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FOCUS ARTICLE

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Data availability and sector-specific frameworks restrict drought impact quantification in the Intermountain West

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Abstract

As is the case for many semi-arid regions globally, drought in the Intermountain West of the United States is a recurrent, costly phenomenon that leaves few aspects of human and natural systems untouched. Here, we focus on drought impact data and evaluation challenges across four non-agricultural sectors: water utilities, forest resources, public health, and recreation and tourism. There are marked commonalities in the way drought indicators—that is, hydrometeorological conditions—are tracked, but considerable differences in how impacts are measured, evaluated, and disseminated. For drought indicator data, researchers and practitioners have a veritable smorgasbord of data at their fingertips. Such data are often spatially and temporally continuous, available at a wide variety of scales, and readily accessible through government-funded online portals. This is in stark contrast to drought impact data, which are typically collected opportunistically, if at all. These data are thus often limited in spatiotemporal scope and difficult to access relative to drought indicators. Concerningly, even within a given sector, the definition of drought impacts, quantitative or otherwise, can vary considerably, making it difficult to evaluate the true cost of drought. Far from being specific to the Intermountain West, these problems are found in most regions experiencing drought. We suggest such challenges are surmountable through the development of a common drought impact framework based around economic damages and purposeful, continuous, government-funded drought impact data collection. These tractable changes will allow for a better quantification of drought's true impacts under both present conditions and climate change scenarios in the Intermountain West and beyond.

This article is categorized under:

Human Water > Value of Water
Science of Water > Water Extremes
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KEYWORDS

climate, data, drought, economic impact, natural hazard

1 | MOTIVATION

Long-lasting, costly, and spatially extensive, droughts exact an enormous toll on human and natural systems (Ding et al., 2011; Wilhite et al., 2007). In a previously published review article, we detailed how water utilities, forest resources, recreation and tourism, and public health suffer drought's effects in the Intermountain West (IMW) of the United States (Wlostowski et al., 2021). This semi-arid, mountainous area is highly exposed to drought as a result of its large and growing population, low annual precipitation (Wise, 2012), the overallocation of limited surface water supplies (Adler, 2008), the importance of water-reliant industries to the regional economy (Wlostowski et al., 2021), and the effects of climate change (Rajagopalan et al., 2009). Spanning a wide elevation extent and a gradient of hydroclimatic conditions, the IMW has experienced recurrent droughts throughout the observed record, including, notably, the 1930s Dust Bowl, the 1950s drought, and ongoing droughts since 2002 that may be part of an emerging, long-term mega-drought (Williams et al., 2020). Although much of the material covered within this article focuses on the IMW, the main lessons and arguments can be applied to any region experiencing drought's ill effects.

Drought conditions in the IMW, as in other semi-arid, mountainous areas, evolve following a general pattern (Wlostowski et al., 2021). Drought typically begins with below-average winter snowfall and reduced snow accumulation (Harpold et al., 2017; Mote et al., 2018), making snowpack a key predictor of seasonal drought conditions (Livneh & Badger, 2020). As diminished snowpacks begin to melt, which they do earlier than normal, soil moisture increases but not to the degree and over the same duration as it would in non-drought years (Harpold & Molotch, 2015). Next comes lower-than-average streamflow (Udall & Overpeck, 2017; Xiao et al., 2018), followed by summer moisture stress in vegetation (Knowles et al., 2018) and lower than normal fuel moisture contents (Bessie & Johnson, 1995; Gedalof et al., 2005; Kulakowski & Jarvis, 2011; Turco et al., 2018). At the same time, water quality parameters in streams, lakes, and reservoirs are likely to degrade (Mosley, 2015) while airborne dust and wildfire smoke fill the air (Achakulwisut et al., 2018; Burke et al., 2020). Once the water year nears its completion in the fall, the land is desiccated, awaiting a new winter of hopefully normal snowfall.

Throughout this evolution, researchers and government agencies can track drought's progression using clearly definable indicators—that is, quantifiable hydrometeorological metrics (Bachmair, Stahl, et al., 2016; Zargar et al., 2011). These indicator data can consist of direct meteorological quantities such as precipitation and air temperature or derived variables such as the Palmer Drought Severity Index (PDSI; Palmer, 1965). Critically, the indicator data used in most research is freely available through online portals supported by government agencies, making them relatively easy to quantify and access.

Ultimately, however, human and natural systems experience drought not as hydrometeorological conditions but as impacts. In the IMW, the transition from a physical phenomenon to a societal one follows a series of cascades linked to drought indicators (Figure 1). Reduced mountain snow accumulation corresponds to reduced ski area visitation along with reduced revenue for the resorts and their towns (Hagenstad et al., 2018). Low snow portends low streamflow, meaning rafting, kayaking, and fishing enthusiasts will have less than desirable conditions. This in turn translates to fewer user days, less spending, and reduced consumer surplus (Leones et al., 1997; Loomis & McTernan, 2014). The same below-average streamflow challenging the recreation and tourism industry also threatens the abilities of many water utilities to fill their reservoirs and ditches (Rajagopalan et al., 2009). Reduced revenue and increased costs are the result (Dilling et al., 2019).

Early snowmelt and low summer rainfall leave forests parched, leading to losses in ecosystem services (Crausbay et al., 2017), widespread forest mortality, and heightened risk of extreme wildfires (Abatzoglou & Williams, 2016; Westerling, 2016). The latter may again reduce recreational opportunities as parks close (Franke, 2000; Wilhelmi et al., 2008) and smoke makes outdoor activity difficult, particularly for those with breathing problems (Alman et al., 2016). Human health risks may also result from increased airborne dust, harmful algal bloom outbreaks, and elevated summer air temperatures (Stanke et al., 2013), all of which are more probable during drought.

This article is motivated by the two notable differences between drought indicators and impacts. One, accessing indicator data is a straightforward process through centralized repositories, but it is markedly more complicated to find impact data if they are collected at all. Two, researchers can often utilize and compare drought indicator data across different disciplines and industries, while impact data are highly specific to a given field or even subfield. Thus, while we can define drought magnitude in terms of hydrometeorological conditions using a clearly defined framework, we cannot easily quantify drought's impact because of data availability and transferability issues.

In this article, we take a closer look at drought research synergies, information gaps, and opportunities. Specifically, in Section 2 we discuss commonalities in drought indicator data across four sectors: water utilities, forest resources,

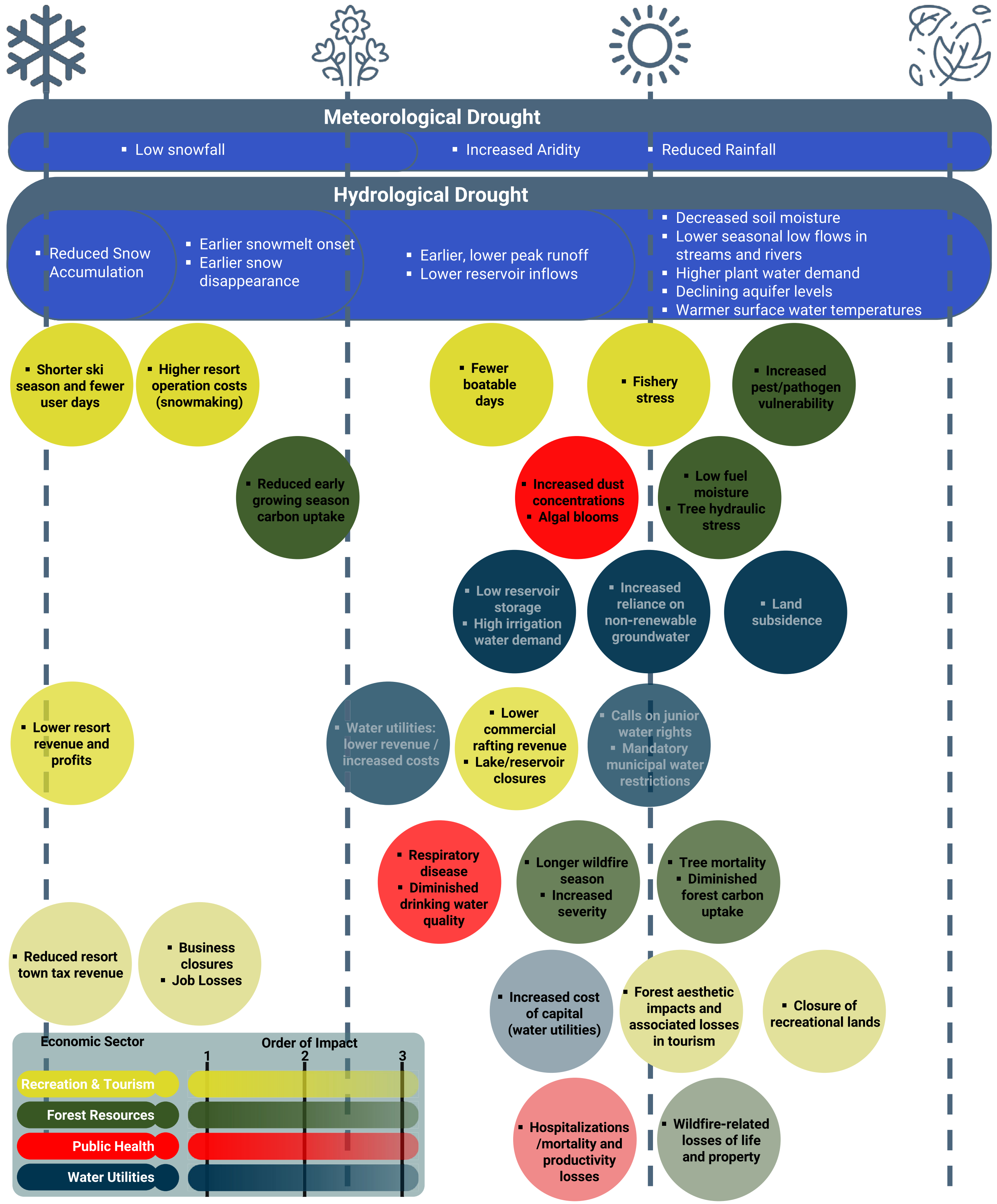

FIGURE 1 Schematic linking drought indicators (blue boxes) to impacts (colored circles) in the IMW region of the United States. In the figure, time moves from left to right with the symbols denoting the seasons (snowflake = winter, flowers = spring, sun = summer, leaves = fall). The shading of each circle and its vertical position represents the order of impact, where first-order impacts are a direct result of a worsening drought indicator. Second-order impacts are then a result of the first-order impact and so on

recreation and tourism, and public health. In this article, we refer to these groups as sectors, while subsector corresponds to a specific entity within a larger grouping. We define the ski industry, for example, as a subsector of recreation and tourism. Notably, we do not cover agriculture in this focus article given its in-depth coverage by other reviews and the wide availability of impact data. Next, in Section 3, we evaluate how a common framework could improve the quantification of drought impacts. Finally, in Section 4, we highlight shortcomings in drought impact data collection and suggest a path forward.

2 | DROUGHT INDICATOR DATA SYNERGIES

2.1 | Indicator data by sector

To evaluate commonalities in drought indicator data, we quantified the proportion of literature from the Wlostowski et al. (2021) drought review that used such data in the four previously introduced sectors: water utilities, forest resources, recreation and tourism, and public health. Indicator data include hydrometeorological variables such as precipitation, air temperature, streamflow, and soil moisture, as well as derived drought metrics and other variables that quantify drought magnitude and/or duration. For each article, we noted whether it considered or evaluated indicator data in a quantitative way.

We found that researchers across the four sectors generally used drought indicators in their work, with 155 out of 280 articles referring to these data in some form. Per-sector utilization ranged from a minimum of 41.2% for public health articles to a maximum of 63.4% for those on water utilities. The former sector was the only one where less than 50% of the reviewed literature utilized hydrometeorological data, with forest resources and recreation and tourism coming in at 51.2% and 62.2%, respectively.

In many cases, the various sectors used similar drought indicators, underscoring their transferability in understanding drought conditions. Unsurprisingly, at least some of the reviewed literature in each sector included keystone meteorological quantities like air temperature and precipitation. This finding also applied to some of the more common derived drought metrics. PDSI and the Standard Precipitation Evapotranspiration Index, for example, could be found in reviewed literature for multiple sectors.

2.2 | Indicator data availability

In addition to the commonalities in drought indicator usage, we found it was typically straightforward to discover and access these data for further analysis. Take PDSI as an example. A simple internet search produces links to background information on the index, online dashboards for live views of current drought conditions, and repositories where users can access gridded PDSI data. This latter point, that data are easily accessible, strongly supports the use of drought indicator data in research and operations (Abatzoglou et al., 2017; Bachmair, Stahl, et al., 2016; Noel et al., 2020; Svoboda et al., 2002). Table 1 shows a small selection of freely available drought indicator data along with their spatial and temporal resolutions, the time spans they cover, and an example source for the data. This reveals a pattern of accessibility at online domains either run by US government agencies or supported by federal research grants.

Furthermore, these publicly accessible drought indicator data come in a multitude of spatial extents and resolutions, from a selection of point locations to high-resolution, gridded continental datasets. They also are available at time extents and resolutions conducive to both long-term studies and sub-annual time series analyses. Many of them additionally meet the FAIR data guidelines, an acronym that corresponds to findable, accessible, interoperable, and reusable (Wilkinson et al., 2016). In no uncertain terms, the ubiquity of freely available, easy-to-download drought indicator data is a boon to the field of drought research.

Another important facet of these drought indicator data is that many of them can be directly adjusted to account for climate change or can be derived from climate models (e.g., Mishra & Singh, 2011). In general, researchers expect the coming decades to bring increases in drought severity and frequency, which are linked to rising air temperatures, reduced precipitation, and increased atmospheric moisture demand (Douville et al., 2021). These first-order variables come directly from the climate models, while hydrologic and land surface models can be run with prescribed future scenarios to estimate how snow accumulation, soil moisture, or streamflow may change in the future (e.g., Christensen & Lettenmaier, 2007). Importantly, future drought indicator data derived from climate model projections are directly

TABLE 1 Information on drought indicator data

Drought type	Data	Spatial resolution	Temporal resolution	Temporal extent	Source
Meteorological	Climate (e.g., air temperature and precipitation)	4 km	Daily and Monthly	1981–present (daily), 1895–present (monthly)	gridMET and PRISM
	Palmer drought severity index	4 km	Monthly	1895–present	Westwide Drought Tracker
	Palmer *Z*-index	4 km	Monthly	1895–present	Westwide Drought Tracker
	Standardized precipitation-evapotranspiration index	4 km	Monthly	1895–present	Westwide Drought Tracker
	Standardized precipitation index	4 km	Monthly	1895–present	Westwide Drought Tracker
	Aridity Index	4 km	Monthly	1895–present	Derived from climate data
Hydrologic	Groundwater well levels	Point	Daily	Varies by well	USGS and DWR
	Streamflow	Point	Daily	Varies by stream gauge	USGS and DWR
	Snowpack water storage	Point	Daily and monthly	1980–present (daily), 1936–present (monthly)	SNOTEL
	Snow cover extent	500 m	Seasonal	2000–present	NSIDC
	Streamflow drought index (Nalbantis & Tsakiris, 2009)	Point	Monthly	Varies by stream gauge	Derived from gauge data
	7Q10 low flow metric	Point	Monthly	Varies by stream gauge	Derived from gauge data
	Soil moisture percentiles	25 km	Daily	2000–present	NWS Climate Prediction Center

Note: The source given is an example—There are often several different repositories for each indicator.

comparable to historic observed and modeled data (e.g., Wehner et al., 2017). Thus, the shared approach to drought indicators allows researchers to quantitatively assess potential future droughts and how they relate to historical conditions.

3 | LACK OF COMMON DROUGHT IMPACT FRAMEWORK

3.1 | Common framework challenges

In contrast to the commonalities in drought indicators, we found drought impacts were often specific to the sector, or even subsector, being studied. In this context, there was no common framework that could convert impact observations or reports into comparable values across spatial and temporal scales and sectors as is done for indicator data. Although framework can have myriad definitions, here we refer to the conceptual model that allows researchers to quantitatively relate drought conditions to the magnitude of drought impacts. An example framework comes from the rafting subsector of recreation and tourism where the known preference of rafters for moderate flow conditions (Stafford et al., 2017) allows researchers to project user day losses and revenue declines as a function of drought-caused low streamflow (Leones et al., 1997; Loomis & McTernan, 2014).

However, even in this framework example, a variable response to conditions complicates matters. In some cases drought-caused reductions in streamflow on one river reach may lead to a sharp decline in rafting user days while another reach remains relatively unaffected by the same flow reduction (Leones et al., 1997). Adding to the complexity of creating a single subsector framework is that rafting industry researchers use a variety of metrics to define impacts: in addition to lost user days, researchers also use preference changes and consumer surplus losses to define the effect of flow reductions (Loomis & McTernan, 2014; Stafford et al., 2017). Thus, even within a single subsector of recreation and tourism, the impact of drought can be challenging to quantify and even harder to compare across locations and/or times.

In other cases, frameworks computing non-market drought impacts such as increased forest mortality may be more intuitive—that is, human decision making does not come into play as it does in the rafting example—but the second-order societal impacts are less clear. This makes quantifying the full range of drought impacts challenging, particularly when different conceptual models and impact types (e.g., ecosystem services, biodiversity, and human health) come into play across the various sectors. For example, how does one compare the impact of reduced streamflow on rafting enjoyment with increased forest mortality and biodiversity loss, or compare increased asthma hospitalizations with failures to deliver water allocations?

3.2 | Common framework proposal and examples

We recognize that dissimilar variables from the different sectors will never be directly comparable. In other words, there is no forest mortality equivalent to reduced rafting enjoyment, nor is there a common unit shared between hospitalizations and water allocations. However, given that at least some of the literature for each sector includes economic damages in dollars, we propose that the monetization of impacts is one way to produce a cross-sector drought impact framework. Thus, finding ways to monetize impacts may help to compare across sectors and improve understanding of drought impacts in the IMW and beyond (Costanza et al., 1997; Daly & Farley, 2004; U.S. Environmental Protection Agency, 2017).

In the most straightforward cases, the framework will be a conceptual linear model that links an observed drought impact (e.g., declines in rafting user days) to a known valuation (e.g., the amount in US dollars each rafter spends per user day) to compute the total monetized impact for a given subsector, location, and time. This can take the form of a simple equation:

$$D = I_{\mathrm{obs}} \times V \tag{1}$$

where D is the calculated damages in US dollars, I_{obs} is the observed impact in a unit specific to the subsector, and V is the valuation scalar in US dollars per impact unit given in I_{obs}. To extend the rafting example, a hypothetical decline of 1000 user days (I_{obs}) would lead to computed damages (D) of \$100,000 when V corresponds to \$100 per user day. (*Note*: US dollars is used here for the IMW, but any national currency can be substituted into the framework.)

In some cases, there will be insufficient observed impact data (I_{obs}) to compute D in Equation (1). As we will discuss further in Section 4 below, impact data are often collected in an ad hoc manner, meaning that I_{obs} may not be available for a given combination of subsector, time, and/or location. Thus, we will need to draw on modeled relationships between drought indicators and drought impacts:

$$I_{\mathrm{est}} = C \times R \tag{2}$$

where I_{est} is the estimated drought impact in a unit specific to the subsector, C is the drought indicator value for current conditions (unit dependent on indicator being used), and R is the empirically derived response scalar in units of I_{est} per drought indicator unit. I_{est} can then be substituted for I_{obs} in Equation (1). This means if previous research produced an empirically derived R value of -100 user days per 1 m^3/s decline in streamflow, we would predict an I_{est} of -1000 user days when C corresponds to a 10 m^3/s streamflow loss. Where possible, we recommend that site- or region-specific R values be used in the framework to account for variations in impact response to drought conditions.

As an example of such a framework in action, the Colorado Water Conservation Board (CWCB) recently evaluated the state's economic exposure to various natural hazards under baseline conditions as well as climate change and population growth scenarios (CWCB, 2020). A key part of the study was the conversion of drought, flood, and wildfire conditions (i.e., indicators) to impacts expressed in the common unit of expected annual damages in 2019 US dollars. This process required the creation of a standard framework that incorporated indicator data, first- and second-order impact data, and empirical models that converted impacts to economic damages as a function of prevailing drought, flood, or wildfire conditions. Thus, although the impact data were unique to the hazards, the shared economic damage framework allowed for aggregating impact assessments across hazards and sectors.

An additional common framework example is the NOAA National Centers for Environmental Information (NCEI) Billion Dollar Disaster database, which collates economic damages from natural disasters (NCEI, 2020; Smith & Matthews, 2015). Cost estimates of drought impacts can also be found in post hoc reports that cover individual sectors (Howitt et al., 2017) or broader swaths of the economy (Luecke et al., 2003; Ryan & Doesken, 2013). However, such reports may not be peer reviewed, the underlying data may be difficult to access, and they serve as a one-time snapshot and not a continuous reporting of drought impacts. A common drought impact framework will face other important limitations.

3.3 | Common framework limitations

A general economic impact framework carries the risk of viewing drought through a strictly human-centric lens and undervaluing the natural capital of ecosystems affected by drought (Crausbay et al., 2017; McEvoy et al., 2018; Raheem et al., 2019). The estimation of economic damages may obfuscate other critical drought impacts such as habitat losses, biodiversity declines, and reduced ecosystem functioning. It may also provide more weight to locations with greater economic activity if vulnerability is not explicitly taken into account (Liu & Chen, 2021), perpetuating patterns of socio-economic inequality (Howell & Elliott, 2019).

Additionally, the framework cannot say who bares the financial burden. Research on other natural disasters shows that the availability of public and private insurance programs means that insurers, landowners, businesses, the government, or some combination thereof ultimately pay for the damages (Kunreuther & Richard, 1998). In a similar vein, a common framework may not include impacts from regionally important sectors that would be affected by drought conditions. This means a true accounting of drought's cost and identifying who covers the damages will be a formidable challenge.

Another limitation of such a framework is that the calculation of economic damages in dollars will be relatively uncomplicated for some sectors but not for others. The winter sports industry, for example, lends itself well to computing direct quantitative linkages between indicators and impacts. Declines in user days as a result of drought conditions can be linked to daily spending profiles to quantify declines in revenue (Hagenstad et al., 2018). In other cases, conversions between first-order drought impacts and economic damages will be less straightforward and often subjective. For forest resources, researchers may convert non-market impacts such as tree mortality to economic damages based on affected area, reduced timber sales, and/or the value of lost ecosystem services (Vose et al., 2016).

It will also be important to consider that true indicator–impact relationships may be more complicated than the two simple linear equations we presented in Equations (1) and (2). Conversions between observable impacts and damages in dollars or between drought indicators and modeled impacts may therefore require non-linear equations, threshold values, or complex empirical methods such as machine learning (Bachmair, Svensson, et al., 2016). We also suggested the use of site-specific valuations; however, this may prove exceedingly difficult for some sectors and locations. Researchers may choose instead to use broadly applicable empirical values from the literature (e.g., Hogeboom et al., 2018) and adapt them to local conditions, if possible, using benefit transfer models (e.g., Loomis, 1992; Shrestha & Loomis, 2001). When applying such models it will be important to consider changes in spatiotemporal scale.

Despite the challenges and limitations of common framework built around economic damages, we feel it would advance the accounting of drought's true costs by quantifying connections between drought indicators and impacts and identifying critical drought thresholds (Bachmair, Svensson, et al., 2016). Another advantage of this quantitative approach is that it allows for climate change analyses where potential future drought impacts can be compared with baseline conditions as is already done with drought indicators (Section 2).

4 | AD HOC DROUGHT IMPACT DATA COLLECTION

4.1 | Sector-specific impact data collection

One of the biggest impediments to the creation of a cross-sectoral drought impact framework is the ad hoc collection of drought impact data (Ding et al., 2011). From a quantitative perspective, it is often easier to track drought indicators than drought impacts (Liu et al., 2020). To illustrate the difference, we can examine the recreation and tourism industry. For this sector, important drought indicator data, such as snow accumulation, streamflow, and air temperature, are available via government-supported online portals (Table 1). Impact data, however, are more difficult to access. Annual ski resort user days, for example, are tracked by the National Ski Areas Association and are reported by multistate regions as the finest publicly available resolution (NSAA, 2021). Rarely are user days publicly given at the state or resort level and not every resort participates (Hagenstad et al., 2018; Wobus et al., 2017).

In Colorado, commercial rafting user days are collected by the non-profit Colorado River Outfitters Association per river basin (CROA, 2018). This contrasts with non-commercial rafting, where data for a given reach may be collected by one of a multitude of organizations, if it all. In some cases, researchers may use surveys to estimate non-commercial rafting user days (Loomis & McTernan, 2011; Stafford et al., 2017), but these are typically done by necessity on a one-off basis for individual rivers or segments and may not be publicly available. In other cases, the government agency with jurisdiction over a given river may collect user day data, but these values may be infrequently collected, difficult to locate, or outdated (e.g., U.S. Forest Service, 1990). However, when up-to-date user day data do exist, they are invaluable in estimating the first-order impacts of drought on recreation and tourism, which are often realized as declining participation and visitation. These then translate to second-order impacts associated with economic damages, including reduced hotel stays, employment, and visitor spending (Thomas et al., 2013).

This recreation and tourism example highlights the fact that if quantitative data are collected and made freely available, they are often only for a single sector or subsector, potentially covering a limited spatial extent. In many cases, publicly accessible data may be confined to a single government agency's purview. For example, the U.S. National Park Service collects and publishes extensive monthly visitation data across its entire network (National Park Service, 2021), allowing researchers and practitioners to track changes in park visitation. When using only this dataset, researchers cannot get the full picture of how regional-level parks visitation varies during drought. If individuals substitute visits to their local low-elevation state park with visits to the high-elevation National Park during extended periods of hot dry weather, then findings based only on the National Park data might suggest visitation increases during drought (Richardson & Loomis, 2005). Similarly, potential visitors to drought-affected mountain resorts may choose to substitute a winter ski visit for a summer mountain biking one (Steiger et al., 2019). Thus, it would be necessary to aggregate data across multiple federal, county, state, and local agencies along with businesses and industry organizations to get an inclusive view of how drought impacts recreation and tourism. In many cases these data are accessible only through direct contact with the groups themselves, or they are not available at all.

For some sectors, spatially and temporally continuous impact data may be available, but these are often first-order impacts that require interpretation to produce societally meaningful values. For forest resources, there is an online database with annual maps of forest mortality resulting from bark beetles and wildfire (Berner et al., 2019). However, these data sources do not indicate the number of homes burned, the total costs of wildfire suppression, or the lost value of harvestable timber nor do they indicate the non-market losses to ecosystem services and human wellbeing. Similarly, users may access information on reservoir pool levels over much of the IMW, but such values do not directly correspond to lost water utility revenue and/or water deliveries. In some states, there are water availability task forces (CWCB, 2018) that translate measurable drought-imposed declines in water supply into human impacts. Often, however, meaningful impacts are tracked by the utilities themselves and their challenges may not be shared with the broader public or research community.

4.2 | Impact data collection examples

That is not to say there are not coordinated impact data collection efforts. In the United States, the Drought Impact Reporter produced by the National Drought Mitigation Center (NDMC) is an invaluable resource for collecting past and present information on drought impacts (Noel et al., 2020; Svoboda et al., 2002). To create the database behind their online tool, the Center harvests reports from the news media, federal agencies, volunteer submissions, and other networks. Users can access these reports directly in near real time or view synthesized impacts produced from the reports. This means much of the impact data tend to be qualitative and reported after the fact, which conflicts with the continuous, quantitative reporting of drought indicators. This mismatch in data type and availability hinders attempts to make quantitative predictions of drought impacts across large geographic domains and a continuous range of drought indicator values using mathematical models (Bachmair, Svensson, et al., 2016).

The NDMC also hosts the Drought Impacts Toolkit, which is an online portal containing links to other web resources, impact reports, and drought assessments (NDMC, 2022). Similarly, the National Integrated Drought Information System (NIDIS) hosts synthesis products, reports, and links to data from other agencies (NIDIS, 2021). The Drought Impacts Toolkit and NIDIS are important clearinghouses for drought information, but they face the same challenges as other programs in that the data provided to them may be qualitative, not collected continuously, and do not share a common analysis unit or framework (e.g., economic damages as discussed in Section 3). Additionally, they both link to external resources, requiring the user to access multiple databases for impact observations.

Another data source is the U.S. Department of Agriculture's (USDA) National Agriculture Statistical Service (NASS). Although it does not explicitly produce and disseminate drought impact data, it does provide timely, freely available quantitative information at multiple spatial and temporal discretizations (USDA, 2020). Thanks to its near-real-time synthesis of survey, economic, and geospatial data, NASS has become indispensable to agricultural drought research (e.g., Al-Kaisi et al., 2013). In this context, NASS serves as an example of what a one-stop drought impact data repository could look like.

4.3 | A combined drought impact data portal

Given the success of government agencies in disseminating drought indicator data (Section 2), a federally funded NASS-like program for quantitative drought impact data is long overdue. At minimum, the program should include a free, publicly accessible drought impact data portal. The supporting database should provide, whenever possible, continuous data summarized at multiple temporal and spatial resolutions (e.g., weekly to monthly local, state, and regional park visitation statistics). All data should also correspond to the FAIR guidelines introduced earlier to ensure ease of access, identifiability, and reproducibility.

Ideally, federal funding will ease the burden of quantitative drought impact data reporting and distribution. The submission of impact data to the portal ought to be as simple as possible with dedicated employees that manage the collection process. Although potential drought impacts are numerous, Wlostowski et al. (2021) indicated a selection of broad impact categories for each of the sectors that may serve as a starting point for the database (Table 2). In some cases, these include non-market drought impacts such as quantitative measures of damages to human health and ecosystem services, while in other cases it may be necessary to establish new quantitative metrics of human and ecosystem wellbeing.

For some impacts, continuous, quantitative data collection already occurs, in which case the program should also automatically ingest available data produced by other groups. In other cases, additional time and financial resources will be needed to collect and synthesize data, a task requiring engagement with multiple agencies, non-governmental organizations, and private businesses. These include but are not limited to the following: the National Park Service; Bureau of Reclamation; U.S. Geological Survey; Bureau of Land Management; U.S. Forest Service; tribal agencies; city, county, and state parks agencies; public water utilities; state water resources boards; public health agencies; recreation groups such as the NSAA or American Whitewater; ski areas; commercial rafting outfitters; and others.

This list of potentially contributing groups highlights the fact that drought is a nationwide challenge. As such, we suggest the program should have a national scope so that users can access drought impact data for their region(s) of interest. Such users may include researchers, water resources managers, economists, public health professionals, and business analysts, among many others. We envision most users requiring quantitative data to better understand and evaluate their exposure and sensitivity to drought. Although an impact data collection and dissemination program will

TABLE 2 A preliminary list of variables that may be included in a drought impact database

Sector	First-order impacts	Second-order impacts	Third-order impacts
Water utilities	Water supply Irrigation demand	Calls[a] Infrastructure damage	Costs revenue
Forest resources	Moisture stress	Wildfire Vegetation mortality Ecosystem service losses	Property damage Suppression costs
Recreation and tourism	User days Season length	Revenue Costs Consumer surplus	Closures Job Losses
Public health	Water quality Air quality	Disease Mental health	Hospitalizations Deaths Productivity

[a]A call is a request from a senior water rights holder to a junior water rights holder or holders (i.e., those whose water rights are more recent) that the latter individual or group stop using or diverting water. Calls may occur during drought, leading to only those with senior water rights receiving their legally prioritized water allocations.

benefit myriad groups, it may still miss important data points, struggle with qualitative survey data, and express changes in impact variables that are not solely attributable to drought. Despite these potential shortcomings, a dedicated program will provide a step in the right direction for quantitative drought impact analysis.

5 | CONCLUSION

Similar to other semi-arid, mountainous regions, drought in the IMW evolves from measurable hydrometeorological conditions to harder-to-quantify impacts, leaving few economic sectors untouched. Often, researchers deploy freely available, temporally continuous, spatially extensive, and transferrable indicator data to track drought conditions. Consistent, quantitative definitions of drought impacts, however, were lacking. In fact, in the articles we evaluated, economic damages were the only impact types to be found in our four selected sectors: water utilities, forest resources, recreation and tourism, and public health. Past this, most work defined drought impacts using a framework, or conceptual model, specific to their economic sector.

We are therefore faced with a multifaceted problem: (1) drought impact data are collected opportunistically; (2) there are few cross-sector quantitative impact data sources; and (3) it is often necessary to translate first-order drought impacts into societally meaningful values. These challenges, in turn, highlight two key opportunities moving forward: the development of a common drought impact framework and improved, more purposeful drought impact data collection. For the former, we suggest creating conceptual models that define drought impacts in terms of economic damages using sector- and location-specific valuations. Although such an approach will have shortcomings, it will enable a more complete accounting of drought impacts, comparisons across sectors, and the inclusion of climate change analyses.

For the latter opportunity, current publicly available drought impact data are often qualitative with the burden of reporting typically placed on those experiencing the impact. Given the vast, cross-sectoral impacts of drought in the IMW, we advocate for a government-funded program that collects and freely disseminates quantitative drought impact data. Ultimately, the creation of transferrable drought impact frameworks supported by coordinated drought impact data collection may facilitate community-wide recognition of historical impacts and bring about the potential to avoid future damages with better analytics.

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CONFLICT OF INTEREST
The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS
Keith S. Jennings: Conceptualization (supporting); data curation (equal); formal analysis (equal); funding acquisition (supporting); investigation (equal); methodology (equal); writing – original draft (lead); writing – review and editing (lead). **Adam N. Wlostowski:** Conceptualization (lead); data curation (equal); formal analysis (equal); funding acquisition (lead); investigation (equal); methodology (equal); project administration (lead); supervision (lead); writing – original draft (supporting); writing – review and editing (supporting). **Rachel E. Bash:** Data curation (equal); formal analysis (equal); investigation (equal); methodology (equal); writing – original draft (supporting); writing – review and editing (supporting). **Jesse Burkhardt:** Conceptualization (supporting); data curation (equal); formal analysis (equal); funding acquisition (supporting); investigation (equal); methodology (equal); writing – original draft (supporting); writing – review and editing (supporting). **Cameron W. Wobus:** Conceptualization (supporting); project administration (supporting); supervision (supporting); writing – review and editing (supporting). **Graeme Aggett:** Conceptualization (supporting); funding acquisition (supporting); project administration (supporting); supervision (supporting); writing – review and editing (supporting).

DATA AVAILABILITY STATEMENT
Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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