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)

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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

92 changing the normal drought reference baseline (Van Loon et al. 2016b). However, fully
93 characterizing the feedback loops between human and natural influences on drought
94 remains challenging.
95   The goal of this paper is to provide an experimental methodology towards a better
96 characterization of several components of the drought feedback loop, specifically to gain
97 understanding on how and why people might take action in response to drought. To this
98 end, we develop an indicator to characterize how natural influences on drought inform
99 *potential* human actions on drought. We use the term "potential", since in this study, we
100 do not have the data to validate whether or not human actions were actually taken as a
101 result of these natural drought influences. In this investigation, we characterize the
102 natural influences by taking a hydrological perspective on drought (Van Loon et al.
103 2016b); specifically, we examine the exceedance of relevant thresholds from historical
104 hydrologic data. For the societal perspective, we examine stakeholder input from
105 interviews, specifically how stakeholders rated the importance of water for different uses.
106 In our attempt to better characterize the potential for drought action, we combine the data
107 from the hydrological and societal perspectives, developing a new, derivative product
108 that we call the Potential Drought Action Indicator (PDAI). Here, by "action", we
109 generally mean some effort towards drought mitigation. Though we do not directly
110 validate the PDAI, we are able to interpret the findings to provide insights to water
111 management policy using additional interview data on stakeholder worldviews and social
112 science theory; this is unique in that it allows us to investigate the theoretical
113 underpinnings that are not typically explored in drought risk studies or stakeholder
114 processes.
115   We demonstrate the PDAI through a place-based assessment of drought risk in south-
116 central Oklahoma, where water availability is highly influenced by drought and
117 management of water resources is contested by local stakeholders; we provide some
118 background and describe this study site in section 2. Section 3 outlines the methodology:
119 sections 3.1 and 3.2 outline the details of the methods used to assess the hydrological and
120 social perspectives, respectively. Details about how the PDAI is developed is provided in
121 section 3.3. In section 3.4, we describe additional interview data on the stakeholder
122 worldviews and provide an overview of the social science theory. Results for our study
123 site are shown in section 4.
124
125 2. Background and Study Site
126   The goal of this paper is to gain insights into the potential for human action on
127 drought, and one suggested way to do this is to study a particular water system in detail
128 (Sivapalan 2012). As such, the PDAI is developed and demonstrated for the Arbuckle-
129 Simpson Aquifer (ASA), a groundwater resource that underlies an area of about 520
130 square miles (1350 square kilometers) in south-central Oklahoma, Climate Division 8
131 (Karl and Koss, 1984). The ASA provides water for municipal supply, ranching, and
132 mining, and is also the source of local springs and streams that support wildlife,
133 recreation, and tourism. Drought is part of the region's history (Silvis et al. 2014), and the
134 ASA is recharged by rainfall, thus making it susceptible to climate variability and
135 change. The ASA has been the center of a water management dispute that arose in 2002
136 when landowners began negotiations to sell their groundwater to an area outside of the
137 ASA, near Oklahoma City. The landowners' actions were quickly contested by a local

138 environmental group, the Citizens for the Protection of the Arbuckle-Simpson Aquifer
139 (CPASA; Shriver and Peaden 2009; Lazrus 2016), which led to a moratorium in 2003
140 that suspended any activities to remove water from the basin until a hydrological study
141 could be conducted. The study included a water balance, hydrogeological study, and
142 groundwater model of the aquifer; the study shows that although water is extracted,
143 groundwater use from the aquifer is relatively small, and that the groundwater-fed
144 streamflow discharge is mostly related to rainfall recharge (Christenson et al. 2011). This
145 was followed by a ruling that reduced the amount of water that could be removed from
146 the aquifer annually by an order of magnitude. This further exacerbated the tensions
147 between the landowners who see the decision as an encroachment on their individual
148 property rights, and CPASA and other community members who see the reduction as a
149 way to protect local water resources (Lazrus 2016). The ASA's susceptibility to drought,
150 as well as its diverse community and contentious management issues, make it an ideal
151 site for exploring the potential for feedback on drought.
152   In this paper, we explicitly combine hydrological and societal perspectives, but
153 historically, these two perspectives would likely be examined in isolation. In fact, this
154 work builds upon and extends two previous studies that focused on the same ASA case
155 study, but were disciplinary in nature: Lazrus (2016) and Towler and Lazrus (2016).
156 Lazrus (2016) describes results of stakeholder interviews collected for the ASA; it offers
157 an anthropological lens through which to examine how stakeholders perceive drought and
158 how those perceptions intersect with their cultural processes. Lazrus (2016) was
159 motivated by the hydrological context of the ASA, but did not engage directly with any
160 quantitative meteorological or hydrological analysis. On the other hand, Towler and
161 Lazrus (2016) take a hydrological perspective, developing a generalized framework that
162 links meteorological drought indices with hydrologic threshold exceedances that are
163 relevant to ASA stakeholders. To identify some of the hydrological thresholds and
164 provide social context, Towler and Lazrus (2016) draw on qualitative insights gathered
165 from the interviews, but do not directly incorporate any of the quantitative interview
166 results into the analysis. In this paper, we extend these two studies to offer a novel,
167 quantitative, interdisciplinary approach, that results in a derivative product, adding value
168 to the preceding studies. Although the PDAI is experimental, conducting this type of
169 study is critical, given the grand challenge of engaging in interdisciplinary research at the
170 climate-water-society interface (McNeeley et al. 2011).
171
172 3. Methodology
173
174   Figure 1 provides the conceptual overview of the study methodology, which is
175 detailed in the subsequent sections.
176
177 3.1 Hydrologic Perspective: Threshold Exceedance
178   To characterize natural influences on drought, we examine drought from a
179 hydrological perspective. Taking a hydrological, rather than meteorological, perspective
180 is advocated by Van Loon et al (2016b), given the closer connection of surface water and
181 groundwater with societal use and management. Here, we use a groundwater (GW) well
182 that has relevance to the community (Towler and Lazrus 2016), has a long available
183 record, and is monitored by water managers in the community: the USGS Fittstown well

184 (USGS 343457096404501). We use data from the beginning of the GW monitoring
185 record through the year the interviews were conducted, which corresponds to 1959-2012.
186 Details of this dataset can be found in Towler and Lazrus (2016).
187   To connect the hydrologic perspective with human action, we examine the historical
188 groundwater data in terms of decision relevant thresholds (Jones 2001). From Towler and
189 Lazrus (2016), we identify two main thresholds relevant to water uses asked about in the
190 interviews (see section 3.2). The first threshold is called a "moderate" threshold: This is a
191 groundwater level of 111 feet below the surface, which is decision relevant because it is
192 when the aquifer begins to be closely monitored because of potential impacts to
193 municipal supply. The second threshold is the "severe" threshold: this is when the
194 groundwater level lowers further, to 117 feet below the surface, which is the level at
195 which artesian springs in the area have minimal flow or stop flowing altogether, affecting
196 uses such as wildlife and recreation. For illustrative purposes, we also look at an
197 "extreme" threshold of groundwater levels to 120 feet below the surface, which have
198 been experienced in the aquifer and further the likelihood of minimal or stopped spring
199 flows (see Figure 2 in Towler and Lazrus 2016).
200   To quantify the threshold exceedance, we calculate the percent frequency of
201 exceedance[1] for each threshold in the historical record. To calculate the exceedance
202 frequency, a time window needs to be selected; we initially examined 5-, 10-, 15-, and
203 20- year windows. Specifically, we calculate the number of months during each x-year
204 running window that the threshold was exceeded across the available record. For
205 example, for the 10-year window, it would be 1959-1968, 1960-1969, etc., all the way to
206 2003-2012. Henceforth, we refer to this as the groundwater drought likelihood.
207   We also calculate the Pearson's correlation coefficient (r) values between the decadal
208 likelihoods and several drought indices for the area. Specifically, we correlate the decadal
209 likelihoods with 10-year running averages of the Palmer Drought Severity Index (PDSI),
210 the Palmer Hydrological Drought Index (PDHI), and the 6-month Standardized
211 Precipitation Index (SP06). Data were downloaded for Oklahoma Climate Division 8
212 from http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp.
213
214 3.2. Social Perspective: Stakeholder Importance Ratings
215   To understand how community members in the ASA region might respond to natural
216 influences drought, we use stakeholder interview data from a previous investigation
217 (Lazrus 2016). Stakeholder interviews (n=38) were conducted in the summer of 2012,
218 following a significant drought in 2011. Interviewee selection followed a targeted
219 snowball sampling strategy whereby interviewees were selected based on their
220 involvement in the ASA water management negotiations, their dependence on or
221 engagement with water resources – for example, in ranching or recreation operations –
222 and recommendations from other interviewees.
223   For this study, the key question examined was how people perceive the importance
224 of water for various uses. We make the assumption that the more important water is
225 perceived to be for a particular use, the greater the potential will be for taking action - in
226 this case, conserving water for that use.

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

227   To understand the importance of water for various uses, interviewees were asked
228 how important (on a Likert scale of 1-5, 5 being very important) water resources are in
229 their community for: a) People's livelihoods, b) Recreational activities, c) Spiritual
230 fulfillment, d) Cultural practices, e) Habitat for plants and animals, and f) Availability of
231 drinking water. Data from these questions was used directly and called "importance
232 ratings", which were integrated into the PDAI (see section 3.3).
233
234 3.3. Creating the Potential Drought Action Indicator (PDAI)
235   We express the PDAI as a function, f, of (i) the decadal probability (P) of the
236 groundwater level, Z, exceeding the hydrologic threshold, z, and (ii) the importance
237 ratings (I):

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

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

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

241 Although different f's could be explored in different contexts, using a product to create a
242 new indicator is based on a frequently used definition of risk, which combines the
243 likelihood of an event and its consequence (Jones and Preston 2011).
244   Here, $P(Z<z)$ is the decadal likelihood of exceeding a particular threshold (e.g.,
245 moderate or severe), per section 3.2. This is multiplied by the importance of water for a
246 particular use, which is directly derived from the stakeholder ratings (section 3.1).
247 Essentially, the importance ratings are used as a weight function to modulate the
248 likelihood of exceedance.
249
250 3.4. Social Perspective: Stakeholder Worldviews
251   We are also interested in exploring *why* people perceive the importance of water
252 for various uses differently. For this, we again interrogate the interview data using a
253 social science theory called The Cultural Theory of Risk (CTR; Douglas 1966; McNeeley
254 and Lazrus 2014). According to CTR, people hold different cultural worldviews about
255 how society should be organized and how society and nature should interact. CTR
256 predicts that people will perceive risks and consequences from hazards when their
257 worldview is challenged. According to this understanding, perceptions are as much about
258 social organization as they are about the physical hazard. Their worldview will also guide
259 their preference for different risk management strategies, or in this case drought actions,
260 making it relevant to our PDAI results. Two of the worldviews described by CTR are
261 individualism and egalitarianism. These represent idealized categories and are useful
262 heuristics, but in reality, people may adhere to some elements of the cultural worldviews
263 more than others. People with individualist views favor weak social bonds and have little
264 need for social structure, preferring individual competition and market-based transaction
265 strategies. For them, nature is a bountiful resource robust to human uses and therefore
266 may not need to be managed for conservation. People with egalitarian views favor strong
267 social bonds and collective decision-making processes. For them, nature is fragile and
268 easily impacted by humans and so must be carefully managed to avoid catastrophe
269 (Thompson et al. 1990). By identifying the cultural processes that lead people to
270 recognize risks and perceive consequences, CTR also helps to diagnose why
271 disagreements arises over risk management; that is, disagreements may arise between
272 constituent groups holding different worldviews when management strategies do not

273   reflect elements of each constituent's predominant worldview (Verweij et al. 2006).

274   To this end, we examined how peoples' importance ratings from section 3.2 were

275   related to their worldviews. If so, it would help us to understand how the PDAI could be

276   operationalized – that is, might people respond more favorably to water management

277   strategies that reflected their own management preferences based on their cultural

278   worldviews? For the CTR, interview questions about worldview used previously tested

279   measures for individualism and egalitarianism developed by Smith and Leiserowitz

280   (2014) as well as additional questions informed by CTR that reflected the particular water

281   management context of the ASA. These questions asked people whether they strongly

282   agreed, agreed, neither agreed nor disagreed, disagreed, or strongly disagreed (on a 5

283   point Likert scale) to a series of statements. Responses were summed for each

284   interviewee to determine a value for individualism or egalitarianism. Follow-up open-

285   ended questions allowed interviewees to elaborate on their worldview preferences and

286   importance ratings.

287

288   4. Results

289

290   4.1. Threshold Exceedance Likelihood

291   Figure 2 shows the historical monthly groundwater time series, including the

292   moderate threshold (111 feet below the surface) and severe threshold (117 feet below the

293   surface) introduced in Section 3.2. Groundwater drought likelihood is calculated as the

294   number of months within each 5-, 10-, 15-, and 20-year running window that the level

295   went below a particular threshold. Drought likelihoods for the selected time windows (5-,

296   10-, 15-, and 20-years) are shown in the Supplemental Material, Figure S1. Results for

297   each time window follow similar patterns, though as expected, the shorter the time

298   window, the greater variability in the likelihood. We selected the 10-year running

299   window for calculating the PDAI as it strikes a balance between shorter time windows

300   that have high variability and likelihood swings (e.g., 5-year windows) and longer time

301   windows (e.g., 15-, and 20-years) where much of the variability gets washed out. As

302   such, Figure 3 shows the decadal likelihood for the moderate and severe threshold. As

303   expected, the higher the threshold, the higher the likelihood of exceedence (i.e., a

304   moderate threshold is exceeded more often than the severe threshold). Further, the

305   likelihoods are correlated (r=.94). We also point out the very close association between

306   the hydrologic threshold exceedance likelihoods and select drought indices for the region

307   (i.e., Oklahoma south-central climate division 8): Table 1 shows that for meteorological,

308   agricultural, and hydrological drought indices, the correlations with the moderate

309   threshold exceedance is >-.9 and with the severe threshold is >-.8. This underscores the

310   notion that for this case study, the hydrological perspective is a good indicator of the

311   natural influences on drought. This is the case because water extraction in the area is

312   relatively low and the groundwater levels are very closely related to rainfall recharge

313   (Christenson et al., 2011). However, we note that that this may not be the case for other

314   groundwater aquifers that are more affected by human extraction (e.g., Tarhule and

315   Bergey 2006). This point is further discussed in the Conclusions.

316   Table 2 shows the exceedance likelihoods of select decades from the historical record

317   for both moderate and severe. Arguably the most relevant decade is the one most recent

318   to when the interviews were conducted: 2003-2012. For 2003-2012, the moderate

319 threshold was exceeded 61% of the time. In the next most recent decades, the
320 exceedance likelihood decreased to 35% (1983-1992) and 31% (1993-2002). Given the
321 close association with drought (Table 1), this suggests that in the decades of the last 30-
322 years, stakeholders experienced relatively dry (2003-2012), relatively average (1983-
323 1992), and relatively wet (1993-2002) decades; these are referred to as the "dry/recent",
324 "average/recent", and "wet/recent" decades, respectively. To put into context, for the
325 moderate threshold, the decade with the lowest exceedance likelihood was 23% (1985-
326 1994), which we call the "very wet" decade, and highest exceedance was 75% (1959-
327 1968), or "very dry" decade. Results follow similar patterns for the severe threshold
328 (Table 2).
329
330 4.2. Stakeholder Importance Ratings
331   Stakeholder interviews reveal that there is more consensus on the importance of water
332 for some water uses than others (Figure 4). On average, water was deemed most
333 important for drinking water, followed closely by habitat for wildlife, and supporting
334 livelihoods. The importance of water for these uses was similar for most stakeholders
335 interviewed, as evident by the tightness of the box plot (Figure 4). On the other hand,
336 there was a spread in responses for recreation, cultural practices, and spiritual fulfillment.
337 Some of the spread in responses on these measures may be due to how interviewees
338 interpreted the water uses (Lazrus 2016).
339   The spread in responses indicates that different stakeholders place different levels of
340 importance on some water uses, such as water for recreation which shows a broader
341 spread than water for drinking water, habitat, or livelihood. For example, one interviewee
342 underscored the importance of water, describing that "Murray County is one of the top
343 tourist attractions with Arbuckle Lake and Chickasaw National Recreation area. So
344 water is the absolute key" (Interview 1). demonstrating a very different perspective,
345 another interviewee noted that "Recreation and water are not critical to me. I mean in
346 this part of the world, they don't necessarily go hand-in-hand because it's a relatively dry
347 place, and there are not that many places to really go and play in the water" (Interview 5).
348
349 4.3 Potential Drought Action Indicator (PDAI)
350   To demonstrate the PDAI, we examine two different water uses: drinking water and
351 recreation, although results for all of the water uses can be found in the Supplemental
352 information (Figure S2).
353   First, we focus on drinking water, which is an example of a water use which exhibited
354 more consensus among interviewees. For drinking water, to calculate the PDAI, we use
355 the moderate threshold, since this is the threshold at which municipal supply is monitored
356 (see Section 3.1). Figure 5 (left) shows the PDAI for drinking water for the different
357 drought conditions (e.g., wet/recent, dry/recent, etc) from Table 1. Results are shown as
358 empirical Cumulative Density Functions (eCDFs) to reflect the discrete nature of the
359 importance ratings. In the eCDFs, the vertical lines represent the PDAI values, and the
360 horizontal lines represent the percentage of data that are equal or less than that value. In
361 Figure 5 (left), as the eCDF moves across drought conditions from very wet to very dry,
362 the PDAI shifts towards higher values, reflecting the increased potential for action under
363 drier conditions. Specifically, the very wet decade has an average PDAI value of 1.1, and
364 the very dry decade has an average PDAI value of 3.7. Given the stakeholder consensus

365 on the importance for drinking water, for each drought condition there is very little range
366 – that is, the eCDFs are fairly vertical. Results are similar when the Moderate threshold is
367 used for the other two water uses, habitat and livelihood, that showed strong consensus
368 (see Figure S2).
369   Next, we focus on the PDAI for Recreation, a water use that shows diverse
370 importance ratings from stakeholders (Figure 5, right). For recreation, to calculate the
371 PDAI, we use the severe threshold, since that is the threshold at which artesian springs
372 have minimal flow or no longer flow (see Section 3.1). Figure 5 (right) shows the PDAI
373 for recreation for the select decadal drought conditions, using the severe threshold
374 likelihoods from Table 1. Similar to drinking water, we see that as we move from wetter
375 to drier, the PDAI also increases; for example, from wet/recent to dry/recent, the average
376 PDAI values are 0.3 and 1.5, respectively. However, given the stakeholder diversity in
377 importance ratings, as we move towards drier conditions, the PDAI becomes more
378 diffuse, spanning a great range of values: in the wet/recent, the PDAI spans from .08 to
379 .4, or for 0.32 units of the PDAI scale, and in the dry/recent it spans from 0.4 to 1.9, or
380 1.5 units on the PDAI scale, indicating a wide range in stakeholder appetite for potential
381 action. Interestingly, the wet/recent decade (1993-2002) was also the wettest decade on
382 record, with the groundwater threshold only being exceeded 8% of the time. Results are
383 similar when the Severe threshold is used for the other two water uses that showed
384 diverse ratings, i.e., cultural practices and spiritual fulfillment (see Figure S2).
385   In Figure 6, we also looked at recreation under the possibility of a new "normal"
386 drought baseline (Van Loon 2016b). It has been suggested that human adaptation to new
387 drought normals can be illustrated by changing thresholds (Vidal et al. 2012; Wanders et
388 al. 2015); here, we show how this could influence the PDAI. To this end, we look at a
389 more extreme threshold that has been identified for Recreation (i.e., GW levels below
390 120 feet, see section 3.1), under the dry/recent period: the eCDF curve shifts back to the
391 left, towards lower action potential, with average PDAI of 0.9, reflecting this new
392 normal. This is relevant given climate change projections that suggest that the ASA will
393 likely become drier in the future (Towler et al. 2016; Liu et al. 2012).
394   Finally, in Figure 7, we narrow our focus to the most recent decade (i.e., dry/recent,
395 2003-2012), and compare both drinking water and recreation with the moderate and
396 severe thresholds, respectively. From Figure 7, we see that drinking water has a higher
397 action potential than recreation: the average PDAI for drinking water is 3, while it is
398 about 1.5 for recreation. This is an artifact of the thresholds selected for each respective
399 water use (i.e., moderate for drinking water and severe for recreation). This makes sense
400 from a human standpoint, since drinking water is a primary consumptive use, and
401 recreation is a more discretionary use. However, this could be more subjective for other
402 water uses (e.g., spiritual fulfillment). Although it may seem counterintuitive at first, we
403 purposely pair the moderate threshold with the primary use to indicate this hierarchy, but
404 this does not mean that exceedance of the severe threshold would not also prompt action
405 (or further action) to ensure adequate drinking water supplies. However, it does make the
406 assumption that for a more discretionary use, like recreation, action would not be
407 prompted until this severe threshold was exceeded.
408   Another key point from Figure 7 is that drinking water spans a smaller range on the
409 PDAI scale than recreation, which is more diffuse. Specifically, for drinking water, the
410 eCDF only falls between 2.4 and 3.5; this is due to the agreement across respondents on

411 the importance of water to this use (i.e., Figure 4). On the other hand, the recreation
412 PDAI eCDF covers of a larger range of values – here it spans from 0.4 to 1.9, similarly
413 reflecting the range of stakeholder responses. This shows that for water uses where values
414 are diverse, the appetite for potential action will be diverse as well.
415   In summary, the key points from these results: the PDAI increases with (1) drier
416 decadal drought conditions and (2) water use thresholds that are exceeded more often.
417 Further, it shows that for water uses where perceived importance is diverse among
418 stakeholders, the PDAI will be diverse as well, and this is exacerbated under drier
419 conditions.
420 4.4. Management Implications based on Worldviews
421   To understand the management implications, we need to look at the results alongside
422 of CTR. Results from the CTR questions show that both individualist and egalitarian
423 worldviews were represented by the interviewees (Figure 8) and that some of the spread
424 in the importance responses can be explained by worldview (Table 3). Although not all of
425 the results are statistically significant, the sign of each correlation coefficient is opposite
426 between the egalitarianism and individualism measures, indicating that people holding
427 each worldview have opposing importance ratings (Table 3). The water use that showed
428 the most variance explained by worldview was recreation: $r^2=20\%$ (16%) for
429 Egalitarianism (Individualism). These correlations provide initial insight about the role of
430 worldview in how people assess the importance of water and, by extension, their appetite
431 for potential drought action.
432   Results from the CTR questions, along with the PDAI, point to some implications for
433 water management policy. CTR posits that disagreement over resource management
434 strategies may arise among constituents with diverse worldviews for two
435 reasons (McNeeley and Lazrus 2014): first, as demonstrated in Table 3, worldviews
436 explain some of the variance in how important people think that local water resources are
437 for different activities - and thus presumably *whether or not* maintaining water for those
438 activities should be prioritized by water management. For example, in recreation, because
439 of the large spread in importance ratings, which can partially be explained by CTR, there
440 is an increase in the PDAI categories from the wet/recent to average/recent to dry/recent
441 decades; this implies that people will disagree on whether or not water should be
442 managed for recreation, potentially leading to disagreements that could hinder sustainable
443 water management. Second, is *how* water should be managed, even when people agree on
444 its importance. In drinking water, there is consensus on importance – even among people
445 with different worldviews – presumably indicating that people agree that water needs to
446 be managed for drinking water. However, because of the different worldviews, there is
447 still potential for disagreement over how it should be managed. That is, those with
448 egalitarian preferences advocate for management that is collectively debated,
449 implemented, and enforced whereas those with individualist preferences favor
450 management that is individually enacted and market-based. We see this in our qualitative
451 data: for example, one interviewee with individualist preferences said: "we have to have a
452 set of rules that everyone understands. And once those rules are set you can't have a
453 bunch of water Nazis trying to make judgment calls about how someone's using their
454 water. So, if I can use a certain amount - tell me what that amount is, and then stay the
455 hell out of my business" (Interview 2). The finding means that disagreement is not solely
456 due to threats to water resources – such as more frequent drought – but rather that it can

457 also arise from disagreement about the strategies designed to manage water and address
458 drought.
459
460 5. Conclusions
461   Our study implements a conceptual methodology combining hydrological and
462 societal perspectives to understand drought action potential. Results from stakeholder
463 interviews in the study site reveal that people perceive the relative importance of water
464 for various uses differently, as shown by the notable variability that existed across certain
465 water uses. A retrospective analysis of groundwater threshold exceedance shows that in
466 recent decades, stakeholders experienced a wide range of likelihoods of exceeding
467 relevant thresholds, and these corresponded drought conditions. These pieces of
468 information are brought together through the PDAI. We find that for a given water use,
469 drier conditions increase the frequency of exceeding the threshold, and hence increase the
470 PDAI. The PDAI is tied to the threshold selected for each water use: we find that the
471 PDAI is higher for more moderate thresholds, i.e., thresholds that are exceeded more
472 often. And conversely, as thresholds become more extreme, which can illustrate human
473 adaptation to new drought normal, the PDAI decreases. Finally, we find that for water
474 uses where stakeholder values are diverse, the PDAI will be diverse as well, and this is
475 exacerbated under drier conditions.
476   We can also ask why values might be diverse, and what that might mean about
477 how people are affected by water scarcity and how they will respond. To this end, the
478 study also examined worldview, as measured by the CTR, which can help to diagnose
479 *why* disagreement may arise over water management and point to some implications for
480 water management policy. In the stakeholder sample, we found a diverse range of
481 worldviews on the individualist/egalitarian spectrum. Further, for some water uses, the
482 importance people attribute to water can be partially explained by worldview. This
483 implies that there are two potential sources for disagreement over water management:
484 first, where there is variability in people's perception of importance, there may be
485 disagreement over whether or not a water resource needs to be managed (e.g., with water
486 for recreation). Second, even where there is consensus on people's perceived
487 importance, there is still potential for disagreement over how these water resources
488 should be managed according to different preferences of worldviews (e.g., with drinking
489 water). We are careful to say *potential* disagreement because (i) our analysis only
490 investigates CTR as one of the many factors explaining importance and (ii) by
491 understanding stakeholder worldviews, potential disagreement across sectors can be
492 predicted and ideally avoided. The latter finding suggests that water management policies
493 will be more successful if they follow a strategy whereby elements of each worldview are
494 represented in the solution (Verweij et al. 2006).
495   Although reducing disagreement is always important for promoting sustainability, it
496 is particularly important for management planning under potentially increasing drought
497 due to climate change, as has been predicted for this area (Towler et al. 2016; Liu et al.
498 2012). We examined this by examining possible adaptation to a new normal, where we
499 illustrate how a more extreme threshold lowers the PDAI.
500   We develop and demonstrate this methodology as a step towards closing the drought
501 feedback loop, but note that there are caveats and limitations that warrant discussion. A
502 conceptual overview of the contribution of our study to the drought feedback loop is

503 shown in Figure 9, and we use this figure to identify five places where there is scope for
504 future enhancements; each number below corresponds to a place in the drought feedback
505 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

549   drought. However, we note that empirical validation is important for indicator
550   development and refinement. We recommend that future project designs include
551   a validation component in the methodology. This could take the form of follow-
552   up interviews, such as direct feedback from stakeholders on if the indicator
553   reflects their willingness to take action for certain water uses at certain drought
554   levels. Methods, including stakeholder processes, for developing and evaluating
555   drought indicator effectiveness have been put forth in the drought community
556   (Steinemann and Hayes 2005 Steinemann and Cavalcanti 2006, Steinemann et al.
557   2015). Other options for validation can be indirect, such as looking at historical
558   data, like government and local reports, media, and/or other collected response
559   information, e.g., in the United States the US Drought Impact Reporter (Wilhite et
560   al. 2007). Promising methods for mining social media, such as Twitter, have also
561   been developed (Demuth et al. 2018) and could be adapted for evaluative
562   purposes.
563   Although the methodology to develop the PDAI is experimental, we posit that
564 explicit efforts to combine natural and human perspectives is critical to gaining a deeper
565 and more nuanced understanding of drought feedbacks, and this paper provides a novel
566 contribution to this end.
567
568 Data Availability
569 Groundwater data from the USGS Fittstown well (USGS 343457096404501) is available
570 from the USGS National Water Information System Web Interface
571 https://nwis.waterdata.usgs.gov/nwis/gw. Drought index data for Oklahoma Climate
572 Division 8 is available from: http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp
573 Inquiries on the stakeholder data from the interviews can be sent to hlazrus@ucar.edu
574

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754   Tables
755
756   Table 1. Correlation Between Select Drought Indices* and the Likelihood (P) of
757   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

758   * Drought indices for Oklahoma Climate Division 8 downloaded from:
759   http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp
760
761

762 Table 2. Decadal Likelihood (P) of Groundwater (Z) Level Going Below Moderate (Md) and Severe (Sv) Thresholds for Recent
763 Decades, as Well as Respective Driest, Median, and Wettest Decades.
764

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)

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766

767   Table 3. Correlation and Statistical Significance of Worldviews, as Quantified by the

768   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*

769   * = Significant at the 90% percentile
770   **= Significant at the 99% percentile
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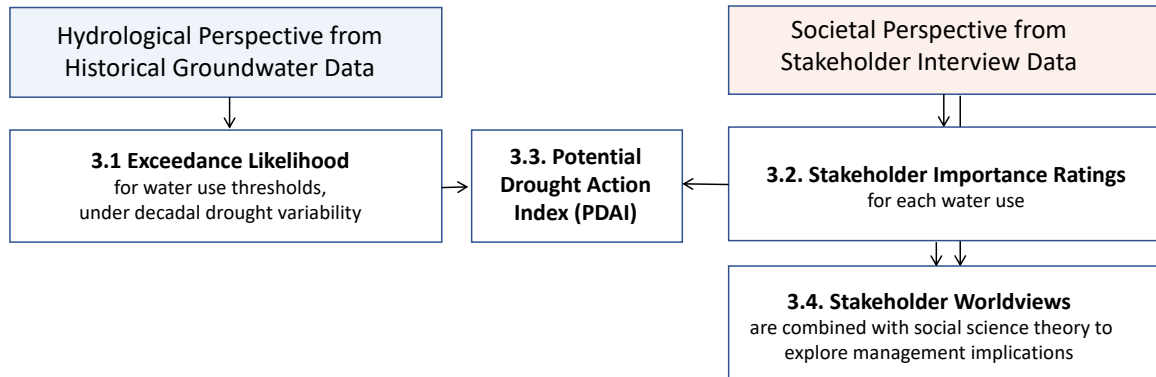
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777 Figure 1. Conceptual overview of the methodology that combines a hydrological
778 perspective from historical groundwater data with a societal perspective from stakeholder
779 interview data to quantify the Potential Drought Action Indicator (PDAI); stakeholder
780 worldviews from the interviews and social science theory are used to explore
781 management implications.
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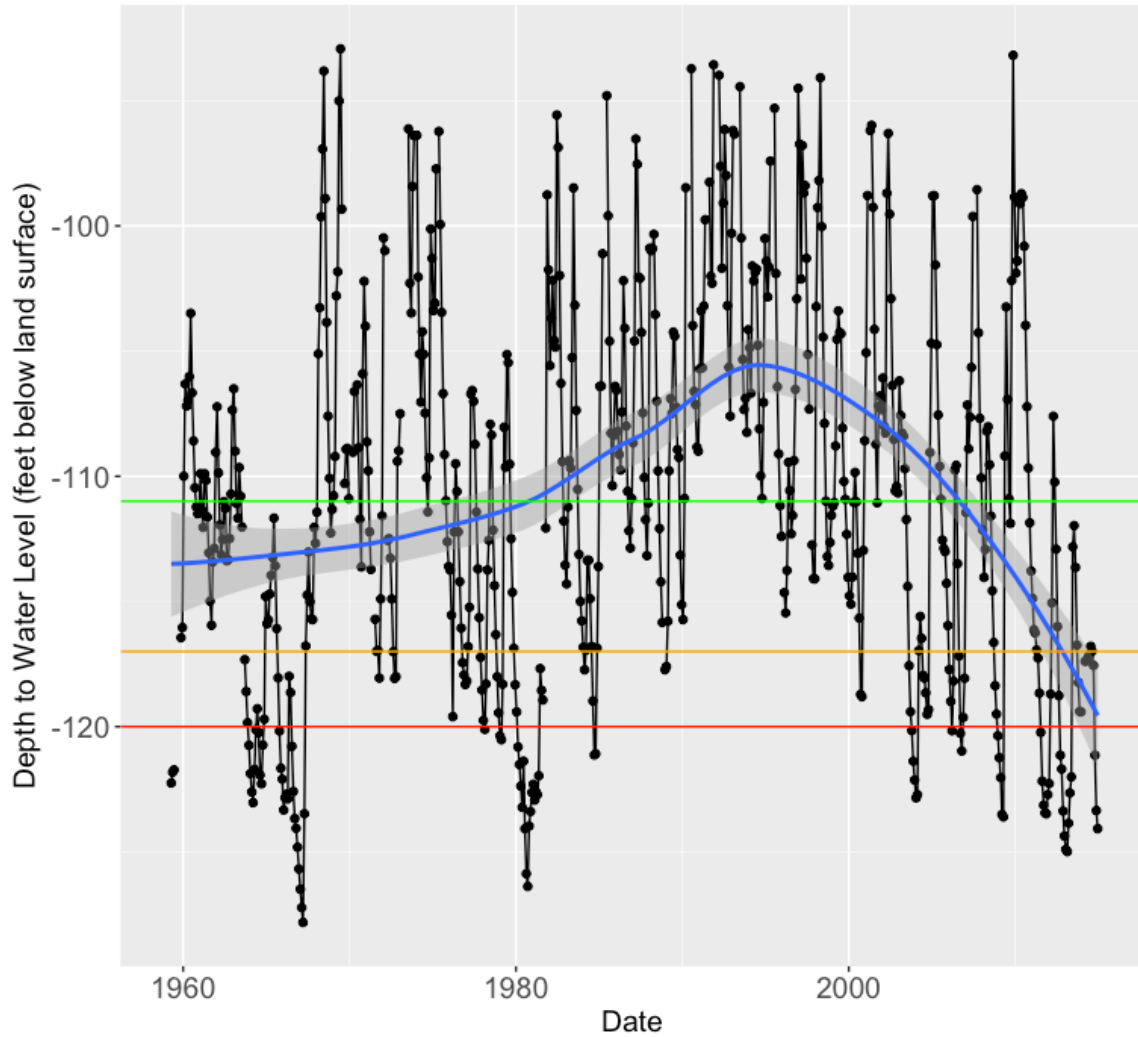
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785
786   Figure 2. Monthly groundwater time series; blue line is smoother average, green line is
787   the moderate threshold (= -111 feet) and the orange line is severe threshold (=-117 feet);
788   the red line is an extreme threshold (= -120 feet) that is used to illustrate a possible new
789   normal drought threshold.
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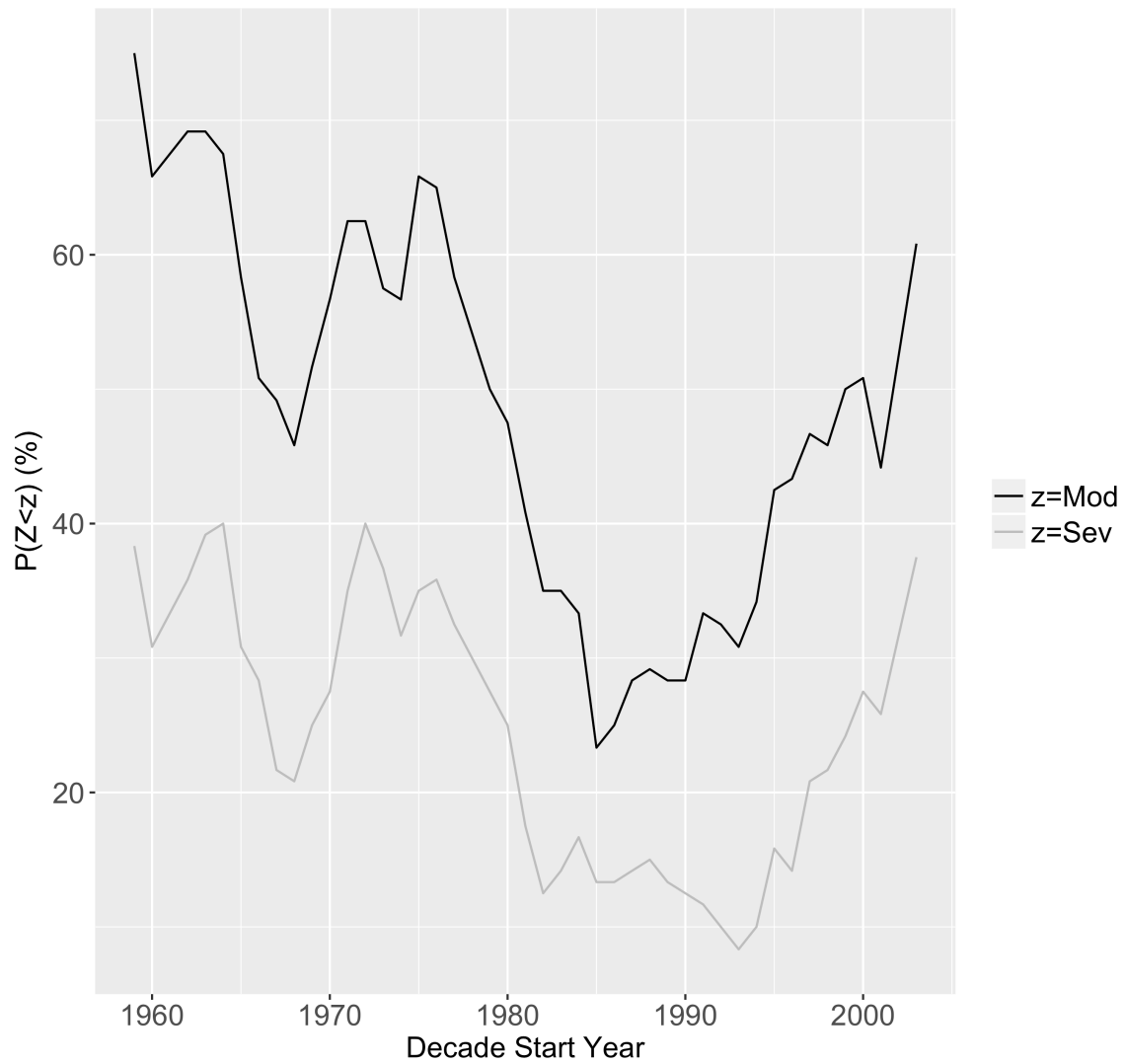
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Figure 3. Decadal likelihood (P) of the depth to groundwater level (GW) going below the
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793   moderate (y=-111 ft) and severe thresholds (y=-117 ft).
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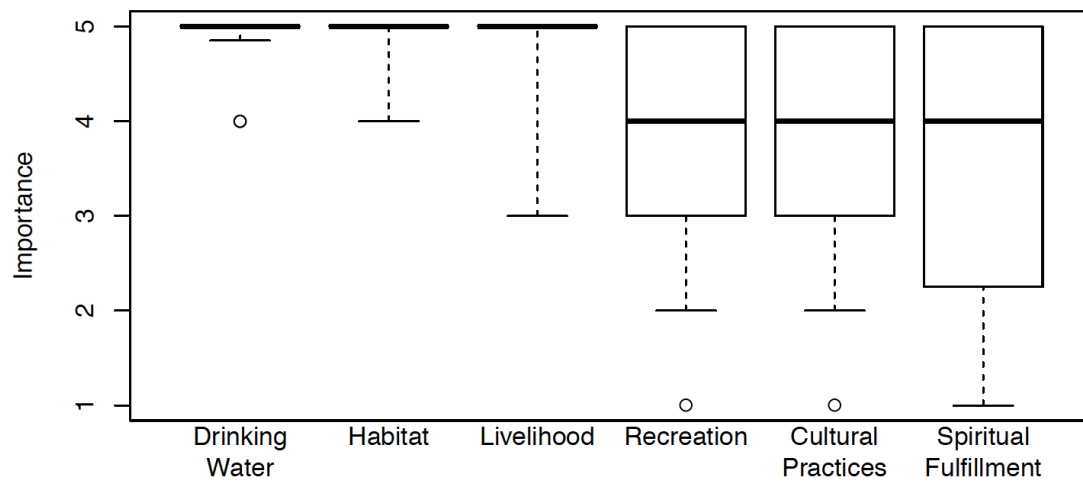
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799 Figure 4. Rated importance of water for each water use from stakeholder surveys (N=38).
800 Responses are shown as box plots, where the box represents the 25th and 75th percentile,
801 the line is the median, and the whiskers are the 5th and 95th percentile. Outliers are
802 shown as points outside the box and whiskers.
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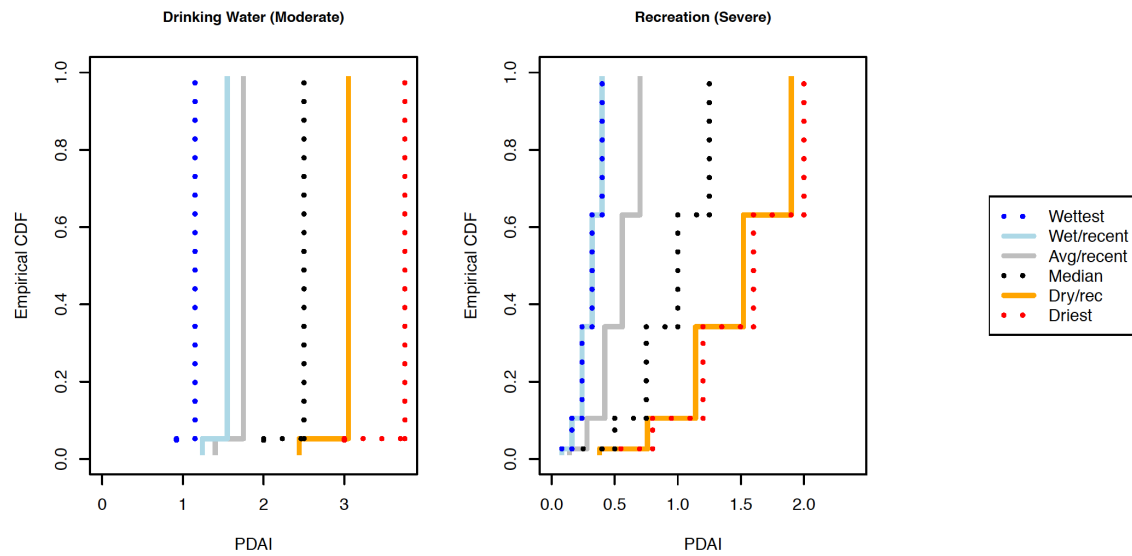
821
822 Figure 5. Empirical cumulative density functions (eCDFs) for the PDAI (Potential
823 Drought Action Indicator) for drinking water using the moderate threshold (left) and for
824 recreation using the severe threshold (right), under the wettest, wet/recent,
825 average/recent, dry/recent, and driest historical decades.
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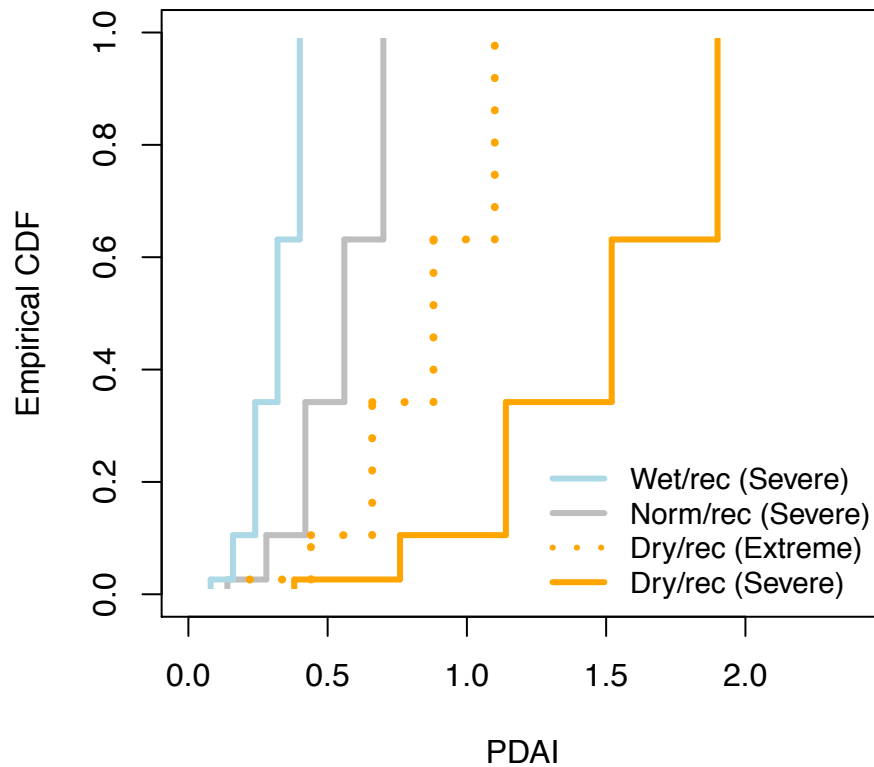
830
831 Figure 6. Empirical cumulative density functions (eCDFs) for the PDAI (Potential
832 Drought Action Indicator) for recreation under the wet/recent (1993-2002), normal/recent
833 (1983-1992), and dry/recent (2003-2012) for the severe threshold, as well as the
834 dry/recent for the extreme threshold.
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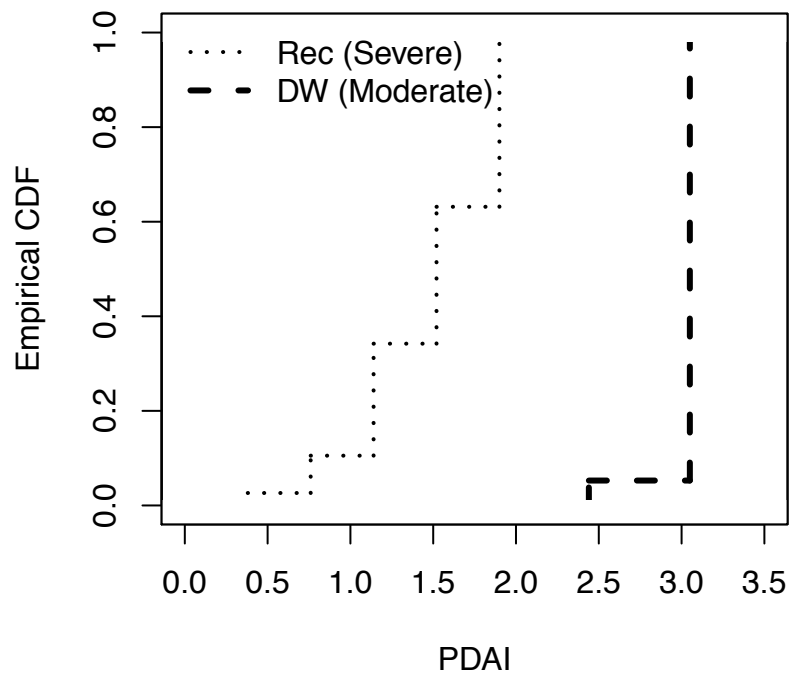
838
839 Figure 7. Empirical cumulative density functions (eCDFs) for the PDAI (Potential
840 Drought Action Indicator) for recreation (Rec) using the severe threshold and for
841 drinking water (DW) using the moderate threshold for the dry/recent decade (2003-2012).
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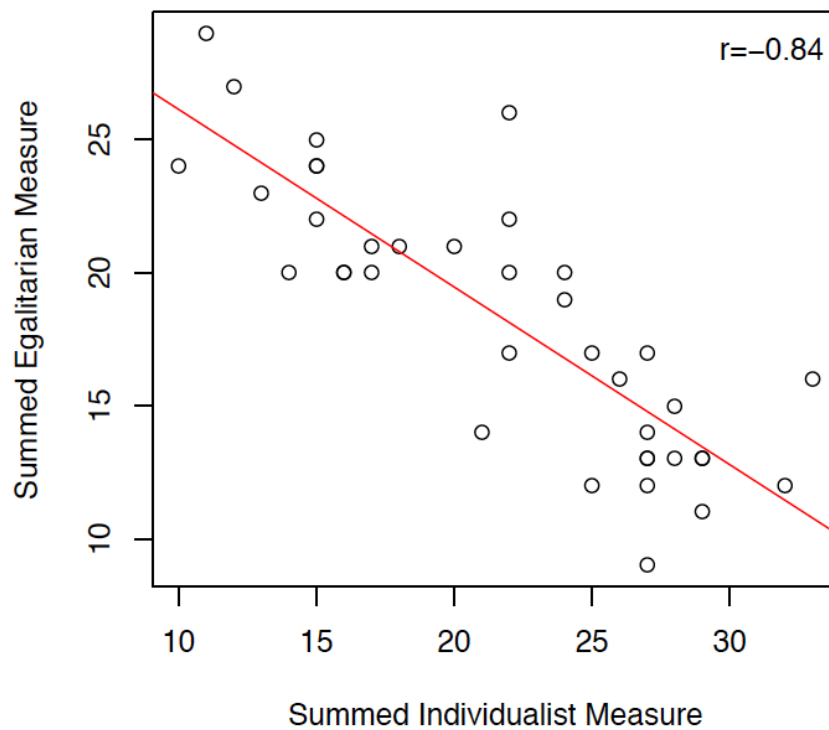
844
845   Figure 8. Summed responses for individualism versus egalitarianism for each interviewee
846   (n=38) show that both individualist and egalitarian worldviews were represented by the
847   interviewees . The egalitarianism and individualism measures were strongly inversely
848   correlated (r=-0.84).
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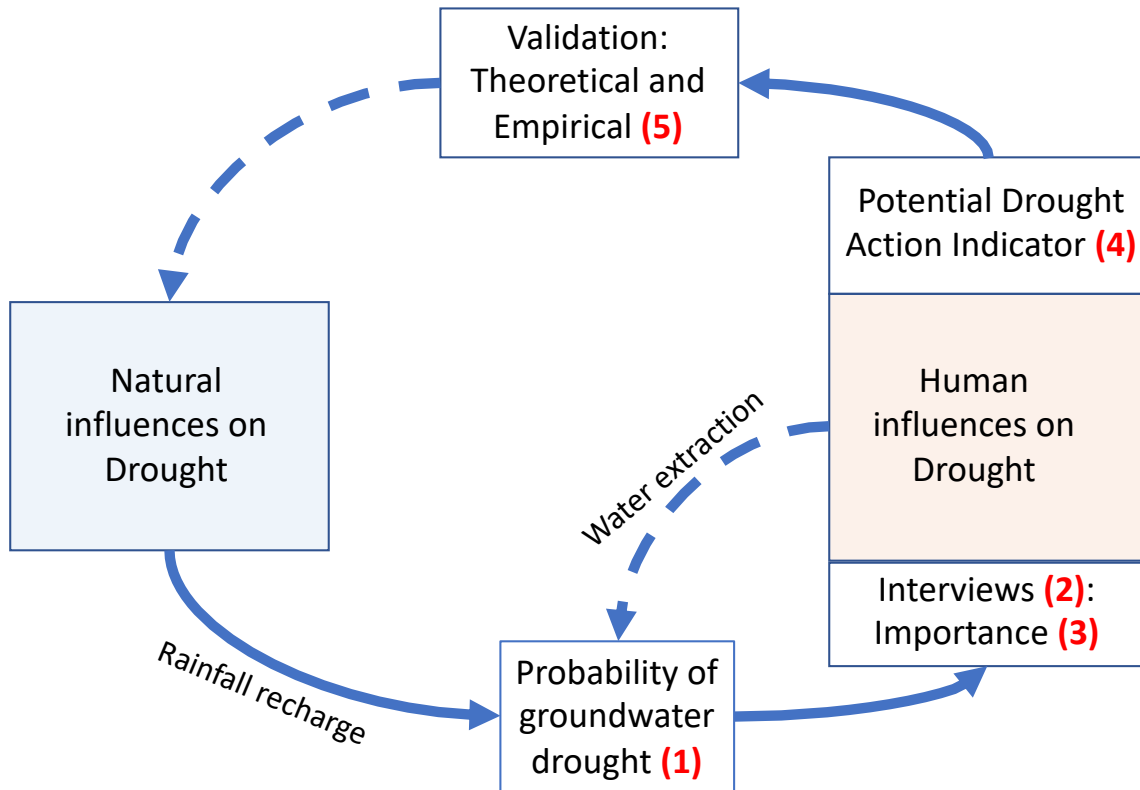
850
851 Figure 9. Conceptual map of drought feedback loop components addressed in this study
852 (blue solid lines) and remaining gaps (blue dashed lines). Numbers correspond to
853 discussion points in Conclusions.