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Drought Diagnosis: What the Medical Sciences Can Teach Us

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Key Points:

- Analysis of recent droughts shows that drought diagnosis is often insufficient leading to unsuccessful strategies to deal with drought
- Drought diagnosis can be improved by using an analogy with the medical diagnostic process
- This emphasizes that the focus of a comprehensive drought diagnosis should be to prescribe treatment that reduces drought impacts

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Drought management is currently informed by a variety of approaches, mostly responding to drought crisis when it happens. Toward more effective and integrated drought management, we introduce a conceptual drought diagnosis framework inspired by diagnostic concepts from the field of medicine. This framework comprises five steps: 1. Initial diagnostic assessment; 2. Diagnostic testing; 3. Consultation; 4. Communication of the diagnosis; and 5. Treatment and prognosis. To illustrate the need for the proposed approach, four case studies of recently drought-affected regions were selected: the city of Cape Town, the state of California, the Northeast region of Brazil, and the Horn of Africa. Contrasting elements for these cases include the geographic extent and political boundaries, climate, socio-economics, and the relevance of different water resources (e.g., rainfall, reservoirs, and aquifers). For each case, we identified documented practices and policies and reflected on them in terms of drought misdiagnosis or incomplete diagnosis that have aggravated socio-economic and environmental drought impacts. A common example is the preference for technical solutions (e.g., installing infrastructure to augment water supply), rather than measures that reduce vulnerability. Analysis of these four drought case studies confirmed the anticipated need for a comprehensive approach to drought diagnosis for more successful treatment and prevention of drought. Using an analogy with medical science can be helpful toward comprehensively diagnosing droughts for a variety of contexts and assessing the effectiveness of proposed interventions. This framework can help drought managers to be more proactive in enabling drought-affected regions to become more drought resilient in the future.

Plain Language Summary

Droughts are becoming more common around the world, are occurring in new areas, lasting longer, and are affecting more people. When drought hits, we often experience water shortages, which can affect agriculture leading to food shortages. Additional drought impacts on health, lifestyle, and ecosystems include drying rivers and lakes, dust storms, water use restrictions, a lack of snow, dying forests, and wildfires. In extreme cases, droughts cause famine, disease, and migration. The fact that such drought impacts regularly make the news shows how ineffectively we currently manage drought; because the common practice is to respond to drought crisis as it happens rather than preparing in advance. Considering drought as a health disorder, we can follow the process used in medicine to diagnose that disorder and prescribe treatment. We suggest using this approach would enable us to identify where and how a location is vulnerable to drought and work on treatments. We could improve the health of a location before drought hits, thus reducing drought impacts. We discuss four recent drought cases: the city of Cape Town, state of California, Northeast region of Brazil, and Horn of Africa, to illustrate how drought could be better dealt with using our proposed approach.

1. Introduction

Studies often talk of "diagnosing" drought, a term inspired by medical science that is suggestive of analysis of symptoms and causes leading to a thorough understanding of an illness or disorder to enable treatment. After all, drought is akin to a chronic and complex disorder for which we wish to lessen symptoms and ideally prevent altogether. However, we show that there is no consensus as to what a "drought diagnosis" entails, neither across nor within disciplines. Yet the medical science literature provides us with the steps of the diagnostic process, exchanging the disorder for the drought and the patient for the region of interest, that would deliver a comprehensive, collaborative, and contextualized assessment to enable us to develop a treatment plan. We propose that this diagnostic approach, inspired by medicine and explained in Section 2, could be utilized to improve *treatment* of drought and to generally improve *the health* of a region to prevent drought or render it less impactful.

Drought affects around 100 million people every month (Smirnov et al., 2016) and this number is increasing: The changing climate means droughts are increasing in frequency, severity, and duration, and are occurring in previously unaffected areas (IPCC, 2021), for example, due to reduced snowfall (Huning & AghaKouchak, 2020), increased temperature (Bloomfield et al., 2019), or changed rainfall regimes (Feng et al., 2013). Studies of future climate predict more abundant meteorological droughts globally (Spinoni et al., 2020), while the risk of hydrological and agricultural droughts will increase due to increased temperatures (Sheffield & Wood, 2008). These climatic drought drivers are compounded by anthropogenic drivers. Water use and demand are increasing due to population and economic growth (Boretti & Rosa, 2019). What's more, population growth rates are highest in semi-arid drought-affected regions, such as the Sahel, the Horn of Africa, and Central Asia (World Bank, 2021a). Finally, water resources are declining due to human interventions such as over-abstraction, land use change, contamination, and construction of water infrastructure (Boretti & Rosa, 2019).

Identifying natural and human drivers of drought is a major scientific challenge (Van Loon et al., 2016). Nevertheless, dealing with drought requires identifying how humans induce and modify exposure and vulnerability to drought. Rather than aggravate drought, human actions can also alleviate drought and its impacts. Exposure and vulnerability are used in this context according to the Intergovernmental Panel on Climate Change (IPCC) definitions: Exposure is "the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected"; Vulnerability is "the propensity or predisposition to be adversely affected… [encompassing] sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (IPCC, 2014).

Global maps of drought risk by Carrão et al. (2016) and Meza et al. (2020) showed that drought risk correlates more strongly with exposure than with drought as a hazard (hazard being the severity and frequency of drought assessed by analyzing historical precipitation, streamflow, and evapotranspiration). Additionally, the countries with the greatest drought risk were those with the highest vulnerability. In other words, it is the human rather than the climatic factors that are putting livelihoods most at risk of drought.

Many recent studies have called for greater focus on human aspects of drought, in recognition that this natural hazard is intertwined with human influences on the water cycle and feedbacks of society on drought (e.g., Haile et al., 2020; Van Loon et al., 2016; Wanders & Wada, 2015). Indeed, a new term, *anthropogenic drought*, was proposed by AghaKouchak et al. (2021) to encourage consideration that drought is not a product but rather a process with which there are continuous feedback relationships with human activities and environmental impacts beyond the spatiotemporal range of the drought itself. The frequency at which drought impacts make the news around the world indicates that we need to better diagnose this process and these relationships to prevent drought or mitigate its impacts.

There are frequent calls to improve the current ineffectiveness of drought management practices by focusing on the underlying causes of drought rather than the more common reactive practice of crisis management (e.g., FAO, 2019; Wilhite et al., 2014; Wilhite & Pulwarty, 2005). We will go further and state that there is a need for more comprehensive, collaborative, and contextualized assessment of drought that identifies and evaluates all the causes and exacerbating factors, both natural and anthropogenic, unique to the region of interest. Such holistic assessment is necessarily interdisciplinary because cross-sectoral drought decision-making must consider the natural, engineered, governance, socio-economic, agricultural, industrial, energy and transportation characteristics that make a region susceptible to drought. Guidance literature from the Integrated Drought Management Program (IDMP) and others has for many years urged a shift from crisis management to risk management, from costly, ineffective, poorly coordinated, poorly targeted reactive "solutions" to investment in building resilience by addressing the root causes of vulnerability (e.g., IDMP, 2014; IDMP et al., 2017; Wilhite, 2000). Yet, when Hagenlocher et al. (2019) reviewed drought risk assessments, they found that a small minority of studies considered more than a single dimension of vulnerability (e.g., 83% focused on social dimensions alone) with few integrating dimensions (e.g., physical, economic, or governance), and less than 40% considered any types of solutions. Another review of drought risk assessments by Blauhut (2020) similarly showed that impacts were analyzed dominantly with a specific thematic focus, for example, 60% considered only agricultural impacts—and 75% of those were analysis of impacts on a specific crop.

There are numerous examples in the literature of water and drought mismanagement that led to inadequate address or even aggravation of drought impacts. We will illustrate how insufficiently applying the diagnosis procedure leads to a misdiagnosis, generally resulting from an overly narrow understanding of the drought threat—such case studies are described in Section 3. This can be oversimplified by stating that, for example, engineers may look for engineering solutions to drought such as reservoir construction while agronomists may propose agricultural solutions such as increased irrigation efficiency; both of which solutions may increase water scarcity for downstream users (Grafton et al., 2018; van Oel et al., 2018). Furthermore, in preparing a global drought risk map (Meza et al., 2020) found that some countries with calculated low or intermediate drought risk had nevertheless registered multiple drought events on the EM-DAT international disaster database (https://www.emdat.be/). This was due to considerable spatial heterogeneity with regard to drought risk within countries, emphasizing the need for localized contextualized drought assessment.

An important research question is not only how human actions induce or propagate drought (Van Loon et al., 2016), but how human systems—through engineering, land use, agriculture, governance, and socio-economics—have established a situation where drought is a threat. Moreover, human systems can also be mobilized to better deal with drought. In other words, because humans have created situations where certain groups and sectors are at risk of drought, they can also improve these situations. This study aims to encourage research toward drought risk reduction by presenting a methodology to comprehensively, collaboratively, and contextually diagnose drought to better deal with drought.

2. Drought Diagnosis

We aimed to develop a diagnostic procedure for the assessment and treatment of drought. To this end, we first reviewed published literature from a range of disciplines to analyze the use of the term "diagnosis," and its derivatives in relation to drought. The aim was to categorize the context in which "drought diagnosis" or "diagnosing drought," and so on, was used. A systematic literature search was conducted, which is described in the Supplementary Information.

The review revealed that consensus does not exist in the 40+ applicable papers that used the term on what it means to diagnose drought, neither across nor within disciplines. What's more, it was extremely rare to come across an explicit definition of what the authors meant by diagnosing drought. To "diagnose drought" can refer to: evaluating a drought's climatological and/or non-climatological causes; analyzing its frequency, duration, and severity; determining its type (e.g., meteorological, hydrological, etc.); assessing its impacts and resilience to those impacts, and; development of drought management strategies. These points are all vital to improve understanding of drought at a particular location and to then use this knowledge to avoid or lessen drought impacts. An all-encompassing definition of drought diagnosis would have to incorporate all these identified definitions to encourage their consideration in the process of diagnosing drought. Therefore, we propose adopting the most widely known and understood definition of diagnosis, that used in the field of medicine, and applying it to drought.

We argue that drought diagnosis more closely aligning with the medical definition shifts the focus from merely improving understanding to finding a cure, or at least reducing symptoms as much as possible following the analogy of drought being a chronic disorder. Furthermore, it emphasizes a diagnosis and treatment that is patient-specific, in other words, contextualized to a drought region and its vulnerabilities, rather than a generic solution.

2.1. Borrowing From Medical Literature: The Diagnostic Process

A dictionary definition of "diagnosis" is *the identification of diseases by the examination of symptoms and signs and by other investigations* (Collins, 2021). By adopting this definition, we can leverage the wealth of experience and description within medical literature to guide the drought diagnostic process. Particularly for complex health situations, the diagnostic process is a complex, collaborative activity that involves information gathering and clinical reasoning with the goal of determining a patient's health problem and consequently how to treat it. The aim of such a process is an accurate diagnosis made in a timely manner, thus giving the patient the best opportunity for a positive health outcome because decision making will be tailored to a correct understanding of the patient's health problem (Balogh et al., 2015). Translated to drought, the patient is considered the region of interest—holistically, including the people, social systems, ecosystems, and economic sectors—and symptoms are the drought impacts (who is the doctor is discussed in Section 4). Diagnosis is establishing what caused these symptoms and informing ways in which to treat them. Therefore, an accurate and timely drought diagnosis would provide the best opportunity to successfully apply prevention, mitigation, and preparedness measures specific to local drought characteristics and impacts.

The commonly described steps of the diagnostic process are synthesized here:

1. Initial diagnostic assessment (*anamnesis*)—Evaluation and history of symptoms, patient history, physical examination
2. Diagnostic testing—Further analyses to confirm the diagnosis
3. Consultation—Obtaining a second opinion from specialists

Steps 1–3 are a circular continuous process of information gathering, integration, and interpretation, involving iterative hypothesis generation as more information is learned (e.g., Balogh et al., 2015).

4. Communication of the diagnosis
5. Treatment and prognosis

Diagnosis of complex health problems (we similarly consider drought to be a complex problem) starts with an initial diagnostic assessment, or *anamnesis*. Anamnesis, that stems from the Greek words *ana* (bring again) and *mnesis* (memory), means recollecting all the facts related to the patient and the illness. Anamnesis is considered the most important step in medicine, because it is the basis of the doctor-patient relationship and because (technological) solutions can only be put to good use if the human side is sufficiently recognized. This is also particularly relevant in diagnosis of drought, emphasizing the importance of conducting drought diagnosis with the participation of stakeholders. The stakeholders will be able to describe the impacts (symptoms) and share their opinions on the potential causes and drivers. Comprehensive drought diagnosis thus ideally starts with identifying the relevant stakeholders and identifying the symptoms they experience.

Diagnostic testing follows identification during the initial diagnostic assessment of what is not known and needs to be further investigated.

Just as medical professionals regularly require consultations with specialists to gain a second opinion and to confirm a diagnosis, drought researchers and policymakers should consult and collaborate with specialists from a range of disciplines—an independent second opinion decreases the risk of tunnel vision and overlooked impacts (for instance if not all stakeholders are well-represented). Diagnostic error in medicine commonly results from insufficient experience and speciality expertise (WHO, 2016); the same can be inferred for drought diagnosis, such as when engineers identify only drought causes related to physical infrastructure and consequently propose only hard engineering solutions like the construction of dams (Medeiros & Sivapalan, 2020). Additionally, coproduction of a drought diagnosis together with drought-affected stakeholders utilizes local contextualized knowledge and is supported by a common maxim in medicine: "Just listen to your patient, he is telling you the diagnosis" (attributed to William Osler in Gandhi, 2000).

Underlying medical diagnosis is an elaborate pre-existing taxonomy of diseases that a doctor relies on. A taxonomy does not exist for drought, other than perhaps categorizing by drought type (meteorological, agricultural, hydrological, etc.). We are concerned here with how society is impacted by drought; therefore, it is the socio-economic and environmental drought impacts that need to be averted or lessened. The myriad combinations of drivers and impacts mean such a taxonomy may not be possible for drought. As shown in Section 3, rather than being a weakness, the lack of a drought taxonomy means initially inconceivable causes of drought may not be overlooked in favor of more familiar diagnoses—a misdiagnosis issue well known to medicine (e.g., Kempe et al., 1962). Similarly, an extensive knowledge base on treatment effectiveness and possible side-effects are not available for drought. Though again, rather than being a weakness, this means treatments must be contextualized to the specific drought-affected region and researchers must be open to identifying any possible side-effects of treatment. The communication and treatment steps are another example of how drought science can learn from the medical field. Doctors discuss potential treatments with their patients, providing prognoses (how the disorder is likely to proceed) and ask for their preferences, which may be objective or subjective (e.g., local or general

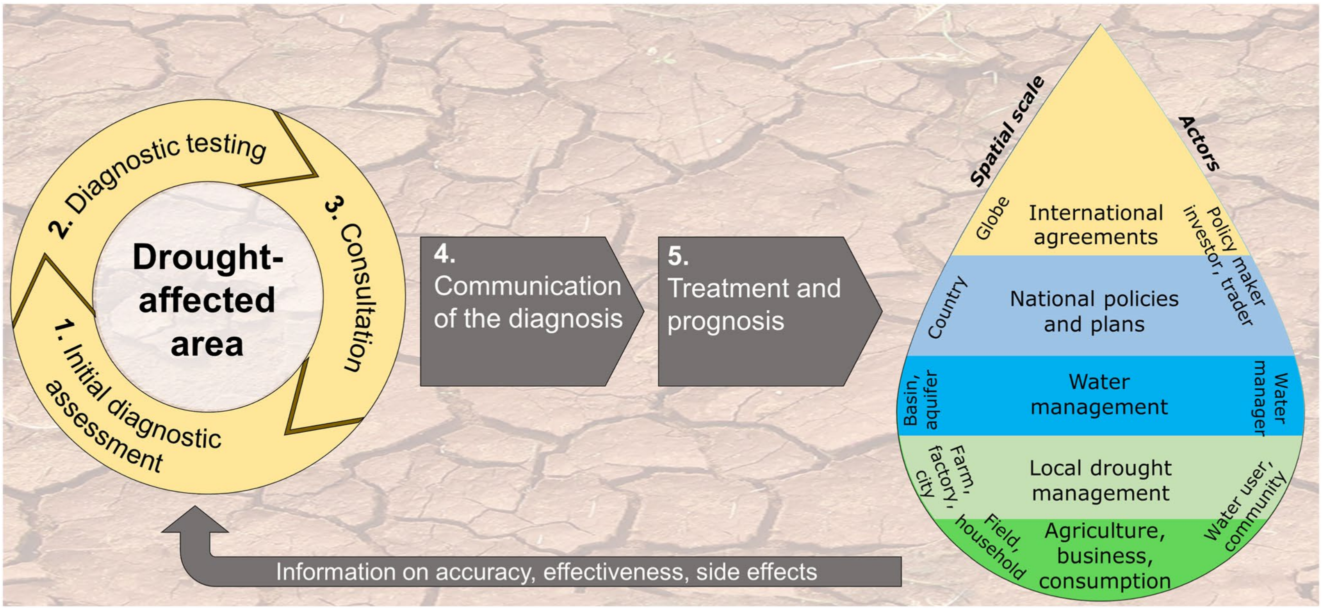

Figure 1. Conceptualization of the drought diagnostic process. Steps 1–3 are a cycle of information gathering, integration, interpretation, and identification of what further assessment is necessary. The diagnosis is updated as new information is learned, including during and following treatment (represented by the lower feedback arrow). In a variation from the medical analogy, steps 4 and 5, the communication of the diagnosis and the treatment and prognosis, would be specific to the various actors, systems, and scales (on the right). These various actors would also necessarily coproduce the drought diagnosis and treatment plan alongside drought researchers. The spatial scales, systems, and actors shown in the figure are illustrative rather than exhaustive and may include those that are outside the drought-affected area.

anesthesia, tablets or injections, etc.); this increases the likelihood that the treatment plan will be followed. Similarly, coproducing drought risk reduction strategies will best support the actual implementation of the designed plans.

2.2. Applicability to Drought Assessment

This is a methodological guide for conducting a comprehensive, collaborative, and contextualized drought diagnosis to enable development of treatment (or solutions) for drought. In addition, this enables us to identify where the health of the systems in a region could be improved before a drought to prevent drought or make them less impactful. A conceptualization of the drought diagnostic process is presented in Figure 1 and subsequently described.

1. Initial diagnostic assessment (anamnesis)
   - *Evaluation and history of symptoms = Evaluation and history of impacts*: the drought impacts. Evaluation must consider both direct drought impacts—reduced river flow, soil moisture, and groundwater levels—and, more importantly, indirect drought impacts—water scarcity, food insecurity, economic losses, unemployment, ill health, migration, conflict, ecosystem damage (for an extensive list of drought impacts see IDMP (2014)). This evaluation should identify the most vulnerable social, economic, and environmental sectors in consultation with local stakeholders.
   - *Patient history = Drought history*: the history of drought risk in the region. This step analyses past drought events to assess the drought hazard, exposure, and vulnerabilities. It is important to evaluate how these determinants have changed over time, focusing especially on recent developments, for example, increasing water demand, land use changes, or dependency on particular water infrastructure. Drought hazard is assessed by evaluating when droughts occurred, their type, frequency, duration, severity, and geographic extent; drought indices are thus useful (see IDMP, 2016). Exposure and vulnerability are assessed by evaluating the socio-economics, agriculture, industry, policy decisions and policy responses, and governance, especially to identify where they have created heterogeneity in exposure and vulnerability; calculation of

water demand and water use by different users is applicable here. For full guidance on drought risk assessments, see World Bank (2019).

- *Physical examination = Physical characterization*: physical characteristics that increase the likelihood of impactful droughts. The physical characteristics are largely unchangeable within a drought management plan and any drought treatment must work with these characteristics. Key elements are the projected regional and global climate (i.e., the likelihood of meteorological drought). Just as important are the natural and human-modified hydrology (e.g., the total water storage capacity in natural lakes and rivers, constructed reservoirs, and aquifers, relative to annual renewable water availability to assess the susceptibility to hydrological drought). Further important elements include soil type (the susceptibility to agricultural drought), ecosystems (vulnerability to environmental drought), and the risk of other compounding natural hazards.

2. *Diagnostic testing*: further data collection and analysis to confirm the diagnosis and inform which causes of drought impacts can be treated. Diagnostic testing would involve analyzing potential drought drivers and aggravating factors identified in the initial diagnostic assessment that have not been previously investigated. It could thus be similar to "detection and attribution," applied in climatology to detect and attribute extreme events, to determine which treatable drivers and aggravating factors generate significant drought impacts. Diagnostic testing could involve, for example, collection of narratives to assess perceived climate change impacts or increased vulnerabilities and exposure; household surveys or citizen science monitoring of domestic water use or drought impacts; remote sensing analysis of informal water infrastructure; political ecology study of governance structures and power relationships; gray literature analysis of drought management policy and field research of the effectiveness of its implementation; participatory research or serious games to evaluate farmers' decision-making on crop and seed selection, planting timing and drought coping strategies; and assessment of virtual water transfer utilizing import/export data.
3. *Consultation*: recognition that alternative expertise needs to be brought into a diagnosis. This could be cross-disciplinary advice if the diagnostic testing reveals that drought impacts are, for example, less related to water management but more due to agricultural choices or governance structures. This step also emphasizes the importance of local expertise and stakeholder participation in the diagnostic process. Crucially, coproduction of the diagnosis with the range of actors shown in Figure 1 would facilitate the development of drought prevention, mitigation, and preparedness strategies that are not beyond financial, political, physical, or cultural bounds.

Figure 1 shows that steps 1–3 are part of a cycle of information gathering, integration, interpretation, and identification of what further assessment is necessary. The diagnosis is updated as new information is learned. It is important to identify if sufficient information has been gathered to be confident in the diagnosis and subsequent prescribed treatment.

4. *Communication of the diagnosis*: ensuring that the drought diagnosis reaches and is utilized by relevant stakeholders. Whereas the consultation step refers to information gathering, this communication step refers to information dissemination. As illustrated in Figure 1, it is crucial for the communication of the diagnosis to be contextualized, understandable and useful for different groups of stakeholders. Coproduction of the diagnosis with representatives of all the relevant stakeholder groups would facilitate this step of the diagnostic process.
5. *Treatment and prognosis*: a comprehensive collaborative diagnosis, which includes adaptation and mitigation strategies and policy advice, will enable the development of a contextualized drought preparedness plan specific to a range of different scales and stakeholders. In addition, the plan should aim toward a more proactive approach to improve the general health of the relevant systems making impactful drought less likely, that is, aiming to reduce exposure and vulnerability. Note that, as shown in Figure 1, insights gained from applying the treatment, such as ineffective measures or unanticipated side effects, should be fed back to improve the accuracy of the diagnosis and to potentially adjust the treatment. Drought diagnosis can also provide a drought prognosis: 1. How a drought is likely to develop and what its impacts will be; 2. How the drought may respond to "treatment" (i.e., will certain impacts be lessened, will there be any side-effects?); and 3. How the region could be made less susceptible to drought (i.e., prevention rather than cure). Hence, the prognosis could provide early warning by identifying a condition before its symptoms become apparent. Note that this step requires ethical considerations: some symptoms might be treated at the expense of others. Indeed, it must be appreciated that avoiding drought impacts altogether is likely impossible, thus, many "treatments" or "solutions" are actually risk reduction strategies.

2.3. Issues of Incomplete or Misdiagnosis

Medical misdiagnosis cases often involve failures in the stages of the initial diagnostic assessment (Balogh et al., 2015). Analogous examples exist within the drought literature of misdiagnosis or incomplete diagnosis that led to incorrect treatment that worsened rather than alleviated drought impacts. There are abundant drought studies assessing aspects of the *drought history* and *physical examination*, such as those that compute drought indices or calculate total water storage available in constructed reservoirs. Less common, or selectively conducted, is an *evaluation and history of impacts* (King-Okumu et al., 2020; Wilhite et al., 2007). This discrepancy may be for reasons of data availability, ease of analysis, disciplinary background of those conducting the drought assessment, or because there is a vested interest in leading the analysis toward a drought treatment that favors a particular group (Kallis, 2008; Kchouk et al., 2021). For example, drought impacts such as regional economic losses from decreased crop production are typically more straightforward to evaluate using openly available formal (governmental) data that predominantly arise from larger commercial farms. This type of drought diagnosis could lead to solutions of increasing water availability for large farms, which may satisfy only high-level stakeholders. Drought impacts on smallholder farms such as reduced livelihood, food insecurity, and migration may be given less consideration because the necessary data are rarely available requiring substantial interdisciplinary investigation (i.e., *diagnostic testing*). Solutions are therefore less likely to provide relief to smallholder farmers or might even aggravate the impacts on smallholder farmers who were (intentionally or unintentionally) disregarded in the *initial diagnostic assessment*. Comprehensive, collaborative, and contextualized drought diagnosis following Figure 1 may result in drought treatments far from the water perspective involving, for example, road construction, crop insurance, support of agricultural extension agents, cash transfers, or conflict resolution (e.g., Brooks et al., 2005; Detges, 2016; Poděbradská et al., 2020). Thus, drought researchers and stakeholders should remain open to all solutions.

3. Drought Case Studies

The following case studies were selected to illustrate drought misdiagnosis, or incomplete drought diagnosis, resulting from narrow drought assessment that has resulted in insufficient and inappropriate treatment. We present the research available in the literature showing how current and historic drought assessment at the case study locations compares with our drought diagnostic process.

The selected case studies have deliberately contrasting scales, socio-economics, drought drivers, and impacts, and are at different stages of implementing integrated drought management. The case studies demonstrate, however, that there are common causes of drought misdiagnosis, which result from insufficient consideration of one or more of the steps of the diagnostic process presented in Section 2.2.

The case studies' locations are shown in Figure 2. Table 1 provides background information for comparison.

3.1. Cape Town, South Africa

3.1.1. Situation

Cape Town lies at the southwestern tip of Western Cape, South Africa (Figure 2). The province has a Mediterranean climate along the coast though with hotter summers and colder winters inland; average annual precipitation ranges from around 300 to 900 mm (Botai et al., 2017). The Western Cape Water Supply System is almost entirely reliant on rainfall, consisting of six large reservoirs with a combined capacity of around 900 Mm^3; agriculture consumes 29% of this supply and 71% supplies the Greater Cape Town urban area where household consumption is responsible for a 70% share (DWS, 2018).

The infamous "Cape Town Water Crisis" occurred in 2017–2018 when reservoir levels became so low (<20% capacity) that "Day Zero" was approached, when municipal water supply would halt and Cape Town would become the world's first major city to run out of water (Sousa et al., 2018). The Greater Cape Town area experienced 3 years, 2015–2017, of below average rainfall, a meteorological drought event with a return period estimated at several hundred years (Wolski, 2018). Previous multi-annual droughts occurred fairly recently from 2008–2011 to 1997–2000 (Botai et al., 2017) and water usage restrictions were introduced in 2000–2001 and 2004–2005 (Matthews, 2005). However, the measures progressively introduced from 2016 to 2018 were the most stringent with city-wide water pressure reductions, increased water tariffs, water rationing with large fines for exceedance

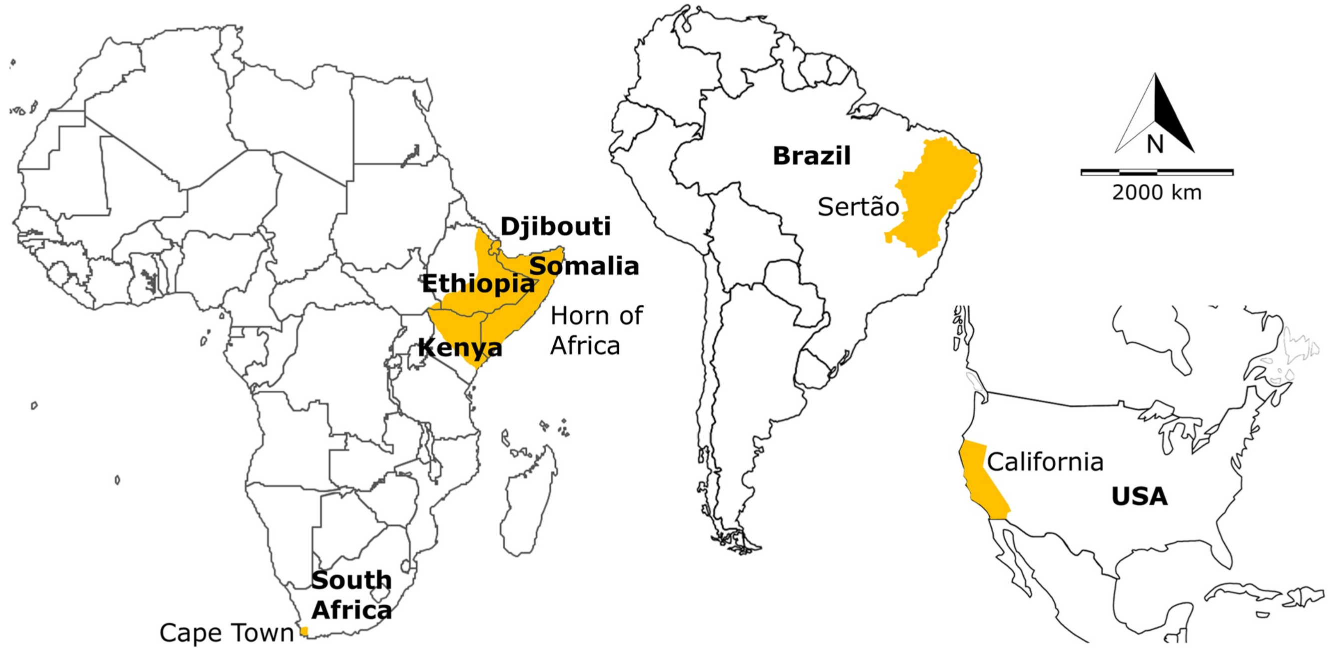

Figure 2. Location maps of the four selected drought case studies (Table 1).

along with online "naming and shaming," and establishment of the world's first "water police"—a squad of 60 officers acting largely on neighbor tip-offs to investigate water misuse (McCarthy, 2018; Parks et al., 2019).

Since the 1980s, water management had been guided by models of excellent repute that linked real-time and predicted stream flows, water storage, river basins, transmission channels, and demand projections, which could crucially be used to assess risks of supply failures to different categories of users and evaluate the effectiveness of responses such as restrictions (Muller, 2018). The models had guided policymakers suggesting where and when new reservoirs would be required to meet rising demand from the increasing population (a doubling from 2 to 4 million from 1987 to 2014); indeed in 2009, the models indicated water supplies would fall short by 2015 (Muller, 2018; World Population Review, 2021). The traditional diagnosis considered that impacts of drought could be mitigated by simply constantly expanding the reservoir network as demand grew. However, by the 2000s, policymakers were swayed by environmentalist pressures to reduce dam construction and the high necessary capital investment was diverted elsewhere, the cost of further infrastructure considered to outweigh the drought risk (Muller, 2018). When the 2015–2018 drought hit, drought management quickly became crisis management prioritizing reducing water consumption and rationing the remaining water supply from the reservoirs (Parks et al., 2019).

3.1.2. Misdiagnosis

There is a significant body of literature examining the Cape Town Water Crisis, which details what was missed by policymakers and decision-makers in the lead up to the drought. The causes, symptoms, and oversights can be mapped onto the diagnostic process of Section 2.2. Muller (2020) argues that there was overreliance on demand management to balance supply and demand in the rapidly growing city. This argument suggests an insufficient *physical examination*, an underappreciation of the physical characteristics of the area, namely the capacity of the water storage infrastructure. Muller (2020) further noted that demand calculations had failed to appreciate that even though agriculture typically consumed less water than its quota permitted, during periods of drought the agricultural consumption from the municipal supply would increase, demonstrating a lack of thorough assessment of *drought history*. Indeed, during the drought there was criticism of agricultural water consumption at the expense of urban supply (Robins, 2019). However, a thorough *evaluation and history of impacts* would have shown that agriculture was already severely affected and reduced agricultural production had impacted the national economy, local food prices and consequent nutritional intake, and employment of up to 50,000 seasonal workers; the latter points having a disproportionate impact on the poor (GroundUp, 2021).

Table 1
Details of the Four Drought Case Studies (Figure 2)

Location	Scale	Köppen climate[a]	Population	Gini index[b]	Number of scientific studies[c]	Main drought impacts
Cape Town, South Africa	City	Csa	4 million	0.62	144	Water scarcity, reduced economy
California, USA	State	Csa, Csb, BSk, BSh, BWk, BWh	39.6 million	0.49	3,370	Groundwater depletion and consequent subsidence, ecosystem loss (forest die-off, drying rivers, increased delta salinity), wildfires, reduced hydroelectricity output
Sertão, Northeast Brazil	Multi-state	BSh, Aw	27.8 million	0.57	634	Water scarcity, food insecurity, poor health, poverty, migration
Horn of Africa (Djibouti, Ethiopia, Kenya, Somalia)	Multi-country	BSh, BWh	~80 million	~0.39	1,683	Water scarcity, food insecurity and famine, disease, migration

[a]Csa = hot summer Mediterranean, Csb = warm summer Mediterranean, BSk = cold semi-arid, BSh = hot semi-arid, BWk = cold desert, BWh = hot desert, Aw = savanna (Beck et al., 2018). [b]The Gini index, or Gini coefficient, is a measure of economic inequality among a population. A score of 0 represents perfect equality and 1 represents perfect inequality. The Cape Town value is for the Western Cape, which is slightly better than the national score of 0.65, which is the global worst (source: StatsSA, 2019). The California value ranks as the fifth-worst US state; the national score is 0.48 (source: US Census Bureau, 2019). The Northeast Brazil region ranks worst of Brazil's five regions; the national score is 0.55, which is the ninth-worst in the world (source: CEIC, 2017). The individual Horn of Africa scores are: Djibouti 0.43, Ethiopia 0.35, Kenya 0.41, Somalia 0.37 (source: World Bank, 2021b). [c]Refers to the number of scientific publications identified by Web of Science when searching for *drought* AND *[case study region]*; see the Supplementary Information for further detail.

Mid-drought it was common for politicians amongst others to blame climate change. Even though climate change would increase the likelihood of such droughts, this would only expose the vulnerability of a water system so completely reliant on rainfall designed to cope with only a one in 50 years drought event (wrongly) assuming stationarity (Otto et al., 2018). Again, this reflects a poor *physical examination*, or, an underappreciation of the physical characteristics of both the water infrastructure and the climate systems. Other politicians blamed each other for the crisis: the Democratic Alliance (DA) led City of Cape Town and Western Cape governments blamed the national ruling party, the African National Congress (ANC), for withholding funding and support to embarrass and tarnish the DA while the ANC accused the DA of poor forward planning (Saunderson-Meyer, 2018). Proposals by policymakers following the drought showed faith in the traditional diagnosis, that is, there is no evidence of an updated diagnosis, as solutions are mostly to augment water supplies through (in order of significance): basin transfer, desalination, groundwater exploration, and waste water reuse (COCT, 2020).

Further *diagnostic testing* through a political ecology lens proposes an alternative hypothesis. While inequality is well-known in South Africa (Table 1) and socio-economic assessment is a requisite aspect of the *drought history* step of the diagnostic process, political ecology analysis suggests that the 2015–2018 drought accelerated and exacerbated a pre-existing water crisis. Savelli et al. (2021) and Enqvist et al. (2020) showed how Cape Town's political legacy encouraged unsustainable levels of water consumption amongst the (white) elite and tolerated chronic water insecurity amongst (black) informal dwellers. In past decades as investment increased and the reservoir network expanded, the beneficiaries were the wealthier citizens who could afford, and were thus able to use, more water. Meanwhile, despite progressive policies to ensure universal access to water and basic services, precarious living conditions and poor access to water services prevailed in the townships (McDonald, 2012). Per capita water consumption ranged from 10 L per day in informal settlements that accounted for only 4% of the city's water consumption, up to 1000s L per day in upper class areas that, combined with middle classes, comprised approximately 38% of the population but consumed 70% of the city's supply (Robins, 2019; Savelli et al., 2021). For further illustration of this water inequality, 140 million L per day went to gardens, 100 million L per day went to golf courses, and 10 million L per day to the city's 68,000 swimming pools, which alone consume as much water as 47,000 low-income households (McDonald, 2012).

Through 2015–2018 this existing inequality in water use persisted leading to unequal experiences of drought and water insecurity for diverse social groups. While wealthier households had to make the most drastic reductions to their municipal water consumption or face high tariffs and fines, their socio-economic situation meant coping strategies were available enabling them to maintain existing lifestyles, such as purchase of bottled water and rain-water storage tanks, use of spring water collected outside the city, drilling of private boreholes where hydrogeo-logically feasible (up to 30,000), and the use of swimming pools as reservoirs (Robins, 2019; Savelli et al., 2021). The experience for township dwellers was markedly different: the Free Basic Water policy that ensured 6000 L per household per month—often insufficient due to large numbers occupying each household—was suspended in place of tariffs that were unaffordable to many; the same household water restrictions were applied in townships as in middle and upper class areas though the average number of dwellers per household being so much higher meant much less water per person (intensive installation of meters restricted household water use); interruptions to water supply meant lifestyle changes such as reducing showering, clothes washing, and house cleaning and getting up and cooking before 4 a.m. to take advantage of water availability (Robins, 2019; Savelli et al., 2021).

Therefore, a more comprehensive and contextualized diagnosis reveals that preparation for the next drought should not focus solely on augmenting the water supply. The health of the system as a whole needs to be improved with a change of political and economic focus to a more sustainable and equitable distribution of the available water across society (Enqvist et al., 2020; Savelli et al., 2021).

3.2. California, USA

3.2.1. Situation

California lies on the Pacific coast of southwest USA (Figure 2). With 39.6 million inhabitants, it is the most populous state in the USA and if it were an independent country, it would rank fifth in the world for the size of its economy (Forbes, 2020; World Population Review, 2021). Precipitation mostly falls in winter months as snow in the Sierra Nevada mountains and rainfall predominantly in the north of the state. While 80% of precipitation falls in the winter, around 75% of demand is in the summer and while 75% of supply originates from the north of the state, 80% of demand is from the south (Purkey et al., 2007; Water Education Foundation, 2021). Water use averages around 50% for the environment, 40% for agriculture, and 10% for urban supply, the latter including industrial and domestic uses (Mount & Hanak, 2016).

To bridge the spatiotemporal gap between water supply and demand, the state heavily relies on groundwater and water transfers into the state. Groundwater supplies 40% of the state's water, increasing to 60% during drought years (Stokstad, 2020). The Central Valley Project in 1937 and the California State Water Project in the 1960s developed the largest multi-purpose integrated water delivery system in the country. This system provides water supply to ~27 million people and irrigates 300,000 ha of farmland. Although this system is the fourth-largest generator of hydroelectricity in the state, moving many km^3 of water, it comes at the cost of also being the largest electricity consumer (SOC, 2021). California is one of the largest fruit producers in the United States (CDFA, 2020), and one of the leaders in the production of high economic value and water consumptive goods such as alfalfa, almonds, pistachios, and cotton (Johnson & Cody, 2015)

California is a drought-prone state; notable recent drought events occurred in 1976–1977, 1987–1992, 2007–2010, 2012–2017, 2018, and 2020–2021 (NIDIS, 2021). Recent droughts are increasingly attributed to anthro-pogenic climate change, as higher air temperatures and reduced precipitation have resulted in less snowpack built during the winter (December–February), and earlier melting during the spring (March–May, AghaKouchak et al., 2014; Berg & Hall, 2017; Diffenbaugh et al., 2015). The reduced snowpack reduces water availability for the summer months, but the water from early snow melting could contribute to storage in California's reservoirs. However, the early snow melting coincides with the California flooding season, when the multi-purpose reser-voirs are kept at safety (low) levels. As such, California water managers rely on seasonal forecasts for reservoir operations to decide when and how much water to release for flood control and how much water to maintain to

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supply the summer months' demand (Cohen et al., 2020; Wanders et al., 2017). Hence, when more water than is needed is released during the flood control period and unexpected drought hits, the region relies mostly on groundwater and inter-state transfers. Although groundwater abstraction can buffer short-term drought impacts in agriculture and domestic water supply, multi-year droughts compound decreased groundwater recharge with increased reliance on groundwater abstraction and an increasing water demand. *Diagnostic testing* shows that the level of groundwater use is unsustainable leading to multiple severe side effects. Studies utilizing NASA's Gravity Recovery and Climate Experiment (GRACE) satellite mission showed aquifers are depleting (Scanlon et al., 2012; Thomas et al., 2017); satellite-based interferometric synthetic aperture radar (InSAR), continuous global positioning systems (CGPS), and extensometer data showed that the ground is subsiding (Chaussard et al., 2017; Faunt et al., 2016); and analysis of physical, biogeochemical and biological changes showed that aquatic ecosystems are declining (Christian-Smith et al., 2011; Winder et al., 2011).

During the 2012–2017 drought, around 123 million trees were lost (US Forest Service, 2019). The resulting abundance of flammable dead woody material fuelled extensive wildfires, including those of 2020, which were the most extensive on record burning 4% of California (Swain, 2021). These wildfires lead to fatalities, infrastructure damage, loss of ecosystems, and poor air quality with associated health impacts both locally and across the USA as smoke was transported by atmospheric currents (Shi et al., 2019; Wu et al., 2018). California's rivers have legislated minimum environmental flow requirements; however, they may not always be met during droughts adversely affecting river ecology (Stewart et al., 2020). An additional impact of hydrological droughts is reduced hydroelectricity production, resulting in additional costs passed on to the consumer measured in US$ billions along with the environmental cost of increased fossil fuel use for energy production, such as an extra 23 million tonnes of CO_2 emissions from 2012 to 2015 (Gleick, 2015). Drought impacts on leisure activities include the ski industry suffering from a lack of snow and low water levels affecting boating and fishing (Lund et al., 2018).

3.2.2. Misdiagnosis

Misdiagnosis of drought in California has stemmed from the assumption that continually increasing groundwater abstraction will buffer water shortage, and this has largely mitigated severe impacts on irrigated agriculture in the short term. However, this is an example of a short-term palliative treatment worsening the long-term chronic disease. Appreciation of this misdiagnosis led to introduction of California's Sustainable Groundwater Management Act in 2014, which requires reaching basin groundwater sustainability by 2040. Achieving this aim could fundamentally alter California's agriculture as it will need permanent fallowing of some irrigated areas, land use change to facilitate groundwater recharge in wetter years, and some claim there will probably still be a requirement for significant infrastructure investment for additional basin transfer (Nelson et al., 2016). However, broader *evaluation and history of impacts* reveals drought impacts independent of reaching basin groundwater sustainability, such as reduced hydroelectricity generation, forest die-off, and declining ski industry.

Since the early 1900s, the economy and population of California grew through extensive infrastructure developments. With 95% of its residents living in urban areas, the highest percentage in the country, cities have expanded in environmentally, economically, and socially unsustainable ways and generated conflicting demands with agriculture for adequate drinking water supply (Di Baldassarre et al., 2021; US Census Bureau, 2012). The legacy of dam construction and high groundwater abstraction that drove this growth has led to a lock-in condition with unsustainable levels of water consumption that are very difficult to reverse (Di Baldassarre et al., 2021).

To meet the increasing water demand and ensure water access, since the 1930s, California implemented a complex hierarchical water rights system with priorities based on when their water rights were claimed (Attwater & Markle, 1987). This system is neither fair nor efficient. *Diagnostic testing* estimated that California had allocated water rights of about five times the volume of water available in an average year (Grantham & Viers, 2014). Furthermore, when a drought hits, junior water rights (often located far from the river streams and the water pipeline grid) are required to reduce consumption, while senior riparian water users can abstract as much as their water rights grant them (Null et al., 2016). While this measure reduces overall consumption, continued water abstraction at the riparian zones leads to reduced downstream flows and off-grid water availability, directly impacting underprivileged communities and ecosystems. *Treatment* for these drought impacts would include revising the current water rights system. However, because California water rights are tied to the value of the land, updating them infers an entire socio-economic restructuring. Currently, such unequal water access and restrictions are accelerating cycles of inequality and deprivation, leading to potential armed conflicts (Barlow et al., 2017) and worsening ecological impacts (Stewart et al., 2020).

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Reliance on infrastructure and out-of-state waters, such as from the Colorado River, has also led to conflicts, such as the disputes over water distribution between California and Arizona (Stern & Sheikh, 2020). During drought years, California has ensured allocation of a minimum amount of water, while Arizona must deal with reduced supply. These measures and the increasing frequency of droughts directly led to the death of Colorado River Delta ecosystems in Mexico (Owen et al., 2017). Although California aims to ensure minimum environmental flows locally, ecosystem impacts downstream and out of state have been largely overlooked (Rivera-Torres & Gerlak, 2021).

A wealth of studies have conducted further *diagnostic testing* linking California's drought impacts to anthropogenic climate change (AghaKouchak et al., 2014; Berg & Hall, 2017; Mann & Gleick, 2015). Future climate projections warn of a potential climate shift towards arid desert conditions (Beck et al., 2018), thus policymakers are again advocating for supply side solutions such as dam construction and managed aquifer recharge (Perry & Praskievicz, 2017). However, it seems apparent that *treatment* requires reductions in water consumption, potentially requiring fundamental adjustments to agricultural practices and lifestyles as well as revision of water rights and inter-state water transfer agreements.

3.3. Sertão, Northeast Brazil

3.3.1. Situation

The *Sertão* is a semi-arid region of Northeast Brazil, sometimes known as the "Drought Polygon," comprising 10 states: Alagoas, Bahia, Pernambuco, Paraíba, Rio Grande do Norte, Ceará, Maranhão, Piauí, Sergipe, and Minas Gerais (Figure 2). This region makes up 13.2% (1,128,697 km^2) of Brazil and with a population of 27.8 million is one of the world's most densely populated dryland regions (SUDENE, 2017). Rainfall is relatively high for a semi-arid region, averaging around 750 mm per year, though it is concentrated into just 4 months with high spatial heterogeneity, intense rainfall events, and significant interannual variability (Martins & Reis Junior, 2021). High temperatures and low humidity cause annual evapotranspiration exceeding 2,000 mm, while poor shallow soils above crystalline geology create a lack of aquifers and only intermittent rivers (Magalhães, 2017).

Northeast Brazil is drought-prone with one of the worst occurring in 1877–1879; known as The Great Drought, it was the most impactful in the history of Brazil, when up to 500,000 people died of famine and mass migration was triggered (Greenfield, 2001). The most recent drought lasted from 2012 to 2018 and was both the most prolonged and most severe in terms of rainfall deficit since rainfall monitoring began around 110 years ago (Pontes Filho et al., 2020). It proved devastating to many agricultural, livestock, and industrial producers (Gutiérrez et al., 2014). Smallholder farmers, who comprise 28% of the population and 95% of the agricultural sector, were hardest hit due to their reliance on rainfed agriculture for their livelihoods. Crop losses were estimated at 70%–80% and economic losses at over US$3 billion (Brito et al., 2018). As reservoir volumes collapsed, towns and cities suffered from a lack of domestic water supply and an increase in water-related disease due to poor water quality, in addition to food insecurity (Eakin et al., 2014).

Droughts preceding the mid-twentieth century were severely impactful due to insufficient infrastructure and logistics (for example, water and grain storage and delivery), as well as overly political, fragile, and unqualified public administration (for example, drought mitigation programs were uncoordinated, and there was a lack of transparency and communication with society, Martins & Magalhães, 2015). Subsequently, government approaches to deal with drought focused for a long time only on increasing water supply: especially heavy investments were made in the 1990s and 2000s on water infrastructure which was perceived as a definitive and effective *treatment* (Martins & Reis Junior, 2021). Emergency government responses during the 2012–2018 drought were based on an *evaluation and history of impacts* and included tanker trucks to supply water to rural towns, food donations in the most vulnerable areas, and creation of work fronts (government work projects) with the aim of employing drought-affected populations during drought to build dams and roads. These actions are in addition to emergency financial responses aimed at farmers including subsidized grain prices to prevent decimation of livestock, and renegotiation of farmers' debt (Magalhães, 2017).

3.3.2. Misdiagnosis

Drought misdiagnosis stems from the focus on dam construction, oriented by the paradigm of "fight against drought"; the rationale that hydraulic solutions like reservoirs, wells, water supply systems, and irrigation projects would prevent water shortage, thus reducing exposure and vulnerability to drought (Machado & Rovere, 2018; Silva, 2003). This idea was reinforced by the hydraulic mission approach that was ongoing worldwide since the nineteenth century and defined as "the strong belief that every drop of water flowing into the ocean is a waste and that the state should develop hydraulic infrastructure to capture as much water as possible for human use" (Wester, 2008). When capacity of the large strategic reservoirs in some areas exceeded average annual runoff volume by a factor of two (demonstrating an insufficient *physical examination* of the hydrometeorology), inter-basin transfers were constructed; though all this water infrastructure principally maintains supply to the large coastal cities and industrial areas, and formal irrigation areas (Medeiros & Sivapalan, 2020).

To preserve their own water supply, rural municipalities and smallholders have constructed countless small informal and unmonitored reservoirs; the most recent estimate by FUNCEME (*Fundação Cearense de Meteorologia e Recursos Hídricos*) is that there are 105,813 such reservoirs in Ceará state alone (FUNCEME, 2021). However, holding back water upstream exacerbated hydrological drought downstream (van Langen et al., 2021) and the perceived increased water security that reservoir construction provided may have led to further unsustainable water use. The impact of these small reservoirs would likely be unknown in any *physical examination* due to uncertainty over their number and capacity; only further *diagnostic testing*, such as through remote sensing analysis and numerical modeling, can show that their presence can extend hydrological drought by up to 80% (Ribeiro Neto et al., 2021). What's more, de Araújo and Bronstert (2016) demonstrated that the small informal reservoirs are an insufficient *treatment* for smallholders as they cannot buffer long-term droughts.

Diagnostic testing revealed that politics is a recurrent drought driver with studies claiming that government officials formerly withheld emergency response or profiteered through its provision (Herwehe & Scott, 2018). Bedran-Martins and Lemos (2017) described how "the drought industry" was not conducive to increasing resilience because drought-affected vulnerable rural populations depended on state-sponsored social programs to survive and politicians exchanged placement in these programs for votes. What's more, these programs addressed only the symptoms and not the causes of vulnerability so failed to build long-term resilience, and, because political survival depended on their votes, there was little incentive for politicians to reduce vulnerability. In 2014, the Drought Monitor (https://monitordesecas.ana.gov.br/) was implemented in Northeast Brazil. It is a map of current drought conditions, updated monthly, based on several drought indices. Drought conditions on the map dictate the deployment of water trucks to alleviate drought-induced water scarcity, thus depoliticizing emergency response. However, Martins and Magalhães (2015) noted that a time of political transition can still affect drought response in terms of public finance. In 2013, for example, the mayor who had assumed control of a *Sertão* municipality did not have access to the available resources to respond to the initial stages of the 2012–2018 drought in part because his predecessor had withheld pertinent information.

The impacts of droughts on smallholder farmers have been reduced by the implementation of policies that were not initially intended as strategies to reduce drought impacts but ended up benefiting the part of the population that was most affected. *Diagnostic testing* suggests that policies far from the water perspective play a role in reducing vulnerabilities. The nationwide social program to alleviate poverty by providing a minimum income, the *Bolsa Família*, is most effective at treating the worst drought symptoms particularly improving food security (Sena et al., 2018). The Brazilian Food Acquisition Program (PAA) seeks to promote the productive inclusion of farmers and guarantee the population's access to healthy food. In the context of drought, the PAA functions as a food safety net for vulnerable populations (Mesquita & Milhorance, 2019). The main objective of the Program for the Promotion of Rural Productive Activities (*Fomento*) is to stimulate the generation of work and income and promote food and nutritional security; it has helped to improve the adaptability of smallholder farmers (Mesquita et al., 2020). These *treatments* demonstrate that reducing vulnerability is more effective than treating symptoms.

From the water perspective, the greatest positive impacts to smallholder farmers are from the Cisterns program. This program is based on the construction of social technologies for rainwater harvesting, with positive impacts on food and water security for beneficiaries (Arsky, 2020; Fagundes et al., 2020), and with the potential to promote climate adaptation (Cavalcante et al., 2020). Cisterns represent the paradigm shift in Northeast Brazil toward "living with drought" (Arsky, 2020; Silva, 2003). Furthermore, the program is an example of how family farming innovations can be transformed into public policies, as through the action of civil society its dissemination has reached the level of national policy (Santana & Arsky, 2016).

The *treatment* of drought remains based on the traditional (mis)diagnosis prescribing improvement of infrastructure while drought policies remain short-term and uncoordinated—especially across the three administrative levels (federal, state, and municipal)—and very sector-oriented (Martins & Reis Junior, 2021). New basin transfer projects, such as the São Francisco Water Transfer, are under construction and were designed to guarantee current demand though there are already plans for new irrigation projects and to attract businesses to the region that may not be water sensitive (Roman, 2017). What is more, climate models project that the region will experience reductions in precipitation combined with increased evapotranspiration, ultimately suggesting an increased likelihood of droughts over the coming decades (Gondim et al., 2018). Without greater focus on managing demand and resolving issues of where the water will be brought, for what and for whom, the drought *prognosis* for Northeast Brazil is for vulnerability and exposure to increase.

3.4. Horn of Africa

3.4.1. Situation

The Horn of Africa comprises the arid to semi-arid region of the African continent that stretches easternmost into the Arabian Sea. We consider here the most drought-prone Horn of Africa region to include the entirety of Somalia and Djibouti as well as significant proportions of Ethiopia and Kenya (Figure 2). The region has a population of around 80 million with some of the highest population growth rates in the world at around 3%, equating to a doubling of population every 23 years (World Bank, 2020). There are significant differences between the countries in terms of Human Development Index, though all are ranked below 140 out of 180 countries (UNDP, 2020). The discrepancies are more pronounced in the ND-GAIN Country Index that summarizes a country's vulnerability to climate change and other global challenges: Djibouti ranks 117, Kenya 152, Ethiopia 157, and Somalia at 179 is the second most vulnerable country on Earth (ND-GAIN, 2018). Rainfall is sparse, generally under 500 mm per year, evapotranspiration is high due to temperatures averaging over 27°C, and water resources are generally ephemeral and unprotected (Ghebrezgabher et al., 2016). Rainfed agriculture and pastoralism provide livelihoods for the majority of the population though much of the region is unsuitable for agriculture and food is imported (Arcanjo, 2020).

Droughts in the Horn of Africa are increasing in frequency and severity (Nicholson, 2014). Consequently, drought-driven humanitarian emergencies are becoming more common where millions of people face chronic water and food insecurity (Thomas et al., 2020). Hardest hit in terms of preventable death and malnutrition are pastoral communities who number in the tens of millions comprising around 10% of Ethiopia's population, 20% of Djibouti's and 70% of Somalia's population, yet who have been politically marginalized since colonial times (IGAD, 2007; Thomas et al., 2020).

Compounding these droughts are land degradation and desertification caused by drought but exacerbated by overgrazing and other poor agricultural and land management practices often because people concentrated or were driven into drought-prone areas (Mengisteab, 2012).

In the last decade, the Horn of Africa has experienced almost continuous severe drought peaking in 2011 and 2017 with an easing of drought conditions during only 2012–2015 (Funk, 2020; Reliefweb, 2021). In Somalia, failed rains cause widespread crop losses and livestock deaths leading to famine and cholera outbreaks (Prinsloo, 2017). In Northern and Eastern Kenya, pastoralists seeing their livestock decline search for greener pastures and consistent water sources resulting in violent clashes between groups, rustling, and poaching of wildlife from national parks, which additionally impacts Kenya's tourism industry (Kioko, 2013). Ethiopia is synonymous in the public consciousness with the drought-induced famines of the 1970s and 1980s; still today, emergency food aid is a regular requirement due to the predominance of rainfed agriculture, which provides livelihood for 89% of the population and constitutes 39% of GDP (Gross Domestic Product, Kassawmar et al., 2018; Haile et al., 2019). Djibouti imports around 80% of its food (Qu et al., 2019) meaning it is less directly vulnerable to drought and also less indirectly affected by drought in the Horn of Africa causing food price rises because most food imports originate outside of the region (OEC, 2019).

3.4.2. Misdiagnosis

The same drought with the same hydrometeorological effects may be experienced across the Horn of Africa, yet the impacts are experienced very differently by each country and by each diverse group of inhabitants. Drought diagnosis and treatment must therefore be contextualized to different locations within the region. Although there have been successful efforts in the region targeting vulnerability, comprehensive drought diagnoses are lacking, resulting in pessimistic prognoses in the face of increasing droughts. That is, *initial diagnostic assessments* have been conducted and treatments developed, though not sufficiently comprehensively and collaboratively to increase resilience for all. Further research, that we would consider *diagnostic testing*, is sparser than for other areas of the world (see Table 2 and Kchouk et al. (2021)) and often reveals that the drought drivers include the previously prescribed drought treatments.

Although Ethiopia is considered the country with the highest population in Africa affected by drought, government initiatives such as cash/food-for-work programs, environmental rehabilitation, and sustainable intensification of agriculture have lifted millions out of poverty thus reducing vulnerability (Haile et al., 2019; Shiferaw et al., 2014). For example, the droughts of 2003–2004 and 2010–2011 were more severe and extensive than 1984–1985, but only that earliest drought saw tens of millions face starvation and around 750,000 deaths (Haile et al., 2019). Nevertheless, this vulnerability-reducing treatment was insufficient and comprehensive drought diagnosis is needed because recent droughts still required emergency food aid for millions. Combined government and non-governmental organisation (NGO) efforts in semi-arid Kenya involving sand dam construction, capacity building regarding soil and water conservation techniques, and diversification of agricultural practices have similarly decreased vulnerability to drought by improving water and food security as well as lifting people from poverty (Kairu, 2021). However, some say these programmes are anti-pastoralist, who have their own traditional drought coping strategies, forcing them from their traditional lands and into settled agriculture increasing their vulnerability to drought (Farah et al., 2003; Fratkin, 2014).

Regarding Somalia, while failed rains are blamed for drought impacts (Funk, 2020; Prinsloo, 2017), *diagnostic testing* could show that the real driver is the humanitarian situation the population find themselves in. Somalia is exceptionally vulnerable to natural hazards due to the millions of internally displaced persons (IDPs) living in destitute temporary camps after fleeing from conflict or migrating from areas where previous droughts and overgrazing have caused desertification and loss of livelihoods (Reliefweb, 2021). This issue spills over into neighboring regions. The low-middle income status and political stability of Kenya means it should be better able to cope with drought (Haile et al., 2019). However, in addition to dealing with its own food security during drought, there is the additional burden of over 250,000 Somalis residing in refugee camps within Kenya who fled famine and chronic insecurity in Somalia (UNHCR, 2021). In Ethiopia, Somali refugees number around 200,000, and this is combined with over 3 million Ethiopian IDPs who were displaced due to ethnic and border-based conflicts, as well as collapsed crop production and water resources following droughts, locust invasions and floods (Reliefweb, 2020). This displacement puts even greater pressure on scarce resources and exposes a greater number of vulnerable people. Djibouti also hosts IDPs as desertification makes life increasingly untenable in rural areas; informal settlements are appearing in wadi beds on the edges of Djibouti City that are vulnerable to flash floods that occur every few years (Nour Ayeh et al., 2014).

Drought diagnosis must consider the effects of humanitarian aid that has traditionally been used as a solution to drought in the Horn of Africa. In other words, research should consider the feedback arrow in Figure 1 concerning *information on accuracy, effectiveness, and side effects* of previous measures. In Somalia, the people most impacted by famine often do not receive food aid due to: conflict preventing access; long-term instability reducing the presence of donor agencies; armed groups and officials diverting aid elsewhere; and low-status groups lacking the social capital to access aid (Menkhaus, 2012). In the wider Horn of Africa region, it has been pointed out that emergency relief alone is insufficient unless it is supported by development to build drought-resilient societies (Muller, 2014). Emergency response solidifies vulnerabilities, to drought and other natural hazards, by increasing reliance on donor agencies and the government. It is criticized as being inefficient, ineffective, untimely and a disincentive to the sustainable use of natural resources because it does not promote self-reliance (Wilhite, 2000).

Another critical element for reducing vulnerability is a drought early warning system (EWS). However, the Horn of Africa lacks hydrometeorological observational data (Walker et al., 2016); conflict and political instability restrict access for monitoring of drought impacts; and EWS are only effective in saving lives when combined with currently lacking mechanisms for early actions (Muller, 2014). An additional impact of political instability is created by the transboundary nature of water resources. The Juba and Shebelle basins were the breadbasket of Somalia for decades until the fall of the government in 1990. Nowadays, the irrigation and flood prevention schemes have fallen into disrepair, local operational knowledge has been lost, and there are concerns that

Table 2
Synthesis of the Four Drought Case Studies

Case study	1. Initial diagnostic assessment	2. Diagnostic testing	3. Consultation	4. Communication of diagnosis	5. Treatment and prognosis
Cape Town, Western Cape, South Africa	Incomplete diagnosis suggested drought driven by rainfall deficit and insufficient reservoir storage capacity.	Insufficient	Insufficient	Successful communication during the crisis (countdown to Day Zero) led to water use reductions.	Incomplete diagnosis led to water use restrictions and plans for water supply augmentation. The prognosis is that these actions do not address the drought impacts experienced by the vulnerable.
	Agricultural water consumption increases (up to its quota) during droughts. Water infrastructure has not kept pace with the city's growth and is unsuitable for current (and future) climate.	Political ecology analysis uncovered the significance of water use inequality.	Involve disciplines beyond engineering and work with most vulnerable, particularly inhabitants of townships.	More focus could be given to prevention of excessive water use during non-drought periods.	Comprehensive and collaborative diagnosis indicates that treatment requires equitable and sustainable distribution of available water resources throughout society.
California, USA	The increasing demand for agricultural and urban water supply led to unsustainable water abstractions, particularly of groundwater during drought years.	Analysis showed that aquifers are depleting, the ground is subsiding, and aquatic ecosystems are declining.	Involved natural scientists and engineers from a range of disciplines.	Communication of the prognosis during drought periods has led to temporary reductions in domestic and agricultural water use.	The 2014 Sustainable Groundwater Management Act seeks to balance abstraction and recharge and sets minimum environmental flow legislation. Demand-side water use restrictions continue to be imposed during drought periods.
	Unsustainable water consumption driven by infrastructure augmentation. Anthropogenic drought drivers compounded by climate change-induced rainfall and snowfall deficit and heat.	Water rights and inter-state transfers negatively impact the underprivileged and ecosystems. Acknowledgment that California is a dry state.	Involve social scientists, economists, politicians, and affected communities and industries to strategize how to reduce unsustainable levels of water consumption.	Arid conditions and droughts projected to be "the new normal"; this must be candidly communicated along with implications for water use.	The water rights system and inter-state water transfer agreements should be revised to be more equitable and sustainable. Reducing water consumption will likely require substantial changes to agricultural practices (e.g., shifting away from water-intensive crops) and lifestyles.

Table 2
Continued

Case study	1. Initial diagnostic assessment	2. Diagnostic testing	3. Consultation	4. Communication of diagnosis	5. Treatment and prognosis
Sertão, Northeast Brazil	Incomplete diagnosis suggested that droughts are driven by rainfall deficit, limited aquifers, and previously insufficient though now excessive reservoir storage capacity.	Investigation of the politics of the region showed how it has contributed to preserving vulnerability.	Involved mostly institutions concerned with water management, thus responses generally related to augmenting water supply.	It is challenging to utilize the Drought Monitor data to inform policy- and decision-making.	Incomplete diagnosis led to water supply augmentation (more reservoirs, basin transfers) and emergency response (water trucks, temporary jobs, crop insurance). In the past, vulnerabilities were preserved by paternalism and clientelism.
	Droughts are projected to worsen and there is uncertainty over which sectors, where, and to what extent, will benefit from new inter-basin water transfers.	Downstream water users impacted by small informal reservoirs upstream. There are beneficial impacts of policies unrelated to drought but aimed at reducing vulnerabilities.	Involve different expertise for example, social development, agriculture, health, public policy, climate change, and local actors to contribute to reducing water use conflicts.	Communication of diagnosis should be multi-level to all actors and sectors aiming to produce timely information for decision-making before drought impacts occur.	Requires expansion of non-water-related approaches to reduce exposure and vulnerability. Policy coordination and collaborative agreements needed across scales and long-term (considering climate change) for water allocation regarding new inter-basin transfers and for managing water demand.
Horn of Africa	Incomplete diagnosis considers drought drivers to be failed rains, reliance on rainfed agriculture, desertification, and poverty.	Insufficient	Insufficient	Insufficient	Existing measures to reduce vulnerability and provide humanitarian aid are insufficient and inequitable; the prognosis is that the most vulnerable will continue to be most severely impacted.
	Important drought drivers also include conflict, political instability, and numbers of displaced persons especially those in temporary camps.	Should consider societal impacts of humanitarian aid, transboundary cooperation, and environmental rehabilitation.	Include both the most vulnerable, particularly pastoralists, and top-level government ministers and international mediators.	Increase drought monitoring and establish drought early warning system. Ensure the early warning and subsequent actions reach most vulnerable.	Comprehensive and collaborative diagnosis would likely indicate that treatment requires reversal of environmental degradation, conflict resolution, and political cooperation.

Note. For each case study, the traditional or historic misdiagnosis or incomplete diagnosis is presented above the dashed line and a direction toward comprehensive drought diagnosis is presented below.

upstream irrigation schemes constructed in Ethiopia adversely affect water availability in Somalia though there was no government in Somalia to engage with during their planning (Reliefweb, 2016).

Drought prevention and mitigation in the Horn of Africa requires substantial improvement to the health of the system rather than the current practice of inequitably distributed development and emergency relief. Treatment must involve decreasing the number of vulnerable people. *Diagnostic testing* would likely show the need to reverse environmental degradation, find political solutions to the ongoing conflicts, subsequently improve cross-border collaboration to better manage transboundary water and pasture resources and population displacements, reduce reliance on rainfed agriculture, and increase the density of hydroclimate monitoring.

3.5. Synthesis of Drought Case Studies

Table 2 synthesizes the case studies showing how the five steps of the drought diagnostic process have been incompletely conducted or omitted. The table also suggests how a comprehensive and collaborative drought diagnosis could lead to improved treatment and drought prognosis. Despite the differences between the case studies, a principle similarity in all cases is the need for societal changes, mostly involving equitable distribution of water resources and rights, conflict resolution, and reducing the number of exposed and vulnerable livelihoods.

4. Discussion

The drought case studies illustrate that even though drought diagnoses have been conducted by researchers and authorities to varying extents and solutions have been proposed, drought impacts are very likely to re-occur. Until the drought diagnoses more comprehensively consider the full range of water users, their drought histories including the causes of their vulnerabilities, the full range of drought impacts, and then collaboratively work toward contextualized solutions, we will continue to see drought impacts felt most keenly by the most vulnerable.

The four case studies presented are representative of other drought-affected areas. Cape Town is not the only city that has faced a "Day Zero" in recent years: São Paulo in 2015 was without water for 12 hr a day, forcing the closure of many businesses and industries (Robins, 2019); Chennai in 2019 resorted to delivering 10 million liters of water per day by train from a reservoir 360 km away, though it only fed the city's piped water system to which the poorest do not have access (Trivedi & Chertock, 2019), and; Istanbul in 2021, with its reservoirs at below 25% capacity, had the government resort to "pray for rain" ceremonies (McKernan, 2021). California is not dissimilar to other high-income regions, such as southeast Spain and southeast Australia, where droughts, heat waves and wildfires are becoming the new climate change-induced normal and policymakers attempt to balance agricultural and environmental water needs (Cramer et al., 2018; Steffen et al., 2019). Brazil is akin to other large countries, such as Mexico, China and India, all of which perceive the solution to drought to be inter-basin transfer mega-projects delivering water from their wet regions to their drought-prone regions, often at great (and arguably unsustainable) economic and environmental cost (Shumilova et al., 2018). Finally, there are other parts of the world like the Horn of Africa where the same drought affects millions of people across numerous countries. For example, parts of Central Asia and the Middle East similarly have great discrepancies in wealth and drought coping strategies between constituent countries, conflict-driven agricultural disruption and populations of IDPs, and poor records in cross-border cooperation and pro-environmental policies (Mosello, 2008; Sowers et al., 2011). The fact that droughts in these additional examples regularly make the news (PreventionWeb, 2021) suggests that they could also have been used as misdiagnosis case studies.

The aim of this study is not to present a drought assessment methodology to replace existing guidance concerning the three pillars of drought management and conducting drought risk assessments. Rather, the aim is to build on that guidance. We present a complementary methodology encouraging greater interdisciplinary and multi-actor collaboration leading to more comprehensive diagnosis for improved and contextualized solutions. Drought management plans are generally considered to have three components: 1. Monitoring and early warning; 2. Risk and impact assessment, and; 3. Mitigation and response. The diagnostic steps presented in Section 2.2 show that drought diagnosis contributes to the second and third pillars: *risk and impact assessment* to enable more effective planning of *mitigation and response*. Additionally, while drought *monitoring and early warning* has received a lot of attention, drought indicators and indices are mostly restricted to hydrometeorological anomalies with little incorporation of drought impacts in the monitoring (Bachmair et al., 2016). Therefore, the comprehensive and collaborative analysis of contextualized impacts means that drought diagnosis can contribute to this first pillar of drought management planning by guiding selection of indicators for *monitoring and early warning* of vulnerability to drought impacts, that is, to provide early warning of vulnerabilities so that they can be addressed prior to drought occurrence. It is deliberate that *an evaluation and history of drought impacts* is the first step in the diagnostic process—in the same way that a patient would firstly explain their symptoms—to emphasize that drought diagnosis is coproduced with affected stakeholders for the purpose of preventing their drought impacts.

The key principles referring to the title of this article, "what the medical sciences can teach us" are:

1. Diagnosis is focused on finding a treatment, that is, drought diagnosis should be solutions-oriented rather than aimed at increasing understanding only.
2. The starting points of a diagnosis are the symptoms and the patient's history, that is, acknowledgment that drought is not a water problem, it is a society problem.
3. The emphasis on being patient-focused translates to the need for participatory methods and coproduction of a diagnosis with stakeholders.
4. The *diagnostic testing* and *consultation* steps encourage interdisciplinarity and consideration of broader drought drivers and actors not traditionally incorporated into drought assessment.
5. A systematic approach should be followed when conducting a diagnosis in order not to overlook any impacts, causes, and potential treatments.
6. The unique combinations of causes and impacts require patient-specific (contextualized) treatment.

Our proposed approach complements though goes further than existing IDMP guidance by emphasizing the need to look beyond hydrometeorology. In addition to water management interventions, options for dealing with drought could involve programmes focusing on agriculture, education, financial support, conflict resolution, and so on, or other initiatives that focus on causes of drought impacts rooted in inequality and injustice regarding access to water and user rights. The approach is in accord with the #NoNaturalDisasters movement: "… whilst some hazards are natural and unavoidable, the resulting disasters almost always have been made by human actions and decisions," which was recently supported by the United Nations Office for Disaster Risk Reduction (UNDRR) through the Sendai Framework (UNDRR, 2021a). The approach also responds to the "call to action" that concludes the recent UNDRR Special Report on Drought (UNDRR, 2021b). Our diagnostic process accordingly provides a "new tool for risk-informed decision-making" aiming to "better understand the causes of vulnerability that are a function of human agency," "draw on the long history of research and practices within the DRR community together with knowledge enshrined in traditional and indigenous wisdom," "allow iterative learning and innovation [in drought management]," and "build enabling conditions for the transition to drought-related, systemic risk governance." In agreement with the recent IPCC (2021) report, proposed solutions may be grand and difficult to enact but the consequences of inaction on society and ecosystems will be significant. Notwithstanding the medical analogy, this is also akin to a systems approach and the discipline of sociohydrology in accepting that we are part of complex dynamic and interacting systems and must look for long-term solutions (Clayton & Radcliffe, 2018; Sivapalan et al., 2012). This is not to say that our diagnostic approach is only applicable at large spatiotemporal scales; it would be equally applicable at municipality and village scales where *treatments* with immediate benefits could be identified. Indeed, we would argue that multi-scale assessment and multi-scale treatments are fundamental for drought risk reduction.

Medical diagnosis typically involves the same medical professional conducting the diagnosis and prescribing the treatment. With a drought diagnosis, it is uncertain who the doctor is. This is another reason why drought is a complex issue because there is no logical single person (or discipline or group), analogous to a general practitioner or family doctor, to conduct a drought diagnosis. The diagnostic process presented here therefore aims to guide the various specialists, be they researchers, NGOs, politicians, water managers, disaster managers, or water users.

A drought diagnosis on the other hand may be conducted by researchers who then advise others who will make decisions on treatment (ideally it would be conducted together). Therefore, it does not necessarily require a misdiagnosis or incomplete diagnosis to result in incorrect treatment; a comprehensive and contextualized drought diagnosis with appropriate solutions may not be acted upon, for example, for cost, political, or cultural reasons. Unfortunately, the medical sciences teach us that patients can disbelieve diagnoses and solutions (consider vaccinations), ignore warnings (e.g., smoking), or decide that no action is a better option (e.g., terminal patients). Just as medical patients are entitled to accept or refuse treatment, drought-affected stakeholders may also choose not to comply with drought preparedness, adaptation or mitigation solutions. Simply because it is not in their own personal short-term or long-term interest, when there is competition over resources for instance. There could similarly be tension between individual and collective interests: a medical doctor usually advises a single patient with one single interest whereas a drought-affected region includes large communities of affected individuals with conflicting interests. Assuming that all stakeholder groups are represented, because drought is about a scarcity, drought treatment and prevention are often about how to distribute this scarce good. Ethical considerations are thus unavoidable: Who gets what at the expense of whom? Is the aim to minimize suffering (following Bentham's principle, and then, what is considered suffering?) or minimize economic loss? Even if a drought diagnosis could be thoroughly comprehensive, in terms of information and actors, distributing a scarce good means disappointing some and making ethical choices. The question of who has the legitimacy to make this choice also remains unanswered in the field of medicine. An analogy is providing a very expensive treatment to one person, at the expense of many cheaper treatments to many others; is this the decision of the doctor or is this legislation?

The *consultation* step of the diagnostic process, and the emphasis on the process being collaborative, are therefore crucial. Drought diagnosis and subsequent treatment should be coproduced by an interdisciplinary team of drought researchers, the policymakers and decision-makers, and representatives of the full range of actors and drought-affected stakeholders. Participatory methods that incorporate the expertise and perspectives of all interested groups should lead to building of mutual trust, confidence, and respect (Walker et al., 2021), resulting in appropriate and acceptable drought treatment for all those involved.

5. Conclusions

Using analogies with medical sciences can be helpful toward comprehensively diagnosing droughts for a variety of contexts. Identifying misdiagnosis and assessing the effectiveness of proposed interventions (treatment, prognosis) could help drought managers be more proactive and help drought-affected regions become more drought-prepared in the future. The proposed approach for drought diagnosis provides a conceptual framework to support scientists and policymakers to go beyond existing guidance for achieving integrated drought management objectives.

Data Availability Statement

This paper utilizes existing published material and does not analyse any new data.

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