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Drought and groundwater management: Interconnections, challenges, and policyresponses

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Abstract

Droughts have severe impacts on the economy, society, and environment. They also have impacts on groundwater and vice versa. While most analyses consider drought and groundwater as disconnected, we argue that drought and groundwater management should be conjunctively considered. This article presents some key interconnections, identifies challenges, and discusses illustrative policy responses. We highlight several advancements found in international scientific research and describe future directions for drought and groundwater management. While many technological innovations have improved our understanding of drought and groundwater's complex nature, policy and governance advances have not kept pace.

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Drought management, Groundwater management, Water governance, Drought policy, Groundwater policy.

Introduction

Though droughts are a normal part of the hydrologic cycle, their frequency and severity are increasing. Droughts can cause severe socioeconomic, environmental, and political impacts, especially for arid/semi-arid regions that are highly vulnerable to consequences of groundwater overdraft [1–5]. Conversely, groundwater management affects droughts in many ways, with emergency strategies often deployed (e.g., drilling more wells) that can exacerbate groundwater depletion [6]. Aridification is likely to increase, and droughts are likely to be worsened, due to climate change [7]. Therefore, users need a greater understanding of how to appropriately manage drought and groundwater [3,8]. As the 2022 United Nations report states, groundwater has vast potential and attention must be paid to its careful management [9].

Certainly, decision-makers, water users, and scientists have discovered new innovations for understanding and managing groundwater in drought conditions [10]. For instance, the European Groundwater Directive (2006/118/EC) has been designed to complement the more comprehensive 2000 Water Framework Directive (WFD), which was established as an integrated water management approach [11].

However, drought and groundwater management tend to be considered separately and not as an integrated system. While advances have been made in several areas – from new indicators to specific strategies like managed aquifer recharge – it appears that governance advancements lag for drought and groundwater.

This need for greater understanding of drought and its direct connection with groundwater does not appear to correspond with the availability of published research. We did not find an extensive published literature that links drought and groundwater. In this context resides the value of our contribution.

This article's primary purposes are thus to 1) share recent contributions about the conjunctive analysis of drought and groundwater management and 2) synthesize recent innovations and highlight gaps and opportunities in characterizing, managing, and governing groundwater. We closely examine major systemic interactions involved with classifying drought and groundwater, interrelated impacts of drought, governance measures, policy responses, and future challenges (Figure 1). It should be noted that there are multiple feedbacks between these elements within a single water system, with climate change further complicating the system. We begin with a discussion of our methodology. Next, we describe major interactions between drought and groundwater. We then discuss selected management and policy responses like data and modelling tools, recharge and conjunctive management between surface water and groundwater. Special attention is given to governance and economic instruments. Finally, we share our outlook for major challenges, followed by brief conclusions.

Materials and methods

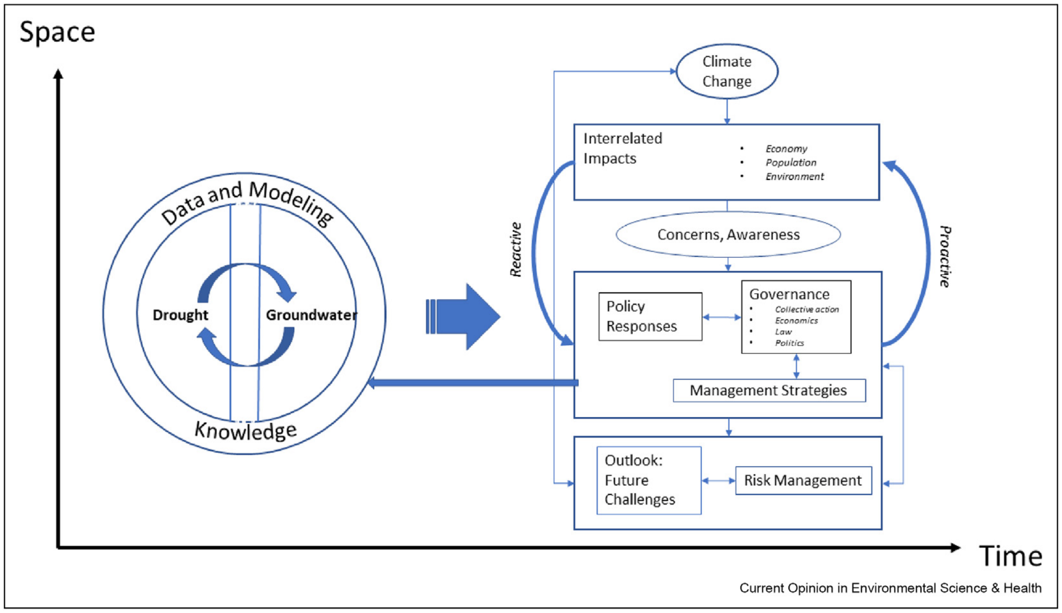
First, we relied on our own knowledge of the literature focusing on drought and groundwater. Based on this, we chose to analyze drought and groundwater conjunctively. An important component of our methodology was a search using Scopus and Google Scholar for articles published since 2019 using the terms “drought” and “groundwater management”. From an initial list of over 250 articles that we carefully examined, we chose 68 that exemplify, more directly, current literature themes in drought and groundwater management. We excluded non-open access articles and book chapters.

To strengthen our search, we conducted a further search of articles focused on “drought management and groundwater management” in January 2022. Surprisingly, only 23 articles were published from 1990 to 2021 according to a Scopus article title search (and only six in an open access format). We also conducted a Scopus search for the terms “drought management” and “groundwater management”. While this search revealed a much larger collection of documents, most did not directly concern the connection between drought management and groundwater management. We aimed for international geographic diversity. Next, we organized findings based on several themes prominent in the literature on drought and groundwater management. These themes are structured around the characterization and interconnected impacts, which includes advances in measurement, monitoring and modeling - as well as current and potential challenges. We gave policy responses special attention, and within this the case of governance and economic instruments. It is worth highlighting that this organization is our own and is not comprehensive. There are, surely, rich contributions in other languages like Spanish and French that are not incorporated. On top of these disclaimers, our article is limited by length. Despite these limitations, we believe our work contributes to the current understanding of the major science and policy issues related to drought and groundwater. We detail our findings below.

Characterization and interconnections between drought and groundwater

Recent research demonstrated how drought and over-abstractions can significantly impact groundwater level recovery and groundwater quality long after droughts occur. Linking groundwater modeling with drought

Figure 1



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Analytical framework. Source: Authors.

policy is needed to improve water management. While plenty of data on groundwater and drought exist, some data are at the wrong scale and needs to be linked to other proxy data and/or downscaled. This is part of taking a systemic approach to improve drought predictions and preparations.

Researchers have utilized several indicators to better understand various characteristics of hydrological drought on groundwater and that of groundwater deficits, including groundwater levels [12,13], impacts of exploitation [12,14], land management [15,16], and crop management [15,17]. Drought can slow groundwater level recovery in agricultural areas compared to forested areas [12]. Abstractions, particularly at rates that exceeded natural recharge, can prolong groundwater deficits [14], decrease streamflow [18] and impact long-term water storage [19]. Groundwater deficits can be better managed through increasing the areal coverage of fallow land, crop type choices [15], irrigation types [17], and monitoring irrigation water use [20]. Much research has been recently published (e.g. Refs. [19,21–24]) on linking data from the Gravity Recovery and Climate Experiment (GRACE) with other remote sensing data and models to measure changes in underground water storage. While GRACE data can be effective for determining how large-scale agricultural pumping negatively impacts long-term groundwater storage [19,22] and land subsidence [25], its coarse resolution requires linkages with other small-scale remote sensing techniques and models [19,23–27]. Interferometric synthetic aperture radar (InSAR) has also been employed for characterizing land subsidence caused by groundwater depletion [28].

A firmer inclusion of groundwater modeling into drought policy is essential for more effective water systems management (see also the EU Groundwater Directive [11]). Modeling innovations include the linkage of aquifer responses with decision-making [30,31] and distinguishing the effects of hydrologic deficits and overexploitation [13,32]. Linking groundwater modeling with crop water modeling in data-scarce situations has been explored to address water-food linkages [30] and actual evapotranspiration loss [33]. Other scholars linked model outputs with drought indices [13] and downscaled global climate model projections to understand future aquifer impacts [34].

Droughts can significantly impact groundwater quality and vice versa. Recent studies have found post-drought increases in nitrate concentrations [35] and increases in certain redox-sensitive ions and metals [36]. Groundwater quality can also help determine the suitability for best agricultural practices in drought-prone regions [37]. Droughts, coupled with over-abstractions, can lead to adverse human health outcomes for groundwater-dependent populations [38,39]. In some locations (e.g., India, Italy, Mexico), poor rural families are forced to rely upon groundwater with concentrations of arsenic that increase during drought and exceed international health standards [40–42]. New methods include employing a signal analysis technique to understand groundwater deficit risk and vulnerability [43] and using reactive transport models for groundwater quality management and drought mitigation [44]. Other novel methods included linking turnover time with groundwater's vulnerability to pumping [45] and groundwater pollution risk [46].

Given the long-lasting impacts that drought may have on groundwater, predicting future droughts, identifying future uses and management priorities are all necessary. Drought management is difficult given that its very definition is dependent on several hydrological and societal factors [47,48]. More long-term data [49] are needed to improve our understanding of droughts and groundwater management. This data can be used for improving predictions of drought through synthesizing multiple hydrometerological forecasting products [50] and linking large-scale climate systems and their teleconnections with local and regional rainfall [51]. Machine learning for predicting hydrological variables (such as groundwater levels) may also be employed soon [7,52,53]. Technological advances have allowed for greater understanding of long-term groundwater quantity and quality trends connected with drought. Yet a greater linkage with other data and policies are needed.

Management responses

Following Varady et al. [54], water management is understood as the actions for implementing policies, laws, and decisions. Management innovations have manifested through linking surface water and groundwater, connecting water and energy, increasing water efficiencies, and improving managed aquifer recharge (MAR) based on location and timing. Yet the lack of integrated, systems-level management continues to limit overall efficacy of policy responses.

Conjunctive surface water-groundwater management has been widely cited in the literature for buffering supplies in times of drought [1,31,55–60]. The conjunctive approach comes also from the perspective of drought management itself [9,29]. One novel proposal was to conjunctively operate a surface reservoir and subsurface dams to address drought severity in South Korea [59]. Fully coupled hydrologic models have been built to analyse conjunctive management under drought conditions, allowing for minimizing reservoir deficits while introducing a recovery time for groundwater levels [61].

Managed aquifer recharge (MAR) is becoming more prevalent worldwide to improve groundwater security

[62], including drought-prone regions in Australia [63], Iran [64], and the US [65]. Researchers have investigated and proposed specific effective management strategies like using flood flows for recharge and irrigation and developing groundwater reserves for droughts [3,6,30] depending on how droughts propagate [51]. Emerging research themes include identifying best locations for recharge, determining which techniques are most effective, and using MAR as part of conjunctive management [65]. Pathways for studying locational factors have included the determination of critical factors for successful recharge, including the adopted infiltration area [64,66,67], implementation time frame [66,68], and whether infiltration or injection is more effective [63]. Linking surface water and groundwater management through conjunctive management and MAR continues to grow in use as techniques become more sophisticated and creative. Yet, the localized approach to implementing these techniques could prove to be insufficient as climate change continues to worsen drought severities.

Governance and policy

Though certain advances in groundwater governance, management, and economics have been made, including through collective action efforts, compensation schemes, and stakeholder involvement, many issues surrounding drought management and groundwater are related to gaps in governance. There is a need to include drought policies in long-term planning efforts and gather more data to effectively apply economic tools.

Governance can be defined in this context as actors (not only governments) designing and applying policies [69] through institutional contexts with a normative foundation [70]. Similarly, groundwater governance has been defined as the overarching framework of groundwater laws, customs, and regulations, as well as stakeholder engagement processes [71]. While scientific advances are clear in some transboundary groundwater basins, like in North America [72,73], emerging problems of groundwater insecurity are linked to governance gaps. Groundwater management and politics are also interrelated through income and power disparities, as is shown in the case of the San Joaquin Valley (US) [74] and in southeastern Spain [60]. The Angas Bremer irrigation district (Australia) is a rare example of local collective action towards groundwater management [75]. Not surprisingly, in many regions of the world the complex nexus between droughts and groundwater is not part of national proactive policies or is insufficiently enacted in development planning and legislation [4,76,77].

Increased pressures on groundwater have created the need for novel adaptation strategies. Innovative adaptations include employing a trade-off frontier framework linking clean energy, drought resilience, and groundwater sustainability [78]. Various adaptation measures can be enacted dependent on drought severity [76,79]. Oftentimes, such as in California's Central Valley (US), smaller, domestic wells are much more vulnerable to drought duration as unsustainable management favors larger, agricultural users [79]. Arguably, drought imbalances could be addressed through compensation schemes that consider the opportunity costs of water use [80].

Economic policy tools generally have had limited influence towards more comprehensive drought management and sustainable groundwater use but should play a more significant role. This is true even in regions like the European Union, where the pricing mechanism is stated as a central piece of the WFD [11]. The application of sound economic instruments is, however, not without problems. Using economic tools requires the collection of good data on water uses, water rights, and prices [81]. Effective metering for all uses is a prerequisite for the application of economic tools [29,58]. With limited or non-existent control of well permits, as well as inadequate pricing structures for surface and groundwater, there are few incentives for water efficiency and conservation [3]. An inadequate pricing system may also explain low awareness in many places of the world where water is still regarded a free commodity [81]. A systematic approach, involving the participation of local stakeholders, is important for managing groundwater resources [82,83].

Regarding the economics of agricultural groundwater extractions versus extractions for domestic wells, Stone et al. [80] present illustrative findings derived from Tulare County in California (US). Using a welfare maximizing approach, they found that limiting depth to groundwater is not an effective policy because agricultural opportunity costs far exceed domestic well costs. Enforcing regulation and negotiating among water user groups has transaction costs (see also in Jordan [76]). Though the awareness of the need for sound groundwater governance, policy, and management is growing [84], many gaps remain unfilled. More policies need to be enacted and tested for effectiveness.

Outlook for drought and groundwater management

The outlook for drought and groundwater management is very challenging and will require crafted knowledge and coherent policy responses [3,7,72]. Scientific understanding will be needed to inform and guide decision making, and thus reduce management uncertainties, using more multidisciplinary approaches [48,57] and complex systemic models of water reallocation [7,31]. It is thus essential to better understand decision-making processes for climate change preparedness [75] as there is no mechanism to optimally extract water during drought conditions [31]. Given the slow movement of groundwater, anthropogenic impacts may last for a relatively long time. Surface water interconnections imply that deteriorated groundwater quality will eventually adversely affect surface water quality, thereby reducing water availability [11]. In the European context it is recognized that the economic assessment of drought impacts is complex and under-researched [85]. As shown in the Asian experience, greater recognition and understanding of political economy issues will be needed [56].

The combined threat of droughts and stricter groundwater regulations will force hard choices on all (especially agricultural) users and decision makers [47]. This uncertain climate and regulatory context call for diversifying water sources and crop choices (see California's Central Valley, US [2]). Diversification and demand may increase the transfer of rural water to cities and strengthen the need for well-crafted agreements [60,86] and regulations despite associated economic costs [1,87]. Groundwater will likely be exploited in new locations, such as sub-Saharan Africa [88]. Part of the challenge in these areas will be establishing isotopic baselines to understand groundwater quality dynamics [89] and determining the suitability of groundwater for best agricultural practices in drought-prone regions [37].

Groundwater management is at the interface of drought and flood policy [29,90], although policymakers do not always see these interconnections until there is a crisis. Monterrey's (Mexico) experience shows that building urban resilience to droughts requires focusing on interconnections between droughts, floods, groundwater, and surface water [81,91].

Though several advancements highlighted above will undoubtedly aid managers in this task, political commitment and long-term planning are critical for a challenging future. The issue of finance deserves special attention in this perspective [92]. A key issue is fostering productive cooperation while incorporating local context [69,72,77,93,94].

Conclusions

Our review of the recent literature confirms the crucial and timely relevance of focusing on drought and groundwater management. The review highlighted the need for both a greater understanding of their interconnected impacts and a long-term, systemic perspective. The latter considers varying and complex spatial—temporal characterizations with multiple, overlapping jurisdictions. These characterizations include using remote sensing data to understand changes in storage, linking data for understanding drought, and modelling to link water, food, and policy decisions. While these technologies have helped scientists make great progress on understanding relationships between drought and groundwater management, much is left to be discovered.

Groundwater quality and management techniques have seen advancements. Poorer groundwater quality resulting from droughts and impacts to human health has been further explored. New adaptation measures have been developed and tested, particularly in the areas of MAR and conjunctive management.

However, more holistic, long term, proactive, risk-based policy responses are needed. Too often, reactive emergency measures are commonly implemented through restricting water distribution, rationing, and/or scarcity pricing. Structural, supply-led responses may only exacerbate current problems. Mitigation strategies are oftentimes not reflective of true water scarcity and the negative environmental externalities, in addition to strong political opposition from powerful parties. There is space for economic non-market valuation, with a particular focus on the quantification of costs and benefits. Ultimately, managing drought and groundwater is at the interface of sound economics and political commitment.

Given the fundamental necessity of drought and groundwater management, science-based evidence must be incorporated into public policy. Governance for drought and groundwater should be tailored not only to local conditions but also to governance settings [81]. In these complex landscapes, informed risks will be essential for well-crafted policy design and implementation [95], especially in the context of climate change [96]. Last, but not least, there is the pressing need to find better ways to communicate groundwater issues during droughts. The international experience [5,48,57,97,98] shows that educating and communicating groundwater issues in droughts are crucial and challenging tasks.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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