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Key Points:
- *Anthropogenic drought* is primarily governed by the joint impacts of natural renewable water variability, climate change, and human decisions
- *Anthropogenic drought* and water bankruptcy will become more ubiquitous under current development and climate change trajectories
- Ideally, human interactions should be incorporated in models that include land-atmosphere interactions, water balance and energy balance

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Anthropogenic Drought: Definition, Challenges, and Opportunities

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Abstract Traditional, mainstream definitions of drought describe it as deficit in water-related variables or water-dependent activities (e.g., precipitation, soil moisture, surface and groundwater storage, and irrigation) due to natural variabilities that are out of the control of local decision-makers. Here, we argue that within coupled human-water systems, drought must be defined and understood as a *process* as opposed to a *product* to help better frame and describe the complex and interrelated dynamics of both natural and human-induced changes that define *anthropogenic drought* as a compound multidimensional and multiscale phenomenon, governed by the combination of natural water variability, climate change, human decisions and activities, and altered micro-climate conditions due to changes in land and water management. This definition considers the full spectrum of dynamic feedbacks and processes (e.g., land-atmosphere interactions and water and energy balance) within human-nature systems that drive the development of *anthropogenic drought*. This process magnifies the water supply demand gap and can lead to water bankruptcy, which will become more rampant around the globe in the coming decades due to continuously growing water demands under compounding effects of climate change and global environmental degradation. This challenge has de facto implications for both short-term and long-term water resources planning and management, water governance, and policymaking. Herein, after a brief overview of the anthropogenic drought concept and its examples, we discuss existing research gaps and opportunities for better understanding, modeling, and management of this phenomenon.

Plain Language Summary This article reviews research and progress on the notion of *anthropogenic drought* broadly defined as drought events caused or intensified by human activities. Most commonly used drought definitions are based on deficit in hydrologic/meteorologic drivers such as precipitation and runoff. Within coupled human-water systems, however, drought must be defined and understood as the complex and interrelated dynamics of both natural and human-induced changes. This *anthropogenic drought* definition considers the full spectrum of dynamic feedbacks and processes (e.g., land-atmosphere interactions and water and energy balance) within human-nature systems. Ideally, *anthropogenic drought* and the corresponding human interactions should be incorporated in models that include land-atmosphere interactions, water balance, and energy balance. In this article, we review

existing research gaps and opportunities for better understanding, modeling, and management of this phenomenon.

1. Introduction

Natural climate variability governs how much water can be expected at any given location in the absence of human modifications of the availability and flow of water. Some 6,000 years ago, Lake Mega-Chad in northern Africa was the largest freshwater lake in the world that was once the size of modern-day Germany. This water body now exists as today's Lake Chad—about a thousand times smaller than the original lake (Armitage et al., 2018b). This is an example of a relatively rapid and dramatic change in regional freshwater resources due to natural climate variability. However, natural climate variability is not necessarily the primary driver of the observed variability in water availability, water stress, or environmental changes in the *Anthropocene* (Apurv et al., 2019; Cayan et al., 2010; Diffenbaugh et al., 2015; Kwon & Lall, 2016; Lewis & Maslin, 2015; Lewis et al., 2011; Nazemi et al., 2017; Steffen et al., 2011; Van Loon et al., 2016a). In many places around the world, water stress and environmental changes are now driven by human activities and therefore are "anthropogenic" in nature (AghaKouchak et al., 2015; Alian et al., 2019; Barnett et al., 2006; Breyer et al., 2018; Di Baldassarre et al., 2017; Loucks, 2015; Madani, 2014; Nazemi & Wheater, 2015; Sivapalan, 2015; Wheater & Gober, 2015). For instance, several recent drought events in California (Diffenbaugh et al., 2015), Spain (Van Loon & Van Lanen, 2009), Brazil (Silva et al., 2015; Van Loon et al., 2016a), China (Jiang, 2009; Qiu, 2010; K. Xu et al., 2015), and southern Africa (Yuan et al., 2018) are largely attributed to a suite of human activities, including urbanization, deforestation, surface water and groundwater overdraft, and human-induced climate change (S. Ashraf et al., 2019; Schewe et al., 2014; Vicuna & Dracup, 2007; Wood et al., 1997; Yuan et al., 2017).

Since the mid-nineteenth century, population growth along with major industrial and agricultural developments have increased both water consumption and exposure to droughts, which have consequently translated into escalating costs of major drought events (Di Baldassarre et al., 2018b; Etienne et al., 2016; Güneralp et al., 2015; Kreibich et al., 2019; Liu et al., 2018; Marengo & Espinoza, 2016; Wilhite et al., 2007; Winsemius et al., 2018), and catalyzing societal tensions and political unrest (Nazemi & Madani, 2018). Traditionally, drought classification schemes include meteorological drought (deficit in precipitation), agricultural drought (soil moisture deficit), hydrological drought (deficit in surface water, storage, and/or groundwater), and socioeconomic drought (deficit in water-dependent economic goods and agricultural products leading to societal impacts) (Dai, 2011; Dracup et al., 1980; A. K. Mishra & Singh, 2010; Wilhite & Glantz, 1985). More recently, this traditional classification has been expanded to include ecological drought (i.e., impacts of drought on ecosystems; Crausbay et al., 2017; Slette et al., 2019), human-induced and/or human-modified hydrologic drought (Van Loon et al., 2016).

While the different classifications of droughts offer innovative perspectives about the disparate impacts of drought, these definitions generally treat drought as a *product* rather than a *process*. This product-focused approach typically quantifies, predicts, and projects deficit in water-related variables or water-dependent activities (e.g., precipitation, soil moisture, water surface storage, groundwater, grains and energy generation) due to natural and climatic variabilities. As a result, these definitions: 1) do not consider the two-way interactions (i.e., feedback relationships) of human activities with changing drought, water stress risk, and/or micro-climate conditions; 2) do not address the compounding effects of human-induced climate change with local water and land management practices (Dale, 1997) within a coupled human-nature system; and 3) do not account for water stress impacts on the environment, particularly beyond temporal and spatial domains in which a particular drought occurs (Crausbay et al., 2017).

Due to the magnitude and extent of anthropogenic alteration of the hydrologic cycle, many regions around the world face perpetual water shortage conditions because of the large imbalance between water supply and demand such that water shortage, the main consequence of drought, exists even during wet years. The existing *product*-oriented definitions of drought cannot fully capture such conditions and explain their dynamics to provide policy and management insights. With an increasing appreciation for the fact that water problems cannot be fully understood by excluding humans from hydrologic systems (Madani & Shafiee-Jood, 2020), we argue that within coupled human-water systems, drought must be defined and understood as a *process* as opposed to a *product*. Understanding drought as a multidimensional, multiscale phenomenon characterized by compounding processes that involves feedbacks between human and nature, provides new insights that will be useful for planning and management of water resource systems. This paper adopts a *process*-based approach to describe anthropogenic drought (AghaKouchak, et al., 2015) as a phenomenon that can lead to *water bankruptcy* in the coupled human-water system (Madani, 2019; Madani et al., 2016), and expected to become more ubiquitous in the coming decades under current development trajectories and climate change patterns (Borgomeo et al., 2014).

We note that integrating human activities/decisions in drought studies is not a new topic. Water resources scholars have produced a large body of literature on the impacts of human activities on local water availability and management (e.g., Alborzi et al., 2018; B. Ashraf et al., 2017; Castelletti et al., 2008; Garcia et al., 2019; Herman et al., 2015, 2016; Simonovic, 1992; Sivapalan et al., 2012; Srinivasan et al., 2018; You & Cai, 2008; Boelens et al., 2016; Di Baldassarre et al., 2015; Montanari et al., 2013; Wesselink et al., 2017). Also, droughts are increasingly being studied from an impact perspective (Blauhut, 2020; Hagenlocher et al., 2019) considering not only the risk but also societal exposure and vulnerability (e.g., Blauhut et al., 2016; Carrão et al., 2016; Meza et al., 2020). In this article, we attempt to bring together relevant ideas from different communities together with a focus on the human dimension of drought, highlighting the progress, research gaps, and opportunities ahead.

1.1. Anthropogenic Drought: The Two-Way Interactions of Human Activities and Drought

Anthropogenic drought is governed by the interplay of natural renewable water variability, climate change, human effects, and altered micro-climate conditions. In natural systems, water shortage depends solely on the variability of renewable water, which can be evaluated using physical definitions of drought based on the departure of current conditions from average historical condition (Wilhite & Glantz, 1985). On a global scale, the anthropogenic emission of greenhouse gases affects natural climate variability, which can change the frequency and intensity of dry spells or intensify and prolong droughts (i.e., flash droughts, Otkin et al., 2018).

At the core of the notion of anthropogenic droughts is water stress caused or intensified by human activities (e.g., increased water consumption beyond what nature can provide—see Figure 1). Where development activities outweigh the effects of natural variability and climate change on water supply, water shortage can persist at a local to regional scales despite episodes of above average renewable water availability. Human water use has exceeded the available renewable water in many parts of the world (Gleick & Palaniappan, 2010; Vörösmarty et al., 2000). This phenomenon is symptomized by chronic or emerging water shortage (Kummu et al., 2016; Simonovic, 2002; Srinivasan et al., 2017) or in extreme cases water bankruptcy (Madani, 2019; Madani et al., 2016), a key consequence of anthropogenic droughts. Example development related signs of anthropogenic drought are groundwater table decline, drying-up of lakes and wetlands, and diminished streamflows, especially ecological flows. An artifact of water-intensive development activities is the creation of micro-climate zones with substantially altered hydrological dynamics (e.g., surface-water groundwater interaction, soil moisture, and evapotranspiration in major irrigated agricultural areas), which affects our ability to apply different drought definitions. For example, a period of lower than average rainfall may not translate into agricultural drought due to irrigation keeping soil water content and evapotranspiration high.

Drought is a creeping phenomenon and anthropogenic drought is no exception. Since the 1950s, the population of the United States has almost doubled (Shrestha & Heisler, 2011; Singh et al., 2014). Consequently, agricultural and industrial activities have grown substantially (Cosgrove & Loucks, 2015; McDonald et al., 2011), leading to increased water consumption by nearly 100% relative to the 1950s (Figure 2). In the same period, precipitation (an indicator of natural water availability) has exhibited substantial variability (Hoegh-Guldberg et al., 2018; Sheffield et al., 2012). Since all components of an ecosystem are optimized to coevolve with each other, changes in one component can lead to significant chain reactions in the ecosystem; thus human-induced water stress caused by increasing water demand can lead to major environmental changes (e.g., changing flow regimes, loss of habitats, etc.). Even under the most optimistic assumption that climate change will not limit our water supplies in the future, anthropogenic impacts would still occur

Figure 1. Increased water demands heighten stresses on surface and groundwater resources: A schematic illustration of anthropogenic drought, broadly describing water stress caused by urbanization, population growth, industrial and agricultural development, greenhouse gas emissions, and land use change. The world is moving toward more extensive and intensive human development including expansion of urban areas and highly populated regions.

as a result of increases in global water demand (Di Baldassarre et al., 2018; Madani et al., 2016; Mehran et al., 2017).

The phenomenon of anthropogenic drought can be better described by examining the interactions and feedbacks between natural drivers and hydrological processes (e.g., meteorological, agricultural, and hydrological drought) and anthropogenic drivers and changes in human behavior (e.g., anthropogenic climate change, land use/land cover change, increasing water consumption, and management practices). Figure 3 depicts the connections between the two realms: we can trace multiple hydrological responses (on the left) to the anthropogenic drivers (on the right). Anthropogenic activities have contributed to exogenous (e.g.,

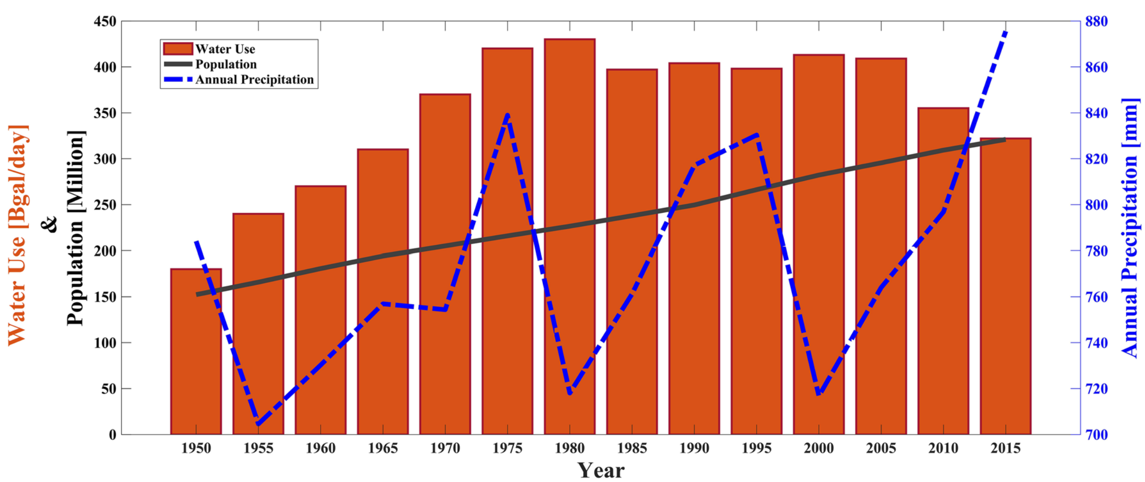

Figure 2. Trends in human water use (Billion gallons per day, Bgal/day; orange bars), population (millions), and annual precipitation (mm) in the United States. Sources: water use information (http://water.usgs.gov/watuse); population (United States Census Bureau); and precipitation (http://www.ncdc.noaa.gov/cag/).

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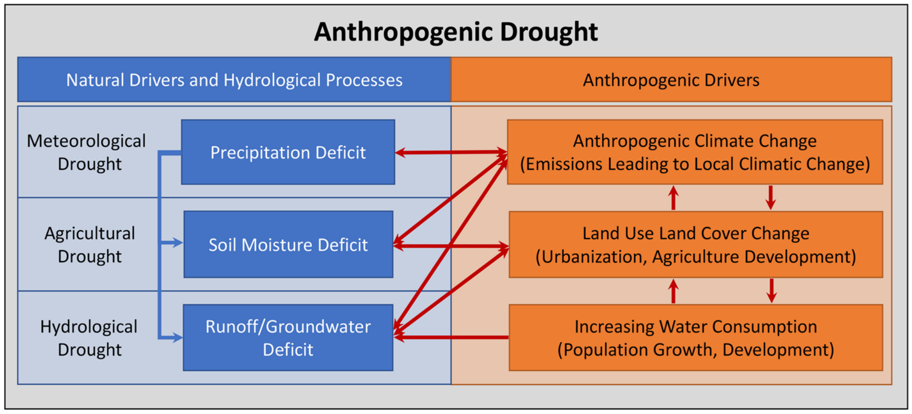

Figure 3. Exogenous human-induced and natural drivers and endogenous drivers of anthropogenic drought and their corresponding interactions. This is a simplified figure focusing on a few feedback relationships for visualization purposes; in reality, there are more complex interactions and feedback relationships. In general, changes in precipitation (or any other driver) can also alter the land cover condition or limit/accelerate development in a certain region. The notion of anthropogenic drought refers to the processes involved in formation and intensification of droughts from both exogenous and endogenous perspectives.

change in meteorological condition) and endogenous (e.g., change in local water demand, reservoir management) impacts on water availability. For example, due to population growth and industrial development, that is, an endogenous change, greenhouse gas concentrations have increased dramatically leading to substantial changes in global and regional climatic extremes that can lead to droughts, that is, an endogenous change—see Cayan et al. (2010), Stoll et al. (2011), Trenberth (2001). Previous studies have attributed changes in precipitation (Fischer & Knutti, 2015, 2016; Papalexiou & Montanari, 2019) and temperature (Freychet et al., 2018; Papalexiou et al., 2018) and hence, the frequency and severity of both meteorological and agricultural droughts to human activities (Apurv et al., 2017; Hoerling et al., 2012; Q. Sun et al., 2017; Trenberth et al., 2015; Zhao & Dai, 2015). This indicates that anthropogenic activities are not only changing *local water demand*, but also *meteorological conditions* leading to *exogenous* biophysical impacts on natural water availability that cannot simply be managed by decision-makers over short time scales (Mehran et al., 2015). On the other hand, *endogenous* changes correspond to local and regional policies (e.g., urbanization, agricultural/industrial development), which can impact and be influenced by water resources management.

These two exogenous and endogenous effects are indeed interrelated: For instance, anthropogenic climate change can exacerbate heatwaves, increasing water demand, thereby aggravating droughts (Cheng et al., 2019). Depending on local climate conditions, land management practices, such as irrigation, can influence local hydrological phenomena such as precipitation. We can also draw feedbacks from hydrological conditions to anthropogenic activities. For example, during the 2012–2016 California drought, reduced hydropower production capacity was offset by natural gas leading to a substantial increase in greenhouse gas emissions of the energy sector compared to predrought conditions (Hardin et al., 2017). In Central Valley, California, large-scale irrigation has altered the regional temperature and precipitation patters (Sorooshian et al., 2014). The notion of *anthropogenic drought* addresses these two-way interactions, that is, feedbacks, between local water use/demand and changes in water availability caused by human activities. Most current models designed to study human activities/decision on droughts do not consider land-atmosphere dynamics, energy balance and other relevant feedback loops. We argue that to better understand the notion of *anthropogenic drought*, human interactions should be incorporated in models that include land-atmosphere interactions, water balance and energy balance, and their relevant feedback loops.

1.2. Environmental Consequences of Anthropogenic Drought

The environmental impacts of anthropogenic drought can be seen globally in both developed and developing countries. A number of studies that examined tree health, productivity, and mortality in forests around

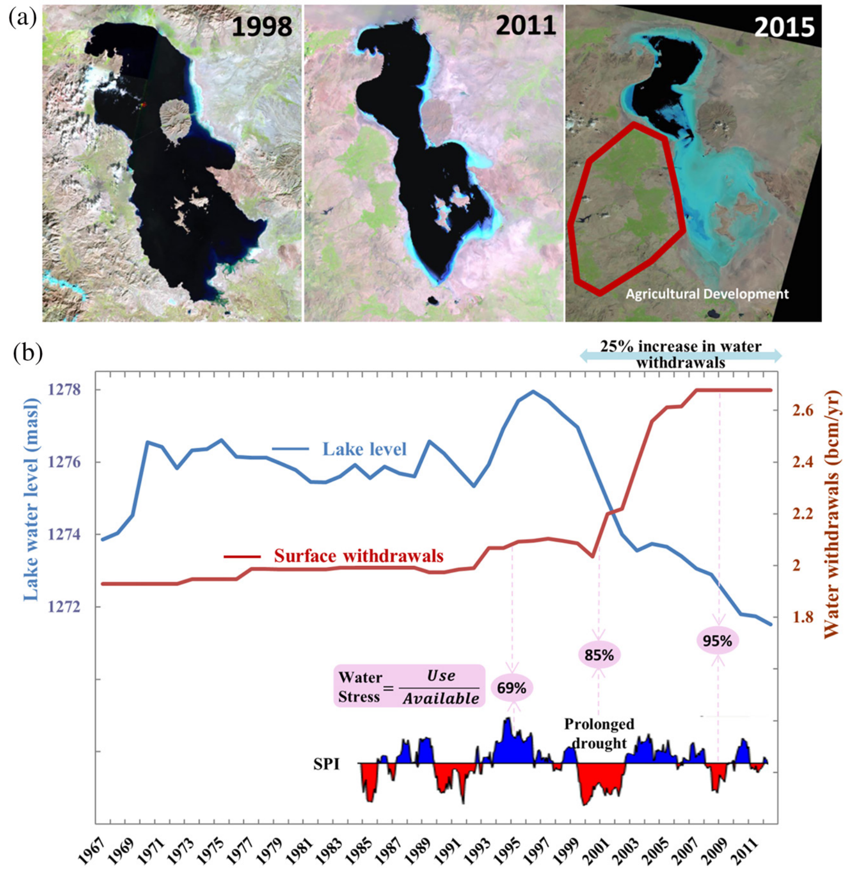

Figure 4. (a) The area of Lake Urmia has decreased substantially in the past two decades (images derived from LandSat imagery). There are multiple causes including increased human water use in the region. (b) Key attributes of the lake-basin interaction including observed lake level, standardized precipitation index (SPI), and surface water withdrawals. The basin's recent wet (blue) and dry (red) periods are illustrated in SPI. Post-1998 drop in lake level corresponds to a substantial increase (∼25%) in surface water withdrawals during and after the prolonged drought of 1998–2002 (modified after Alborzi et al., 2018).

the world have found that climate warming has increased tree mortality rates in recent decades (Beck et al., 2011; Brando et al., 2019; Phillips et al., 2009; Van Mantgem et al., 2009). Moreover, there are many stressed lakes and wetlands around the world that have been affected by continuously increasing water withdrawals (Kofron, 2019; Okpara et al., 2016; Tao et al., 2015; Wine et al., 2019; Wurtsbaugh et al., 2017), and hence the resulting *anthropogenic drought*. Lake Urmia, located in northwestern Iran, is a recent exemplar of this situation (Figure 4). Despite having survived many extreme droughts in the past, Lake Urmia lost about 80% of its surface area at the turn of the 21st century with most of the change happening between 2009 and 2016 (AghaKouchak et al., 2015; Madani et al., 2016). The post-1998 drop in lake level corresponds to a substantial increase (∼25%) in surface water withdrawals during and after the prolonged drought of 1998–2002 (Alborzi et al., 2018). Even in recent years, extremely wet conditions have not been able to fully restore the lake and its ecosystem.

When extreme environmental conditions occur, questions often arise regarding the potential role of human water management versus climate variability and change, both of which are important and deserve attention and scrutiny. However, a question less commonly asked is: what is the impact of increased human water demand in creating such extreme environmental conditions? In the past 15 years, about 20 man-made reservoirs became operational in the Lake Urmia basin (Alizadeh-Choobari et al., 2016), diverting the lake's freshwater inflow mostly for agricultural uses (Khazaei et al., 2019) (Figure 4). As Lake Urmia is a hypersaline lake, its desiccation will increase the frequency of salt storms generated from the exposed lakebed. Salt storms will likely reduce the productivity of the surrounding agricultural lands with the potential to

10.1029/2019RG000683

cause migration out of the region. Degrading air, land, and water quality can have serious health effects (Danaei et al., 2019) including birth defects, and chronic respiratory and eye diseases. This is a classic case of anthropogenic drought and human-induced changes leading to substantial environmental degradation.

Anthropogenic droughts will become more widespread globally, especially in developing countries, as populations grow and societies seek higher standards of living and related water demands soar (Ebi & Bowen, 2016; Madani, 2014; Schewe et al., 2014; Wanders & Wada, 2015). Developed countries also face similar challenges. For instance, in response to substantial population growth and water demand increase in dry regions of California over the past century, major infrastructure and water transfer projects have greatly altered the amount of available environmental water (He et al., 2017). Reduced environmental water because of anthropogenic activities combined with drought and natural variability, have led to unsustainable environments for California's native and endangered fish including delta smelt and Coho salmon (Hwan & Carlson, 2016; Power et al., 2015). Intermittent streams which provide rearing and breeding habitat for river biota, are highly vulnerable to prolonged dry spells (Hwan & Carlson, 2016), and their conditions are worsened by reduced environmental water allocation caused by *anthropogenic droughts*. Maintaining aquatic habitats and food webs, especially during droughts, requires (a) sufficient and good quality environmental water to ensure the hydrologic connectivity of the main stem pools and a healthy aquatic habitat; and (b) sustained baseflow in streams, typically driven by groundwater discharge. There are many examples where drying wetlands due to overabstraction are artificially watered during drought conditions. For example, in Spain (Van Loon & Van Lanen, 2013) and the UK (Soulsby et al., 1999), groundwater is pumped or water is transferred into the catchment artificially to prevent water bodies from drying up. Israel has announced plans to pipe water from the Red Sea to the restore Dead Sea and Iran will soon complete the construction of its interbasin water transfer infrastructure to increase water inflows into Lake Urmia. This management strategy to counteract *anthropogenic drought* is associated with both positive and negative consequences (Cowx, 2000).

The answer to the frequently asked question “How much rain is needed to end the drought?” is dependent on anthropogenic activities increasing and decreasing water stocks (Van Loon et al., 2016). Areas where anthropogenic droughts have created a new normal system state are effectively experiencing permanent water shortages regardless of rainfall amounts (e.g., central plateau of Iran [Gohari et al., 2017]). A well-documented effect of increased human water demand in such areas is the depletion of groundwater resources (Famiglietti et al., 2011; Voss et al., 2013), which is an important sign of anthropogenic drought (Mustafa et al., 2017) and water bankruptcy. If groundwater falls below a critical threshold, baseflows may no longer be sufficient to maintain a healthy ecosystem (Power et al., 2015). Elements of California's recent drought, including groundwater table decline (Famiglietti, 2014; Simon Wang et al., 2016; Thomas et al., 2017) are generic examples of anthropogenic drought that many parts of the world will grow into during the coming decades due to continuously growing and diversifying water demands.

1.3. Compounding Impacts of Climate Change and Human Water Use

The water cycle is tightly coupled with human activities, for example, increased water demand, man-made infrastructure, land and hydrologic alterations (Konar et al., 2019; Vogel et al., 2015). In the so-called non-free-flowing rivers, around 23.5% of the river discharge is regulated by more than 30,000 large dams (Döll et al., 2020; Poff, 2019; Shiklomanov, 2000; White, 2005; Zhou et al., 2016). Dams and reservoirs provide the capacity to regulate flows and deal with climate variability (i.e., droughts and floods), offering the opportunity to manage water resources based on local and downstream needs (Palmer et al., 2008; Rangecroft et al., 2019). On the other hand, increasing water supplies (e.g., through building reservoirs, interbasin water transfer, or desalination plants) has historically increased competition for water and overall human water use (Di Baldassarre et al., 2018; Gohari et al., 2013; Mirchi et al., 2012, 2014). Figure 5 shows increases in storage (Figure 5a) and desalination capacity (Figure 5b) and corresponding human water use over time in Melbourne, Australia, and Kuwait, respectively. In both cases, additional water resources created opportunities for further growth and development and hence, increased water competition and use over time (Madani & Mariño, 2009).

Anthropogenic drought can be classified as a compound phenomenon, created by a multidriver process. A compound phenomenon here broadly refers to an event or hazard with multiple interacting drivers (Wahl

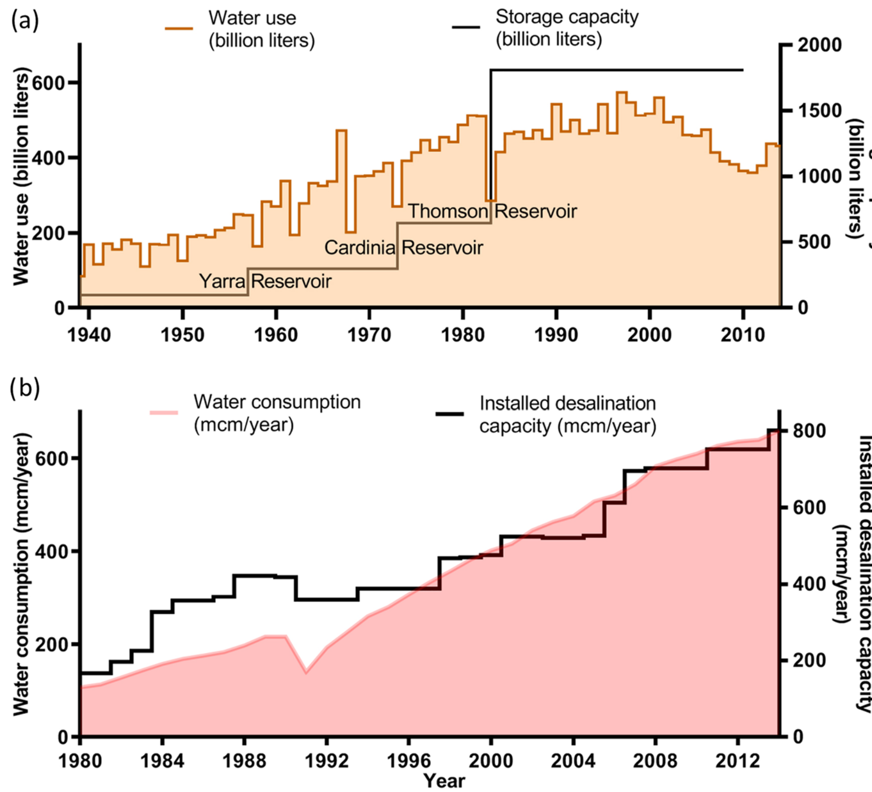

Figure 5. Increase in (a) storage and (b) desalination capacity and the corresponding human water use over time in Melbourne, Australia, and Kuwait, respectively.

et al., 2018; Zscheischler et al., 2018). The interactions and feedback relationship between these drivers, namely natural variability of renewable water, climate change, increasing water demands, and human-altered micro-climate conditions over time and space constitute the anthropogenic drought phenomenon that is evidenced by water stress and bankruptcy. Currently, global climate models coupled with hydrologic or land-surface models are widely used to evaluate future droughts and changes in water availability (Bierkens, 2015; McDonald et al., 2011). Most hydrologic science studies primarily focus on large scale atmospheric conditions such as a change in precipitation (Barnett et al., 2006) while ignoring the human component (Nazemi & Wheater, 2015; Wheater & Gober, 2015), and hence the compounding effects of climate change and human water use on local water management (Wanders & Wada, 2015). However, research by the water resources systems community has already established an important fact: drought will have greater impacts in a human-water system in which water use continuously increase over time (e.g., C. M. Brown et al., 2015; Kasprzyk et al., 2009; J. Lund et al., 2018; J. R. Lund & Reed, 1995; Trindade et al., 2017; Zeff et al., 2016). Thus, in places where water use continues to increase, the impacts of future droughts are expected to grow, even without accounting for the effects of climate change on intensifying terrestrial aridity (Sherwood & Fu, 2014). If climate change intensifies and/or prolongs droughts in the future, the overall impacts will be even greater. Thus, it is increasingly important to include human water use and the local capacity (e.g., local infrastructure systems and management plans) to cope with variability in future water availability assessments.

Although integrating infrastructure systems into hydrologic models and incorporating their operation rules is typically not straightforward, several modeling frameworks have made great progress in representing some of the key components including irrigation, dams and reservoirs, desalination plants, and local water use (Ahmadalipour et al., 2019; Bertoni et al., 2019; Carmona et al., 2017a, 2017b; Castelletti et al., 2008; Draper et al., 2003; Gailey et al., 2019a, 2019b; Garcia et al., 2019; Gold et al., 2019; Gupta et al., 2020; Herman et al., 2015, 2016; Jenkins et al., 2004; Kasprzyk et al., 2009; Medellín-Azuara et al., 2008; Mehran et al., 2017; Moallemi et al., 2019; Müller et al., 2016; Pinter et al., 2019; Quinn et al., 2020; Rajsekhar

& Gorelick, 2017; Rheinheimer et al., 2015; Schewe et al., 2014; Simonovic, 1992; Srinivasan et al., 2018; Tian et al., 2019; Trindade et al., 2019; Z. Xu et al., 2020; Yeh, 1985; You & Cai, 2008). When integrating man-made infrastructure is not possible, projected changes in future water availability should be presented relative to the local infrastructure designed to cope with climatic extremes (e.g., dams and reservoirs). Such an analysis should consider downstream social and environmental effects, resilience to multiyear events, effects of reservoir operating rules, and the unintended increased water use downstream of reservoirs.

The multifaced nature of water management has been convincingly theorized and documented in the rich and expansive body of water resource systems literature since the 1950s (C. M. Brown et al., 2015; Kaspryzk et al., 2018; Loucks, 2020; Loucks & van Beek, 2005; Loucks et al., 1981; Maass et al., 1962; Madani & Shafiee-Jood, 2020; Mirchi et al., 2010; Simonovic, 2009; Vogel et al., 2015). Water resources system research has incorporated concepts of water supply and demand to examine robust water resources plans under constraints of water availability in light of changing water supply and demand. Indeed, water management actions can contribute to the prevalence of permanent anthropogenic droughts, for example, by concealing the signs of water shortages by artificially increasing water supply (e.g., desalination and water transfer), so the society cannot see the effect of worsening water scarcity (Gohari et al., 2013). In such a case, a process-based approach can offer a more realistic view of water availability and drought. Evidently, water resources systems models can be leveraged to examine the compounding drivers and feedbacks that cause permanent, and in many cases growing, water shortages that may lead to water bankruptcy (Madani et al., 2016).

1.4. Research Gaps and Opportunities

In the following, we discussed research gaps and opportunities to improve the understanding, modeling, and management of anthropogenic drought.

(a) Lack of indicators or comprehensive assessment frameworks for describing anthropogenic droughts: A myriad of indicators has been proposed to characterize droughts from different perspectives (Bachmair et al., 2016; Hao & Singh, 2015; Heim, 2002; A. K. Mishra & Singh, 2010; Mukherjee et al., 2018). The Standardized Precipitation Index (SPI) (Mckee et al., 1993) is widely used as a measure of meteorological droughts, whereas standardized soil-moisture (SSI) (Hao & AghaKouchak, 2013) and runoff (SRI) (Shukla & Wood, 2008) have been used for monitoring agricultural and hydrological droughts, respectively. In recent years, a variety of hybrid drought indicators have been proposed, such as the Aggregate Drought Index (ADI) (Keyantash & Dracup, 2004), the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010), the Joint Deficit Index (JDI) (Kao & Govindaraju, 2010), the Combined Drought Indicator (CDI) (Sepulcre-Canto et al., 2012), and the Multivariate Standardized Drought Index (MSDI) (Hao & AghaKouchak, 2014). However, most existing indicators do not consider human water use and/or local water storage (Lloyd-Hughes, 2014). In a recent effort, Mehran et al. (2015) introduced a hybrid framework for incorporating local water storage and human water demand termed Multivariate Standardized Reliability and Resilience Index (MSRRI). This measure integrates information on the inflow and reservoir storage relative to the local water demand to describe the drought condition. MSRRI focuses on processes/phenomena that cannot be simply controlled or altered by humans (e.g., local precipitation and climate variability), and representation of the local capacity to respond or adapt to droughts. However, MSRRI does not consider different types of resources (e.g., desalination and groundwater pumping) and transfers in and out of basins, detracting from its utility in highly managed systems with different sources of water. Similarly, some existing drought indicators have provided metrics on human water use and local storage (A. Brown & Matlock, 2011; McNulty et al., 2007; Treuer et al., 2017). However, the existing metrics are mainly state (product) indicators as opposed to process indicators (Hjorth & Madani, 2014). This means that while they can capture the drought conditions once they appear, they are often incapable of detecting upcoming droughts with a sufficient lead time to give water managers an opportunity to take timely and cost-effective actions. Therefore, in addition to state indicators, we need to develop indicators and modeling frameworks that help us detect the natural and anthropogenic processes and drivers that lead to droughts. As mentioned earlier in this article, there are a large number of studies including systems-based or socio-hydrology models that integrate human activities/decisions in water resources studies. However, in most studies, the human component is not linked to land-atmosphere dynamics, energy (and/or water) balance and other relevant feedback loops. We argue that to better understand the notion of anthropogenic drought, human interactions should be incorporated in models that include land-atmosphere interactions, water balance and energy balance and other physically based feedback loops related to local and regional climate.

(b) Understanding propagation of the impacts of anthropogenic droughts: Increments in local water use in economically or geopolitically important regions have motivated water transfer projects to meet the substantial local demand. In many parts of the world (e.g., southern California, northeastern China, parts of the Middle East) water demand has increased such that even in the wettest years, water transfer is unavoidable. This means that the environmental impacts of anthropogenic droughts can occur in remote basins. For example, increased dust storms around Owen's Lake, in California, are attributed to water transfers to southern California. Transferring water from California's Sacramento-San Joaquin Delta for agricultural uses in the Central Valley and Southern California, has significantly altered local water availability, causing major environmental damages in the Delta area (Madani & Lund, 2012). Aggressive reservoir construction in the upstream of the Tigris-Euphrates system by Turkey is also believed to have played a major role in exacerbating water problems in Syria and Iraq.

In Syria, the compounding effects of a number of socio-political issues resulted in a major conflict and human crisis. A prolonged drought (Cook et al., 2016; Karnieli et al., 2019; Müller et al., 2016) was among the many factors that might have contributed to triggering turmoil and conflict, though it cannot be considered as the main driver (De Châtel, 2014; Madani & Shafiee-Jood, 2020). In this particular case, the drought impacts were amplified by poor and outdated water management practices and institutions. The overall process resulted in the failure of 75% of farmland between 2006 and 2011, and migration of about 1.5 million people from rural areas to urban regions (Erian et al., 2011; Kelley et al., 2015). However, current modeling frameworks cannot evaluate the propagation of impacts across spatial and temporal scales, produced by a particular drought.

There are opportunities to incorporate (or learn from) trade models for describing the propagation of impacts of extreme events such as droughts. In fact, in a globalized economy, it is critical to understand that local production shocks (especially in major food producing countries) can affect the global trade system and potentially propagate across the world. Exposure of countries to shocks has been widely studied in financial markets, telecommunication networks, and energy trade (Callaway et al., 2000; Davis et al., 2016; Dunne & Williams, 2009; Kali & Reyes, 2010; Marchand et al., 2016; V. Mishra et al., 2019; Nier et al., 2007), but has received little attention when it comes to the propagation of drought impacts on nutrition supply (Carpena, 2019). Food storage and food trade options are the two elements that determine resilience of a country to external food production shocks in other countries (Cottrell et al., 2019; Dalin et al., 2012; He et al., 2019; Marston & Konar, 2017). Figure 6, for instance, shows the global impact of the 2002–2003 North-American drought (United States and Canada) on the calories exported for human consumption in the rest of the world. The deficit can reach 400 kCal/cap/day, nearly 20% of the daily recommended values. This deficit can be offset if the country has enough food storage or trade opportunities to secure their food. More efforts should focus on modeling the propagation of drought impacts across space and time. Considering changes across space and time is important as in many areas may be decoupled from water use due to efficiency gains and/or actual/water imports and exports through agricultural and industrial products (Dalin et al., 2012).

(c) Reduced water quality due to anthropogenic footprint: Urbanization, sea level rise, intensive irrigation, and other human activities can decrease water quality, ultimately reducing the available water for use in a basin. For example, human-induced sea level rise causes the movement of saline water into freshwater aquifers, decimating the local drinking water source. Saltwater intrusion as a result of groundwater pumping in coastal areas can limit the availability of groundwater (e.g., Oman [Zekri et al., 2017]). Water withdrawal, dam building and warming droughts in a changing climate will likely contribute to warmer water temperatures that will negatively affect water quality especially for aquatic habitats (Ahmadi & Moradkhani, 2019; Kraft et al., 2019; Null et al., 2017; Rheinheimer et al., 2015; van Vliet & Zwolsman, 2008; Van Vliet et al., 2013). Drought events can also lead to an increase in river salinity, intensifying water scarcity during low flow periods (Jones & van Vliet, 2018). Intensive irrigation and urbanization also contaminate water supplies by adding harmful chemicals and nutrients (Mosley, 2015). China and India, which together account for about 36% of the total world population are suffering from water scarcity due to a significant

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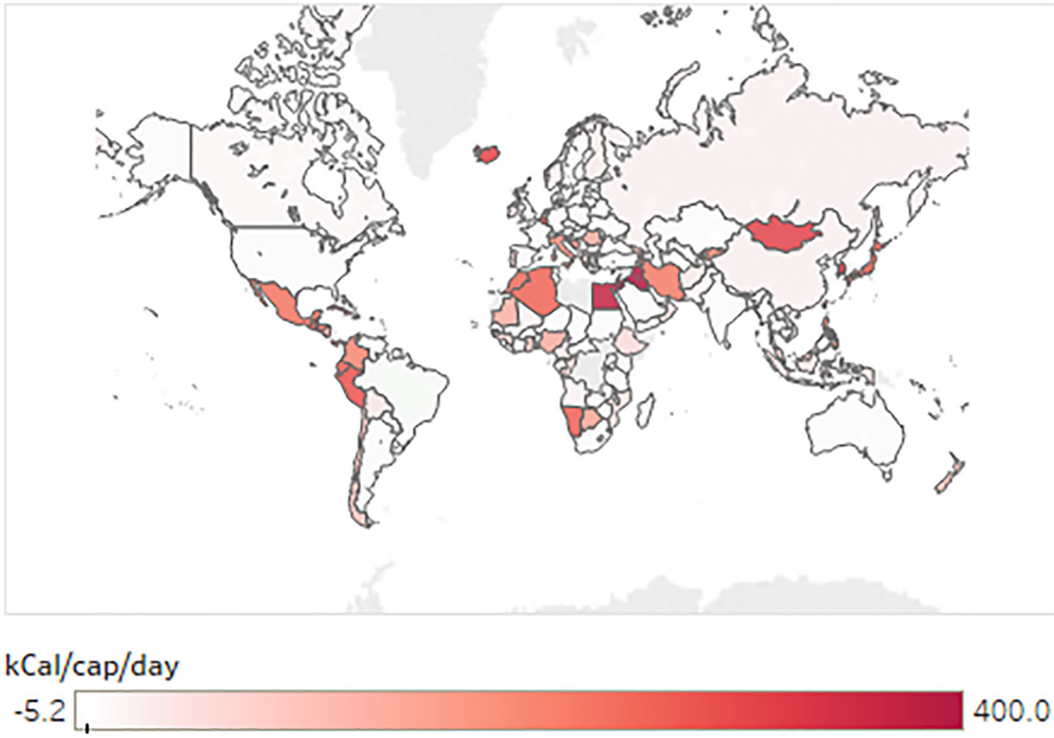

Figure 6. Change in total calories exported to other countries due to the 2002–2003 North-American Drought (data source: Food and Agriculture Organization, FAO; Steduto et al., 2017).

degradation of water quality (Wan et al., 2016). These reductions in water quality decrease the available water for environmental and societal use, and must be taken into account when considering anthropogenic droughts (Van Loon et al., 2016b; van Vliet & Zwolsman, 2008). However, most current drought studies in the literature primarily focus on water quantity. Coordinated research efforts by water quality and quantity communities are needed to explore the water quality implications of anthropogenic droughts. It is crucial to gather information on drought impacts that are related to low water quality (Stahl et al., 2016).

(d) Anthropogenic drought, future development pathways, and climate change: Anthropogenic droughts can be intensified in the future because of the compounding effects of climate change and human activities. Because our changing climate is commingled with a changing society, policy, stakeholder, and science communities should explore different water supply and demand management solutions and tensions that will characterize droughts in a warmer and more populated world with more climatic and socio-political extremes (Greve et al., 2018; Hanak & Lund, 2012; Kahil et al., 2015, 2016; Medellín-Azuara et al., 2008). This issue has not received sufficient attention, especially in the mainstream hydrology and metrology. Projecting how a society develops and how water needs will change in the future is a challenging task (Blöschl et al., 2019; Elshafei et al., 2014; Lettenmaier, 2017). However, there is already a wide range of regional and global development pathways that provide a basis for making progress in this direction. Water-human system dynamics models (Bagheri, 2006; Davies & Simonovic, 2011; Gohari et al., 2017; Mirchi et al., 2012) as well as integrated assessment models (IAMs) for future scenario analysis provide one opportunity for combining development pathways with future climate projections (Hejazi et al., 2014; Kraucunas et al., 2015; D. Wang & Hejazi, 2011). These models can be used to explore different plausible policy actions and evaluate their outcomes, though there are significant uncertainties and assumptions related to scenarios that can potentially affect the outcomes. Research in this direction can lead to policy and management strategies that can potentially reduce the impacts of anthropogenic droughts. However, the currently available models are temporally and spatially coarse and therefore do not allow for the investigation of effects of short-term and regional shocks (e.g., individual droughts). Few agencies have attempted to prepare regional (e.g., U.S. Bureau of Reclamation [USBR, 2017]) and local (e.g., Southern Nevada Water Authority [SNWA, 2015])

IAMs scenarios with high and low demands (Joshi et al., 2020). We envision, nonetheless, that rapid developments in this area will offer exciting opportunities for future research.

(e) Hot droughts in the anthropocene: The term "hot droughts" coined by Overpeck (2013), refers to concurrent hot and dry conditions, which have become more common over the course of the 20th century (Hao, Hao, et al., 2018a; Mazdiyasni & AghaKouchak, 2015). Due to feedbacks and interactions between droughts and high temperatures (Chiang et al., 2018; Fischer et al., 2007; Manning et al., 2018; Seneviratne et al., 2006), the negative impacts of hot drought events will become more devastating as temperatures continue to rise (C. X. Sun et al., 2019; Teuling, 2018; S. Wang et al., 2019; Yuan et al., 2019). These multivariate climate conditions can subsequently impact anthropogenic water demand and water use as shown in the 2018 European drought and heatwave. This is predicted to manifest in increases in crop water demand in the agricultural sector (Mehta et al., 2013). In addition, the frequency and distribution of hot droughts can affect renewable energy generation and current and future energy portfolios (Forrest et al., 2018; Tarroja et al., 2018), which in turn, can increase the energy sector's anthropogenic CO_2 footprint (Hardin et al., 2017) and subsequently influence precipitation conditions and anthropogenic drought severity. Moreover, hot droughts can modify the phenology of plants and change the length of the growing season and the carbon uptake period (Reichstein et al., 2013; Roy et al., 2016; Schwalm et al., 2012). More in-depth research is needed to fully understand changes in phenological development and carbon uptake periods in different parts of the world as there are opposing findings regarding carbon uptake response to increasing temperatures (Bernal et al., 2011; Ciais et al., 2005; Wolf et al., 2016). Recent satellites (e.g., OCO-2 [2015] and Sentinel-5 Precursor [2017]) and future missions (e.g., GeoCarb [2020] and FLEX [2022]) will provide different hydroclimatic variables such as solar-induced chlorophyll fluorescence, soil moisture, snow, and precipitation that can be used to study the ecosystem response to warming droughts, among other things (Hao, Singh, et al., 2018b; Lettenmaier, 2017; Sellers et al., 2018).

As warming projections show increases in drought events (e.g., Dai, 2013; Hirabayashi et al., 2008; Lehner et al., 2017; Spinoni et al., 2018), we must turn our attention to the challenge of hot droughts in the future. We acknowledge that the physical impacts of hot droughts on anthropogenic landscapes (e.g., metropolitan areas) are not easy to quantify, but researchers must close the gap between large-scale climatic studies (concerning drought mechanisms, large-scale climate feedbacks), and local-scale responses and policies (such as human management and use, in response to local physical conditions). We must strengthen our practical understanding of how local environments and communities respond to hot droughts. We need more studies that explore and characterize the interaction of hot drought extremes with local human water demand and environmental water needs. At the same time, without acknowledging the human dimension, we cannot completely capture the mechanisms for changes in hot droughts, and consequently, cannot appropriately project how warming will impact anthropogenic droughts.

(f) Snow drought: Both natural variability and anthropogenic factors play important roles in modulating the amount of snow that accumulates across a region and the timing of snowmelt. Not only are more regions likely going to face challenges related to anthropogenic drought in the coming decades, but a warming climate also increases the likelihood of a low snowpack across many regions (Bonfils et al., 2008; Dierauer et al., 2019; Huning & AghaKouchak, 2018; Nogués-Bravo et al., 2007). In fact, recent studies such as Diffenbaugh et al. (2015) have shown that it is becoming more likely to have concurrent warm and dry conditions such as those that were associated with the severe snow drought in California during 2012–2015 (Berg & Hall, 2017; Mao et al., 2015; Margulis et al., 2016; Shukla et al., 2015). From a global snow drought assessment spanning the last four decades, Huning and AghaKouchak (2020) found that snow droughts (deficits in snow as equivalent water) have become more severe and longer across the western United States, Europe, and eastern Russia during the latter half of years. Snow drought can further complicate anthropogenic drought in many regions worldwide (Huning & AghaKouchak, 2020). As human water demands increase in areas that depend on the snowpack, years of low snowpack accumulation can enhance downstream anthropogenic drought effects and such intensification must be better understood for improving water resources management, minimizing ecosystem stress, etc. A reduced snowpack necessitates the adjustment of water management practices due to less spring snowmelt-derived runoff and shifts from snow to rain (and earlier runoff), which have already been observed due to increases in temperature (Hatchett & McEvoy, 2018; Huning & AghaKouchak, 2020; Li et al., 2017, 2019; Pournasiri et al., 2019; Qin et al., 2020; Tang et al., 2019).

Water managers need to consider storing more water earlier in the season while also weighing storage capacity considerations necessary for minimizing flood risk. However, compensating for the loss of water storage in the snowpack's natural reservoir may not be possible by simply relying on existing reservoirs or building new ones because of a combination of political, social, economical, and environmental issues. Snowpack losses in many regions of the world may outpace our ability to construct critical infrastructure, indicating that solutions must be forged through synergistic efforts across water policy, operations, and management (Mote et al., 2018). Managing snow drought and adapting to changes in the ratio of rainfall to snowfall is also challenging in systems with hydropower generation (Madani et al., 2014), where the changes in temperature and magnitude and timing of flows can impact both electricity supply and demand. Such changes combined with increasing human demands and competition for water pose challenges that complicate drought mitigation, resilience, and management strategies.

Understanding the relationship between anthropogenic drought and snow drought is further complicated by the fact that large populations in regions that are not snow-covered themselves also depend on snowmelt runoff for their water and energy resources during seasons of low precipitation (e.g., in the western United States). Therefore, like the notion of anthropogenic droughts impacting water dependence on remote basins (e.g., via water transfer), snow droughts can affect distant water supplies through the reduced availability of imported water sources and/or recharge of downstream groundwater systems. Also, given the dependence of agricultural systems on snowmelt runoff for instance, the propagation of drought impacts may be manifested in remote regions (Qin et al., 2020). Before we can fully understand the complex coupling between anthropogenic drought and snow drought (and anthropogenic drivers of change), additional comprehensive analyses of snow drought conditions must be performed (Huning & AghaKouchak, 2020). Unlike other more commonly studied drought classifications (e.g., meteorological, agricultural, and hydrological), snow droughts remain poorly characterized across the globe and drought monitoring frameworks often lack snow information—both of which are key considerations for understanding the availability of water resources across snowmelt-reliant regions and thereby, anthropogenic drought conditions.

2. Concluding Remarks

The notion of *anthropogenic drought* underlines that a meaningful description of drought must rely on process-based (rather than product-based) definitions that go beyond water supply changes to include water demands, development plans, policy, and the capacity to cope with extremes and feedbacks among human actions and climate within complex, coupled human-nature systems. This requires embracing a multidimensional definition of drought—a condition in which water stress (societal and environmental) is caused or intensified by the compounding effects of natural variability, climate change, human activities, and modified micro-climates. The water research community has traditionally attempted to characterize different drivers of this phenomenon in isolation, often, looking at the system state and outcome without grasping the complexity of the processes and feedback mechanisms that generated the system state and outcome. It is difficult to quantitatively disaggregate the drivers of anthropogenic droughts and their effects with certainty to say which driver has the dominant impact because of the compounding feedbacks that govern the system state and behavior. Less water availability and growing water use are simultaneous and interacting causes of *anthropogenic drought*. Regional adjustments to reduced water availability must go hand-in-hand with adjustments that are needed due to changes in environmental and societal demands/activities.

Options for mitigating drought impacts are extensive (C. Brown et al., 2012; Cai et al., 2015; Carmona et al., 2017a, 2017b; Connell-Buck et al., 2011; Harou et al., 2010; Trindade et al., 2017; Zeff et al., 2016). Demand management, conservation, water markets, public outreach, and the introduction of innovative technologies are essential for managing anthropogenic droughts. An implication of future *anthropogenic droughts* may be that historical conditions (e.g., with respect to water availability or drought resilience) become less achievable without timely changes and investments. This will entail more difficult choices in prioritizing water needs under extreme conditions and considering a range of behavioral as well as technological options (e.g., conservation, water reuse, improving efficiency—Quesnel et al., 2019; Grant et al., 2013; Cai et al., 2015). Policy makers and societies can take advantage of the opportunity windows provided by extreme events to implement policy that will be politically costly in normal times (Madani, 2019). Australia's Millennium Drought is an example of an event that led to profound changes in public perception and, as a result, substantial policy reforms and demand management and other environmental management strategies (Aghakouchak et al., 2014; Grant et al., 2013). Australia's experience during the Millennium Drought showed that promoting water conservation technologies and innovation by providing incentives can reduce long-term water demand and lessen stress on water resources. Most historical adaptations to drought have served to maintain or expand predrought water supply capabilities. The challenge of the future is how to prioritize water needs and water uses to minimize the impacts on both humans and ecosystems. Careful, reasoned discussions on the value of ecosystem services, along with the prioritization of natural capital investments are critical to water management to maintain resilience across the spectrum of users, including nature.

It is difficult to quantitatively disaggregate the drivers of anthropogenic droughts and their effects with certainty to say which driver has the dominant impact because of the compounding feedbacks that govern the system state and behavior. Less water availability and growing water use are simultaneous and interacting causes of *anthropogenic drought*. Regional adjustments to reduced water availability must go hand-in-hand with adjustments that are needed due to changes in environmental and societal demands/activities. Major breakthroughs in drought management, adaptation, mitigation, resilience assessment, and prediction will not be possible without close collaboration between natural and social scientists, engineers, stakeholders, policy-makers, and operational decision-makers. A transdisciplinary perspective is needed to address the research gaps listed in this paper and unravel the way in which societies influence and respond to *anthropogenic drought*. Research on climate and the integration of water supplies, demands, and their management is important for any part of the world to sustain both economic prosperity and productive native ecosystems under global environmental change.

Data Availability Statement

Water use, population, and precipitation data sets used in Figure 2 are publically available via http://water.usgs.gov/watuse; the United States Census Bureau; and http://www.ncdc.noaa.gov/cag/, respectively. Data in Figure 4 is published in Alborzi et al., 2018. Data used in Figure 6 is publicly available from the Food and Agriculture Organization, FAO (http://www.fao.org/).

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