Reply to comment by M. Heistermann

GENERAL REPLY

My main takeaway from both reviewers' comments is that I failed as an author to communicate the topic and expectations properly for this opinion, and I may have misled the reader as a result. The failure began right at the title, "When is water withdrawal enough?", which was simple, short, and rhetorically evocative. I meant it rhetorically, but it was taken topically and literally, and this left the reader with the initial impression that this was an analysis of where exactly hydrologists and water resource engineers can use water withdrawal data. That was not my main point. This article is written primarily to the *non* hydrologist or water resource engineer who is working on systems involving water use at census and macro scales. Accordingly, I propose this revised title, which is much longer and literal, but hopefully more adequately precise for this audience:

"How should a future water census address consumptive use? (and where can we substitute withdrawal data while we're waiting?)

The opinion makes two points, which I repeat here for emphasis:

1. The way we're measuring consumptive use in the water census context is poorly understood and therefore prone to abuse, and needs to be improved in the future using a more detailed water census data model.

2. Since we don't have that data today, we should sometimes be using census water withdrawal data in place of consumption data in several specific instances where this is a valid substitution… and this choice should be accepted by hydrologists as long as it is properly qualified. This is because the withdrawal data is of higher quality and is less misleading, as compared with presently available consumption data at census scales.

M. Heistermann's comment is helpful in several ways, but most importantly by highlighting that this is an issue that professional hydrologists and water resource engineers will see in a different light than some other scientists- that is, it is a judgment that requires detailed context and professionalism. If one's business is to precisely estimate and employ water balances for a critical task, one will naturally have both the need for, and the means to obtain, the correct data for the engineering or modeling task at hand. These professionals will normally be working at fine scales on projects that require a great deal of precision- and will not be relying on coarse scale water census data. I have attempted to rewrite the opinion to emphasize the census scale, and also to clarify the types of researchers and research questions that might be well served by use of mesoscale withdrawal data- for instance, economists or macroeconomic planners evaluating long term water supply infrastructure capacity needs for a State or river basin. "For what purpose?" This opinion focuses on census scale applications, and this should now be clearer in the revision. Thank you for helping me reach the intended audience, provide context, and qualify claims that were objectionable to the professional hydrologist.

At the same time, I really do intend to opine about the appropriateness of simple net consumptive use (SNCU), so I will re-emphasize the point here. The SNCU assumptions fail to capture the most common cases of human water use in the economy, and we need a more detailed data model. I have tried to clarify the requirements of this more detailed data model in my revised opinion, as well as spending more ink on the identification of the SNCU assumptions and why they matter.

I will disagree on one minor point, which is the usage of Coupled Natural Human Systems (CNH). It may be true that the term has outgrown the original use intended by Liu et al. 2007 and contemporaries, but it is one that I like very much. This wording, as I have used it, forces hydrologists and other natural scientists to place the human element within the framework, and even to view the hydrological system as a peripheral boundary condition or approximate constraint on the "primary" subsystem of interest, which is more often than not the human subsystem. Non-hydrologist CNH researchers are among the most likely to benefit from my opinion expressed here. CNH problems are among the main applications of census scale water data.

I have tried to rely on logic and explanation more than detailed referencing, and have attempted to minimize the external references required for this opinion. It is not a review article or scientific analysis, so it is important to economize. But more importantly, it is important that the opinion is self-explanatory as much as possible.

One way that this opinion could be expanded and improved is to flesh out the European, East Asian, and other global contexts by comparing data availability and quality in these regions and nations. This is however outside the scope of my current opinion. I expect that the general conclusions of this opinion are valid worldwide, although there are a few cities and nations where current water data availability and quality rivals or exceeds that of the United States.

I am thankful the M. Heistermann put in so much thought to the comment, and I recommend it to any reader of the opinion. The caveats and exceptions raised are greatly clarifying, and entirely correct, and will therefore allow the reader to reach their own informed judgments on the topic.

LINE BY LINE REPLY

1. "Withdrawal conservatively bounds consumption", or, in other words, water managers can typically assume C to not exceed W. While it is hard to disagree on that statement, I am wondering under which circumstances that information is actually helpful to support management decisions, and I would hope to see some evidence or corresponding best-practice cases. I am afraid, however, that in water scarce regions - where the issue of consumption matters most - the assumption of withdrawal being equal to consumption can make decisions about water allocation to different users or sectors fairly impossible. The rest of the paragraph about point no1 should also be supported by evidence: it is true, by definition, that C and W will have the same order of magnitude when $U > 0.1$ - but will water managers find "same order of magnitude" a sufficient criterion for decision making? Are there surveys on stakeholder information requirements to support that notion? And, yes, the thermoelectric and industrial sectors may have values of $U > 0.1$, but what about irrigated agriculture – which is the most important water consuming sector due to both large withdrawals and low values of U. Apart from those concerns, I feel like the line of arguments is flawed by an intrinsic contradiction: The author states that for $U > 0.1$, W and C may be assumed to have the same order of magnitude, which might be sufficient given

the fact that the uncertainty of U "is also order-of-magnitude" itself. So, based on that statement, how can a manager be sure that W and C are in the same order of magnitude? Depending on the water using sectors in the region, they can't - which is why they usually need to come up with their own estimates.

BLR: Your argument that W bounding C is unhelpful in water-limited and water stressed circumstances is completely correct. I think we may have a miscommunication on the point of U, however. My intent is to argue that when U approaches 1 (i.e. U >> 0.1) then C approaches W (this isn't really an argument, it's a trivial fact). Irrigated agriculture is usually the only major water user that satisfies this condition, and irrigated agriculture is also the largest water user globally, and a particularly large water user in arid regions that suffer from water stress. Industry and power are often U < 0.1. So in the (arguably) most important case of irrigation-induced water stress, my argument is most applicable. At the same time, I won't argue with you on the point that we need precise consumption data the most in exactly this case, or that in exactly this case local managers will need to collect their own localized and precise data. I have tried to rewrite the paper to clarify that I am not discussing that case, but rather mesoscale census level analysis. See revision lines 2.23, 3.4, 6.34, 7.35. Ultimately, I think your public commentary on this point does the reader a service by pointing out the conditions where my arguments are least applicable, and I expect that the reader will benefit from reading the contrast that you draw here. Your commentary is as long as my opinion, and equally interesting! In summary, I think we are both correct, depending on the circumstances- which is exactly the point you raised, if I am not mistaken. I think my opinon's main flaw is in failing to clearly establish and limit the scope of my argument to census scale research questions, and I hope the (major) rewrite corrects this flaw.

2. "We have some spatially and temporally explicit W data, but not C data": This point is closely related to the first one. It says that spatially and temporally explicit withdrawal data is of comparatively high quality and its resolution in space and time is by no means matched by data on consumption. Computing spatiotemporal patterns of C from W, based on unrepresentative estimates of U, can thus be misleading, assuming that U is varying non-uniformly over magnitudes. And I agree that computing spatial patterns of C, based on unknown U, pretends a level of knowledge that does not exist. However, the reverse conclusion is not valid, either! You cannot conclude that the spatial pattern of W per se is a helpful management proxy. In general, I am curious how large scale patterns of either W or C may exactly be helpful to water resources planners. Again, local decision makers will typically know better than to use uncertain off-the-shelve estimates of U.

BLR: Yes, you precisely understand my point. And I agree that spatial patterns of W are not necessarily representative of spatial patterns of C (except where U >> 0.1, per our discussion on the prior point). This is a great reason for us to use spatial W instead of pretending we have spatial C, at least for census scale analysis. As before, I think we are both correct here, and your public commentary will help the reader grasp the finer points.

3. "Withdrawal is a good index of water use impact and risk": The author only provides

one example to support that claim which is that "fish mortality [caused by water intake of whatever water-related infrastructure or facility] is directly proportionate to withdrawal". That is a very specific impact of water use the generalisation of which is certainly unwarranted! The following statement of water supply risk being proportionate to withdrawals is, in this context, a text-book example of circular reasoning (withdrawal data is enough because withdrawal data is enough), and will probably not hold for basin-scale water resources planning – for the exact reason that consumption may be the decisive control for downstream water availability. Again, it would be helpful to see some evidence to support this point.

BLR: I do not understand your point on circular reasoning; I think I disagree, but without understanding your argument I cannot be sure. Let me restate my point here. In a literal and strictly physical sense, an individual water user's risk depends on whether they can support withdrawal rates, not consumption rates. If the withdrawal pipe is empty, it doesn't matter whether the source can support the consumption rate of the user. This is true in general, and this is what I mean by "risk" in this context. I am not referring to all kinds of risks, but only to these narrow categories of risk. Consumption matters for systemic risk, but not for an individual user's risk. Separately, in a much more narrow instance, fish mortality is proportionate to withdrawal rates. These arguments are summarized on revision Lines 6.24+. The argument is logical, and not evidence based. I am willing to include references to fish-kill by intakes, but I don't think they are necessary in this kind of opinion (unless you insist). I need to keep the reference list short for an opinion, and the arguments should stand mostly on their own. Please help me improve on this if you don't think I have made a self-explanatory point.

4. "Withdrawal rates drives infrastructure capacity and fixed cost": That statement is true, but reflects only a very limited scope of water resources management. Management of a scarce resource is not only a matter of infrastructure. Furthermore, external (or environmental costs) are typically related to consumption (in contrast to the authors statements pertaining to point 3).

BLR: Yes, but withdrawal rates DO drive infrastructure capacity and fixed cost, and this is what I am referring to here (not external costs). See lines 6.34+ for the revised language, which is hopefully a little bit clearer. This argument applies to individual water users, and not only at meso/census scales.

5. "Marginal withdrawal pricing influences water user behavior": Again, that statement is true, but at the same time it is both incomplete and irrelevant. There is a substantial body of literature showing that water use behavior is influenced by many more factors than withdrawal pricing (see e.g. Bosworth et al. 2002). Apart from that, I do not really see how this point is relevant to the topic: even if pricing were the only determinant of withdrawal, how does that help us to represent the effect of consumptive use? How does the idea of "water withdrawal depends on pricing" pertain to the notion of "water withdrawal is a good management proxy"?

The line of argument appears to end in the middle of nowhere...

BLR: It is relevant because economists and water rate/pricing consultants working for water supply utilities and wholesalers usually work on the basis of withdrawal, not consumption. State and national planners would also use this W data to consider issues of infrastructure need and subsidy. Higher water withdrawal prices in turn reduce withdrawal and consumption, benefitting the regional water balance. You are right about external costs, and I did not address those in my original opinion. I have now added this sentence to ensure that the reader does not forget (as I did): "Some exceptions to this pattern involve attempts to price and pay for external costs, such as in the use of water banks where return flows are credited or the use of payments for the ecosystem services of water left in a stream or river." See lines 6.34+ for the revised language.

"Simple net consumptive water use" and other terminology
With the "simple net consumptive water use", the author introduces new terminology (new at least to me) without necessity. I don't see any need to discard the idea of a well defined control volume for any kind of water balance calculations. The notion of a control volume can be applied to any (management) scale. And the attribute "simple" is just as misleading as it is unnecessary.

BLR: I think we have a misunderstanding here. Introducing SNCU terminology and calling attention to the concept (as it is used in the water census) is a core point of my opinion, and this seems to have been missed. I have added an entire figure and an explicit list of SNCU assumptions (as distinct from generic control volume mathematics) to ensure that the reader does not miss this point. See the revision's Figure 1 and lines 3.19+. In summary, SNCU is the way the U.S. water census (and other similar surveys) measure water use and the impact on the control volume, and it has several problematic assumptions that are not broadly understood (except perhaps by professional hydrologists). It is a rare case where these assumptions are even vaguely satisfied, which makes the current census method of reporting C inherently problematic. By contrast, W can be measured and reported without logical errors in most cases. This discussion is both an argument for using W instead of C (for prior census datasets), and also a roadmap for how future measurements of C need to be completely changed to adopt a different logical data model that goes beyond simply assessing U more accurately. This is important! Please let me know how I can more clearly communicate this point to the reader.

Likewise, the author repeatedly emphasizes the term "Coupled Natural-Human System" without doing much more than stating the obvious: that water resources management is of course at the interface of natural and socio-economic systems (besides, the original reference of Liu et al. (2007) in Science was about properties of specific coupled natural-human systems, not about coining a new term of the "Coupled Natural-Human System" in general).

I publicly addressed this point in my reply. Even if Liu et al. didn't use the term the way I am using it, I think my usage is a valid extension of the term, and many have used the term "CNH", even the US NSF in an entire funding program on the topic (https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=13681). The use of the term puts the emphasis on the total system, including human and economic uses of water, and draws the emphasis away from the "control volume" or natural water cycle that

hydrologists and water managers professionally focus upon. The arguments I am making are going to be most helpful to scientists and policymakers who are addressing the CNH problem generally, and at meso/census scales, rather than a focused local hydrology or water resource problem. See lines 2.23+. We may need to agree to disagree here; narrowly focused hydrologists will tend to disagree, and many others will agree, with my characterization. I think both are right, and I think the hydrologist benefits from seeing the problem from the broader perspective (and appreciating that the broader perspective exists). I would be willing to include more references to "CNH" studies, if you insist- but as before, I want to try to keep the reference list to a minimum. The Mayer, Perrone, Rushforth, Ruddell, and Qureshi references are good examples of CNH work.

Situation in the US

While it is of course justified to focus on the situation in the US - with its very unique level of water census collections - the author should put this situation into perspective with other countries that face dramatic water scarcity issues, but which aren't anywhere near the data standards currently prevailing in the US.

BLR: see lines 1.39+, 3.2+, 5.4+. I do not intend to expand the discussion to specific examples outside the US. My intended argument is this: if C data is so scarce even in the most data-rich locations like the US, then the arguments in this opinion are even more applicable globally than in the US.

"Consumptive water use becomes less important, and more overestimated, at macro scales"

That statement (p. 4, l. 27) is bold and fuzzy at the same time. What is meant by "less important"? "Importance" (in terms of "relevance") of consumptive water use is a matter of water availability, a fact that is often ignored also by water footprint community (Heistermann, 2018, section 4, although I admit that's another debate), and I'd like to see evidence to support that statement. The fact that U converges to 0 at the global scale does not imply that it continuously decreases with increasing scale. In specific (semi-arid) climates with intense and widespread irrigation, U might reach its maximum value at the basin scale due to cumulative effects - just take the Aral Sea basin as an example.

BLR: Good point. (and, by the way, I COMPLETELY agree with your 2018 opinion on planetary water boundaries being the wrong measure!) The phrase "important" is too vague. See the rewritten passage on lines 4.27+.

Future water use censuses

In section 4 (p. 7, ll. 4 ff.), the author elaborates briefly on the requirements to future water use censuses. He expands a wish list that includes "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". In the following sentence, the author claims that his "paper [...] provides

guidance on what measurements would be needed to nationally survey consumptive uses of water at census scales". However, I cannot really find that kind of guidance in the manuscript, at least not at a level that actually adds new insight. I also think that such a wish list and requirements to future census are not really the subject of the paper (and shouldn't be, either).

BLR: I really do intend to provide this guidance in the opinion! (see the revised title, for instance) But it was inadequate, mostly because the core argument about the inadequacy of SNCU seems to have been missed. It is debatable whether my opinion adds new insight from the perspective of the professional hydrologist, but I hope that it at least emphasizes where exactly the problem lies (with SNCU assumptions) so that the government officials developing and funding future water census efforts can clearly understand that the current system isn't adequate, and can have a name for the problem and the solution. This is one of the two motivations for this opinion, to provide this motivation for an improved consumptive use census. (the other reason is to help justify use of W in limited cases, since we don't have that improved census yet)

Reply to comment by Anonymous Referee #2

GENERAL REPLY

My main takeaway from both reviewers' comments is that I failed as an author to communicate the topic and expectations properly for this opinion, and I may have misled the reader as a result. The failure began right at the title, "When is water withdrawal enough?", which was simple, short, and rhetorically evocative. I meant it rhetorically, but it was taken topically and literally, and this left the reader with the initial impression that this was an analysis of where exactly hydrologists and water resource engineers can use water withdrawal data. That was not my main point. This article is written primarily to the *non* hydrologist or water resource engineer who is working on systems involving water use at census and macro scales. Accordingly, I propose this revised title, which is much longer and literal, but hopefully more adequately precise for this audience:

"How should a future water census address consumptive use? (and where can we substitute withdrawal data while we're waiting?)

The opinion makes two points, which I repeat here for emphasis:

1. The way we're measuring consumptive use in the water census context is poorly understood and therefore prone to abuse, and needs to be improved in the future using a more detailed water census data model.

2. Since we don't have that data today, we should sometimes be using census water withdrawal data in place of consumption data in several specific instances where this is a valid substitution… and this choice should be accepted by hydrologists as long as it is properly qualified. This is because the withdrawal data is of higher quality and is less misleading, as compared with presently available consumption data at census scales.

Please forgive my refusal to become highly specific about scales of space and time, and my determination to stick with approximate phrases like "census", "meso", and "macro" to define scale. These scales are coarser than point scales, and are the scales at which a census operates in order to preserve anonymity and privacy using statistical aggregation. These are the scales at which it is feasible and lawful for a national government to collect comprehensive and uniform data. Owing partly to space constraints, but more importantly to the nature of an opinion piece, I do not wish to provide a detailed or quantitative analysis of scale.

It is however important for the Simple Net Consumptive Use (SNCU) accounting that I precisely employ the "point" scale of space, and I have done so a revised and hopefully more precise Section 2. In response to your comments and questions on Section 2, I have added an additional figure and an enumerated list to clarify what I mean by the SNCU assumptions. I hope that it is now clear, because I am convinced that this simplification is at the heart of both the capability and disability of our census scale water use data.

LINE BY LINE REPLY

1. Title: the title doesn't reflect the content of the article. Either the article should be

completed to fit the title, or the title should be changed.

BLR: The title has been totally rewritten to be more explicit. The new title is less evocative and provoking, but more specific. This was clearly needed since my first title misled both reviewers badly. See my comments in the public reply.

2. Abstract:
(a) The main hypothesis, that is good-enough water withdrawal data are available
should be stated.

BLR: This is an opinion, so I don't intend to scientifically evaluate any hypotheses. However, I think the thesis statement is summarized in the rewritten abstract: "This discussion clarifies the broad requirements for improved "stock and flow" census scale data model for consumptive water use. While we are waiting for the eventual arrival of a more sophisticated water census, the withdrawal data we already possess are sufficient for some of our most important scientific and applied purposes."

(b) "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": This sentence is not very clear for me

BLR: There is a new explanation of SNCU in much greater detail; see lines 3.21+.

3. Introduction:
(a) P1 Lines 22-25: I'm not sure this assertion is correct, especially when the
water is withdrawn to be stored several months.

BLR: storage is certainly a major problem for consumptive use calculations. This is one of my opinion's points.

(b) P2 lines 3-8: it seems the author is already discussing about future progress
while the main subject of the article is still not well presented.

BLR: I believe the rewritten manuscript may help clarify this.

(c) P2 2nd paragraph: some more information on the type of data that are collected
by the US national censuses of consumptive water should be provided
to the reader: what is the spatial resolution (point scale, state?), the
time scale (monthly, annual, decadal?), and is the type of water (groundwater,
river, lake: : :) of the source of withdrawal or rejection point is provided?

BLR: Please see the rewritten paragraph 2, which may be clearer. But, in general, the reader is best served by reading the cited literature. There is a lot of detail.

4. Section 2 and Figure 1: This part has to be improved.

(a) P3 line 24-25 I don't understand why needing more that two measurements is not compatible with the equation C=W-R; as W can be the sum of several withdraws, as R might be the sum of several return flow. Same comment apply for the case illustrated in Figure 1f.

BLR: See the rewritten lines 3.21+. In summary, there is nothing wrong with C = W-R, but it is the assumptions that go into the calculation of C, W, and R that are the problem. You are right that each term is a sum, but my explanation does not imply otherwise.

(b) P3 Line 30: Of course, it is important to consider the type of water that is removed and where it returns (groundwater, river, lakes, sea ...), as this has a strong impact on the water resource, and I propose to address this point earlier in the article. However, I do not understand why this prevents the estimation of the consumptive use of water: : :.

BLR: See my last reply to your point (a) above.

(c) P4 lines 1-4 Water quality is indeed a strong issue, but, again, doesn't prevents the estimation of the consumptive use of water: : :.

BLR: True. The rewritten introduction refers only to data quality, not water quality.

(d) P4: Of course, most of the withdrawn water won't get back at the exact location it was taken nor at the exact same time: : :. But, again, why this prevents the estimations of the consumptive use of water? To make it clearer the spatial and temporal scale that are focused should be stated.

BLR: Agreed. The revised manuscript is much clearer that it focuses generally on meso/census scale aggregated data, and not on point scales. See lines 2.27, 3.5, 4.39, 8.2, and the expanded section on SNCU and the new Figure 1. In summary, the problem is that our SNCU methods assume point scales of space and time, but then we use the data for studies at aggregated scales of space and time where U is smaller than represented in the data.

(e) P4 2nd paragraph: "Consumptive use declines with spatial and temporal scale" I don't agree: if consumptive water is mostly the one that is taken from the water resource to be mostly evaporated, I don't see how the accumulation of evaporation could decrease in time: : : Except if you consider that this evaporation is then recycled in precipitation, but, then there is a mixture in the notions of water resources and water cycle that is misleading.

BLR: The withdrawal and evaporation is unchanged with spatial and temporal scale, but the return flows (e.g. rainfall recycling) increase with spatial and temporal scale. The net result is decreased consumptive use with increased scale.

…

I don't follow your comment about mixing notions of water resource and water cycle. To me, there is no difference. It's all the water cycle, and it's all a water resource. We are discussing impacts on water stocks, which are mostly (in this opinion) "in-channel" surface water and also ground water stocks. Their return flows do involve other pathways and stocks, such as rainfall recycling.

(f) Another issue is that there is few mentions of the impact that abstractions can have on the different reservoirs, in particular for groundwater, in which abstractions can be definitive (without the possibility of recharge) either because of the compaction of the aquifers or fossil water withdrawals. This might be very important for the sustainability of the water use.

BLR: I see your point that this is an important sustainability issue. However, this is a level of nuance and detail that I did not cover in this opinion.

5. Section 3: I mostly agree with the review of M. Heistermann on this part. So I'm only adding some few comments. My main questions are: which kind of water withdrawal data is enough to be useful? Which time step, spatial resolution, information on the reservoir source (groundwater, lakes, sea, river: : :)? And who needs what?

BLR: Heistermann's comments were apt, and I appreciate your agreement with them (I also mostly agree). Please see my reply to his comments, and also I hope the rewritten manuscript is much more explicit about "who" and what scale.

Minor comments

• Abstract: 1st sentence: Are you sure the water balance equation is the same for hydrologic and hydraulic science? Why empirical observations and not direct observations?

BLR: In my opinion they are the same (at this level of detail).

…

I don't follow your question about empirical vs direct observations. To me these are the same thing.

• P4 line 8: "example of summertime withdrawal and wet-season return has been known to occur" please provides some references.

BLR: Good catch. This was beside my point (and I am not sure why I wrote this sentence), so I removed the offending language.

• P4, line 14: which kind of boundaries are you talking? Is it administrative boundaries, or physical boundary (like surface water, groundwater: : :)?

BLR: Let's call them "socio-political" boundaries. They are not watershed or aquifer boundaries. See line 2.27.

• P4: "We know that UV 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)." Although I still think that mixing water resource and water cycle is not a good idea, stating that we know these numbers is perhaps too definitive, especially in a context of climate change:

BLR: These numbers are examples from the literature, and are approximate. I do think it is appropriate and necessary to give specific numbers since my earlier arguments explicitly call out U ~ 0.1 as a key value.

~~When is~~How should a future water census address consumptive use? (and where can we substitute withdrawal data ~~enough?~~while we wait?)

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Abstract. Despite the centrality of the water balance equation to ~~hydrologic~~hydrology and ~~hydraulic science and engineering~~water resources, in 2018 we still lack adequate 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 water census measurements would be required to more accurately quantify consumptive use for the most common mesoscale use cases. The limitations of ~~human water use at census scales of space and time.~~the currently applied Simple Net Consumptive Use (SNCU) assumptions are discussed for several common use cases. Fortunately, ~~a wide range~~several applied water management, economics, and policy questions can be sufficiently addressed using currently available withdrawal numbers. ~~When a more advanced~~ in place of 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.~~consumption numbers. This discussion clarifies the ~~problems we need to solve to measure humans'~~broad requirements for improved "stock and flow" census scale data model for consumptive ~~use of~~ water ~~at census scales, and argues that~~ use. While we are waiting for ~~these data~~ the eventual arrival of a more sophisticated water census, the withdrawal data we already possess are ~~adequate~~sufficient 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. "Point" scale flows of water in this equation may be expressed in either gross or net quantities, although there is a critical difference between the gross and net. All flows are gross in reality, and the net term is a theoretical abstraction which aggregates and combines multiple flows. 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). Classical 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.~~The USGS definition implies in practice a relatively fine spatiotemporal boundary on the control volume. The two definitions may coincide, depending on the details. Whereas the classical hydrologist or water engineer can afford the luxury of fine-tuning the a control volume and set of observations to fit the specific problem at hand, a water census must make hard choices about feasibility, cost, scale, and standardization of the census's water balance data model.

~~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~~**The US water census estimates annual water use by economic sector at an aggregated county scale, with data reported once every five years.** ~~"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 in the spatially aggregated region, but ~~had~~found a very wide range of uncertainty for these data (Shaffer and Runkle, 2007). The forthcoming 2015 water use census employs improved methods of estimating and modelling 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 data 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~~logical exceptions exist even for the best-in-class thermoelectric power ~~plants~~water census data model, such as the Palo Verde nuclear power plant in Arizona which is cooled entirely by reclaimed wastewater from the Phoenix metropolitan area.

A recent US national water footprint study concluded that the precision of our existing census-style 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 in efficiency, process, and treatment beginning around 1980 has dramatically altered water use intensity~~ and water quality, in part because the~~. The US 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 and return flows especially by irrigated agriculture.

Classical hydrologists and water resource engineers tend to work at fine spatiotemporal scales and on problems that require highly precise but localized water balance data- for instance, when designing or operating a large dam. By contrast, water census data is more commonly employed by economists, policymakers, sociologists, industrial engineers, and researchers of broader Coupled Natural-Human systems problems (CNH, Liu et al., 2007) at meso scales and regional socio-political boundaries where these coupled systems most richly interact (Lant et al., in review). The latter cohort currently faces a stark mid-term reality: the near-total lack of observations of consumptive water use by humans and their economy. Fortunately for the latter cohort, observations of human water withdrawal provide a partial but useful picture of the role of water in a coupled natural human system. These withdrawal data are far more plentiful than consumption data at census scales (admittedly, 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, even in data-rich regions like the US). This difference between the abundance of consumption and withdrawal based water use numbers exists for historical and cost reasons- but also because withdrawal observations are radically simpler in concept for real-world use cases.

Proposals for a Water Information Administration (WIA) or for an enhanced USGS water use census (Fishman, 2016, Michelsen et al., 2016, Perrone et al., 2015) may become a reality in coming decades. Calls for an international "water internet" built on the Internet of Things may eventually be realized (Patterson et al., 2017). When these are built it will take decades longer to accumulate a useful history of water use. In the meantime, we face the possibility that the longitudinal, systematic, detailed, national scale consumptive water use census data we need will not become available nationwide or globally until at least the middle of the 21st century. This opinion's author and most of its readers will be retired from water science by then. This gap raises two questions: (Section 2) What is a proper census data model for consumptive water use?, and (Section 3) When can census water withdrawal data replace consumptive use data? Because of the lack of high-quality consumptive water use census data in the US~~,~~ (and globally), and to inform the design of an eventual solution to this water data drought, we need to ~~consider~~discuss what can and cannot be accomplished with existing census scale water ~~withdrawal~~ data. The scope of 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~~focuses on water census scale data in the US (mesoscale, statistically aggregated) and on its applied uses in coupled natural human systems management and policy, rather than on classical hydrology and water resource engineering science- although some of the discussion is relevant to classical applications, and to global water data efforts.

~~2~~2 What is a proper census data model for consumptive water use ~~measurement is complicated~~?

Although water use metering is not yet universal, ~~interval, monthly, or annual scale metering of~~ water withdrawal reporting is mandatory in many US States and cities, ~~at least~~especially 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 water 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. The equation can be solved for a single user or a group of users. At first glance these equations appear trivial because only two measurements are required (either W and R or W and U~~).~~), along with the point location in time and space, and

the user's identity. But the reality is surprisingly complicated in concept, and this complication and its implied cost to census observations is the ~~major~~main reason ~~that~~why better consumptive water use data has not been collected~~.~~ in the past.

For clarity, this paper will coin a term for the water census style simplification of a water user's net effects on the natural environment's water balance: Simple Net Consumptive Use (SNCU, Figure 1). The assumptions involved in SNCU water use accounting in a water census, as a special case of the standard control volume approach, are:

1. Spatial Point Scale control volume (which maximizes net use by minimizing return flows),
2. Insignificant Storage at the time constant (which tends to be valid only at longer timescales above the water year),
3. Fast Return Flows relative to the time constant (a corollary to #2),
4. Return to the Source of Withdrawal (at the same location and time, see #1, #3),
5. Return Flows of Similar Quality to withdrawals, and
6. Homogenous User Groups where all aggregated individuals share similar use profiles and identity.

[FIGURE 1 HERE]

Figure 2 illustrates six of the more common "out of channel use" complications where ~~the~~ simple net consumptive ~~use equation is~~does not ~~applicable~~hold. In these six instances, and in other more obscure instances (e.g. see Solley et al., 1998), a more detailed water census data model ~~and water use data collection standard~~ is required to accurately measure the ~~basic~~ consumptive water use of a human ~~agent~~user (or group of users) in the system. Each of these instances requires more than five observations to characterize (user, point location, time, W, R or U), because each is more complicated than the SNCU instance.

[FIGURE ~~1~~2 HERE]

It is easy to identify common cases where a human water user would need to report more than ~~two~~five 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 and most world regions 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~~2a). Both runoff and infiltration flows are largely unmeasured for agriculture, although models and remote sensing have established good guesses for evaporation. Many municipalities withdraw from groundwater stocks and return treated wastewater to surface waters (Figure ~~1b~~2b). 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~~ground water and return to surface ~~waters~~water. 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~~2c), raising the issue of "grey" water footprints (Hoekstra et al., 2011), and of the need to separately account for stocks of differing quality (Ruddell et al., 2014). But many of these users are located near coastlines and make use of ocean or Great Lake water, mitigating local surface water impacts~~.~~ due to near-infinite availability. 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~~2d). 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~~2e). Some users, ~~for instance~~especially public supply and water transfer operations, pass water through to secondary users (Figure ~~1f~~2f). As often as not, more than one of these complications exist simultaneously. In-channel uses of water by human and natural users are also considerable~~.~~; aquatic ecosystems and human recreationalists use water non-consumptively within a stream channel. These uses could be considered to "withdraw" in the sense that they cannot exist without the flow rate, but the consumption coefficient on these uses is zero. 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~~2. The most common use cases require more conceptual sophistication than simple net consumptive use accounting can offer, and a more detailed networked data model is required to account for these cases.

Other challenges also exist. The true consumptive water use coefficient ~~is~~U tends to be smaller than ~~we normally consider,~~the numbers published at census scales because there is a mathematical error in the usual employment of consumptive use at census scales. Consumptive use coefficients are typically quantified at the point scale of space and time (at the pipe), but the resulting point scale consumptive use coefficient U is often ~~incorrectly~~erroneously employed at aggregated scales~~.~~ of space and time (e.g. the annual county scale). Given the circular nature of the water cycle, Consumptive use generally (but not monotonically) 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~~ For a nonpoint control volume~~, U_V, making the simple consumptive use equation~~ V the coefficient U is actually a different variable than the point scale U, so $C_V = U_V W_P$ and $C_P = U_P W_P$, and $U_V \leq U_P$ ~~$U_V W$.~~in most cases. We know that U_V for evaporative water uses like irrigation 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~~work occurs at meso and macro scales, not point scales (Scanlon et al., 2017, Lant et al., in review). ~~All~~Most catchment hydrology applications operate at coarser scales than the "immediate environment" or "point~~".~~" scale of space and time. A water census data model must therefore explicitly include spatio-temporal scale and control volume corrections, which is a tall order given the myriad scales at which census data is collected and at which its users do their science.

~~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 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.~~Additionally, the information quality of consumption data (R or U) must match W for these to be combined properly. In the US and most global locations, we currently have much better W data than C data at census scales. 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~~If error is concentrated in the U term, W is likely to be dramatically more accurate than C. It is misleading and possibly incorrect to calculate spatially and temporally explicit consumptive water use C using a spatially and temporally non-representative U~~. Most of the~~, because it is difficulty to appropriately qualify the errors introduced. The spatio-temporal information content comes from W, and what is provided by U is likely to be anti-informational.

~~Third,~~ A final challenge is the institutional and socio-political complexity involved in the implementation of a water census. For instance, the USGS is a single federal agency with a funded mandate to collect water use data nationwide. Collection of water consumption data requires participation by municipalities (for multiple urban uses) and environmental agencies (for water quality), along with the private sector and the census bureaus (for attribution of water use to economic purposes), and wastewater utilities (for return flows) in myriad local and State jurisdictions. Water withdrawal ~~is a good index of water use impact and risk. In one of the complicating instances covered in Figure 1,~~ data, by contrast, is much simpler to collect because it only involves a State water supply agency, and/or direct surveys of water users, either of which may have records of simple withdrawal ~~will usually be a better index of hydrologic alteration than simple~~ from the natural environment or from public supply. A census water data model for consumptive use must be capable of managing a much wider range of institutional contexts and data sources, as compared with a simple withdrawal data model or with the use of SNCU assumptions.

The complications presented in Figure 2 should not surprise us because the natural water cycle is a looping network comprised of gross flows and water quality transformations, not a line or a point, and the addition of the human economy makes this water network even more complicated. Accordingly, the proper water use data model is a network by which water is moved, stored, used, transferred between users, transformed in quality, and (sometimes) returned to the original water source- but just as often returned to a different source. As a result, the proper census water use data model for consumptive use must explicitly treat spatiotemporal scale, production of water, transfer of water, pass-through of water to other users, transformation of water quality, return flows to water stocks other than the source (i.e. negative consumption), storage, and delayed flow and use. This new data model should be a "stock-and-flow" water accounting model (Ruddell et al. 2014, and many others) and might include natural capital accounts of water (Costanza et al., 1997). This new data model should separate pass-through water producers and conveyers (e.g. the Central Arizona Project or a public supply utility) from the end users of water (e.g. factories, farmers, fish, power plants, or residents). This new water census data model is a challenging requirement for a water census to address, even approximately, for an entire country's retinue of water stocks and water users, or for the multiple scales at which the data is required by users. In many cases the primary data does not currently exist (other than withdrawal data), and even where it does there is a great deal of detailed accounting work necessary. Yet this is what we need from a future water census.

3 When can census water withdrawal data replace consumptive use data?

Simple net consumptive use accounting is misleading in many census applications. A water census program measuring this broader spectrum of data is not likely to produce usable data resources in the short term, owing to the cost and complexity involved. Where does this leave us in the short term? 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 at census scales. There are several instances where researchers and managers could be well served by use of water withdrawal data as an approximation of, or even replacement for, consumptive water use data. As emphasized in the introduction, these instances emphasize meso and census scale applications, although in some cases fine-scale applications are warranted.

Most obviously, consider that withdrawal conservatively bounds consumption, especially in the simple net consumptive use case. In the simple net consumptive use case 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 leaving adequate water in the channel. 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 $U \geq 0.1$ will generally be true except for the oldest thermoelectric and industrial facilities. U often approaches 1 ($W = C$) for irrigated agriculture, the largest water user worldwide and in the US. 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 2, neither W nor C are adequate, but in the simple net consumptive use case, W is often a decent conservative proxy for C. This is why the Michigan Water Withdrawal Assessment Process uses withdrawal-based water use estimates as a preliminary screen for potential aquatic ecosystem impacts of water use, but not as the final word for decisions (Hamilton and Seelbach, 2011). The use of W as a conservative bounded estimate for C is not helpful when we are studying water supply stress in water-stressed locations where W is a large fraction of available water, because the difference between W and C can be critical for this application. But for other applications, and especially where simple net consumptive use

assumptions are valid, the substitution of W for C is often useful, and may be a best practice if we have good W data but poor C data (as is currently the case for census scale data).

Consider also that W is superior to C as an index of some types of impacts and risks associated with water use. Aquatic ecosystem impacts caused by water intake fish mortality is proportionate to ~~withdrawal, not consumption.~~W, not C. Thermoelectric, public supply, and industrial systems risk curtailment of operations if inadequate intake water is available (e.g. the withdrawal-to-availability index WTA). If withdrawal requirements exceed available water, it does not help that C or U are small. Similarly, the operating capacity of a water diversion, transportation canal, or water supply tunnel is limited by its ability to withdraw and convey at a maximum rate, not by the amount of water it consumes. Consumption is a water supply risk ~~is another good example, because risk is~~ factor at aggregated scales, and it contributes indirectly to the availability of water to support withdrawal. But for the granular water user at the local scale, these aspects of risk and impact are more proportionate to ~~withdrawal demands and available~~the rate of flow of water ~~stocks~~, rather than ~~to~~the volume of water ~~consumption~~consumed.

~~Fourth, withdrawal~~ Water infrastructure cost is the most important example of a management decision conditioned heavily on withdrawal rates ~~drive infrastructure capacity and fixed cost.~~. Peak withdrawal rates are the main driver our water infrastructure's fixed costs and are therefore a key variable in long-term economic decision making and strategy for water supply infrastructure. While water census data will not be used for most local water infrastructure engineering work, water is a capital-intensive and infrastructure-heavy sector of the human economy~~. Fixed~~ and water infrastructure ~~cost~~figures prominently in macroeconomic planning where census data is ~~human and physical in nature.~~heavily employed. At the local scale, 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~~ capacity of the system. Sewerage and wastewater treatment costs are likewise proportionate to ~~upstream withdrawal volumes.~~flow rates. Wholesale water prices and bulk water rights are ~~denominated~~priced 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~~Higher withdrawal prices translate to reduced demand, and in some cases into reduced consumption. Some exceptions to this pattern involve attempts to price and pay for external costs, such as in the use of water banks where return flows are credited or the use of payments for the ecosystem services of water left in a stream or river. But in general, infrastructure costs correlate to W, more than to C, and W is the correct measure for analysis of cost and price.

~~Fifth, marginal withdrawal~~Finally, water withdrawal rates influence water user behaviour through water use 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~~. Most municipal water ~~systems, and one could imagine a world with more sophisticated internal metering and billing~~users are billed at marginal rates that ~~incorporates water use timing, quality, and net consumption.~~cover marginal operating costs, and marginal operating costs for public water ~~have long been~~supply systems are 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~~behaviour, even for the least sophisticated residential water consumers (Arbués et al., 2003). 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. But, because withdrawal is what ~~customers~~ the users of public supply pay for on the margin, ~~it is reasonable~~water customers are adjusting their behaviour to ~~assume that most consumers' water use decisions are driven primarily by~~economize withdrawal ~~rates~~, not consumption. Customer water withdrawal data is therefore what water economists and pricing consultants usually need to do their work.

In summary, water withdrawal data can substitute for, or even replace water consumption data for several common census scale applications of water data. These applications notably include (a) where a conservative (i.e. high) approximation for C is acceptable, (b) where risk, impact, and decision making factors are proportionate to flow rates (rather than consumed volumes), (c) the design of water infrastructure where fixed capital costs which are often proportionate to peak flow rates, and (d) the economics of water users (especially in public supply systems). W should not replace C in circumstances where an accurate in-channel water balance is required, for example on the Lower Colorado River Basin where a 5% difference in consumption can trigger or avert a legal water emergency.

4 Conclusions

~~Our scientific and policy questions require~~Our census-scale water research requires a 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~~That 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~~ , like the ~~multiplication of~~natural water cycle, is more of a circular network than a ~~simple consumptive use coefficient by measured withdrawal adds little to our understanding, and is misleading in the most common human water use cases.~~point or line. In some ~~cases W is~~of the simplest special cases withdrawal based numbers are approximately sufficient, and in most other cases simple net consumptive use is insufficient~~. A~~ (Section 2). A water census 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, and embrace a "stock and flow" data model that considers the complicated network of water users that store, pass-through, and transform water. 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~~.~~ based on this argument. 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~~ at point-of-use ~~accounting~~scales. An expanded census needs to address spatiotemporal scale, production of water, transfer of water, pass-through of water to other users, separation of water producers/conveyers from end users, transformation of water quality ~~at withdrawal and~~ , return~~, seasonal timing, specific stream segment~~ flows to water stocks other than the source (i.e. negative consumption), storage, and delayed flow and ~~aquifer sources, multiple~~use, using a "stock 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.~~flow" data model. This paper explains why, and provides guidance on ~~what measurements~~some of the use cases that would ~~be needed~~need to ~~nationally survey consumptive uses of~~be addressed by an improved 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~~coupled natural human systems.

While we wait ~~for that water use data~~those future advances, simple and widely available census scale water withdrawal data is already available and 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~~some important applications ~~of~~. The applications where water withdrawal data can be substituted for or replace water consumption data ~~include water resource policy, socio-hydrology, water~~ tend to operate at meso and macro scales, emphasizing considerations of systemic risk, infrastructure cost, and economics~~, ecohydrology, municipal and industrial water management, water use regulation and law, water footprints, and Life Cycle Analysis.~~. Researchers ~~studying CNH topics~~and managers should proceed to use withdrawal-based water use numbers with confidence and peer reviewers should reasonably accept this ~~approach~~choice, especially if the ~~special cases and limitations discussed~~considerations in this paper are appropriately addressed.

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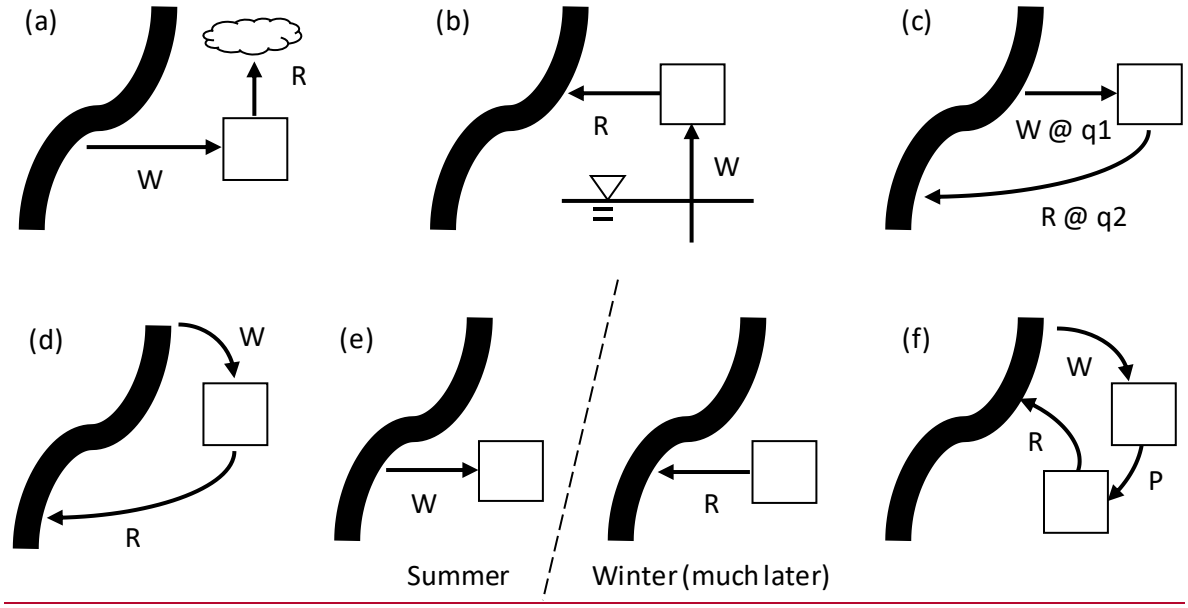

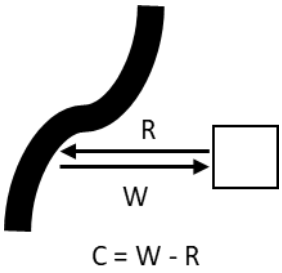

~~Figure :~~

Figure 1: The trivial, but confounding, simple net consumptive use case. Water is withdrawn (W), rapidly used by a single user or group of users, and then a smaller amount is returned (R) immediately to the exact point of withdrawal at sufficiently similar water quality. This is a convenient accounting for water resource management work, but it belies the significant complications involved in real-world water uses (see Figure 2).

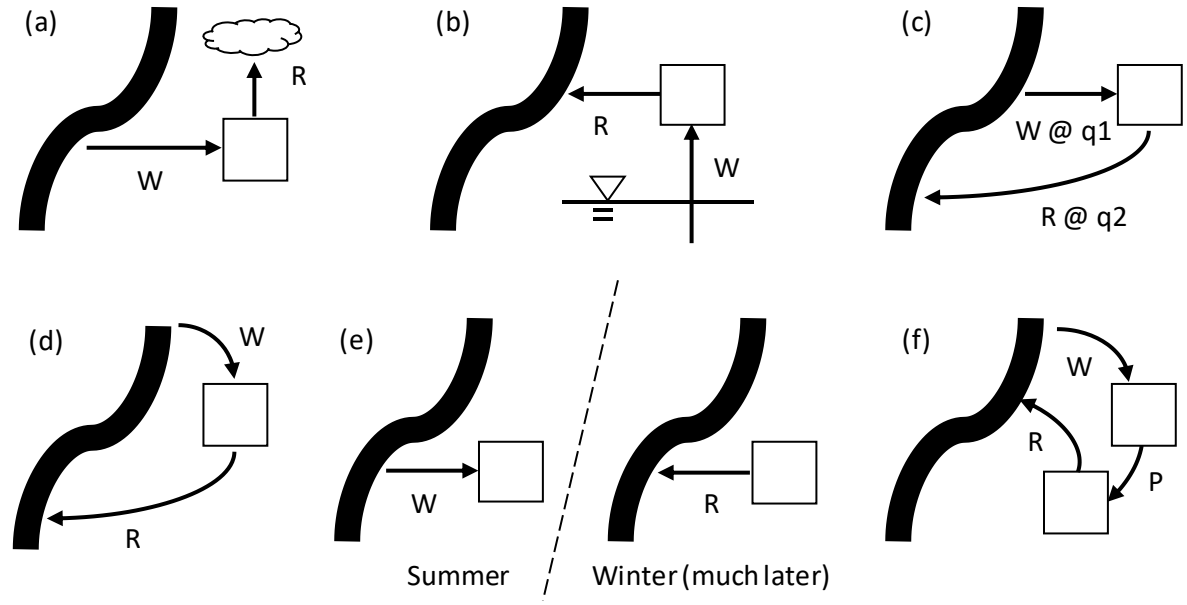

Figure 2: Six common out-of-channel water use cases that confound a simple net consumptive use (SNCU) calculation~~:~~ (see Figure 1): (a) return flow R to a different pool, for instance evaporative use of irrigation water, (b) return of groundwater withdrawal W to surface water, a special case of (a), (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.