Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-53
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 13 March 2018

Hydrology and Earth System Sciences
Open Access
Discussions

When is water withdrawal data enough?

Benjamin L. Ruddell[1]

[1]School of Informatics Computing and Cyber Systems, Northern Arizona University, Flagstaff, AZ, USA

Correspondence to: Benjamin L. Ruddell (Benjamin.ruddell@nau.edu)

Abstract. Despite the centrality of the water balance equation to hydrologic and hydraulic science and engineering, in 2018 we lack empirical observations of consumptive use of water by humans and their economy. It is therefore worth considering what we can do with the withdrawal-based water use data we already possess, and what future measurements would be required to more accurately quantify consumptive use for the most common cases of human water use at census scales of space and time. Fortunately, a wide range applied water management and policy questions can be addressed using currently available withdrawal numbers. When a more advanced water use census is implemented, Simple Net Consumptive Use (SNCU) methods are insufficient for most common cases of human water use. Presented here are the common special cases that complicate consumptive use calculations. This discussion clarifies the problems we need to solve to measure humans' consumptive use of water at census scales, and argues that- while we are waiting for these data- the withdrawal data we already possess are adequate for some of our most important scientific and applied purposes.

1 Introduction

The "water balance", or the volumetric conservation equation for water, lies at the heart of methods employed in the science of hydrology and the applications of water resource engineering. Flows of water in this equation may be expressed in either gross or net quantities. The USGS National Water Census defines consumptive use as "The part of water withdrawn that is evaporated, transpired, (embedded) into products… consumed by humans or livestock, or otherwise removed from the immediate water environment." (Maupin et al., 2014). Hydrologists define consumptive use of water using a control volume approach such that consumption is the net of gross withdrawal and gross return flow. The two definitions coincide when the control volume is spatially and temporally small, yielding a concept we name Simple Net Consumptive Use of water (SNCU). Simple net consumptive use is a net flow term in the water conservation equation, and the term is associated with a process that is consuming the water.

Water balances are employed by economists, sociologists, and management practitioners of the Coupled Natural-Human system (CNH, Liu et al., 2007). Unfortunately those coupled natural human system scientists face a stark short-term and mid-term reality: the near-total lack of accurate empirical observations of consumptive water use by humans and their economy at census or mesoscales. Observations of water withdrawal provide a partial picture of the coupled natural human system water balance and are far more plentiful at meso and macro scales, although water withdrawal observations still lag far behind the data available for other parts of the coupled natural human system such as food, energy, or consumer data. Proposals for a Water Information Administration (WIA) or for an enhanced USGS water use census (Fishman, 2016, Michelsen et al., 2016) may become a reality in coming decades. Calls for a “water internet” built on the Internet of Things may eventually be realized (Patterson et al., 2017). In the meantime, we face the possibility that the longitudinal, systematic, detailed, national scale consumptive water use data we need will not become available nationwide or globally until at least the middle of the 21st century.

The last national censuses of consumptive water use in the US were in 1982 (Commerce, 1986) and in 1995 (Solley et al., 1998). The 1982 study covered manufacturing sector water withdrawal and discharge statistics for each state, region, and industry group but not the more important agricultural, energy, and urban sectors. The 1995 study covered consumptive use by all major sectors: Domestic/Commercial, Industrial/Mining, Thermoelectric, and Irrigation/Livestock, and attempted to evaluate five types of in-channel and out-of-channel flows: Withdrawal, Delivery/release, Conveyance loss, Consumptive use, and Return flow. However, the validity and precision of the consumptive use data available for the 1995 water census is questionable due to a lack of primary observations of return flows (Ward and Pulido-Velazquez, 2008, Qureshi et al., 2010, Gates et al., 2012), and those methods were dropped from newer studies. A single study of the Great Lakes region by the USGS established seasonal patterns of withdrawal and consumption of water, but had a very wide range of uncertainty for these data (Shaffer and Runkle, 2007). The forthcoming 2015 water use census employs improved methods of estimating consumptive use in the important Thermoelectric and Irrigated Agricultural sectors (Diehl and Harris, 2014, Senay et al., 2013), but other sectors are still not addressed due to a lack of adequate primary data or methods for their estimation. It is generally believed that methods for thermoelectric power water use estimation are of higher quality than for other sectors, due to (a) the high quality of withdrawal reporting to the Energy Information Administration, (b) discharge reporting and water temperature regulation by the Environmental Protection Agency, (c) the relatively “simple” nature of thermoelectric withdrawals, and (d) the relative precision with which thermoelectric power processes can be modelled by engineers (Averyt et al., 2013a, Macknick et al., 2012). However, categorical exist even for power plants, such as the Palo Verde nuclear power plant in Arizona which is cooled entirely by reclaimed wastewater from the Phoenix metropolitan area.

A recent national water footprint study concluded that the precision of our existing consumptive use coefficient data is so poor that it leaves us with little information on how human water withdrawals affect hydrological water balances on a national scale (Rushforth and Ruddell, 2017)- although such studies have been attempted (Averyt et al., 2013b). Historical consumptive water use snapshots are inadequate because of severe limits on data quality and availability in most economic sectors and US regions. Most of this data is badly outdated, because technological change beginning around 1980 has dramatically altered water use intensity and water quality, in part because the Clean Water Act’s wastewater treatment regulations and costs have driven improvements in economic water use efficiencies. Some US States have better data, but most States barely meet the county-level water withdrawal reporting standards of the five-year USGS national water use census (Maupin et al., 2014), and many US States systematically neglect reporting of groundwater use especially by irrigated agriculture.

Because of the lack of high-quality consumptive water use data in the US, and to inform the design of an eventual solution to this water data drought, we need to consider what can and cannot be accomplished with existing census scale water withdrawal data. This discussion will help us develop a measurement standard that overcomes the limitations of simple net consumptive use, and will help researchers to make the best possible use of currently available data.

2 Consumptive water use measurement is complicated

Although water metering is not yet universal, interval, monthly, or annual scale metering of water Withdrawal is mandatory in many US States and cities, at least for large water users (W, units of volume, mass, or their time rates). Water Consumption or consumption coefficient data is not widely available (C). Calls for "net metering" of these water users' return flows (R) date back decades, based on the perceived need for simple net consumptive use data. A water user's simple net consumptive use equation is $C = W - R$, and a common reformulation employs the consumptive use coefficient (U) in place of R, yielding $C = U\ W$. At first glance these equations appear trivial because only two measurements are required (either W and R or W and U). But the reality is surprisingly complicated, and this complication and its cost is the major reason that better consumptive water use data has not been collected. Figure 1 illustrates six of the more common "out of channel use" complications where the simple net consumptive use equation is not applicable. In these six instances, and in other more obscure instances (e.g. see Solley et al., 1998), a more detailed data model and water use data collection standard is required to accurately measure the basic consumptive water use of a human agent in the system.

[FIGURE 1 HERE]

It is easy to identify common cases where a human water user would need to report more than two measurements in order to accurately characterize the impact of their water use on the wider coupled natural human system- that is, cases that are not compatible with simple net consumptive use accounting. The largest out-of-channel consumptive water use in the US is irrigated agriculture, which is characterized by large withdrawals from surface water and groundwater stocks and large returns to the atmosphere via evaporation along with small returns to surface and groundwater stocks via infiltration and runoff (Figure 1a). Both runoff and infiltration flows are largely unmeasured for agriculture, although models have established good guesses for evaporation. Many municipalities withdraw from groundwater stocks and return treated wastewater to surface waters (Figure 1b). As an example, Mayer et al. (2016) found that municipalities and industries in the Great Lakes region have a net-negative consumptive use of in-channel surface water on average (with important exceptions), because on average these users withdraw from groundwater and return to surface waters. Many thermoelectric power plants and industrial users are characterized by large withdrawals from surface water stocks followed by return of lower-quality water (Figure 1c), raising the issue of "grey" water footprints (Hoekstra et al., 2011). But many of these users are located near coastlines and make use of ocean or Great Lake water, mitigating local surface water impacts. Gravity-fed irrigated agricultural projects often withdraw from surface water and return a smaller amount of flow a distance downstream, creating a localized dewatering impact along a reach of a stream (Figure 1d). Water storage facilities can withdraw large amounts of water at one part of the water year and return it during another time; this can benefit surface flow management if floodwater is stored and used for dry season demands, but the opposite example of summertime withdrawal and wet-season return has been known to occur (Figure 1e). Some users, for instance public supply, pass water through to secondary users (Figure 1f). As often as not, more than one of these complications exist simultaneously. In-channel uses of water by human and natural users are considerable. Aquatic ecosystems and human recreationalists use water non-consumptively within a stream channel. Evaporative and infiltration losses from reservoirs can be a large in-channel consumptive use of water associated with the water supply, flood control, and hydroelectric services of dams. Reservoirs involve most of the complications in Figure 1. Many control volume, watershed, or catchment flows are unmeasured, especially transfers across boundaries, making consumptive water use a problematic concept for real-world control volumes. It is clear that the most common cases require more sophistication than simple net consumptive use accounting can offer.

The true consumptive water use coefficient is smaller than we normally consider, because there is a mathematical error in the usual employment of consumptive use. Consumptive use coefficients are typically quantified at the point scale of space and time (at the pipe), but the resulting consumptive use coefficient U is often incorrectly employed at aggregated scales. Given the circular nature of the water cycle, Consumptive use declines with spatial and temporal scale, such that $U = 0$ by definition over long timescales at global spatial scales (allowing for small gains and losses due to fuel cells, nuclear reactions, long-lasting pollution, and exchanges with outer space). At nonpoint spatial and temporal scales there are two consumptive use coefficients, one at the pipe, U_P, and one considering recycling flows within the nonpoint control volume, U_V, making the simple consumptive use equation $C_V = U_P U_V W$. We know that U_V for evaporative water uses is roughly 0.9 for regional river basins or US States at annual timescales, closer to 0.5 for continental scales, and close to zero during intense convective precipitation weather events (Dirmeyer and Brubaker, 2007). Consumptive water use becomes less important, and more overestimated, at macro scales using conventional data and methods. Corrections need to be made to accurately calculate C at macro scales above the "immediate water environment" or "point" scale where the USGS accounts for water use. Most coupled natural human system water research occurs at meso and macro scales, not point scales (Scanlon et al., 2017, Lant et al., in review). All catchment hydrology applications operate at coarser scales than "point".

There is institutional complexity buried in the consumptive use concept. The USGS has a single-agency mandate to collect water use data, but many of these complicated flow and quality data require participation by municipalities (for multiple urban

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uses) and environmental agencies (for water quality), along with the private sector and the census bureaus (for attribution of water use to economic purposes), in myriad local and State jurisdictions. Consumption data is politically complicated..

3 What is water withdrawal data useful for?

We have argued that in all but the most idealized and rarest cases simple net consumptive use is misleading, because several additional measurements are fundamentally necessary- and at a finer spatial and temporal scale than is covered by mesoscale census data. We have also argued that a national program measuring this broader spectrum of data is not likely to produce usable data resources in the short term. Where does this leave use? Fortunately, the water withdrawal numbers we already possess provide a substantial portion of the information we need to assess the human water economy and its effects on the natural environment. There are several reasons why coupled natural human system researchers may be well served by water withdrawal data.

First, withdrawal conservatively bounds consumption, at least in the simple net consumption case. If we are dealing with one of the rare cases where simple net consumptive use is applicable, C is bounded between zero and W. This makes W a conservative estimate of C, from the perspective of a water resource planner who is concerned with assuring adequate water supply. When W is small, C will also be small. Unless U is very small ($U < 0.1$), C and W are guaranteed to be on the same order of magnitude. In general, U is increasing over time in the US due to rising water use and energy use efficiencies and increased recycling of water, so this rule $U > 0.1$ will generally be true except for the oldest thermoelectric and industrial facilities. Similar orders of magnitude is decent data quality when you consider that our current uncertainty regarding U for most water users is also order-of-magnitude. If we are dealing with one of the complicated situations considered in Figure 1, neither W nor simple C are adequate. In the simple net consumptive use case, W is a decent and conservative proxy for C.

Second, we have some spatially and temporally explicit W data, but not C data. The USGS water use census collects spatial water withdrawal data at the county resolution every five years. Our current consumptive use coefficient data for the US comes from a handful of studies of unrepresentative locations using outdated snapshots in time. But since $C = U\,W$, both W and U are equally weighted in the calculation of consumptive water use. As a result, for any given county and five-year timespan, W is likely to be dramatically more accurate than C. It is misleading to calculate spatially and temporally explicit consumptive water use C using a spatially and temporally non-representative U. Most of the information content comes from W, and what is provided by U is likely to be anti-informational.

Third, withdrawal is a good index of water use impact and risk. In one of the complicating instances covered in Figure 1, withdrawal will usually be a better index of hydrologic alteration than simple consumptive use. Aquatic ecosystem impacts

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caused by water intake fish mortality is proportionate to withdrawal, not consumption. Water supply risk is another good example, because risk is proportionate to withdrawal demands and available water stocks, rather than to water consumption.

Fourth, withdrawal rates drive infrastructure capacity and fixed cost. Water is a capital-intensive and infrastructure-heavy sector of the human economy. Fixed infrastructure cost is human and physical in nature. Capital and maintenance costs for pipes and pumps are engineered, sized, and priced on the basis of peak gross flow rates. Maintenance and administration costs on this infrastructure stock are largely fixed and proportionate to the size and complexity of the system. Sewerage and wastewater treatment costs are likewise proportionate to upstream withdrawal volumes. Water rights are denominated using withdrawal rates- typically annual withdrawal rates. Peak withdrawal rates drive our water infrastructure's fixed costs and are therefore a key variable in long-term economic decision making and strategy for water supply.

Fifth, marginal withdrawal pricing influences water user behavior. For better or worse, most water deliveries are billed on a volumetric withdrawal basis (plus a connection fee covering fixed costs), and not on the basis of consumption or of quality. There are exceptions, such as unmetered connection-fee billing in some older municipal water systems, and one could imagine a world with more sophisticated internal metering and billing that incorporates water use timing, quality, and net consumption. Marginal operating costs for water have long been dominated by electricity and chemical costs to pump and treat water (Clark et al., 1976). This is true for all kinds of water users, ranging from small residential users to the largest agricultural and industrial operations. In most cases the volume and price of a withdrawal is the only information visible to the customer in a water transaction. We know that marginal costs and prices strongly influence economic behavior, even for the least sophisticated residential water consumers (Arbués et al., 2003). Because withdrawal is what customers pay for on the margin, it is reasonable to assume that most consumers' water use decisions are driven primarily by withdrawal rates.

4 Conclusions

Our scientific and policy questions require significantly more detailed spectrum of water use data capable of resolving the complicated human-natural systems interface. Simple net consumptive use of water (simple net consumptive use) is a necessary quantity for classical hydrology and hydraulics, but is neither necessary nor sufficient for most coupled natural human system questions. It is clear that pentannual-timescale water withdrawal data falls far short of fundamental requirements for human water use monitoring. However, it is equally clear that the multiplication of a simple consumptive use coefficient by measured withdrawal adds little to our understanding, and is misleading in the most common human water use cases. In some cases W is approximately sufficient, and in most other cases simple net consumptive use is insufficient. A data model capable of handling the most common cases of human water use in the CNH system must therefore go far beyond the two-measurement simple net consumptive use standard. In retrospect, the decision of the USGS's National Water Census team to focus on a problem they could solve- publishing national water withdrawal data- would seem to have merit. Surveys of water withdrawal are feasible and they approximately address many of the most important economic, socio-hydrological, and CNH problems with a minimum of cost and complexity- at least at the aggregated mesoscales where census data are published.

An expanded future water census needs to go far beyond the development of better consumptive use coefficients for simple net consumptive use accounting. An expanded census needs to address water quality at withdrawal and return, seasonal timing, specific stream segment and aquifer sources, multiple and specific stocks, accurate attribution of use to legally responsible human agents, multiple uses of a withdrawal, multiple processes, and return flow, in addition to simple withdrawals. This paper explains why, and provides guidance on what measurements would be needed to nationally survey consumptive uses of water at census scales. Some excellent groundwork on improved water use measurement has been laid recently (e.g. Diehl and Harris, 2014, Dunham et al., 2017), but we need to build on recent work to define a standard for how each aspect of water use should be measured for the complicated special cases that arise in CNH systems.

While we wait for that water use data, simple and widely available water withdrawal data is useful for a wide range of common CNH questions. Water withdrawal is a good policy and management index for intensity, impact, and risk of water use, and it is often more valid index than simple net consumptive use. CNH applications of water withdrawal data include water resource policy, socio-hydrology, water economics, ecohydrology, municipal and industrial water management, water use regulation and law, water footprints, and Life Cycle Analysis. Researchers studying CNH topics should proceed to use withdrawal-based numbers with confidence and peer reviewers should accept this approach, especially if the special cases and limitations discussed in this paper are appropriately addressed.

Acknowledgements

The authors acknowledge funding from the National Science foundation, ACI-1639529, and the Great Lakes Protection Fund, #946. The research and opinion is that of the authors, and not necessarily of the funding agencies. The authors acknowledge helpful conversations on this topic with Manu Lall of Columbia University and Eric Evenson of the USGS (emeritus).

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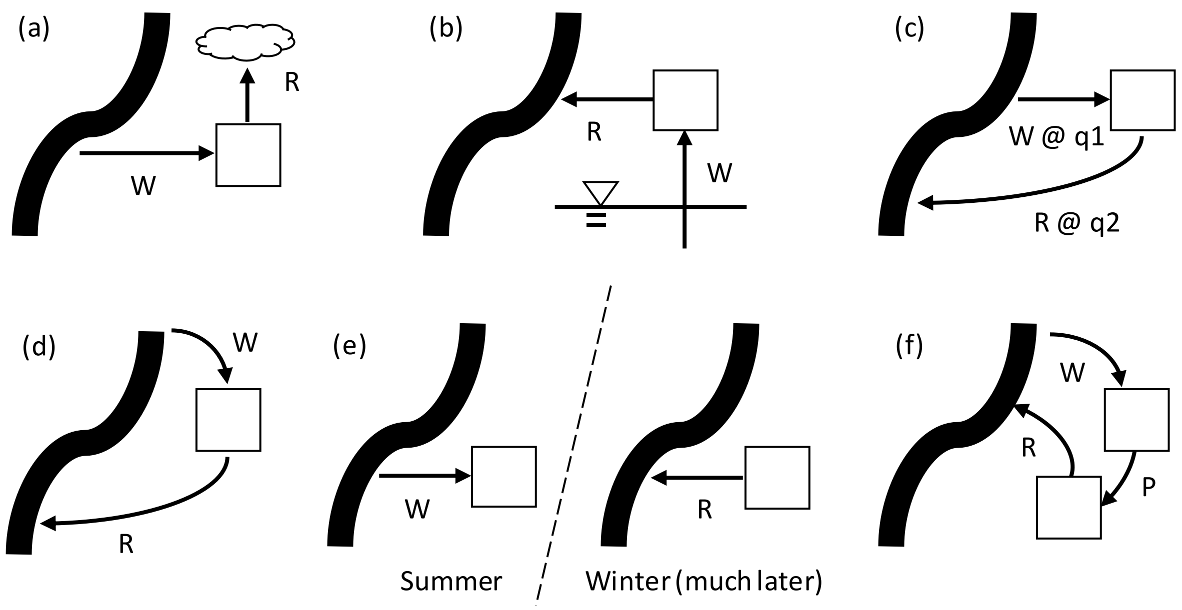

Figure 1: Six common out-of-channel water use cases that confound a simple net consumptive use (SNCU) calculation: (a) return flow R to a different pool, for instance evaporative use of irrigation water, (b) return of groundwater withdrawal W to surface water, a special case of (a), (c) return at a different quality q2 compared to withdrawal q1, (d) return far downstream or upstream from the point of withdrawal, (e) return much later than withdrawal, implying storage, and (f) pass-through P to a secondary user. The thick black line represents the "channel", a surface water source like a river, the cloud represents the atmosphere, and the triangle-marked line represents groundwater. Arrows represent water withdrawals and returns.