Editor Decision: Publish subject to minor revisions (review by editor) (10 Feb 2019) by Nunzio Romano
Comments to the Author:
Dear Authors:
Your revised paper is close to final acceptance, but I would invite you to read the comments from Ref.#2 and see if some additional changes can be done to your paper. Overall and to the benefit of a wider readership, please consider to improve the writing and some plots. Should you disagree with some comments, please clearly explain why.

Response to Editor:

Thank you for your review. We have read and considered the comments by Ref#2. We have incorporated many of their suggestions, which has helped to improve the readability of the paper. We provide a point-by-point response to their comments below, followed by the manuscript that includes the "tracked changes" to show any changes to the document.

Report #2

Review: Characterising the Potential for Drought Action from Combined Hydrological and Societal Perspectives, Towler et al.

Reviewed February 2019

Author's general response on Report #2:

We thank the reviewer for the thoughtful and detailed review. We appreciate your comments, in particular your suggestions from the literature that help provide more context for our work, your specific recommendations on how to clarify our writing and plots, as well as the useful feedback that helped to tighten up the discussion of our work. Below, we provide a point-by-point response to your comments, and also briefly point out the two structural changes here:

(1) As suggested, we moved the discussion of "Future Enhancements" and Figure 9 out of the Conclusions section, and into its own section of the Discussion (section 4.5). Within this section, your comments helped us to expand some of the points in Figure 9, as well as to add some discussion on the transferability of the method and connection with operational drought products.
(2) Second, we have taken your suggestions of incorporating the figures from the Supplemental Information (SI) into the main manuscript. As such, we no longer have an SI section.

Summary:
Linking groundwater to drought response actions to develop a new indicator, the Potential Drought Action Indicator (PDAI). The PDAI is applied in south-central Oklahoma where there are disputes around the use and management of groundwater in the Arbuckle-Simpson Aquifer (ASA). The indicator aims to understand what actions people may take in response to drought and when they may take them. The PDAI is built around water users perceptions on the

importance of water for specific uses. This is a novel approach, but perhaps difficult to see how this could be rolled out more widely – particularly in an operational setting.

Recommendation:
I enjoyed the paper in its attempts to incorporate management actions with physical indicators of drought, better understanding the link between indicators and impacts, but also management actions is crucial to improve monitoring and early warning of droughts in human modified systems. However I feel the paper needs major revisions before it can be accepted. Please see below.

Overarching Comments:

The aims of the paper should include a view on how this will be useful for operational monitoring systems and the additional information it will provide on top of what is already available e.g. through the National Drought Mitigation Centre Drought Monitor etc.
We agree that there is scope within the Discussion to comment on how an index like the PDAI is complementary to existing drought products. This point is also related to a later comment about the transferability of the research. As such, in the Discussion, following the discussion of the key points of Figure 9, we have added (line 553):

> "Related to the points above is the question about how the PDAI could connect with existing operational products and its transferability to other locations. In our case, groundwater threshold exceedance was linked with water use impacts. Ideally, the PDAI could be modified to incorporate an operational drought indicator that is associated with impacts; however, evaluations of the connection between monitored indicators and impacts has been limited (Bachmair et al 2016)."

There is no validation of the new indicator – this is crucial in order to see whether the indicator works --- could it be validated against Drought Impact Reporter response data? If not, include in the discussion why it's not possible to use DIR data.
In the Future Enhancements (section 4.5), we address the need for validation in Point 5 in our discussion of Figure 9. We have extended this discussion to include the suggested Tijdemen et al 2018 paper, as well as the limitations of the DIR for validation (e.g., Lackstrom et al. 2013). Here is the excerpt, additions in bold (line 543):

> "Other options for validation can be indirect, such as looking at historical data, like government and local reports, media, and/or other collected response information, e.g., in the United States the US Drought Impact Reporter (DIR; Wilhite et al. 2007). **Tijdemen et al (2018) examined the relationship between drought indicators and impact data from the DIR; however, it has been noted that the DIR would benefit form a more systematic and coordinated collection effort (Lackstrom et al. 2013), which presents challenges for its interpretation**."

How can this approach be applied in other locations? Would the same interviews need to be repeated? I gather the link to the world views is an attempt to see how it could be transferred elsewhere, but unless these world view responses are also available then can it be transferred? The groundwater level thresholds used here were clearly related to management actions or changes in system behaviour – it would be useful to address how you would obtain these data elsewhere. This should also be considered in a discussion on the transferability of this research.

It is interesting to think about the transferability of the research. First, in terms of your comment about: "The groundwater level thresholds used here were clearly related to management actions or changes in system behaviour – it would be useful to address how you would obtain these data elsewhere", this relates to your previous question about how this work relates to operational products. Here we note that ideally, the hydrologic perspective term of the PDAI could be modified to incorporate an operational drought indicator that is associated with impacts; however, this is difficult since the connection between monitored indicators and impacts is lacking (Bachmair et al 2016). The second question here is about the transferability of the worldview responses. Although the responses themselves may not be transferable, the idea behind the cultural theory of risk worldview measures is that they are loosely universal, that is, they should apply fairly well to any context within the broad culture for which they were initially put together, in this case the United States (Smith and Leiserowitz 2014). Worldview measures can also be build-on and tailored to a particular context (Lazrus 2016), which can provide additional insights for particular applications. We have added text to this effect in the Future Enhancements section 4.5 (line 553):

> "Related to the points above is the question about how the PDAI could connect with existing operational products and its transferability to other locations. In our case, groundwater threshold exceedance was linked with water use impacts. Ideally, the PDAI could be modified to incorporate an operational drought indicator that is associated with impacts; however, evaluations of the connection between monitored indicators and impacts has been limited (Bachmair et al 2016). In terms of the transferability of the social perspective, the idea behind the cultural theory of risk worldview measures is that they are loosely universal, that is, they should apply fairly generally to any context within the broad culture for which they were initially put together – in this case, the United States (Smith and Leiserowitz 2014). However, worldview measures can also be tailored to a particular context (Lazrus 2016), which might need to be revised for other applications."

The fact interviews were undertaken during a drought may have skewed the responses from stakeholders – there is often a loss of memory about droughts after an event has ended, if the questionnaire was repeated, would the same levels of importance be assigned to the water uses? Although it may not be possible to repeat the surveys, this question of bias should be addressed in the discussion.

We agree with this point, and do address this in the Discussion (section 4.5), point 2. Now we explicitly add-in this notion of bias (line 500, change in bold):

2. "Our interviews were conducted following a drought event, and we recognize that the timing of the interviews will likely affect the responses, **possibly introducing a bias**. For instance, interviews conducted during wet or average conditions might elicit less polarized responses, since drought impacts haven't been recently experienced. We note that our approach of applying the interview responses across different climate conditions (i.e., wettest to driest) makes the assumption that the importance of water uses and management preferences are stationary. We acknowledge that different climate conditions, as well as cultural change, technological innovation, climate adaptation, and other processes are likely to influence the cultural factors we investigated here and may mediate how people interact with their environments. Future work could investigate how responses change with different climate conditions over time, and the subsequent implications for drought action. However, hazards and disasters research is almost always conducted immediately after an event, so this is a

wise-spread epistemological issue with both pros and cons in terms of what we learn from post-disaster research."

L207-212: There is not enough information provided on how you derived the drought indicators (PDSI, PDHI and SPI) and what data were used. You should include brief descriptions of the methods (e.g. including what distribution was used to derive the SPI, what years were data available etc.) and crucially the references for each and which variables from the data you cite were used for each. This should be introduced before the cross-correlations with decadal groundwater likelihoods. There is a general imbalance throughout between the discussion and description of hydrology compared to the social sciences.

We have added specific information on the drought indicators, along with the relevant citations. However, we note that we did not need to derive the indices ourselves, rather we downloaded readily-available data from the NOAA National Climatic Data Center, which we provide the url for (http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp). In terms of readability and flow of the paper, we have opted to keep the description in the same paragraph (rather than to move it earlier in the Methods), but have revised it to include more details. The revised excerpt from the text (line 214):

> "Specifically, we correlate the decadal likelihoods with 10-year running averages of several drought indicators from different categories. As a measure of agricultural drought, we use the well-known Palmer Drought Severity Index (PDSI; Palmer, 1965) that is based on a water balance of precipitation, soil moisture, potential evapotranspiration, and runoff. We also look at the Standardized Precipitation Index (SP), which only considers the effect of precipitation variability on drought (McKee et al., 1993). The SP can be calculated to consider different time scales: for example, the 1-month SP (SP01) considers short-term conditions, and the 24-month SP (SP24) considers longer-term conditions (i.e., precipitation from the last 2 years). We use the 6-month SP (SP06). To measure hydrological drought, we use the Palmer Hydrological Drought Index (PDHI; Palmer 1965), which is a modification of the original PDSI to account for longer-term dryness that affects water storage, streamflow and groundwater. NOAA's National Climatic Data Center provides this historical data for United States climate divisions; we downloaded monthly data from 1959 to 2012 for Oklahoma Climate Division 8 from http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp."

The conclusion introduces new material – it should cover the content of the paper in a standalone manner. I suggest you create a new section 4.5 on future enhancements and the drought feedback loop described in Fig 9 – i.e. Lines 500-562. It may also be helpful to consider a section to discuss how you see the PDAI working alongside existing monitoring tools and the Drought Impact Reporter to manage and monitor droughts in near-real-time – this may then feed into your section on future enhancements.

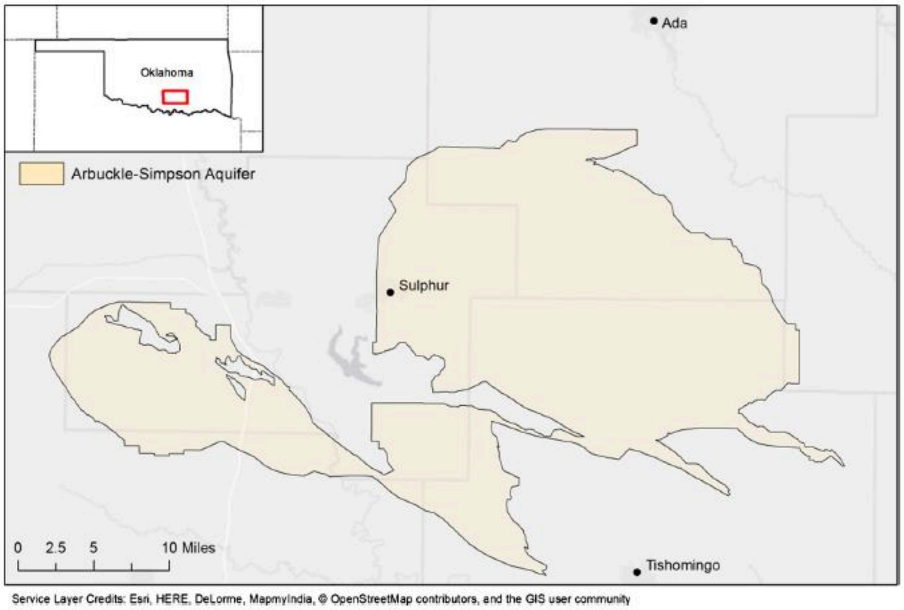
We agree with this suggestion. We have moved the "Future Enhancements" discussion and Figure 9 to a new section 4.5 (line 482). in the Discussion. Further, as addressed in an earlier response, we now provide our view on how it could work with existing monitoring tools, as well as the associated challenges.

Individual Comments:

It would be helpful to include a map of the area as figure 1, to include the ASA, Oklahoma City and the locations where you undertook interviews

We note that our paper is already quite long, with 9 Figures. In the interest of space, we have chosen not to add another figure to the manuscript. However, for the benefit of the reviewer, we provide here the figure used in Lazrus (2016):

Fig. 1 Map of south central Oklahoma showing towns, surface water, and the Arbuckle-Simpson Aquifer



L58: add Bachmair et al. 2016 (https://onlinelibrary.wiley.com/doi/full/10.1002/wat2.1154) reference here which assessed global MEW providers and found a lacking in impacts (on society and the environment) in the monitoring systems
Thank you, this has been added.

L67: do you mean more systematic monitoring of impacts or indicators? Make this clear, I think it means impacts(?)
Yes, thank you we have added it to now say: "systematic impacts monitoring"
L91: add Tijdeman et al 2018 (https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2017WR022412 to the Pulwarty reference here
We have added the reference.
130: what is Climate Division 8? Please provide context for the international audience who may not be familiar with this
We have added more context and a reference for readers who are not familiar with climate divisions (line 130):

> "This area is part of Oklahoma, Climate Division 8 (Karl and Koss, 1984), which is one of the 344 climate divisions that the United States is divided into for reporting purposes, based on climate as well as several other considerations (Guttman and Quayle 1996)."

Guttman, N. B., and R. G. Quayle, 1996: A historical perspective of U.S. climate divisions. Bull. Amer. Meteor. Soc., 77, 293–303, doi:10.1175/1520-0477(1996)077<0293:AHPOUC>2.0.CO;2.

L157: "an anthropological lens through which to examine how stakeholders perceive" grammar could be improved here
We have revised that sentence (line 159):

"Lazrus (2016) describes results of stakeholder interviews collected for the ASA; it offers an anthropological perspective, examining how stakeholders perceive drought and how those perceptions intersect with their cultural processes."

L223: the grammar of this key question could be improved

We have revised the sentence (line 240):

"For this study, we examined the question: "How do people perceive the importance of water for various uses?""

L241-243: the grammar improving, as it is this paragraph doesn't read as a complete sentence. What other functions would you apply and for what purposes – perhaps provide an example here

We have revised the sentence and added an example of another function (line 258):

"Multiplying two terms to create a new indicator is based on a frequently used definition of risk, which combines the likelihood of an event and its consequence (Jones and Preston 2011). However, we point out that the form of f is flexible, e.g., it could be additive, etc."

L245-248: Am I correct in thinking therefore that a PDAI is computed for each of the 6 water uses described L229-231? Make this clear in Section 3.3

Yes, that is correct. We have added (line 267):

"The PDAI was calculated for all 6 of the water uses asked about in Section 3.2."

Add into Section 3.3 that lower PDAI equates to less potential for action and higher PDAI indicates greater likelihood of action for clarity.

We have added this (line 266): "In this definition, a lower PDAI equates to less potential for action and higher PDAI indicates greater likelihood of action."

Section 3.4: it would be interesting to see the questions and statements used to establish the world views, these be included in the supplementary information

The questions are included in Lazrus (2016), so we have added to the text (line 298, change in bold):

"For the CTR, interview questions about worldview used previously tested measures for individualism and egalitarianism developed by Smith and Leiserowitz (2014) as well as additional questions informed by CTR that reflected the particular water management context of the ASA; **all questions can be seen in Tables 1 and 2 of Lazrus (2016)**."

We also note we have taken your suggestion to replace several figures in the main text with the figures form the SI, therefore we no longer have an SI section. For the benefit of the reviewer, we include Table 1 and 2 from the Lazrus (2016) paper here:

Table 1 Universal egalitarian and individualist indices

	Mean	SD	Alpha
Universal Egalitarian Index (n = 38)			0.74
In my ideal society, all basic needs (food, housing, health care, education) would be guaranteed by the government for everyone.	2.05	1.138	
I support government programs to get rid of poverty.	3.29	1.271	
Discrimination against minorities is still a very serious problem in our society.	3.50	1.202	
The world would be a more peaceful place if its wealth were divided more equally among nations.	2.84	1.175	
Universal Individualist Index (n=38)			0.86
The government interferes too much in our everyday lives.	3.18	1.353	
Government regulation of business usually does more harm than good.	2.97	1.197	
People should be allowed to make as much money as they can, even if it means some make millions while others live in poverty.[a]	3.84	.916	
If the government spent less time trying to fix everyone's problems, we'd all be a lot better off.	3.03	1.345	
Our government tries to do too many things for too many people. We should just let people take care of themselves.	3.08	1.239	

Response scales range from 1 (Strongly disagree) to 5 (Strongly agree); based on Smith and Leiserowitz (2014).

[a] This question was difficult for some interviewees to understand, perhaps because it has two parts and one could conceivably agree with one part while disagreeing with the other. However, even if this measure is removed from the analysis, it does not affect Cronbach's alpha (alpha for this item if deleted is 0.863).

Table 2 Contextual egalitarian and individualist indices

	Mean	SD	Alpha
Specific Egalitarian Index (n = 38)			0.75
Water should be managed by a communal process in which everyone has an equal say.	2.84	1.220	
Individual water rights need to be limited for the sake of the collective good.	3.76	1.218	
Specific Individualist Index (n = 38)			0.68
Individuals should be able to determine how best to use water on their own property.	2.87	1.234	
Restrictions on how property owners can use water on their property are an infringement of individual rights.	2.79	1.318	

Response scales range from 1 (Strongly disagree) to 5 (Strongly agree)

Figure 1 is not mentioned in the text, introduce this in Section 3.3

Figure 1 is introduced right after "3. Methodology", and it provides the conceptual overview of sections 3.1., 3.2, and 3.3. This reads (line 177): "Figure 1 provides the conceptual overview of the study methodology, which is detailed in the subsequent sections."

Figure 2 & Figure S1: As figure 2 is the same as the 10 year panel of Figure S1, is suggest that Figure S1 is removed from SI and replaces Figure 2. As it is, it represents unnecessary duplication and due to the different plotting style (including different y-axes) and different captions, provides potential for confusion.

This is a good suggestion, though we note that it is Figure 3 where the 10 year panel is the same as Figure S1 (Figure 2 is the raw groundwater time series). As suggested, we have replaced Figure 3 with Figure S1 and updated the caption. The text now reads (line 315): "Drought likelihoods for the selected time windows (5-, 10-, 15-, and 20-years) are shown in Figure 3."

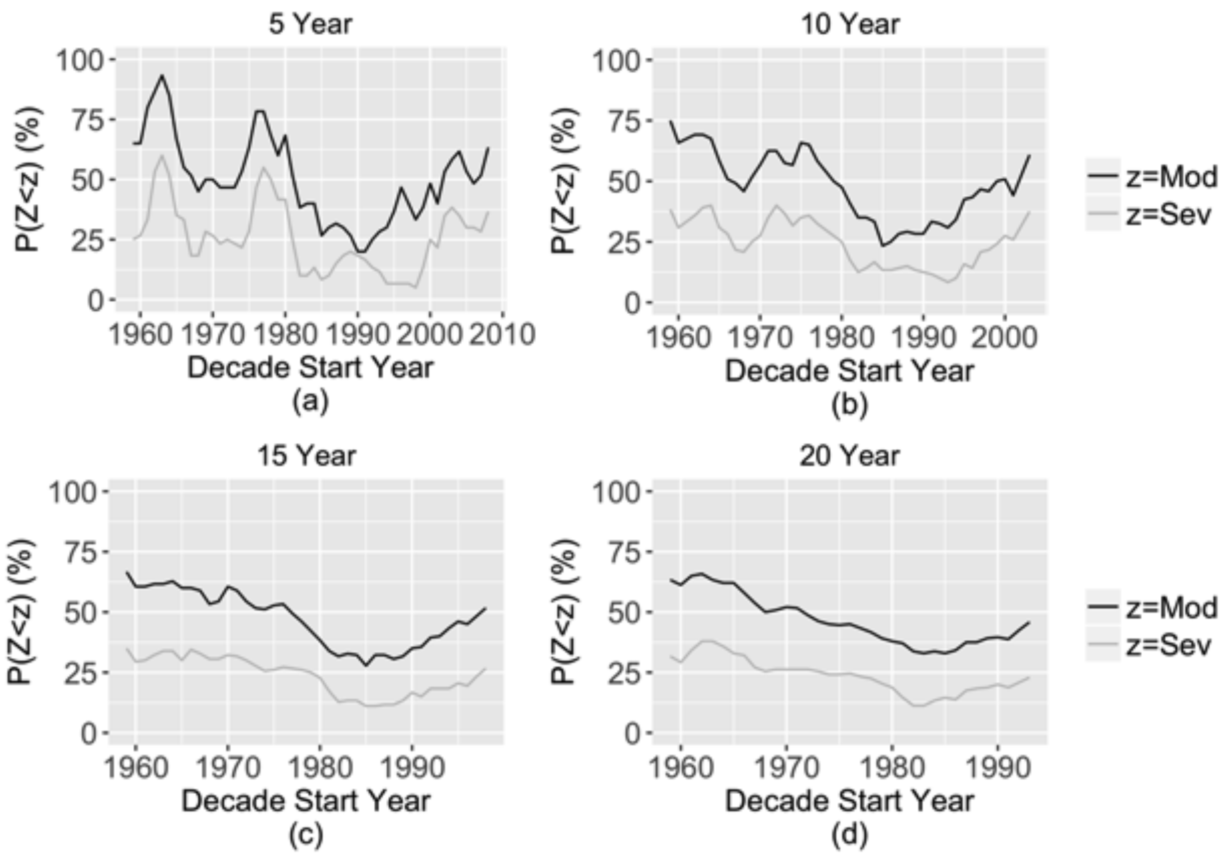


Fig. 3. Groundwater drought likelihood (P) of the depth to groundwater level (Z) going below the moderate (Mod, z=-111 ft) and severe thresholds (Sev, z=-117 ft) for time windows from 5 to 20 years.

L300: ‘that have high variability and likelihood swings (e.g. 5-year windows) and longer time…’ not needed

We removed “and likelihood swings”, but left the other parts in to illustrate the relative comparison between the short and longer windows, which provides partial justification for why we selected the 10-year window.

L301: ‘gets washed out’ colloquial – replace with ‘is smoothed out’ or ‘is removed’ or similar.

We replaced it with your suggestion: “is smoothed out”.

L305 (and throughout): are these correlations significant? Please include p-value/indication of significance

We have added that this is significant at the 99% confidence level. For the benefit of the reviewer, the p-value is 1.3e-21. The text reads (line 324):

> “Further, the likelihoods are correlated (r=.94) and significant at the 99% confidence level.”

L306: ‘and selected drought indices’ select should read ‘selected’

This has been fixed.

L306: ‘hydrologic threshold exceedance’ – this refers to the groundwater exceedance, it should say groundwater, not hydrologic for consistency (especially as hydrological drought indicators are used elsewhere to discuss the PDHI)

“Hydrologic” has been changed to “groundwater”.

L307-308: when the established drought indicators were introduced, these drought type categories (meteorological, hydrological, agricultural) were not given – include these in the methods section, and you could include the indicators following the appropriate drought type in brackets

We now introduce the agricultural (PDSI), meteorological (SP06), and hydrological (PDHI) drought indices in the Methods (line 216), and put the indicators following the appropriate drought types here now as well (line 327).

Table 1: what is the significance of these correlations?

We have updated Table 1 to indicate the significance, which is over 99% level for all the drought indices examined:

Table 1. Correlation Between Select Drought Indices* and the Likelihood (P) of Groundwater (GW) Level Going Below Moderate (Mod) and Severe (Sev) Thresholds

Drought Index		Correlation	
Type	Name	P(GW<Mod)	P(GW<Sev)
Agricultural	Palmer Drought Severity Index (PDSI)	-0.92**	-0.83**
Hydrological	Palmer Hydrological Drought Index (PDHI)	-0.95**	-0.84**
Meteorological	Standardized Precipitation Index - 6 month (SP06)	-0.94**	-0.82**

* Drought indices for Oklahoma Climate Division 8 downloaded from: http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp

** = Significant at the 99th percentile

Although we don't include the p-values in the manuscript Table 1, we include the p-values below for the benefit of the reviewer:

Drought Index		Correlation		P-value	
Type	Name	P(GW<Mod)	P(GW<Sev)	P(GW<Mod)	P(GW<Sev)
Agricultural	Palmer Drought Severity Index (PDSI)	-0.92**	-0.83**	4.6E-19	1.3E-12
Hydrological	Palmer Hydrological Drought Index (PDHI)	-0.95**	-0.84**	7.5E-23	3.3E-13
Meteorological	Standardized Precipitation Index - 6 monht (SP06)	-0.94**	-0.82**	5.4E-21	3.6E-12
	** = Significant at the 99% percentile				

L310-311: It would be nice to include a plot of the rainfall, river flow and groundwater levels for the area together to show the variability of these variables over the time period (and/or the indicators themselves). It would then be possible to see the relationship between the flows and ASA levels

We currently do include the groundwater level time series (Figure 2), but creating a new plot that also includes rainfall and river flow is not critical to the paper. Further, we are already at 9 figures, and have replaced several single panel plots with multi-panel plots from the former SI.

L313-315: when discussing other aquifers and the potential impact of greater human influences on levels, the properties of the aquifer will also play an important role in the relationship with the PDHI/SPI/PDSI etc. as for example, a more slowly responding aquifer may have a poor relationship with the hydrology due to increased propagation times.

This is a good point. We have added to this paragraph (line 333, changes in bold):

> "However, we note that that this may not be the case for other groundwater aquifers that are more affected by human extraction (e.g., Tarhule and Bergey 2006) **or aquifers with different properties (e.g., slower hydrologic responses due to increased propagation times). This point is further discussed in the Discussion (section 4.5 Future Enhancements)**."

L316 & Table 2: how did you select these decades? This selection should be introduced in the methods.

We have added this to the Methods (line 209):

> "For the analysis, we look at the three most recent decades (i.e., 1983-1992, 1993-2002, and 2003-2012), as well as the highest, median, and lowest decades in terms of the groundwater drought likelihood."

L320-328: "Given the close association of drought (Table 1) this suggests …" Is there a word missing here? Do you mean the strong correlations between the groundwater levels and the other drought indicators? However, I don't think that you can say that because these indicators are correlated that stakeholders experienced dry/average/wet decades. Is the reference to Table 1 a mistake? This paragraph should be made much clearer – this paragraph underlines the suggestion to include time series plots of the variables/indicators as then readers could visualise the dry/wet/average years you discuss here (which could be labelled/marked on these plots too).

We have revised this paragraph, removing the reference to Table 1 and the statement about how stakeholders experienced different conditions. The purpose of this paragraph is to present results from Table 2, specifically the decadal likelihoods of the groundwater levels going below the severe and moderate thresholds. Results are described for the three most recent decades (i.e., 1983-1992, 1993-2002, and 2003-2012), as well as the decades with the highest and lowest groundwater likelihoods from the record. We don't feel that adding another time series plot is necessary, and as mentioned previously, we are already at 9 figures, including having replaced several single panel plots with multi-panel plots from the former SI. The revised paragraph is now (line 338):

> "Table 2 shows the exceedance likelihoods of select decades from the historical record for both moderate and severe. First, we look at the three most recent decades (i.e., 1983-1992, 1993-2002, and 2003-2012), in which relatively wet, average, and dry conditions occurred. For 2003-2012, the moderate threshold was exceeded 61% of the time, which we refer to as the "dry/recent" decade. In the next most recent decades, the exceedance likelihood decreased to 35% (1983-1992) and 31% (1993-2002), which we refer to as "average/recent" and "wet/recent" decades, respectively. To put into context, for the moderate threshold, the decade with the lowest exceedance likelihood was 23% (1985-1994), which we call the "wettest" decade, and highest exceedance was 75% (1959-1968), or "driest" decade. Results follow similar patterns for the severe threshold (Table 2)."

L344: full stop after '(Interview 1)' should be a comma. And comma after perspective should be a full stop.

We had a typo that has been corrected: There should be a period (which is what we believe you mean by full stop) after (Interview 1), but the typo was that the following word should have been capitalized, which I believe caused the confusion. Now it reads (line 361):

> "For example, one interviewee underscored the importance of water, describing that "Murray County is one of the top tourist attractions with Arbuckle Lake and Chickasaw National Recreation area. So water is the absolute key" (Interview 1). Demonstrating a very different perspective, another interviewee noted that "Recreation and water are not critical to me. I mean in this part of the world, they don't necessarily go hand-in-hand because it's a relatively dry place, and there are not that many places to really go and play in the water" (Interview 5)."

Section 4.3: is it possible to include the results for all the water use categories in your description of the results – it is a shame not to include them as you show the data in Fig S2.

This is a good suggestion, and we have replaced Figure 5 with Figure S2. The figure is below:

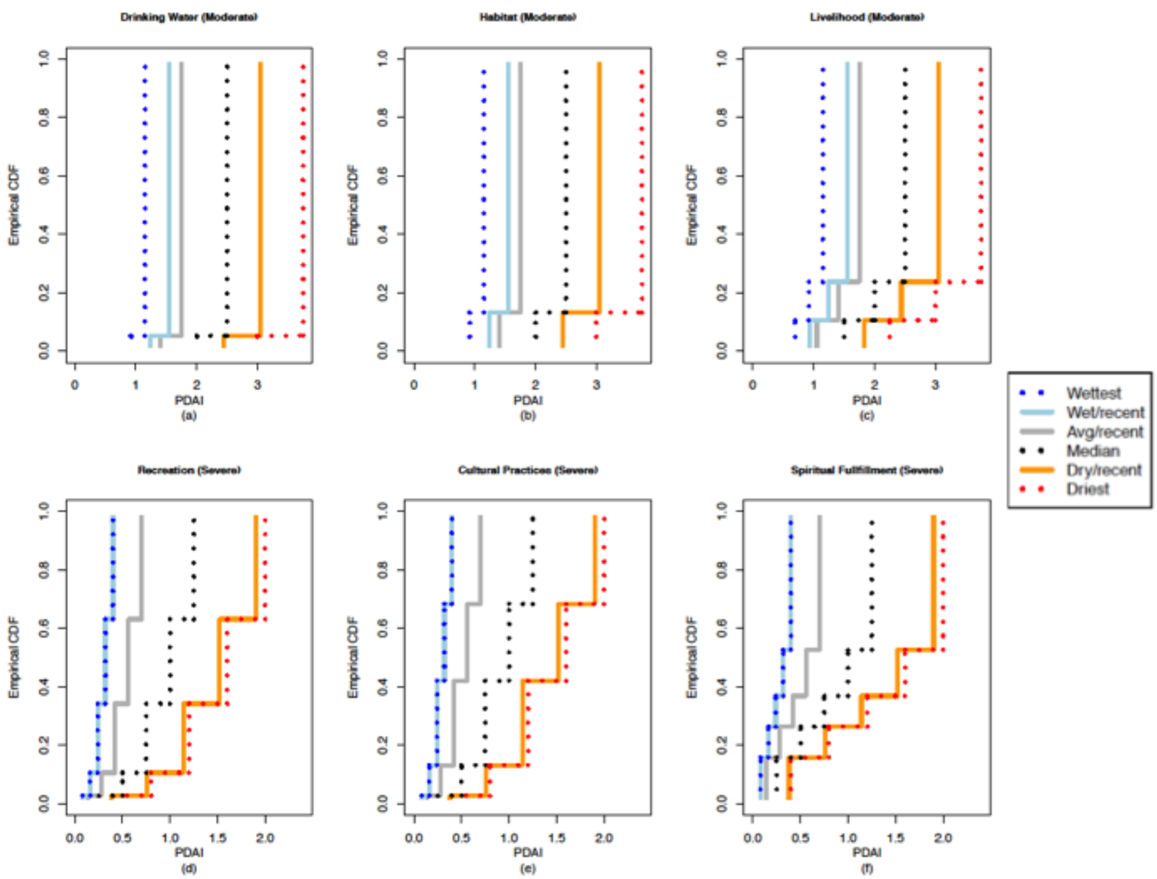


Figure 5. Empirical cumulative density functions (eCDFs) for the PDAI (Potential Drought Action Indicator) for water uses using the moderate threshold (a-c) and for water uses using the severe threshold (d-f), under the wettest, wet/recent, average/recent, median, dry/recent, and driest historical decades.

We have also modified the first paragraph of the Results to reflect this change (line 370):

> "The PDAI is calculated for all of the water uses (Figure 5). Here, the top row shows results for water uses using the moderate threshold (Figure 5a-c) and the bottom row shows results for water uses using the severe threshold (Figure 5d-f). Because the results across the rows are quite similar, we will focus on the results for drinking water (Figure 5a) and then recreation (Figure 5d)."

Figure 5 and Figure S2 for recreation are different – in Fig S2 the lines for driest and dry/rec are the same but in Fig 5 they are different. The equivalent figures for drinking water are identical between Fig 5 and S2 – is this intentional or is there a mistake here? If the data in Fig 5 and S2 are meant to be the same, and given the previous comment, you could just replace Fig 5 with Fig S2

Thank you for finding this, as the figures should be identical; the Recreation in the manuscript is correct (i.e., it is consistent with Table 2). Just for the information of the reviewer: as shown in the legend, the old Fig S2 had used a "very dry" decade (which was from a previous exploratory analysis) rather than the "driest" decade which was used in Figure 5. Now, both use the "driest" decade, and as indicated in the previous response, we have replaced Figure 5 with the corrected Figure S2.

L360: 'of data that are equal to or less than that value.' 'to' missing from sentence

This has been added.

L375: 'from wetter to drier' is this referring to the difference between moving between the eCDFs for the wetter/drier decades? If so, make this clear by adding 'from wetter to drier decades'.

We have added this.

Figure 7 would be more interesting if you include the other water uses, especially as you mention PDAI for spirituality on L402

As mentioned in a previous response, we have now included the PDAI for all of the water uses in Figure 5, but focus the rest of the results analysis on drinking water and recreation. Using just drinking water and recreation are adequate to make the point for Figure 7, which is to compare the moderate and severe thresholds.

Table 3: these correlations (although some are significant) are very low – I'm not sure it's really possible to really draw any conclusions from these results.

This is true, which is why we are careful to say that they "provide initial insight about the role of worldview in how people assess the importance of water". We also edit the discussion of the correlations in Table 3 to highlight the relatively low correlations, although two-thirds (8/12) are statistically significant at the 90^{th} percentile (line 446):

> "Although the correlations are relatively low, eight out of twelve are statistically significant at the 90^{th} percentile or higher."

L427-429: you use the term variance here but I'm not sure this is correct as this is the difference between the correlations for individualism and egalitarianism squared. You should change the word variance here to 'difference'.

We see how this was confusing, as we use Pearson correlation coefficient (r) in Table 1, and then refer to r^2 in this section without any explanation. To clarify, we remove the word "variance" and refer directly to the r values in the table; the sentence has been modified to read (line 450):

> "The water use that showed the highest correlation with worldview was recreation: r=0.45 for Egalitarianism and r=0.40 for Individualism."

L455: I think that your 'finding shows that this disagreement is not solely due to threats…' (rather than mean)

This has been changed.

L467: '…and these corresponded to drought conditions.' Missing 'to' from this sentence

This has been added.

L469: this should be made clear that you mean exceeding the groundwater threshold. The conclusion should succinctly summarise the paper, which includes mentioning the groundwater exceedance and other drought indicators calculated.

We have added "groundwater" and "drought indices" to make it more specific (line 571, additions in bold):

> "A retrospective analysis of groundwater threshold exceedance shows that in recent decades, stakeholders experienced a wide range of likelihoods of exceeding relevant thresholds, and these corresponded to drought **indices**…. We find that for a given water use, drier conditions increase the frequency of exceeding the **groundwater** threshold…"

L506: point 1 – groundwater levels in the ASA closely resemble the climate rainfall signal – you talk about other aquifers having different human activities, but what about where the aquifer properties mean it also naturally behaves differently and levels may not closely resemble the rainfall.

This is related to a similar point the reviewer raised earlier, but we have also added this to the point 1 in the Future Enhancements section (line 489, addition in bold):

1. "For the natural influence on drought, we examine the probability of groundwater drought. In our case, the groundwater levels are closely related to rainfall recharge, which is a function of natural climate variability. We recognize that this is not the case for many groundwater aquifers, where human activities, such as groundwater extraction, may trump the natural climate signal (e.g., Tarhule and Bergey 2006), often leading to water scarcity, rather than a natural phenomenon of temporary water deficiency. In many systems a full water balance would need to be examined to understand the relative contributions of extraction versus moisture deficit to the likelihood of going below a relevant hydrologic threshold. **Further, other aquifers may have different properties; for example, some aquifer's natural response may be different and the levels may not closely resemble rainfall."**

L547: point 5 – you should reference Tijdeman et al 2018 (https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2017WR022412) here which looks at the linkages between meteorological and hydrological drought indices for near-natural and influenced catchments in the US. It also looks at the relationship between the indicators and impact data from the DIR.

Thank you for this reference, we have added it in point 5 (line 546):

> "Tijdemen et al (2018) examined the relationship between drought indicators and impact data from the DIR; however, it has been noted that the DIR would benefit form a more systematic and coordinated collection effort (Lackstrom et al. 2013), which presents challenges for its interpretation."

Figure 2: What period is used to create the 'smoother' average? The should be given in the caption

It was created using the default "loess" method smoother in R's ggplot, which is a type of local smoother. We have added to the caption: "Figure 2. Monthly groundwater time series; blue line is **a local** smoother average…"

Figure 4: could be improved if the y-axis was labelled with more/less important in addition to the numbers 1-5

We updated the caption to reflect the fact that 5 is very important (changes in bold):

> "Figure 4. Rated importance of water for each water use from stakeholder surveys (N=38) **on a Likert scale of 1-5, 5 being very important**. Responses are shown as box plots, where the box represents the 25th and 75th percentile, the line is the median, and the whiskers are the 5th and 95th percentile. Outliers are shown as points outside the box and whiskers."

Figure 7: in the caption the abbreviation Rec is used for recreation, but elsewhere in the paper rec has been used for 'recent' – avoid this multiple uses of the same abbreviation for clarity.

Thank you, we have changed "Rec" to Recreation and updated the figure and caption:

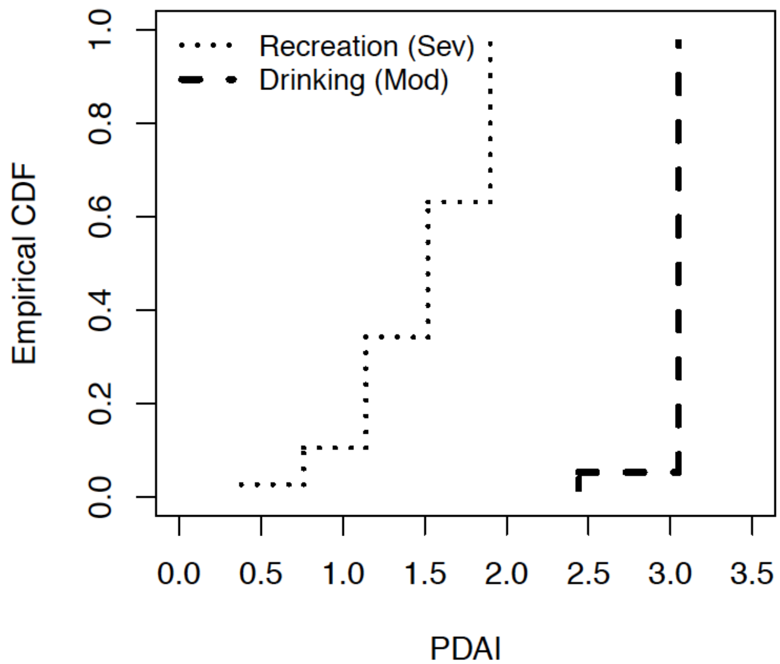


Figure 7. Empirical cumulative density functions (eCDFs) for the PDAI (Potential Drought Action Index) for recreation using the severe (Sev) threshold and for drinking water using the moderate (Mod) threshold for the dry/recent decade (2003-2012).

Characterizing the Potential for Drought Action from Combined Hydrological and Societal Perspectives

Erin Towler[1], Heather Lazrus[1], Debasish PaiMazumder[1,2]
[1] National Center for Atmospheric Research, P.O. Box 3000, Boulder CO 80307-3000
[2] AIG, American International Group, Cat Management & Analytics Center of Excellence, Philadelphia, PA

Correspondence to: Erin Towler (towler@ucar.edu)

Revised for HESS – Hydrology and Earth System Sciences. https://www.hydrology-and-earth-system-sciences.net/

Abstract

Drought is a function of both natural and human influences, but fully characterizing the interactions between human and natural influences on drought remains challenging. To better characterize parts of the drought feedback loop, this study combines hydrological and societal perspectives to characterize and quantify the potential for drought action. For the hydrological perspective, we examine historical groundwater data, from which we determine the decadal likelihoods of exceeding hydrologic thresholds relevant to different water uses. Stakeholder interviews yield data about how people rate the importance of water for different water uses. We combine these to quantify the Potential Drought Action Indicator (PDAI). The PDAI is demonstrated for a study site in south-central Oklahoma, where water availability is highly influenced by drought and management of water resources is contested by local stakeholders. For the hydrological perspective, we find that the historical decadal likelihood of exceedance for a moderate threshold associated with municipal supply has ranged widely: from 23% to 75%, which corresponds well with natural drought variability in the region. For the societal perspective, stakeholder interviews reveal that people value water differently for various uses. Combining this information into the PDAI illustrates that potential drought action increases as the hydrologic threshold is exceeded more often; this occurs as conditions get drier and when water use thresholds are more moderate. The PDAI also shows that for water uses where stakeholders have diverse views of importance, the PDAI will be diverse as well, and this is exacerbated under drier conditions. The variability in stakeholder views of importance is partially explained by stakeholders' cultural worldviews, pointing to some implications for managing water when drought risks threaten. We discuss how the results can be used to reduce potential disagreement among stakeholders and promote sustainable water management, which is particularly important for planning under increasing drought.

Key words
Drought feedbacks, hydrologic drought, climate variability, social perception, cultural worldviews, water management

1. Introduction

Drought can pose significant challenges to meeting the water needs of society and ecosystems, which has led to increased interest in understanding and managing drought risk now and into the future (e.g., Georgakakos et al. 2014). There are many definitions of drought, with the classic definitions including meteorological, hydrological, agricultural, and socioeconomic (Wilhite and Glantz 1985). Similarly, many different drought indices have been developed (Mishra and Singh 2010). The main driver of drought in most definitions and indices of drought is natural climate variability (Van Loon 2016a), which is where efforts to improve prediction and modeling have focused (see Mishra and Singh 2011 and references therein). Even with advances in drought prediction, drought remains one of the most expensive hazards affecting the United States (NCDC 2015), reinforcing the idea that social factors must also be considered for drought planning (Wilhite and Buchanan-Smith 2005; Bachmair et al. 2016).

The need for more proactive drought planning has led to increased interest in the development of drought management plans (e.g., Wilhite et al. 2000, Wilhite et al. 2005, Knutson et al. 1998). Drought risk management requires identifying drought indicators and triggers (Steinemann and Hayes 2005), which can be developed and evaluated using stakeholder processes to make them useful for decision-making (Steinemann and Cavalcanti 2006, Steinemann et al. 2015). Further, the need to better link drought indices with impacts has been recognized (Bachmair et al. 2016). Frameworks to link drought indicators directly with impacts are emerging (Bachmair et al. 2016; Stagge et al. 2015 ; Towler and Lazrus 2016), though there is still a need for more systematic impacts monitoring (Lackstrom et al. 2013). Ostrom (1990) found that assessments that can account for how people value, perceive, and make decisions about resources such as water, particularly when water is scarce, are critical for guiding policies that meet management goals and stakeholder needs, and thus promote sustainable management of water resources. Dessai and Sims (2010) explored public perceptions of drought and climate change to understand barriers to action and paths towards sustainable management. Lazrus (2016) examined how stakeholders perceive drought and how drought intersects with their cultural processes.

Recent work has highlighted how the natural and human causes of drought are intertwined, and that researchers must consider both in any examination of drought (Van Loon 2016a). This general notion has been echoed in the hydrologic science literature (Wagener et al. 2010), as well as the natural hazard (Jones and Preston 2011) and climate change literature (Oppenheimer et al. 2014). This has also motivated the new science of socio-hydrology, which explores the dynamics and co-evolution of human and water systems (Sivapalan 2012). Van Loon et al. (2016b) describe a new framework that explicitly acknowledges the human dimension of drought. They outline several research gaps, including a gap in our understanding of the human feedbacks on drought.

Understanding human feedbacks on drought is important, but has not been well studied, partially because of its complexity and potential for nonlinear feedbacks (Van Loon et al. 2016b). Drought feedbacks can be influenced by many factors, for example, through science and technology (Polsky and Cash 2005), historical lessons learned (McLeman et al. 2014), and management strategies (Maggioni 2015). Further, feedbacks may be positive, i.e., the drought is made worse, or negative, the drought condition is alleviated (Pulwarty 2003; Tijdeman et al 2018). In addition, these interactions and feedbacks can result in changing the normal drought reference baseline (Van Loon et al. 2016b). However, fully characterizing the feedback loops between human and natural influences on drought remains challenging.

The goal of this paper is to provide an experimental methodology towards a better characterization of several components of the drought feedback loop, specifically to gain understanding on how and why people might take action in response to drought. To this end, we develop an indicator to characterize how natural influences on drought inform *potential* human actions on drought. We use the term "potential", since in this study, we do not have the data to validate whether or not human actions were actually taken as a result of these natural drought influences. In this investigation, we characterize the natural influences by taking a hydrological perspective on drought (Van Loon et al. 2016b); specifically, we examine the exceedance of relevant thresholds from historical hydrologic data. For the societal perspective, we examine stakeholder input from interviews, specifically how stakeholders rated the importance of water for different uses. In our attempt to better characterize the potential for drought action, we combine the data from the hydrological and societal perspectives, developing a new, derivative product that we call the Potential Drought Action Indicator (PDAI). Here, by "action", we generally mean some effort towards drought mitigation. Though we do not directly validate the PDAI, we are able to interpret the findings to provide insights to water management policy using additional interview data on stakeholder worldviews and social science theory; this is unique in that it allows us to investigate the theoretical underpinnings that are not typically explored in drought risk studies or stakeholder processes.

We demonstrate the PDAI through a place-based assessment of drought risk in south-central Oklahoma, where water availability is highly influenced by drought and management of water resources is contested by local stakeholders; we provide some background and describe this study site in section 2. Section 3 outlines the methodology: sections 3.1 and 3.2 outline the details of the methods used to assess the hydrological and social perspectives, respectively. Details about how the PDAI is developed is provided in section 3.3. In section 3.4, we describe additional interview data on the stakeholder worldviews and provide an overview of the social science theory. Results for our study site are shown in section 4.

2. Background and Study Site

The goal of this paper is to gain insights into the potential for human action on drought, and one suggested way to do this is to study a particular water system in detail (Sivapalan 2012). As such, the PDAI is developed and demonstrated for the Arbuckle-Simpson Aquifer (ASA), a groundwater resource that underlies an area of about 520 square miles (1350 square kilometers) in south-central Oklahoma. This area is part of Oklahoma, Climate Division 8 (Karl and Koss, 1984), which is one of the 344 climate divisions that the United States is divided into for reporting purposes, based on climate as well as several other considerations (Guttman and Quayle 1996). The ASA provides water for municipal supply, ranching, and mining, and is also the source of local springs and streams that support wildlife, recreation, and tourism. Drought is part of the region's history (Silvis et al. 2014), and the ASA is recharged by rainfall, thus making it susceptible to climate variability and change. The ASA has been the center of a water management dispute that arose in 2002 when landowners began negotiations to sell their groundwater to an area outside of the ASA, near Oklahoma City. The landowners' actions were quickly contested by a local environmental group, the Citizens for the Protection of the Arbuckle-Simpson Aquifer (CPASA; Shriver and Peaden 2009; Lazrus 2016), which led to a moratorium in 2003 that suspended any activities to remove water from the basin until a hydrological study could be conducted. The study included a water balance, hydrogeological study, and groundwater model of the aquifer; the study shows that although water is extracted, groundwater use from the aquifer is relatively small, and that the groundwater-fed streamflow discharge is mostly related to rainfall recharge (Christenson et al. 2011). This was followed by a ruling that reduced the amount of water that could be removed from the aquifer annually by an order of magnitude. This further exacerbated the tensions between the landowners who see the decision as an encroachment on their individual property rights, and CPASA and other community members who see the reduction as a way to protect local water resources (Lazrus 2016). The ASA's susceptibility to drought, as well as its diverse community and contentious management issues, make it an ideal site for exploring the potential for feedback on drought.

In this paper, we explicitly combine hydrological and societal perspectives, but historically, these two perspectives would likely be examined in isolation. In fact, this work builds upon and extends two previous studies that focused on the same ASA case study, but were disciplinary in nature: Lazrus (2016) and Towler and Lazrus (2016). Lazrus (2016) describes results of stakeholder interviews collected for the ASA; it offers an anthropological ~~lens~~ perspective, ~~through which to~~ examin~~e~~ing how stakeholders perceive drought and how those perceptions intersect with their cultural processes. Lazrus (2016) was motivated by the hydrological context of the ASA, but did not engage directly with any quantitative meteorological or hydrological analysis. On the other hand, Towler and Lazrus (2016) take a hydrological perspective, developing a generalized framework that links meteorological drought indices with hydrologic threshold exceedances that are relevant to ASA stakeholders. To identify some of the hydrological thresholds and provide social context, Towler and Lazrus (2016) draw on qualitative insights gathered from the interviews, but do not directly incorporate any of the quantitative interview results into the analysis. In this paper, we extend these two studies to offer a novel, quantitative, interdisciplinary approach, that results in a derivative product, adding value to the preceding studies. Although the PDAI is experimental, conducting this type of study is critical, given the grand challenge of engaging in interdisciplinary research at the climate-water-society interface (McNeeley et al. 2011).

3. Methodology

Figure 1 provides the conceptual overview of the study methodology, which is detailed in the subsequent sections.

3.1 Hydrologic Perspective: Threshold Exceedance

To characterize natural influences on drought, we examine drought from a hydrological perspective. Taking a hydrological, rather than meteorological, perspective is advocated by Van Loon et al (2016b), given the closer connection of surface water and groundwater with societal use and management. Here, we use a groundwater (GW) well that has relevance to the community (Towler and Lazrus 2016), has a long available record, and is monitored by water managers in the community: the USGS Fittstown well (USGS 343457096404501). We use data from the beginning of the GW monitoring record through the year the interviews were conducted, which corresponds to 1959-2012. Details of this dataset can be found in Towler and Lazrus (2016).

To connect the hydrologic perspective with human action, we examine the historical groundwater data in terms of decision relevant thresholds (Jones 2001). From Towler and Lazrus (2016), we identify two main thresholds relevant to water uses asked about in the interviews (see section 3.2). The first threshold is called a "moderate" threshold: This is a groundwater level of 111 feet below the surface, which is decision relevant because it is when the aquifer begins to be closely monitored because of potential impacts to municipal supply. The second threshold is the "severe" threshold: this is when the groundwater level lowers further, to 117 feet below the surface, which is the level at which artesian springs in the area have minimal flow or stop flowing altogether, affecting uses such as wildlife and recreation. For illustrative purposes, we also look at an "extreme" threshold of groundwater levels to 120 feet below the surface, which have been experienced in the aquifer and further the likelihood of minimal or stopped spring flows (see Figure 2 in Towler and Lazrus 2016).

To quantify the threshold exceedance, we calculate the percent frequency of exceedance[1] for each threshold in the historical record. To calculate the exceedance frequency, a time window needs to be selected; we initially examined 5-, 10-, 15-, and 20- year windows. Specifically, we calculate the number of months during each x-year running window that the threshold was exceeded across the available record. For example, for the 10-year window, it would be 1959-1968, 1960-1969, etc., all the way to 2003-2012. Henceforth, we refer to this as the groundwater drought likelihood. For the analysis, we look at the three most recent decades (i.e., 1983-1992, 1993-2002, and 2003-2012), as well as the driest, median, and wettest decades in terms of groundwater drought likelihood.

We also calculate the Pearson's correlation coefficient (r) values between the decadal likelihoods and several drought indices for the area. Specifically, we correlate the decadal likelihoods with 10-year running averages of several drought indicators from different categories. As a measure of agricultural drought, we use the well-known Palmer Drought Severity Index (PDSI; Palmer, 1965) that is based on a water balance of precipitation, soil moisture, potential evapotranspiration, and runoff. We also look at the Standardized Precipitation Index (SP), which only considers the effect of precipitation variability on drought (McKee et al., 1993). The SP can be calculated to consider different time scales: for example, the 1-month SP (SP01) considers short-term conditions, and the 24-month SP (SP24) considers longer-term conditions (i.e., precipitation from the last 2 years). We use the 6-month SP (SP06). To measure hydrological drought, ~~the Palmer Drought Severity Index (PDSI),~~we use the Palmer Hydrological Drought Index (PDHI; Palmer 1965), which is a modification of the original PDSI to account for longer-term dryness that affects water storage, streamflow and groundwater. NOAA's National Climatic Data

[1] We note that groundwater threshold levels are negative; so here we define "exceedance" as going below (more negative) than the threshold.

Center provides this historical data for United States climate divisions; we ~~and the 6-month Standardized Precipitation Index (SP06). Data were~~ downloaded monthly data from 1959 to 2012 for Oklahoma Climate Division 8 from http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp.

3.2. Social Perspective: Stakeholder Importance Ratings

To understand how community members in the ASA region might respond to natural influences drought, we use stakeholder interview data from a previous investigation (Lazrus 2016). Stakeholder interviews (n=38) were conducted in the summer of 2012, following a significant drought in 2011. Interviewee selection followed a targeted snowball sampling strategy whereby interviewees were selected based on their involvement in the ASA water management negotiations, their dependence on or engagement with water resources – for example, in ranching or recreation operations – and recommendations from other interviewees.

For this study, we examined the ~~key~~ question ~~examined was: "~~ ~~h~~How do people perceive the importance of water for various uses?"~~.~~ We make the assumption that the more important water is perceived to be for a particular use, the greater the potential will be for taking action - in this case, conserving water for that use.

To understand the importance of water for various uses, interviewees were asked how important (on a Likert scale of 1-5, 5 being very important) water resources are in their community for: a) People's livelihoods, b) Recreational activities, c) Spiritual fulfillment, d) Cultural practices, e) Habitat for plants and animals, and f) Availability of drinking water. Data from these questions was used directly and called "importance ratings", which were integrated into the PDAI (see section 3.3).

3.3. Creating the Potential Drought Action Indicator (PDAI)

We express the PDAI as a function, *f*, of (i) the decadal probability (P) of the groundwater level, Z, exceeding the hydrologic threshold, z, and (ii) the importance ratings (I):

$$PDAI = f(P(Z<z), I) \qquad \text{(Equation 1)}$$

Here, we define *f* as the product (i.e., multiplication) of the two explanatory terms:

$$PDAI = P(Z<z) \times I \qquad \text{(Equation 2)}$$

Multiplying two terms to create a new indicator is based on a frequently used definition of risk, which combines the likelihood of an event and its consequence (Jones and Preston 2011). However, we point out that the form of ~~Although different~~ *f*~~-s~~ is flexible, e.g., it could be additive, etc. ~~could be explored in different contexts, using a product to create a new indicator is based on a frequently used definition of risk, which combines the likelihood of an event and its consequence (Jones and Preston 2011).~~

Here, P(Z<z) is the decadal likelihood of exceeding a particular threshold (e.g., moderate or severe), per section 3.2. This is multiplied by the importance of water for a particular use, which is directly derived from the stakeholder ratings (section 3.1). Essentially, the importance ratings are used as a weight function to modulate the likelihood of exceedance. In this definition, a lower PDAI equates to less potential for action and higher PDAI indicates greater likelihood of action. The PDAI was calculated for all 6 of the water uses asked about in Section 3.2.

3.4. Social Perspective: Stakeholder Worldviews

We are also interested in exploring *why* people perceive the importance of water for various uses differently. For this, we again interrogate the interview data using a social science theory called The Cultural Theory of Risk (CTR; Douglas 1966; McNeeley and Lazrus 2014). According to CTR, people hold different cultural worldviews about how society should be organized and how society and nature should interact. CTR predicts that people will perceive risks and consequences from hazards when their worldview is challenged. According to this understanding, perceptions are as much about social organization as they are about the physical hazard. Their worldview will also guide their preference for different risk management strategies, or in this case drought actions, making it relevant to our PDAI results. Two of the worldviews described by CTR are individualism and egalitarianism. These represent idealized categories and are useful heuristics, but in reality, people may adhere to some elements of the cultural worldviews more than others. People with individualist views favor weak social bonds and have little need for social structure, preferring individual competition and market-based transaction strategies. For them, nature is a bountiful resource robust to human uses and therefore may not need to be managed for conservation. People with egalitarian views favor strong social bonds and collective decision-making processes. For them, nature is fragile and easily impacted by humans and so must be carefully managed to avoid catastrophe (Thompson et al. 1990). By identifying the cultural processes that lead people to recognize risks and perceive consequences, CTR also helps to diagnose why disagreements arises over risk management; that is, disagreements may arise between constituent groups holding different worldviews when management strategies do not reflect elements of each constituent's predominant worldview (Verweij et al. 2006).

To this end, we examined how peoples' importance ratings from section 3.2 were related to their worldviews. If so, it would help us to understand how the PDAI could be operationalized – that is, might people respond more favorably to water management strategies that reflected their own management preferences based on their cultural worldviews? For the CTR, interview questions about worldview used previously tested measures for individualism and egalitarianism developed by Smith and Leiserowitz (2014) as well as additional questions informed by CTR that reflected the particular water management context of the ASA; all questions can be seen in Tables 1 and 2 of Lazrus (2016). These questions asked people whether they strongly agreed, agreed, neither agreed nor disagreed, disagreed, or strongly disagreed (on a 5 point Likert scale) to a series of statements. Responses were summed for each interviewee to determine a value for individualism or egalitarianism. Follow-up open-ended questions allowed interviewees to elaborate on their worldview preferences and importance ratings.

4. Results

4.1. Threshold Exceedance Likelihood

Figure 2 shows the historical monthly groundwater time series, including the moderate threshold (111 feet below the surface) and severe threshold (117 feet below the surface) introduced in Section 3.2. Groundwater drought likelihood is calculated as the number of months within each 5-, 10-, 15-, and 20-year running window that the level went below a particular threshold. Drought likelihoods for the selected time windows (5-, 10-, 15-, and 20-years) are shown in ~~the Supplemental Material, Figure S1~~Figure 3. Results for each time window follow similar patterns, though as expected, the shorter the time window, the greater variability in the likelihood. We selected the 10-year running window for calculating the PDAI (e.g., Figure 3b), as it strikes a balance between shorter time windows that have high variability ~~and likelihood swings~~ (e.g., 5-year windows) and longer time windows (e.g., 15-, and 20-years) where much of the variability ~~gets washed~~is smoothed out. ~~As such,~~ Figure 3b shows the decadal likelihood for the moderate and severe threshold. As expected, the higher the threshold, the higher the likelihood of exceedence (i.e., a moderate threshold is exceeded more often than the severe threshold). Further, the likelihoods are correlated (r=.94) and significant at the 99% confidence level. We also point out the very close association between the ~~hydrologic~~ groundwater threshold exceedance likelihoods and selected drought indices for the region (i.e., Oklahoma south-central climate division 8): Table 1 shows that for meteorological (SP06), agricultural (PDSI), and hydrological (PDHI) drought indices, the correlations with the moderate threshold exceedance is >-.9 and with the severe threshold is >-.8. This underscores the notion that for this case study, the hydrological perspective is a good indicator of the natural influences on drought. This is the case because water extraction in the area is relatively low and the groundwater levels are very closely related to rainfall recharge (Christenson et al., 2011). However, we note that that this may not be the case for other groundwater aquifers that are more affected by human extraction (e.g., Tarhule and Bergey 2006) or aquifers with different properties (e.g., slower hydrologic responses due to increased propagation times). This point is further discussed in the Discussion section 4.5 (Future Enhancements)~~the Conclusions~~.

Table 2 shows the exceedance likelihoods of select decades from the historical record for both moderate and severe. First, we look at the three most recent decades (i.e., 1983-1992, 1993-2002, and 2003-2012), in which relatively wet, average, and dry conditions occurred. ~~Arguably the most relevant decade is the one most recent to when the interviews were conducted: 2003-2012.~~ For 2003-2012, the moderate threshold was exceeded 61% of the time, which we refer to as the "dry/recent" decade. In the next most recent decades, the exceedance likelihood decreased to 35% (1983-1992) and 31% (1993-2002), which we refer to as "average/recent" and "wet/recent" decades, respectively. ~~Given the close association with drought (Table 1), this suggests that in the decades of the last 30-years, stakeholders experienced relatively dry (2003-2012), relatively average (1983-1992), and relatively wet (1993-2002) decades; these are referred to as the "dry/recent", "average/recent", and "wet/recent" decades, respectively.~~ To put into context, for the moderate threshold, the decade with the lowest exceedance likelihood was 23% (1985-1994), which we call the "~~very wet~~wettest" decade, and highest exceedance was 75% (1959-1968), or "~~very dry~~driest" decade. Results follow similar patterns for the severe threshold (Table 2).

4.2. Stakeholder Importance Ratings

Stakeholder interviews reveal that there is more consensus on the importance of water for some water uses than others (Figure 4). On average, water was deemed most important for drinking water, followed closely by habitat for wildlife, and supporting livelihoods. The importance of water for these uses was similar for most stakeholders interviewed, as evident by the tightness of the box plot (Figure 4). On the other hand, there was a spread in responses for recreation, cultural practices, and spiritual fulfillment. Some of the spread in responses on these measures may be due to how interviewees interpreted the water uses (Lazrus 2016).

The spread in responses indicates that different stakeholders place different levels of importance on some water uses, such as water for recreation which shows a broader spread than water for drinking water, habitat, or livelihood. For example, one interviewee underscored the importance of water, describing that "Murray County is one of the top tourist attractions with Arbuckle Lake and Chickasaw National Recreation area. So water is the absolute key" (Interview 1). dDemonstrating a very different perspective, another interviewee noted that "Recreation and water are not critical to me. I mean in this part of the world, they don't necessarily go hand-in-hand because it's a relatively dry place, and there are not that many places to really go and play in the water" (Interview 5).

4.3 Potential Drought Action Indicator (PDAI)

The PDAI is calculated for all of the water uses (Figure 5). Here, the top row shows results for water uses using the moderate threshold (Figure 5a-c) and the bottom row shows results for water uses using the severe threshold (Figure 5d-f). Because the results across the rows are quite similar, we will focus on the results for To demonstrate the PDAI, we examine two different water uses: drinking water (Figure 5a) and then recreation (Figure 5d), although results for all of the water uses can be found in the Supplemental information (Figure S2).

First, we focus on drinking water, which is an example of a water use which exhibited more consensus among interviewees. For drinking water, to calculate the PDAI, we use the moderate threshold, since this is the threshold at which municipal supply is monitored (see Section 3.1). Figure 5a (left) shows the PDAI for drinking water for the different drought conditions (e.g., wet/recent, dry/recent, etc) from Table 21. Results are shown as empirical Cumulative Density Functions (eCDFs) to reflect the discrete nature of the importance ratings. In the eCDFs, the vertical lines represent the PDAI values, and the horizontal lines represent the percentage of data that are equal to or less than that value. In Figure 5a (left), as the eCDF moves across drought conditions from very wetwettest to very drydriest, the PDAI shifts towards higher values, reflecting the increased potential for action under drier conditions. Specifically, the very wetwettest decade has an average PDAI value of 1.1, and the very drydriest decade has an average PDAI value of 3.7. Given the stakeholder consensus on the importance for drinking water, for each drought condition there is very little range – that is, the eCDFs are fairly vertical. Results are similar when the Moderate threshold is used for the other two water uses, habitat and livelihood, that showed strong consensus (see Figure S25b and 5c).

Next, we focus on the PDAI for Recreation, a water use that shows diverse importance ratings from stakeholders (Figure 5, rightd). For recreation, to calculate the PDAI, we use the severe threshold, since that is the threshold at which artesian springs have minimal flow or no longer flow (see Section 3.1). Figure 5d (right) shows the PDAI for recreation for the select decadal drought conditions, using the severe threshold likelihoods from Table 12. Similar to drinking water, we see that as we move from wetter to drier decades, the PDAI also increases; for example, from wet/recent to dry/recent, the average PDAI values are 0.3 and 1.5, respectively. However, given the stakeholder diversity in importance ratings, as we move towards drier conditions, the PDAI becomes more diffuse, spanning a great range of values: in the wet/recent, the PDAI spans from .08 to .4, or for 0.32 units of the PDAI scale, and in the dry/recent it spans from 0.4 to 1.9, or 1.5 units on the PDAI scale, indicating a wide range in stakeholder appetite for potential action. Interestingly, the wet/recent decade (1993-2002) was also the wettest decade on record, with the groundwater threshold only being exceeded 8% of the time. Results are similar when the Severe threshold is used for the other two water uses that showed diverse ratings, i.e., cultural practices and spiritual fulfillment (see Figure S25e and 5f).

In Figure 6, we also looked at recreation under the possibility of a new "normal" drought baseline (Van Loon 2016b). It has been suggested that human adaptation to new drought normals can be illustrated by changing thresholds (Vidal et al. 2012; Wanders et al. 2015); here, we show how this could influence the PDAI. To this end, we look at a more extreme threshold that has been identified for Recreation (i.e., GW levels below 120 feet, see section 3.1), under the dry/recent period: the eCDF curve shifts back to the left, towards lower action potential, with average PDAI of 0.9, reflecting this new normal. This is relevant given climate change projections that suggest that the ASA will likely become drier in the future (Towler et al. 2016; Liu et al. 2012).

Finally, in Figure 7, we narrow our focus to the most recent decade (i.e., dry/recent, 2003-2012), and compare both drinking water and recreation with the moderate and severe thresholds, respectively. From Figure 7, we see that drinking water has a higher action potential than recreation: the average PDAI for drinking water is 3, while it is about 1.5 for recreation. This is an artifact of the thresholds selected for each respective water use (i.e., moderate for drinking water and severe for recreation). This makes sense from a human standpoint, since drinking water is a primary consumptive use, and recreation is a more discretionary use. However, this could be more subjective for other water uses (e.g., spiritual fulfillment). Although it may seem counterintuitive at first, we purposely pair the moderate threshold with the primary use to indicate this hierarchy, but this does not mean that exceedance of the severe threshold would not also prompt action (or further action) to ensure adequate drinking water supplies. However, it does make the assumption that for a more discretionary use, like recreation, action would not be prompted until this severe threshold was exceeded.

Another key point from Figure 7 is that drinking water spans a smaller range on the PDAI scale than recreation, which is more diffuse. Specifically, for drinking water, the eCDF only falls between 2.4 and 3.5; this is due to the agreement across respondents on the importance of water to this use (i.e., Figure 4). On the other hand, the recreation PDAI eCDF covers of a larger range of values – here it spans from 0.4 to 1.9, similarly reflecting the range of stakeholder responses. This shows that for water uses where values are diverse, the appetite for potential action will be diverse as well.

In summary, the key points from these results: the PDAI increases with (1) drier decadal drought conditions and (2) water use thresholds that are exceeded more often. Further, it shows that for water uses where perceived importance is diverse among stakeholders, the PDAI will be diverse as well, and this is exacerbated under drier conditions.

4.4. Management Implications based on Worldviews

To understand the management implications, we need to look at the results alongside of CTR. Results from the CTR questions show that both individualist and egalitarian worldviews were represented by the interviewees (Figure 8) and that some of the spread in the importance responses can be explained by worldview (Table 3). Although the correlations are relatively low, eight out of twelve are statistically significant at the 90th percentile or higher. Further, ~~not all of the results are statistically significant,~~ the sign of each correlation coefficient is opposite between the egalitarianism and individualism measures, indicating that people holding each worldview have opposing importance ratings (Table 3). The water use that showed the highest correlation ~~most variance explained by~~with worldview was recreation: r^2=0.45~~20% (16%)~~ for Egalitarianism and r=0.40 for ~~(~~Individualism~~)~~. These correlations provide initial insight about the role of worldview in how people assess the importance of water and, by extension, their appetite for potential drought action.

Results from the CTR questions, along with the PDAI, point to some implications for water management policy. CTR posits that disagreement over resource management strategies may arise among constituents with diverse worldviews for two reasons (McNeeley and Lazrus 2014): first, as demonstrated in Table 3, worldviews explain some of the variance in how important people think that local water resources are for different activities - and thus presumably *whether or not* maintaining water for those activities should be prioritized by water management. For example, in recreation, because of the large spread in importance ratings, which can partially be explained by CTR, there is an increase in the PDAI categories from the wet/recent to average/recent to dry/recent decades; this implies that people will disagree on whether or not water should be managed for recreation, potentially leading to disagreements that could hinder sustainable water management. Second, is *how* water should be managed, even when people agree on its importance. In drinking water, there is consensus on importance – even among people with different worldviews – presumably indicating that people agree that water needs to be managed for drinking water. However, because of the different worldviews, there is still potential for disagreement over how it should be managed. That is, those with egalitarian preferences advocate for management that is collectively debated, implemented, and enforced whereas those with individualist preferences favor management that is individually enacted and market-based. We see this in our qualitative data: for example, one interviewee with individualist preferences said: "we have to have a set of rules that everyone understands. And once those rules are set you can't have a bunch of water Nazis trying to make judgment calls about how someone's using their water. So, if I can use a certain amount - tell me what that amount is, and then stay the hell out of my business" (Interview 2). The finding ~~means~~ shows that disagreement is not solely due to threats to water resources – such as more frequent drought – but rather that it can also arise from disagreement about the strategies designed to manage water and address drought.

4.5. Future Enhancements

We develop and demonstrate this methodology as a step towards closing the drought feedback loop, but note that there are caveats and limitations that warrant discussion. A conceptual overview of the contribution of our study to the drought feedback loop is shown in Figure 9, and we use this figure to identify five places where there is scope for future enhancements; each number below corresponds to a place in the drought feedback loop in Figure 9:

1) For the natural influence on drought, we examine the probability of groundwater drought. In our case, the groundwater levels are closely related to rainfall recharge, which is a function of natural climate variability. We recognize that this is not the case for many groundwater aquifers, where human activities, such as groundwater extraction, may trump the natural climate signal (e.g., Tarhule and Bergey 2006), often leading to water scarcity, rather than a natural phenomenon of temporary water deficiency. In many systems a full water balance would need to be examined to understand the relative contributions of extraction versus moisture deficit to the likelihood of going below a relevant hydrologic threshold. Further, other aquifers may have different properties; for example, some aquifer's natural response may be different and the levels may not closely resemble rainfall.
2) Our interviews were conducted following a drought event, and we recognize that the timing of the interviews will likely affect the responses, possibly introducing a bias. For instance, interviews conducted during wet or average conditions might elicit less polarized responses, since drought impacts haven't been recently experienced. We note that our approach of applying the interview responses across different climate conditions (i.e., wettest to driest) makes the assumption that the importance of water uses and management preferences are stationary. We acknowledge that different climate conditions, as well as cultural change, technological innovation, climate adaptation, and other processes are likely to influence the cultural factors we investigated here and may mediate how people interact with their environments. Future work could investigate how responses change with different climate conditions over time, and the subsequent implications for drought action. However, hazards and disasters research is almost always conducted immediately after an event, so this is a wise-spread epistemological issue with both pros and cons in terms of what we learn from post-disaster research.
3) We use stakeholders' importance ratings as a proxy for their willingness to take action in relation to particular water uses, where by "action", we generally mean some effort towards drought mitigation. The interviews included questions about the importance of different water uses to test the application of the Cultural Theory of Risk (usually applied in a more global sense) to a specific water management issue, which had not been done before (Lazrus 2016). For the purposes in this paper, multiplying the importance ratings by the probability served as a way to make an objective characterization of drought subjective, that is, we wanted to modulate the groundwater drought probability by each individual stakeholder's lens.
4) The formulation of the PDAI strongly affects the conclusions drawn. Our formulation of the PDAI follows from other precedents in risk management that take the product of the likelihood of an event and its importance (Jones and Preston 2011; Oppenheimer et al. 2014). However, the functional form of the PDAI is flexible, allowing it to be tailored to other locations. As such, we note that the PDAI, as well as the best data to use to calculate it, will depend on the needs of the community, as well as the water system context.
5) We use social science theory to interpret our results, and to better understand the theoretical underpinnings of how and why people take action in response to

drought. However, we note that empirical validation is important for indicator development and refinement. We recommend that future project designs include a validation component in the methodology. This could take the form of follow-up interviews, such as direct feedback from stakeholders on if the indicator reflects their willingness to take action for certain water uses at certain drought levels. Methods, including stakeholder processes, for developing and evaluating drought indicator effectiveness have been put forth in the drought community (Steinemann and Hayes 2005 Steinemann and Cavalcanti 2006, Steinemann et al. 2015). Other options for validation can be indirect, such as looking at historical data, like government and local reports, media, and/or other collected response information, e.g., in the United States the US Drought Impact Reporter (DIR; Wilhite et al. 2007). Tijdemen et al (2018) examined the relationship between drought indicators and impact data from the DIR; however, it has been noted that the DIR would benefit form a more systematic and coordinated collection effort (Lackstrom et al. 2013), which presents challenges for its interpretation. Promising methods for mining social media, such as Twitter, have also been developed (Demuth et al. 2018) and could be adapted for evaluative purposes.

Related to the points above is the question about how the PDAI could connect with existing operational products and its transferability to other locations. In our case, groundwater threshold exceedance was linked with water use impacts. Ideally, the PDAI could be modified to incorporate an operational drought indicator that is associated with impacts; however, evaluations of the connection between monitored indicators and impacts has been limited (Bachmair et al 2016). In terms of the transferability of the social perspective, the idea behind the cultural theory of risk worldview measures is that they are loosely universal, that is, they should apply fairly generally to any context within the broad culture for which they were initially put together – in this case, the United States (Smith and Leiserowitz 2014). However, worldview measures can also be tailored to a particular context (Lazrus 2016), which might need to be revised for other applications.

5. Conclusions

Our study implements a conceptual methodology combining hydrological and societal perspectives to understand drought action potential. Results from stakeholder interviews in the study site reveal that people perceive the relative importance of water for various uses differently, as shown by the notable variability that existed across certain water uses. A retrospective analysis of groundwater threshold exceedance shows that in recent decades, stakeholders experienced a wide range of likelihoods of exceeding relevant thresholds, and these corresponded to drought ~~conditions~~indices. These pieces of information are brought together through the PDAI. We find that for a given water use, drier conditions increase the frequency of exceeding the groundwater threshold, and hence increase the PDAI. The PDAI is tied to the threshold selected for each water use: we find that the PDAI is higher for more moderate thresholds, i.e., thresholds that are exceeded more often. And conversely, as thresholds become more extreme, which can illustrate human adaptation to new drought normal, the PDAI decreases. Finally, we find that for water uses where stakeholder values are diverse, the PDAI will be diverse as well, and this is exacerbated under drier conditions.

We can also ask why values might be diverse, and what that might mean about how people are affected by water scarcity and how they will respond. To this end, the study also examined worldview, as measured by the CTR, which can help to diagnose *why* disagreement may arise over water management and point to some implications for water management policy. In the stakeholder sample, we found a diverse range of worldviews on the individualist/egalitarian spectrum. Further, for some water uses, the importance people attribute to water can be partially explained by worldview. This implies that there are two potential sources for disagreement over water management: first, where there is variability in people's perception of importance, there may be disagreement over whether or not a water resource needs to be managed (e.g., with water for recreation). Second, even where there is consensus on people's perceived importance, there is still potential for disagreement over how these water resources should be managed according to different preferences of worldviews (e.g., with drinking water). We are careful to say *potential* disagreement because (i) our analysis only investigates CTR as one of the many factors explaining importance and (ii) by understanding stakeholder worldviews, potential disagreement across sectors can be predicted and ideally avoided. The latter finding suggests that water management policies will be more successful if they follow a strategy whereby elements of each worldview are represented in the solution (Verweij et al. 2006).

Although reducing disagreement is always important for promoting sustainability, it is particularly important for management planning under potentially increasing drought due to climate change, as has been predicted for this area (Towler et al. 2016; Liu et al. 2012). We examined this by examining possible adaptation to a new normal, where we illustrate how a more extreme threshold lowers the PDAI.

~~We develop and demonstrate this methodology as a step towards closing the drought feedback loop, but note that there are caveats and limitations that warrant discussion. A conceptual overview of the contribution of our study to the drought feedback loop is shown in Figure 9, and we use this figure to identify five places where there is scope for future enhancements; each number below corresponds to a place in the drought feedback loop in Figure 9:~~

1) ~~For the natural influence on drought, we examine the probability of groundwater drought. In our case, the groundwater levels are closely related to rainfall recharge, which is a function of natural climate variability. We recognize that this is not the case for many groundwater aquifers, where human activities, such as groundwater extraction, may trump the natural climate signal (e.g., Tarhule and Bergey 2006), often leading to water scarcity, rather than a natural phenomenon of temporary water deficiency. In many systems a full water balance would need to be examined to understand the relative contributions of extraction versus moisture deficit to the likelihood of going below a relevant hydrologic threshold.~~
2) ~~Our interviews were conducted following a drought event, and we recognize that the timing of the interviews will likely affect the responses. For instance, interviews conducted during wet or average conditions might elicit less polarized responses, since drought impacts haven't been recently experienced. We note that our approach of applying the interview responses across different climate~~

conditions (i.e., wettest to driest) makes the assumption that the importance of water uses and management preferences are stationary. We acknowledge that different climate conditions, as well as cultural change, technological innovation, climate adaptation, and other processes are likely to influence the cultural factors we investigated here and may mediate how people interact with their environments. Future work could investigate how responses change with different climate conditions over time, and the subsequent implications for drought action. However, hazards and disasters research is almost always conducted immediately after an event, so this is a wise-spread epistemological issue with both pros and cons in terms of what we learn from post-disaster research.

3) We use stakeholders' importance ratings as a proxy for their willingness to take action in relation to particular water uses, where by "action", we generally mean some effort towards drought mitigation. The interviews included questions about the importance of different water uses to test the application of the Cultural Theory of Risk (usually applied in a more global sense) to a specific water management issue, which had not been done before (Lazrus 2016). For the purposes in this paper, multiplying the importance ratings by the probability served as a way to make an objective characterization of drought subjective, that is, we wanted to modulate the groundwater drought probability by each individual stakeholder's lens.

4) The formulation of the PDAI strongly affects the conclusions drawn. Our formulation of the PDAI follows from other precedents in risk management that take the product of the likelihood of an event and its importance (Jones and Preston 2011; Oppenheimer et al. 2014). However, the functional form of the PDAI is flexible, allowing it to be tailored to other locations. As such, we note that the PDAI, as well as the best data to use to calculate it, will depend on the needs of the community, as well as the water system context.

5)6) We use social science theory to interpret our results, and to better understand the theoretical underpinnings of how and why people take action in response to drought. However, we note that empirical validation is important for indicator development and refinement. We recommend that future project designs include a validation component in the methodology. This could take the form of follow-up interviews, such as direct feedback from stakeholders on if the indicator reflects their willingness to take action for certain water uses at certain drought levels. Methods, including stakeholder processes, for developing and evaluating drought indicator effectiveness have been put forth in the drought community (Steinemann and Hayes 2005 Steinemann and Cavalcanti 2006, Steinemann et al. 2015). Other options for validation can be indirect, such as looking at historical data, like government and local reports, media, and/or other collected response information, e.g., in the United States the US Drought Impact Reporter (Wilhite et al. 2007). Promising methods for mining social media, such as Twitter, have also been developed (Demuth et al. 2018) and could be adapted for evaluative purposes.

Although the methodology to develop the PDAI is experimental, we posit that explicit efforts to combine natural and human perspectives is critical to gaining a deeper and more nuanced understanding of drought feedbacks, and this paper provides a novel contribution to this end.

Data Availability

Groundwater data from the USGS Fittstown well (USGS 343457096404501) is available from the USGS National Water Information System Web Interface https://nwis.waterdata.usgs.gov/nwis/gw. Drought index data for Oklahoma Climate Division 8 is available from: http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp Inquiries on the stakeholder data from the interviews can be sent to hlazrus@ucar.edu

Acknowledgements

Thank you to community members in the Arbuckle-Simpson Aquifer area, Julie Demuth, and Rebecca Morss. This study is supported by National Oceanic and Atmospheric Administration grant NA11OAR4310205 and National Science Foundation EASM grants AGS-1048829 and AGS-1419563. NCAR is sponsored by the National Science Foundation.

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Tables

Table 1. Correlation Between Select Drought Indices* and the Likelihood (P) of Groundwater (GW) Level Going Below Moderate (Mod) and Severe (Sev) Thresholds

Drought Index		Correlation	
Type	Name	P(GW<Mod)	P(GW<S
Agricultural	Palmer Drought Severity Index (PDSI)	-0.92**	-0.8
Hydrological	Palmer Hydrological Drought Index (PDHI)	-0.95**	-0.8
Meteorological	Standardized Precipitation Index - 6 month (SP06)	-0.94**	-0.8

Drought Index		Correlation	
Type	Name	P(GW<Mod)	P(GW<Sev)
Agricultural	Palmer Drought Severity Index (PDSI)	-0.92	-0.83
Hydrological	Palmer Hydrological Drought Index (PDHI)	-0.95	-0.84
Meteorological	Standardized Precipitation Index - 6 month (SP06)	-0.94	-0.82

* Drought indices for Oklahoma Climate Division 8 downloaded from:
http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp
** = Significant at the 99% percentile

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Table 2. Decadal Likelihood (P) of Groundwater (Z) Level Going Below Moderate (Md) and Severe (Sv) Thresholds for Recent Decades, as Well as Respective Driest, Median, and Wettest Decades.

P(Z<Mod) (%)	P(Z <Sev) (%)	Comment	Decade
61	38	Dry/recent decade; most recent decade to interviews	2003-2012
35	14	Average/recent decade; third most recent decade	1983-1992
31	8	Wet/recent decade; second most recent decade	1993-2002
75	40	Driest decade; highest exceedance likelihood	1959-1968(Mod); 1964-1973(Sev); 1972-1981(Sev)
50	25	Median decade; median exceedance likelihood	1999-2008(Mod); 1979-1988(Mod); 1969-1978(Sev); 1980-1989(Sev)
23	8	Wettest decade; lowest exceedance likelihood	1985-1994(Mod); 1993-2002(Sev)

Table 3. Correlation and Statistical Significance of Worldviews, as Quantified by the Egalitarian and Individualist Measures, with Importance Ratings for Each Water Use.

Water Use	Egalitarian	Individualist
Drinking Water	-0.20	0.27*
Habitat	0.24*	-0.25*
Livelihood	0.13	-0.09
Recreation	0.45**	-0.40**
Cultural Practices	0.42**	-0.29*
Spiritual Fulfillment	0.18	-0.23*

* = Significant at the 90% percentile
**= Significant at the 99% percentile

Figures

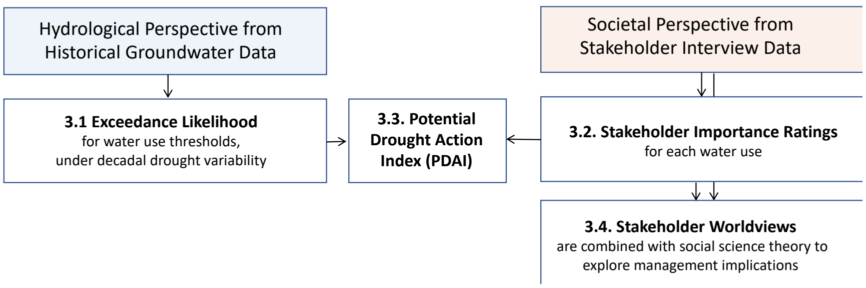


Figure 1. Conceptual overview of the methodology that combines a hydrological perspective from historical groundwater data with a societal perspective from stakeholder interview data to quantify the Potential Drought Action Indicator (PDAI); stakeholder worldviews from the interviews and social science theory are used to explore management implications.

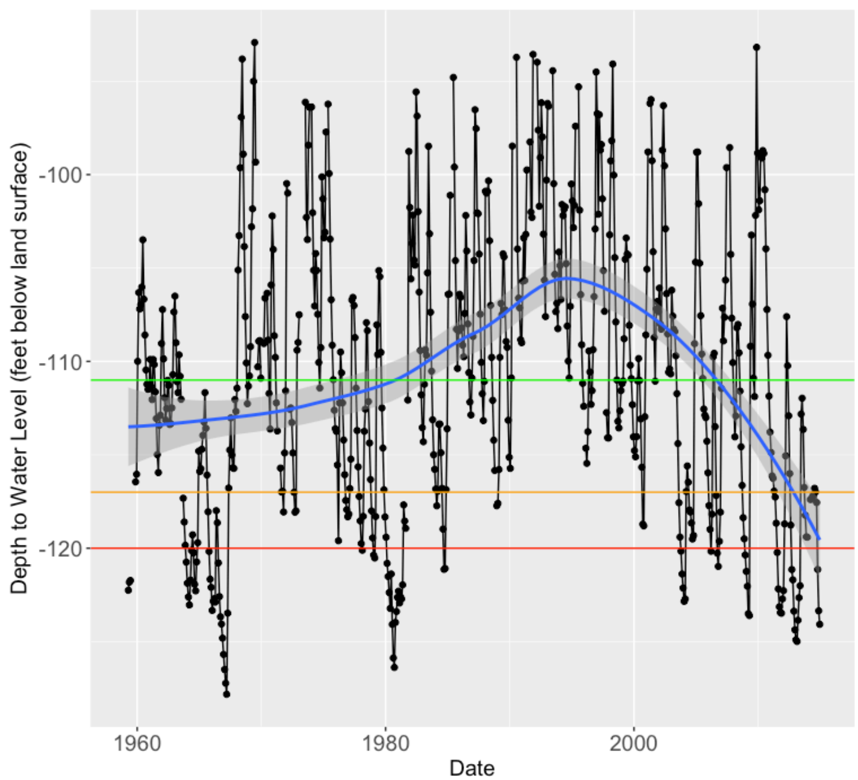
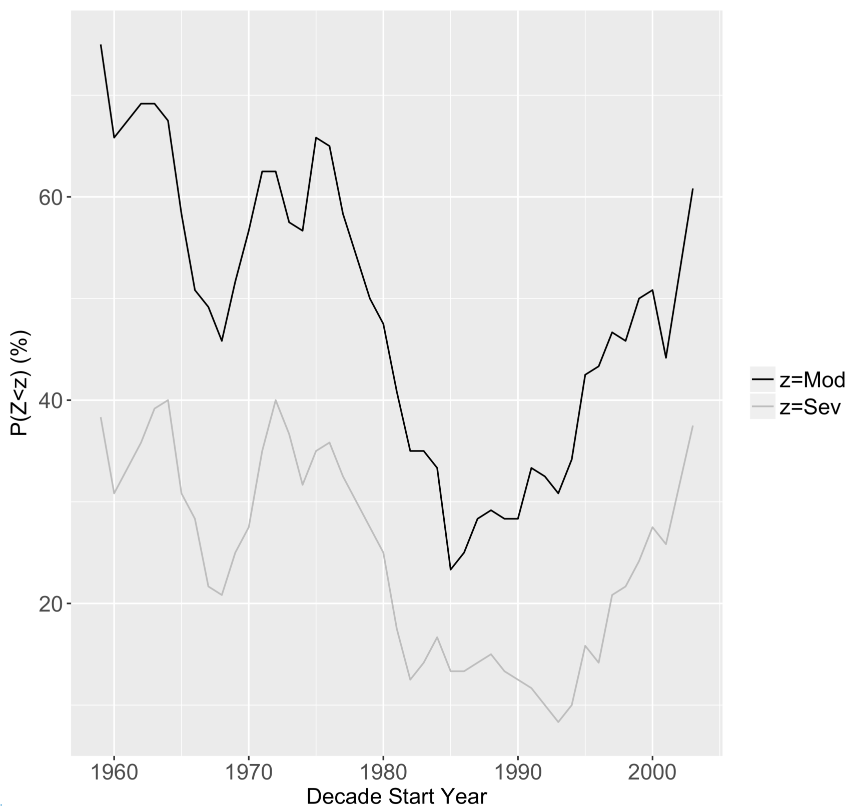


Figure 2. Monthly groundwater time series; blue line is a local smoother average, green line is the moderate threshold (= -111 feet) and the orange line is severe threshold (=-117 feet); the red line is an extreme threshold (= -120 feet) that is used to illustrate a possible new normal drought threshold.


P(Z<z) (%)
20
40
60
1960
1970
1980
1990
2000
Decade Start Year
z=Mod
z=Sev

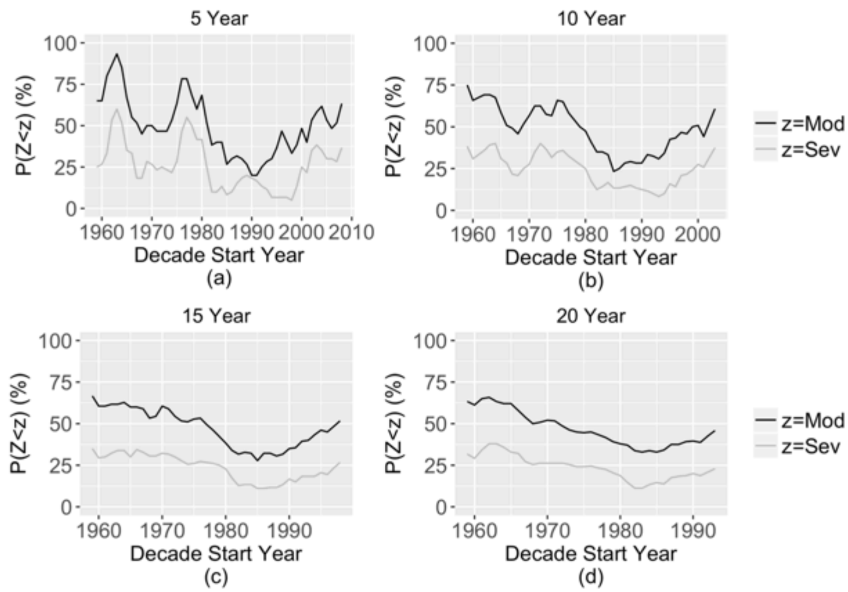
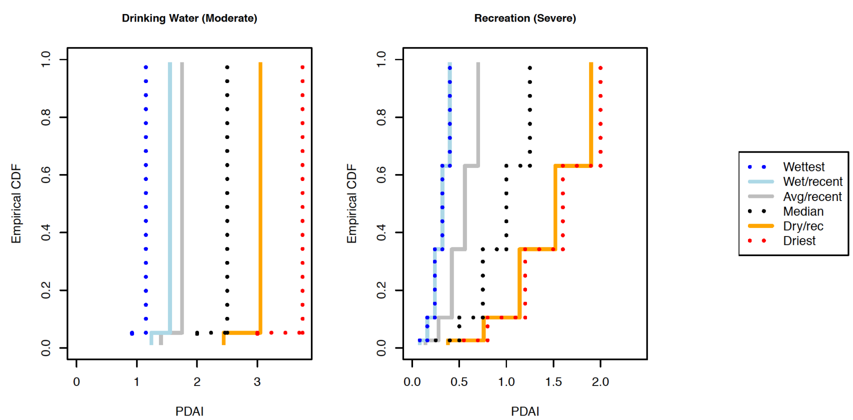


Figure 3. Groundwater drought likelihood (P) of the depth to groundwater level (Z) going below the moderate (Mod, z=-111 ft) and severe thresholds (Sev, z=-117 ft) for time windows from 5 to 20 years~~Decadal likelihood (P) of the depth to groundwater level (GW) going below the moderate (y=-111 ft) and severe thresholds (y=-117 ft)~~.

Figure 4. Rated importance of water for each water use from stakeholder surveys (N=38) on a Likert scale of 1-5, 5 being very important. Responses are shown as box plots, where the box represents the 25th and 75th percentile, the line is the median, and the whiskers are the 5th and 95th percentile. Outliers are shown as points outside the box and whiskers.
~~Rated importance of water for each water use from stakeholder surveys (N=38). Responses are shown as box plots, where the box represents the 25th and 75th percentile, the line is the median, and the whiskers are the 5th and 95th percentile. Outliers are shown as points outside the box and whiskers~~.



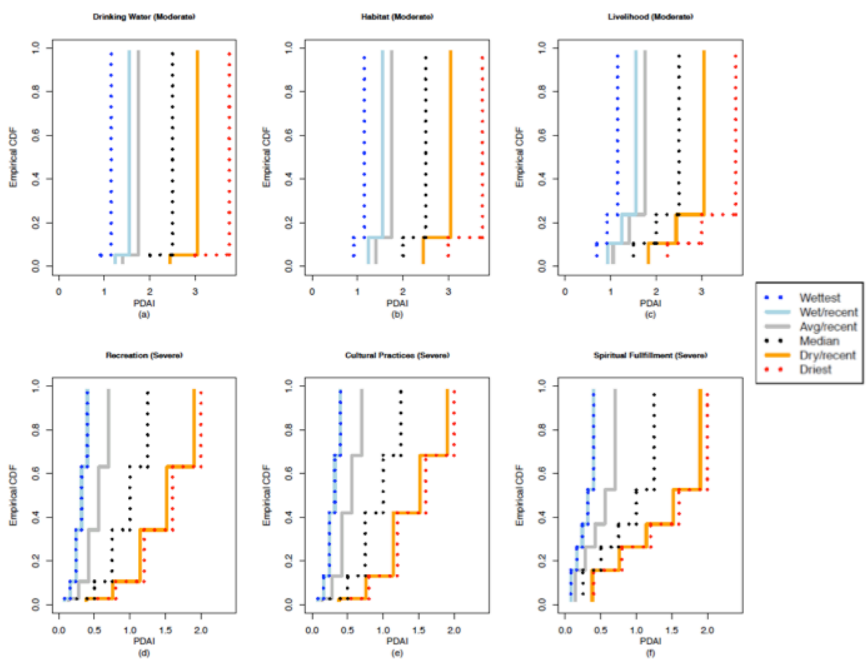


Figure 5. Empirical cumulative density functions (eCDFs) for the PDAI (Potential Drought Action Indicator) for water uses using ~~drinking water using~~ the moderate threshold (~~left~~a-c) and for ~~recreation~~water uses using the severe threshold (~~right~~d-f), under the wettest, wet/recent, average/recent, median, dry/recent, and driest historical decades.

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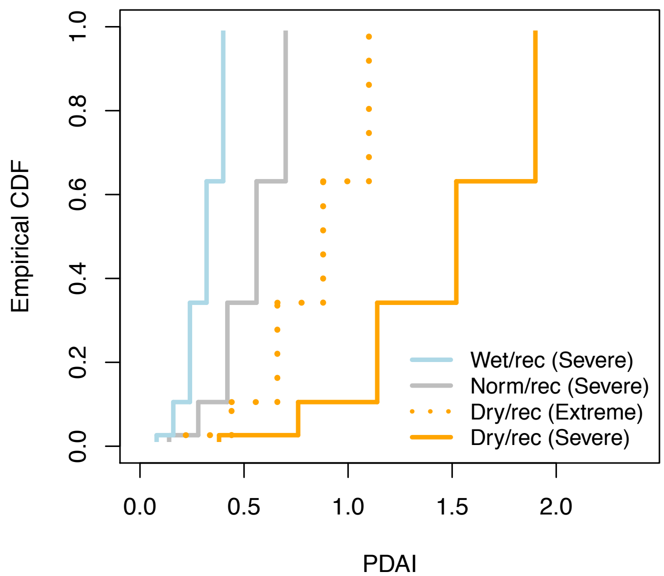
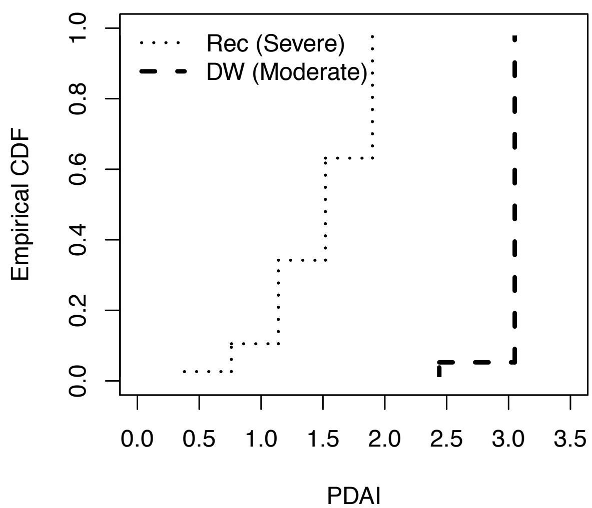


Figure 6. Empirical cumulative density functions (eCDFs) for the PDAI (Potential Drought Action Indicator) for recreation under the wet/recent (1993-2002), normal/recent (1983-1992), and dry/recent (2003-2012) for the severe threshold, as well as the dry/recent for the extreme threshold.


Rec (Severe)
DW (Moderate)
Empirical CDF
0.0
0.2
0.4
0.6
0.8
1.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
PDAI

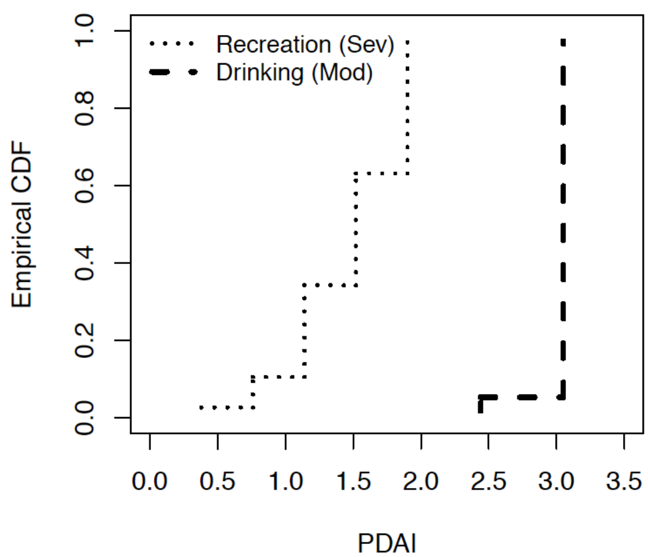

Recreation (Sev)
Drinking (Mod)
Empirical CDF
0.0
0.2
0.4
0.6
0.8
1.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
PDAI

Figure 7. Empirical cumulative density functions (eCDFs) for the PDAI (Potential Drought Action Index) for recreation using the severe (Sev) threshold and for drinking water using the moderate (Mod) threshold for the dry/recent decade (2003-2012).Empirical cumulative density functions (eCDFs) for the PDAI (Potential Drought Action Indicator) for recreation (Rec) using the severe threshold and for drinking water (DW) using the moderate threshold for the dry/recent decade (2003-2012).

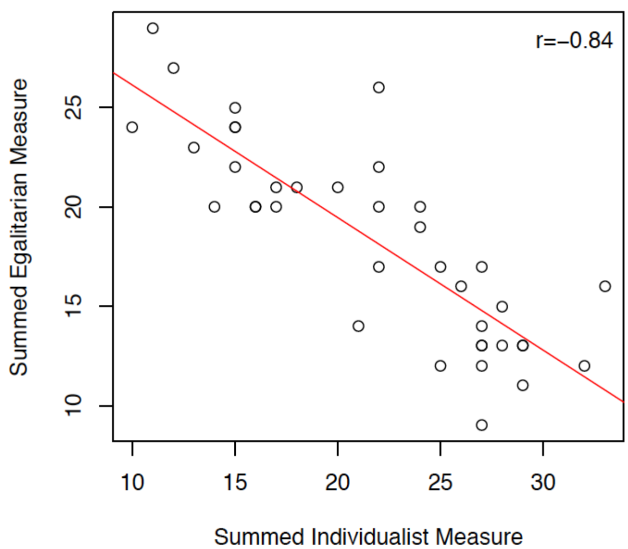


Figure 8. Summed responses for individualism versus egalitarianism for each interviewee (n=38) show that both individualist and egalitarian worldviews were represented by the interviewees . The egalitarianism and individualism measures were strongly inversely correlated (r=-0.84).

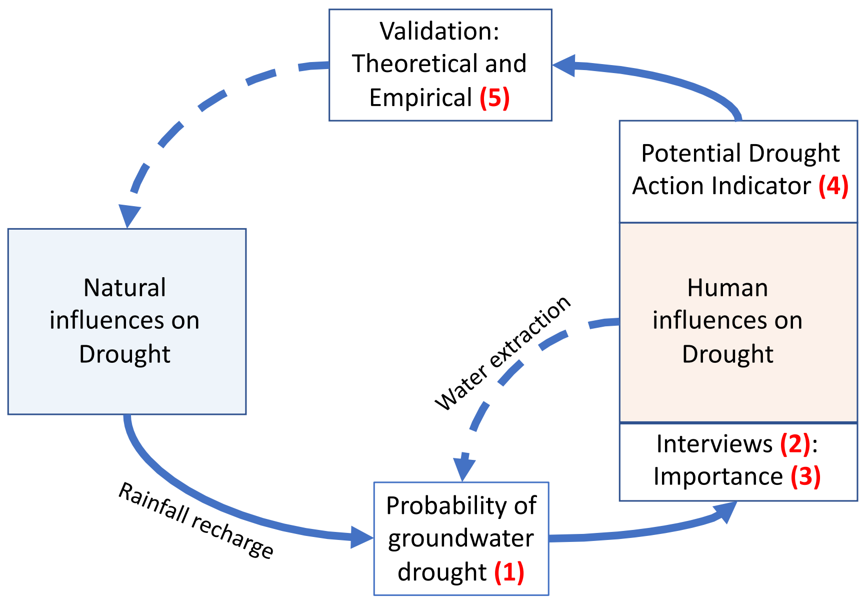


Figure 9. Conceptual map of drought feedback loop components addressed in this study (blue solid lines) and remaining gaps (blue dashed lines). Numbers correspond to discussion points in Conclusions.