

Enhancing Drought Monitoring and Early Warning for the United Kingdom through Stakeholder Coinquiries

JAMIE HANNAFORD

Water Resources Science Area, Centre for Ecology and Hydrology, Wallingford, United Kingdom, and Irish Climate Analysis and Research Units, Department of Geography, Maynooth University, Kildare, Ireland

KEVIN COLLINS

Applied Systems Thinking in Practice, School of Engineering and Innovation, The Open University, Milton Keynes, United Kingdom

SOPHIE HAINES

Institute for Science, Innovation and Society, University of Oxford, Oxford, United Kingdom

LUCY J. BARKER

Water Resources Science Area, Centre for Ecology and Hydrology, Wallingford, United Kingdom

(Manuscript received 19 April 2018, in final form 7 August 2018)


ABSTRACT

Drought is widely written about as a complex, multifaceted phenomenon, with complexity arising not just from biophysical drivers, but also human understanding and experiences of drought and its impacts. This has led to a proliferation of different drought definitions and indicators, creating a challenge for the design of drought monitoring and early warning (MEW) systems, which are a key component of drought preparedness. Here, we report on social learning workshops conducted in the United Kingdom aimed at improving the design and operation of drought MEW systems as part of a wider international project including parallel events in the United States and Australia. We highlight key themes for MEW design and use: “types” of droughts, indicators and impacts, uncertainty, capacity and decision-making, communications, and governance. We shed light on the complexity of drought through the multiple framings of the problem by different actors, and how this influences their needs for MEW. Our findings suggest that MEW systems need to embrace this complexity and strive for consistent messaging while also tailoring information for a wide range of audiences in terms of the drought characteristics, temporal and spatial scales, and impacts that are important for their particular decision-making processes. We end with recommendations to facilitate this approach.

1. Introduction

Drought hazards are an intrinsic feature of the climate regime of a given location, but the impacts on society and the environment can be mitigated through drought management frameworks. These rely on monitoring and early warning (MEW) systems to track the onset/decay of drought conditions and to quantify drought severity, thus enabling appropriate and timely management actions.

Existing MEW systems operate at a range of scales, from catchments and regions through to national and continental scales (e.g., Pulwarty and Sivakumar 2014). MEW systems typically involve the use of drought indicators and indices (WMO and GWP 2016) to monitor the status of rainfall, river flows, groundwater levels, and other hydrometeorological variables, relative to historical precedents. Some MEW systems also include forecasting of these indicators over time scales of days to seasons, and beyond. In designing MEW systems, a key consideration is *which* indicators to use to characterize drought hazard.

 Denotes content that is immediately available upon publication as open access.

Corresponding author: Jamie Hannaford, jaha@ceh.ac.uk



This article is licensed under a [Creative Commons Attribution 4.0 license](http://creativecommons.org/licenses/by/4.0/) (<http://creativecommons.org/licenses/by/4.0/>).

DOI: 10.1175/WCAS-D-18-0042.1

© 2018 American Meteorological Society

Drought indicators have proliferated in recent decades. While distinctions between certain “types” of drought may be readily drawn (e.g., meteorological compared to agricultural), this proliferation is partly due to the absence of a universal definition of drought. However, this may be a meaningless endeavor (Lloyd-Hughes 2014) given the many different sectors impacted and their different definitions, framings, and perceptions of drought (e.g., Smakhtin and Schipper 2008; Kohl and Knox 2016).

Bachmair et al. (2016a) surveyed over 40 MEW systems from around the world. They reported an emphasis on hydrometeorological indicators, and generally less consideration of impacts on society or the environment. Recently, there has been a growing effort to validate hydrometeorological indicators using impact information (Bachmair et al. 2016b; Stagge et al. 2015). However, there is little consensus in the literature on what this means for choosing indicators, their translation to impacts, and the implications for MEW systems. There is, we argue, also a key role for stakeholders and user input in designing MEW systems. To address this gap, the “Drought Impacts: Vulnerability Thresholds in Monitoring and Early-Warning Research (DrIVER)” project explored MEW systems and drought impacts on three continents (Europe, North America, and Australia), combining quantitative analysis of indicators and impacts with learning from stakeholder coinquiries (Collins et al. 2016). Fundamentally, DrIVER aims to bring these two strands together to make recommendations for enhancing existing and future MEW systems.

In this paper, we report on such an approach applied in the United Kingdom, a DrIVER case study country with well-developed drought management systems, but with a very complex interplay of actors involved in drought decision-making and a multitiered arrangement of established, operational MEW systems and emerging MEW products. Our findings are based primarily on a stakeholder coinquiry developed over the course of two workshops and supported by ongoing work on the development and testing of new hydrometeorological indicator and impact datasets, the relationships between them, and prototype MEW tools. We bring this to bear to address the following research questions:

- How do framings of drought and drought management influence MEW practices and needs for a broad range of stakeholders?
- How should the above be used to improve current MEW systems or design new systems to meet multiple user requirements?

This paper is structured as follows. First, we describe the U.K. context, setting out the current drought management framework and MEW systems. Second, we outline the methodology and workshop design. Third, we present outcomes in terms of six key themes. We conclude by

setting the findings in the context of MEW design and making recommendations for future development of multi-stakeholder MEW systems.

2. The U.K. context: Drought management and current MEW systems

The United Kingdom is a wet country as a whole, but has experienced a number of major drought episodes in recent years (e.g., Parry et al. 2013). Parts of southeast England are relatively water scarce and vulnerable to multiyear droughts (Folland et al. 2015). Drought is recognized as a key issue [e.g., in the Cabinet Office Risk Register (Cabinet Office 2017)], particularly given projections of increased drought severity in the future (Watts et al. 2015), although arguably droughts are not part of public consciousness compared to other hazards. Perhaps partly for this reason, there is no U.K.-wide drought-focused MEW system comparable with, say, the U.S. Drought Monitor. However, the United Kingdom has a dense, high-quality hydrometeorological observation network and a number of intersecting MEW efforts (introduced below).

The United Kingdom has a very long-established framework for long-term water resources and drought planning. There are various other governance arrangements in place, including implementation of EU legislation, and there are many key actors and processes involved in drought management (e.g., Robins et al. 2017; Lange and Cook 2015). In England, the Environment Agency (EA) is responsible for managing impacts of drought on people and the environment. The EA produces voluntary drought plans, which set out how it will operate and communicate during a drought and what actions will be taken to ensure the environment is protected. Similar arrangements exist in the other countries of the United Kingdom (e.g., SEPA 2016) which, for brevity, are not expanded upon here.

In an international context, one of the interesting features of U.K. water management is the mixed ownership of water utilities. In England, privately owned water utilities have a statutory obligation to produce water resources management plans (WRMPs) setting out long-term strategic investment, and drought plans (DPs) setting out what actions they will take during a drought, typically with reference to various triggers (e.g., reservoir levels) at which a number of actions can be taken (e.g., communications campaign, temporary use bans, pressure reduction). As an example, Fig. 1 shows a reservoir control curve, triggers, and a summary of actions. Statute requires that water companies consult the EA [Section 39B (7a) of the Water Industry Act (1991)] and the Water Services Regulation Authority (Ofwat), the economic regulator [Section 39B (7b) of the Water Industry Act (1991)], before they prepare their statutory drought plans and water

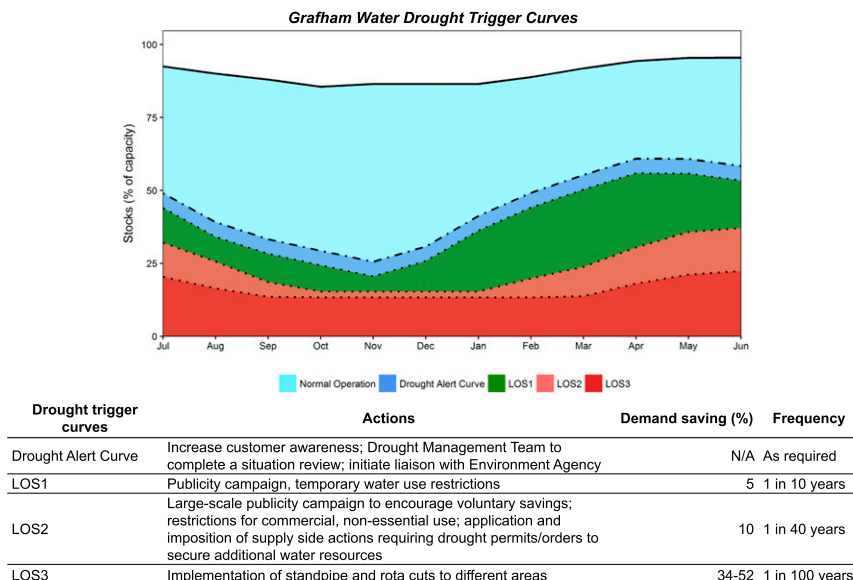


FIG. 1. Reservoir control curve and trigger levels for Grafham Water, Cambridgeshire, United Kingdom. Note that the data and actions presented may change in the future (after Anglian Water 2014).

resources management plans [Sections 37A (8a) and (8b) of the [Water Industry Act \(1991\)](#)]. Parallel planning frameworks exist in Scotland, Wales, and Northern Ireland, although water company ownership differs.

In addition to these “regulatory” stakeholders, there is a wide range of statutory and nonstatutory organizations involved in drought risk management. While agriculture is not as significant a proportion of the U.K. economy as in some other western societies [e.g., in southern Europe, the United States, or Australia; see [World Bank \(2017\)](#)], it is a major water user, accounting for some 20% of freshwater abstraction in England and Wales (including aquaculture and forestry) ([Office for National Statistics 2015](#)). Irrigation has major economic benefits and is of particular importance in the drier East of England ([Rey et al. 2016](#)). Similarly, the energy sector demand in 2011 for water (for cooling and hydropower) in England and Wales paralleled domestic water consumption ([Byers et al. 2014](#)), and together these account for almost 60% of freshwater abstraction, while manufacturing accounts for 11% ([Office for National Statistics 2015](#)). These sectors alone cover many thousands of organizations, businesses, and stakeholders, each with particular concerns, needs, and views about water management and drought preparedness.

The main operational MEW carried out under legal duty is by the EA, the Scottish Environment Protection Agency (SEPA), Natural Resources Wales (NRW), and the “Department for Infrastructure—Rivers” in Northern Ireland. Each monitors river flows, groundwater, and other variables at key locations through

regular reports (e.g., water situation reports (WSRs); www.gov.uk/government/collections/water-situation-reports-for-england). While similar in aim, the reports diverge in their methodology and formats and are not all publicly available. The National Hydrological Monitoring Programme (NHMP; <https://nrfa.ceh.ac.uk/nhmp>), operated by the Centre for Ecology and Hydrology and British Geological Survey, has provided an accessible, independent monthly U.K. “Hydrological Summary” since 1988. These organizations have also produced the “Hydrological Outlook UK” ([Prudhomme et al. 2017](#)), a monthly operational hydrological seasonal forecasting service, since 2013. As in other countries, impacts are not systematically collated ([Bachmair et al. 2016a](#)), or at least published, in routine MEW updates via WSRs or the NHMP. The EA do collate impacts information via incident management processes, and these are referred to in internal documentation and shared with partners, but not necessarily made publicly available.

While the examples above are the main large-scale U.K. MEW activities, MEW is also undertaken on a range of finer scales by a very wide range of stakeholders. Hydro-metric data, including water supply-focused indicators such as reservoir levels and other triggers, are gathered by water companies and shared in dialogue with regulators, but they are not always publicly available. MEW information is also gathered at the local scale by a wide range of actors (e.g., farmers monitoring soil moisture; rivers trusts and interest groups monitoring river levels on a reach scale), and these parties will, naturally, often keenly observe and record drought impacts that have a direct bearing

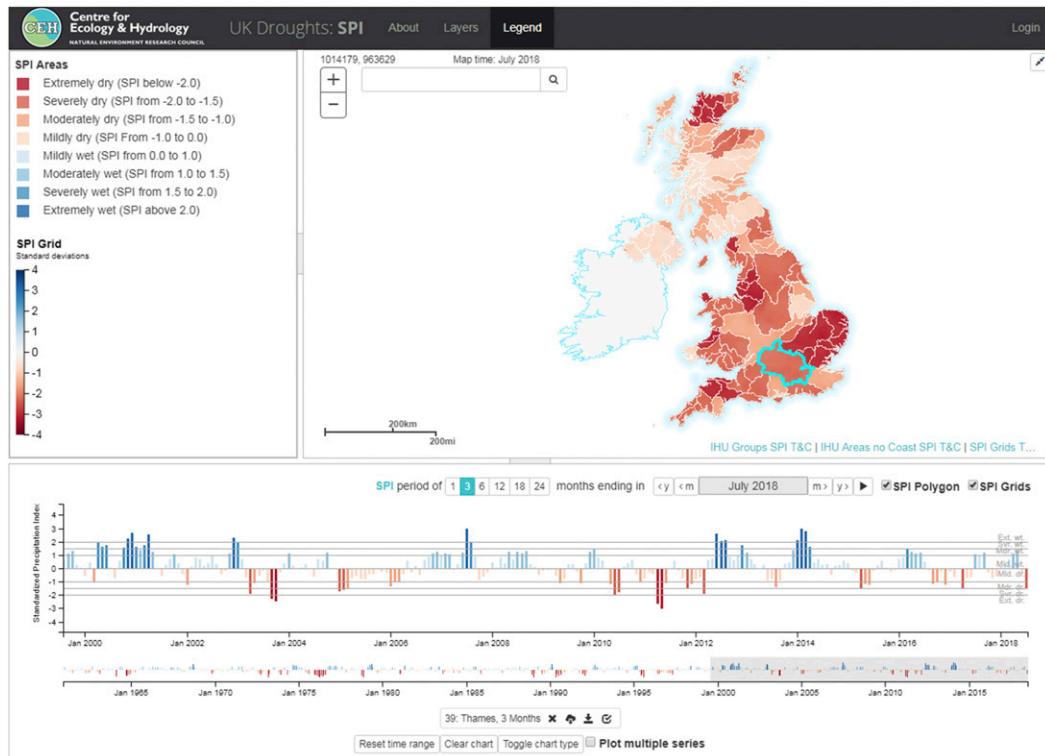


FIG. 2. The UK Drought Portal showing interactive mapping and time series visualization functionality. The indicator shown is the 3-month SPI (SPI3), showing the severity of meteorological drought conditions across the United Kingdom in summer 2018. The user-defined time series shown is for the catchment (the Thames) selected in southeast England.

on their livelihoods and interests. However, these informal efforts are not coordinated or collated centrally.

In summary, there are formal MEW systems that underpin dialogue between key statutory stakeholders, and a wide range of other MEW efforts, but these are not currently well integrated.

U.K. drought MEW efforts focus on rainfall, river flows, and other hydrological variables. Generally the focus of the NHMP and WSRs is on absolute values of these variables, or simple, rank-based methods like percentiles. With the notable exception of Scotland (Gosling 2014), there are few operational uses of the dedicated drought indicators that are widely used internationally (e.g., WMO and GWP 2016), such as the standardized precipitation index (SPI). Recently, several DrIVER studies have explored the use of the SPI and similar indicators in the United Kingdom (see Barker et al. 2016 and Svensson et al. 2017), and these have now formed the basis of a novel MEW system, the UK Drought Portal (Fig. 2; <https://eip.ceh.ac.uk/droughts>). From June 2017, monthly updates of the SPI have enabled current conditions to be explored in a dynamic mapping and time series visualization environment, offering more scope for user-defined information than the static online documents

currently available via WSRs or the NHMP. The addition of more indicators to the Portal (representing river flows and groundwater) is currently in development.

Major changes to water management legislation and practice in the United Kingdom are underway (Robins et al. 2017). These include changes to DPs to align them with WRMPs, and adopting stochastic methods to respond to the objective of resilience set out in Section 22 of the Water Act (2014) and address EA drought planning guidance that strongly encourages water supply companies to plan for droughts worse than those in their historical records (Environment Agency 2015). Other areas of uncertainty include abstraction reform, which has the potential to open up water markets and trading (Wentworth and Mayaud 2017), and legislative changes associated with Brexit (Robins et al. 2017). Thus, drought agendas and practices in the United Kingdom are changing at a rapid pace, with limited clarity on indicators and the role of MEW systems in policy and decision-making. Keeping this in mind, and given the diverse interpretations and experiences of drought, DrIVER researchers sought to engage with a range of stakeholders to identify crucial concerns and opportunities for improving U.K. MEW.

3. Methodology

Our starting point was recognizing the messiness (Ackoff 1974) and complexity of drought as an idea and situation that arises from ongoing scientific uncertainty, interdependency, and multiple perspectives of diverse stakeholders (Collins and Ison 2009; Lange et al. 2017). On the basis that no single group can proclaim the nature of the problem and its solution, DrIVER researchers in all three case study areas [North Carolina, Adelaide, and the United Kingdom; see Collins et al. (2016)] were committed to a *social learning* process alongside other stakeholders. In brief, social learning can be characterized by one or more of the following elements: *convergence* of goals, criteria, and knowledge about the nature of the situation; the *co-creation* of knowledge, which provides insight into the causes of, and the means required to transform or progress a situation; and *concerted action* whereby different activities collectively contribute to situation improvement (SLIM 2004). Consistent with social learning, situation improvement is always contextual and defined by those involved in the situation (see Wallis et al. 2013; Foster et al. 2016). This provides the imperative for the wider involvement of stakeholders in social learning to recognize and work with multiple framings and contexts of drought and MEW, to help develop more systemic and integrated policy and actions.

Conceived as a social learning coinquiry into drought MEW, the design of the U.K. research was centered on two U.K. stakeholder workshops, organized to run in series with one Australian and two U.S. workshops. Collins et al. (2016) describe in more detail the interplay between the international workshops and make comparisons between the outcomes from the three different continental settings. This model enabled researchers from different country teams to participate, ensuring cross-fertilization of ideas regarding event design and content, and to gain key critical insights into European, U.S., and Australian MEW experiences and how these might differ according to environmental/technological factors and also legal/political cultures (Jasanoff 2005). For efficiency and to minimize stakeholder fatigue, the two U.K. workshops were co-organized in partnership with other U.K. drought research projects funded under the U.K. Drought and Water Scarcity (DWS) Programme, including Improving Predictions of Drought for User Decision Making (IMPETUS) and Historic Droughts (see acknowledgments in this paper, and for further information see links at the DWS Programme website: <http://aboutdrought.info/>).

The first workshop (WK1) was attended by over 40 delegates from a range of sectors and professions, including water supply companies, regulators, environmental

nongovernmental organizations (NGOs), agriculture-related organizations, power generation companies, public health agencies, and consumer bodies (see Collins et al. 2015). Invited stakeholders were selected and invited building on partnerships being developed through the DrIVER and related droughts projects.

WK1 explored participants' framings, expectations, and needs relating to drought, indicators, and MEW systems by combining open discussion in mixed (i.e., mixed professions/sectors) groups of stakeholders, scientific presentations from international partners, and plenary sessions. Using conversation maps (Fig. 3), after McKenzie (2005), participants were asked specific but open questions such as, "How do we know we are in a drought?" designed to trigger discussion from diverse viewpoints rather than presuppose particular MEW expectations and experiences. A second key question—"What should the MEW of the future look like?"—moved the discussion toward actions. The plenary sessions between the conversation mapping activities were facilitated by project researchers and involved reporting the key discussion points by stakeholders followed by collective agreement of "meta-themes," issues, and actions (see Collins et al. 2015). The social learning design enabled flow between group work, sifting, and categorization, scientific presentations, and plenary discussion, culminating in suggestions for an action plan.

While the social learning design remained consistent, the methods of U.K. workshop 2 (WK2) were adapted in response to the findings of WK1. A key development was the iteration through a "worked example" of the 2010–12 drought—a recent event in institutional memory (see Parry et al. 2013). This progressed the specific question of WK1, "What should the MEW of the future look like?" by using the UK Drought Portal as an example of a novel MEW system. The session involved using a mock-up (Fig. 4) of a possible future version of the UK Drought Portal to explore potential benefits, garner specific feedback, and design input to explore the "art of the possible." Current and planned MEW innovations that could realistically be added to the portal in the near future were used at key points throughout the event, and included high spatial resolution information; consistent rainfall/river flow/groundwater indicators; use of historical "benchmarks"; example forecasts (using real hindcasts from IMPETUS); and use of observed impact information [real impacts taken from the European Drought Impact Report Inventory (EDII); Stahl et al. (2016)]. Key questions for this activity were, "What decisions would this new information support?" and "What would you do differently?" Subsequent sessions focused on linking indicators in future MEWs with the types of impacts experienced in various sectors. As with WK1, the event was well attended



FIG. 3. Example of two “conversation maps” from WK1 used to record participatory breakout group work. Participants thread together conversations from the central “trigger” (each pen color represents a different participant). The key five points from each group were summarized at the end and reported back in plenary.

(with over 30 delegates) but with a deliberately selected group of related sectors: public water supply, agriculture-related organizations, and the environment (principally regulators from the EA). This focus enabled further development of mutual understanding and social learning among core project stakeholders, and consideration of how their concerns might interact or diverge during drought events. Unlike WK1, delegates were seated in sector-based groups for all activities to more closely simulate decision-making discussions and clarify divergences between sector orientations.

4. Results: Emerging themes

This section discusses key insights emerging from WK1 and WK2 according to six high-level themes identified by participants. Although the themes are presented separately in the following subsections, the boundaries were less distinct in the workshop discussions.

a. Types of droughts

Our results show different actors have different concerns and divergent definitions of the “same” drought event. While keen to avoid endless definitional problems, and recognizing conventional distinctions between meteorological, hydrological, and agricultural droughts, participants in both workshops also wanted MEW systems to accommodate the complexity and multifaceted nature of droughts and impacts as experienced from their different contexts, at different times. Thus, “whisky droughts” and “salmon droughts” in Scotland, and “navigational droughts” (as defined by the Canal and River Trust) framed stakeholders’ thinking about the properties of droughts likely to impact their operations and thus future MEW design.

Furthermore, WK1 participants highlighted spatial and temporal variability in the occurrence of the hydrometeorological drought hazard, for example, short versus multiannual droughts, and regional contrasts between northwest and southeast England—all of which necessitates regional “tailoring” of MEW information. The WK2 water supply sector participants affirmed this distinction between northwest England, where medium to long range forecasting is potentially useful in the context of rapidly responding catchments (see also Lopez and Haines 2017), and the southeast, where situation monitoring is more useful because of the slow evolution of multiannual droughts (e.g., Folland et al. 2015).

WK1 and WK2 participants also noted the difference in resilience (spatial and temporal) of water supply systems arising, for example, from different degrees of connectedness and conjunctive use of sources. These factors influence resilience to different types of drought events (Anderton et al. 2015) as some areas will be more vulnerable than others, even within the same meteorological drought. WK2 agriculture participants noted also the geographical variation in “types” of agricultural drought stress: for example, types of cropping, (e.g., rain-fed or irrigated) and location in the country (Rey et al. 2016, 2017). The latter distinction reflects water supply/demand balances, the type of drought and impacts depending very much on existing vulnerability and water availability. This explains variations around the country but also through time; Rey et al. (2017) found significant improvements in resilience to drought over time in eastern England as farmers have adapted and become less vulnerable to a given deficit.

b. Indicators and impacts

The proliferation of indicators in the academic literature was matched by a similarly wide range of indicators used by participants to “know when we are in a

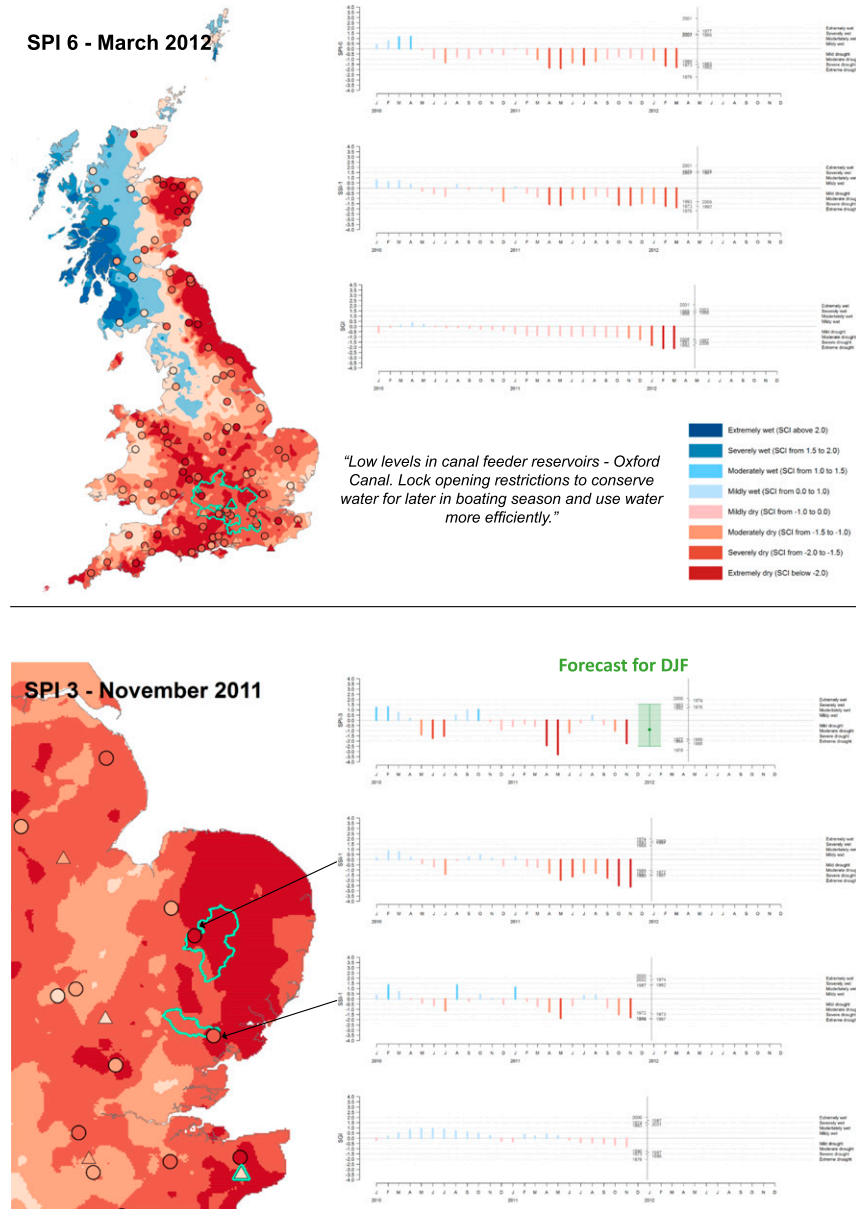


FIG. 4. Mock-up of a possible future integrated monitoring portal, showing two elements for the 2010–12 drought. (top) The 6-month SPI (SPI-6) for Great Britain overlain with the 1-month standardized streamflow index (SSI-1) and the standardized groundwater index (SGI). It also includes time series plots of these indicators (with historical benchmark events for comparison) and an example drought impact report from the EDII. (bottom) SPI-3 for East Anglia overlain with the SSI and SGI and plots for two SSI series and an SGI series. It also includes a winter (December–February) SPI forecast for East Anglia (based on real hindcasts) shown in green using the upper/lower bounds and median of the ensemble forecast.

drought.” A key concern across both workshops was the extent to which indicators relate to reality. Although a MEW system may show very severe (drought) conditions in terms of rainfall, there may not be drought impacts “on the ground.” In WK2, the upper panel in Fig. 4 was challenged because it showed a severe

drought in some western areas (based on rainfall and river flows), which did not agree with local knowledge in terms of impacts experienced. Similar contradictions between MEW information and on the ground perceptions have been reported in the United States (Kohl and Knox 2016).

In parallel to the differentiation in type of droughts experienced across different sectors, impacts are not linear or uniform in onset, distribution, scale, and severity, or predictability. Farmers could experience impacts “overnight” at planting time, whereas water utilities would only become concerned over a monthly or seasonal time scale. Participants in WK1 expressed a need for future MEW systems to recognize and assess the societal and economic costs and consequences for different types of drought events and different “severities” (quantified in terms of duration, intensity, return period, etc.), arising from variations in vulnerability. Thus, a given event severity will give rise to different impacts for different sectors across different spatial and temporal scales according to particular configurations of social and biophysical systems. This has been further demonstrated through quantitative work on indicator–impact relationships for the United Kingdom (Bachmair et al. 2016b).

Participants noted that while impacts are often used to define drought, in the United Kingdom this is usually undertaken in hindsight rather than actively monitored and reported publicly. In England, during drought events, the EA monitors and reports impacts internally within weekly “drought management briefings,” but these are not necessarily systematic nor made public as an aid to decision-making for external stakeholders. Other stakeholders like water companies and farmers are, clearly, acutely aware of impacts and track them for their own purposes.

Both workshop discussions suggested a need for dynamic impact monitoring in an open and transparent way as, for example, undertaken with the U.S. Drought Impact Reporter (DIR; droughtreporter.unl.edu/map/), which was discussed at both workshops as an example of a system for capturing impacts in near-real time and feeding them into MEW. Currently, the DIR is predominantly based on media reports, which often lag the emergence of impacts. Thus, while the DIR holds some promise for dynamic impact monitoring, there are comparatively fewer submissions made by observers and it is not fully incorporated into operational monitoring, although significant progress is being made in this direction [K. Smith, National Drought Mitigation Centre (2018), personal communication; see also Lackstrom et al. (2017)].

As if all this were not enough, both workshops raised a fundamental question: “What are impacts and what are indicators?” Researchers have differentiated these on the basis of biophysical indicators and tangible (normally negative) social and environmental impacts (e.g., Stahl et al. 2016). This distinction is the basis of the growing trend toward using impacts to “ground truth”

MEW indicators (e.g., Bachmair et al. 2016a,b). However, workshop participants found the distinctions very fuzzy and struggled with determining absolute impacts or indicators (especially in the WK2 exercise of mapping indicators onto specific impacts). For example, for water supply stakeholders, their drought “impact” is on supply, for example, in terms of reservoir stocks, which could be considered an indicator by consumers. This reveals the relative nature of impacts and indicators depending on a stakeholder’s “position” in a drought event and their particular framings, concerns, and responsibilities. The WK2 water supply participants extended this further by noting the interconnectedness of sectors and impacts. Water supply management actions, such as drought orders, can exacerbate environmental impacts and may have knock-on impacts on agriculture, recreation, and commercial sectors, which can lead to tensions. This was also reaffirmed by the “environmental” (regulatory) stakeholders who recognized their official remit of decision-making is focused on impacts in rivers, reservoirs, and irrigation, but the impacts of their decisions may be broader—for example, mental health impacts on the farming community.

While it was nearly universally agreed that determining impacts on the environment is crucial for drought management, it was accepted that the evidence base for ecological impacts is relatively limited, in part because of incomplete understanding of the links between hydrological states and ecological impacts over time, particularly the nature and extent of ecosystem recovery from drought stress (e.g., Dollar et al. 2013). Workshop participants underscored the importance of ecologically meaningful indicators, and moreover requested an indicator of ecosystem recovery time.

Finally, participants in both workshops highlighted that there is a whole host of “untapped” impact variables, some of which are not yet included in centralized MEW systems, and some of which are not monitored at all. For example, in the United Kingdom, regulators routinely conduct a wide range of monitoring activities (e.g., water quality, temperature, biological status), which are relevant for drought early warning and in England have been used to support a national drought surveillance network (Dollar et al. 2013). Citizen science initiatives offer significant potential to fill gaps, for example, to record drying of headwaters; currently, these are underexploited in the United Kingdom for drought, notwithstanding progress in other areas like water quality (e.g., www.catchmentbasedapproach.org/resources/volunteer-monitoring). Other key sources included Earth observation [e.g., to track vegetation health; Bachmair et al. (2018)], which is a cornerstone of continental-scale systems such as the European Drought Observatory, but is

not yet built into public U.K. MEW systems. Agriculture attendees in WK2 stressed that technologically sophisticated, finescale monitoring is already undertaken at the farm level, which could be assimilated into a larger-scale MEW system. This could be particularly advantageous for monitoring variables that are currently not well covered by in situ monitoring networks—for example, soil moisture—but could also include information of on-farm impacts.

c. Capacity and decision-making

While keen to improve MEW systems, participants signaled a need for learning about decision-making requirements and understanding the capacities of stakeholders to respond to MEW information in a range of contexts. Discussions highlighted distinct contrasts—for example, between water supply and agriculture. A phrase highlighted in both workshops from the water supply participants was “It’s all about the drought plans!” These legally required DPs are well resourced, embedded, and clearly set out what water companies will do and when, based on specific triggers. In contrast, there is no WRMP or DP for agriculture—“farmers have to just get on with it.” Although good lines of communication exist between farmers and other sectors (Rey et al. 2017), the agricultural stakeholders in WK1 noted they sometimes feel “left to their own devices and have to respond to impacts that are already happening.” Participants observed that water supply sector planning has a 25-yr horizon, and while many agricultural businesses engage in long-term planning, this is not formalized or statutory (although water companies do consider agricultural abstractions in supply/demand balances in WRMPs and there are increasing efforts to bring agricultural stakeholders into the planning process, e.g., Water Resources East, www.waterresourceeast.com/).

To this end, more dynamic, high-resolution MEW tools like the UK Drought Portal were considered useful innovations in delivering local-scale information over and above current systems. Even so, within agriculture, major differences were noted in capacities and decision-making processes between different users. In discussing how users would interpret the UK Drought Portal, or other MEW products, alongside many other factors under consideration, it was widely agreed in WK2 that for the agricultural community especially, interpretation and operationalization by trusted intermediaries would be needed for information to be understood and acted upon. Such intermediaries may include organizations such as the National Farmers Union (NFU), who already collate a range of weather-related services for farmers (www.nfuonline.com/cross-sector/environment/weather/), the Agriculture and Horticulture Development Board (AHDB), and in

certain catchments, abstractor groups [see Rey et al. (2017) for discussion on the role played by the latter in communicating with regulators and other stakeholders around drought status].

d. Uncertainty: Past and future

This theme recurred throughout: stakeholders all wanted more certainty, but appreciated that decisions are made in complex situations where there is uncertainty/lack of confidence in forecasts (Lopez and Haines 2017) and also significant and increasing uncertainties in using the historical record as a basis for planning in a climate-changing world (e.g., Watts et al. 2015).

Even so, historical benchmarks (or comparisons) were highlighted as useful aspects of any MEW, as an intuitive way for managers to appraise current status in the context of past droughts (and past drought experiences). In addition, historical benchmarks are useful for stress-testing drought plans (e.g., Watts et al. 2012) and “ground truthing” indicators against observed impacts. However, some participants also questioned the use of historical droughts: WK2 water supply participants noted the significant changes in supply systems and therefore resilience, such that a given rainfall accumulation/river flow would not translate into the same impacts or severity relative to historical droughts (see also Bachmair et al. 2016b). Water companies now plan for events more severe than those in the historical record, using a range of simulation approaches to extrapolate beyond past observations (e.g., Anderton et al. 2015; Water UK 2016). Participants considered how such complexity could be brought into large-scale, national MEW frameworks. Although there were no easy answers, it was noted that highlighting risk could be useful at least for communications and could parallel flood terminology, for example, identifying the “reasonable worse case.”

While interpreting past droughts was the source of much uncertainty, forecasting future droughts proved an equally rich topic for discussion at both workshops, especially around the operational utility of seasonal forecasts. Despite advances in skill (e.g., Scaife et al. 2014) and improved accessibility of hydrological forecasts (Prudhomme et al. 2017), it was generally agreed that forecasts are still not readily useable for decision-making by water companies. Water company attendees said they generally use forecasts “qualitatively,” for context, rather than as “evidence” to trigger actions.

All workshop participants desired more accurate and less uncertain MEW systems/products and forecasts. Environmental regulators wanted improved confidence in forecasts of drought development, duration, and termination. Farmers were satisfied with short-term weekly forecasting, but noted crop decisions are made on conditions of the previous year and months in advance of

the potential drought state, owing to contracts arrangements and markets, with limited consideration of the drought outlook for the following year. While seasonal forecasting offers considerable potential in this sector, and better MEW and forecasting could influence cropping decisions (e.g., type, location, and timing) to reduce risks of drought, inherent uncertainties in forecasting at the seasonal scale and beyond remain a major constraint.

e. Communication

Participants in WK1 highlighted the key roles of definitions, perceptions, communication processes, and education needs in drought management: MEW systems do not operate in a vacuum where only the hydroclimatic state is important. Following this, participants wanted improved MEW systems to help enable consistent messaging regarding the complexities of drought. Problems of communication were typified by the 2012 drought, continuing during significant summer rainfall and flooding (Parry et al. 2013), but despite the challenges, it was generally felt that communication in that drought-to-flood event was successful.

While WK2 participants noted that new tools such as the UK Drought Portal are useful visually and allow historical and regional comparisons for internal and external communications in a more standardized way, communication is closely linked to trust, which can be a barrier to the uptake of new systems and indicators. Issues of trust permeated other discussions around communication: water companies in WK2 also referred to “credibility” in terms of having to act on issues such as leakage to maintain the trust of other stakeholders and the public when issuing drought permits.

The two workshops also made it clear that there is no universal, neutral language of communication that meets everyone’s needs. The word “drought” itself was noted in both workshops as sensitive; there may be very real financial repercussions for commercial sectors, for example, agriculture where retailers might turn to other suppliers if a drought is expected in certain areas, creating loss of income and uncertainty of supply. An important—but not the only—aspect of this is communicating the skill/confidence of drought forecasts to users.

Finally, visibility of drought impacts was highlighted as a key issue in communications. Environmental impacts are important and recognized by the general public. Workshop participants suggested that if regulatory and water company DPs are successful in mitigating environmental impacts, the expected impacts of drought may not arise or be visible. This suggests that MEW

systems based on evidential impacts may not offer a “true” picture of a drought event if the impacts are mitigated or hidden before they can be recorded and communicated, with implications for garnering public support.

f. Governance

This theme emerged from a complex set of discussions in both workshops. Linked to drought definitions, it became apparent that “declaring” a drought was politically and organizationally sensitive for many reasons including reputation, commercial interests, media interest, and public perception and responses. This led to the recognition of fundamental questions about the ownership and governance of MEW systems, such as, “Who is technically and legally responsible for declaring a drought (over) given the differentiation in drought impacts in different sectors?” In turn, this prompted questions on “ownership” of drought and MEW systems, with wide-ranging implications for responsibilities and collective, coordinated responses—for example, “Who is responsible if a drought is ‘declared’ incorrectly?” and “Who funds and owns the MEW and who carries the responsibility of interpreting data?” While there was no consensus on answers to these questions, participants did note that governance considerations are a key part of drought preparation and the design of MEWs, especially where MEW outcomes could potentially be contradictory. Participants in WK2 felt that “new” MEW systems like the UK Drought Portal could be useful as an additional source of evidence in the governance of drought, such as applying for drought orders. However, it was recognized that multiplicity of data and indicators could prove problematic as it opens up the possibility of challenge based on alternative sources.

This led to further discussion about the nature of drought declaration. While in other countries drought declaration is formal (e.g., Botterill and Hayes 2012), in the United Kingdom, declaring a drought is informal and more for communication purposes; it does not have any statutory basis [although authorization by the Secretary of State of an application for a drought order under Section 73 of the Water Resources Act 1991 is a de facto drought declaration]. A comparison was drawn with floods that are also not declared as such, but are much more visible. The relative intangibility of drought, combined with the potentially contentious management decisions such as abstraction licenses and resource allocation, make drought declaration particularly politically “loaded.” Furthermore, some locations are vulnerable to water shortage even without drought conditions: water availability (taking account of

demand) is the crux, and needs to be set in the context of abstraction licensing, which participants noted was challenging enough already [“How much of the shortfall is due to ‘natural’ drought versus human use?”; see [Van Loon et al. \(2016\)](#)], even before considering the potential complexities of future abstraction reform.

5. Discussion and recommendations

Returning to the aims of this study, the thematic sections above have highlighted the complexity of drought as an idea, its management, and the implications of this complexity for MEW design and optimization. The different framings of potential users lead to divergent views on what MEW systems are for, how to interact with them, how they should be operated/governed and by whom, and how they should link with existing regulatory systems. There were key differences between “sectors” in terms of drought definitions, drought impacts, institutional capacity, and engagement with drought. A notable example is the comparison between water supply, which has 25-yr WRMPs and where impacts can be slowly evolving, and agriculture, where there is no statutory requirement for long-term planning for drought, which is just one of many shocks faced by farmers and where impacts can happen very rapidly.

Similarly, organizations such as water companies and regulators have existing plans specifically for drought. This means that MEW systems face a barrier to uptake, namely, that any indicators must be translated into the context of existing DPs. This was noted in both workshops: any “novel” indicators being proposed (e.g., the SPI used by the UK Drought Portal) need to be related to local-scale triggers and impacts. More broadly, this speaks to the divide between large-scale, centralized regional to national MEW systems (e.g., WSRs, hydrological summaries, the UK Drought Portal) and local, operational MEW and drought management carried out by a wide range of actors (water companies, farmers, etc.). This highlights a “translation imperative” between centralized MEW systems and local operational needs, which has been highlighted elsewhere in the literature. MEW indicators can be used to set triggers for action (e.g., [Steinemann et al. 2015](#); [Botterill and Hayes 2012](#)). However, in most large-scale, public-facing MEW systems, outputs are “awareness” indicators for a wide range of stakeholders rather than triggers for specific sectors. These awareness indicators set the wider context for stakeholders’ own “private” operational triggers (e.g., reservoir trigger levels). The translation imperative highlights a need for better understanding of the (dis)connections between information and decisions, and

especially the social and institutional factors influencing the usability of warnings, forecasts, and other information products that are intended to inform preparedness (e.g., [Rayner et al. 2005](#); [Kohl and Knox 2016](#)).

For MEW design, the problem of different definitions/framings/decision-making processes is arguably insurmountable; the old adage “one cannot please all of the people, all of the time” holds some sway. National/regional MEW systems need to provide information for a range of potential users, and rely on “translation” activities and the use of intermediaries (e.g., in linking to water company DPs or working with farmers, respectively). Who undertakes and owns these translation activities, and how the consistency of messaging is maintained remain important questions. The diversity in MEW users’ requirements underscores a clear need to maintain MEW systems with multiple indicators tailored to particular sectors. Conversely, both workshops highlighted the political need for government ministers and other policymakers to have a simple, single answer to questions such as, “How severe is the drought?” This tension between single “composite” indicators and multiple, tailored indicators has precedent ([WMO and GWP 2016](#); [Bachmair et al. 2016a](#)). Composite indicators are widely used internationally, and typically blend a wide range of hydrometeorological indicators into a single indicator, using a range of both quantitative (typically, multivariate statistical approaches) and qualitative techniques to achieve the blending. The most notable example is the U.S. Drought Monitor, with categories running from D0 “abnormally dry” to D4 “drought-exceptional,” variants of which are used around the world.

For the United Kingdom, from [Mawdsley et al. \(1993\)](#) onward, and as also discussed in [Lloyd-Hughes \(2014\)](#), there has generally been a tendency to avoid sweeping definitions of drought severity within a single, overarching indicator in favor of a more nuanced multi-indicator approach (Mawdsley’s “basket of indicators”). A qualitative composite indicator is employed by the [Environment Agency \(2017\)](#), based not on a single definition of drought, but three broad types (environmental, agricultural, and water supply) and a simple, traffic-light concept of drought status (normal, developing drought, severe drought, recovering). While this is appropriate given the complex and multifaceted nature of drought, it also leads to a certain fuzziness—it is not transparent in the outputs what indicators or triggers are used to lead to such status. Similar debates can be recognized in the international literature (e.g., [Botterill and Hayes 2012](#)).

As evident in the workshop discussions, droughts and their impacts are diverse and dynamic. Even if a

key difficulty of distinguishing indicators from impacts could be resolved, indicators for monitoring need to accommodate and represent this diversity as a drought develops. But current indicators are inadequate in this respect, and skillful seasonal forecasting is in its infancy, at least in practical terms. While all sectors identified the central role of impacts, it is clear that, as with international experience, impacts are not currently a central part of MEW systems at a broad scale, and systematic impact data collation is lacking. A further complicating factor is that there is not a one-way path from “indicator,” such as rainfall, through to “impact” on society—this chain depends on definitions of what constitutes an indicator or an impact, the mediating role of terrestrial and aquatic ecosystems, and a complex chain of feedbacks. Increasingly, drought is seen from a systems perspective, with humans playing a key role as agents in mitigating or exacerbating a hydrological drought to the extent that a reframing of drought as a sociohydrological system is underway (e.g., [Van Loon et al. 2016](#); [Lange et al. 2017](#)).

Our findings lead us to question whether it is desirable, or even possible, to create a consensus about using indicators: despite very real privations, drought is by its very nature a contestable idea. While it may not seem helpful for everyone to be starting from different points, it is inevitable that multiple framings of drought and its impacts exist and are dependent on the interests and values of the “observer.” Our findings in this regard chime with other international research, for example, the “multiple ways of knowing drought” of [Kohl and Knox \(2016\)](#). Furthermore, as many workshop participants from across sectors made clear, drought is but one of many factors shaping decisions that involve water resources. The degree of flexibility in a MEW system and the extent to which it can include local/sector knowledge is a key design consideration and one that we suggest will be important in determining use and trust in any MEW. Where indicators do not agree, user communities need to rely on discontinuities being communicated openly by trusted sources and intermediaries and incorporating this into, rather than driving, decision-making. A flexible approach that accounts for context differentiation offers a better basis for drought management than a deterministic and singular overreliance on MEW data and outputs.

We end by synthesizing our findings to make the following recommendations for the design of large-scale, multi-stakeholder, multisectoral MEW systems in the United Kingdom, including consideration of how they interact with extant, finer-scale localized MEW. While we have grounded these recommendations in concrete

actions relevant to the United Kingdom, we suggest the key principles are of relevance to MEW systems in other international settings:

- A combination of the *basket of indicators* approach to cater to a wide community of users, alongside some simple *composite indicators* to provide high-level drought status for government, policymakers, the media, and general public. The basket of indicators already exists in current systems, for example, the Hydrological Summary and WSRs. Qualitative composite indicators are used by the EA, but there is a disconnect between the “basket” approach and the high-level messages. We recommend investigation of quantitative, multivariate composite indicators such as those used in the U.S. Drought Monitor and increasingly adopted elsewhere in the world.
- The above combination implies a *modular system*, with a core based on simple hydrometeorological indicators that are meaningful for all users, with options to provide add-on modules/apps with consistent, sector-relevant indicators (for agriculture, water companies, the energy sector, etc.). Technologies like the UK Drought Portal could prove to be beneficial as the core of this modular system, allowing seamless, interactive multiscale visualization of and access to an agreed set of indicators. Add-on modules may reside elsewhere but should be integrated or linked. These must be codeveloped by researchers and users; and while the indicators can be different, consistency and comparability of presentation are crucial.
- The need to accommodate *capacity and decision-making needs* of users: some users want technical information (SPI, severities, probabilities); some require high-level information (answering questions such as, “Is the drought getting worse in my catchment?”). Systems like the UK Drought Portal are well adapted for the former. The latter may need different modes of presentation (e.g., podcasts, webinars) through trusted sector-dependent intermediaries—for example, the NFU or abstractor groups, Rivers Trusts, catchment partnerships—with capacity-building opportunities.
- Using *historical information* as benchmarks: such standards are widely understood, but MEW systems should recognize both nonstationarity and the expectation for larger events by chance; further work is needed to incorporate information from the stochastic approaches being used in WRMPs/DPs for planning for droughts beyond the historical record. Current research on expanding our historical understanding of hydrological drought through reconstructed streamflow datasets ([Smith et al. 2018](#)) and extensive ensembles of

synthetic hydrometeorological data (Guilod et al. 2018) provide opportunities for improving the historical analogs, and “what if” or “reasonable worst case” scenarios that may feature in future MEW systems.

- Integrating *forecasting* into MEW: while currently available weather and hydrological forecasts may not command sufficient confidence among most potential users to provide a basis for high-stakes decision-making, they may be incorporated alongside other sources to inform decision processes, and to facilitate discussions among forecasters, decision-makers, and regulators about information needs and risk perceptions. Research is already underway within IMPETUS and ENDOWS to explore how to improve forecast performance, relevance, and usability given recent advances in hydrological forecasting skill, particularly in some regions/seasons, and forecast accessibility [notably through the Hydrological Outlook UK; see Prudhomme et al. (2017) and references therein].
- MEW systems must recognize users are dealing with *hydrological variability* in the round, from drought to floods, along with a whole host of other stressors.
- An *impact-focused* approach: bringing impacts into public MEW systems where possible. This entails synthesizing existing information from routine monitoring (e.g., water quality) and using novel approaches (e.g., citizen science) for variables that are not yet monitored, and highlights a need for informatics solutions to integrate and synthesize information. The DIR and the EDII could provide models, noting however that neither of these are yet fully used operationally; this represents an important avenue for research in the United Kingdom and internationally.
- Addressing the gap in *ecosystem health*: there is a particular need for improved understanding of ecological status and recovery, and ecosystem response to droughts, and to bring this understanding into MEW systems. England benefits from a nascent drought surveillance network that provides a way forward, but there remains a need to better understand the link between hydrological and ecological drought status.

Acknowledgments. This study is the joint outcome of several projects that co-organized the stakeholder engagement activities: a Belmont Forum project DrIVER (funded in the United Kingdom by NERC, Grant NE/L010038/1); several projects within the NERC Drought and Water Scarcity Programme (Historic Droughts NE/L01016X/1; IMPETUS NE/L010267/1 and NE/L010488/1; and a knowledge exchange follow-on project ENDOWS awarded under the same grants);

and the Oxford Martin Programme on Resource Stewardship. We thank Anglian Water for providing the data for Fig. 1. We are grateful to the many stakeholders and researchers who attended the workshops and thank them for their valuable contributions. There are no conflicts of interest. Because of the confidential nature of some research materials, not all data can be made accessible. Please contact the author for more information.

REFERENCES

- Ackoff, R. L., 1974: *Redesigning the Future: A Systems Approach to Societal Problems*. Vol. 10. Wiley-Interscience, 260 pp.
- Anderton, S., R. Ledbetter, and C. Prudhomme, 2015: Understanding the performance of water supply systems during mild to extreme droughts. Environment Agency Tech. Rep. SC120048/R, 61 pp., https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/484944/Performance_of_water_supply_systems_during_mild_to_extreme_droughts_report.pdf.
- Anglian Water, 2014: Drought Plan 2014. Anglian Water Rep., 125 pp., <http://www.anglianwater.co.uk/environment/our-commitment/our-plans/drought-plan.aspx>.
- Bachmair, S., and Coauthors, 2016a: Drought indicators revisited: The need for a wider consideration of environment and society. *Wiley Interdiscip. Rev.: Water*, **3**, 516–536, <https://doi.org/10.1002/wat2.1154>.
- , C. Svensson, J. Hannaford, L. J. Barker, and K. Stahl, 2016b: A quantitative analysis to objectively appraise drought indicators and model drought impacts. *Hydrol. Earth Syst. Sci.*, **20**, 2589–2609, <https://doi.org/10.5194/hess-20-2589-2016>.
- , M. Tanguy, J. Hannaford, and K. Stahl, 2018: How well do meteorological indicators represent agricultural and forest drought across Europe? *Environ. Res. Lett.*, **13**, 034042, <https://doi.org/10.1088/1748-9326/aaafda>.
- Barker, L. J., J. Hannaford, A. Chiverton, and C. Svensson, 2016: From meteorological to hydrological drought using standardised indicators. *Hydrol. Earth Syst. Sci.*, **20**, 2483–2505, <https://doi.org/10.5194/hess-20-2483-2016>.
- Botterill, L. C., and M. J. Hayes, 2012: Drought triggers and declarations: Science and policy considerations for drought risk management. *Nat. Hazards*, **64**, 139–151, <https://doi.org/10.1007/s11069-012-0231-4>.
- Byers, E. A., J. W. Hall, and J. M. Amezaga, 2014: Electricity generation and cooling water use: UK pathways to 2050. *Global Environ. Chang.*, **25**, 16–30, <https://doi.org/10.1016/j.gloenvcha.2014.01.005>.
- Cabinet Office, 2017: National Risk Register of Civil Emergencies: 2017 edition. Cabinet Office Tech. Rep., 71 pp., https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/644968/UK_National_Risk_Register_2017.pdf.
- Collins, K., and R. Ison, 2009: Jumping off Arnstein’s ladder: Social learning as a new policy paradigm for climate change adaptation. *Environ. Policy Gov.*, **19**, 358–373, <https://doi.org/10.1002/eet.523>.
- , J. Hannaford, S. Haines, S. Bachmair, N. Crossman, L. Stephens, and M. Svoboda, 2015: Drought: Understanding and reducing vulnerability through monitoring and early warning systems. DrIVER Project Rep., 29 pp., <http://oro.open.ac.uk/46097/1/DrIVER%20UK%20Workshop%201%20Report%20Final.pdf>.

- , and Coauthors, 2016: Stakeholder coinquiries on drought impacts, monitoring, and early warning systems. *Bull. Amer. Meteor. Soc.*, **97**, ES217–ES220, <https://doi.org/10.1175/BAMS-D-16-0185.1>.
- Dollar, E., and Coauthors, 2013: Monitoring and assessment of environmental impacts of droughts: Literature synthesis. Environment Agency Final Rep. SC120024/R1, 84 pp., https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/291497/LIT_8569_b765dd.pdf.
- Environment Agency, 2015: Write a drought plan. Accessed 31 July 2018, <https://www.gov.uk/guidance/write-a-drought-plan>.
- , 2017: Drought response: Our framework for England. Environment Agency Tech. Rep., 33 pp., https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/625006/LIT_10104.pdf.
- Folland, C. K., J. Hannaford, J. P. Bloomfield, M. Kendon, C. Svensson, B. P. Marchant, J. Prior, and E. Wallace, 2015: Multi-annual droughts in the English Lowlands: A review of their characteristics and climate drivers in the winter half-year. *Hydrol. Earth Syst. Sci.*, **19**, 2353–2375, <https://doi.org/10.5194/hess-19-2353-2015>.
- Foster, N., K. Collins, R. Ison, and C. Blackmore, 2016: Water governance in England: Improving understandings and practices through systemic co-inquiry. *Water*, **8**, 540, <https://doi.org/10.3390/w8110540>.
- Gosling, R., 2014: Assessing the impact of projected climate change on drought vulnerability in Scotland. *Hydrol. Res.*, **45**, 806–816, <https://doi.org/10.2166/nh.2014.148>.
- Guillod, B. P., and Coauthors, 2018: A large set of potential past, present and future hydro-meteorological time series for the UK. *Hydrol. Earth Syst. Sci.*, **22**, 611–634, <https://doi.org/10.5194/hess-22-611-2018>.
- Jasanoff, S., 2005: *Designs on Nature: Science and Democracy in Europe and the United States*. Princeton University Press, 374 pp.
- Kohl, E., and J. A. Knox, 2016: My drought is different from your drought: A case study of the policy implications of multiple ways of knowing drought. *Wea. Climate Soc.*, **8**, 373–388, <https://doi.org/10.1175/WCAS-D-15-0062.1>.
- Lackstrom, K., A. Farris, D. Eckhardt, N. Doesken, H. Reges, J. Turner, K. H. Smith, and R. Ward, 2017: CoCoRaHS observers contribute to “condition monitoring” in the Carolinas: A new initiative addresses needs for drought impacts information. *Bull. Amer. Meteor. Soc.*, **98**, 2527–2531, <https://doi.org/10.1175/BAMS-D-16-0306.1>.
- Lange, B., and C. Cook, 2015: Mapping a developing governance space: Managing drought in the UK. *Curr. Leg. Probl.*, **68**, 229–266, <https://doi.org/10.1093/clp/cuv014>.
- , I. Holman, and J. P. Bloomfield, 2017: A framework for a joint hydro-meteorological-social analysis of drought. *Sci. Total Environ.*, **578**, 297–306, <https://doi.org/10.1016/j.scitotenv.2016.10.145>.
- Lloyd-Hughes, B., 2014: The impracticality of a universal drought definition. *Theor. Appl. Climatol.*, **117**, 607–611, <https://doi.org/10.1007/s00704-013-1025-7>.
- Lopez, A., and S. Haines, 2017: Exploring the usability of probabilistic weather forecasts for water resources decision-making in the United Kingdom. *Wea. Climate Soc.*, **9**, 701–715, <https://doi.org/10.1175/WCAS-D-16-0072.1>.
- Mawdsley, J., G. E. Petts, and S. Walker, 1993: *Assessment of Drought Severity*. British Hydrological Society, 30 pp.
- McKenzie, B., 2005: Conversation Mapping. Systems Development Institute, accessed 18 April 2018, <http://old.cognitive-edge.com/wp-content/uploads/2005/06/29-Conversation-Mapping-BMcK-0605.pdf>.
- Office for National Statistics, 2015: UK environmental accounts: 2015. Office for National Statistics Tech. Rep., 68 pp., <https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/ukenvironmentalaccounts/2015-07-09/pdf>.
- Parry, S., T. Marsh, and M. Kendon, 2013: 2012: From drought to floods in England and Wales. *Weather*, **68**, 268–274, <https://doi.org/10.1002/wea.2152>.
- Prudhomme, C., and Coauthors, 2017: Hydrological outlook UK: An operational streamflow and groundwater level forecasting system at monthly to seasonal time scales. *Hydrol. Sci. J.*, **62**, 2753–2768, <https://doi.org/10.1080/02626667.2017.1395032>.
- Pulwarty, R. S., and M. V. K. Sivakumar, 2014: Information systems in a changing climate: Early warnings and drought risk management. *Wea. Climate Extremes*, **3**, 14–21, <https://doi.org/10.1016/j.wace.2014.03.005>.
- Rayner, S., D. Lach, and H. Ingram, 2005: Weather forecasts are for wimps: Why water resource managers do not use climate forecasts. *Climatic Change*, **69**, 197–227, <https://doi.org/10.1007/s10584-005-3148-z>.
- Rey, D., I. P. Holman, A. Daccache, J. Morris, E. Weatherhead, and J. W. Knox, 2016: Modelling and mapping the economic value of supplemental irrigation in a humid climate. *Agric. Water Manage.*, **173**, 13–22, <https://doi.org/10.1016/j.agwat.2016.04.017>.
- , —, and J. W. Knox, 2017: Developing drought resilience in irrigated agriculture in the face of increasing water scarcity. *Reg. Environ. Change*, **17**, 1527–1540, <https://doi.org/10.1007/s10113-017-1116-6>.
- Robins, L., T. Burt, L. Bracken, J. Boardman, and D. Thompson, 2017: Making water policy work in the United Kingdom: A case study of practical approaches to strengthening complex, multi-tiered systems of water governance. *Environ. Sci. Policy*, **71**, 41–55, <https://doi.org/10.1016/j.envsci.2017.01.008>.
- Scaife, A. A., and Coauthors, 2014: Skillful long-range prediction of European and North American winters. *Geophys. Res. Lett.*, **41**, 2514–2519, <https://doi.org/10.1002/2014GL059637>.
- SEPA, 2016: Scotland’s national water scarcity plan. Scottish Environment Protection Agency Tech. Rep., 37 pp., <https://www.sepa.org.uk/media/219302/scotlands-national-water-scarcity-plan.pdf>.
- SLIM, 2004: Introduction to Social Learning for Integrated Management for policy-makers and practitioners. SLIM Policy Briefing, accessed 18 April 2018, <https://sites.google.com/site/slimsociallearningforiwm/research-outcomes/policy-briefs-1>.
- Smakhtin, V. U., and E. L. F. Schipper, 2008: Droughts: The impact of semantics and perceptions. *Water Policy*, **10**, 131–143, <https://doi.org/10.2166/wp.2008.036>.
- Smith, K. A., M. Tanguy, J. Hannaford, and C. Prudhomme, 2018: Historic reconstructions of daily river flow for 303 UK catchments (1891–2015). NERC Environmental Information Data Centre, accessed 31 July 2018, <https://doi.org/10.5285/f710bed1-e564-47bf-b82c-4c2a2fe2810e>.
- Stagge, J. H., I. Kohn, L. M. Tallaksen, and K. Stahl, 2015: Modeling drought impact occurrence based on meteorological drought indices in Europe. *J. Hydrol.*, **530**, 37–50, <https://doi.org/10.1016/j.jhydrol.2015.09.039>.
- Stahl, K., and Coauthors, 2016: Impacts of European drought events: Insights from an international database of text-based reports. *Nat. Hazards Earth Syst. Sci.*, **16**, 801–819, <https://doi.org/10.5194/nhess-16-801-2016>.
- Steinemann, A., S. F. Iacobellis, and D. R. Cayan, 2015: Developing and evaluating drought indicators for decision-making. *J. Hydrometeorol.*, **16**, 1793–1803, <https://doi.org/10.1175/JHM-D-14-0234.1>.
- Svensson, C., J. Hannaford, and I. Prosdociimi, 2017: Statistical distributions for monthly aggregations of precipitation and streamflow

- in drought indicator applications. *Water Resour. Res.*, **53**, 999–1018, <https://doi.org/10.1002/2016WR019276>.
- Van Loon A. F., and Coauthors, 2016: Drought in the Anthropocene. *Nat. Geosci.*, **9**, 89–91, <https://doi.org/10.1038/ngeo2646>.
- Wallis, P. J., R. L. Ison, and K. Samson, 2013: Identifying the conditions for social learning in water governance in regional Australia. *Land Use Policy*, **31**, 412–421, <https://doi.org/10.1016/j.landusepol.2012.08.003>.
- Water Act, 2014: Chapter 21, Water Act 2014. London, The Stationery Office, accessed 25 July 2018, <http://www.legislation.gov.uk/ukpga/2014/21/contents/enacted>.
- Water Industry Act, 1991: Chapter 56, Water Industry Act 1991. London, The Stationery Office, accessed 24 July 2018, <https://www.legislation.gov.uk/ukpga/1991/56/contents>.
- Water UK, 2016: Water resources long term planning framework (2015–2065). Water UK Tech. Rep., 199 pp., <https://www.water.org.uk/water-resources-long-term-planning-framework>.
- Watts, G., B. von Christerson, J. Hannaford, and K. Lonsdale, 2012: Testing the resilience of water supply systems to long droughts. *J. Hydrol.*, **414–415**, 255–267, <https://doi.org/10.1016/j.jhydrol.2011.10.038>.
- , and Coauthors, 2015: Climate change and water in the UK—Past changes and future prospects. *Prog. Phys. Geogr.*, **39**, 6–28, <https://doi.org/10.1177/0309133314542957>.
- Wentworth, J., and J. Mayaud, 2017: Reform of Freshwater Abstraction. Parliamentary Office of Science and Technology Rep. POST-PN-0546, 5 pp., <http://researchbriefings.files.parliament.uk/documents/POST-PN-0546/POST-PN-0546.pdf>.
- WMO and GWP, 2016: Handbook of drought indicators and indices: Integrated Drought Management Programme (IDMP), Integrated Drought Management Tools and Guidelines Series 2. WMO/TD-1173, 52 pp., http://www.droughtmanagement.info/literature/GWP_Handbook_of_Drought_Indicators_and_Indices_2016.pdf.
- World Bank, 2017: Agriculture, forestry, and fishing, value added (% of GDP). World Bank Group, accessed 24 July 2018, <https://data.worldbank.org/indicator/NV.AGR.TOTL.ZS>.