Editor Decision: Reconsider after major revisions (further review by editor and referees)

Comments to the Author:
Dear Authors:
Your manuscript was evaluated by two reviewers who also have different backgrounds and perceptions of the problem at hand. Notwithstanding that, they both highlighted some key points and raised a few important criticisms. Whereas your study provides a very good scientific contribution to our community, it is less effective in terms of scientific quality and the way choosen to present that work. Major revisions are required, but your preliminary responses show that you are following a good route in revising the original manuscript. In view of the criticisms received, please be advised, however, that another round of referees' evaluation is needed and there will be no guarantee of the final acceptance of the manuscript.

Response to Editor Comments:

We thank the Editor for these comments. We have revised the manuscript to address all the reviewer comments, including clarifying the significance of the work's contribution, as well as being clear on its limitations. These changes were detailed in the preliminary interactive discussion responses. We repeat those responses here, including our General Response, Reviewer 1 Point-by-Point response, and Reviewer 2 point-by-point response. We end with the revised, marked-up manuscript version showing the changes made in red.

AC: General Response

In reading through the comments from both reviewers, we saw that there was one main issue that weaved throughout, namely the need for a more thorough discussion of the study's contribution to drought feedback loop, along with the associated limitations and caveats. To address this, we added a more detailed discussion in the Conclusions section, as well as a new figure to the manuscript, now "Figure 9", below.

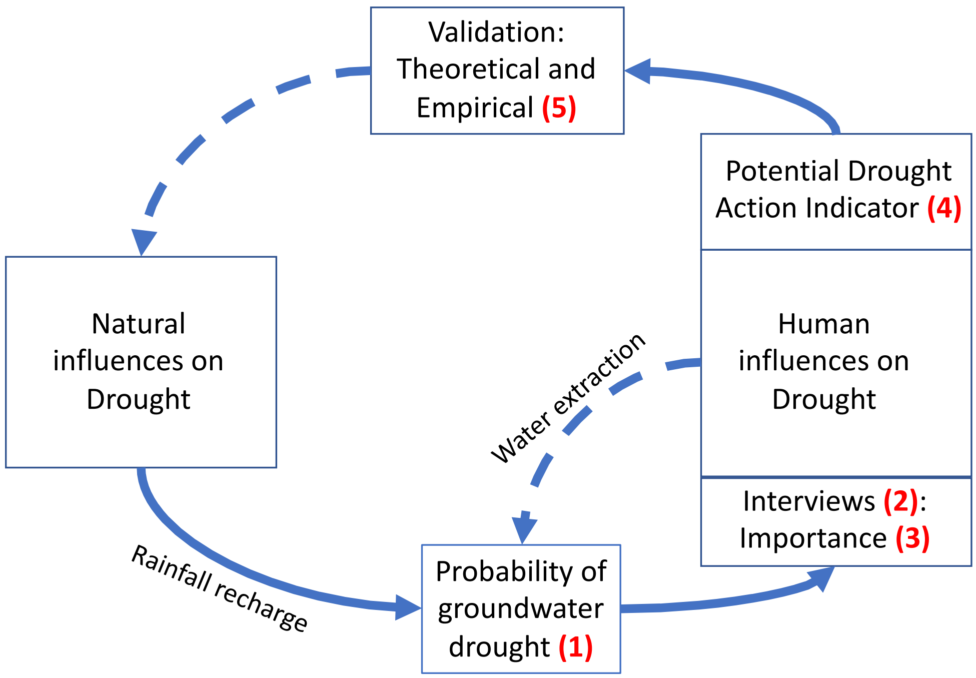

Figure 9. Conceptual map of drought feedback loop components addressed in this study (blue solid lines) and remaining gaps (blue dashed lines). Numbers correspond to discussion points in Conclusions.

Here we provide the excerpt that will be added to the Conclusions section of the manuscript to describe the new Figure 9 and the study limitations:

"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) 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."

Interactive comment on "Characterizing the Potential for Drought Action from Combined Hydrological and Societal Perspectives" by Erin Towler et al.
A.F. Van Loon (Referee) a.f.vanloon@bham.ac.uk
Received and published: 10 May 2018

Response to Referee #1 Comments:

We thank the referee for their valuable comments, and here are our point-by-point responses. Our responses are in red, and note that RC = referee comments, and AC = author comments.

General comments:
RC0. This is an interesting and important paper that shows an approach to bring together natural and social drought processes. The authors propose an index that is composed of groundwater drought probability and stakeholders ratings of the importance of a water use, with the aim of showing the potential for drought action. I think that this is a very important step in drought research. The literature review and framing of the research are excellent. The results are good, but I do find the work quite "thin". The authors use groundwater levels from one well and interview results from a previous study, multiply these into an index, show only part of the results, and then draw conclusions, some of which are quite obvious. I do think that there is potential for the paper to be published and I give a few suggestions to improve the paper below.

AC0. We thank the referee for this constructive feedback, and address the specific suggestions in the responses, below. We also point out a few subtle changes based on feedback from Reviewer #2 to ensure readability of this response: (i) we are changing the "I" in PDAI from "Index" to "Indicator", and (ii) notate GW as "Z".

Specific comments:
RC1) Only the results for drinking water and recreation are shown in Figures 5-7. I would encourage the authors to find a way to show all results. I would suggest combining the plots of the empirical cumulative density functions into one 6-panel figure. I think the different lines will still be visible if you make the figures slightly smaller. Alternatively, the figures of the four remaining water uses can be placed in the appendix / supplementary material and be referred to for more information. Similarly, I suggest to include all decades in Figure 6. It is unclear why some decades have been left out.

AC1. The reviewer raises a good point about providing the ecdf results for all the decades, for all the water uses. To address this, first we update Figure 5 to be a two-panel plot with drinking water and recreation, including all the decades.

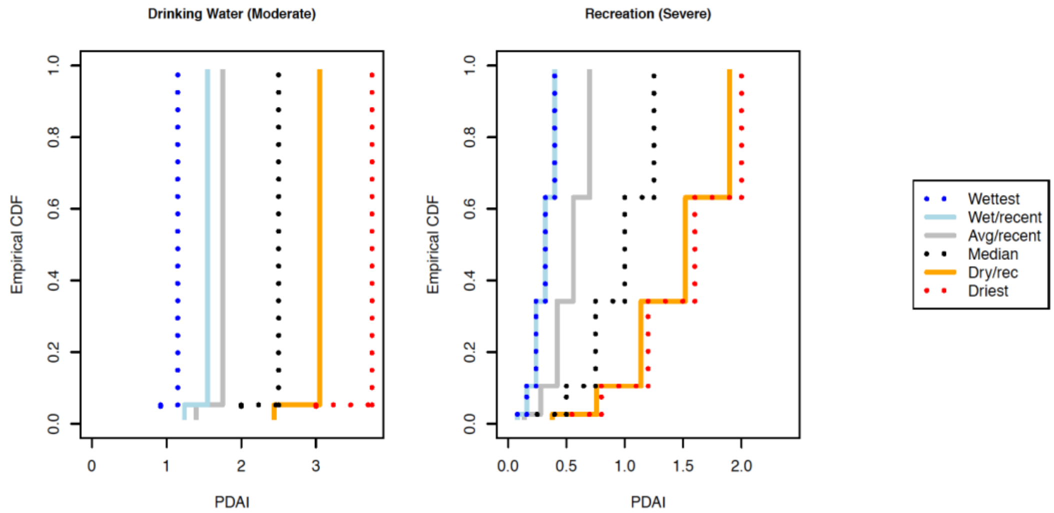

Fig. 5. Empirical cumulative density functions (eCDFs) for the PDAI (Potential Drought Action Indicator) for drinking water using the moderate threshold (left) and for recreation using the severe threshold (right), for their respective wettest, wet/recent, average/recent, dry/recent, and driest historical decades.

Second, we include a 6-panel plot (one for each water use) to the supplemental information. The Supplemental figure (Figure S1) is included below. As a result, the manuscript text has been updated to say (changes in **bold**):

"To demonstrate the PDAI, we examine two different water uses: drinking water and recreation, **although results for all of the water uses can be found in the Supplemental information**."

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 5 (**left**) shows the PDAI for drinking water for the different drought conditions (e.g., wet/recent, dry/recent, etc) from Table 1. 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 or less than that value. In Figure 5 (**left**), as the eCDF moves across drought conditions from very wet to very dry, the PDAI shifts towards higher values, reflecting the increased potential for action under drier conditions. Specifically, the very wet decade has an average PDAI value of 1.1, and the very dry 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 S1).**

Next, we focus on the PDAI for Recreation, a water use that shows diverse importance ratings from stakeholders (Figure 5, right). For recreation, to calculate the PDAI, we use the severe threshold, since that is the threshold at which artesian springs no longer flow (see Section 3.1). **Figure 5 (right) shows the PDAI for recreation for the select decadal drought conditions, using the severe threshold likelihoods from Table 1**. Similar to drinking water, we see that as we move from wetter to drier, 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 S1).**

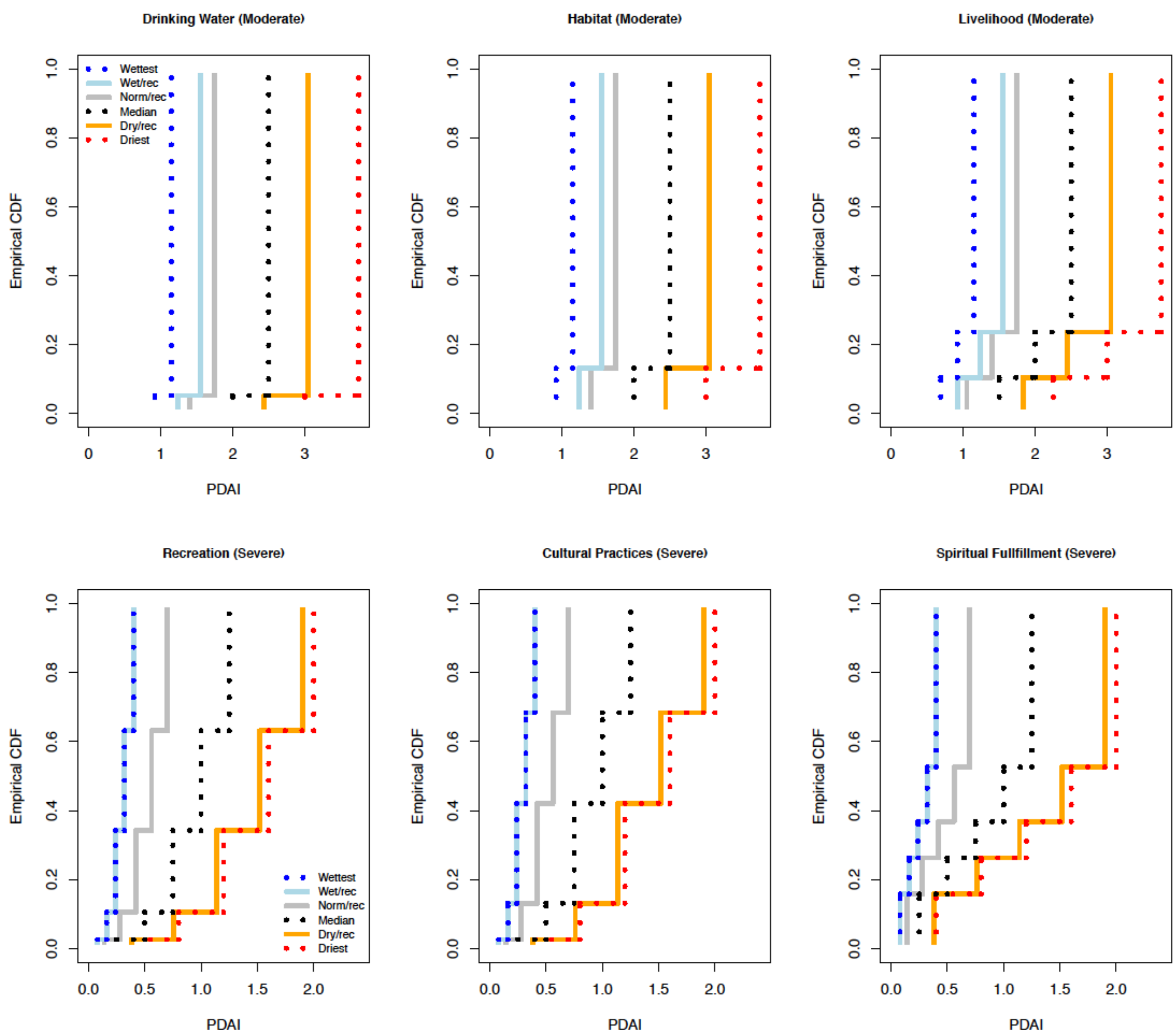

Figure S1. Empirical cumulative density functions (eCDFs) for the PDAI (Potential Drought Action Indicator) for drinking water, habitat, and livelihood using the moderate threshold (top row) and for recreation, cultural practices, and spiritual fulfillment using the severe threshold (bottom row) under the wettest, wet/recent, normal/recent, median, dry/recent, and driest historical decades (see Table 2 for corresponding years).

In creating this figure, we recalled that the decades listed in Table 2 for the "very wet", "median", and "very dry" were all based on the decades of wettest, median, and driest exceedance likelihoods (%s) that corresponded to the *Moderate* Threshold. These did correspond to very wet, normal, and very dry likelihoods for the Severe threshold, but they were not the "wettest", "median", and "driest" likelihoods for the Severe threshold. So, in creating plots that include all the decades for the ecdfs for the water uses that use the Severe threshold (i.e., Recreation, Cultural Practices, and Spiritual Fulfillment), it is more illustrative to show the wettest and driest decades for the severe threshold. Hence, we have updated Table 2, which results in no changes to the P(Z<Mod) column, but slight changes to the P(Z<Sev) column. Specifically, P(Z<Sev) for "very dry" was 38% in 1959-1968 – where 1959-68 was the driest category for the Moderate threshold – but the *driest* decade for the Severe threshold was actually 40%, which occurred in 1964-1973 and 1972-1981. The table has been updated to this effect. Similarly, the "very wet" decade P(Z<Sev) was 13% for 1985-1994, but the wettest decade was 8% in 1993-2002, which is the same as the wet/recent. These changes do not affect the conclusions drawn. We have now updated the table Comment column and figure legends to say "wettest" and "driest" rather than "very wet" and "very dry". These changes are easiest seen by looking at both tables, which are included below, where changes from the old Table 2 to the updated Table 2 are shown in Red here:

Table 2 (UPDATED). Decadal Likelihood (P) of Groundwater (Z) Level Going Below Moderate (Mod) and Severe (Sev) Thresholds for Recent Decades, as Well as 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 2 (OLD). Decadal Likelihood (P) of Groundwater (GW) Level Going Below Moderate (Mod) and Severe (Sev) Thresholds for Recent Decades, as Well as Very Dry, Median, and Very Wet Decades.

Decade	P(GW<Mod) (%)	P(GW<Sev) (%)	Comment
2003-2012	61	38	Dry/recent decade; most recent decade to interviews
1983-1992	35	14	Average/recent decade; third most recent decade
1993-2002	31	8	Wet/recent decade; second most recent decade
1959-1968	75	38	Very dry decade; highest exceedance likelihood
1999-2008	50	24	Median decade; median exceedance likelihood
1985-1994	23	13	Very wet decade; lowest exceedance likelihood

Figure 6 remains the same, but now the text focuses on the concept of the "new normal", and the text has been updated: "In Figure 6, we also looked at recreation under the possibility of a new "normal" drought baseline (Van Loon 2016b)." We further develop this, as can be seen in our response to a later reviewer comment, see RC4 and AC4, below. Figure 7 remains unchanged, as its purpose was focus on the most recent decade (2003-2012) with drinking water and recreation to illustrate the effect of the different threshold.

RC2) I think some form of validation is needed. Either by checking back with the stakeholders whether they agree that the index shows more willingness to take action for certain water uses at certain drought levels, or by using historic information. Are you completely sure that there is no information on drought measures being taken in this area (or a comparable area)? Even not for the most recent drought? Did you consider looking at government reports, (social) media or the US Drought Impact Reporter (which includes lots of information on responses as well)? If you do a bit of this, it gives more backing to the statements like on l. 385-386 that the potential for drought action is diverse because the water use values are diverse (this is obvious because that is what you have put in the equation).

AC2. We agree that empirical validation is an important component, and is a limitation of our current study. Unfortunately, at this point we do not have the resources to check back with stakeholders about the indicator nor to thoroughly investigate historical information. To this point, we tried to be as up-front as we could in the paper, noting in the Introduction (changes in bold): "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…" and "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**." However, we do recognize that we should add more on this point in the manuscript limitations, and further, we appreciate your suggestions of historical information that could be examined, and include them in our discussion. As noted in the General Response, we add Figure 9 and point 5 in the Conclusions (see "5" in General Response, above).

"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 (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

RC3) The interviews were done just after a drought event, which might have influenced the outcomes. Especially since, according to the social memory concept, people might be very aware and willing to save water during and just after a drought, but this awareness and willingness might fade over time when conditions return to normal. I understand that it would take a lot of time to go back into the field and redo the interviews in wet and normal years, but this issue should at least be mentioned in the discussion."

AC3) We agree that the timing of the interviews will influence the outcomes. Here, our purpose was to investigate stakeholder responses after experiencing a drought – which is likely to elicit the most polarized response as compared to non-drought times – and then took the approach of applying that snapshot across different climate conditions. As noted in the General Response, we add Figure 9 and point 2 in the Conclusions (see "2" in General Response, above).:

"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."

RC4) The test of the "new normal" is interesting, but not well developed. Why is it only done for recreation? It would be also interesting for the other water uses, and especially for drinking water. How is the value of 120 feet chosen? Is that a relevant level, because if springs and streams have dried up at 117 feet already, what would be the difference of a level of 120 feet to recreation uses? The paper would be much stronger if you would have a rationale why groundwater levels would go down that much in the future or why different water uses are adapting to lower water availability.

AC4) We wanted to illustrate this concept, but agree that we should provide more rationale for the 120 feet level, which was only available for recreation. This is based on a previous analysis (Towler and Lazrus 2016), the figure I include here for the benefit of the reviewer:

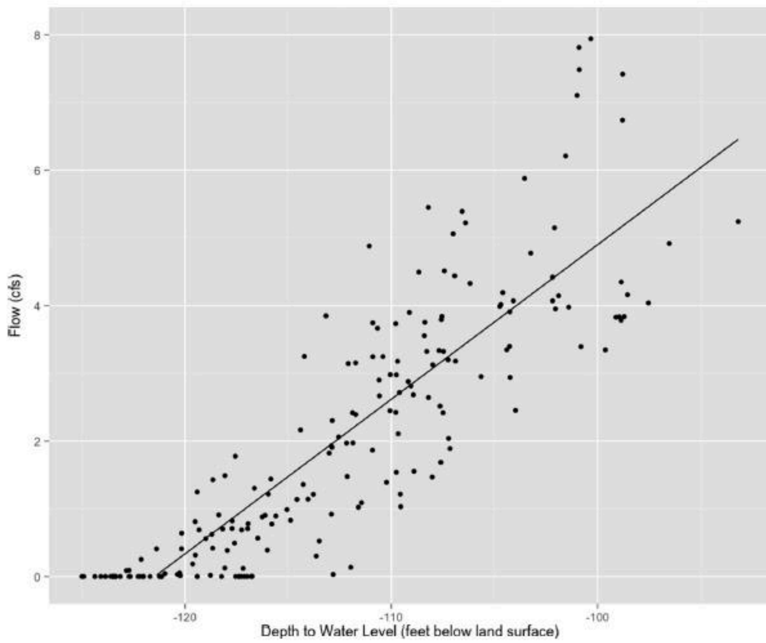

Fig. 2. Scatterplot of monthly Fittstown groundwater depths and Antelope Springs flows ($r = 0.87$).

The x-axis is the same groundwater level data used here, and this is related to spring flows in a Recreation area. From the graph, between -117 and -120 feet below the surface, there is variability in the springs flow, but the linear fit shows a monotonic decrease between the two levels. To clarify this in the paper: "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**)."

RC5) Textual comments: - There is quite a lot of repetition in the paper. For example the sentence that this study combines hydrological and social perspectives of drought comes back a few times. Maybe you do not need to mention it again in the first paragraph of the Methods? Also, the calculation of the PDAI is mentioned in the Methods and the Results (l.326-328). And the results of the differences in PDAI range are mentioned on lines 342-343, 353- 356, and 380-385. It would be good if this could minimised.

AC5) Thanks for pointing these out. We have removed mention of the hydrological and societal perspectives in the first paragraph of the methods, which now reads: "Figure 1 provides the conceptual overview of the study methodology, which is detailed in the subsequent sections." Similarly, we remove the calculation of the PDAI in the Results (formerly l.326-328 that you pointed out), so now it reads: "To demonstrate the PDAI, we examine two different water uses: drinking water and recreation, although results for all of the water uses can be found in the Supplemental information." We opted to leave the specific values of the PDAI range results the first time they are mentioned, but do remove one repetition of the specific range numbers at former lines 380-385, which now reads: "Another key point from Figure 7 is that drinking water spans a smaller range on the PDAI scale than recreation, which is more diffuse."

RC6) - L.106: can't > cannot
AC6) This has been changed.
RC7) - L.124: Climate Division 8 > please explain or give a reference for readers who do not know what Climate Divisions are
AC7) We have added the reference (Karl and Koss 1984):
Karl, T. R., and Koss, W.J.: *Regional and National Monthly, Seasonal, and Annual Temperature Weighted by Area, 1895-1983.* **Historical Climatology Series 4-3**, National Climatic Data Center, Asheville, NC, 38 pp, 1984.
RC8)- L.180: is there a word missing here?
AC8) We have fixed this sentence to read (change in bold): We use data from the beginning of the GW monitoring record through the year the interviews were conducted**, which corresponds to** 1959-2012.
RC9) - There are a lot of references to Figures and Tables in the Conclusions. It would be better is if the Conclusions could be read on a more standalone basis.
AC9) We have removed the references to Figures and Tables in the conclusions.
RC10) More discussion is needed on the limitations of this study. There is a bit now in the last paragraph of the Conclusions, but this could be developed more.
AC10) Based on your feedback, we explicitly address several limitations, outlined in the General Response, above.
RC11)- Figure 2 & 3: please make the axis labels and legend text a bit bigger (maybe also for Figures 5-7)
AC11) Thank you for this input, we have increased the text sizes on these figures.

Interactive comment on "Characterizing the Potential for Drought Action from Combined Hydrological and Societal Perspectives" by Erin Towler et al.

Response to Anonymous Referee #2 Comments:

We thank the referee for their valuable comments, and here are our point-by-point responses. Our responses are in red, and note that RC = referee comments, and AC = author comments.

Referee 2.
RC0. The manuscript by Towler et al. investigates the potential for drought action. The stated "goal of this paper is to provide an experimental methodology towards a better characterization of several components of the drought feedback loop" and the study claims to have done this by "developing an index to characterize how natural influences on drought inform potential human actions on drought." The general topic is important and deserves innovation and systematic research. Unfortunately, I do not really see this was achieved by the presented material. I found the hydrological analysis particularly weak and the relation between drought events, general wetness/dryness, and potentially water scarcity rather than drought defined and elaborated too little for a hydrology journal. The manuscript has some technical issues and lacks a thorough discussion section on uncertainties, biases, and comparing outcomes with other studies. Nevertheless, the material is interesting and an improved version could make a valuable contribution to the topic. My overall assessment is that the manuscript may be more suitable to a journal with less demand on the hydrological science part and perhaps more focus on water resources management or hazards. I hesitate to recommend its publication in HESS.
AC0. We appreciate the reviewer's comments. We address some of these overarching concerns in our General Response above, as well as the more specific comments in our point-by-point responses below. Here, we would like to respond to the reviewer's comment on journal suitability. To this end, we provide an excerpt from the aims and scope of HESS, using bold to highlight the parts of the scope that appealed to us in our selection of this journal for this manuscript: "HESS encourages and supports fundamental and applied research that **advances the understanding of hydrological systems**, **their role in providing water for ecosystems and society**, and the role of the water cycle in the functioning of the Earth system. **A multi-disciplinary approach is encouraged that broadens the hydrological perspective** and the advancement of hydrological science through integration with other cognate sciences and **cross-fertilization across disciplinary boundaries**. HESS, therefore, **aims to serve not only the hydrological science community but all earth and life scientists, water engineers, and water managers**, who wish to publish original findings on the **interactions and feedbacks between the governing processes of the water cycle**….". The selection of a journal is subjective, but from the excerpt above, we believe that our paper lies squarely within the bounds of HESS.
Major comments
RC1) The scientific frame needs to be laid out more specifically. What exactly is meant by Drought Action (title). With the stated goal repeated above, I would first expect a clear definition of and thorough elaboration on what is called the 'drought feedback loop' in the stated goal. To me it remained unclear what is meant by that as well and what it has to do with this study - or where and why exactly is the research gap that is addressed here. In this context, the introduction and discussion ignore literature and existing experience on drought risk management and drought plans and quantitative trigger levels developed with stakeholder processes elsewhere.

AC1. We acknowledge that there are different ways to approach the scientific framing of a drought problem, and have taken steps to better specify how our work fits within our selected frame. As noted in the General Response, above, we saw an opportunity to address this directly in the Conclusions, where we now do a more comprehensive job of identifying our contribution in the drought feedback loop, as well as acknowledging the study limitations; this occurs in Figure 9 and the five corresponding points in the Conclusions (see General Response). Further, we have elaborated on our goal in the Introduction (additions in bold):

"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**."

Another point raised here speaks to the vast drought literature that exists, and the need to better connect with existing experience on drought risk management, drought plans, and quantitative trigger levels developed with stakeholder processes elsewhere. We have added two references and changed a sentence in the Introduction to better illustrate this point; if the reviewer has other specific reference suggestions, please let us know:

"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)**."

However, we also note that our approach is distinctive from stakeholder processes that are explicitly designed to develop a drought plans and quantitative triggers. Rather, one unique aspect of our contribution is to use the social science theory to understand the theoretical underpinnings of how and why stakeholders take action in response to drought. We add text to this effect here (addition in bold):

"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**."

We also add this in point 5 of the Conclusions (also in "5" in "General Response" above):

"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 (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."

Wilhite, DA, Hayes, MJ, Knutson, C, Smith KH, Planning for drought: Moving from crisis to risk management. Journal of the American Water Resources Association, 36(4), p. 697-710. DOI: 10.1111/j.1752-1688.2000.tb04299.x, 2000.

Steinemann, A. C, Iacobellis, S. F., and Cayan, D. R.: Developing and Evaluating Drought Indicators for Decision-Making. *Journal of Hydrometeorology*, *16*(4), 1793–1803. http://doi.org/10.1175/JHM-D-14-0234.1, 2015.

RC2) Overall, the material is presented very much from a descriptive case study perspective, starting with a long description in Background. Each subsection in 3. also starts with a narrative of the case study region's conflicts etc., rather than theoretically presenting the approach and then briefly stating the data of the case study used to illustrate the approach. An international readership as in HESS will be interested in this, not in the case study details.
AC2. The goal of the paper is to put forth a methodology that is developed and demonstrated for a particular case study. Every application will have unique details, but we believe that the details matter. For example, we note in the paper work by Sivapalan (2012), who suggests that one needs to study a particular water system in detail to understand human-hydrology interactions. However, the reviewer makes a good point that we need to explicitly address how this approach can be tailored to other locations. We address this in point 4 of our Conclusions (also listed in General Response Point 4 above):

> "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."

RC3) The manuscript repeatedly states that the study takes a hydrological view on drought. Perhaps my most substantial criticism is that the reader does not receive this hydrological view. As mentioned in the 'Background', the case-aquifer is rain-recharged and feeds springs and rivers as well as groundwater extraction - hence the aquifer's water balance is crucial. A hydrological perspective would need to provide rain and recharge data (or at least climatic water deficit) time series, spring and river flow data as support for when there is drought, and an assessment how the groundwater levels are affected by abstraction as compared to the natural signal (if the van Loon et al. perspective is taken, proof is need what type of drought is considered here exactly). Are there trends - it looks like it? Together with some hydrogeological information, all this is missing and hence I do not see how the occurrence of drought (from a hydrological view a natural phenomenon of temporary water deficit that occurs rarely) can be distinguished from water scarcity or overexploitation. All this needs to be analysed in detail to know what it is exactly that one is feeding into such an index as the one created.
AC3. This is an important comment that has helped us to see how we need to clarify our "piece-of-the-puzzle" on the hydrological perspective. A key point we tried to get across was that the hydrology of this system has been extensively studied elsewhere, and we took the approach of referencing those studies and using the key conclusions in the development of the PDAI. We have added a more specific sentence on the previous study by Christenson et al. 2011 in the

Background: “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).” As such, this allows us to use the probability of groundwater drought as the natural influence of drought in our drought feedback loop, as is now seen in the new Figure 9. We point this out in our new Figure 9 and the limitation of this in Point 1 of our conclusions:

> “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.”

Similarly, we reference some of our previous work – the Towler and Lazrus 2016 – that shows the empirical relationship between groundwater levels and a spring in a Recreation area. For the benefit of the reviewer, we include one previously published figure here from that paper that shows where the Recreation thresholds are derived from:

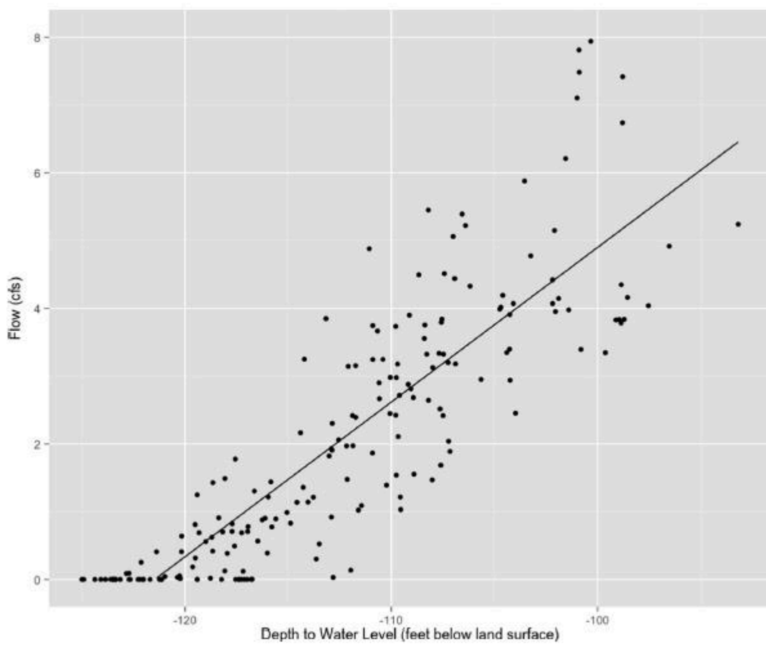

Fig. 2. Scatterplot of monthly Fittstown groundwater depths and Antelope Springs flows ($r = 0.87$).

We also shared this figure with the other reviewer, as they brought up a related point in asking about the -120 feet extreme/new normal threshold, the response to which we share here: The x-axis is the same groundwater level data used here, and this is related to spring flows in a Recreation area. From the graph, between -117 and -120 feet below the surface, there is variability in the springs flow, but the linear fit shows a monotonic decrease between the two levels. To clarify this in the paper, we say: “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**)."

RC4) With the stakeholder process published previously and the very limited hydrological analysis based on one groundwater well record only, the main argument of novelty is the PDAI. For me it was not clear how "potential drought action" is linked to the 'importance' interviews (theoretically). I did not have time to read the cited publication on the stakeholder interviews, but I think the infos given here are not sufficient to understand and follow the argument for a PDAI. Generally, I am not at all convinced about the introduction of yet another index on drought as there is enough confusion over existing drought indices already. Some justification why this is an index (and not just called what it is - function of...are there precedents in other hazards?) and a thorough assessment of transferability and usefulness beyond this case would be needed to justify this as the main contribution to the current debate on the topic.
AC4. We see your point about the proliferation of drought indices, and we want to be sure that we are clear on our study contribution and limitations. First, we have changed the "I" in PDAI from "Index" to "Indicator"; although subtle, we feel that an index is more of a direct measure of something, where in indicator reflects the a more indirect, but insightful, measurement. More concretely, we have also added our conceptual figure, Figure 9, of the drought feedback loop a discussion in point 3 about the Importance ratings:

"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."

Specific or technical comments

RC5) Equations are not numbered and variables are not explained/defined consistently. Unnecessary use of multi-letter variable names (use z with various subs for gw levels and provide units, etc.). Please see HESS instructions for manuscript preparation regarding mathematical notation, use of equations, symbols, etc..
AC5. Thank you. We have fixed and labeled the two equations in the manuscript.

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:

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

RC6) L. 277 Why smoothing by a 10-year running window? Groundwater heads are already smoothed by the dampening processes in the hydrological cycle, but more importantly, any thresholds for management decisions and thus for the analysis will not use that, but actual water level. This requires justification in that respect.

AC6. We agree that we need to add information surrounding this selection. First, we want to clarify that our purpose was to look at the frequency (within a given time window) of a particular drought severity (here groundwater threshold exceedance). We have generalized the approach in the methods: “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.”

Next, in the results, we now reference the different time windows, show the results in the Supplemental Material, but select 10-years for our results to strike a balance between shorter time windows (e.g., 5-years) that show large variabilities and greater time windows (e.g., 15+-year windows) where all of the variability is washed out:

“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 S2. 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 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 out. As such, Figure 3 shows the decadal likelihood for the moderate and severe threshold.”

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

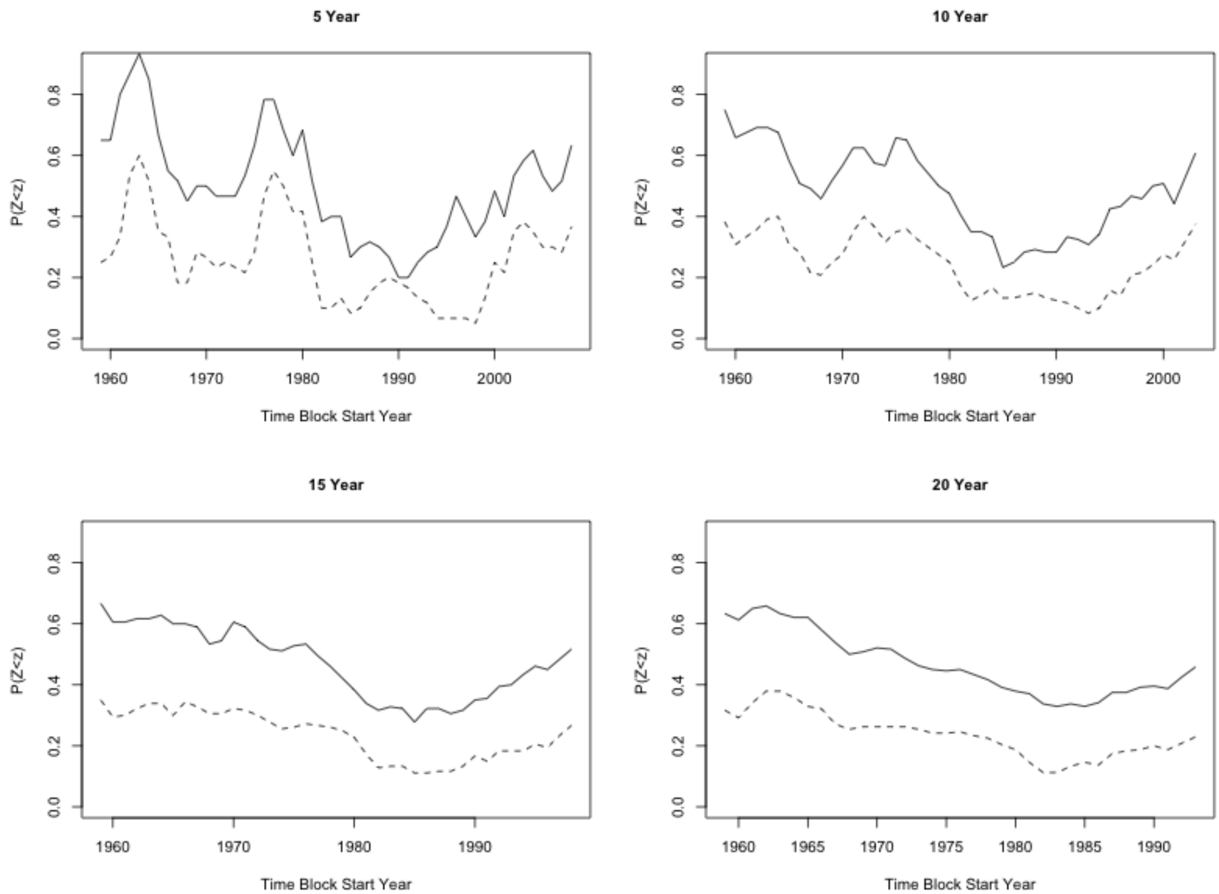

Figure S2. Groundwater drought likelihood (P) of the depth to groundwater level (Z) going below the moderate (z=-111 ft, solid line) and severe thresholds (z=-117 ft, dashed line) for selected time windows.

Also, as mentioned in AC1, we note that our approach is distinctive from stakeholder processes that are explicitly designed to develop a drought plans and quantitative triggers. Rather, one unique aspect of our contribution is to use the social science theory to understand the theoretical underpinnings of how and why stakeholders take action in response to drought. So here, we are not as tied to the actual water levels, and instead are looking at a frequency within a particular time window.

RC7) L. 281ff What exactly is r? Pearson correlation coefficient or some rank correlation? What other indices, etc.? All computations and data need to be introduced in the Data and Methods section. Not here.

AC7. Thank you for pointing this out. r is Pearson correlation coefficient. We have added this information to the Methods:

"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 the Palmer Drought Severity Index (PDSI), the Palmer Hydrological Drought Index (PDHI), and the 6-month Standardized Precipitation Index (SP06). Data were downloaded for Oklahoma Climate Division 8 from http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp."

RC8) L. 288ff? If gw use is low, what is then used - e.g. for drinking water? Wasn't the whole point to analyse the water source that 'is used'? Very confusing. Citations from 2011 and 2006 should not be cited as 'recent' in this context, as a lot may have changed in 10 years.
AC8. Our wording here was a bit confusing, and we note that we have removed the word "recently" and have tightened it up by saying:

"This is the case because water extraction in the area is relatively low (Christenson et al., 2011) and the groundwater levels are very closely related to rainfall recharge." Please also see response AC3, which relates to this comment.

RC9) L. 292ff The classification into wet and dry decades are nice, but what is the relation to the severity and occurrence of the actual drought events?
AC9. We show in Table 3 the Pearson's correlation coefficient between the groundwater drought probability (i.e., the values in Figure 3) and the 10-year running average of PDSI, PDHI, and SP06. For the benefit of the reviewer, we copy Table 3 below, which shows that the relationship to the agricultural, hydrological, and meteorological indices here is quite strong.

Drought Index		Correlation	
Type	Name	P(Z<Mod)	P(Z<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

RC10) How is the link to history made? How can the stakeholder remember what they found important 4 decades ago - this may have been very different from today as life was very different. The constraints on the temporal aspects are not well introduced and not sufficiently discussed.
AC10. We agree that we did not adequately discuss the constraints on the temporal aspects in the previous version. As mentioned in the General response, this is now addressed in point 2 of the conclusions (see General Response and new Figure 9):

"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."

RC11) Section 4. If stakeholders worldview so clearly has opposite rankings in importance, I do not understand why the analysis was carried out on the full sample. Much more logic would be to investigate these two groups separately to obtain more useful results on PDAI or better, incorporate this somehow quantitatively

AC11. Although the stakeholders have different woldviews, and that maps onto their importance rankings, they are still part of the same community and need to make water management decisions together. Part of the purpose of examining the PDAI with all views is to show the spectrum of potential drought action appetite for the community, and how that varies with different water uses.

List of changes to manuscript (see red text in marked up ms):

General

- Changed “index” to “indicator”

Introduction:

- Added two references and referred to previous efforts using stakeholder processes in drought planning (line 60+).
- Clarified that the goal of the paper (line 96+)
- Pointed out that we theoretically validate using social science theory (line 112)

Background

- Added a reference for Oklahoma Climate Division 8 (line 131)
- Gave details on the water balance study that has been performed for the watershed (line 141)

Methodology

- Remove repetition (line 174)
- Clarified the severe threshold (117 feet) and extreme threshold (120 feet) impacts to the artesian springs (line 200).
- Generalized the method for the time windowing approach to get at frequency of exceedance (line 206).
- Added pearson correlation methods to methods section (line 212)
- Numbered equations and fixed notation (line 240)

Results

- Point to results for 5-, 10, 15-, and 20-year time windows in Supplemental Material (Figure S1), and justify our use of 10-year window for results since it strikes a balance between high variability of likelihoods and the likelihoods being washed out (line 298).
- Clarify the close connection between groundwater levels and rainfall recharge from the Christenson et al. (2011) report (line 316)
- Remove repetitive language (line 355)
- Refer to results for all water uses in the Supplemental Material (Figure S2) (line 358, 372, 389).
- Update Figure 5. Now has 2 panels: Drinking Water (left) and Recreation (right), for all decades.
- Update Table 2. Now has the “wettest” and “driest” decades for the Severe threshold (previously it had been wettest and driest for the Moderate, which corresponded to wet and dry conditions for Severe, but not the *wettest* and *driest* for Severe.)
- Remove repetition: remove range amounts (line 415, 416)

Conclusions

- Remove repetition of the Figure/Table numbers that back up the summary statements made in the Conclusions (lines 468-507).
- Add Figure 9 to show drought feedback loop, as well as corresponding numbered places that there could be future enhancements, including (1) Caveat for the need to conduct full water balance, including human withdrawals, in other water systems (lines 514-522), (2) Discussion of the timing of the interviews (post-drought) and their influence on results (line 523-537), (3) Discussion of Importance Ratings and how we applied them

(line 538-547), (4) Discussion of how the PDAI was developed for our case study, but it is flexible and could be tailored to other water contexts (line 548-554), and (5) Discussion of the importance of empirical validation and potential approaches (line 555-570).

Figures (changes not already listed)

- Increased text size on Figures 2, 3, 5, 6, 7.

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 US (NCDC 2015), reinforcing the idea that social factors must also be considered for drought planning (Wilhite and Buchanan-Smith 2005).

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 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). 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, Climate Division 8 (Karl and Koss, 1984). 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 through which to examine 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. ~~In this study, we combine a hydrological perspective using historical hydrological data (section 3.1) with a societal perspective using data from the aforementioned stakeholder interviews (Lazrus 2016; Section 3.2) to quantify the Potential Drought Action Index (PDAI; section 3.3). In Section 3.4, we further examine the data from the interviews, examining stakeholder worldviews using social science theory.~~

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.

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 the Palmer Drought Severity Index (PDSI), the Palmer Hydrological Drought Index (PDHI), and the 6-month Standardized Precipitation Index (SP06). Data were downloaded 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

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

engagement with water resources – for example, in ranching or recreation operations – and recommendations from other interviewees.

For this study, the key question examined was how 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:

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

Although different *f*'s 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.

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. 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 S2. 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 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 out. Figure 3 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 ($r=.94$). We also point out the very close association between the hydrologic threshold exceedance likelihoods and select drought indices for the region (i.e., Oklahoma south-central climate division 8): Table 1 shows that for meteorological, agricultural, and hydrological 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). This point is further discussed in the Conclusions.

Table 2 shows the exceedance likelihoods of select decades from the historical record for both moderate and severe. 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. In the next most recent decades, the exceedance likelihood decreased to 35% (1983-1992) and 31% (1993-2002). 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" decade, and highest exceedance was 75% (1959-1968), or "very dry" 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). 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).

4.3 Potential Drought Action Indicator (PDAI)

~~To calculate the PDAI, we take the product of the decadal likelihood of exceeding a threshold relevant for a water use (section 4.1) and the importance ratings for a water use (section 4.2).~~ To demonstrate the PDAI, we examine two different water uses: drinking water and recreation, although results for all of the water uses can be found in the Supplemental information (Figure S1).

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 5 (left) shows the PDAI for drinking water for the different drought conditions (e.g., wet/recent, dry/recent, etc) from Table 1. 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 or less than that value. In Figure 5 (left), as the eCDF moves across drought conditions from very wet to very dry, the PDAI shifts towards higher values, reflecting the increased potential for action under drier conditions. Specifically, the very wet decade has an average PDAI value of 1.1, and the very dry 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 S1).

Next, we focus on the PDAI for Recreation, a water use that shows diverse importance ratings from stakeholders (Figure 5, right). For recreation, to calculate the PDAI, we use the severe threshold, since that is the threshold at which artesian springs no longer flow (see Section 3.1). Figure 5 (right) shows the PDAI for recreation for the select decadal drought conditions, using the severe threshold likelihoods from Table 1. Similar to drinking water, we see that as we move from wetter to drier, 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 S1).

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 ~~(~.6)~~ on the PDAI scale than recreation ~~(~1.5)~~, 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 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 most variance explained by worldview was recreation: r^2=20% (16%) for Egalitarianism (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 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.

5. Conclusions

Our study implements a conceptual methodology combining hydrological and societal perspectives to understand drought action potential ~~(Figure 1)~~. 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 ~~(Figure 4)~~. A retrospective analysis of groundwater threshold exceedance shows that in recent decades, stakeholders experienced a wide range of likelihoods of exceeding relevant thresholds ~~(Figure 2, Figure 3, Table 2)~~, and these corresponded drought conditions ~~(Table 1)~~. 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 threshold, and hence increase the PDAI ~~(Figure 5, Figure 6)~~. 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 ~~(Figure 7)~~. And conversely, as thresholds become more extreme, which can illustrate human adaptation to new drought normal, the PDAI decreases ~~(Figure 6)~~. 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 ~~(Figure 6 and Figure 7)~~.

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 ~~(Figure 8)~~. Further, for some water uses, the importance people attribute to water can be partially explained by worldview ~~(Table 3)~~. 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 ~~(Figure 7)~~.

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) 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.

References

Bachmair, S., Stahl, K., Collins, K., Hannaford, J., Acreman, M., Svoboda, M., … Overton, I. C.: Drought indicators revisited: the need for a wider consideration of environment and society, Wiley Interdisciplinary Reviews: Water, http://doi.org/10.1002/wat2.1154, 2016.

Christenson, S., Osborn, N.I., Neel, C.R., et al.: Hydrogeology and simulation of groundwater flow in the Arbuckle-Simpson Aquifer, South-Central Oklahoma. Sci. Invest. Rep., 2011–5029, 2011.

Demuth, J. L., Morss, R. E., Palen, L., Anderson, K. M., Anderson, J., Kogan, M., … Henderson, J. (2018). "Sometimes da #beachlife ain't always da wave": Understanding People's Evolving Hurricane Risk Communication, Risk Assessments, and Responses Using Twitter Narratives. *Weather, Climate, and Society*, *10*(3), 537–560. http://doi.org/10.1175/WCAS-D-17-0126.1

Dessai, S. and Sims, C.: Public perception of drought and climate change in southeast England, Environmental Hazards, 9(4), 2010.

Douglas, M: Purity and Danger. Routledge, London, 1966.

Georgakakos, A., Fleming, P., Dettinger, M., et al: Ch. 3: Water resources. In Melillo JM, Richmond T, Yohe GW (eds) Climate change impacts in the United States: The third national climate assessment. US Global Change Research Program, pp 69-112, 2014.

Jones, R.N.: An environmental risk assessment/management framework for climate change impact assessments, Nat. Hazards, 23, 197–230, 2001.

Jones, R.N. and Preston, B.L.: Adaptation and risk management, Wiley Interdiscip Rev: Clim Chang, doi:10.1002/wcc.97, 2011

Karl, T. R., and Koss, W.J.: *Regional and National Monthly, Seasonal, and Annual Temperature Weighted by Area, 1895-1983.* Historical Climatology Series 4-3, National Climatic Data Center, Asheville, NC, 38 pp, 1984.

Knutson, C. L., Hayes, M. J., and Philipps, T.: How to Reduce Drought Risk, Western Drought Coordination Council, Prepared- ness and Mitigation Working Group, Lincoln, 10 pp., available at: http://drought.unl.edu/portals/0/docs/risk.pdf (last access: 18 May 2016), 1998.

Lackstrom, K., Brennan, A., Ferguson, D., Crimmins, M., Darby, L., Dow, K., … Smith, K.: The Missing Piece: Drought Impacts Monitoring. Report from a Workshop in Tucson, AZ, 2013.

Lazrus, H.: "Drought is a Relative Term:" Drought Risk Perceptions and Water

Management Preferences among Diverse Community Members in Oklahoma, USA, Hum Ecol, 44:595, doi:10.1007/s10745-016-9840-y, 2016.

Liu, L., Hong, Y., Bednarczyk, C.N., Yong, B., Shafer, M.A., Riley, R., Hocker, J.E.: Hydro-climatological drought analyses and projections using meteorological and hydrological drought indices: a case study in Blue River Basin, Oklahoma, Water Resour. Manage, 26 (10), 2761–2779, http://dx.doi.org/10.1007/s11269-012-0044-y, 2012

Maggioni, E.: Water demand management in times of drought: What matters for water conservation, Water Resour. Res., 511, 125–139, 2015.

McLeman, R., Dupre, J., Ford, L., Ford, J., Gajewski, K., and Marchildon, G.: What we learned from the Dust Bowl: lessons in science, policy, and adaptation, Popul. Environ., 35, 417–440, doi:10.1007/s11111-013-0190-z, 2014.

McNeeley, S. and Lazrus, H.: The Cultural Theory of Risk for Climate Change Adaptation, Weather, Climate, and Society, 6(4): 506-519, 2014.

McNeeley, S. M., Tessendorf, S. A., Lazrus, H., Heikkila, T., Ferguson, I. M., Arrigo, J. S., … Brugger, J.: Catalyzing Frontiers in Water-Climate-Society Research: A View from Early Career Scientists and Junior Faculty. *Bulletin of the American Meteorological Society*, http://doi.org/10.1175/BAMS-D-11-00221.1, 2011.

Mishra, A. K. and Singh, V. P.: Drought modeling – A review, *Journal of Hydrology*, *403*(1–2), 157–175, http://doi.org/10.1016/j.jhydrol.2011.03.049, 2011.

Mishra, A. K. and Singh, V.P.: A review of drought concepts. Journal of Hydrology 391(1-2):202–216. doi:10.1016/j.jhydrol.2010.07.012, 2010.

NCDC: Billion-Dollar Weather and Climate Disasters, Available online: http://www.ncdc.noaa.gov/billions, 2015.

Oppenheimer, M., Campos, M., Warren, R., et al: Emergent risks and key vulnerabilities. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field CB, Barros VR, Dokken DJ, et al (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1039-1099, 2014.

Ostrom, E: Governing the commons: The evolution of institutions for collective action, Cambridge University Press, New York, NY, 1990.

Polsky, C., and Cash, D. W.: Drought, Climate Change, and Vulnerability: The Role of Science and Technology in a Multi-Scale, Multi-Stressor World. In D. A. Wilhite (Ed.), *Drought and Water Crises: Science, Technology, and Management Issues,* Taylor and Francis, 2005.

Pulwarty, R.: Climate and Water in the West: Science, Information and Decision-making, Water Resources, 124: 4–12, 2003.

Shriver, T. E., and Peaden, C.: Frame Disputes in a Natural Resource Controversy: The Case of the Arbuckle Simpson Aquifer in South-Central Oklahoma, *Society & Natural Resources*, *22*(2), 143–157, http://doi.org/10.1080/08941920801973789, 2009.

Silvis, V., McPherson, R.A., and Lazrus, H.: Climatology of the Arbuckle-Simpson Aquifer region: A report of the water decisions for sustainability of the Arbuckle-Simpson project, NCAR Technical Note NCAR/TN-510+STR, doi: 10.5065/D6Z31WN9, 2014.

Sivapalan, M., Savenije, H. H. G., and Blöschl, G: Socio-hydrology: A new science of people and water, *Hydrological Processes*, *26*(8), 1270–1276, http://doi.org/10.1002/hyp.8426, 2012.

Smith, N. and Leiserowitz, A.: Role of emotion in global warming policy support and opposition, Risk Analysis, doi: 10.1111/risa.12140, 2014.

Stagge, J. H., Kohn, I., Tallaksen, L. M., and Stahl, K.: Modeling drought impact occurrence based on meteorological drought indices in Europe, Journal of Hydrology, 530, 37–50, http://doi.org/10.1016/j.jhydrol.2015.09.039, 2015.

Steinemann, A., and Cavalcanti, L.: Developing multiple indicators and triggers for drought plans, *Journal of Water Resources Planning and Management*, http://ascelibrary.org/doi/abs/10.1061/(ASCE)0733-9496(2006)132%3A3(164), 2006.

Steinemann, A. C., and Hayes, M. J.: Drought Indicators and Triggers. In *Drought and Water Crises: Science, Technology, and Management Issues,* 71–92, 2005.

Steinemann, A. C, Iacobellis, S. F., and Cayan, D. R.: Developing and Evaluating Drought Indicators for Decision-Making. *Journal of Hydrometeorology*, *16*(4), 1793–1803. http://doi.org/10.1175/JHM-D-14-0234.1, 2015.

Tarhule, A., and Bergey, E.A.: Springs in time: comparison of present and historical flows, Report to the Oklahoma Water Resources Institute, 2006.

Thompson, M., Ellis, R., and Wildavsky, A.: Cultural Theory, Westview Press, Boulder, 1990.

Towler, E. and Lazrus, H.: Increasing the usability of drought information for risk management in the Arbuckle Simpson Aquifer, Oklahoma, *Clim Risk Manage*, doi:10.1016/j.crm.2016.06.003, 2016.

Towler, E., PaiMazumder, D., and Holland, G.: A framework for investigating large-scale patterns as an alternative to precipitation for downscaling to local drought, *Climate Dynamics*, doi:10.1007/s00382-016-3116-5, 2016.

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J., … Van Lanen, H. A. J.: Drought in the Anthropocene, *Nature Geoscience*, *9*(2), 89–91, http://doi.org/10.1038/ngeo2646, 2016a.

Van Loon, A. F., Stahl, K., Di Baldassarre, G., Clark, J., Rangecroft, S., Wanders, N., … Van Lanen, H. A. J.: Drought in a human-modified world: Reframing drought definitions, understanding, and analysis approaches, *Hydrology and Earth System Sciences*, *20*(9), 3631–3650, http://doi.org/10.5194/hess-20-3631-2016, 2016b.

Verweij, M., Douglas, M., Ellis, R., Engel, C., Hendriks, F., Lohmann, S., Ney, S., Rayner, S., and Thompson, M: Clumsy solutions for a complex world, Public Administration, 84(4), 847–843, 2006.

Vidal, J.-P., Martin, E., Kitova, N., Najac, J., and Soubeyroux, J.- M.: Evolution of spatio-temporal drought characteristics: val- idation, projections and effect of adaptation scenarios, Hydrol. Earth Syst. Sci., 16, 2935–2955, doi:10.5194/hess-16-2935- 2012, 2012.

Wagener, T., Sivapalan, M., Troch, P. A., McGlynn, B. L., Harman, C. J., Gupta, H. V., and Wilson, J. S.: The future of hydrology: An evolving science for a changing world. Water Resour. Res., 46, W05301, doi:10.1029/2009WR008906, 2010.

Wanders, N., Wada, Y., and Van Lanen, H. A. J.: Global hydrological droughts in the 21st century under a changing hydrological regime, Earth Syst. Dynam., 6, 1–15, doi:10.5194/esd-6-1-2015, 2015.

Wilhite, D. A., and Buchanan-Smith, M.: Drought as Hazard: Understanding the Natural and Social Context, In Drought and Water Crises: Science, Technology, and Management Issues, 2005.

Wilhite, D. A., and Glantz, M. H.: Understanding the drought phenomenon: The role of definitions, Water International, 10(3):111–120, 1985.

Wilhite, D. A., Hayes, M. J., and Knutson, C. L.: Drought Preparedness Planning: Building Institutional Capacity, In Drought and Water Crises: Science, Technology, and Management Issues, 2005.

Wilhite, DA, Hayes, MJ, Knutson, C, Smith KH, Planning for drought: Moving from crisis to risk management. Journal of the American Water Resources Association, 36(4), p. 697-710. DOI: 10.1111/j.1752-1688.2000.tb04299.x, 2000.

Wilhite, D. A., Svoboda, M. D., and Hayes, M. J.: Understanding the complex impacts of drought: A key to enhancing drought mitigation and preparedness. *Water Resources Management*, *21*(5), 763–774. http://doi.org/10.1007/s11269-006-9076-5, 2007.

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<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

Table 2. Decadal Likelihood (P) of Groundwater (Z) Level Going Below Moderate (Mod) and Severe (Sev) 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

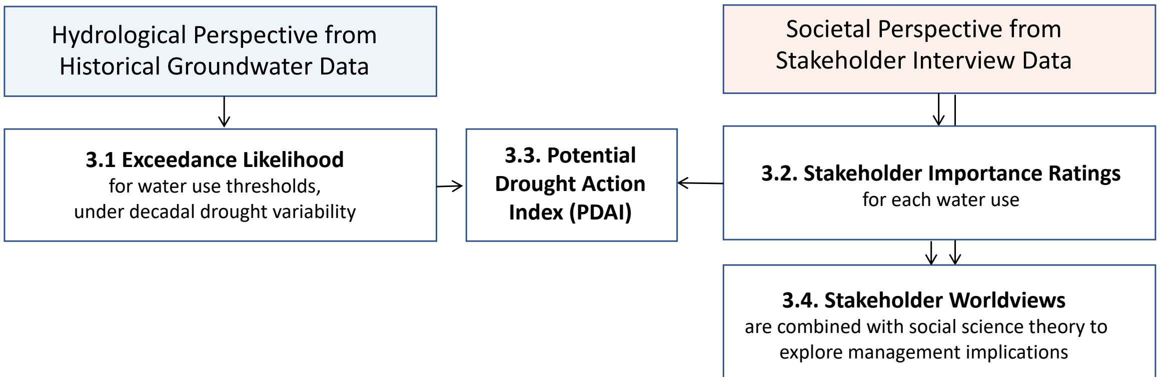

Figure 1. Conceptual overview of the methodology that combines a hydrological perspective from historical groundwater data with a societal perspective from stakeholder interview data to quantify the Potential Drought Action Indicator (PDAI); stakeholder worldviews from the interviews and social science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

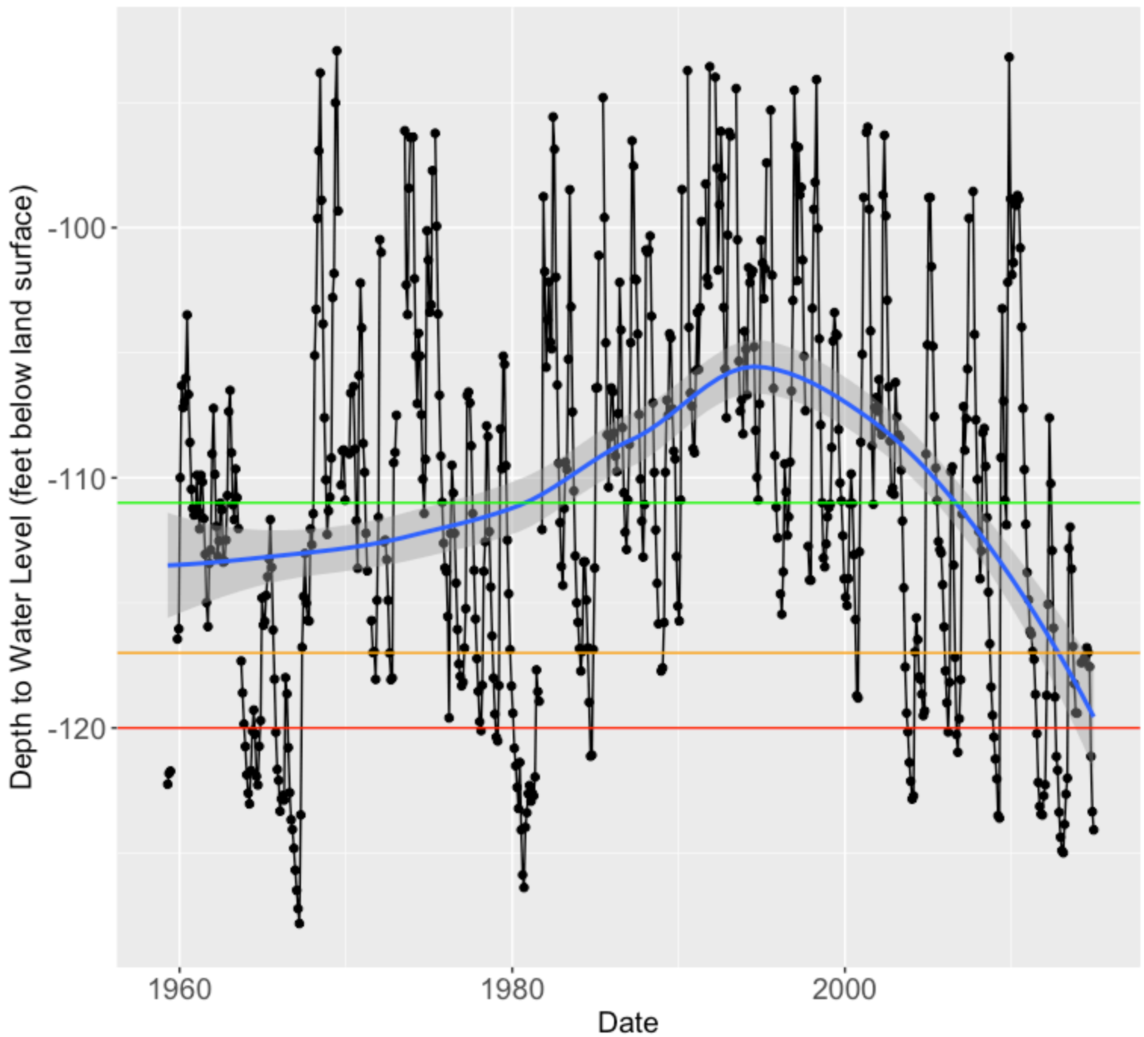

Figure 2. Monthly groundwater time series; blue line is smoother average, green line is the moderate threshold (= -111 feet) and the orange line is severe threshold (=-117 feet); the red line is an extreme threshold (= -120 feet) that is used to illustrate a possible new normal drought threshold.

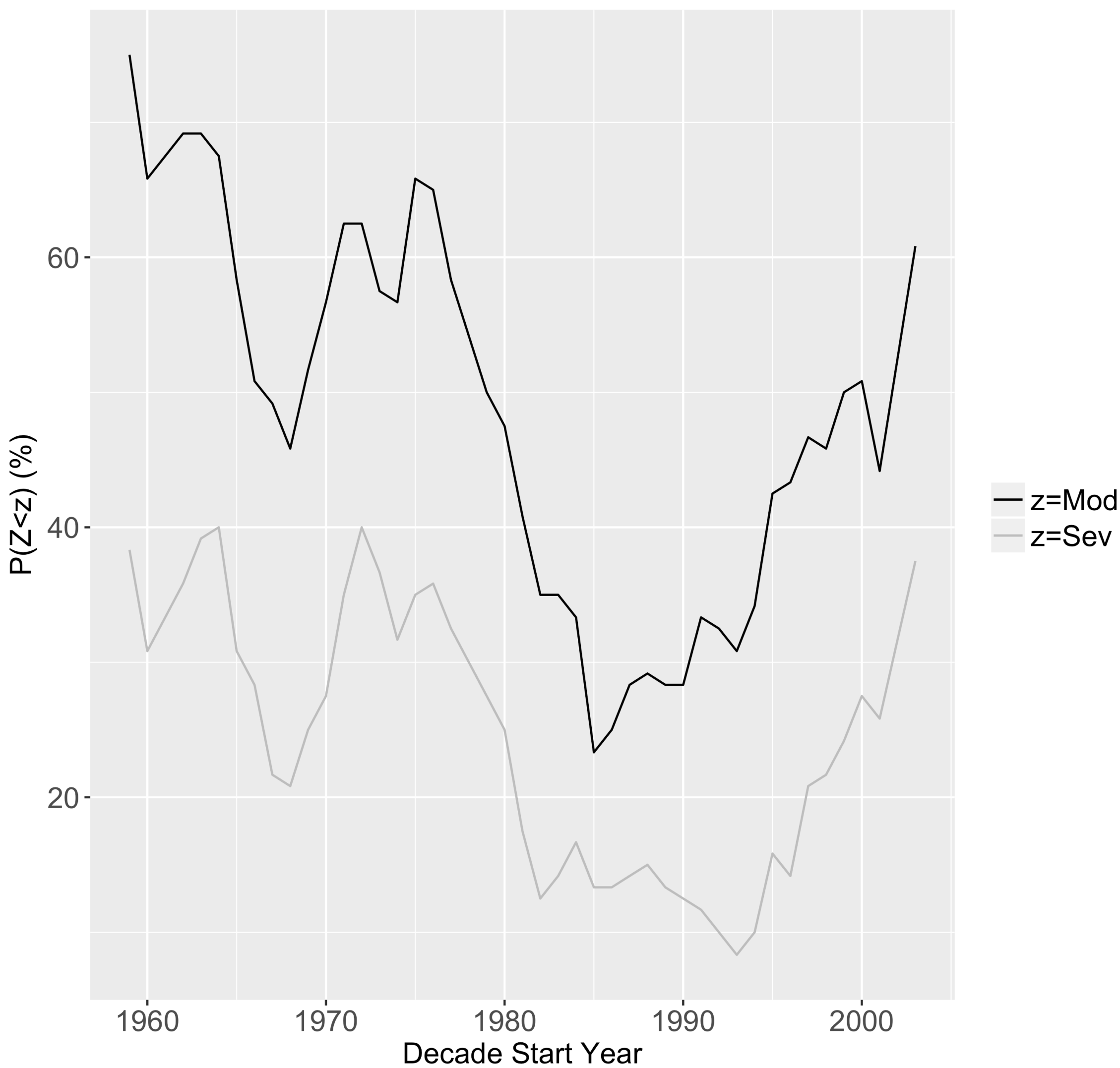

Figure 3. Decadal likelihood (P) of the depth to groundwater level (GW) going below the moderate (y=-111 ft) and severe thresholds (y=-117 ft).

Figure 4. Rated importance of water for each water use from stakeholder surveys (N=38). 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.

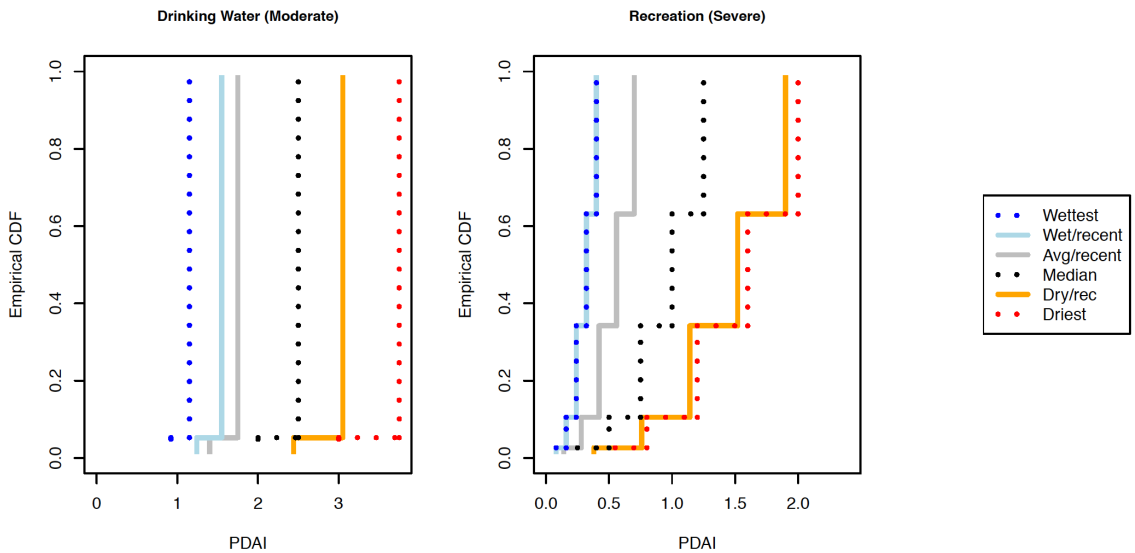

Figure 5. Empirical cumulative density functions (eCDFs) for the PDAI (Potential Drought Action Indicator) for drinking water using the moderate threshold (left) and for recreation using the severe threshold (right), under the wettest, wet/recent, average/recent, dry/recent, and driest historical decades.

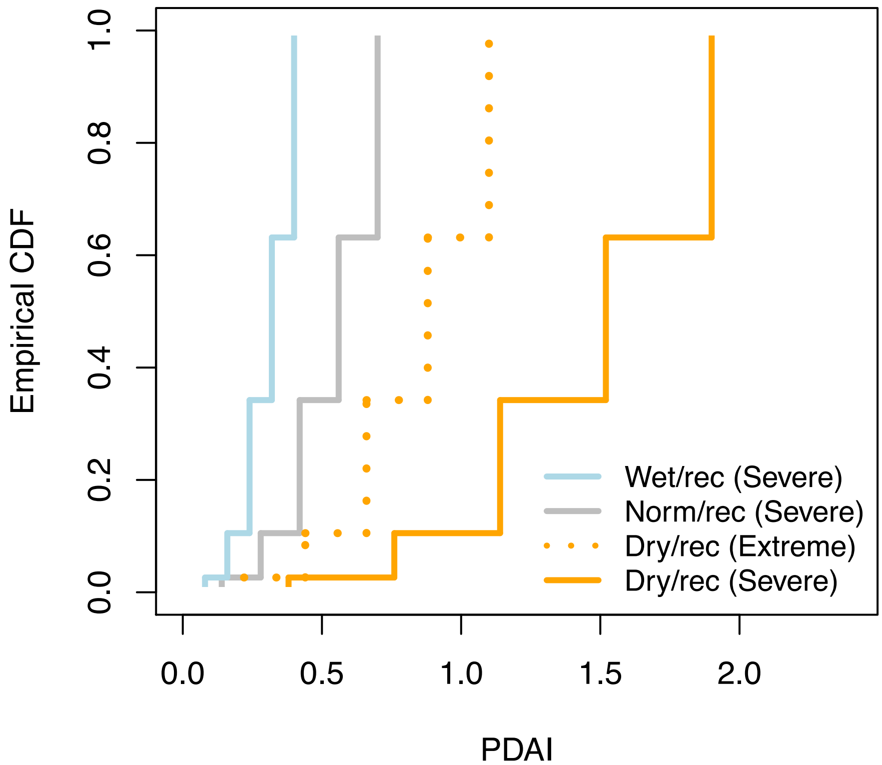

Figure 6. Empirical cumulative density functions (eCDFs) for the PDAI (Potential Drought Action Indicator) for recreation under the wet/recent (1993-2002), normal/recent (1983-1992), and dry/recent (2003-2012) for the severe threshold, as well as the dry/recent for the extreme threshold.

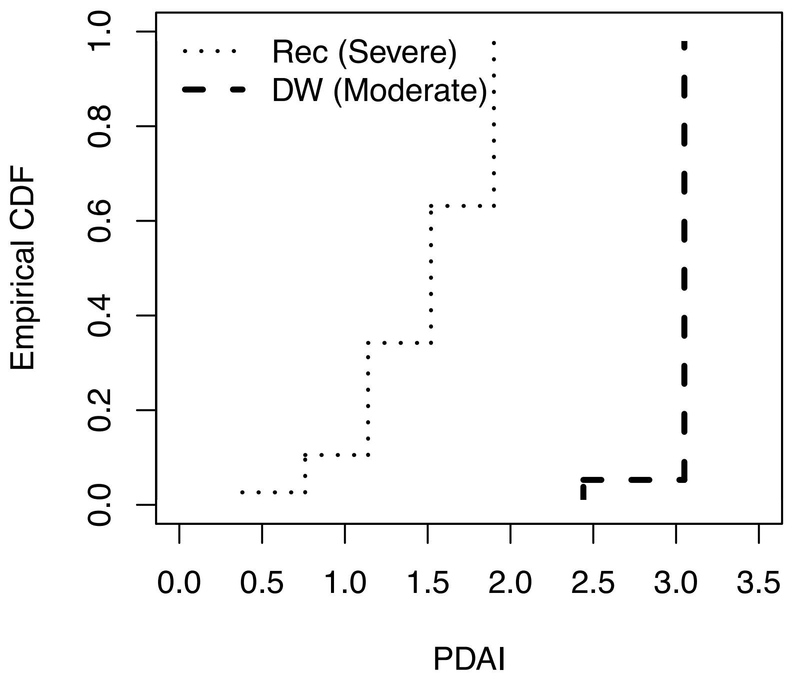

Figure 7. Empirical cumulative density functions (eCDFs) for the PDAI (Potential Drought Action Indicator) for recreation (Rec) using the severe threshold and for drinking water (DW) using the moderate threshold for the dry/recent decade (2003-2012).

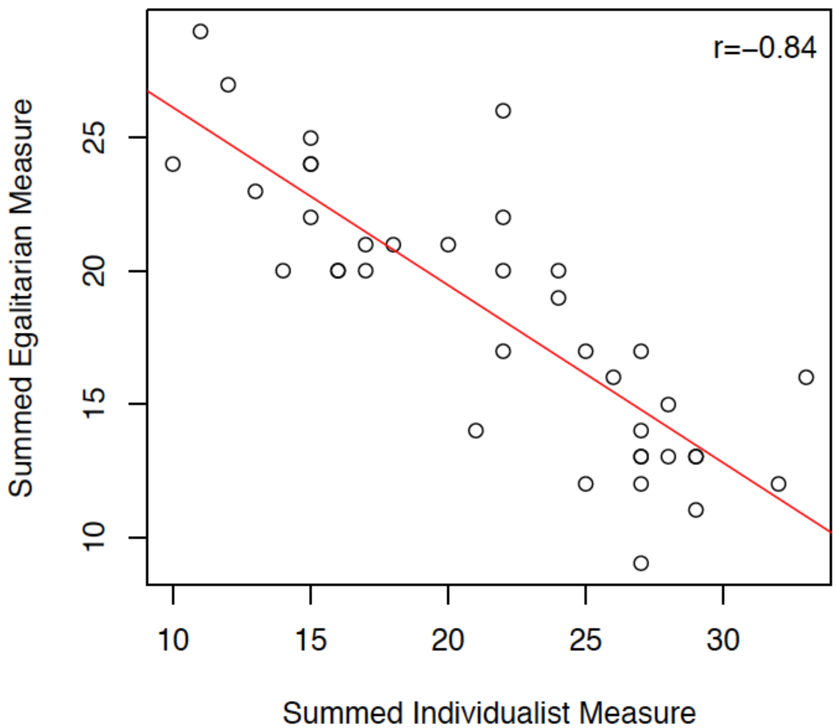

Figure 8. Summed responses for individualism versus egalitarianism for each interviewee (n=38) show that both individualist and egalitarian worldviews were represented by the interviewees . The egalitarianism and individualism measures were strongly inversely correlated (r=-0.84).

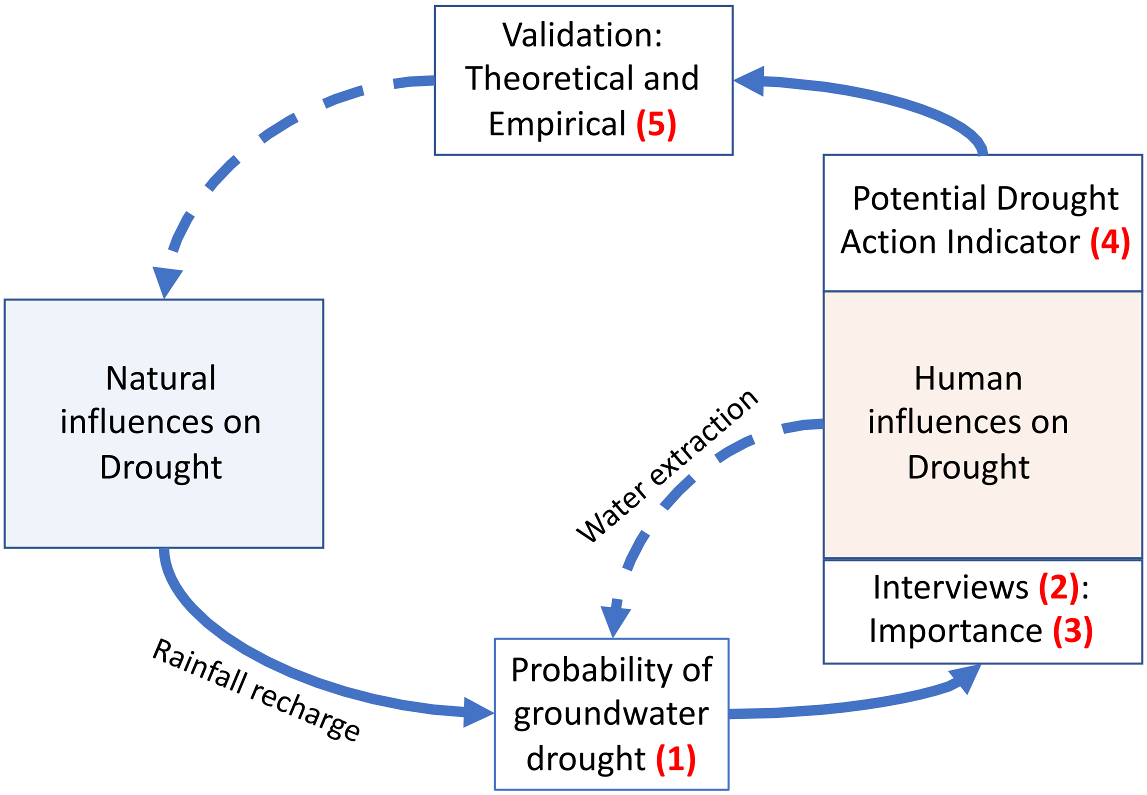

Figure 9. Conceptual map of drought feedback loop components addressed in this study (blue solid lines) and remaining gaps (blue dashed lines). Numbers correspond to discussion points in Conclusions.

Supplemental Figures

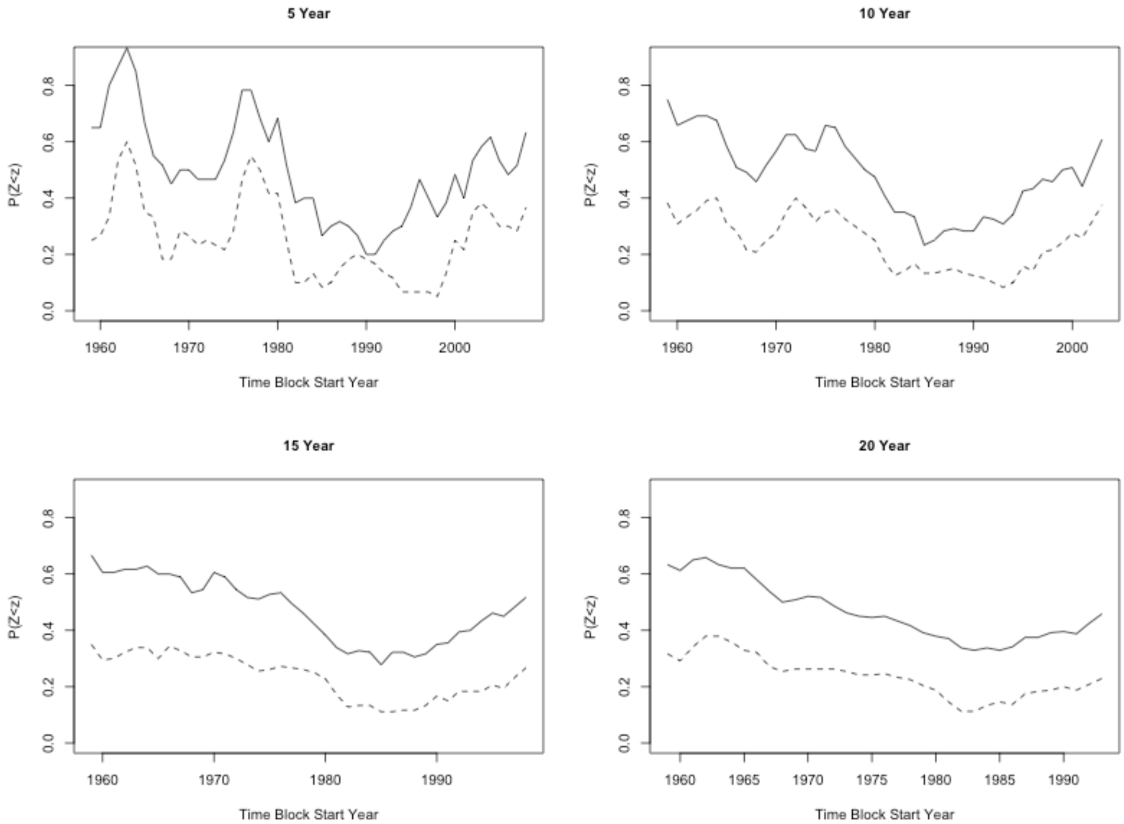

Figure S1. Groundwater drought likelihood (P) of the depth to groundwater level (Z) going below the moderate (z=-111 ft, solid line) and severe thresholds (z=-117 ft, dashed line) for selected time windows.

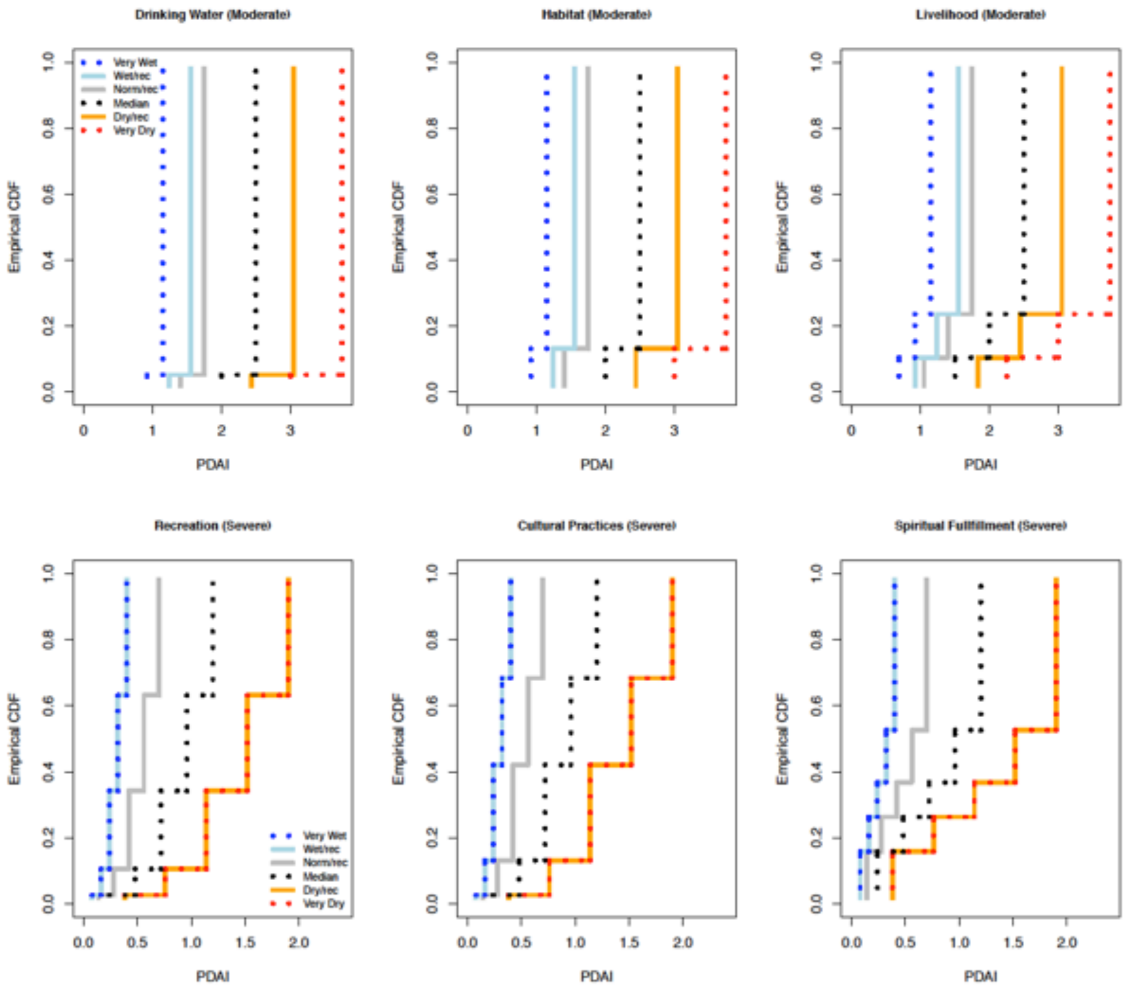

Figure S2. Empirical cumulative density functions (eCDFs) for the PDAI (Potential Drought Action Indicator) for drinking water, habitat, and livelihood using the moderate threshold (top) and for recreation, cultural practices, and spiritual fulfillment using the severe threshold (bottom), under the wettest, wet/recent, average/recent, dry/recent, and driest historical decades.