HESS Opinions: Drought impacts as failed prospects

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Abstract. Human actions induce and modify droughts. Yet, there remain scientific gaps regarding how hydrological processes, anthropogenic dynamics, and individuals' perception of impacts are intrinsically entangled in drought occurrence and evolution. This adds complexity to drought assessment studies, that cannot be addressed by the natural and environmental sciences alone. Furthermore, it poses the challenge of developing ways to evaluate human behavior and its pattern of co-evolution with the hydrological cycle - mainly related to water use and landscape modifications. During field work in Brazil, we observed how drought impacts are experienced by the people that were exposed to a multi-year drought. Evaluating our data, it appeared that Prospect theory, a behavioral economic theory that is usually applied to explain decision-making processes under uncertainty, has explanatory power for what we observed in the field. Therefore, we propose an interdisciplinary approach to improve the understanding of drought impacts emergence by using this theory. When employing Prospect theory in this context, drought impacts are considered failed welfare expectations ("prospects") due to water shortage.. A shifting baseline after prolonged exposure to drought can therefore mitigate experienced drought impacts. We demonstrate that this theory can also contribute to explaining socio-hydrological phenomena such as reservoir effects. This new approach can contribute to bridging natural and social sciences perspectives for more integrated drought management that takes into account the local context.

1 Introduction

During fieldwork conducted by the authors of this paper in the Semiarid region of Brazil (SAB), a farmer was asked how the 2012-2018 multi-year drought event (Marengo, 2020; Cunha et al., 2019a, b, 2018) affected his livelihood and welfare. The farmer responded by asking: "Drought? What drought?". We wondered how a drought event that lasted for almost 7 years and was characterized by an average 60% reduction in annual precipitation had gone unnoticed by someone who had been in the middle of it. A spatial contextualization helped us answer this question. The farmer's property was located at the edge of an upstream reservoir with low water abstraction that retained water throughout this drought event. Therefore, he never experienced water insecurity during this period.

The farmer's response implicitly reveals the relationships between human actions that modify hydrological processes (in this case, the construction of a reservoir) which alter exposure to a drought hazard (in this case, no exposure because of a filled reservoir) and how this in turn influences individuals' own perceptions of disaster occurrence ("Drought? What drought?"). This is in line with the concept of "Drought in the Anthropocene" (Van Loon et al., 2016b), which underlines the need to consider the human component as an inseparable part of the complex and interrelated processes of a drought. It calls for more balance between the analysis of the physical and

43 human component of drought events, where we define drought as an exceptional period of lack of water compared
44 to normal conditions. This is not restricted to a physical cause (e.g., a negative anomaly in rainfall), but can also
45 be caused, or mitigated, by human actions. These ideas are developed in the context of socio-hydrology. This field
46 aims to study the dynamics and co-evolution of human-water coupled systems, with one of the main premises that
47 human actions are an endogenous part of the hydrological cycle (Sivapalan et al., 2012, 2014; Pande and Sivapalan,
48 2017). In other words, people interact with the hydrological system in various ways (e.g. water consumption and
49 landscape modification) and this has the potential to alter hydrological processes, which in turn influence and
50 impact human actions, creating a co-evolution.

51 Perceiving the human component as an inseparable part of the hydrological cycle creates new research avenues,
52 for instance to study drought events and other disasters at scales that are commonly disregarded. For example, by
53 starting from the individuals in the hydrological system that experience impacts, and by evaluating the decisions
54 they make to avoid these impacts. This may reveal the emergence of patterns and phenomena unobserved at other
55 spatio-temporal scales or when focusing on other hydrological variables (Wens et al., 2021, 2019; Van Oel et al.,
56 2012; Walker et al., 2022). Although the patterns of co-evolution between the human component and the
57 hydrological cycle have been widely debated in the scientific literature (Sivapalan et al., 2012; Di Baldassarre et
58 al., 2015; Van Loon et al., 2016b; Di Baldassarre et al., 2019; Tian et al., 2019), gaps remain regarding the
59 relationship between hydrological hazards (e.g., drought), the perception of impact of this hazard, and occurrence
60 of the hazard itself. With the ideas presented in this paper we aim to contribute to this discussion, focusing on
61 drought hazards.

62 We argue that the collectivity of individuals' perception of the impacts that they experience determines the
63 magnitude and the very occurrence of a drought event, this being related to both environmental and socio-economic
64 factors. Using Prospect theory (Kahneman and Tversky, 1979), stemming from the field of behavioral economics,
65 we can explain the emergence of drought impacts, considering impacts as failures in expected welfare due to water
66 shortages. We build our case by first presenting the concept of drought impacts as failed prospects, then the
67 relationship between socio-hydrology and Prospect theory to finally present how this can be applied to real cases
68 of drought events.

2 Impacts as failed prospects

70 Satisfying our needs for welfare, and not just survival, is one of the characteristics that define us as humans. An
71 improved understanding of how this influences decision-making related to water use and landscape modification
72 can lead to a better drought assessment. Human beings, as individuals, anticipate a desirable level of welfare, and
73 then choose among possible prospects those that they believe have the highest chance of achieving this goal
74 (Kahneman and Tversky, 1979). These prospects are the decision options that are associated with an expected
75 outcome within a scenario of uncertainties.

76 The chosen prospect defines how well an individual is adapted to their environmental conditions, and is therefore
77 directly related to their vulnerability and resilience. We propose that when an individual has a failed prospect
78 because of a lack of water, either influenced by a hydroclimatic anomaly and/or human actions, this negatively
79 affects the individuals' level of welfare, which they will feel as an impact and consequently the situation will be
80 perceived as a drought by this individual. For example, a prospect can be the choice a farmer makes to grow a
81 certain crop rather than another, to achieve greater gains or fewer losses depending on the context. This choice is
82 made with the expectation that this crop will contribute to the achievement of the aimed welfare level.

83 If, for instance, the prospect is to grow a water-consuming crop in a region characterized by low water availability,
84 it can be an indication of maladaptation and vulnerability of the individual. In this example, if a precipitation deficit
85 occurs (hazard) and this negatively affects the chosen crops, resulting in an unsatisfactory production (failed
86 prospect), the individual will feel the impact and consider this event to be a drought. If there is, at some point, a
87 critical mass that experiences impacts, this might lead to the (official) declaration of a drought. This is the result

88 of a complex interaction including many factors: those experiencing impact, their societal position, media
89 exposure, power-relations, the political consequences of formally declaring a drought, et cetera.

90 Returning to the real example of the farmer mentioned above. He never had any failed prospects during the multi-
91 year drought event, mainly because he had a secure water source throughout this period and consequently his
92 aimed level of welfare was never affected. Considering this, the simple answer he gave us is coherent and logical:
93 He did not experience impacts related to the negative hydroclimatic anomaly (meteorological drought) that
94 occurred in that region and therefore, for him, a drought event never happened.

95 Considering drought as the collective impacts that emerge as failed prospects due to a lack of water make it
96 necessary to predict how individuals choose which prospects are more attractive to follow. Prospect theory (PT)
97 explains how individuals choose alternatives when the outcome is uncertain (Kahneman and Tversky, 1979)
98 (Tversky and Kahneman, 1986). This theory has been widely debated, especially in the socio-economic sciences.
99 In the environmental sciences it has been applied in different contexts, such as reservoir operation (Bahrami et al.,
100 2022), asymmetries in drought response (Tian et al., 2019), disaster management (Osberghaus, 2017), and
101 irrigation water resources management (Wang et al., 2022).

102 One of the novel concepts that PT presented is that individuals in the real world do not maximize total wealth, but
103 react to possible or perceived gains or losses, which are emotional and short-term. In other words, human beings
104 do not necessarily seek to maximize their net benefits, or utilities, by always choosing the prospects that produce
105 the highest level of benefits (Jones, 1999). To clarify this concept, we invite the reader to participate in a simple
106 experiment (Kahneman and Tversky, 1979) consisting of choosing one of the options in the following two
107 problems: 1) 80% chance of winning $4000 or 100% chance of winning $3000; 2) 80% chance of losing $4000 or
108 100% chance of losing $3000.

109 If you chose the second and first options in problems 1 and 2, respectively, you behaved like most people who
110 participated in such an experiment (Kahneman and Tversky, 1979). This means that you presented "risk aversion"
111 behavior when the prospects are related to certain gains (problem 1) and "risk seeking" behavior when the
112 prospects are related to certain losses (problem 2). The combination of these two patterns illustrates the idea
113 presented by PT that the human tendency is to overvalue a certain (or highly likely) outcome, relative to outcomes
114 that are probable (Kahneman and Tversky, 1979; Edwards, 1996; Levy, 1992). Problem indirectly illustrates
115 another concept presented by PT, which is the "loss aversion" effect. This highlights the asymmetry in an
116 individuals' perception of gains and losses; losses feel more "painful" than gains of equal magnitude feel
117 "pleasurable". The consequences can be the preference for the status quo and the acceptance of riskier prospects
118 to avoid certain losses ("risk seeking" behavior).

119 To define whether the outcome of a prospect is seen as a gain or as a loss, the prospect is compared with a Reference
120 point. The Reference point can be influenced by what is experienced as the status quo or the 'normal' situation,
121 but also by the way the decision problem is perceived (Kahneman and Tversky, 1984). This latter is called the
122 "framing effect", whereby, depending on how individuals perceive and make sense of decision prospects in terms
123 of gains or losses, they will show a tendency towards risk aversion or risk seeking behavior, respectively.

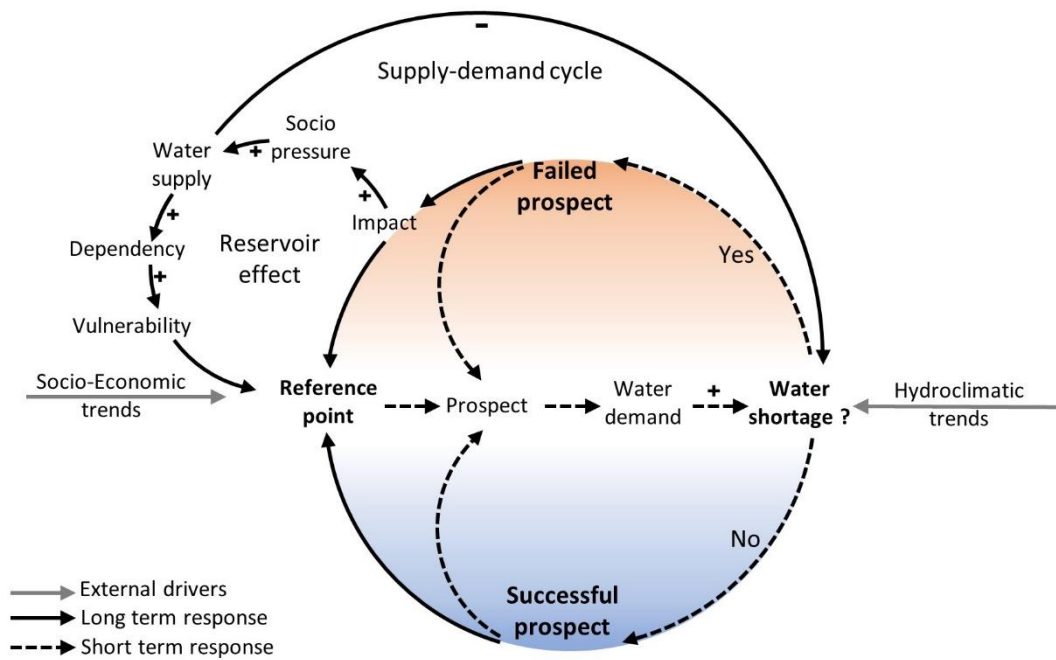
124 **3 Socio-hydrology and Prospect theory**

125 We argue that the onset and propagation of human drought impacts (which we consider to be those that negatively
126 affect the individual's welfare), and socio-hydrological phenomena (e.g. the reservoir effect and supply demand
127 cycle), can be explained through the lens of Prospect theory. Fig. 1 presents an overview of how Prospect theory
128 is related to socio-hydrology phenomena and drought emergence. The first concept to consider from PT is the
129 Reference point, which is the general term for the starting point from which to make different kinds of decisions.
130 For drought assessment, we consider the Reference point as the minimum welfare level that individuals tolerate to
131 feel satisfied and secure with the results of chosen prospects, and deviations from this are defined as a gain or loss.

132 The environment guides the individuals' expectations regarding their level of welfare (Reference point), and with
133 that for choosing the prospects to achieve them. For instance, the Reference point can be influenced by
134 environmental conditions such as water availability, which is related to aspects of food and water security, previous
135 experiences (e.g. past drought events), community interactions (e.g. peer comparison), and socio-economic trends
136 (e.g. production costs, goods prices, local culture and governance). Importantly, the Reference point will vary over
137 space and time. For instance, a higher yield loss might be incorporated as acceptable in the Reference point after
138 years of drought, or in a region with consequent insecure water supply. The higher the Reference point, the greater
139 the potential for human drought impacts.

140 Once the individual has defined their Reference point and delineates the desired level of welfare, they evaluate the
141 decision prospects for achieving it. When faced with a situation of high water availability, individuals have more
142 freedom to choose prospects that offer certain gains (risk aversion behavior, blue cycle Fig. 1) even if this promotes
143 a reckless water use pattern and/or the development of activities that are not necessarily the most adapted to the
144 environmental conditions of the region where they are inserted. Successive gains associated with this behavior, in
145 the short term, will reinforce the selected prospect (short term response, dashed arrow Fig. 1) and, in the long term,
146 raise the Reference point. Levels of welfare below the Reference point will be perceived as losses and avoided,
147 even though the individual may have already experienced such levels as a gain in a previous situation (Framing
148 effect).

149 A series of successful prospects keep the upward trend in the Reference point, and this is maintained as long as
150 the water resources to which the individual has access can sustain their water demand. This continues even if there
151 is an impending drought situation, since the reduction in water consumption while the Reference point is associated
152 with satisfactory water availability can be framed by individuals as a direct decrease in welfare. When water is
153 lacking and it is no longer possible to maintain the water consumption standards that the individual requires, this
154 results in failed prospects and, consequently, drought impacts arise.

155 Initially, the drought situation is typically perceived as a loss, as we consider that it starts after a failed prospect.
156 In the short term, individuals tend to focus on prospects that can at least prevent further losses, even if they were
157 previously seen as risky (risk seeking behavior, orange cycle Fig. 1). However, in the long term, if low water
158 availability persists, it can cause individuals to adjust their expectations by lowering the Reference point. In other
159 words, individuals can be less impacted by water shortages simply because they accept suboptimal outcomes (e.g.
160 lower agricultural production). Once this shift in Reference point occurs, individuals may no longer view the
161 situation as a drought, but rather as the "new normal".

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163   **Figure 1. – The cycle of human drought impacts.** Our hypothesis emphasizes the centrality of the human component (starting
164   from the Reference point) in the emergence of drought impacts with the individual as the primary scale. Moreover, the
165   combination of how they link to the hydroclimatic and socio-economic trends results in the emergence of long-term socio-
166   hydrological dynamics (reservoir effects and supply-demand cycle) that can be explained by concepts related to Prospect theory
167   such as: Reference point; Framing effect; Risk aversion (blue cycle) and Risk seeking (orange cycle) behavior.

168   As water availability gradually increases, either due to natural causes (hydroclimatic trends) or due to the
169   expansion of water infrastructure, individuals are likely to shift away from their lower Reference point and search
170   for prospects that offer more certainty, which restarts a new cycle (blue cycle Fig. 1). We hypothesize that the
171   demand to expand the water infrastructure can be related to when individuals attribute the occurrence of drought
172   impacts to low water availability without considering the suitability of their own chosen prospects in local
173   environmental conditions. This behavior can then, in the long term, result in social pressure to increase water
174   supply (e.g. reservoir construction and water transfer), and when this is met, individuals can re-enter the cycle of
175   increasing water consumption (blue cycle, Fig,1). As the demand continues to rise, it can eventually offset the new
176   maximum supply capacity. This can lead to more social pressure to increase water availability, thereby creating a
177   vicious cycle (Supply-demand cycle, Fig.1), greater dependency on water infrastructure, and greater vulnerability
178   to drought events (Reservoir effect, Di Baldassarre et al., 2018, Fig.1).

179   **4 Prospect theory and drought - insights from the Brazilian semiarid region**

180   The 2012-2018 meteorological drought in the Semi-Arid region of Brazil (SAB) is used as a practical example
181   that highlights how Prospect theory fits into the narrative of drought impacts as failed prospects. We focus on
182   Ceará state, which is one of the sub-regions most impacted by this event. Fig. 2 presents the percentage anomaly
183   of annual precipitation relative to the long-term climatological average (1981-2011) of SAB and Ceará state during
184   the 2012-2018 drought event. The years prior to this drought were characterized by precipitation levels above the
185   climatological average, which meant that most reservoirs in Ceará had stored volumes close to their maximum
186   capacity.

187   This region has a historical susceptibility to drought events and in recent times, there has been observable change
188   in the preparation and management of such disasters. This change is related to a shift from a "fighting against
189   drought" perspective, which relied on hard solutions such as significant investments in water infrastructure, to a
190   "cope with drought" perspective which relies on soft solutions such as renewed focus on public policy towards
191   adaptive measures and integrated water resources management (Cavalcante et al., 2022; Medeiros and Sivapalan,

2020). Nevertheless, the high water availability experienced during the years prior to the 2012-2018 drought contributed to the support of high water demand productive activities, such as rice paddies and irrigated fruit crops.
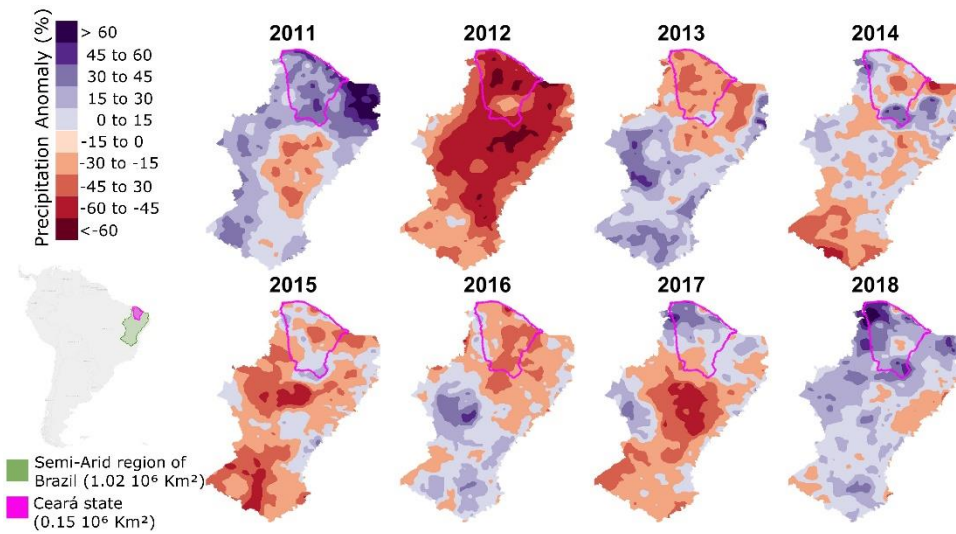
Figure 2. Precipitation variability in the Semi-Arid of Brazil during the drought 2012-2018. Percentage anomaly of annual precipitation relative to the long-term average (1981 to 2011) using the Climate Hazards center InfraRed Precipitation with Stations (CHIRPS, Funk et al., 2015) dataset available on https://www.chc.ucsb.edu/data.

Before the occurrence of this drought, Ceará had already been experiencing a gradual growth of dairy cattle farming which was intensified during this event. Farmers increasingly started to see this activity as a prospect more adapted, from a local perspective, to droughts because it guarantees a source of perennial income and serves as a capital reserve (part of the herd can be sold at any time). Furthermore, it is considered that cattle farming is less dependent on locally produced inputs and on the spatio-temporal heterogeneity of the precipitation regime when compared to rainfed crops.

Fig. 3 presents an overview of Prospect theory applied to the Ceará study case. We hypothesized, based on field interviews, that periods of high water availability provided a certain stability to farmers who depended on rainfed crops (short term positive response, first blue dashed arrow, Fig 3). However, the following and more frequent occurrence of intense meteorological drought events caused them to experience consecutive production losses (failed prospects) which led the individuals to view the exclusive production of rainfed crops as a riskier prospect (short term negative response, red dashed arrow, Fig. 3) and dairy production as a prospect that would avoid further losses (long term negative response, red arrow, Fig. 3). One of the barriers that made individuals view this activity as unattractive or risky was the low and volatile price of a liter of milk in the local market. This changed when associations of small dairy producers were created, and they started to have more bargaining power within the dairy industry. In this new socio-economic trend, individuals began to see cattle farming as a prospect more adapted to drought and which promotes more certain gains (short term positive response, second blue dashed arrow, Fig. 3). This is further evidenced by farmers who had already adopted this activity due to previous drought events and that continued to favor this kind of prospect even in later periods of greater water availability (long term positive response, second blue arrow, Fig. 3).
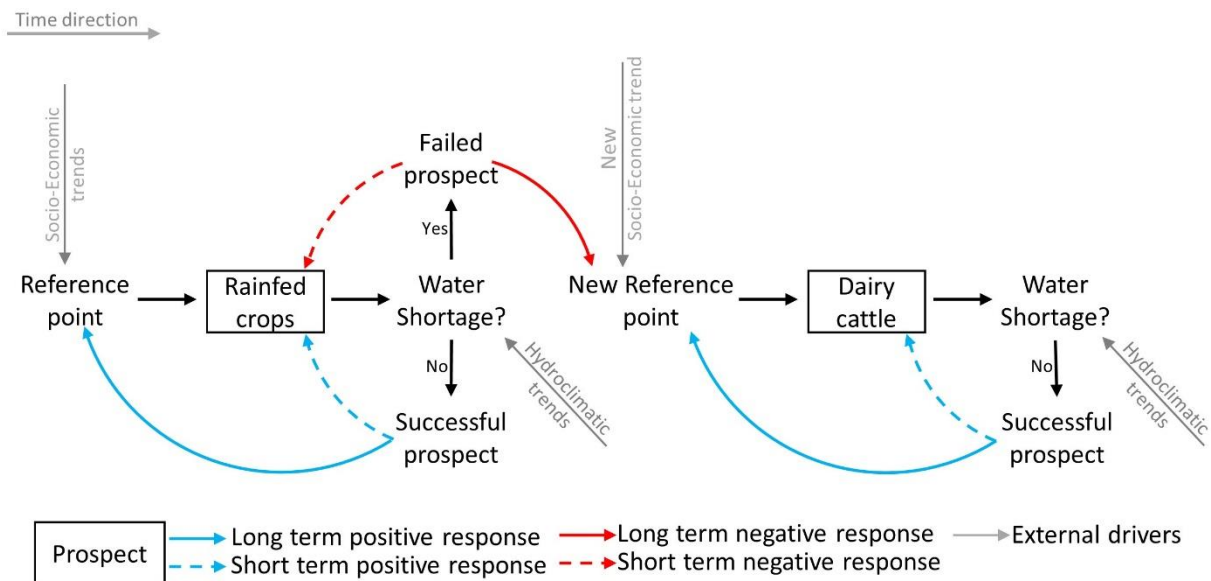
Figure 3. Prospect theory in socio-hydrology applied to Ceara study case.

The expansion of dairy production in Ceará has resulted in the increase of small (informal) reservoirs to support forage production and to provide water for livestock consumption. In some regions the high concentration of small reservoirs decreased the surface runoff connectivity of the watershed, impacting the recharge of large reservoirs downstream that serve multiple purposes (Ribeiro Neto et al., 2022). As a result, the persistence of this hydrological impact affects the region's water availability, since the large reservoirs remain at reduced water storage levels for longer periods, which in turn can influence individuals' perception of water security (component of welfare) and consequently their definition of the Reference point.

Interviews with farmers and agricultural extension officers regarding desirable reservoir volumes illustrated the concept of the Reference point and how it can vary according to previous experiences. Interviews revealed that volumes were consistently around 5% during the 2012-2018 drought; the lower water availability had become the status quo (or the Reference point). Therefore, increased volumes up to 20% of capacity were celebrated, because they were considered gains, even though such a level would have been considered a loss prior to the multi-year drought.

Based on the case study presented here we identified situations that can be analyzed using the Loss aversion effect. Loss aversion is related to the attempts of individuals to adapt to drought, aiming in general to avoid greater losses through measures that reduce water demand. We observed that one of these adaptations was the search for hybrid bovine breeds, resulting from the crossing of local breeds that are resistant to drought with European breeds that have a higher milk production. These hybrid breeds were already known by the local farmers, but they were long seen as not worth the investment, due to the high cost of acquisition. However, during the 2012-2018 drought, an acceleration in herd replacement by these hybrid breeds was observed. Many farmers decided to sell part of their herd to raise capital to invest in these hybrid breeds. They realized that it would be safer, in a scenario of low water availability, to maintain a smaller but more productive herd.

The increase in the number of wells in Ceará between 2012-2018 is another practical example that illustrates the Loss aversion effect. For Ceará, this alternative water supply can be considered a risky prospect, as it presents high implementation costs and is associated with uncertainties to whether a viable water resource will be found for exploitation. Either because of the water quality (brackish groundwater is common) or because crystalline geology often provides low yield. Therefore, it is perceived that individuals in this region who chose to install wells were willing to take more risks to avoid greater losses.

5 Simulating Prospect theory effects - applications, challenges and opportunities

249 The lack of considering patterns of co-evolution between hydrological processes and human dynamics within a
250 hydrological system was mainly because human dynamics were considered insignificant and due to the low spatio-
251 temporal resolution at which hydrological models originally operated. Implicitly, the idea existed that it would be
252 impossible or unfeasible to implement anthropogenic actions as an intrinsic component of the hydrological cycle,
253 which has been successively refuted by various studies related to drought assessment (Wens et al., 2021, 2019;
254 Van Oel et al., 2012; Streefkerk et al., 2023; Wens et al., 2020; Bakarji et al., 2017; Van Oel et al., 2018).

255 The presented concept of (human) drought impacts as failed prospects provides a different perspective to
256 incorporate the socio-hydrological characteristics of a region into drought analysis. Drought impacts as failed
257 prospects can especially contribute to the improvement and development of drought monitoring and early warning
258 systems, socio-hydrological characterization, drought risk analysis, forecast/re-analysis of drought events, and
259 support the development of public policies for the mitigation and prevention of drought impacts. On the other
260 hand, the Prospect theory has limitations - mainly related to the lack of explanatory power on how decisions are
261 made, especially related to the definition of an individual's Reference point, and how this is influenced by the
262 environment and the full range of affective and emotional states.

263 We consider that, when applied to drought assessment, the Reference point is related to the minimum level of
264 individuals' well-being to feel satisfied with the outcome of the chosen prospects. To represent this concept, it is
265 necessary to study the evolution of human dynamics, mainly related to how water and land have been used over
266 time by individuals in the hydrological system. Agent-based models (ABM) are a promising framework for these
267 kind of studies, as they allow explicit probabilistic simulation of human decision-making with the ability to
268 respond, learn and adapt to variations in environmental states and other agents (Schrieks et al., 2021). Moreover,
269 it has been successfully applied in socio-hydrological studies, combined with hydrological and/or agricultural
270 models (Wens et al., 2021, 2019; Streefkerk et al., 2023). These types of analyses often require expertise and
271 methods usually associated with the social sciences, such as interviews, workshops, companion modelling, and
272 serious games (Massuel et al., 2018; Acosta-Michlik and Espaldon, 2008; Pouladi et al., 2019; van Duinen et al.,
273 2016). This further underlines that drought assessment studies are conceptually interdisciplinary and therefore
274 require solutions beyond those associated only with the natural sciences.

275 The possibility of explaining the occurrence of a drought event through the use of Prospect theory endorses the
276 importance of the human component in drought assessment, besides bringing new discussions on this topic. The
277 core concept presented here advocates for a greater focus on the human component within drought assessment
278 studies and places the emergence of human impacts as a precursor to the disaster. This viewpoint contrasts with
279 the methodological approach of numerous studies in which drought events are analyzed only considering the
280 spatio-temporal variability of hydrometeorological variables, disassociated from the human component (Kchouk
281 et al., 2022). Furthermore, the Reference point concept provides a theoretical basis for considering drought impacts
282 dynamically, in contrast to the static vision on drought impacts that is now often encountered: in drought
283 assessment studies. Prolonged drought impacts lead to a change in the individuals' perception of drought
284 occurrence, the impacts have become the new "normal" situation and are therefore no longer experienced as
285 impacts. Moreover, we argue that the concept of drought impacts as failed prospects reinforces the perspective
286 that drought is first and foremost a socio-hydrological phenomenon that materializes in the form of a disaster.

287 **6 Conclusion**

288 We demonstrated the application of the concept of drought impact as a failed prospect. We argue that the collective
289 perception of individuals regarding the emergence of drought impacts plays a crucial role in both the magnitude
290 and the occurrence of this kind of disaster. We argue that Prospect theory, which originates from behavioral
291 economics, can provide a new angle to analyze the human dimensions of drought by including the individual's
292 perception on the center of analysis. We presented the idea that drought impacts arise when individuals perceive
293 they haven't achieved their desired welfare level due to water shortage. This observation emerged from the multi-

year drought event that occurred in the Semi-Arid region of Brazil from 2012-2018 as a case study. Applying Prospect theory and its concepts, such as the "Reference point" helped us understand that individuals' perception of drought impacts emergence varies over time. In simpler terms, prolonged water shortage periods can be seen as a new "normal" situation. Consequently, individuals may no longer experience impacts, since their welfare expectations would be aligned with the new water availability condition. Other concepts, such as the "loss aversion effect" and "framing effect" helped us understand the individual's tendency to change their water consumption pattern only when this resource is lacking, as well as their tendency to adapt to drought events.

This understanding offers the opportunity to bridge the knowledge gaps related to the human influences on drought events by acknowledging the individual human dimensions. We showed the potential of Prospect theory in addressing interdisciplinary methodological and conceptual gaps between natural and social sciences. The hypothesis presented here can contribute to the identification of new socio-hydrological phenomena and improve the understanding of phenomena already described in the literature. Furthermore, our insights contribute to the demand for a change of perspective on how studies related to disasters of hydro-meteorological extremes, especially drought events, should be conducted, bringing new ideas about the importance of representing the human component . We also support the idea of bringing more balance between the "socio" and "hydro" component in studies related to drought assessment, in which more interdisciplinarity should be sought, as hydrology and meteorology alone simply do not provide the means to understand human dynamics within the (socio-)hydrological cycle.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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