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Article title: Drought indicators revisited: the need for a wider consideration of environment and society

Authors:

Full name and affiliation; email address if corresponding author; any conflicts of interest

Sophie Bachmair*	[Hydrology, Faculty of Environment and Natural Resources, University of Freiburg, Germany; sophie.bachmair@hydrology.uni-freiburg.de]
Kerstin Stahl	[Hydrology, Faculty of Environment and Natural Resources, University of Freiburg, Germany]
Kevin Collins	[Open University, Milton Keynes, United Kingdom]
Jamie Hannaford	[Centre for Ecology & Hydrology, Wallingford, United Kingdom]
Mike Acreman	[Centre for Ecology & Hydrology, Wallingford, United Kingdom]
Mark Svoboda	[National Drought Mitigation Center, University of Nebraska-Lincoln, USA]
Cody Knutson	[National Drought Mitigation Center, University of Nebraska-Lincoln, USA]
Kelly Helm Smith	[National Drought Mitigation Center, University of Nebraska-Lincoln, USA]
Nicole Wall	[National Drought Mitigation Center, University of Nebraska-Lincoln, USA]
Brian Fuchs	[National Drought Mitigation Center, University of Nebraska-Lincoln, USA]
Neville D. Crossman	[CSIRO Land and Water, Adelaide, SA, Australia]
Ian C. Overton	[CSIRO Land and Water, Adelaide, SA, Australia]

Abstract

[Drought indicators are proliferating, but with little consideration of which are most meaningful for describing drought impacts. A number of recent reviews compare different drought indicators, but none assess which indicators are actually used in the many operational drought monitoring and early warning efforts, why they were selected, or whether they have been 'ground-truthed', i.e., compared with information representing local drought conditions and/or impacts. Also lacking is a comprehensive assessment of the state of monitoring of drought impacts. To help fill this gap, we combine a review of drought indicators and impacts with a survey of 33 providers of operational drought monitoring and early warning systems from global to regional scales. Despite considerable variety in the indicators used operationally, certain patterns emerge. Both the literature review and the survey reveal that impact monitoring does exist but has rarely been systematized. Efforts to test drought indicators have mostly focused on agricultural drought. Our review points to a current trend towards the design and use of composite indicators, but with limited evaluation of the links between indicators and drought impacts. Overall, we find that much progress has been made both in research and practice on drought indicators, but monitoring and early warning systems are not yet strongly linked with the assessment of wider impacts on the environment and society. To understand drought impacts fully requires a better framing of drought as a coupled dynamic between the environment and society.]

Introduction

[Drought poses a threat to water and food security, to every water-use sector, and thus to livelihoods, in virtually every climate zone. In recent years, a number of major droughts have revealed the vulnerability of even wealthy societies to drought and caused conflicts among water users. Drought can perturb the environment, at least temporarily, with a reduction in ecosystem condition and resilience and a loss of ecosystem services. With climate projections suggesting that droughts will intensify in many regions[1] the magnitude of drought and associated impacts is likely to increase. At the same time, drought is an elusive phenomenon that differs substantially from other natural hazards, making its management a challenging task.[2] First, it is a slowly developing hazard without a distinct onset and end; second, it is not precisely and universally defined[3,4]; third, drought is multifaceted, affecting different parts of the hydrological cycle, ecosystems and sectors of society; and fourth, impacts of drought are often non-structural and difficult to quantify or monetize.[5,6]

While little can be done to prevent low precipitation, drought monitoring and early warning can lessen societal vulnerability by providing more lead-time for responding to drought, planning responses and avoiding a potential crisis situation. A drought early warning system (DEWS)[7,8] consists of monitoring and early warning components. According to the World Meteorological Organization (WMO) a drought monitoring system should track, assess and report climate and water supply trends and current conditions (e.g., rainfall, reservoirs, impacts, etc.).[9] An early warning system is the "set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss".[10(p12)] DEWS are therefore not limited to monitoring and forecasting but may also include further components – for example, capacity to disseminate information via communication networks, or assessment of response and management options alongside the measuring of the current water situation. The design of a DEWS is complicated by the lack of a universal drought definition (see Belal et al.[11] for a selection of drought definitions). Generally, two types of drought definitions can be distinguished: conceptual and operational.[3] Conceptual definitions aim to explain the general idea. For instance, drought is a "deficiency of precipitation from expected or 'normal' that, when extended over a season or longer period of time, is insufficient to meet demands”.[12(pA-1)] Operational definitions, in contrast, are targeted towards determining drought onset, severity, and termination for practical applications (e.g., declaration of drought or activation of drought plans for response and mitigation measures).

Operational definitions are typically based on the use of drought indicators. Identifying and selecting appropriate drought indicators for DEWS is complicated by multiple ways of thinking about droughts. Wilhite and Glantz[3] differentiate four types of drought – meteorological, agricultural, hydrological, and socio-economic – to describe the propagation of precipitation deficits through the hydrological cycle and its impacts. Over time, several sub-types have been proposed. For example, groundwater drought is treated as an additional category, but it has also been subsumed under hydrological drought (see Wilhite and Glantz[3] or Mishra and Singh[13] on drought types). Another proposed type is ecological drought, although there is a dearth of information on this type despite some ecological metrics being implicit in economic indicators. A vast range of drought indicators has been proposed (>100 according to Lloyd-Hughes[4]) or are used in operational DEWS for monitoring different types of drought in various regions and for different purposes. In addition, novel indicators are frequently published. A recent trend, aimed at capturing a more integrated picture of the drought hazard, has been the design of composite indicators.[14] Such indicators include multiple types of data.

There is little consensus on which indicators are most meaningful for the measurement of drought impacts on society and the environment. A drought impact is “an observable loss or change that occurred at a specific place and time because of drought”.[15] There is a multitude of possible drought impacts (see Wilhite and Glantz[3] or Stahl et al.[16] for a comprehensive list). Common classifications differentiate between economic, ecological, and social impacts, or between direct (also termed primary) and indirect (or secondary) impacts, i.e. direct biophysical impacts, and consequences of these impacts.[3,5,6] A few examples are reduced crop yield, forest dieback, increased mortality of aquatic and terrestrial species, water supply shortages, reduction of hydropower production, impaired navigability of streams, or impacts on human health. Society needs information about when and where drought conditions (expressed by some indicator) translate into impacts. Such information can help people prepare and react proactively, e.g., by developing management and response strategies to mitigate impacts.

Despite several existing reviews of drought indicators (Table 1), what is missing is an integrated review that bridges the gap between scientific developments and current practices in operational DEWS, including a link to drought impacts. To date, there is little knowledge of which indicators are actually used in the many operational DEWS, why they were selected, and whether they have been compared with recorded local drought conditions and/or impacts. Also lacking is a comprehensive assessment of the state of monitoring of drought impacts. The aim of our article is therefore to answer the following research questions:

1. What types of drought indicators exist and which are used in operational DEWS?
2. What is the motivation behind the design of different indicators and their selection for operational use?
3. What are current practices for drought impact monitoring?

4. Have drought indicators been 'ground-truthed', i.e., compared with information representing local drought conditions or impacts?

Our research questions are addressed using two complementary approaches. Firstly, through a synthesis of the published literature on drought indicators and drought impacts, and secondly, through a survey targeted at providers of drought monitoring and early warning information. We close with a summary of current developments and trends regarding drought indicators and their usage in DEWS, and identify knowledge gaps and ways forward.]

[Methods]

[Given the many drought indicators that have been proposed for drought monitoring and the large number of review papers evaluating them, our focus was on synthesizing existing reviews rather than re-reviewing individual indicators. Tables 1 and 2 list the review articles we analyzed. To assess whether drought indicators have been ground-truthed (research question 4), we also collected original research papers dealing with testing of drought indicators, i.e., papers investigating how drought indicators are linked to other indicators or to drought impacts. The papers identified were classified according to the type of linkage (indicator-indicator versus indicator-impact), whether a novel indicator is proposed, and, in case of an indicator-impact linkage, the type of impact variable (Table 3). All papers were selected on the basis of expert knowledge and a snowball search using cross-references and forward citations of highly cited papers.

The online survey focused on (public) providers of drought monitoring and early warning information for public consumption, rather than water utilities or other entities that do monitoring for their own internal business purposes. The survey consisted of open and closed format questions regarding the type of organization and early warning system, reasons for the initiation of the system, use of drought indicators (individual and composite), reasons for the selection of indicators, status of impact monitoring, attempts to ground-truth indicators with impacts, and current indicator developments (the wording of many of the questions can be seen in the figures presented in this study). The invitation to participate in the survey was distributed via email to approximately 70 known DEWS providers and experts; the survey ran from the end of November 2014 until April 2015. We received 33 usable replies (excluding double entries from the same organization). The majority of participating organizations represented either universities/research institutions (48%) or governmental agencies (45%), followed by international (non-governmental) organizations (12%); multiple ticks were possible regarding the type of organization. The geographical coverage of the systems ranged from global to regional scale (global: 36%, continental: 6%, national: 27%, regional: 24%, other (e.g., basin scale): 6%). Several systems integrate different scales, e.g., global and continental, or national and regional scale; the preceding numbers only account for the largest named scale. Continental scale systems cover North and South America, Europe, Africa, and Australia. Most of the national systems cover European countries. Regional systems are distributed globally and either span several countries, or represent systems at sub-national scale. Many of the surveyed DEWS cover developed countries rather than developing countries.]

[What types of drought indicators exist and which are used in operational drought early warning systems?]

[Review of literature]

[Following the terminology used by the US National Drought Mitigation Center (NDMC), a 'drought indicator' can be a single parameter (e.g., rainfall or streamflow at a particular gauging station) or an index combining many kinds of data.[17] An index typically involves computation, e.g., some sort of normalization or combining multiple parameters to produce a numerical index value. In this study we use 'drought indicator' as an overarching term to cover any parameters or indices that are used to characterize and quantify drought. A comprehensive synopsis of existing drought indicators is impractical given the vast (and growing) number of available indicators. Several review papers describe the method for calculation of different indicators and/or evaluate their strengths and limitations. While some of the selected reviews (Table 1) examine a wide range of indicators (e.g., 74 indicators reviewed by Zargar et al.[18]), others focus on certain types of indicators, or indicators for a specific region or purpose. Different classification schemes have been used to group drought indicators. A common classification is according to drought type, e.g., precipitation- and temperature-based indicators for meteorological drought, soil moisture or vegetation stress indicators for agricultural drought, and indicators based on streamflow, reservoir or groundwater levels for hydrological drought (see Dai[19] or Zargar et al.[18] for commonly-used indicators falling into these classes). Less common are indicators for socio-economic drought, which have been associated with imbalances in supply and demand of economic goods due to drought, leading to economic and social impacts.[20] We will return to socio-economic drought indicators in the section on impact monitoring.

Some indicators do not fit into these classification schemes. One such group is remote sensing indicators, which provide information on several variables, such as land surface temperature, cloud cover, soil moisture, and vegetation status. Remotely sensed vegetation stress indicators such as the Normalized Difference Vegetation Index (NDVI)[21] and Vegetation Condition Index (VCI)[22] are biophysical indicators of a lack of precipitation, but can also be seen as representing drought impacts. Poor vegetation health as a consequence of drought can cause losses in agriculture and forestry systems or a decline in ecosystem condition and thus loss of ecosystem services. Another group not fitting into the drought classification scheme is composite indicators, also termed joint, multivariate, comprehensive, combined, multi-scalar, aggregate, or hybrid indicators.[14] Such indicators provide an integrated picture by including data on multiple types of drought. While commonly agreed composite indicators are by definition multi-dimensional, the boundaries determining which indicators fall into this category are quite fuzzy. We define a composite indicator as a blend of different stand-alone indicators. Examples are the US Drought Monitor (USDM)[23] or the Combined Drought Indicator (CDI).[24] For our review, indicators based on more than one input variable, such as the Standardized Precipitation Evaporation Index (SPEI)[25] or the Palmer Drought Severity Index (PDSI),[26] are considered to be a stand-alone or individual indicator rather than composite. One of the earliest approaches to designing a composite indicator was the USDM, which is based on six key stand-alone indicators and many supplementary indicators. The USDM is unique as it also incorporates local expert knowledge and impact information.[23] Hao and Singh[14] review different composite indicators and discuss the strengths and weaknesses of each method. While composite indicators have the advantage of providing a comprehensive picture of drought, the selection of drought-related variables going into the composite indicator and the methods for combining this information require careful attention and evaluation.[14]

Indicators can also be categorized based on the methodology for calculation, the spatial and/or temporal resolution, or the data source. Methods for calculation include percent of normal, cumulative anomaly, or percentiles of some drought variable. A trend over the last twenty years has been towards standardized indicators such as the Standardized Precipitation Index (SPI).[27] Standardized indicators can be thought of as a class of indicators, as the concept of standardization has been extended to nearly all drought-relevant variables: precipitation and evapotranspiration,[25] modeled grid cell runoff and routed streamflow,[28,29] observed streamflow,[30] groundwater,[31] snow melt and rainfall,[32] and the PDSI.[33] Standardization has the advantage of consistent interpretability among the standardized indicator family, with the indicator value representing the number of standard deviations from the average cumulative deficit.[34] But limitations may arise from the methodology, such as record length, reference period and selection of a probability distribution for model fitting (see Núñez et al.[35] for a short review on limitations).

In contrast to the wealth of studies proposing novel indicators or reviewing their strengths and weaknesses, very few studies have investigated which indicators are used in operational DEWS. For the US, the NDMC created a searchable database of indicators used by states, according to their drought plans (http://drought.unl.edu/Planning/DroughtPlans/StateDroughtPlans/PlansbyTrigger.aspx). In a review of 33 drought plans for US states, Quiring[36] found that reservoir levels and PDSI were most often used, followed by precipitation, streamflow and other indicators. A recent review focusing on drought plans for the western United States revealed that several indicators are used, yet some states rely on certain "primary indicators".[37(p96)] For other regions, information on the use of drought indicators for operational purposes may be published in drought plans of water utilities or other entities. As far as we are aware there is no overarching review summarizing this information. Nevertheless, there is review literature that recommends indicators that could be used for operational purposes. For example, in 2009, the WMO held an Inter-Regional Workshop on Indices and Early Warning Systems for Drought in Lincoln, Nebraska, USA, to review drought indicators. The 54 workshop participants from 22 countries recommended that the SPI be used by national meteorological and hydrological services globally to characterize meteorological drought, and that separate recommendations be made for hydrological and agricultural drought.[38]]

[Survey]

[Survey participants were asked which individual drought indicators they currently use for their DEWS, and whether they provide a composite indicator. Respondents could select between several common indicators per type of drought, or 'Other' (followed by a free text field to allow them to specify which) or 'None' (Figure 1). Results are discussed by drought type (socio-economic drought is assessed in the section on drought impact monitoring):

- Meteorological drought: The three most often used indicators are SPI, precipitation percentiles, and other indicators based only on precipitation, e.g. accumulated rainfall deficit, percent of normal. The SPEI is used by one third of the surveyed systems. For other indicators, participants named return period estimates for rainfall deficiencies, days without rain, heat related indicators and evaporation. The most common accumulation periods for meteorological indicators are 1, 3, 6, and 12 months (Figure 1). Several systems also provide precipitation-based indicators for accumulation periods up to 72 months. The mixture of short, intermediate, and long accumulation periods accounts for the need to monitor indicators relevant for a wide range of drought impacts with different response times.

- Agricultural drought, Soil moisture and vegetation conditions: soil moisture deficit/anomaly and NDVI are the most commonly used, followed by several other indicators such as the standardized soil moisture index, root stress, and remotely sensed vegetation stress indicators.
- Hydrological drought: Streamflow percentiles and reservoir levels are the most common. Other indicators include stock/farm pond conditions, water allocation levels, and mountain snowpack/snow water equivalent.
- Groundwater drought: 'None' was the most frequent reply, followed by groundwater level percentiles.

Overall, the percentage of 'None' and skipped answers increased moving from meteorological to hydrological, agricultural, and groundwater drought (see Figure 1). This highlights that those variables that are harder to measure and/or model at representative scales are underrepresented indictors in operational DEWS. This is a major gap given the fundamental need for indicators representing drought propagation in different domains of the hydrological cycle and at various spatial and temporal scales.

About 40% of the respondents produce a composite indicator. A variety of indicators go into each composite indicator, commonly covering several types of drought and/or data sources and/or scales. A few examples are the US Drought Monitor, the Multivariate Standardized Drought Index (MSDI), and indicators combining, for example, SPI, soil moisture anomalies, and FAPAR anomalies (Fraction of Absorbed Photosynthetically Active Radiation); PDSI, SPI, and NDVI; or precipitation, temperature, soil moisture, snow pack, and reservoir levels.]

[What is the motivation behind the design of different indicators and their selection for operational use?]

[Review of literature]

[There is relatively little literature on the motivations for indicator design or application. The rationale for proposing novel indicators cited in the literature is to design indicators that are superior to existing ones. For example, they seek to capture missing components of drought, make indicators more robust, increase spatial and/or temporal resolution, or enhance the applicability to certain regions, climate regimes, or sectors. Strategies for improvement include developing techniques for more data sparse areas or merging several indicators as an integrative assessment of drought (Hao and AghaKouchak[39]; Ma et al.[33]; Staudinger et al.[32]; Narasimhan and Srinivasan[40]; Zhang and Jia.[41]).

Drought monitoring based on a single drought-related variable is insufficient for detecting drought and its diverse consequences.[13,14] The propagation of drought through the hydrological cycle is a major influence on how drought actually impacts society, and numerous studies have demonstrated that meteorological drought does not always equate to agricultural or hydrological drought (e.g., review by Van Loon[42]). This lack of equivalence calls into question the purpose of indicators and what they are trying to measure, which in turn highlights a key aspect of monitoring, namely: How is drought understood and how is this understanding represented within current DEWS? With some exceptions (see for example Medd and Chappells[43]; Vogel et al.[44]; Hayman and Parks[45]) the literature reports little on the *framing* of drought – i.e. ways in which drought can be conceptualized and interpreted. Different understandings and diverse framings of drought will determine the aims, design, structure and content of DEWS, such as what is excluded and what indicators are required.[46] The framing of drought depends on the water governance context in a given country or region, including laws and policies related to water rights and on local understanding, as reflected in discourse in the media and among individuals and communities.[47,48] Given this complexity, it may come as no surprise that indicators tend to represent a precipitation shortfall or hydrological shortage, and exclude social aspects and impacts.

As a result of this complexity, developing and selecting an appropriate indicator for decision making is problematic. An inadequate indicator may lead to a delayed or pre-emptive response,[49] perhaps with unintended consequences. The worst case is indicators that do not match impacts and experiences occurring on the ground, thus losing credibility with decision makers or the public. Thus, the main motivation for designing composite indicators is to reduce this risk by merging several indicators to obtain an integrated view of drought.]

[Survey]

[We asked the survey participants to rate the importance of reasons behind the selection of individual drought indicators (see Figure 2 for selectable response categories). Data availability and the timeliness of data were the most important reasons followed by simplicity of interpretation, demonstrating that pragmatism drives indicator choice. Good experiences from other organizations, common practices, stakeholder consultation, expert advice, and literature were all rated with intermediate importance. Costs were of relatively low importance, which could be explained by the use of freely available indicators. Other reasons noted were "long standing and well accepted local practices", "[u]niversality of indicator when applied globally", and prior investment in the initial development of the indicator, along with reasons linked to the predefined response categories (Figure 2).

An additional factor clearly influencing the choice of indicators is the purpose and targeted audience of the different operational DEWS. About half of the participants' systems are specifically geared towards drought (45%) and the rest cover drought-related environmental conditions (e.g., water or vegetation status monitoring). More than two-thirds of the systems are not targeted to a specific user group or sector (e.g., agriculture, water supply, and/or the environment). Other participants made a distinction between the use for research, operational managers, decision makers, or the general public. One reply addressed changing demands over time: the DEWS "[u]sed to be geared toward the decision maker. Now [it] has to meet desires of everyone."

Survey replies regarding the motivation for initiating the DEWS (Figure 3) further explain drought indicator selection. The most frequent reason was 'Occurrence of (a) severe drought event(s)', followed by a request by the government/governmental agencies/local authorities or by certain stakeholders (Figure 3). The key role of a severe drought event opening up windows of opportunity for policy and long-term risk management has been reported elsewhere.[50] It is possible that ad-hoc systems initiated following an event are strongly governed by practical issues and pragmatic choices. This would tie back to data availability and timeliness of data as the main motivations for the selection of indicators.]

[What are the current practices for drought impact monitoring?]

[Review of literature]

[To better understand the current state of drought impact monitoring, the challenges of tracking such information need to be highlighted. A key challenge is the many possible drought impacts (see Table 2 for an overview of review papers covering specific impact types), and differences in how people understand drought and perceive drought impacts. This arises because of different framings of different individuals or organizations within the drought system (see Hayman and Rickards[45]) and their different roles giving rise to diverse experiences of the 'same' drought. As stated in the introduction, we define a drought impact as "an observable loss or change that occurred at a specific place and time because of drought".[15] The US NDMC distinguishes between physical manifestations of drought, such as a lack of precipitation, soil moisture, or water in hydrological systems, and impacts. Hence, low water levels in a river are an indicator of the physical manifestation of drought, not a drought impact. The resulting consequences (e.g., poor water quality, dead fish, and reduced tourism activity) are considered as impacts. The variability of concepts around impacts is discussed in Stahl et al.[16] and Lackstrom et al.[51]

Another challenge is that impacts are a function of the vulnerability of the affected area, population, economic sector, or ecosystem, leading to differences in impact types, severity, and time of occurrence for similar drought characteristics.[5] Impacts may not be visible, or may be disconnected spatially and temporally from the drought event, due to long response times (e.g., tree dieback), and occurrence outside of the main affected area because of the interconnectedness of industries and sectors.[3,52] Indirect impacts complicate monitoring efforts. For example, reduced crop yield may trigger secondary effects such as food shortages, reduced income for farmers and agribusiness, increased prices for food and timber, unemployment, reduced government tax revenues, increased crime rates and mass migration.[5] There is further complexity from the multi-causality of impacts. An example is crop damage caused by a combination of weather-related hazards rather than simply rainfall deficit.

These challenges mean drought impacts are not easy to measure, quantify, and/or monetize. Nevertheless, there are several sources of data related directly or indirectly to drought impacts, for example:

- Databases containing textual evidence of drought impacts from reports, newspaper articles, etc., such as the US Drought Impact Reporter;
- Risk management and loss data collected by governments and/or (re)insurance firms;
- Information on the number of affected people and economic damage of large drought events, such as the Emergency Events Database (EM-DAT, www.emdat.be);
- Crop yield statistics;
- Satellite measurements of vegetation stress;
- Databases on wildfire occurrence;
- Information on water use restrictions by water utilities, and;

- Monitoring of water quality and ecological impacts (e.g., the Environment Agency Drought Surveillance Network in England and Wales[53]).

The above data varies across spatial and temporal resolution and scale, and whether it can be used as real-time information, or only for retrospective analysis. There is no system harmonizing impact data from different sources and/or organizations globally, as available for drought indicators, e.g., through the Global Drought Portal Data (http://www.drought.gov/gdm/). For most types of drought impacts (except for agriculture and other insurable risks) no data collection standards exist, resulting in low data availability and/or low consistency of information, e.g., Ding et al.[52] Furthermore, reporting of impacts is ad-hoc and only when they are felt, rather than continuous monitoring of a system's state, e.g., Dollar et al.[54]; Smith et al., 2014.[55] This prohibits a systematic assessment of drought impact evolution and the link of impacts to established drought indicators, both going in and coming out of drought. For these reasons, Lackstrom et al.[51] identified impact monitoring as the 'missing piece' of drought early warning. The authors draw their conclusion based on a workshop on drought impact monitoring in the US, discussing opportunities, barriers, and best practices.

One advantage of impact monitoring using narrative accounts is that information on different impact types is collected and archived, e.g., impacts affecting a range of sectors, not only agriculture or water supply.[5,56] The current benchmark of near real-time monitoring of drought impacts is the US Drought Impact Reporter (DIR; http://droughtreporter.unl.edu), which is an online tool for impact collection and reporting. The majority of impact reports in the DIR comes from accounts discovered via an automated media search.[5] Other sources for populating the DIR are impact reporting by stakeholders, local authorities, the public, or volunteers; or tapping into other reporting systems. Recently, citizen science initiatives like CoCoRaHS (Community Collaborative Rain, Hail and Snow Network) have contributed to impact reporting.[55]

Other regions also have text-based impact inventories, but the systems differ in terms of information channels used, search methods, and operational mode (real-time monitoring versus retrospective search of impacts, systems allowing for public retrieval of information and entries via a web interface versus systems in research mode). The Canadian Agroclimate Impact Reporter (http://www.agr.gc.ca/atlas/air) represents a near real-time system similar to the DIR, yet only focuses on agricultural impacts. It relies on a volunteer network of farmers who complete a monthly survey on any climate-related impacts they may have experienced. A database that is strongly modeled after the US DIR is the European Drought Impact report Inventory (EDII; http://www.geo.uio.no/edc/droughtdb).[16] However, the EDII was designed as a research database focusing on impacts of past drought events.[16] The majority of EDII entries are from published reports and papers that were assembled by researchers in retrospect, although the database has been recently opened up for public entries. A further European based system is the "Drought in the Media" portal by the European Drought Observatory (http://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1060). As the name suggests, it makes use of a media monitor to retrieve information on droughts and related topics world-wide. For Australia, newspaper articles covering water-related issues have been collected within a research initiative.[57]

Despite the potential to capture the diversity of drought impacts, text-based impact monitoring also has challenges.[5,16,51,58,59] Examples are: (1) media selection or publishing bias of what impacts are reported; (2) identification of relevant search terms for retrieving articles, especially in different languages, and; (3) the human factor of citizen science initiatives, e.g., fluctuating motivation of volunteers, varying user perception of impacts over time, and personal incentives or disincentives for reporting.[51,60] Also, the question remains how to use such qualitative data as an indicator or source for testing, e.g., whether and how to quantify or otherwise incorporate it into DEWS. While the USDM already integrates impact information, further possibilities on how to use such data need to be explored.]

[Survey]

[We asked whether data on drought impacts are collected within the participants' systems, and if yes, what kind of data and how. Fifty-five percent of participants collect impact data, and 42% do not (Figure 1). Data on crop damage or yield are collected most frequently, followed by media reports. Other data, such as tree ring records, "satellite products" (presumably on vegetation stress), data on water quality, aquatic ecosystems, or demand, were also named. Respondents also stated impact data collection is fragmented and often ad-hoc during or after an event. Several respondents highlighted that other agencies or organizations collect such data, but the data are not transferred to or distributed/displayed by the DEWS. One respondent noted that data are gathered within individual research projects, yet there is no standardized collection and archiving. Other respondents were vague on whether impact data collection is a sporadic or permanent effort, and whether and how the data are used and/or disseminated. A few responses also demonstrated different understandings of the term 'impact', e.g., referring to low streamflow as an impact.]

[Have drought indicators been 'ground-truthed', i.e. compared with information representing local drought conditions, or impacts?]

[Review of literature]

[We analyzed 70 studies of drought indicator evaluation in the broadest sense, i.e. papers investigating how drought indicators are linked to other indicators, or to drought impacts (Table 3). About two thirds of these studies cross-compared the performance of different indicators. The most common aims of the studies we reviewed were to: (1) evaluate the spatial and temporal consistency of drought identification using multiple indicators; (2) address indicator uncertainties regarding underlying data sources and methodology of calculation (e.g., representativeness of remotely sensed soil moisture versus station-based data; (3) investigate lag times between different types of drought; (4) evaluate indicators for a certain region or application, or; (5) test the utility of a proposed indicator against existing ones. More than one third of the studies on indicator-indicator linkage proposed a novel indicator, either an individual or a composite one.

Less than half of the studies evaluated indicators with impact. Some studies investigated both indicator-indicator, and indicator-impact linkages, hence there is some double counting; remotely sensed vegetation indicators were treated as both indicators and impacts (Table 3). Different types of impact variables were used for indicator evaluation: about half of the studies used crop yield; ca. 20% used vegetation health based on remotely sensed indicators; ca. 20% used text-based impact data from the EDII or the US DIR; and roughly 10% used other, or several impact variables in parallel (e.g., tree rings, forest growth). Additionally, several studies used the US Drought Monitor for ground-truthing indicators. However, since the USDM is not a single impact variable but rather a blended indicator also incorporating some impact information, we considered these studies to fall into the category of indicator-indicator linkage. Although our proportions are approximate, they demonstrate that the majority of studies rely on either historical crop yield or remotely sensed vegetation stress. Hence, mostly agricultural drought indicators are tested. Evaluation approaches for indicators relevant for societal, economic, and environmental impacts are sparse, highlighting a major gap in our understanding, given the widely discussed multifaceted nature of drought impacts.

Several common themes evolved from the analysis of the 70 studies. First, when a novel indicator is proposed, a common approach is to compare it to existing indicators, often well-known or benchmark indicators for certain regions (e.g., SPI, or the US Drought Monitor for US-wide applications). Additional evaluation with drought impacts is rare, and mostly conducted using crop yield (e.g., Narasimhan and Srinivasan[40]; Potop[61]; Rhee et al.[62]; Sepulcre-Canto et al.[49]). Second, while there are numerous studies cross-comparing the performance of different indicators, there is no standard approach and methods for evaluation, and baseline indicators vary widely. Most studies either compared drought characteristics calculated by means of several indicators, or applied correlation or regression analysis. A small number of studies evaluated indicator performance using techniques for appraising skill, as typically used in forecast evaluation (e.g., Haslinger et al.[63]; Kumar et al.[64]). Third, most studies focus on some case study region, catchment, or country. Continental or global scale assessments are scarce but include Dai[65]; Vicente-Serrano et al.[66]; Vicente-Serrano et al.[67]

As a result, generalizable information on the performance of indicators and their link to drought impacts is difficult to distill from the many studies reviewed. Some studies report similar findings regarding a specific indicator, such as better performance of the self-calibrated PDSI or Standardized PDI over PDSI,[33,68] or SPEI outperforming SPI when linked to local-scale hydrological variables or drought impacts.[58,67,69,70] Apart from this, one commonality seems to be that indicator performance and response times for different types of droughts or impacts are region specific. This was shown by several studies investigating the link between meteorological drought and streamflow,[63,71–73] SPI and groundwater indicators,[31,64] and between different indicators and crop yield, vegetation condition, or text-based impact reports.[58,70,74,75] In addition to regional particularities, indicator performance was found to vary among crops,[76] and impact types (e.g., impacts on agriculture, water supply, or energy and industry).[58,70,74] Hence, an overall lesson learned is that a regional and application-specific evaluation is necessary prior to selecting any drought indicator. This makes impact or local-scale water status observations a necessity, perhaps by including evaluation by stakeholders or expert elicitation, as has been practiced in the US (e.g., Steinemann[77]; Steinemann and Cavalcanti[78]; Svoboda et al.[23]) and elsewhere.[79,80]]

[Survey]

[Seventy-three percent of respondents reported evaluating individual indicators with impacts (Figure 4). This is a high proportion given that a smaller percentage of respondents reported collecting impact data (55 percent). This suggests that impact data for evaluation are collected in retrospect, for a specific purpose or event, but these data are not continuously available/monitored. Composite indicators were less often evaluated with impact data (54%). Both qualitative (e.g., feedback from stakeholders, testing against local knowledge) and quantitative evaluations (e.g., statistical analysis) were reported. A quantitative evaluation was more common for individual indicators than for the composite ones. Evaluation approaches using stakeholder involvement may partly explain why indicators have been assessed in terms of their meaning for impacts, even though formal impact monitoring is not as widespread. Examples of qualitative evaluation techniques are "occasional targeted questionnaires" to a wide user community, or "discussions with selected stakeholders on what indicators are used and what indicators are useful, and related to impacts". The quantitative evaluation involved either: (1) small-scale comparison and/or statistical analysis regarding which indicators best correspond to crop yield, other impact variables, local-scale soil moisture/streamflow/reservoir levels, or indicators such as the USDM, or; (2) assessing the forecasting skill of indicators and/or their ability to predict historical drought events. One comment highlighted the need to balance between indicator skill and value for stakeholders when assessing the overall usefulness of indicators. Where there was no evaluation of indicators, the main reasons given were a lack of personnel and/or time constraints (Figure 4).]

[Current trends, knowledge gaps, and needs for future development]

[Results from survey and literature]

[To gain insight into current developments of indicator usage in operational DEWS, we asked whether survey participants intended to develop new or additional drought indicators in the future, and if so, what and why. Most participants (82%) replied 'yes' or 'possibly' and some commonalities emerged about trends and reasons for the design of further indicators. Several respondents planned to add existing commonly-used indicators (e.g. indicators representing different types of drought than those currently monitored, or vegetation status from satellite data). In addition, many participants stated their intention to work on the improvement of the currently-used indicators by, for example: (1) refining the methodology or models; (2) using more or better quality input datasets, and; (3) providing higher spatial or temporal resolution, and/or different format datasets (e.g., gridded data). Only a few novel indicators or tools are being developed that go beyond an improvement of methodology. An example is the design of a composite indicator, which appears to receive marked interest by the respondents. Six participants intend to develop such an indicator or explore possibilities in this respect, while 13 of the 33 surveyed systems already provide a composite indicator. Another factor driving indicator development is the requirement to simplify interpretation by users, and better address stakeholders' needs and/or relevance for certain impacts, as mentioned several times. One participant stated that "[r]ather than developing new indicators (so many are available already), a better goal would be to provide tailored drought information for specific uses".

Many of these trends are reflected in the current literature. Several participants referred to their own publications regarding indicator evaluation or design of novel indicators. However, research papers specifically addressing how to customize indicators for user needs are rare (but include, for example, Steinemann et al.[81]; Steinemann and Cavalcanti[78]). Instead, recent research has: (1) extended the concept of indicator standardization and improved the standardization methodology (e.g., Stagge et al.[34]; Vicente-Serrano et al.[25]); 2) assessed multi-indicator drought climatologies at global or continental scales (e.g., Lloyd-Hughes and Saunders[82]; Spinoni et al.[83];Touma et al.[84]) because drought characteristics and derived drought climatologies based on several indicators may differ from those based on a single one[8,23,78]; (3) designed composite indicators[14], and; (4) utilized modelled and satellite-derived data for DEWS and integrated it into composite indicators to tackle challenges of data scarcity and human resources (e.g., Rhee et al.[62]; Zhang and Jia[41]; Hao et al[85]), especially in developing countries (e.g., Anderson et al.[86]; Dutra et al.[87]).]

[Knowledge gaps and ways forward in DEWS research and applications]

[The above trends underline the perennial conflict between trying to provide tailored information for particular users or economic sectors, and at the same time providing information for everyone, often through a single composite indicator. On the one hand, blending several indicators may enhance interpretability for users of the systems, since the diverse information from potentially conflicting indicators is streamlined and simplified into one answer. On the other hand, any blending approach obviously involves the subjective choice of indicators, weights, and thresholds for delineation of intensity classes, which may make the interpretation less intuitive or relevant. Since a 'one-size-fits-all' DEWS does not exist, we advocate integrating knowledge from several sources and at different scales without losing detail at smaller spatial scales. The widely publicized USDM, for instance, is not meant to replace information from local water suppliers. Calls for a single source of information aim to simplify what might otherwise be a patchwork of local requirements, but circumstances certainly arise where local utilities' information provision is quite different from a typical single-source message of a larger scale DEWS. Any DEWS should thus seek to integrate rather than reduce complexity to provide meaningful information.

At the same time, we propose that decision-makers in any drought situation adopt an operational drought definition tailored to their own needs. One approach to achieve this, in addition to stakeholder engagement, may be ground-truthing drought indicators with local-scale information on drought conditions or impacts. One aspect of DEWS that is often not explicitly included but that was specifically studied in our survey and review is the connection of drought indicators to impacts. The analysis of research papers dealing with drought indicator evaluation showed that there are numerous studies assessing the performance of (novel) indicators against others, yet evaluation with local-scale water status or impact data other than crop yield is rare. One main reason hindering local-scale indicator testing is a lack of widespread monitoring of (1) variables representing hydrological and groundwater drought, as revealed by the survey, and (2) drought impacts. The scarcity of water status observations, especially for groundwater, reflects the common focus on drought seen through the lens of rainfall and soil moisture that can be easily (remotely) monitored and/or modelled. In general, the lack of hydrological indicators probably reflects a lack of widely accessible, shared hydrometric data at the regional, national or international scales (e.g., Hannah et al.[88]; Viglione et al.[89]) rather than a complete lack of such observations.

While the survey replies showed that efforts are made to collect impact data, the data are rather fragmented and often do not feed directly into the DEWS (see also Lackstrom[51]). Wilhite and Glantz (1985)[3] found that "most scientific research related to drought has emphasized the physical over the societal aspects of drought".[3(p119)] Three decades later, impact monitoring to better integrate societal aspects into early warning is still in its infancy, except for a few advanced systems like the US DIR and some initiatives in other countries. Incorporating observer networks may be a way forward to better integrate local knowledge into high-tech drought monitoring. One such example is the previously mentioned CoCoRaHS network in the US, but arguably the greatest potential for observer networks to advance drought monitoring is in developing countries. In data-poor environments with less available DEWS infrastructure, but where mobile communication uptake is high, citizen science can fill in gaps in in-situ networks and provide a link between on-the-ground impacts and large-scale data from earth observation. Examples are projects to utilize cell phones to report drought impacts (e.g. practiced in Ethiopia[90] and Somalia[91]) or the concept of 'Paysan Observateur' (observing farmers) in Mali.[92] Collectively, such initiatives offer a way of re-framing drought to include societal impacts, but a task remains on how indicators and impacts can be integrated. Recent initiatives in water management suggest developing social learning systems (see Blackmore and Ison[93]) may be a way to enable diverse stakeholders to engage with monitoring and early warning systems and practices in order to improve their utility for a wide community of end users.

Although not specifically surveyed and reviewed, ecology and ecosystem services are additional under-represented aspects that emerged during the research and discussion. Although many drought indicators implicitly include terrestrial and freshwater ecosystems – for example, through monitoring soil moisture that is critical for plant growth – explicit indicators of ecological drought are rare. An exception is in the UK where there has been some progress toward developing indicators of ecosystem health for use in drought monitoring[54]. However, one could question whether droughts are 'harmful' to ecosystems. Much depends on the human context: if culturally important ecosystems are lost, we may consider the drought to be ecologically and culturally negative. However, there is evidence that droughts eliminate weak members of species and prevent growth of invasive species, and so can have a positive impact on the ecosystem.[94] Particular challenges to incorporating ecological issues include recovery of ecosystems after drought.[95] Droughts may negatively affect services to people from ecosystems, such as recreation from boating or fishing in rivers, although these are not strictly ecological indicators. Extended severe droughts, or frequent droughts, may cause an ecosystem to go beyond its threshold tolerances and therefore transition into new ecosystem types[96]. This usually causes a loss of ecosystem services that society relies upon. Although not a specific focus of our review and survey, we note that ecosystem services are absent from current DEWS indicators and appraisal of those indicators.]

Conclusion

[The aim of this work was to revisit drought indicators that are used in drought monitoring and early warning. Our synthesis of literature on drought indicators and impacts together with our survey of providers of drought early warning information tackled questions on the operational use of indicators, the motivation behind the design and selection of different indicators, current practices for drought impact monitoring, and any related ground-truthing of drought indicators with local drought conditions, and/or impacts. In summary, there is considerable variety in the indicators used by operational DEWS, though this variety is not nearly as wide as the range of indicators that have been published. Moreover, certain trends exist: common drought indictors, such as the SPI, are used very widely, and approximately 40% of the surveyed DEWS also provide a composite indicator. The survey confirmed that providers of monitoring and early warning services are constrained by pragmatic considerations such as variables that are easy to measure, and readily available in a timely manner. Perhaps less expected was that more than half of the survey participants collect impact data, although in the literature this has been referred to as the 'missing piece' of drought monitoring. A closer look at the replies revealed that very few systematic approaches exist and thus data collection efforts are mostly fragmented. As a result, impact data are not widely used in operational systems, e.g. for ground-truthing indicators – an exception being agricultural drought, where yield or vegetation stress data have been used to test indicators.

The two complementary approaches of literature synthesis and surveying DEWS providers allowed us to develop an integrated picture of the current state of drought indicator research and practices in operational DEWS. This revealed key knowledge gaps, and particular challenges for future development of DEWS. There is a need for indicators representing drought propagation in different domains of the hydrological cycle and at various spatial and temporal scales, systematic impact data collection for ground-truthing indicators, and better understanding of drought's various economic consequences. Consideration of environmental impacts is still in early stages, and ecosystem services have yet to be integrated into monitoring and early warning frameworks. We also note that the underlying framing of drought – a major consideration in terms of how DEWS are designed and their ascribed purpose – remains largely unexplored in the literature. Citizen science initiatives and other social learning approaches that explore drought framing and DEWS design offer opportunities to explore multiple understandings of drought impacts and improve indicator design and use. While large-scale, big-picture, integrated indicators such as the US Drought Monitor are valuable, we see additional need for further research and development of DEWS systems tracing drought's cascading effects through specific ecological, economic and social contexts.]

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Figure captions

[Figure 1: Survey replies on the use of individual indicators in the drought early warning systems for different types of drought and impact data collection.

Figure 2: Survey replies on the importance of reasons for selecting the currently used individual indicators. Participants were asked to rate all reasons that apply. The dots represent the mean importance score, the bars the range; n= number of replies per category.

Figure 3: Survey replies on the reasons for initiating the drought early warning system (several ticks possible). The category 'Request by the government' represents 'Request by the government/governmental agencies/local authorities' in the original survey.

Figure 4: Survey replies on evaluating the selected drought indicators with drought impacts. Participants could tick both qualitative and quantitative evaluation, and several categories regarding the reasons for no evaluation.]

Tables

[Table 1: Reviews on drought indicators. Drought indicator type: V=various, M=meteorological, A=agricultural, H=hydrological (including groundwater), C=composite, O=other (e.g., remote sensing indicators)

Authors	Year	Scope		Drought indicator type						Topic
		Focus on indicators	Indicators among other aspects	V	M	A	H	C	O	
Hao and Singh[14]	2015	x						x		Composite indicators: methodologies, strengths and limitations
Pedro-Monzonis et al.[97]	2015	x		x					x	Drought and water scarcity indicators in the context of water resources planning
AghaKouchak et al.[98]	2015	x							x	Drought monitoring using remote sensing observations
Van Loon[42]	2015		x	x			x			Several aspects of drought including different indicators
Zhang et al.[99]	2013	x							x	Remote sensing indicators in the context of impacts on forest ecosystems
Belal et al.[11]	2012		x	x					x	Several indicators, focus on remote sensing
Sivakumar et al.[8]	2011	x				x				WMO/UNISDR Expert Group Meeting: article collection on agricultural drought indices (usage, strengths and limitations)
Zargar et al.[18]	2011	x		x						Comprehensive review of 74 drought indicators
Dai[19]	2011		x							Several aspects of drought including different indicators
Mishra and Singh[13]	2010		x	x						Several indicators: description, strengths and limitations
Quiring[100]	2009	x			x					Meteorological drought indicators: description, strengths and limitations
White and Walcott[101]	2009	x		x						Various indicators, focus on relation to impacts on rural Australia
Heim[102]	2002	x		x						Major drought indicators used in the US
Keyantash and Dracup[103]	2002	x		x						Several indicators: description, strengths and limitations

Table 2: Reviews on drought impacts

Authors	Year	Drought impact type				Topic
		Various	Economic/ agricultural	Ecological	Societal	
Lackstrom et al.[51]	2013	x				Impact monitoring
Smith et al.[55]	2015	x				Impact monitoring
Stahl et al.[16]	2015	x				Impact monitoring
Logar and van den Bergh[6]	2011	x				Cost assessment of drought damage
Ding et al.[52]	2013		x			Full scope of economic impacts
Economic Research Service, US Department of Agriculture[104]			x			Case study: impacts on US agriculture 2012
Mosley[105]	2015		x	x	x	Impacts on water quality
Dollar et al.[54]	2013			x		Ecological impacts focusing on rivers, lakes, wetlands and ponds
Matthews and Marsh-Matthews[106]	2003			x		Impacts on fish
Stanke et al.[107]	2015				x	Impacts on public health
Centers for Disease Control and Prevention, U.S. Environmental Protection Agency[108]	2010				x	Impacts on public health

Table 3: Original research papers assessing the link between different indicators, or between indicators and impacts; n=number of studies

Linkage type	n	Categorization	n	Studies
Indicator-indicator	55	Between existing indicators	35	Anderson et al.[109]; Carrao et al.[110]; Ceglar et al.[111]; Chandrasekar and Sesha Sai[112]; Choi et al.[113]; Dai[65]; Dieker et al.[114]; Edossa et al.[115]; Gao et al.[116]; Gouveia et al.[117]; Gu et al.[118]; Guttman[119]; Haslinger et al.[63]; Jain et al.[120]; Ji and Peters[121]; Keyantash and Dracup[103]; Kumar[122]; Kumar et al.[64]; Li and Rodell[123]; Lorenzo-Lacruz et al.[71]; McEvoy et al.[69]; Morid et al.[124]; Naumann et al.[125]; Potop et al.[126]; Quiring[100]; Quiring and Ganesh[75]; Rahiz and New[73]; Scaini et al.[127]; Shukla et al.[128]; Tadesse and Wardlow[129]; Vasiliades and Loukas[130]; Vicente-Serrano and López-Moreno[72]; Vicente-Serrano et al.[67]; Vicente-Serrano et al.[131]; Xia et al.[132]
		Between a proposed novel indicator and existing ones	20	Anderson et al.[133]; Bloomfield and Marchant[134]; Gu et al.[135]; Hao et al.[85]; Hao and AghaKoucha[39]; Ma et al.[136]; Ma et al.[33]; Martínez-Fernández et al.[137]; Mendicino et al.[138]; Narasimhan and Srinivasan[40]; Potop[61]; Rajsekhar et al.[139]; Rhee et al.[62]; Staudinger et al.[32]; Trnka et al.[140]; Vicente-Serrano et al.[25]; Vicente-Serrano et al.[141]; Wells et al.[68]; Zhang and Jia[41]; Ziese et al.[142]
Indicator-impact	31	Crop yield	14	Ceglar et al.[111]; Diodato and Bellocchi[143]*; Hlavinka et al.[144]; Kattelus et al.[145]; Martínez-Fernández et al.[137]*; Mavromatis[146]; Narasimhan and Srinivasan[40]*; Potop[61]*; Potop et al.[126]; Potopova et al.[76]; Quiring and Papakryiakou[147]; Rhee et al.[62]; Rossi and Niemeyer[148]; Sun et al.[149]*
		Remotely sensed vegetation stress	7	Choi et al.[113]; Gouveia et al.[117]; Gu et al.[135]*; Gu et al.[118]; Ji and Peters[121]; Quiring and Ganesh[75]; Vicente-Serrano et al.[131]
		Text-based data	6	Bachmair et al.[150]; Bachmair et al.[58]; Blauhut et al.[74]; Dieker et al.[114]; Stagge et al.[70]; Tadesse and Wardlow[129]
		Other impact variables or several in parallel	4	Núñez et al.[35]; Sepulcre-Canto et al.[49]*; Vicente-Serrano et al.[67]; Vicente-Serrano et al.[151]

Colored font: study additionally assesses indicator-impact linkage;
*Impact variable used for evaluating the proposed novel indicator
]

Further Reading/Resources

[Table 1 and 2]

Related Articles

DOI	Article title
10.1002/wat2.1085	Hydrological drought explained
10.1002/wcc.81	Drought under global warming: a review