Drought Attribution Studies and Water Resources Management

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INTRODUCTION. Droughts have major effects on society based on their overall impact on water availability for competing sectors and the environment during an event (Bachmair et al. 2016). Agricultural production can decline due to low soil moisture or irrigation-water availability. Energy production can fall due to low reservoir levels in hydropower dams or low streamflow availability for cooling thermal power plants. Water supplies to municipal and industrial users may be reduced due to low streamflow, reservoir, and groundwater levels. Inland navigation can be restricted as water levels in channels drop. Recreational uses of lakes and streams may be hindered with associated economic impacts. Drought also affects water quality as instream flow declines and can affect aquatic ecosystems, fish and wildlife. Droughts lead to low soil moisture and vegetation moisture content, which are associated with increasing wildfire risk, particularly in the American West (Juang et al. 2022). The challenge of water allocation to satisfy all competing demands is made even more difficult during a prolonged drought. A major responsibility of water resources managers everywhere, therefore, is to operate and manage water supply systems in a way that mitigates drought impacts (Tsakiris et al. 2013) to ensure reliable water supplies of sufficient quality for all competing demands. A warming climate adds even more complexity to the challenges associated with effective water management as the frequency and magnitude of drought and other hydrologic extremes change (Cai et al. 2015; Schewe et al. 2014; Wilhite et al. 2020).

This paper discusses how climate attribution science can support water resources management decision making during droughts and is relevant to both the attribution research community and water resource managers. Climate attribution science seeks to explain the causes of extreme events and in particular the possible role of anthropogenic climate change. We identify information that water managers can obtain from climate attribution studies and the types of attribution analyses that will be most useful for drought management with a particular focus on reservoir management.

USE OF DROUGHT INFORMATION IN WATER RESOURCES MANAGEMENT. Water resources managers make long-term plans for drought by looking for alternative sources of water supply and by increasing storage. Managers can also take short-term action when a drought occurs by implementing drought contingency plans to ensure that the most critical water uses are prioritized for water allocation. On the demand side, managers can implement demand reductions in the form of voluntary or mandatory water supply curtailments and by limiting non-essential water use to maintain available water supply for essential use. Three aspects of drought management are particularly important for the attribution community to understand.

a. Water Resources Planning – Estimating Future Supply.

Long-term plans and investments for drought mitigation routinely require estimates of how much water supply or hydropower will be available from storage during extreme drought conditions; these estimates are generally based on historical observations. An important term used by the U.S. Army Corps of Engineers (USACE) related to water availability is "firm yield," which is defined as "the largest consistent flow rate (demand) that can be provided throughout a period of historic stream-flow" (USACE, 2018). The firm yield is limited by the critical period of low flow in the observed record, which varies depending on demands and available storage capacity. In Texas, "firm yield is the maximum water volume a reservoir can provide each year under a repeat of the drought of record using anticipated sedimentation rates and assuming that all senior water rights will be totally utilized, and all applicable permit conditions met." (Texas Water Development Board, 2021). Other organizations define yield based on the annual probability of occurrence that is estimated from the observed record (State of Kansas, 2005). As the climate changes in coming decades, it is likely that current estimates of firm yield underestimate future droughts because of the impacts of warming, higher evaporation rates, and changes in precipitation patterns that are not included in historically-based estimates. Thus, it is important that drought attribution studies include the role of each of these factors in estimating the frequency, intensity, and persistence of future drought events.

b. Reservoir Storage

At the heart of multi-purpose reservoir operations is a balancing act between the fraction of reservoir capacity that is held open to capture excess inflows of water during floods (the flood control space) and a conservation pool used to store water for multiple uses that might be impacted by drought and low flow conditions (Brekke et al, 2009a; Brekke et al, 2009b). Drought information has the potential to inform planning decisions and operating rules for these reservoir storage allocations. First, in long-term planning, if droughts are projected to become more severe, there may be interest in reallocating flood-control storage to expand the conservation pool to provide additional future water supply. However, this reallocation may increase the risk of more flood damages. A second interest is how flood storage varies during the year. In regions of the country where snowpack is a major factor, flood storage is increased during the winter and the conservation pool is then refilled during spring snowmelt. Seasonal flow patterns may change with a warming climate as will be shown below in the discussion of snow droughts. A third possible use of drought information is to inform reservoir operations when a drought is forecasted to occur. For example, a conservation pool could be increased to store more water when a drought is likely. Water managers could temporarily reallocate a small percentage of the flood control space using a deviation from the water control plan in order to respond to unforeseen circumstances (USACE, 2016). However, drought predictions may be quite uncertain, and increases in conservation pool storage come necessarily at the cost of reduced flood-control pools so that this kind of management action can increase the risk for flood damages. Some water supply and hydropower reservoirs do not have flood storage space but can also benefit from drought attribution studies to inform drought responses.

c. Operations - Drought Triggers

The aim of drought responses is typically to ensure that critical needs and demands for water will be met without interruption; as a result, water allocation for non-essential water use may need to be restricted or cut off. The issue becomes identifying the beginning and end of a drought, which can be estimated using a variety of drought indicators, and when and for how long such measures need to be implemented. This is accomplished using drought triggers, which are predetermined threshold values of drought indicators that dictate when drought responses should begin or end (Steinemann et al., 2005). The drought indicator used to trigger action typically depends on the specific sector and water use. For example, agriculture might use an indicator related to soil moisture. Reservoir management might use low reservoir inflows or storage levels or low snowpack volumes to initiate drought plans.

Many droughts are related to long-term climate patterns such as El Niño/Southern Oscillation (ENSO), the Madden-Julian Oscillation (MJO), or other large-scale sea-atmosphere interactions. The status of these climate patterns could be used to condition drought triggers when a drought is more or less likely. Future warming may change precipitation patterns and further complicate our ability to predict these patterns and their connection with droughts particularly with respect to our ability to choose appropriate trigger thresholds.

PREVIOUS DROUGHT ATTRIBUTION STUDIES. Previous essays in Explaining Extreme Events from a Climate Perspective (EEE) provide examples of recent U.S. droughts and associated attribution studies. In such studies, the tension is between contributions from naturally occurring climate patterns and potential contributions from the warming climate. Droughts can be driven by higher temperatures, precipitation deficits, or a combination of the two. Warming temperatures contribute to droughts through increased vapor pressure deficits that result from the fact that the atmosphere can increasingly hold more water; the result is increased evapotranspiration rates and reduced snowpack. Several recent droughts have been exacerbated by higher vapor deficits and evaporative demands (Albano et al., 2022; Williams et al, 2020). Since higher temperatures are a direct result of increasing greenhouse gas concentrations in the atmosphere, droughts due to changing thermodynamic conditions are often easier to attribute to climate change, though there are exceptions (e.g., Swain et al. 2020). Precipitation deficits can be influenced in a warming climate by changing thermodynamic conditions as described above or changing dynamical conditions (via hemisphere and/or regional shifts in atmospheric circulation). Due to the indirect effect of greenhouse gas concentrations on precipitation, the ability to attribute changes in precipitation patterns (and therefore the frequency and intensity of droughts due primarily to precipitation deficits) to climate change is more complex.

Traditionally, droughts have been confronted mostly as precipitation deficits (meteorological drought), which can later lead to deficits in streamflow (hydrologic drought), soil moisture (agricultural drought), and the economic activities of a region (socioeconomic drought). Recent definitions of drought have also considered deficits in the amount of precipitation falling as snow even though total precipitation may be normal or even above normal (snow drought; Harpold et al. 2017), and which may adversely affect the timing and magnitude of winter and spring streamflows. Each of the above types of drought can also be classified as a flash drought, which refers to a drought that occurs quicker than normal due to a combination of multiple hazards, such as low precipitation, clear skies and high temperatures with attendant higher-than-normal evaporative demands (Otkin et al. 2018). The sudden widespread drought of 2012 across the central U.S., for example, is considered a flash drought due to the combination of persistent sunny skies, low precipitation, and high temperatures (Fuchs et al. 2015); over $30 billion of agricultural damages have been ascribed to this flash drought (NOAA NCEI 2022). Recognizing the specific type of drought that is occurring is important due to the way in which each of them manifest themselves, resulting in the need for an appropriate response by water managers. Recent examples of different types of drought are provided below.

a. 2012–15 California Drought (precipitation deficit)

Winter precipitation in California comes from North Pacific storms and atmospheric rivers that are transported eastward under the influence of the North Pacific jet stream. In the drought of 2012-2015, there was a persistent high-pressure anomaly over the northeastern Pacific Ocean, resulting in a blocking pattern that displaced the jet stream, reduced onshore storm arrivals, and caused record low precipitation and high winter temperatures (Swain et al., 2014; Wang and Schubert, 2014; Funk et al., 2014). Swain et al. (2014) concluded that the relationship between the blocking patterns in the northeastern Pacific and California precipitation is well represented in the CMIP5 20th century simulations and the frequency of occurrence of these blocking patterns increased in the 20th century. Wang and Schubert (2014) said "an assessment of the role of the long-term warming trend shows that it forces a high anomaly over the northeast Pacific resulting in less North Pacific storms reaching California," but "also leads to increased atmospheric humidity over the northeast Pacific, thus, facilitating wetter events over California." Funk et al. (2014) found that the long-term warming trend in SSTs did not contribute substantially to the 2013–14 drought although climate models did show warming in the North Pacific SSTs. The difference in the results shows the uncertainty of future climate patterns, which is important information to provide to water managers. The blocking pattern is a condition where California droughts are more likely, and this information could potentially be used by water managers to better inform drought triggers and reservoir storage decisions. Warm conditions over the continent, like those during the 2012–2015 period, increase atmospheric demands for water (essentially, potential evapotranspiration) and are increasingly prevalent (Albano et al. 2022). This means that for every unit of precipitation that falls, less runoff or recharge is typically generated super-charging recent droughts. However, warming will also increase atmospheric humidity leading to wetter events when they occur. Large floods can occur even during drought conditions (Dettinger, 2016). The possibility of large floods even in the midst of drought shows the risk of reallocating reservoir flood storage space to conservation storage. Attribution studies can help water managers to decide whether drought episodes need to be managed one by one, or whether they are harbingers of new “normals” that require more systematic, permanent adaptations. These studies illustrate the complexity of droughts due to the multitude of environmental and meteorological variables. Knowledge of these complexities provides a basis for more informed management and adaptation of reservoir storage allocations between flood management and resource conservation.

b. 2014–15 Snowpack Drought in Washington State.

In many parts of the country, water supplies depend on snowpack. Winter precipitation is stored as snow for months at a time reducing the need for manmade reservoirs. In May 2015, the state of Washington declared a drought emergency because of a remarkable lack of snowpack despite near normal precipitation. The average temperature in the Cascade region during the winter of 2014–15 was the highest on record. According to Fosu et al. (2016) this snow drought was mostly “a result of unprecedented warmth that caused cold-season precipitation to fall as rain rather than snow on the mountains.” The winter had extremely positive sea surface temperature (SST) anomalies off the Pacific Northwest (Fosu et al., 2016). Harpold et al. (2017) described water-supply differences between a "dry" snow drought and a "warm" snow drought. In a dry snow drought, the lack of snowpack is due primarily to a lack of precipitation, and both winter and summer streamflow and water supplies suffer. During a warm snow drought, precipitation amounts may be normal or even high but falls as liquid rain rather than snow, and significant melting of what snow does exist may occur. As a result, winter streamflow is increased, resulting in a depletion of available streamflow and water supply during the following warm season. Both types of snow drought reduce available water to meet water supply needs. Warm snow droughts present a challenge to seasonal reservoir operating plans due to the low snowmelt during the spring season and higher flows in the winter. Attribution studies can explain occurrence of the types of changing temperature and precipitation patterns that drive snow droughts, separating climate-change enhanced episodes versus underlying ocean conditions and blocking patterns. This information can help inform potential adjustments of seasonal reservoir allocations between conservation and flood-control storage.

c. 2017 Northern Great Plains Drought (high temperatures)

Another kind of drought that may become more likely in a warming climate is drought driven or enhanced by increased evaporation. Such a drought occurred in the Northern Great Plains during the spring and summer seasons of 2017. A positive height anomaly stalled over the northwestern United States and the northern Great Plains contributed to the heat wave and resulting drought. Hoell et al. (2019) and Wang et al. (2019) discussed this drought in EEE. Hoell et al. (2019) indicated that anthropogenic greenhouse forcing may have contributed to the intensity of the drought due to increases in evapotranspiration and reductions in soil moisture. Wang et al. (2019) concluded that SST anomalies played a large role in establishing those conditions and that there is “no appreciable increase in the risk of precipitation deficits but an increased risk of heat waves in the northern High Plains” due to global warming. The increased risk of heat waves (and associated increased evaporative demands) increase drought risks and challenges for water managers in at least two ways: by increased occasions of soil moisture deficiencies and by increased evaporation of whatever precipitation does fall. Attribution studies can help resource managers to sort out the natural climate variability and climate-change-driven contributions to evaporative-demand driven future droughts. Water managers can use this information to decide when their firm yields, drought-response triggers, and drought-mitigation actions are becoming out-of-date.

CONCLUSIONS. Historically, drought has been mostly discussed and measured in terms of precipitation deficits. However, increasingly, droughts reflect precipitation deficits but also reductions in snow-water storage and increases in evaporative demands. Consequently, attribution studies need to recognize and include these “new” forms of drought in their scopes. Drought attribution studies show the impact of higher temperatures in combination with precipitation deficits in modern droughts. High temperatures are principal drivers of warm snow droughts and droughts enhanced by increased evaporation. Water managers will increasingly need to reconsider long-term water supply planning and whether estimates of firm yield using historical records are still adequate to estimate water availability for future droughts. Many may also want to consider increasing conservation storage in reservoirs to provide more supply during droughts even if flood risk increases. Balancing competing demands for flood mitigation and drought-mitigating conservation storage emphasizes the need for a risk-based approach to decision-making. Attribution studies can offer important insights into causes and trends that these approaches will need. Water managers may want to update drought triggers to initiate drought contingency plans sooner if higher temperatures in combination with low precipitation and clear skies quicken the onset of drought. By connecting temperature and precipitation patterns to their underlying meteorological drivers (e.g., SST patterns in the Pacific NW) these studies can also help identify early signs of enhanced risk for drought conditions. To be most useful, attribution studies should highlight the climate patterns associated with observed droughts, their predictability, and how they are changing with a warming climate. Drought attribution studies should not restrict themselves to explanations of precipitation deficits. Climate scientists and water managers need to continue to improve communication to better understand drought causes and which specific kinds of information are needed to improve water management.

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