Lathuillière, M. J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A. V., Ridoutt, B., Oki, T., Worbe, S., and Pfister, S. (2018). "The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE)." *The International Journal of Life Cycle Assessment*, 23(2), 368–378.

Bruce, B., Prairie, J., Maupin, M., Dodds, J., Eckhardt, D., Ivahnenko, T., Matuska, P., Evenson, E., and Harrison, A. (2018). *Comparison of U.S. Geological Survey and Bureau of Reclamation Water-Use Reporting in the Colorado River Basin*. Scientific Investigations Report.

Cai, X., Wallington, K., Shafiee-Jood, M., and Marston, L. (2018). "Understanding and managing the food-energy-water nexus – opportunities for water resources research." *Advances in Water Resources*, 111, 259–273.

Chapagain, A. K., Hoekstra, A. Y., and Savenije, H. H. G. (2006). "Water saving through international trade of agricultural products." *Hydrol. Earth Syst. Sci.*, 10(3), 455–468.

Chini, C. M., Djehdian, L. A., Lubega, W. N., and Stillwell, A. S. (2018). "Virtual water transfers of the US electric grid." *Nature Energy*, 3(12), 1115.

Chini, C. M., and Stillwell, A. S. (2017). "Where Are All the Data? The Case for a Comprehensive Water and Wastewater Utility Database." *Journal of Water Resources Planning and Management*, 143(3).

Culp, P. W., Glennon, R., and Libecap, G. (2014). *Shopping for Water: How the Market Can Mitigate Water Shortages in the American West*. Discussion Paper, Stanford Woods Institute for the Environment, 40.

Dieter, C. A., Maupin, M. A., Caldwell, R. R., Harris, M. A., Ivahnenko, T. I., Lovelace, J. K., Barber, N. L., and Linsey, K. S. (2018). *Estimated use of water in the United States in 2015*. Circular, USGS Numbered Series, U.S. Geological Survey, Reston, VA, 76.

Dolan, F. C., Cath, T. Y., and Hogue, T. S. (2018). “Assessing the feasibility of using produced water for irrigation in Colorado.” *Science of The Total Environment*, 640–641, 619–628.

Duan, K., Caldwell, P. V., Sun, G., McNulty, S. G., Zhang, Y., Shuster, E., Liu, B., and Bolstad, P. V. (2019). “Understanding the role of regional water connectivity in mitigating climate change impacts on surface water supply stress in the United States.” *Journal of Hydrology*, 570, 80–95.

ecoinvent. (2017). “ecoinvent version 3.4.” <http://www.ecoinvent.org/> (Jan. 18, 2018).

Fereres, E., Villalobos, F. J., Orgaz, F., Minguez, M. I., van Halsema, G., and Perry, C. J. (2017). “Commentary: On the water footprint as an indicator of water use in food production.” *Irrigation Science*, 35(2), 83–85.

Flörke, M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F., and Alcamo, J. (2013). “Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study.” *Global Environmental Change*, 23(1), 144–156.

Gil, Y., David, C. H., Demir, I., Essawy, B. T., Fulweiler, R. W., Goodall, J. L., Karlstrom, L., Lee, H., Mills, H. J., Oh, J.-H., Pierce, S. A., Pope, A., Tzeng, M. W., Villamizar, S. R., and Yu, X. (2016). “Toward the Geoscience Paper of the Future: Best practices for documenting and sharing research from data to software to provenance.” *Earth and Space Science*, 3(10), 388–415.

Gleick, P. H. (1994). “Water and Energy.” *Annual Review of Energy and the Environment*, 19(1), 267–299.

Grubert, E., and Brandt, A. R. (2019). “Three considerations for modeling natural gas system methane emissions in life cycle assessment.” *Journal of Cleaner Production*, 222, 760–767.

Grubert, E., and Sanders, K. T. (2018). “Water Use in the United States Energy System: A National Assessment and Unit Process Inventory of Water Consumption and Withdrawals.” *Environmental Science & Technology*.

Grubert, E., and Webber, M. E. (2015). “Energy for water and water for energy on Maui Island, Hawaii.” *Environmental Research Letters*, 10(6), 064009.

Grubert, E. (2016). “Water Consumption from Hydroelectricity in the United States.” *Advances in Water Resources*, 96, 88–94.

Hall, C. A. S., Lambert, J. G., and Balogh, S. B. (2014). “EROI of different fuels and the implications for society.” *Energy Policy*, 64, 141–152.

Harte, J., and El-Gasseir, M. (1978). “Energy and Water.” *Science*, 199(4329), 623–634.

Hoekstra, A. Y. (2016). “A critique on the water-scarcity weighted water footprint in LCA.” *Ecological Indicators*, 66, 564–573.

Hoekstra, A. Y., Chapagain, A., Aldaya, M. M., and Mekonnen, M. M. (Eds.). (2011). *The water footprint assessment manual: setting the global standard*. Earthscan, London ; Washington, DC.

Hoekstra, A. Y., and Mekonnen, M. M. (2012). “The water footprint of humanity.” *Proceedings of the National Academy of Sciences*, 109(9), 3232–3237.

Horsburgh, J. S., Tarboton, D. G., Hooper, R. P., and Zaslavsky, I. (2014). “Managing a community shared vocabulary for hydrologic observations.” *Environmental Modelling & Software*, 52, 62–73.

ISO. (2014). “ISO 14046:2014 - Environmental management -- Water footprint -- Principles, requirements and guidelines.” <https://www.iso.org/standard/43263.html> (May 11, 2017).

Lampert, D. J., Cai, H., and Elgowainy, A. (2016). "Wells to wheels: water consumption for transportation fuels in the United States." *Energy Environ. Sci.*, 9(3), 787–802.

Leão, S., Roux, P., Núñez, M., Loiseau, E., Junqua, G., Sferratore, A., Penru, Y., and Rosenbaum, R. K. (2018). "A worldwide-regionalised water supply mix (WSmix) for life cycle inventory of water use." *Journal of Cleaner Production*, 172, 302–313.

Loucks, D. P. (2015). "Debates—Perspectives on socio-hydrology: Simulating hydrologic-human interactions." *Water Resources Research*, 51(6), 4789–4794.

Madden, N., Lewis, A., and Davis, M. (2013). "Thermal effluent from the power sector: an analysis of once-through cooling system impacts on surface water temperature." *Environmental Research Letters*, 8(3), 035006.

Marston, L., Ao, Y., Konar, M., Mekonnen, M. M., and Hoekstra, A. Y. (2018). "High-Resolution Water Footprints of Production of the United States." *Water Resources Research*.

Marston, L., Konar, M., Cai, X., and Troy, T. J. (2015). "Virtual groundwater transfers from overexploited aquifers in the United States." *Proceedings of the National Academy of Sciences*, 112(28), 8561–8566.

Maupin, M., Kenny, J., Hutson, S., Lovelace, J., Barber, N., and Linsey, K. (2014). *Estimated Use of Water in the United States in 2010*. Circular, USGS.

Mauter, M., and Palmer, V. (2014). "Expert Elicitation of Trends in Marcellus Oil and Gas Wastewater Management." *Journal of Environmental Engineering*, 140(5), B4014004.

Mekonnen, M. M., Gerbens-Leenes, P. W., and Hoekstra, A. Y. (2015). "The consumptive water footprint of electricity and heat: a global assessment." *Environ. Sci.: Water Res. Technol.*, 1(3), 285–297.

Meldrum, J., Nettles-Anderson, S., Heath, G., and Macknick, J. (2013). "Life cycle water use for electricity generation: a review and harmonization of literature estimates." *Environmental Research Letters*, 8(1), 015031.

Mielke, E., Anadon, L. D., and Narayanamurti, V. (2010). *Water Consumption of Energy Resource Extraction, Processing, and Conversion*. Energy Technology Innovation Policy Discussion Paper Series, Discussion Paper, Harvard Kennedy School, Cambridge, Mass., 52.

Mudd, G. M. (2010). "The Environmental sustainability of mining in Australia: key mega-trends and looming constraints." *Resources Policy*, 35(2), 98–115.

National Renewable Energy Laboratory. (2012). "U.S. Life Cycle Inventory Database." <https://www.nrel.gov/lci/> (Dec. 13, 2018).

Núñez, M., Pfister, S., Roux, P., and Antón, A. (2013). "Estimating Water Consumption of Potential Natural Vegetation on Global Dry Lands: Building an LCA Framework for Green Water Flows." *Environmental Science & Technology*, 47(21), 12258–12265.

Peer, R. A. M., and Sanders, K. T. (2018). "The water consequences of a transitioning US power sector." *Applied Energy*, 210, 613–622.

Pfister, S., Boulay, A.-M., Berger, M., Hadjikakou, M., Motoshita, M., Hess, T., Ridoutt, B., Weinzettel, J., Scherer, L., Döll, P., Manzardo, A., Núñez, M., Verones, F., Humbert, S., Buxmann, K., Harding, K., Benini, L., Oki, T., Finkbeiner, M., and Henderson, A. (2017). "Understanding the LCA and ISO water footprint: A response to Hoekstra (2016) 'A critique on the water-scarcity weighted water footprint in LCA.'" *Ecological Indicators*, 72, 352–359.

Pfister, S., Koehler, A., and Hellweg, S. (2009). “Assessing the Environmental Impacts of Freshwater Consumption in LCA.” *Environmental Science & Technology*, 43(11), 4098–4104.

Pfister, S., Vionnet, S., Levova, T., and Humbert, S. (2015). “Ecoinvent 3: assessing water use in LCA and facilitating water footprinting.” *The International Journal of Life Cycle Assessment*, 1–12.

Pradinaud, C., Núñez, M., Roux, P., Junqua, G., and Rosenbaum, R. K. (2018). “The issue of considering water quality in life cycle assessment of water use.” *The International Journal of Life Cycle Assessment*, 1–14.

Quinteiro, P., Ridoutt, B. G., Arroja, L., and Dias, A. C. (2018). “Identification of methodological challenges remaining in the assessment of a water scarcity footprint: a review.” *The International Journal of Life Cycle Assessment*, 23(1), 164–180.

Scanlon, B. R., Reedy, R. C., and Nicot, J.-P. (2014). “Comparison of Water Use for Hydraulic Fracturing for Shale Oil and Gas Production versus Conventional Oil.” *Environmental Science & Technology*.

Scanlon, B. R., Ruddell, B. L., Reed, P. M., Hook, R. I., Zheng, C., Tidwell, V. C., and Siebert, S. (2017). “The food-energy-water nexus: Transforming science for society.” *Water Resources Research*, 53(5), 3550–3556.

Shaffer, K., and Runkle, D. L. (2007). *Consumptive Water, Use Coefficients for the Great Lakes Basin and Climatically Similar Areas*. US Geological Survey Reston, VA.

Sivakumar, B. (2012). “Socio-hydrology: not a new science, but a recycled and re-worded hydrosociology.” *Hydrological Processes*, 26(24), 3788–3790.

Sivapalan, M., Savenije, H. H. G., and Blöschl, G. (2012). “Socio-hydrology: A new science of people and water.” *Hydrological Processes*, 26(8), 1270–1276.

Smith, F. M. (2016). “Does coal mining in West Virginia produce or consume water? : a net water balance of seven coal mines in Logan County, West Virginia, an aquifer assessment, and the policies determining water quantities.” Thesis.

Solley, W. B., Pierce, R. R., and Perlman, H. A. (1998). *Estimated use of water in the United States in 1995*. Circular, USGS Numbered Series, U.S. Dept. of the Interior, U.S. Geological Survey ; Branch of Information Services [distributor],.

Stagge, J. H., Rosenberg, D. E., Abdallah, A. M., Akbar, H., Attallah, N. A., and James, R. (2019). “Assessing data availability and research reproducibility in hydrology and water resources.” *Scientific Data*, 6, 190030.

Taussig, D. C. (2014). “The Devolution of the No-Injury Standard in Charges of Water Rights.” *University of Denver Water Law Review*, 18, 116–153.

US DOE. (1980). *Technology Characterizations: Environmental Information Handbook*. US Department of Energy, Washington D.C.

US DOE. (2006). *Energy demands on water resources: Report to Congress on the interdependency of energy and water*. US Department of Energy, Washington, D.C.

USGS. (2018). “USGS Water Use Terminology.” <https://water.usgs.gov/watuse/wuglossary.html> (Jan. 12, 2018).

Wang, F., Wang, S., Li, Z., You, H., Aviso, K. B., Tan, R. R., and Jia, X. (2019). “Water footprint sustainability assessment for the chemical sector at the regional level.” *Resources, Conservation and Recycling*, 142, 69–77.

White, and Morgan. (1979). “Sour Gas Boosts CIG’s Supply.” *Oil and Gas Journal*, (June 25), 78.

Zhen, L., Lin, D. M., Shu, H. W., Jiang, S., and Zhu, Y. X. (2007). “District cooling and heating with seawater as heat source and sink in Dalian, China.” *Renewable Energy*, 32(15), 2603–2616.

Table 1. Proposed definitions for common water use terms

Term	Definition
Water quality	
Freshwater	Water with less than 1,000 milligrams per liter (mg/L) total dissolved solids (TDS).
Brackish water	Water with TDS between 1,000 and 3,000 mg/L.
Saline water	Water with TDS between 3,000 and 50,000 mg/L, including all seawater.
Not RO treatable water	Water with TDS exceeding about 50,000 mg/L, making it too salty for membrane-based desalination, notably reverse osmosis (RO). This water is distinguished from saline water due to the management implications of not being able to use membrane technologies to desalinate.
Water source	
Surface water	Water with its most recent origin in a natural water body above the earth’s surface, for example in a lake, river, or ocean.
Groundwater	Water with its most recent origin below the earth’s surface in an aquifer.
Blue water	Fresh surface water or groundwater.
Reuse	Water with its most recent origin at the end of an external anthropogenic process and held in anthropogenic storage rather than discharged to a natural source. Same-facility multiple use is not considered reuse. Reuse volumes are not themselves blue water.
Green water	Water consumed in the form of precipitation that does not become runoff or enter long-term groundwater storage.
Water flow	
Water consumption	Removal of water from its originating source (e.g., a stream or an aquifer) without directly returning it. Consumptive uses include evaporation, incorporation, and discharge to a nonoriginating body (including groundwater that is discharged at the surface or surface water that is discharged to groundwater).
Water withdrawal	Removal of water from its originating source (e.g., a stream or an aquifer) whether or not it is returned.
Water discharge	Return of water to the environment in liquid form, whether or not it is returned to the water’s most recent originating source.
Return flow	Return of water to its originating source. Equivalent to withdrawal less consumption.

Table 2. Recommendations for reporting on units commonly used in water intensity metrics

Unit	Recommendations
Agriculture	
tonne or other mass unit	Clarify: Which tonne or ton (e.g., metric, imperial/long, short)? Note that an imperial/long ton is not equivalent to an American short ton. Also report: conversion factors for price and area under cultivation to facilitate research on water intensity per unit of currency or land.
dollar or other currency	Also report: date of price, conversion factors for mass and area.
crop-specific terms	Define, and also report: conversion factors for price, mass, and area.
hectare or other area unit	Also report: yield, conversion factors for price and mass.
Energy	
kilowatt-hour, megawatt-hour, etc.	Clarify: Before or after losses, and which losses? For example: net or gross at power plant? After transmission and/or distribution losses? Recommend: Only use kilowatt-hour for quantifying electrical energy. Avoid use for primary energy units.
gigajoule and other heat units	Clarify: Before or after losses, and which losses? For example: net or gross at power plant? After transmission and/or distribution losses? For non-heat based energy resources, like hydroelectricity, wind, and solar photovoltaics, clearly state use of electricity heat-equivalents or other assumptions about primary energy input.
kilowatt, megawatt, etc.	Caution: This is a power unit and is rarely appropriate for water intensity studies. In rare cases where capacity is a valuable metric (e.g., for solar panels, where capacity is a proxy for area, and area drives water demand), include capacity factor and plant efficiency.
tonne or ton (e.g., of coal or biomass)	Clarify: Which tonne or ton (e.g., metric, imperial/long, short)? Note that an imperial/long ton is not equivalent to an American short ton. Also report: energy density of fuel; price of fuel; pre- or post-processing status.
cubic meter or cubic foot (e.g., of natural gas, biogas, or hydrogen)	Clarify: pressure and temperature. Also report: energy density of fuel; price of fuel; pre- or post-processing status. Note that pipeline-quality natural gas is tightly standardized, but wellhead gas and biogas are not.
liter or gallon (e.g., of gasoline or biofuels)	Clarify: Oxygenate content, particularly in areas with ethanol oxygenation. Also report: energy density of fuel; price of fuel; pre- or post-processing status.
barrel (e.g., of oil or steam)	Also report: energy density of fuel; price of fuel; pre- or post-processing status. Note that not all oil has the same energy density, and processing gain during refining means that a barrel in is less than a barrel out. Note that not all steam has the same temperature and pressure, which greatly affects its energy density and value.
facility units (e.g., “mine,” “well,” “panel”, “turbine,” “plant”)	Also report: capacity, capacity factor, efficiency. Where appropriate, report physical characteristics relevant for water use volumes like volume (mines, wells), well bore length (wells), surface area (water reservoirs), and full time equivalent employees (for any facility where domestic water is a significant portion of use).
dollar or other currency	Also report: date of price; physical quantity; energy density; pre- or post-processing status.
Municipal and Commercial	
customer	Clarify: definition of customer (e.g., individual, household, or customer meter)? Note that a single meter might serve an entire apartment building, for example. Also report: time step.
person	Clarify: person, household, or customer meter? Clarify: in service territory, city, or other jurisdictional boundary? Also report: time step.
household	Clarify: household or customer meter? Clarify: in service territory, city, or other jurisdictional boundary?

	Also report: time step; average number of people in household; relevant data like number and type of fixtures assumed per household.
dollar or other currency	Also report: date of price, conversion factors for relevant indicators like number of units, production location, etc.

Fig. 1. Bars show impact of different definitions of "water" on the estimated total water consumption associated with the US energy system, presented as a percentage of unaltered, published values in Grubert & Sanders (2018). Left blue and orange stacked bars indicate unaltered blue water and non-freshwater; Middle stacked green bars add green water; Right stacked grey bar adds power plant-thermal pollution-associated grey water.

Fig. 2. Waterfalls show the influence on estimated 2014 US energy sector water consumption of redefining consumptive use for select transfer types (blue, green, light blue, brown, and red labels) and activities (horizontal axis). Influence for A) total, and B) freshwater consumption.

Fig. 3. Bars show energy content of natural gas embodied in a unit of natural gas electricity by supply chain stage as a percentage of the energy content ultimately delivered to the consumer, using natural gas data and stage definitions according to Grubert & Brandt (2019) and Grubert & Sanders (2018).

Fig. 4. Timeline shows the age of data in a commonly cited resource (Gleick, 1994). Red = publication date; blue = estimate date (when available); green = assumed actual data age (when available). Icons and captions show major events in the energy industry with large effects on water quantity, contextualizing how significant changes have been since data were collected and published.

Fig. 5. Bars show estimated water consumption for US energy using different assumptions about consumptive water intensity for energy processes. 100% = Total consumption for US energy estimated by Grubert & Sanders (2018); base data described in Supplementary Data File, referencing (Gleick 1994; Grubert and Sanders 2018).