Environmental Research Letters

TOPICAL REVIEW • OPEN ACCESS

Drought vulnerability and risk assessments: state of the art, persistent gaps, and research agenda

To cite this article: Michael Hagenlocher *et al* 2019 *Environ. Res. Lett.* **14** 083002

Environmental Research Letters

OPEN ACCESS

RECEIVED
12 December 2018

REVISED
14 March 2019

ACCEPTED FOR PUBLICATION
17 May 2019

PUBLISHED
22 July 2019

TOPICAL REVIEW

Drought vulnerability and risk assessments: state of the art, persistent gaps, and research agenda

Michael Hagenlocher[1], Isabel Meza[1], Carl C Anderson[2], Annika Min[1], Fabrice G Renaud[2], Yvonne Walz[1], Stefan Siebert[3] and Zita Sebesvari[1]

[1] United Nations University, Institute for Environment and Human Security (UNU-EHS), UN Campus, Platz der Vereinten Nationen 1, 53113 Bonn, Germany

[2] University of Glasgow, School of Interdisciplinary Studies, Dumfries Campus, Rutherford/McCowan Building, Dumfries DG1 4ZL, United Kingdom

[3] Department of Crop Sciences, University of Göttingen, Von-Siebold-Strasse 8, D-37075 Göttingen, Germany

E-mail: hagenlocher@ehs.unu.edu

Keywords: drought, risk assessment, review, human dimension, research gaps

Supplementary material for this article is available online

Abstract

Reducing the social, environmental, and economic impacts of droughts and identifying pathways towards drought resilient societies remains a global priority. A common understanding of the drivers of drought risk and ways in which drought impacts materialize is crucial for improved assessments and for the identification and (spatial) planning of targeted drought risk reduction and adaptation options. Over the past two decades, we have witnessed an increase in drought risk assessments across spatial and temporal scales drawing on a multitude of conceptual foundations and methodological approaches. Recognizing the diversity of approaches in science and practice as well as the associated opportunities and challenges, we present the outcomes of a systematic literature review of the state of the art of people-centered drought vulnerability and risk conceptualization and assessments, and identify persisting gaps. Our analysis shows that, of the reviewed assessments, (i) more than 60% do not explicitly specify the type of drought hazard that is addressed, (ii) 42% do not provide a clear definition of drought risk, (iii) 62% apply static, index-based approaches, (iv) 57% of the indicator-based assessments do not specify their weighting methods, (v) only 11% conduct any form of validation, (vi) only ten percent develop future scenarios of drought risk, and (vii) only about 40% of the assessments establish a direct link to drought risk reduction or adaptation strategies, i.e. consider solutions. We discuss the challenges associated with these findings for both assessment and identification of drought risk reduction measures, and identify research needs to inform future research and policy agendas in order to advance the understanding of drought risk and support pathways towards more drought resilient societies.

1. Introduction

Droughts are recurring slow-onset hazards that can potentially have major direct and indirect impacts on human and natural systems, including terrestrial and freshwater ecosystems, agricultural systems, public health, water supply, water quality, food security, energy, or economies (e.g. through tourism, transport on waterways, forestry) (Schwalm *et al* 2017). While drought generally refers to a lack of water compared to normal conditions (Van Loon *et al* 2016), droughts are commonly grouped into four major types, including (i) meteorological or climatological, (ii) hydrological, (iii) agricultural or soil moisture, and (iv) socio-economic drought (Wilhite and Glantz 1985). They are characterized in terms of their frequency, severity, duration, and extent (Zargar *et al* 2011). According to existing conceptual models (Wilhite and Glantz 1985, Van Loon *et al* 2016), these drought types generally occur in a particular sequence: climate variability leads to a precipitation deficit that instigates a meteorological drought, which when combined with high potential evapotranspiration leads to an agricultural or soil moisture drought. Hydrological droughts occur as a delayed hazard associated with the effects of temperature anomalies, precipitation shortfalls, and/or anthropogenic demand pressures on surface or subsurface water supply, such as streams, reservoirs, lakes or groundwater. Socioeconomic drought is associated with the impact of an inadequate supply of some economic goods resulting from meteorological, agricultural, and hydrological droughts (Wilhite 2000, Zargar *et al* 2011, Van Loon *et al* 2016, Wang *et al* 2016). However, despite the progress that has been made in classifying and characterizing different drought types, no commonly accepted definition of what comprises a drought hazard exists (Mukherjee *et al* 2018).

Over the past decades, drought events across the world have caused damage to human wellbeing, the environment, and the economy. While there is ambiguity regarding drought trends in the past century (Andreadis and Lettenmaier 2006, Sheffield *et al* 2012, IPCC 2013, Trenberth *et al* 2013, McCabe and Wolock 2015) due to a lack of direct observations and the dependency of trends on drought index choice, it is expected that drought hazards will increase in both frequency and severity in many regions across the globe in the coming decades as a result of climate change (Sheffield and Wood 2008, Dai 2011, IPCC 2012, Trenberth *et al* 2013, UNCCD 2016). Despite the high uncertainty regarding future trends, risk assessments are needed in order to understand and ultimately reduce the risk of negative impacts associated with droughts.

Today it is widely acknowledged that risk, i.e. the potential for adverse impacts or consequences, is not driven only by natural hazards (droughts, floods, etc), but results from the interaction of hazards, exposure, and vulnerability (IPCC 2012, 2014). According to the Intergovernmental Panel on Climate Change (IPCC), exposure in this context refers to the 'presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected' by such hazards (IPCC 2014, p 5). Vulnerability is the predisposition to be adversely affected, resulting from the sensitivity or susceptibility of a system and its elements to harm combined with a lack of short-term coping capacity and long-term adaptive capacity (IPCC 2014). Due to its complex, multi-dimensional nature (Turner *et al* 2003, IPCC 2014), drought risk can therefore not be adequately represented solely by a single factor or variable, such as a rainfall deficiency or poverty (Chambers 1989). Rather, it is often driven by a variety of context and impact-specific factors, including environmental, social, economic, cultural, physical and/or governance-related aspects (Birkmann *et al* 2013, Hagenlocher and Castro 2015).

Cross-sectoral and impact-specific assessments of *who* and *what* (e.g. people, agricultural land) is at risk *to what* (e.g. meteorological or soil moisture drought), as well as *where* and *why*, will be key for the identification of targeted drought risk reduction, resilience-building, and drought adaptation strategies (IPCC 2014, González Tánago *et al* 2016, UNCCD 2016). The need to understand, assess, and monitor drought risk is underscored by relevant international agreements and initiatives such as the Sendai Framework for Disaster Risk Reduction 2015–2030[4] (UNISDR 2015) or the 2018/19 UNCCD Drought Initiative[5]. A range of approaches exist for assessing vulnerability and risk in the context of climate change and natural hazards such as droughts. These include quantitative, qualitative, and increasingly mixed-methods approaches that combine both (Schneiderbauer *et al* 2017). Promoting and integrating a plurality of approaches can produce complementary information to better explain the complexity of processes that mediate vulnerability and risk. The choice of the approach depends not only on the scale of analysis (local to global), but also on the scope of the assessment, such as understanding root causes, identifying spatial and temporal patterns and hotspots of risk, etc. Qualitative vulnerability and risk analysis often makes use of a wide array of data collection techniques such as interviews, focus group discussions (FDGs), or storylines to reveal context-specific root causes of risk. In contrast, quantitative assessments tend to apply criteria and indicators to assess vulnerability and risk, often in a spatially explicit manner.

In addition to assessing current patterns of risk such as risk hotspots, the analysis of past trends and dynamics and the development of future scenarios in vulnerability and risk have sparked increasing interest and attention in recent years for a number of reasons. The analysis of past trends or risk dynamics through repeated risk assessments can support the monitoring and evaluation of risk reduction and adaptation options (Hagenlocher *et al* 2018b). Future risk scenarios can provide useful inputs for precautionary, preventive, and adaptive planning (Garschagen and Kraas 2010, Birkmann *et al* 2015). A recent review of climate risk assessments concluded that while the number of studies that include temporal dynamics is growing, the majority of future-oriented assessments do not consider scenarios of exposure and vulnerability (Jurgilevich *et al* 2017) instead focusing on the hazard element of the risk concept.

Many of the steps in quantitative drought risk assessments, such as data imputation, outlier treatment, normalization, weighting of indicators or proxies, and aggregation, introduce uncertainty into the modeling/analysis result. Statistical validation—in the form of both sensitivity/uncertainty analysis and the

[4] The Sendai Framework for Disaster Risk Reduction (2015–2030) is a 15 year non-binding agreement adopted by UN member states that serves as a road map for disaster risk reduction until 2030.

[5] The UNCCD Drought Initiative (2018/2019) promotes the development of national drought risk management plans.

regression of risk assessment outcomes against observed impacts or losses (e.g. crop losses, number of people affected)—has proven to provide relevant information on the reliability, validity, and methodological robustness of risk assessments and their outcomes (Schmidtlein *et al* 2008, Fekete 2009, Tate 2012, 2013, Hagenlocher and Castro 2015, Welle and Birkmann 2015, Feizizadeh and Kienberger 2017). However, its application in the field of risk assessment remains largely underdeveloped.

Over the past decades, a number of review articles have been published focusing on (i) drought classifications and definitions (Mishra and Singh 2010), (ii) the assessment and monitoring of drought hazards in general (Rossi *et al* 1992, Mishra and Singh 2011, Zargar *et al* 2011, Li and Zhou 2014, Hao and Singh 2015, Yihdego *et al* 2019), (iii) the role of remote sensing for mapping drought hazards (Belal *et al* 2014, AghaKouchak *et al* 2015), and (iv) vulnerability to drought (González Tánago *et al* 2016, Zarafshani *et al* 2016). However, a review of existing concepts, methods, approaches, and studies on drought vulnerability and people-centered integrated risk assessments is still lacking.

This paper seeks to close this gap by analyzing the state of the art and identifying key gaps regarding the assessment of drought risk with a focus on people. Furthermore, the paper aims to evaluate to what extent existing drought risk assessments suggest potential solutions for drought risk reduction or adaptation. A synthesis of the findings informs a recommended agenda for future research.

2. Methods

A systematic literature review was conducted to synthesize and better understand (i) how people-centered drought risk is currently conceptualized and assessed in the scientific literature, (ii) how existing assessments are linked to the identification of drought risk reduction or adaptation strategies and measures, and (iii) what gaps and research needs exist. The following questions guided the analysis:

1. How are existing assessments distributed across geographic regions (e.g. continents, countries) and spatial scales (local to global)?
2. How is drought risk conceptualized?
3. Does each assessment specify the drought type analyzed, and if so, which type of drought hazard was considered?
4. Which drivers of vulnerability and drought risk are used in existing risk assessments?
5. Which assessment approaches (e.g. qualitative, quantitative, or mixed methods; index-based assessments versus. dynamic simulations) were used? Was sensitivity and/or uncertainty analysis or any form of validation of results applied?
6. Are temporal dynamics considered (e.g. past trends, future scenarios of drought risk) or is the focus largely on evaluating current patterns and hotspots of drought risk?
7. To what extent are assessments of drought vulnerability and risk linked to the identification and planning of drought risk reduction and/or adaptation options? When they are, which measures are proposed?
8. Which key gaps exist in understanding, characterizing, and assessing drought risk?

Peer-reviewed research articles were identified from the Web of Science and Scopus databases covering the period from January 1970 to December 2018 based on a set of pre-defined search terms focusing on people-centered drought risk assessments (table 1). The search was conducted between December 2017 and January 2018 and re-run during the revision process in February 2019. A systematic approach that only includes peer-reviewed articles was selected to ensure transparency, reproducibility, and quality of the analysis following an adapted workflow for systematic literature reviews as proposed by Rudel (2008), Hofmann *et al* (2011) and Plummer *et al* (2012).

In a second step, the titles, keywords, and abstracts of the identified articles were screened independently by three researchers and allocated to a 'YES', 'NO', or 'PERHAPS' list based on each author's judgment of relevance to the search criteria. The respective decision was cross-checked by the two other researchers and assessed for its relevance for the review. Whenever an article was allocated to the PERHAPS list by one of the three authors, the full article was read by all three researchers in order to decide whether or not to include it in the review (YES list) or not (NO list), and the outcomes discussed and cross-checked. In a third step, a coding scheme focused on the aforementioned guiding questions was developed for in-depth content analysis of the final set of articles and implemented in MAXQDA software (VERBI Software 2017). Finally, the information was analyzed using descriptive and statistical methods in Excel software. The following sections are structured according to the eight questions outlined above.

In order to respond to question number four on vulnerability factors a classification scheme was developed to inform the content analysis of the articles, drawing on a scheme proposed by González Tánago *et al* (2016). In a first review of factors of vulnerability in the context of droughts they grouped vulnerability factors into biophysical and socioeconomic dimensions and 11 sub-dimensions. Based on their work and the more recent grouping of drought vulnerability indicators into social, economic, and infrastructural dimensions by Carrão *et al* (2016), the finale scheme

Table 1. Search terms and inclusion and exclusion criteria used to identify studies to be considered for this review.

Database		Search terms
Web of science (Topic)		Drought risk OR drought vulnerab*
	AND	Driver* OR factor* OR caus*
	AND	Assess* OR index OR indic* OR analy* OR evaluat* OR map* OR quantif* OR monitor* OR measur* OR model* OR spatial
	AND	Socioecon* OR socio-econ* OR social OR econom* OR social ecological OR socioecological OR socio-ecolog* OR SES OR environm* OR ecolog* OR politic* OR governan* OR demograph* OR institution*
	NOT	Forest OR tree
Scopus (Title)		(Drought AND risk) OR (drought AND vulnerability)
Inclusion criteria		• Peer-reviewed articles from January 1970 to December 2018 (no articles are listed in Scopus or Web of Science dating back to before 1976) • English literature • Articles conducting an assessment of vulnerability and drought risk for people (acknowledging that drought risk for people can be directly linked to the vulnerability of social-ecological systems)
Exclusion criteria		• Review articles, opinion pieces, non-peer-reviewed literature • Drought hazard assessments that do not consider exposure or vulnerability • Assessments focusing only on exposure, vulnerability, or risk of natural resources or ecosystems (e.g. water resources, plant/tree species, crop types, aquatic ecosystems)

Table 2. Number of articles initially identified and finally considered in the review.

		1st review			Final review	
	Initial search	YES	NO	PERHAPS	YES	NO
Scopus	573	73	450	46	91	478
Web of science	568	10	530	27	14	553
Combined	1141	83	980	73	**105**	1031
Double counting	5					

applied here encompasses a list of seven dimensions and 24 sub-dimensions or vulnerability factors (table 3).

3. Results

3.1. Bibliometric analysis

Based on the systematic search protocol, a total of 1141 articles were identified, including 568 articles from Web of Science and 573 from Scopus. Following the multi-step process described above, the number of articles considered for the final review was reduced to 105 (table 2; supplementary material 1 is available online at stacks.iop.org/ERL/14/083002/mmedia).

Overall, more than 95% of the assessments were published after 2005—the year the Hyogo Framework for Action[6] (HFA) (UNISDR 2005) was adopted by 168 governments—and almost 60% of all assessments were published in the past four years, i.e. between 2015–2018 (supplementary material 1). This is not surprising given the strong call for risk assessments in the HFA 2005–2015 and in the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR 2015), which was adopted in 2015.

Figure 1 shows the geographic distributions, by climate zone and by spatial scale, of all the assessments reviewed. The most assessments (46%) were conducted in Asia, followed by Africa (29%) (figure 1), and in mainly dry (34%) or tropical (19%) climates or across climates. As such, the studies are highly concentrated in a few countries, namely China (18), India (11), the United States (9), Ethiopia (6), and Brazil (5). In terms of spatial scales, assessments at the sub-national level are dominant, with only very few studies that draw conclusions at the global or local/community level.

3.2. Conceptualization of drought risk

The review demonstrates that a variety of different risk definitions have been used as a conceptual underpinning for characterizing and assessing drought risk and highlights two contrasting developments (figure 2). First, there is an increasing number of studies that follow the conceptual understanding of risk as

[6] The Hyogo Framework for Action (HFA 2005–2015) 'Building the Resilience of Nations and Communities to Disasters' was endorsed by the UN General Assembly in the Resolution A/RES/60/195 following the 2005 World Disaster Reduction Conference in Hyogo, Japan. It is a 10 year plan to explain, describe and detail the work that is required from all different sectors and actors to reduce disaster losses until 2015. In 2015, the Hyogo Framework for Action was replaced by the Sendai Framework for Disaster Risk Reduction (2015–2030).

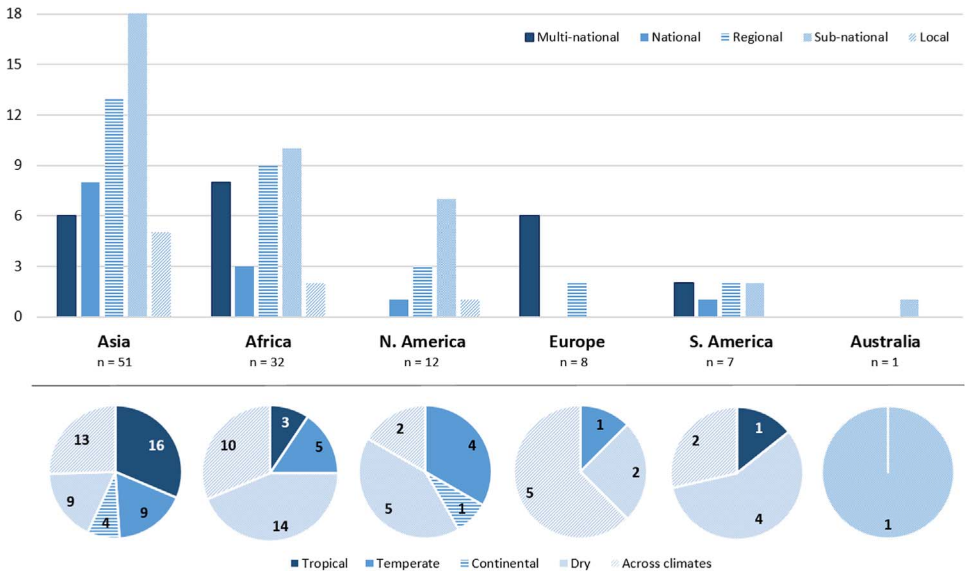

Figure 1. Number of drought risk assessment articles considered in this review by spatial scale and climate zone. One global assessment (Carrão *et al* 2016) is excluded from this figure.

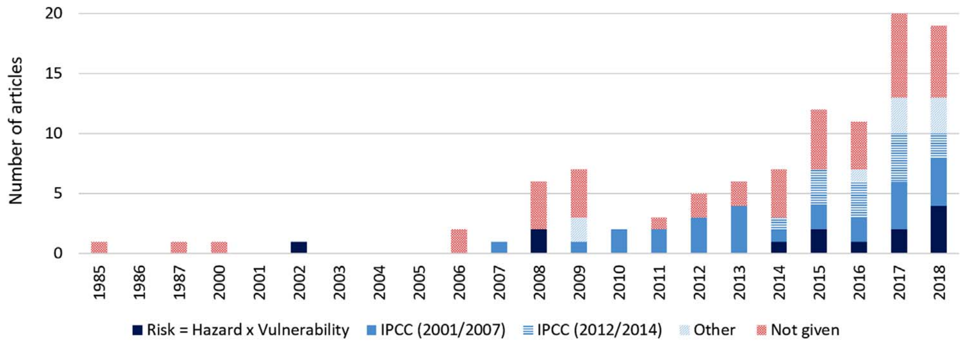

Figure 2. Risk definitions considered in the reviewed articles (including trend over the years).

promoted by the IPCC. Second, there is an increasing number of drought risk assessments that do not specify how drought risk is conceptualized in their assessment (i.e. they do not provide any definition of risk).

The majority of articles that provided a definition of drought risk used the IPCC concepts of 2001 (IPCC 2001) and 2007 (IPCC 2007). However, since the publication of the IPCC SREX Report (IPCC 2012) and the subsequent Fifth Assessment Report (IPCC 2014), there has been a shift in the conceptualization of risk towards a stronger focus on assessing the risk of specific consequences or impacts that may harm a system, wherein risk is a function of (drought) hazard, exposure, and vulnerability (IPCC 2014). This has been reflected to some degree in studies assessing drought risk (Kim *et al* 2015, van Duinen *et al* 2015, Zhang *et al* 2015, Blauhut *et al* 2016, Carrão *et al* 2016, Asare-Kyei *et al* 2017, Bacon *et al* 2017, Sena *et al* 2017), although the share of assessments applying this newest concept since its release has remained fairly stable. For information on definitions classified as 'other' in figure 2 is provided in supplementary material 3.

The ambiguity in definitions is also reflected when analyzing how vulnerability—as a key component of risk in the IPCC AR5—is conceptualized and operationalized in existing drought risk assessments. Of the articles reviewed, 34% consider sensitivity and/or susceptibility, 25% consider adaptive capacities and only 14% consider coping capacity as sub-components of vulnerability. Eleven percent of all papers include drought hazard characteristics and 14% include exposure[7] as part of vulnerability.

The review reveals that although different types of drought hazards are acknowledged in the scientific literature, more than 60% of the assessments published on drought risk do not explicitly specify the type of

[7] Here, exposure is understood based on the IPCC (2014) definition as 'exposed elements'. Thus, even if authors used the term 'exposure', it was not considered to have been conceptually applied if only hazard characteristics were used as proxies.

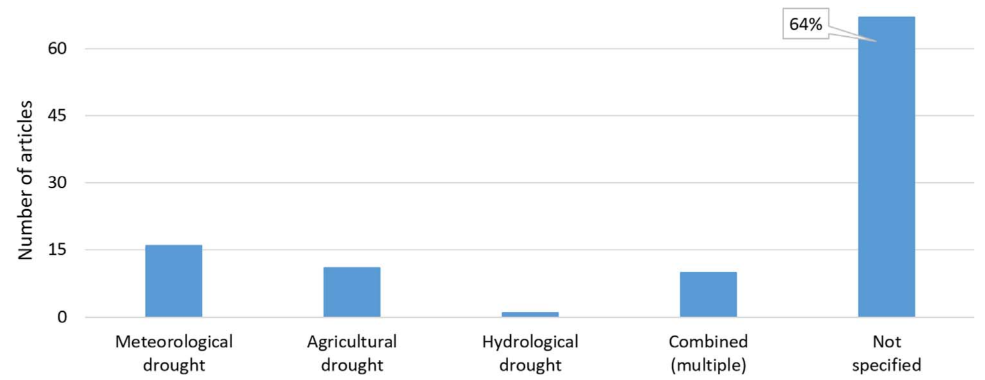

Figure 3. Type of drought hazard(s) explicitly considered in the 105 reviewed articles. Combined (multiple) means that multiple types of drought hazards (and associated indices) were considered in the analysis.

drought hazard that is addressed (figure 3). This is particularly relevant for drought given that the different drought types have very different implications in terms of potential impacts and policies to mitigate these impacts (Wilhite 2000).

Although it is increasingly acknowledged that droughts cannot be seen as purely natural hazards (Van Loon *et al* 2016) and there is a need to consider the complex interactions between natural and human systems when analyzing vulnerability and risk (Turner *et al* 2003), the review clearly shows that the majority of existing drought vulnerability and risk assessments still focus largely on the social dimension and do not apply an integrative social-ecological systems (SES) perspective. Out of the 105 articles that were reviewed, only 18 (17%) applied an SES perspective. This confirms a persistent gap in vulnerability and risk assessments that was recently highlighted by Sebesvari *et al* (2016) in their review of vulnerability assessments in coastal river deltas.

3.3. Assessment of drought risk

3.3.1. Assessment approaches

The review of existing drought risk assessments revealed that the majority of studies applied quantitative (56%) or mixed-methods (32%) approaches, while purely qualitative approaches are rather rare (11%) and have mostly been applied at the sub-national level with results extrapolated to explain phenomena at broader spatial scales (Nelson and Finan 2009, Saha *et al* 2012, Ayantunde *et al* 2015, Birhanu *et al* 2017).

In terms of assessment methodology, more than half of the assessments used an index-based approach (62%) to tackle the complexity of drought risk, followed by dynamic simulation methods (12%) and lastly the more qualitative method of using narratives or story lines (8%). For example, Carrão *et al* (2016) use a static, index-based approach to map the global patterns of drought risk by integrating hazard, exposure, and vulnerability indicators into a composite risk index. Meanwhile, Martin *et al* (2016) apply a process-based, spatially-explicit social-ecological model for analyzing system dynamics contributing to drought risk for pastoral households in Morocco. In contrast, Ayantunde *et al* (2015) use qualitative methods (FDGs, community workshops, seasonal calendars, etc) to analyze the patterns and causes of drought risk in three agro-pastoral communities in Western Africa.

3.3.2. Factors and indicators to characterize drought vulnerability and risk

The review of literature conducted here has revealed that factors related to poverty and income (49%), technology (47%), education levels (34%), or the availability and quality of infrastructure (34%) were deemed important drivers of vulnerability and risk by almost one third of all reviewed assessments (table 3).

Following the classification scheme of table 3, 65 different indicators (18 belonging to the social dimension, 13 to the economic dimension, seven to the physical dimension, two to the crime and conflict dimension, eight to the governance dimension, nine to the environmental dimension, eight to the farming practices dimension) were identified during the review which can serve as a basis for future vulnerability and risk assessments (see supplementary material 2 for the complete list of indicators).

In order to identify and incorporate the potentially varying relevance and contribution of factors and indicators to vulnerability and risk in the context of natural hazards, a wide variety of weighting schemes have been developed (OECD 2008). These schemes can be categorized as being based on statistical models (e.g. regression analysis, principal component analysis) or on experts and/or community participatory consultation (e.g. ranking, budget allocation, Delphi methods). In most of the assessments reviewed here (57%) the authors did not explicitly specify their weighting methods, which is also in line with findings from a recent review of disaster risk, vulnerability, and

Table 3. Vulnerability dimensions and sub-dimensions used in the 105 studies considered in this review.

Vulnerability dimensions and sub-dimensions (factors)	Number of papers ($n = 105$)
Social	
• Education (e.g. illiteracy; indigenous and local knowledge)	34 (32%)
• Gender (e.g. gender inequality)	14 (13%)
• Social capital (e.g. social networks)	11 (10%)
• Health status (e.g. alcohol and substance use; restricted mobility/disability; malnutrition; mental health; disease prevalence)	13 (12%)
• Health services (e.g. health insurance)	7 (6%)
• Remoteness (e.g. rural/remote populations)	9 (9%)
• Awareness and information (e.g. drought awareness; early warning, access to information; underestimation of drought risk)	9 (9%)
• Water demand	8 (8%)
Economic	
• Poverty and income (e.g. income diversification; poverty; unemployment; problematic debt; dependency ratio)	49 (47%)
• Inequality	3 (3%)
• Savings, credits and loans (access to)	8 (8%)
• Markets (e.g. access to markets; market fragility)	12 (11%)
• Insurance (e.g. agricultural/animal/crop/drought insurance)	5 (5%)
Physical	
• Availability and quality of infrastructure (e.g. transportation; water and sanitation; energy; water tanks; reservoirs; wells; water quality)	34 (32%)
Crime and conflict	
• Stability (e.g. crime; war and conflict)	6 (6%)
Governance	
• Plans and strategies (e.g. drought planning and investment in disaster prevention and preparedness; water management planning)	8 (8%)
• Corruption and law enforcement (e.g. lack of trust in institutions)	3 (3%)
• Participation (e.g. public participation in governance; political representation)	6 (6%)
• Assistance (e.g. availability of food aid; development/aid projects (ODA))	6 (6%)
Environmental	
• Soil condition and quality (e.g. degradation/desertification)	15 (14%)
• Protection and conservation (e.g. protected areas; livestock health condition; soil and water conservation practices)	14 (13%)
Farming practices	
• Technology (e.g. access to technology; irrigation; use of agricultural inputs (fertilizer); fodder)	49 (47%)
• Pesticide use	2 (2%)
• Crop type (e.g. resistance; diversification)	7 (7%)

resilience indices (Beccari 2017). Thirty-two percent of the reviewed assessments used statistical methods and ten percent used participatory, expert-based approaches.

3.3.3. Past trends, current patterns, and future scenarios
Fifty-four percent of the reviewed drought risk assessments are static, that is, they represent a snapshot in time. For the remaining 46%, most studies focus on assessing past trends (32%) and only 11 articles (10%) explore future scenarios of drought risk. Four percent of the articles do not specify the time frame of their analysis. Similar to other future-oriented risk assessments (e.g. in the context of sea level rise, flooding, etc)—where the focus is often on the modeling-based analysis of

Table 4. Drought risk reduction and adaptation options proposed by the authors of the reviewed studies.

DRR or adaptation solution	Examples
Structural measures	• Implementation and use of irrigation infrastructure • Water supply systems (e.g. dams, pipelines, cisterns) • Maintenance of water supply systems (desalinization and wastewater treatment plants, reducing leakage rates) • Early warning systems • Farming technology (use of, investment in) (e.g. machinery)
Non-structural measures (individual, household, or farm level)	• Water conservation • Diversification of livelihood strategies • Education and training (e.g. in water conservation, farming practices, drought awareness, drought risk management) • Fertilizer/manure (use of, increase in) • Pesticide/herbicide/pest control (use of, increase in) • Migration (temporal, permanent)
Non-structural measures (government level)	• Providing better access to credits and financial instruments • Implementation of social assistance and social protection programs • Access to finance instruments (credit, savings, markets) • Implementation of crop/climate risk insurance schemes • Investment in research and development • Water management practices/policies • Drought, water and climate change adaptation plans/policies • Mainstreaming indigenous and local knowledge into policy planning • Drought/emergency response and preparedness (equipment, facilities, funds) • Risk-informed (land use) planning
Non-structural measures (ecosystem-based)	• Soil conservation practices • Changing farming practices (e.g. crop diversification, drought resistant crops, adjusting planting dates, climate-smart agriculture, horticulture, intercropping, rotations) • Reclamation of degraded land • Water harvesting • Expanding the number and coverage of protected natural areas

different hazards (Garschagen and Kraas 2010)—the review has revealed that out of the 11 articles that claim to develop future 'risk scenarios', only two studies analyzed future scenarios combining multiple risk components (hazard, exposure or vulnerability) (Melkonyan 2014, Vargas and Porter 2017). The remaining nine future-oriented assessments also focused only on future drought hazards without including future exposure or vulnerability scenarios.

3.3.4. Validation of risk assessments

Our analysis shows that less than 20% of the drought risk assessments reviewed here have conducted any form of validation of their results and only 12% have conducted a statistical sensitivity or uncertainty analysis. To date, only four studies (less than four percent) have conducted both a validation of the outcomes of the risk assessment against observed impacts and sensitivity analysis (Huang *et al* 2014, Asare-Kyei *et al* 2017, Wu *et al* 2017).

3.4. Drought risk reduction and adaptation

Effective drought risk assessments are those that center around the ultimate objective of being used or useful for disaster risk reduction (DRR)[8] and/or adaptation[9] strategies. While strategies should be based on context-specific empirical findings—taking into account both drivers and patterns of risk—the assessments should also consider what actions individuals and institutional bodies are already taking and their effectiveness.

Less than half (40%) of the assessment papers reviewed make a direct link to drought risk reduction or adaptation strategies. Those that do comprise a wide array of structural (i.e. engineering-based or technological) and non-structural (e.g. capacity building, ecosystem-based approaches) solutions (table 4).

[8] Disaster risk reduction aims at preventing new and reducing existing disaster risk and managing residual risk (based on UNISDR terminology; https://unisdr.org/we/inform/terminology).

[9] Here, adaptation refers to the process of adjustment to changing drought frequency, intensity, duration, or extent (based on IPCC 2014).

4. Discussion: persisting gaps, and research agenda

Existing review articles on the topic so far have primarily concentrated on (i) drought concepts and definitions (Mishra and Singh 2010), (ii) indicators, methods and tools for the assessment and monitoring of drought hazards (e.g. Mishra and Singh 2011, Zargar *et al* 2011, Li and Zhou 2014, Hao and Singh 2015, Yihdego *et al* 2019), or more recently (iii) vulnerability to drought (González Tánago *et al* 2016, Zarafshani *et al* 2016). This paper complements these reviews by conducting a systematic review of people-centric drought risk assessments published between January 1970 and December 2018. Despite the boost in drought risk research over the past decades, the review has revealed and re-confirmed a number of persistent knowledge gaps of conceptual, methodological, and practical nature and relevance. In synthesizing these gaps, a number of needs have been identified that should be addressed in future research.

Table 5 summarizes persisting gaps and the related needs from a conceptual, methodological and practical perspective.

4.1. Conceptual gaps and needs

Our analysis shows that more than 60% of the reviewed studies do not explicitly specify the type of drought hazard that is addressed and re-confirms that a broad variety of definitions of drought vulnerability and risk are used. This creates not only terminological and taxonomic confusion when operationalized in assessments, but also complicates the comparability of assessments and their outcomes—a gap that has also been emphasized in previous studies (Ebi and Bowen 2016, Bacon *et al* 2017, Wu *et al* 2017). While context is crucial and other operational definitions of risk may be more appropriate depending on region and purpose (Wilhite 2000), providing a definition is important for producing scientifically rigorous and comparable work. There is increasing recognition that the causes of drought impacts on people and factors that dictate severity are complex, interact with each other, and are often features of coupled SESs (Van Loon *et al* 2016). The majority (83%) of existing people-centric drought risk assessments still focus largely on the social dimension and do not necessarily apply an integrative approach when characterizing drought hazards, vulnerability, or risk. As demonstrated in table 3, only 13%–14% of the reviewed articles considered factors such as soil conditions or quality or the protection of ecosystems in their assessments. Particularly when assessing drought risk in the context of agricultural systems (including people whose livelihood depends on agriculture), which are by definition SES, an SES perspective could help to understand and evaluate the role of degraded ecosystems as a driver of drought risk. Furthermore, an SES perspective can help to better understand the role of ecosystems and their regulating services as an opportunity for drought risk reduction—a gap that has also been highlighted by Asare-Kyei *et al* (2017). These gaps demonstrate the need for enhanced conceptual models that underscore the complex, differential interplay between drought hazards, exposure, vulnerability, and impacts while acknowledging the relevance of human-environmental interaction in each of these components. The latest definitions put forward by the IPCC in its Fifth Assessment Report (IPCC 2014), widely acknowledged by both the DRR and climate change adaptation communities, can help to overcome the existing terminological confusion.

4.2. Methodological gaps and needs

When dealing with droughts, embracing complexity is necessary for understanding the multi-dimensional nature of drought risk. Over recent years, index-based approaches have been promoted as useful tools to measure, compare, and monitor the complexity of risk associated with natural hazards and climate change (Sherbinin *et al* 2017) and have been gaining in popularity. Our analysis confirms this trend, with more than half of the reviewed assessments using index-based approaches (62%). However, their usefulness for policy support has also been subject to criticism (Hinkel 2011), given that indices are static in nature and do not capture the complexities and dynamics (e.g. nonlinearities and feedback loops) of vulnerability and risk (Hagenlocher *et al* 2018a). It is thus crucial to develop and apply methods, such as Bayesian or system dynamics modeling, that are able to both capture complexity and deliver simple messages for policy-making and allocation of resources.

The analysis has also shown that the relevance of individual hazard, exposure, and vulnerability indicators for explaining different drought impacts is poorly understood and tackled in assessments: 57% of the indicator-based risk assessments that were reviewed did not explicitly specify any weighting method. Future research should tackle this gap by exploring different ways for evaluating indicator weights (e.g. expert-based versus statistical approaches) and compare the findings by means of sensitivity analysis to evaluate the effect of weighting schemes.

Preventive planning for risk reduction and of adaptation measures requires a forward-looking perspective, and ideally should be based on different scenarios of future drought risk for a given region and impact—a need that has been increasingly emphasized over the past years (Garschagen and Kraas 2010, Birkmann *et al* 2015). In addition, the monitoring of risk trends and changes in risk components and indicators over time can contribute to the monitoring and evaluation of risk reduction and adaptation measures. This has also been recently highlighted as a pressing need (Hagenlocher *et al* 2018b). Interestingly, 54% of

Table 5. Summary of knowledge gaps of conceptual, methodological, and practical nature and identified needs related to people-centered drought vulnerability and risk assessments that could inform future research and policy agendas.

	Gaps	Needs
Conceptual perspective on drought risk for people	1. Existing frameworks that explain pathways from drought hazard to impacts are hazard-centric and do not sufficiently take into account exposure and vulnerability as drivers of drought risk and impacts	1. Adoption of conceptual framework(s) for characterizing drought risk that define risk of negative impacts as a function of hazard, exposure, and vulnerability
	2. Human-environmental interaction is increasingly attributed to the occurrence of droughts, but not yet well conceptualized in drought vulnerability and risk assessments	2. More attention should be devoted to understanding the role of ecosystems and their services as a driver of drought risk and opportunity for increasing resilience
Methodological perspective on assessing drought risk for people	1. Vulnerability and risk assessments are mostly static and do not employ dynamic approaches (e.g. simulation) to tackle the complexity of drought vulnerability and risk	1. Further research to assess the dynamics of risk (spatial dynamics, temporal dynamics, inter-indicator relations)
	2. Assessments often use the same set of vulnerability indicators for different sectors, context, and scales, neglecting inherent differences	2. Further research on sector, context, and scale-specific indicators and the development of an indicator library that could be used for different contexts
	3. There is little evidence of relevance of individual drought vulnerability indicators as determinants of drought risk and potential impacts	3. Further research on the relevance of individual drought vulnerability indicators (e.g. indicator weights)
	4. Few drought vulnerability and risk assessments conduct any form of validation	4. Further research on validation of assessments (including technical and user validation) and analysis of the sensitivity of the contribution of individual indicators to an overall assessment
Practical perspective on drought risk for people	1. Assessments that focus on current conditions or past trends dominate; there is a lack of future scenarios of drought hazards, exposure, vulnerability, and risk (relevant for preventive planning)	1. Linking of future research on exposure, vulnerability and risk to scenarios of relevant planning processes and a consideration of global change
	2. Less than half of the assessments provide entry points for potential solutions (e.g. drought risk reduction or adaptation measures)	2. Provision of guidance on how risk assessments can support the identification, planning, monitoring and evaluation of risk reduction and adaptation strategies
	3. Ecosystem-based solutions for risk reduction and adaptation are underrepresented	3. Further research on the role of ecosystem-based solutions

the existing drought risk assessments are static in nature, i.e. they represent a snapshot in time, while the evaluation and development of future scenarios of drought risk (ten percent of all studies) is a rather recent phenomenon (the first paper in our review to develop future scenarios was published in 2009) and heavily underdeveloped aspect. In order to support the planning of adaptation strategies, scenarios of future risk pathways—in all components of hazard, exposure, and vulnerability—are urgently required.

The validation of risk assessments presents another persisting gap given the need of decision makers and practitioners for up-to-date and reliable data and information. Despite major progress in sensitivity and uncertainty analysis in the context of risk research (Fekete 2009, Tate 2012, 2013, Feizizadeh and Kienberger 2017), our analysis has shown that less than ten percent of all risk assessments reviewed here have conducted any form of validation of their results using impact data and only 12% have conducted a statistical sensitivity or uncertainty analysis. These findings are in line with gaps identified by Asare-Kyei *et al* (2017).

4.3. Practical gaps and needs

Risk assessments should ideally not be an end in themselves, but be linked to the identification, planning and prioritization of options for preventing and managing drought risk or adapting to changing conditions. The IPCC AR5 (IPCC 2014) identified the lack of assessments focusing on the actual implementation of adaptation measures and their potential positive or negative effects, a finding further confirmed in this review. While just under half of the studies reviewed here (40%) make a direct link to drought risk reduction or adaptation strategies, only very few of these articles consider or recommend ecosystem-based approaches, leaving the potential of nature-based solutions (NbS) for drought risk reduction and mitigation (Kloos and Renaud 2016, UN 2018) far from being realized. Hence, more research is needed to evaluate the role of ecosystems and their services not only as drivers of drought risk, but also as an option for drought risk reduction and adaptation.

5. Conclusions

Reducing drought risk and associated direct and indirect impacts through targeted risk reduction and adaptation has become a global priority, as reflected by recent global initiatives and frameworks (e.g. the 2018/19 UNCCD Drought Initiative, Sendai Framework for Disaster Risk Reduction 2015–2030, Sustainable Development Goals, and the upcoming 2020 GAR Special Report on Drought) as well as by the steadily increasing number of drought risk assessments over the past decades. Efforts to reduce drought risk and adapt to changing environmental conditions by prioritizing and allocating funding and resources should be based on a sound understanding, characterization, and assessment of the drivers, patterns, and past trends as well as projected future patterns of drought risk. However, despite major advances over the past decades in terms of developing better methods and tools for characterizing individual components of risk, the review has revealed and re-confirmed a number of persistent knowledge gaps—of conceptual, methodological, and practical nature—which need to be urgently confronted in order to advance the understanding of drought risk for people, improve its assessment, and support pathways towards more drought resilient societies.

Acknowledgments

The research is part of the project GlobeDrought (Grant No. 02WGR1457C) funded by the German Federal Ministry of Education and Research (BMBF) through its Global Resource Water (GRoW) funding initiative. The authors would like to thank Lorina Schudel, Andrea Ortiz Vargas, and Liliana Marulanda for their support with coding additional papers during the revision process and thank the three anonymous reviewers for their valuable comments and feedback which have helped to improve the manuscript.

Author contributions

MH, IM, AM and ZS designed the review strategy. The review was conducted by IM, CA and MH. All authors contributed to the interpretation of the results and the development of the proposed research agenda. MH drafted the manuscript with inputs from all authors. All authors approved the manuscript.

ORCID iDs

Michael Hagenlocher https://orcid.org/0000-0002-5254-6713
Isabel Meza https://orcid.org/0000-0002-8557-9175
Fabrice G Renaud https://orcid.org/0000-0002-0830-1196
Yvonne Walz https://orcid.org/0000-0003-3781-5038
Stefan Siebert https://orcid.org/0000-0002-9998-0672
Zita Sebesvari https://orcid.org/0000-0001-7686-1227

References

AghaKouchak A *et al* 2015 Remote sensing of drought: progress, challenges and opportunities *Rev. Geophys.* **53** 452–80
Andreadis K M and Lettenmaier D P 2006 Trends in 20th century drought over the continental United States *Geophys. Res. Lett.* **33** L10403
Asare-Kyei D *et al* 2017 Development and validation of risk profiles of West African rural communities facing multiple natural hazards *PLoS One* **12** e0171921
Ayantunde A A, Turner M D and Kalilou A 2015 Participatory analysis of vulnerability to drought in three agro-pastoral communities in the West African Sahel *Pastoralism* **5** 13
Bacon C M *et al* 2017 Vulnerability to cumulative hazards: coping with the coffee leaf rust outbreak, drought, and food insecurity in nicaragua *World Dev.* **93** 136–52
Beccari B 2017 A comparative analysis of disaster risk, vulnerability and resilience composite indicators *PLOS—Curr. Disasters* **8** 1–56
Belal A A *et al* 2014 Drought risk assessment using remote sensing and GIS techniques *Arab. J. Geosci.* **7** 35–53
Birhanu Z *et al* 2017 Understanding resilience dimensions and adaptive strategies to the impact of recurrent droughts in Borana Zone, Oromia Region, Ethiopia: a grounded theory approach *Int. J. Environ. Res. Public Health* **14** 1–18
Birkmann J *et al* 2013 Framing vulnerability, risk and societal responses: the MOVE framework *Nat. Hazards* **67** 193–211
Birkmann J *et al* 2015 Scenarios for vulnerability: opportunities and constraints in the context of climate change and disaster risk *Clim. Change* **133** 53–68
Blauhut V *et al* 2016 Estimating drought risk across Europe from reported drought impacts, drought indices, and vulnerability factors *Hydrol. Earth Syst. Sci.* **20** 2779–800
Carrão H, Naumann G and Barbosa P 2016 Mapping global patterns of drought risk: an empirical framework based on sub-national estimates of hazard, exposure and vulnerability *Glob. Environ. Change* **39** 108–24
Chambers R 1989 Vulnerability, coping and policy *IDS Bull.* **37** 33
Dai A 2011 Drought under global warming: a review *Wiley Interdiscip. Rev. Clim. Change* **2** 45–65
Ebi K L and Bowen K 2016 Extreme events as sources of health vulnerability: drought as an example *Weather Clim. Extremes* **11** 95–102
Feizizadeh B and Kienberger S 2017 Spatially explicit sensitivity and uncertainty analysis for multicriteria-based vulnerability assessment *J. Environ. Plan. Manage.* **60** 2013–35
Fekete A 2009 Validation of a social vulnerability index in context to river-floods in Germany *Nat. Hazards Earth Syst. Sci.* **9** 393–403

Garschagen M and Kraas F 2010 Assessing future resilience to natural hazards—the challenge of capturing dynamic changes under conditions of transformation and climate change ed R Custer *et al Proc. Int. Disaster and Risk Conf., IDRC 2010* (Davos) pp 209–13
González Tánago I *et al* 2016 Learning from experience: a systematic review of assessments of vulnerability to drought *Nat. Hazards* **80** 951–73
Hagenlocher M and Castro M C 2015 Mapping malaria risk and vulnerability in the United Republic of Tanzania: a spatial explicit model *Population Health Metrics* **13** 1–14
Hagenlocher M *et al* 2018a Vulnerability and risk of deltaic social-ecological systems exposed to multiple hazards *Sci. Total Environ.* **631–632** 71–80
Hagenlocher M *et al* 2018b *Climate Risk Assessment for Ecosystem-based Adaptation A Guidebook for Planners and Practitioners* (Bonn: GIZ)
Hao Z and Singh V P 2015 Drought characterization from a multivariate perspective: a review *J. Hydrol.* **527** 668–78
Hinkel J 2011 Indicators of vulnerability and adaptive capacity: towards a clarification of the science-policy interface *Glob. Environ. Change* **21** 198–208
Hofmann M E, Hinkel J and Wrobel M 2011 Classifying knowledge on climate change impacts, adaptation, and vulnerability in Europe for informing adaptation research and decision-making: a conceptual meta-analysis *Glob. Environ. Change* **21** 1106–16
Huang L, Yang P and Ren S 2014 The vulnerability assessment method for Beijing Agricultural Drought *IFIP AICT 419* pp 269–80
IPCC 2001 *Climate Change 2001: Impacts, Adaptation, and Vulnerability, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press) (https://doi.org/10.1002/joc.775)
IPCC 2007 *Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel* (Cambridge: Cambridge University Press)
IPCC 2012 *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* ed C B Field *et al* (Cambridge: Cambridge University Press)
IPCC 2013 *Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed D Stocker *et al* (Cambridge: Cambridge University Press)
IPCC 2014 *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed V R Barros *et al* (New York: Cambridge University Press)
Jurgilevich A *et al* 2017 A systematic review of dynamics in climate risk and vulnerability assessments *Environ. Res. Lett.* **12** 13002
Kim H *et al* 2015 Assessment of drought hazard, vulnerability, and risk: a case study foradministrative districts in South Korea *J. Hydro-Environ. Res.* **9** 28–35
Kloos J and Renaud F G 2016 Overview of ecosystem-based approaches to drought risk reduction targeting small-scale farmers in Sub-Saharan Africa *Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice* ed F G Renaud *et al* (Cham: Springer International Publishing) pp 199–226
Li B and Zhou G 2014 Advance in the study on drought index *Shengtai Xuebao/Acta Ecol. Sin.* **34** 1043–52
Martin R *et al* 2016 Livelihood security in face of drought—assessing the vulnerability of pastoral households *Environ. Modelling Softw.* **75** 414–23
McCabe G J and Wolock D M 2015 Variability and trends in global drought *Earth Space Sci.* **2** 223–8
Melkonyan A 2014 Environmental and socio-economic vulnerability of agricultural sector in Armenia *Sci. Total Environ.* **488–489** 333–42
Mishra A K and Singh V P 2010 A review of drought concepts *J. Hydrol.* **391** 202–16
Mishra A K and Singh V P 2011 Drought modeling—a review *J. Hydrol.* **403** 157–75
Mukherjee S, Mishra A and Trenberth K E 2018 Climate change and drought: a perspective on drought indices *Curr. Clim. Change Rep.* **4** 145–63
Nelson D R and Finan T J 2009 Praying for drought: persistent vulnerability and the politics of patronage in Ceará, Northeast Brazil *Am. Anthropologist* **111** 302–16
OECD 2008 *Handbook on Constructing Composite Indicators: Methodology and User Guide* (Paris: OECD Publications) (https://doi.org/10.1787/9789264043466-en)
Plummer R, de Loë R and Armitage D 2012 A systematic review of water vulnerability assessment tools *Water Resour. Manage.* **26** 4327–46
Rossi G *et al* 1992 On regional drought estimation and analysis *Water Resour. Manage.* **6** 249–77
Rudel T K 2008 Meta-analyses of case studies: a method for studying regional and global environmental change *Glob. Environ. Change* **18** 18–25
Saha D K, Kar A and Roy M M 2012 Indicators of drought vulnerability for assessing coping mechanism in arid Western Rajasthan *Ann. Arid Zone* **51** 1–9
Schmidtlein M C *et al* 2008 A sensitivity analysis of the social vulnerability index *Risk Anal.* **28** 1099–114
Schneiderbauer S, Calliari E, Eidsvig U and Hagenlocher M 2017 The most recent view of vulnerability *Science for Disaster Risk Management 2017: Knowing Better and Loosing Less* ed K Poljanšek *et al* (Luxembourg: Publications Office of the European Union) pp 68–82
Schwalm C R *et al* 2017 Global patterns of drought recovery *Nature* **548** 202
Sebesvari Z *et al* 2016 A review of vulnerability indicators for deltaic social–ecological systems *Sustain. Sci.* **11** 575–90
Sena A *et al* 2017 Indicators to measure risk of disaster associated with drought: implications for the health sector *PLoS One* **12** e0181394
Sheffield J and Wood E F 2008 Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations *Clim. Dyn.* **31** 79–105
Sheffield J, Wood E F and Roderick M L 2012 Little change in global drought over the past 60 years *Nature* **491** 435
Sherbinin A D, Apotsos A and Chevrier J 2017 Mapping the future: policy applications of climate vulnerability mapping in West Africa *Geogr. J.* **183** 414–25
Tate E 2012 Social vulnerability indices: a comparative assessment using uncertainty and sensitivity analysis *Nat. Hazards* **63** 325–47
Tate E 2013 Uncertainty analysis for a social vulnerability index *Ann. Assoc. Am. Geogr.* **103** 526–43
Trenberth K E *et al* 2013 Global warming and changes in drought *Nat. Clim. Change* **4** 17
Turner B L *et al* 2003 A framework for vulnerability analysis in sustainability science *PNAS* **100** 8074–9
UN 2018 The United Nations World Water Development Report 2018: Nature-Based Solutions for Water (http://unesdoc.unesco.org/images/0026/002614/261424e.pdf)
UNCCD 2016 The ripple effect: A Fresh Approach to Reducing Drought Impacts and Building Resilience (https://unccd.int/sites/default/files/documents/27072016_The ripple effect_ENG.pdf)
UNISDR 2005 Hyogo framework for action 2005–2015: building the resilience of nations and communities to disasters *World Conf. on Disaster Reduction* (https://doi.org/10.1017/CBO9781107415324.004)
UNISDR 2015 Sendai Framework for Disaster Risk Reduction 2015–2030. Geneva, Switzerland (http://unisdr.org/files/43291_sendaiframeworkfordrren.pdf)
van Duinen R *et al* 2015 Empirical analysis of farmers' drought risk perception: objective factors, personal circumstances, and social influence *Risk Anal.* **35** 741–55

Van Loon A F *et al* 2016 Drought in the anthropocene *Nat. Geosci.* **9** 89–91

Vargas R and Porter C 2017 Vulnerability to drought and food price shocks: evidence from ethiopia *World Dev.* **96** 65–77

Wang W *et al* 2016 Propagation of drought: from meteorological drought to agricultural and hydrological drought *Adv. Meteorol.* **2016** 6547209

Welle T and Birkmann J 2015 The World risk index—an approach to assess risk and vulnerability on a global scale *J. Extreme Events* **2** 1550003

Wilhite D A 2000 Drought as a natural hazard: concepts and definitions *Drought: Glob. Assess.* **19** 3–18

Wilhite D A and Glantz M H 1985 Understanding: the drought phenomenon: the role of definitions *Water Int.* **10** 111–20

Wu H *et al* 2017 Assessment of agricultural drought vulnerability in the guanzhong plain, China *Water Resour. Manage.* **31** 1557–74

Wu J J *et al* 2017 Global vulnerability to agricultural drought and its spatial characteristics *Sci. China Earth Sci.* **60** 910–20

Yihdego Y, Vaheddoost B and Al-Weshah R A 2019 Drought indices and indicators revisited *Arab. J. Geosci.* **12** 69

Zarafshani K *et al* 2016 Vulnerability assessment models to drought: toward a conceptual framework *Sustainability* **8** 588

Zargar A *et al* 2011 A review of drought indices *Environ. Rev.* **19** 333–49

Zhang Q *et al* 2015 Assessment of drought vulnerability of the Tarim River basin, Xinjiang, China *Theor. Appl. Climatol.* **121** 337–47