Droughts

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adaptation, climate change, drought indicators, drought vulnerability

Abstract

This chapter provides an interdisciplinary review of the drought literature. Droughts are widely perceived as hydroclimatic hazards. In reality droughts are socioenvironmental phenomena, produced by admixtures of climatic, hydrological, environmental, socioeconomic, and cultural forces. The complexity and context specificity of drought confound severity and impact assessments. Interdisciplinary analyses of drought events and collective assessments with the participation of scientists, policy makers, stakeholders, and the public provide promising new ways of producing information for understanding and managing droughts. Global warming is likely to exacerbate droughts in many semiarid, snow-fed, and coastal basins. Research on historical and paleoclimates warns about the prospect of decadal or centennial megadroughts. Enhancing adaptive capacity becomes essential in the face of such uncertain future extremes. But policies remain locked in supply-side food and water technologies. Policies for the support of impoverished, vulnerable groups, investments in water conservation and appropriate, low-scale technologies can reduce drought vulnerability but face political-economic barriers.

Contents

1. INTRODUCTION: CONCEPTUALIZING DROUGHT

Droughts affect more people than any other climatic hazard (1). A lot has been written about droughts, but our understanding remains, at best, patchy. Various natural and social sciences study different aspects of drought. Apart from one edited collection (2), there has been little communication across disciplines. This chapter offers the first interdisciplinary review of the literature.

Drought: a temporary lack of water, which is, at least partly, caused by abnormal climate conditions and is damaging to an activity, group, or the environment

There are scores of drought definitions (3, 4). Drought is conceived here as a temporary lack of water, which is, necessarily but not exclusively, caused by abnormal climate and which is damaging to an activity, group, or the environment. This "conceptual definition" (3) is open enough to encompass different operational perspectives. But it is narrow enough to distinguish drought from affiliated concepts: scarcity and aridity. Water stress or scarcity, for example, need not have a climatic origin or be temporary. Unlike drought, aridity is not abnormal or temporary (e.g., a desert). Seasonal aridity too is a normal feature of the climate (e.g., the recurrent dry period after a monsoon).

Abnormal precipitation shortfalls are caused by large-scale disruptions at the global circulation pattern of the atmosphere (5). Whether a certain lack of precipitation causes a drought depends on the local climate. For example, small shortfalls mark critical departures in arid but not in humid climates. Droughts depend also on

1. rain effectiveness, i.e., rainfall intensity and number of rainfall events (6);
2. rain timing, i.e., lack of water is more critical in the principal season of occurrence, in the start of the rainy season, or in principal plant growth stages;
3. spatial distribution of rain in relation to the location of water resources and demands;
4. hydroenvironmental factors, such as soil, reservoir, snowpack, or aquifer storage and vegetation; and
5. uses, e.g., different crops have varying water quantity and timing needs, and cities and farmers differ in their water needs.

Droughts operate at different temporal scales, from days to years (a one-year drought refers to a water shortage in a one-year period in relation to the normal water availability in the same one-year periods in the past). Different temporal scales are relevant depending on water resources and uses of interest (7).

The word drought subsumes phenomena with different temporal characteristics and causation structures. There are meteorological droughts (abnormal precipitation deficits), agricultural droughts (abnormal soil moisture deficits), hydrological droughts (abnormal streamflow, groundwater, reservoir, or lake deficits), and water supply droughts (abnormal, temporary failures of supply to meet demands). The distinction is not just semantic. Soil moisture conditions respond to precipitation shortfalls on relatively short timescales. Streamflow, reservoir and groundwater droughts are experienced progressively later. Termination follows the reverse order; aquifers recover last (6, 8). Meteorological droughts have atmospheric causes. Hydrological, agricultural, and, especially, supply droughts are affected in addition by environmental and socioeconomic factors (9).

Natural scientists frame the social dimension of droughts into a black box called "socioeconomic drought," i.e., droughts that impact some social good/function. But in a sense, all droughts that we humans care about are socioeconomic (hence, the reference to damages in the drought definition of this paper). There are three main ways in which social factors relate to droughts: vulnerability, causation, and perception. First, hydrometeorological droughts of similar severity are dissimilarly felt among regions and groups. Poverty, demography, production patterns, and other socioeconomic factors produce differential vulnerabilities. Second, river flows, groundwater, dam reserves, and soil moisture are affected by water management, withdrawals, and land uses. Human agency, policies, and socioeconomic factors are part of the causal structure of hydrological, agricultural, and supply droughts. Third, what is perceived as an abnormal or damaging lack of water varies between cultures and epochs and changes with evolving understandings and practices.

This chapter treats drought as a combined hydroclimatic, environmental, and socioeconomic product. It proceeds from the physical dimension of droughts (Sections 2–3) to the socioeconomic (Sections 4–7). Section 2 reviews the hydrometeorological literature on measuring and forecasting drought. Section 3 looks at predictions of climate change impacts and droughts. Section 4 shifts to an evaluation of the socioeconomic impacts of drought. Section 5 focuses on the drought vulnerability of rural communities, especially in the developing world. Section 6 examines how institutions, uneven power relations, and discourses relate to water supply droughts.

Policy responses are examined in various parts of this review. Adaptation by means of climatic information is visited in Section 2. Policies that enhance the adaptive capacity of rural communities are discussed in Section 5. Section 7 in turn focuses on technological and institutional adaptations in the water sector.

Different disciplinary perspectives of drought dominate each section. Disciplinary literatures are reviewed in their own terms. My perspective is strong at the end of Sections 2 and 6, where I discuss the limits of natural and social scientists' treatments of drought. Throughout this chapter, a case is made that the complexity of drought confounds simple

Vulnerability: the propensity of a system to damage or harm. It is a function of the exposure and sensitivity of the system to the hazard and its adaptive capacity

Climate change (modern global warming): changes in global mean surface-air temperature caused by post-Industrial Revolution–increased atmospheric concentration of carbon dioxide

Discourse: an ensemble of ideas, concepts and categorizations expressed in practices that give meaning to physical and social realities

Adaptations: adjustments in socioeconomic systems in response to actual or expected climatic stimuli and their effects

PDSI: Palmer Drought Severity Index

assessments. This leads to the concluding call for integrated, interdisciplinary case study analyses and for collective processes of scientific assessment (Section 8). I argue that, although we might know less than we would like about droughts, we know enough to act and reduce the vulnerability of the most vulnerable.

2. HYDROMETEOROLOGICAL DROUGHT ASSESSMENTS

This section looks at drought hazard research and its two major lines of investigation:

1. measuring the frequency and severity of drought, which are the bases for monitoring and early-warning systems; and
2. understanding the association between atmospheric circulation and drought, the basis for drought forecasting (10).

Excellent technical reviews of this literature exist (5, 11, 12). The emphasis here is on its relationship to policy. A key finding is that the extreme complexity of drought confounds single metrics and assessments. A new, more collective model of policy-relevant drought science seems to be emerging. The last two parts of this section look at the social use of hydrometeorological information.

2.1. Drought Metrics

Measuring the severity of drought is essential for real-time monitoring and for assessing and comparing different events. Severity is a function of drought intensity, duration, and spatial coverage (6). Intensity refers to the degree of lack of water, typically in relation to the historical record. Spatial coverage is often measured by the total area or percentage of a territory affected by a drought of a given intensity (13).

Operational drought definitions identify thresholds that mark an event's onset and termination (3, 13). For example, in the early twentieth century, the U.S. Weather Bureau identified drought as occurring after 21 or more days with rainfall 30% or more below normal for the period (11). Modern definitions make use of indicator values, such as three or more months of the Palmer Drought Severity Index (PDSI) (**Table 1**) being lower than -2 (4).

Droughts are complex to measure, and compared to other natural hazards, such as earthquakes or hurricanes, they have important differences:

1. Droughts accumulate slower and over longer periods. Droughts operate at different timescales (a one-month drought, important for some crops, may not give rise to a multiyear drought, important for a city's reservoir). A few days of heavy rain may abruptly end a long drought. This makes it particularly hard to identify an onset or end of a drought (6).
2. Droughts have diffuse, nonstructural impacts. Very dissimilar use(r)s are impacted in diverse ways by different types of lack of water (e.g., crop versus city) (1).
3. Spatial coverage is heterogeneous (13).
4. Hydroenvironmental and socioeconomic factors determine how severely droughts are experienced (14).
5. Drought is a relative concept, defined as a departure from the historical record. The record differs spatially and changes temporally.

There is agreement within the drought scientific community that unlike other hazards, a universal drought metric or operational definition is not possible (6, 15). Drought indicators have to be problem, context and user specific (16). However, certain tasks, such as global assessments or distributive policies (e.g., relief aid, regulatory exemptions, or preparedness investments), require indicators applicable across contexts.

Several metrics have been developed to assess drought. The advantage of precipitation-based indicators over hydrological or water supply indicators is that the record is not influenced by human or environmental factors (12). But meteorological anomalies do not always materialize into drought impacts. Hydrological and supply indicators provide information about drought severity closer to where it matters.

Table 1 provides a condensed review of common indicators [see also (11, 12)]. The PDSI has been a widely used indicator. In spite of advances in calibrating PDSI to different contexts (17, 18), most climatologists agree that the indicator fares unsatisfactorily in applications and regions different from those for which it was developed (agriculture in the U.S. Midwest) (8). Another limitation of PDSI is that it has a single intrinsic timescale. An attractive feature of the Standarized Precipitation Index (SPI) is that it is computable at different timescales (7). Many meteorological and water authorities also use variations of percentile definitions (i.e., classifying rainfall/streamflow events from the record according to percent probability of their occurrence; drought defined as an event that falls in the low percentiles, e.g., a streamflow that occurs in less than 20% of the record. See the decile method in **Table 1**). A latest development is satellite image vegetation condition indices (VCIs), which are useful in areas not covered well by hydrometeorological stations (19).

Most indicators agree about significant droughts and calm periods in the record (4, 12, 17, 20). Still, indicator values may differ considerably for specific periods and places (from one indicating severe drought to another indicating no drought). There might be significant time lags in identification of onset and termination of drought (12). Using multiple indicators together can provide better overall appraisals of drought conditions. But indicator values and scales are not always comparable (4, 21). One way to compare them is to convert their observed values to a frequency distribution of equivalent percentiles (4, 22). For example, the U.S. Drought Monitor's Objective Blend of Drought Indicators (OBDI) is the weighted average of the percentiles for observed PDSI, a crop soil moisture index, and 30-day precipitation, weighted 5/12, 5/12, and 1/6, respectively. In turn, the raw value is analyzed with respect to its historical frequency of occurrence, rendering an OBDI percentile (23).

The U.S. Drought Monitor is considered as one of the best drought assessment systems internationally (1, 15, 23). Unlike other national or regional systems, which assess drought on the basis of a single indicator, the Monitor provides data for OBDI, PDSI, SPI, VCI (**Table 1**), a crop moisture index, the percentage of normal rainfall, daily streamflow, snowpack, and soil moisture for each of the climatic divisions of the United States (11, 15). In addition, the Monitor synthesizes this information into an overall drought assessment of five severity levels. Levels relate to different indicator values and their historical probability of occurrence (**Figure 1**.[1] The lead responsibility for producing the weekly Monitor rotates among nine authors, who are heads of U.S. meteorological agencies, who sequentially take two- to three-week shifts. Indicators aid the lead author to determine the average drought severity for different U.S. regions, but qualitative judgment is critical. The remaining eight authors and nationwide experts respond to the leader's first draft. Over 130 regional and local scientists also participate in the process. They provide local data and help contextualize indicators to local conditions (23). The final Monitor map is accompanied by a qualitative narrative by the lead author accounting for drought aspects and local conditions/specificities not captured by quantitative data (23).

SPI: Standardized Precipitation Index

IPCC: Intergovernmental Panel on Climate Change

The approach of the Monitor is characteristic of new models of doing policy-relevant science for complex systems, of which the Intergovernmental Panel on Climate Change (IPCC) is a notable example (24). Collective processes among scientists aim to integrate quantitative information from multiple sources with qualitative judgments. Process, more than scientific tool, determines the quality and legitimacy of assessment. Good processes involve inclusive, direct, frequent,

[1] D4, an exceptional Monitor drought, can happen less than 2 years out of 100. D3, an extreme drought, can happen 2 to 5 years out of 100; D2, severe drought, can happen 5 to 10 years out of 100; D1, moderate drought, can happen 10 to 20 years out of 100. D0 refers to abnormally dry conditions and is expected 20 to 30 years out of 100. D3 is associated with PDSI –4.0 to –4.9, precipitation <60% of normal for 3 months, SPI –1.6 to –1.9 and VCI 6–15.

Table 1 Comparison of main drought indices (8, 11, 12)

Metric	Data[a]	Calculation	Drought definition and severity scale	Strengths	Weaknesses	Who uses it
Days of rain	R	Consecutive days with little or no R, or total R during a specified period of time	Drought if days with no rain > place-specific maximum or R for given period <place-specific minimum R	Intuitive and communicative Easy to measure	Not comparable. Valid only for specific application in specific region (11) Does not assess increasing or decreasing severity Abrupt termination of drought	Meteorological agencies until first half of twentieth century (still used in some areas)
Percent of average rainfall (runoff or streamflow)	R (RF, SF)	Divide actual R (or RF, SF) for a given period by multiyear average for this period	Drought if percent <place-specific minimum The lower the percent, the more intense the drought	Intuitive and communicative Easy to measure Useful for reservoir management	Average is not the same as normal in variable climates (mean ≠ median) (145) Cannot compare departure from average for locations with different climates	Water agencies and providers around the world Media
Deciles (146)	R	Divide distribution of occurrences over a long-term R record into tenths of distribution (deciles)	Scale: deciles 1–10 Drought if R in third through fourth decile Extreme drought in deciles 1–2 (i.e., R not exceeding 10%–20% of record)	Easy to measure Accurate statistical measurement of departure from normal, comparable across contexts	Impacts from statistical departures vary depending on local conditions Accurate calculations require a long data record	Australian authorities Several other authorities around the world use variations of a percentile approach to define drought

Palmer Drought Severity Index (PDSI) (147)	R, T, ET, SM, RF	Calculates a series of water balance terms for a generic two-layer soil model. Fluctuations in the hypothetical moisture supply are compared to a reference set of water balance terms to compute dimensionless cumulative departure of moisture supply	Scale: −6 to 6 (typically −4 to 4) Drought if <0 −0.5 to −0.99 incipient dry spell −2 to 2.99 moderate drought −4 and less extreme drought	Takes evapotranspiration and soil moisture into account Most effective where impacts sensitive to soil moisture Factors in antecedent conditions Calculable from basic data	Arbitrary algorithms (148) Nonintuitive classification Undefined generic timescale (7); may lag drought termination (8) Complex computation and reduced transparency Calibrated for U.S. Great Plains' conditions; limited applicability in locations with climatic extremes, mountainous terrain, or snow-pack unless calibrated (but see 18)	Meteorologists and agronomists U.S. National Oceanic and Atmospheric Administration Studies on regional/global drought assessment and climate impact assessment studies
Standardized Precipita-tion Index (SPI) (7)	R	The long-term R record is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for location and desired period is 0.	Scale: −2 and less, to 2 and more Drought when SPI continuously <0 −1 to −1.49 moderate −1.5 to −1.99 severe −2 and less extreme	Can be computed at different timescales as they relate to different types of drought (agricultural, streamflow, groundwater) Uses only one input variable (R) so calculations are simpler than PDSI	Long climatic record needed Changes from month to month as new data is incorporated Does not consider hydroenvironmental factors and seasonal differences in evapotranspiration	State of Colorado Increasingly used in United States and in regional/global scientific studies of drought United States Drought Monitor

Table 1 (*Continued*)

Metric	Data[a]	Calculation	Drought definition and severity scale	Strengths	Weaknesses	Who uses it
Vegetation Condition Index (VCI) (19)	GVI	Satellite measures visible and near-IR radiance as a proxy for health of vegetation. Vegetation associated to drought severity, adjusted for land climate, ecology, and weather conditions	Scale: 0–100 Drought if VCI <50 (mean)	Real-time monitoring of onset and progression of drought. Good for early warnings Useful for areas not covered well by precipitation or hydrological stations (Africa)	Limited utility during cold seasons when vegetation is dormant Ground conditions other than drought affect vegetation index	Remote sensing studies of drought United States Drought Monitor
Total water deficit (149)	SF	Sum of flows below some truncation level (mean or impact-related minimum) Product of time during which flows are below truncation level and average departure of streamflow	Drought if deficit >0	Intuitive and communicative Easy to measure	Long streamflow record needed River regulation and other human impacts distort streamflow record Problems in scaling up from individual streams to region/river basin	Hydrologists
Days of supply remaining (150)	RS, D	Calculates the days a reservoir (or system) can satisfy demand using storage capacity, forecasted future inflows, and predicted demands	Drought if days <system-specific threshold	Communicative Takes demand into account	System-specific thresholds; limited comparability Sensitive to models' assumptions about demand and inflows	Variations used by many urban water providers around the world

[a]Abbreviations: R, precipitation; T, temperature; ET, evapotranspiration; SM, soil moisture; RF, runoff; SF, streamflow; GVI, global vegetation index; RS, reservoir storage; D, demand.

and transparent processes of interaction, deliberation, and learning between scientists and social actors (24).

2.2. Drought Prediction

Meteorological droughts result from many complex, often synergistic, atmospheric causes. A major breakthrough in drought forecasting has been the discovery of strong teleconnections between sea surface temperature (SST) phenomena, such as the El Niño/Southern Oscillation (ENSO) and hydroclimatic anomalies (25). This has significantly improved forecasting capabilities (5), especially in regions where associations are strong (26). In Australia, for example, meteorological services routinely produce seasonal drought outlooks for farmers (27, 28).

In spite of recent advances, teleconnection indices account for a small part of drought variance in many regions (29). Even in areas with strong ENSO influence, prediction accuracy is ~60% to 70% for ENSO years and is substantially less accurate overall because ENSO is active in only half of the years (5). Climate change may to some extent invalidate the statistical relationships used for forecasts, which were developed from earlier historical data (28). Added uncertainty comes from downscaling regional forecasts to local effects.

2.3. The Use of Climatic Information

Using drought forecasts offers substantial economic benefits. This is confirmed by "perfect forecasts-perfect adopters" models (30), more realistic available forecast-constrained adoption models (27), and economic evaluations of actual cases where forecasts are used (31).

Yet, overall, forecasts remain underutilized. Many water managers and farmers keep using "rules of thumb," natural indicators, and other experiential proxies (27, 32). One reason for this is deficiencies in the forecasts themselves, stemming from the aforementioned uncertainties. A failed forecast can undermine user confidence for a long time (27).

But in addition to scientific climate factors, there are important social scientific factors that constrain adoption (31). Users' lack of awareness about the availability or usefulness of forecasts is only a partial explanation. Social science studies show that users do want climatic information, but often in formats different than those produced by scientists (31, 34). Users often view forecast accuracy differently than do forecasters. For example, whereas scientists are working to improve across-the-board prediction accuracy, users are more interested in improved certainty about extreme events. They put more weight in avoiding mistakes rather than maximizing returns (27, 35). Steinemann (31) found in the state of Georgia, in the United States, that the reported accuracy of meteorological forecasts is not meaningful for water managers because it does not distinguish between a wet season that was forecast to be dry and a dry season that was forecast to be wet, the latter posing more risks to them. Georgia managers also wanted forecasts expressed in terms of anomaly from the climatological normal (the meteorological service reported deviations from the boundary of the most-favored tercile) in a single value in terms of percentiles, consistent with other drought indicators. With her research, Steinemann acted as a mediator and translated available meteorological forecasts into a single-forecast indicator, suitable for management tasks. Such producer-user mediators (31), or larger boundary information organizations (32, 36), are essential for tailoring forecasts to needs.

In some places and for some people, access to climatic information is hindered by social inequalities. In the Sahel, in spite of the demand for climatic information, few farmers or herders have access to forecasts (37). In the United States and Mexico, poor small landholders and ethnic minorities use climatic information much less than large holders or farmers of European origin. Reasons include stressed finances, lack of surplus time, illiteracy, inability to use computers, and differential treatment by authorities (38). Information designs and delivery channels often cater to the needs of the most

Teleconnections: correlations between rainfall at specific locations and surface pressure values over much of the globe

SST: sea surface temperature

ENSO: El Niño/Southern Oscillation

profitable and not to the most vulnerable users (38, 39).

Coping: a distinct component of adaptive capacity referring to shorter-term, temporary responses that maintain well-being under conditions of stress

GCMs: global circulation models

2.4. Discussion: Hydrometeorological Information and Social Systems

The U.S. Drought Monitor and joint scientist/user-produced forecasts suggest that drought assessment is no longer a process carried out by individual scientists in their labs. They are social processes among scientists and between scientists and the social actors who use the information. The drought literature has not yet engaged with the thorny organizational issues of this new type of scientific activity. There are questions concerning who can participate and with what rights in the production of information or how legitimate synthesis and consensus among different views are to be achieved.

There is also a second way in which the natural-social boundary needs to break down. Hydrometeorological factors are not the only causes of hydrological, agricultural or supply droughts. By framing drought event analysis only in hydrometeorological terms, many natural scientists prejudge causation (40). But as Agnew & Warren (40) argue, an environmental (physical) change should not be confused with an environmental problem. The latter has a multiplicity of social and physical causes. For example, hydrometeorological assessments dominated media and policy debates concerning the causes of the Sahel drought famine in the 1970s. But the disaster was also caused by economic and land-use changes that depleted water and soil resources, and by political conflicts that eroded local coping capacity (40). Crucially, unlike hydrometeorological factors, such social causes could be acted upon (16, 40). Hydrometeorological analysis is an essential part of, but should not dominate, drought explanations.

Similarly, the precipitation or streamflow indicators that dominate drought assessment provide valuable information about hazard stresses, but these are not always relevant to the final impacts. Useful monitoring systems should combine hydrometeorological information with supply-, vulnerability-, and impact-related indicators. Yet there is a remarkable absence in the drought literature of such integrated indicator/monitoring systems.

3. CLIMATE CHANGE AND DROUGHT

Climate change predictions are not accurate or spatiotemporally specific enough to link them quantitatively to measures of drought. However, there is enough evidence to suggest that drought will increase in the coming decades as a problem, globally and especially in some semiarid, snow- and glacier-fed regions, owing to climate change or natural, multidecadal climatic variability.

3.1. Climate Change Models and Drought

Global warming should increase ocean and land evaporation. In principle, evaporation increases precipitation, but higher temperatures reduce soil moisture. The direction of precipitation and moisture changes will vary regionally and seasonally given climate feedbacks (41, 42). Regions where precipitation will decrease and temperature will increase should experience more droughts (41). Droughts are not just about decreases in means, but also about variability (43). Global warming is expected to exacerbate extreme hydrological variability as the water-holding capacity of the atmosphere and evaporation increase, accelerating the hydrological cycle (44–46).

It is difficult to know what will happen in any particular continent/region, and even less so in specific locales. Climate projections are usually produced by global circulation models (GCMs) forced with greenhouse-gas emissions scenarios. Global temperature predictions are reasonably robust. There is less agreement concerning regional changes (41). Precipitation is much more poorly modeled than temperature. GCMs differ even on the sign of predicted precipitation change at specific locales (47). GCMs do not systematically analyze drought-relevant parameters, such as changes in the number of days with rain, rainfall intensity, variability in water balance variables, and large-scale disturbances such as ENSO (48). Detection of ongoing change is confounded by the short span of reliable records, by natural decadal/centennial climatic variability, and by human modifications of hydrological processes (49).

The IPCC, a collective global scientific assessment process with the involvement of hundreds of scientists and government representatives, provides the most authoritative source of climate assessment. The remainder of this section discusses consistent messages concerning droughts from the last two IPCC assessments (2001 and 2007) and the studies these peer review.

First, there is very high confidence concerning the world regions that will experience increasingly drier conditions. Runoff in the Mediterranean, southern Africa, western United States/northern Mexico, and northeastern Brazil will decrease 10% to 30% by the end of the century (49). A comparison of 15 GCMs finds a consistent prediction of reduced soil moisture over these same regions, Central America, and Australia and a decrease during the growing season in Amazon, West Africa, and monsoon Asia. This suggests a worldwide increase of agricultural droughts (50).

Second, there is high confidence that precipitation variability and associated drought risk will increase in many areas (49). On the basis of Burke and colleagues' (51) computation of PDSI from the Hadley Centre global climate model (HadCM3), the IPCC (52) concludes that there will likely be an overall global increase of drought-affected areas by the end of the century. Drought-affected areas will increase over low latitudes and midlatitude continental interiors in summers. It seems likely that globally drought-affected areas have already increased since the 1970s, particularly in the tropics and subtropics (51, 53). Arid and semiarid regions are particularly exposed to climate change (49). Although no overall drying trends are discerned for whole regions/continents, such as Europe, United States, or China, substantial increases in drought severity and coverage are found for parts of them, such as southern and southeastern Europe (54), western United States (55), and northern China (56). For example, in southern and southeastern Europe, droughts with an intensity of today's 100-year droughts may recur every 10 to 50 years by the 2070s (54).

Third, there is high confidence that global warming reduces mountain glacier and snow cover. One sixth of the world's population depends on snowpack or glacier-fed river basins (57). Warming will cause seasonal shifts in streamflow, an increase in the ratio of winter to total runoff, and possibly reductions in low flows (reviews in References 42, 49, and 57).

Fourth, there is very high confidence that sea levels will rise (52) and salinize aquifers and estuaries (42, 49). Freshwater availability in coastal areas that depend on groundwater or estuary water will decrease. This should increase the likelihood of water supply droughts.

These four findings allow us to locate regional hot spots: arid and semiarid regions that already suffer from drought in low and midlatitudes, coastal zones, and snow-/glacier-fed basins. Local effects, however, will depend on the hydroenvironmental structure of specific catchments within these regions. Factors, such as storage, climate seasonality, or evapotranspiration, mediate between meteorological drought and impacts. Catchment impact models are confounded by uncertainty and disagreements between GCM predictions (49) and spatial grid mismatches (though downscaling is improving; see reviews in References 49 and 58). Drought assessments at the catchment or supply system levels tend to be of an explorative type, identifying worst-case, rather than likely, scenarios (59). This limits their use in planning. In fact, when water managers plan for climate change, they do so in terms of changes in average supply and demand, typically adding a safety factor to design estimates (42, 60).

3.2. Past Climate and Abrupt Megadroughts

Historical records and paleoclimatic proxies, such as tree rings or lake sediment cores, dramatically challenge conceptions of normal climate on the basis of twentieth-century instrumental records (61, 62). They reveal abrupt transitions to prolonged multidecadal droughts and multicentury regimes with conditions significantly drier than present (61, 63) in semiarid regions of western North America (61, 64) and tropical Africa (65, 66). For example, tree rings from Sierra Nevada in the western United States reveal two multidecadal droughts (AD 1020–1070 and AD 1250–1360) unlike any experienced recently in severity and duration. Six similar drought episodes occurred between 6000 BC to AD 1 (61, see also 61a for similar results). The causes of such megadroughts are poorly understood. Combined SST anomalies from different ocean basins must play a significant role (63).

Collapse of past civilizations, such as the Maya, has been correlated to extreme multidecadal droughts (67–69). But there are no simple cause-effect relationships between drought and society (61). Societies, which survived several big droughts, collapsed in later similar ones. War and economic or political changes that eroded adaptive capacity have also been associated with collapse. It is also not always easy to distinguish empirically collapse from adaptive migration (61).

Natural climatic variability confounds projections of climate change impacts (42) and puts into question drought assessments and predictions, water resource plans, and allocated water rights made on the basis of short, recent spans of the climatic record. For example, in the Colorado basin, the allocation compact between seven U.S. states was struck in 1922 on the basis of the 1906–1921 hydrological record. Historical records and 1000-year paleoclimatic river flow reconstructions reveal that this period was an exceptionally wet one (70, 71). From a longer term perspective, the recent sequence of dry years, which emptied Colorado reservoirs to historic lows, appears less extreme than previously thought (71). Droughts in basins like Colorado might be less about unusual climate and more about unrealistic social demands and perceptions, which are based on short records of experience.

What today appears as unusual or extreme might be perceived more normal in the future as our climate changes, the past climate becomes better known, and society adapts to the new conditions. It is the speed of change relative to adaptation and the magnitude of drought extremes in relation to evolved baseline conditions that are of paramount importance. These are less well studied by climate models.

4. SOCIOECONOMIC IMPACTS

Droughts cause reductions in crops, rangeland, forest productivity, surface and groundwater levels, as well as increased fires and livestock and wildlife mortality rates (72). These have repercussions on water and food supply and on economic activity. This section explains why drought's socioeconomic impacts are so hard to measure. Preliminary global disaster data is presented before the economics literature on drought impacts.

4.1. Methodological Problems

Drought impacts are very hard to assess because (*a*) identifying/assessing the hazard itself is difficult (Section 2) and (*b*) droughts have no visible (infra)structural damages but instead have diffuse, indirect impacts. These are not always easy to trace (1) for the following reasons:

- Secondary consequences, e.g., food price changes, can be more important than primary impacts, such as production losses (73). Effects ripple long after the natural hazard is over. In India, rural households coping with drought stop sending their children to school (74). This in turn has longer-term socioeconomic consequences.
- Social vulnerability and other stressors, such as war, poverty, or recession combine

with droughts to produce impacts (14). Isolating drought's effects from those of other variables becomes increasingly difficult the more indirect the impacts are (e.g., consider isolating the effect of drought on food prices from the effect of global market changes, geopolitical changes, consumer demands, and others).

- The definition of a baseline for assessment (i.e., what would the situation be without a drought) depends on assumptions about changes in other socioeconomic variables (75).
- At larger national or international scales, there might be indirect benefits from droughts (e.g., for farmers in regions competing with those affected by drought) (72).
- Total sums hide distributional differences. Droughts affect different groups in different ways. Some impacts can be quantified in monetary terms and compared. Others, such as deaths or irreversible environmental and cultural damages, cannot.

In spite of calls for formal drought impact accounting methodologies (76), there is no significant research in this direction. Data providers (state agencies, media, insurance companies, and aid organizations) seldom follow sophisticated or standardized methods (75, 77). For example, many studies equate economic impacts to gross domestic product (GDP) decreases in drought years (see Reference 78). Single, in-depth case investigations (14, 79) provide detailed and insightful information, but they are methodologically diverse and cannot be compared.

4.2. Global Drought Disaster Data

The Emergency Events Database (EM-DAT) is a main source of international information on disasters (75). **Table 2** provides cumulative data of impacts from major droughts in different continents. Data sources and analysis are subject to the problems discussed above. Numbers are indicative (75). Still some general conclusions can be drawn. First, droughts' toll on human life, suffering, and the economy is very high. Second, there are important differences between continents: More disasters and greater loss of life is reported in Africa; more people are affected, but less lethally, in Asia; and greater economic damages are experienced in the West. Third, it is not possible from this (or other) data to verify claims about trends of growing drought impacts [cf. (72)] given the undercollection of data before the 1980s.

4.3. Economic Assessment Methods

There is a proliferating economic literature on drought impact assessment. However, this is not concerned with the measurement of actual incurred drought costs. It models the monetary costs of future climate change and, by association, the benefits of mitigation or adaptation, using droughts as proxies for hypothetical future extreme conditions.

In biophysical-agroeconomic models, crop physiology models are forced with temperature-precipitation inputs from hypothetical or historical droughts. Yield estimates are aggregated for larger areas and incorporated into socioeconomic models, which predict changes in supply and prices (30, 43, 80). A drought equivalent to the "Dust Bowl" disaster of the 1930s was found to drop the value of agricultural production in the Missouri-Iowa-Nebraska-Kansas area by 17%, or 2.7 billion dollars (1982) (80). The costs of climate change can be derived using scenarios about how much more often such droughts will happen. Coupled hydrological-economic models (81) follow a similar bottom-up approach.

Top-down, Ricardian evaluations correlate variations in land value across space (e.g., average land prices in different counties) with variations in climate (e.g., average county precipitation or a variability index) (30, 82). Multiple regressions control for other variables that influence land values. Land-climate coefficients ("sensitivities") are derived and used to evaluate

Table 2 Drought disasters and their impacts (154)[a]

Years/impacts	Africa	Asia	South and Central America and Caribbean	North America	Europe	Australia, New Zealand, Melanesia, and Micronesia
1970–1979						
Reported disasters	31	22	11	1	1	4
People affected	24,400,000	229,900,000	16,400,000	0	—	—
People killed	119,000	81	0	0	0	0
Damages ($)	599,200	393,200	2,400,000	3,000,000,000	—	—
1980–1989						
Reported disasters	71	22	19	4	9	3
People affected	89,300,000	481,900,000	24,200,000	30,000	3,200,000	151,000
People killed	552,000	2,200	0	0	0	0
Damages ($)	2,600,000	942,900	1,600,000	4,800,000	5,200,000	6,000,000,000
1990–1999						
Reported disasters	56	31	29	3	15	9
People affected	87,400,000	196,500,000	16,700,000	0	9,200,000	7,900,000
People killed	447	2,900	12	0	0	60
Damages ($)	2,200,000	19,100,000	2,600,000	2,100,000,000	11,700,000	4,800,000
2000–2007						
Reported disasters	64	41	28	4	11	2
People affected	108,900,000	585,300,000	3,400,000	0	1,100,000	0
People killed	1,200	200	53	0	2	0
Damages ($)	900,000	9,100,000	2,400,000	4,400,000,000	2,800,000	2,000,000,000

[a]The criterion for disaster is 10 or more people reported killed, 100 or more reported affected, a call for international assistance, or a declaration of a state of emergency. People affected are those requiring immediate assistance during an emergency situation plus those injured or homeless. Damages include economic losses directly or indirectly related to the disaster in U.S. dollars on the date the disaster occurred. The database is compiled from various sources including UN, governmental and nongovernmental agencies, insurance companies, research institutes, and press agencies and validated by EM-DAT staff (75).

the economic cost of drought climates and future climate change. Applicability is mainly constrained to agricultural regions where land value-climate correlations are stronger, although there have also been studies of residential property values (83). Omitted variables that influence land values are a main source of biased estimates. Furthermore, whereas biophysical-agroeconomic models assume no adaptation (i.e., climate change translates to production costs with no mediation by farmer adjustments), Ricardian models assume perfect adaptation. The full range of adaptations is in essence embedded in the determinants of land value (30). This assumption of spatial-time equivalence is problematic. The personal, institutional, and financial endowments for responding to drought that are so often refined in arid places cannot be assumed to be available automatically and free of cost to humid areas in transition to a more severe drought regime (84, 85). The reliance on historical climate-land value relations undermines the ability of Ricardian models to predict heretofore unobserved climatic conditions (30).

5. DROUGHT VULNERABILITY AND ADAPTIVE CAPACITY

The same drought affects different areas, or people within the same stricken areas, very differently (38, 86). Vulnerability mediates hazard and impacts. Vulnerability is a function of exposure, sensitivity, and adaptive capacity

(87).[2] This section argues that, like hazard or impact assessment, complex causation confounds vulnerability assessment. Next, rural case studies, which identify some generic and historical factors that structure vulnerability, are discussed.

5.1. Drought Vulnerability Assessment

Measuring vulnerability is important for drought and famine warning systems (48), for proactive planning, and for allocating aid (88). Analysts who assess vulnerability define metrics given their perception of important impacts and proper responses to reduce them, with an eye to data availability (89–91). Typical regional drought vulnerability indicators include water availability and use, GDP or poverty, population (density), and proxies for resource and social infrastructures or institutional capacities (48, 91). Individual indicators are summed into a vulnerability index (either assuming they all carry the same weight or are weighed according to the subjective judgment of the analyst), computed for spatial-administrative subdivisions, and illustrated on vulnerability maps (91).

Vulnerability maps visualize regional hot spots and focus policy or media attention (91). But vulnerability assessments have several weaknesses. First, the relevance and weight of indicators are subjective and change with scale, degree of data aggregation, and context of application (88). Second, single indices hide instances where a system is becoming more vulnerable in one way, but less in another (92). Consider, for example, a region whose GDP per capita increases, as do summer demands for irrigation water. Vulnerability might decrease as people have more money to access water and food and increase as water stress intensifies. It is unlikely that any cumulating index can do justice to these conflicting trends. Third, indicators presume and oversimplify causation, missing important qualitative differences or nonlinear relationships. For example, population growth, assumed in most studies to increase vulnerability by increasing resource stress, can also be a force of economic growth that may (or may not) reduce vulnerability. Fourth, most of the vulnerability indicators developed are for developing-world contexts and have little applicability in the industrial world.

An alternative to subjective indicators derived by external analysts or administrators are collective vulnerability assessments with the participation of scientists, policy makers, and the vulnerable themselves (90, 93). As Smit & Wandel (90) describe participatory vulnerability assessments, researchers begin with an appraisal of current risk conditions, employing ethnographic in-community methods, interviews, and focus groups and collecting published and unpublished literature. The means by which people deal with risks and the factors and processes that constrain choices are also identified. Information then from other scientists, policy analysts, and decision makers is integrated into the analysis to characterize future exposures, sensitivities, and ways the community may potentially plan for or respond to them. Opportunities to reduce future vulnerabilities are debated in public or stakeholder meetings. The final product is not a vulnerability score or rating but information on the structure of vulnerability and ideas on how adaptive capacity can be increased and exposure sensitivities decreased.

Participatory vulnerability assessments are in their infancy. Promises of context-relevant indicators and community empowerment (48) remain to be proven. Their context specificity may come at the expense of cross-context comparability. Local bias may limit the use of local assessments in interlocal distributions. There also has been little engagement until now with procedural and substantive issues (e.g., who can participate and with what rights, relation between researchers and participants,

[2] Some terminological confusion is created by hydrometeorological assessments, which are titled drought vulnerability assessments. These equate vulnerability with the risk of a region experiencing a hydroclimatic drought of a given severity. In the terminology used here, this is an assessment of a region's exposure to a hazard, not its vulnerability.

how differences are resolved, integration into policy).

Economic globalization: trade liberalization and accompanying national policies of subsidy reduction and cost recovery of social services

5.2. Drought Vulnerability in Rural Areas and Adaptation Policies

Place-based vulnerability case studies employ an eclectic mix of qualitative and quantitative methods and data. Rather than measurement, the aim is to provide insights on vulnerability structure. A key insight of vulnerability case studies is that it is not so much whole countries or regions that are vulnerable to drought but it is specific groups within: smallholder agriculturalists and pastoralists, especially those relying on rainfall; landless laborers with casual employment; and destitute people forced out of productive activities, such as refugees and the underemployed (38, 48, 89, 92, 94). What characterizes vulnerable groups is not poverty per se but a failure of "entitlements," which is lack of the assets, income, and resources necessary to buffer livelihood from drought (87, 95, 96). Uneven political-economic power along lines of class, race, ethnicity, caste, gender, and age produces uneven access to the necessary informational, technological, and financial resources (38, 96, 97). Most vulnerability studies focus on smallholder farmers, pastoralists, or ranchers in peripheral, drought hazard-prone regions. Vulnerability differs substantially between the developing world, where impacts include famines and livelihood loss, and the West, where the concern is economic or asset loss. But some common patterns emerge.

Technology is no panacea. Irrigation, mechanization, and chemicals reduce agricultural vulnerability to climate variability. But new technologies are often inaccessible to those who most need them (39). Depending on the context of application, they might also have negative consequences. For example, new technologies bring into production marginal, water-scarce lands, often in less favorable climates of higher drought risk (14, 98). Although irrigation buffers against short-term drought, multiyear droughts can exhaust reservoirs and aquifers, causing much damage (14, 88). If agriculture has expanded and intensified in irrigated regions, losses might, in fact, be greater than in rain-fed areas (14). Low-income farmers who go into debt to acquire advanced technologies often become more vulnerable than their counterparts who use traditional techniques without purchased inputs (14).

Traditional adaptations reduce vulnerability but are under increasing pressure. Small farmers or herders are not merely passive victims of drought. There is a remarkable diversity of long-held, successful adaptive practices, which often escape the radar of distant policy makers. They include variants of land fallowing, temporal switching to drought-resistant crops, small-scale land and water interventions, and storage strategies (e.g., of fodder) (14, 74, 98–100). Community institutions, beliefs, redistribution rituals, and other forms of social capital spread drought risk (14, 98). Such community adaptations are not stuck in time. In many places, they have evolved into hybrid mixes of traditional-modern practices (101, 102). However, adaptations resilient to normal climatic variation often fail in longer, repetitive droughts, especially under mounting stresses from economic globalization (87, 89, 92, 98).

Diversification enhances adaptive capacity. Diversification includes production variation, such as planting several crop species together or combining cultivation with livestock. Increasingly, it involves also employment (income) diversification with off-farm incomes and remittances from migrating relatives (86, 87, 92, 103). In sub-Saharan Africa, diversified households with specializing individuals appear as the most drought-resilient arrangement (86). But access to favored diversification strategies and the quality of available options are often unevenly distributed along class/income or gender lines (86, 101).

Coping is a distinct dimension of adaptive capacity. Its exhaustion marks disasters (86). Exceptional coping activities start when normal adaptations are insufficient (86). The progressive disposal of insurance and productive assets, such as livestock or machinery, signifies coping exhaustion. It typically precedes destitution and forced migration in developing countries (104) or selling/abandoning farms in western contexts (99, 105). Repetitive stresses erode coping potential. Because of its creeping nature, drought often becomes an integrated part of people's lives through psychological coping (106). As coping and normal practices mix, it takes only a minor stress to precipitate a disaster (90).

European colonization of America, Asia, and Africa and opening of markets to global trade increased vulnerabilities dramatically. Vulnerability generally increases in periods of major political-economic transitions and under unequal power and economic relations that limit access for part of the population to vital resources (107). European colonization of Mexico (14), Morocco (98), India (107), China (107), and Brazil (108) involved privatization of common lands and the concentration of the best soils to a few large landholders. Small farmers were displaced to marginal, drought-prone soil (14, 98). Water-intensive export crops substituted subsistence-oriented, water-efficient cultivations. Production intensification caused the abandonment of fallowing (98). Local production systems, social capital, and traditional redistributive institutions broke down (14). Brazil, China, and India experienced the worst famines in history at the end of nineteenth century. Intense El Niño droughts found there a peasantry marginalized in drought-prone soil or out of farming. Colonial authorities removed subsidies and relief programs in the name of competition principles. Large landholders found opportunities to speculate and profit in the midst of the drought, exacerbating food shortages (14, 107, 108).

Neoliberal policy reforms exacerbate the vulnerabilities of the most vulnerable. Trade and access to markets is a vital adaptation strategy for poor farming households (38, 86, 99, 101). But economic globalization and neoliberal reforms combine with drought stresses to mount pressure on small farmers (91). Neoliberal reforms bear certain similarities with the colonization period: enclosure of remaining commons (86), land privatization and consolidation (14, 38, 39), and removal of state relief support and subsidized services (38, 86). In a study of ranchers in Arizona, Eakin & Conley (99) find that drought combines with poor cattle prices and high feed costs owing to global market changes, which strain ranchers' resources. Environmental policy and encroaching urban growth limit access to previously available pastures. Ranchers, especially smaller operations, are increasingly tempted to sell ranch property to development interests. In Mexico, the North American Free Trade Agreement policy reforms, devaluation, and rise of interest rates make access to credit very difficult for *ejidatarios* (small farmers of communal lands). Land concentrates to large holders and agribusinesses with access to the capital necessary to smooth drought calamities, and the *ejidatarios* migrate to cities (14). Eriksen and colleagues (86) find that in Kenya and Tanzania economic globalization changes dramatically the choice set of coping strategies (also see References 38 and 39 for Mexico). For example, privatization of land in one community limited access to indigenous plants, whose use was an important safety net during droughts for the most vulnerable community members excluded from principal coping strategies. The counterargument to criticisms of neoliberal reforms is that the short-term costs of restructuring will pay off in the longer term by economic growth, which will eventually reduce vulnerability (see the "inverted U hypothesis" in the sidebar Growth, Technology, and Adaptation) (78).

State policies can reduce rural drought vulnerability, but they seldom do. There is relative agreement among vulnerability scholars concerning the attributes of sound policies for the rural contexts they study. First, central level monitoring, disaster preparedness, and relief planning are vital (97, 104, 111, 112). Second, priority should be on fair adaptation, i.e., reducing the vulnerability of the most vulnerable (87, 92). Reducing poverty and enhancing access to decisions and financial resources reduces vulnerability (92). Third, policies should respect local complexity and support the creativity of people, enhance ongoing adaptations and coping mechanisms, and stimulate diversification (86, 92). Fourth, state financial insurance and local customary safety nets are vital in crisis periods and should be maintained (14, 87, 92).

Unfortunately, few investments go into supporting local adaptation and coping strategies compared to conventional, and more expensive, productivist solutions that increase water or food supply (86, 94). Often these are not accessible by the most vulnerable groups (e.g., high costs of acquiring new productive machinery or accessing irrigation water). Development decisions and policies affect local adaptive capacity but do not seem to take it into account (92). Adaptation policy initiatives are often nullified by broader geopolitical and globalization forces (90). Pro-poor drought relief programs have proved effective in preventing famines (111), but policies of structural adjustment constrain state support and shift risk to individuals, removing safety nets and subsidized social (health, education) services (86, 111, 113, 114).

Urban vulnerability is understudied. Vulnerability studies focus on rural contexts where dependency to water (rainfall) is direct. The few works that do refer to urban vulnerability conceive it as the risk of water supply drought (115, 116). The unit of analysis is the water supply system, not the household. This makes sense as the water system buffers urban households from the hazard. Urban household vulnerability can be assumed equivalent to water supply vulnerability. But in developing world (mega)cities, many households dot not have access to network water supply. They depend on various water sources, including rainfall. We know very little about the characteristics of vulnerable groups in these cities and the structure of their vulnerability. Furthermore, in developed world cities with full water access, water rationing or increasingly stringent water policies are likely in a scenario of future megadroughts. It is important to study (*a*) the differential vulnerabilities of various types of households to such policies (e.g., poor households may be more vulnerable to higher prices) and (*b*) the potential degrees of freedom different households have (or may have) at their disposition to adapt to occasional rationings (e.g., use of secondary sources, temporary change of water-use practices).

6. THE SOCIAL CONSTRUCTION OF DROUGHTS

The political ecology (109) works reviewed in this section emphasize active human agency, rather than passive vulnerability, in the construction—material and discursive—of droughts. Two insights are presented. First, droughts might be profitable for powerful interests given how institutions distribute costs and benefits. This explains the lack of water conservation policies to avert droughts. Second, the way we perceive and talk about droughts is conditioned by, and reinforces, certain politics. In the concluding section, I discuss some limitations of political-ecological works.

6.1. Institutions, Power, and Drought

Economics, politics, and regulatory frameworks explain why water utilities often underinvest in conservation and drought preparedness during "good times" (110). The lumpiness and capital intensity of water infrastructure render operational supply costs minuscule compared to fixed costs (117). Water consumption increases revenue at a low cost. Water utilities have an incentive to maximize consumption and revenue rather than reduce demand. Demand management and occasional use of secondary sources often reduce drought risk, but they increase expenditures and reduce revenue. There are strong incentives to expand consumption when reservoirs are full and to smooth it with conservation when a drought comes and the short-term marginal costs of emergency measures or new supply become high (110). Emergency supplies or new waterworks are often subsidized by the state, providing a further economic disincentive to utilities to conserve water (110, 118, 119). In the case of private utilities, new waterworks count as capital investments that increase assets or are used by regulators to set prices and profits. Research of Athens's, Greece, 1990–1992 drought (120) shows that "waiting until there is a drought" (121) was the least-cost strategy for Athens's water utility [see Bakker's (9) similar argument for a very different geographical and regulatory context].

From an economist's perspective, regulatory reforms should decouple agencies' revenue from water consumption and internalize the future costs of droughts to current uses (117). Radical political ecologists see instead externalities, or cost displacement in their terminology, as a structural feature of capitalist accumulation (109). According to the disaster capitalism thesis (107, 122), disasters, such as droughts, are instrumental in sustaining capital accumulation in the face of social opposition. On the one hand, disasters are critical moments when the cost displacement of past growth, or neoliberal policies and associated private profits, becomes apparent. For example, Kaika (118) attributes the 1990 exhaustion of Athens's reserves not so much to meteorological drought but to urban growth and increasing consumption. Kaika maintains that drought was no accident. Water policies in the years preceding the drought were tailored to keep the costs of real estate low and instigate urbanization, for example, by subsidizing the expansion of the network to the suburbs (110, 118). Similarly, Haughton (123) attributes Yorkshire's 1995 drought, not to weather anomalies but, to the water company's profit-seeking strategies, which after privatization underinvested in drought-prevention capacities and cut down staff.

On the other hand, the sense of urgency of disasters serves to shift attention away from root causes while providing pretexts for further profit making and for policies that reinforce the root causes. Nevarez (121) shows how Santa Barbara's water agency found a pretext in the 1985–90 drought to reintroduce a defeated ballot for a water transfer without which the city faced a moratorium on new urban development. Alarming ads of brown lawns and of Santa Barbara without water convinced the public to vote in favor of the transfer. As Nevarez documents, real estate businesses that benefited from the lift of the growth moratorium were the main funders of the agency's campaign. Likewise, Kaika (118) identifies the construction magnates who benefited from the multimillion euro waterwork contracts the government distributed with emergency extraparliamentarian procedures during Athens's 1990 drought. In addition, she argues that the government used the crisis to increase water prices without public resistance, paving the way for the controversial privatization of the city's water agency. Solway (114) finds a similar pattern in a different context, rural Botswana; official discourses attributed declines in rural production to the 1979–1987 drought. But Solway argues that they were primarily an outcome of land privatization reforms and removal of subsidies. In turn, drought legitimated rural policies that deepened the dependency of citizens on the state and consolidated the privatization of production, favoring powerful rural elites.

6.2. Deconstructing Drought Discourses

The above arguments need not invoke conspiracy theories. Power politics are often a matter of shared class assumptions (108), ideologies, and discourses (9). According to political ecologists, discourses are an indirect way through which power is exercised. Hegemonic, taken-for-granted ideas and concepts delimit how a problem is conceived and what solutions are sought. Discourses include not only the language and written texts used to talk about droughts but also practices and technologies of representation, such as assessments, maps, and forecasts (9). Political ecologists take particular issue with discourses of drought as an imminent crisis and discourses of drought as a natural hazard. The focus on weather, in their view, elides culpability and naturalizes causation directing attention away from questions of political agency, i.e., who is to blame or who stands to benefit from drought (124). Public debate is depoliticized and the power of expert scientists increases (121). Unity, political consensus, and (moral) discipline become important in the face of an external climatic threat (118, 121). In addition, naturalizing discourses privilege technological or market resolutions. As Swyngedouw (109, p. 47) puts it "a climate of actual, pending or imagined water crisis serves not only to instigate further investment in the expansion of the water-supply side . . . but also fuels and underpins drives towards commodification. As the price signal is hailed as a prime mechanism to manage 'scarcity,' the discursive construction of water as a 'scarce' good becomes an important part of a strategy of commodification, if not privatization."

In contrast to other analyses, which see media discourses as simply ignorant (125) or context dependent (126), political ecologists emphasize the ideological, political-economic, and discursive association of media with the corporations that benefit from drought disasters and subsequent reconstruction activities (118). Powerful interests do not just construct and impose discourses (although sometimes this might be the case). The relationship is reciprocal: Discourses provide platforms upon which different interests associate (9).

Discourse deconstruction has a creative potential insofar as it reveals unsaid ideological assumptions and helps structure alternative framings that can enable new interest coalitions (48). For example, discourses of a drought as a politically economical, instead of meteorological, crisis draw attention to institutional changes, rather than mere technological or market fixes (109, 118). Discourses that recognize drought as a temporary condition, which threatens conveniences and not basic needs, at least in the Western world, open up the possibility for policies of temporary rationing and conservation, instead of continuous supply expansion (110, 119, 121).

6.3. Discussion: Limitations of the Social Construction Perspective

The (de)construction of scientific discourse and political ecologists' openly anticapitalist politics alienate many natural scientists (127). Political ecologists' situated (value-positioned) analyses require strong, verifiable empirical support if they are to be more than mere ideology. Unfortunately, some claims that intuitively make sense to the favorably inclined remain empirically unsupported. It is when the documentation of causation (e.g., how precisely power or discourse coalitions form, operate, and affect explanation/response to drought) is weak that the disaster capitalism thesis may seem to some as a conspiracy theory (127).

Political ecologists assume implicitly that, independent of hydrometeorology, if the social side of the system were different (e.g., no urban growth, or if losses and consumption are controlled), water supply drought would not occur. This allows an exclusive focus on the political-economic drivers or discourses that preclude such social alternatives and, in a way, "cause" drought. Yet drought is not just an average, but an extreme phenomenon. And water not used is not necessarily water stored for the future. One cannot presume that a drought will not happen if politics are different without adequately engaging the hydrometeorological and infrastructural specificities of the case.

Political ecological analyses raise expectations of counterfactual assumptions. If, for example, supply, growth, or neoliberal policies are to blame for resource exhaustion, which are the alternative politics or institutions that could manage resources more effectively and equitably? Political ecologists' prescriptions are often vague, hinting about democratization (109, 118) with a major overhaul of capitalist institutions. However, in my view, this failure to engage with what can do better does not undermine political ecology's insights concerning why water resources are managed the way they are or why unsustainable policies that reproduce droughts are so difficult to change.

7. WATER MANAGEMENT AND ADAPTATION

Water technologies and institutions are part of the repertoire of social adaptation to droughts. All water management interventions, such as integrated water resource management, management of ecosystem services, and water pricing, regulate the available quantities of water and are relevant to drought adaptation. But an exhaustive review of the water policy literature is beyond the purposes of this chapter; readers are referred to References 49 and 128. Instead, this section discusses briefly three key issues/options in drought adaptation: water supply versus water conservation, markets for water reallocation, and drought plans.

7.1. Water Supply and Conservation

Supply-side adaptive techniques increase the quantity of water regulated through infrastructure. Conservation techniques reduce the withdrawal of freshwater. Water management options are typically compared in terms of their yield and social, economic, and environmental benefits (42, 49). The literature lacks specific analyses of the suitability of different options in the context of intensifying droughts and climate change, rather than say, water shortages or stress in general. Climate change and drought pose additional challenges: (*a*) uncertainty about future conditions; (*b*) greater or new types of temporal variability, with new extremes; and (*c*) the need to account for the climate change mitigation performance of alternatives (Section 3).

A comparison of supply and conservation options relates to broader debates about sustainability (see the sidebar Growth, Technology, and Adaptation). **Table 3** synthesizes existing information about water management options in terms of general and climate change–related objectives. With caveats, large-scale supply options have more certain output but higher environmental, social, and economic costs than conservation (**Table 3**). They also tend to contradict climate change mitigation objectives.

Conservation is less sensitive to uncertainty about future conditions than, say, dams or transfers. If climate change alters catchment hydrology, waterworks might turn out to be misplaced or have lower yield than projected. Desalination is decoupled of hydroclimatic conditions and hence has a safer yield. But the affordability of its output is sensitive to increasing energy prices.

In response to increasing variability, all options have something to suggest for them. Dams can store increasingly irregular flows, protect people from floods and droughts, and increase flexibility in the temporal allocation of water to different uses. Transfers enable diversion to climatically different areas, reducing vulnerability to spatially confined droughts. Desalination separates water supply from climate variability, and conservation adapts consumption to drier conditions and reduces vulnerability to extremes.[3]

An important finding is that new supply tends to generate demand through positive economic and political feedbacks (110, 129). Increases in storage capacity are often followed by population and consumption growth in served areas, nullifying insurance against droughts (110). Smaller supply works avoid instigating consumption and have fewer financial and social/environmental costs. Small dams and rainfall harvesting schemes are an interesting option, especially for rural areas in the developing world. Small desalination plants for temporary use during droughts consume less energy and increase drought security rather than subsidize further growth. They can be useful

[3] A caveat might be demand hardening, i.e., the hypothesis that reduced water consumption will make it harder to reduce demand further in extreme periods. There are no studies yet assessing the real plasticity of demand or how gross demand decreases might affect the necessity or feasibility of additional temporary reductions in extreme periods.

Table 3 Supply and conservation drought adaptation options and some comments on their potential advantages (+) and disadvantages (–) (42, 49)

	Water management (in the context of new extremes and increasing variability)	Flexibility (in the context of uncertainty about future conditions)	Climate change mitigation	Costs	Environment	Social impacts
Dams and transfers	(+) Additional storage for extremes, seasonal shifts or environmental flows (+) Diversification of supply to new climatic areas/sources (+) Well-tested and developed technologies (–) Additional storage or yield unreliable because of climate change, especially in basins already heavily regulated where new supply works might decrease replenishment of existing ones	(+) Operation can be adjusted to climatic conditions (–) High costs; expensive to remove dams if they turn out to be ineffective or misplaced	(+) Emissions reduction if hydroelectricity produced (–) Energy consumption if pumping involved (–) Emissions from production of materials (cement) (–) Emissions during construction (transport) (–) Flooded soils major source of methane, especially in the tropics	(–) High costs for big-scale projects, especially in areas where best sites have already been dammed	(–) Reduced environmental flows, habitat changes, barriers to species movement	(–) Displacement of populations from dammed areas (–) Social movements of opposition

Desalination	(+) Stable production, independent of climate (−) Unfavorable if climate change mitigation policies toughen up or energy costs/taxes rise	(+) Small-scale, reversible intervention (+) Can be operated only when needed	(−) High energy consumption (although it can be less than water transfers or groundwater pumping in some areas)	(+) Reasonable capital costs (+) Low costs for treating brackish groundwater or estuary water (−) High (although decreasing) operational costs	(−) Damage to coastal habitats and sea water quality by brine discharges and heated water	(−) Competing for scarce coastal zone land
Conservation demand management, leakage control, wastewater reclamation, improved supply efficiency	(+) Reduces reliance on freshwater and vulnerability to climate instability (−) Uncertain results because of reliance on untested technologies (reclamation, leakage detection) or because of unpredictability and instability of individual behaviors (demand management) (−) Not appropriate for developing world areas where consumption is low	(+) Low-regret investments (−) Demand hardening (?)	(+) Low energy use (exception, reclamation might consume substantial energy)	(+) Relatively low costs (exception, reclamation)	(+) Insignificant environmental impacts	(+) Relief of resource conflicts (−) Higher prices to reduce demand may burden low-income groups unless designed with a pro-poor perspective (−) Public health risks from reclaimed water

for higher-income, coastal areas with salinized aquifers/estuaries.

Policy and public debates about alternatives rarely go beyond intuitive assessments (see, for example, Reference 130). Scientific methods of assessing alternatives include benefit-cost, cost-effectiveness, and multicriteria frameworks (131, 132) and scenario-based risk models dealing with climatic uncertainty (42, 81, 133). Integrated models that couple climate change with socioeconomic scenarios and risk-based assessments of alternative water management options are needed.

Scientific assessments "assume that there is, in practice, a process through which adaptations are selected and implemented, and that the relative evaluation analysis fits into this process" (90). In reality, policy decisions are more complicated, governed by political-economic processes, and do not always make use of formalized assessments. In spite of a rhetorical shift to integrated twin-track policies of supply- and demand-side management, in practice, the supply-side track continues to move faster, reinvigorated by discourses of climate change–inflicted water scarcity in the West and the need for western-type growth elsewhere (see, for example, References 130 and 134).

7.2. Water Markets

Voluntary water reallocations (markets) can be less expensive than new supplies (131). They provide a flexible additional option for redistributing water during droughts (135). They can be particularly useful in areas where low-priority, water-inefficient agricultural production consumes water that could be conserved or transferred to urban uses. Markets require, however, sophisticated regulatory systems, which are difficult to implement in most countries (136). Property rights are a market prerequisite. In areas where there are no formal water rights, establishing and monitoring rights can be controversial (137).

Climate change will reduce and change the timing of runoff. Independent of the market question, there is a need for reforming rights of use, formal or customary, to adapt to the new conditions and render them flexible to change during temporary extremes. A perverse effect of the prospect of markets is that by increasing the economic value of water, they increase users' resistance to rights' reforms.

Water markets are unavoidably highly regulated. Third parties have to be protected from environmental and social damages (e.g., job losses if water sale revenue does not trickle down to the community). State monitoring and adjudication capacities are essential because the fluidity of water and the instability of weather complicate property rights (136, 138). Generally, market reallocations have been limited to temporary transfers. Permanent exchanges of rights have higher economic and third-party risks and have been less common (136, 138). In California, drought water banks were established in the early 1990s, the state's water agency acting as a broker between interested parties for temporary purchases and sales of water (135).

7.3. Drought Planning

Drought plans at national, regional, and local levels promise to help reduce drought vulnerability (139). Drought planning includes proactive measures (e.g., conservation and reallocations) and contingency provisions, i.e., establishing drought stage triggers and defining the measures to be implemented during each stage (e.g., rationing, use of lower-quality water, water transfers). Collaboration between different agencies and stakeholders is important. Controversial measures (e.g., compensated transfers) and cooperative actions are better if agreed upon before a crisis. There is a lot of reporting on specific regional or national drought planning initiatives that conform to certain normative ideals (139) but very little in-depth and ex post facto research on the operation and effectiveness of existing plans.

From the few studies that do exist, a conclusion is that drought planning suffers when disjointed, as it often is, from other development-environment decision-making processes (140).

Confusion in the way drought is understood and measured by different stakeholders can also complicate drought planning (93). National and local capacities to participate effectively in drought planning are highly variable (141) and are undermined by reduced state budgets and human resources. Participatory local processes can build capacities and empower communities to respond to droughts (142, 143). Central authorities, however, often take control during crises, disempowering local actors (142).

8. CONCLUSIONS

The study of droughts is an extremely complex endeavor. Meteorological droughts result from many, often synergistic, climatic causes. These remain incompletely understood. Their effects are buffered or exacerbated by multiple interacting environmental, hydrological, and socioeconomic factors. Droughts combine with other stressors to affect unevenly, either directly or indirectly, a multitude of social and ecological functions, which are valued differently by various groups. These dynamics are often nonlinear and operate at different temporal and spatial scales. Climate variability and change, bringing in additional uncertainties, make long-term predictions a wild guess. Defined as an abnormality from historical experience and in relation to needs, the meaning of drought evolves as climate and knowledge about it change and as human practices adapt, or simply change. Tasks that may seem simple to the uninitiated, such as measuring or monitoring a drought as well as assessing and comparing drought impacts or the vulnerability of communities, become extremely complex. Simplifications, delimited by political-economic dynamics and predisposition to certain responses, govern the attribution of causation.

But complexity need not paralyze analysis or action. New ways of organizing science offer hopeful prospects for producing action-relevant knowledge. And although we know less than we would like, we already know enough to act.

8.1. Interdisciplinary Drought Analysis

Meteorologists and hydrologists dominate policy-relevant explanations of droughts. Drought impacts, loosely defined, are traced to hydrometeorological causes. Detailed assessments evaluate how abnormal a particular event is. Yet different models, indicators, or datasets may give conflicting evaluations. And lack of sufficiently long records uninfluenced from human or environmental factors render interpretation contentious. But natural scientists maintain a preparadigmatic view that severity of impact must be the outcome of the abnormality of the hazard. If natural scientists are wrong to presume, rather than prove, the primacy of hydrometeorological over social causes, social scientists often commit the reverse fallacy. Many stay within the comfort of their expertise, content to highlight social causes and deconstruct drought discourses.

Drought analysis would benefit by moving from the skies, literal or intellectual, to the ground. Region- or place-based droughts and impacts on specific groups (low reservoir levels, service interruptions, crop failures, famines) should be the starting point of analysis, not meteorological anomalies or theoretical paradigms. The search for causation should gradually move outward and upward, analyzing the relative weights (14) or complex interactions (9) of vulnerabilities and adaptation failures, political-economic drivers and concomitant decisions, hydroenvironmental changes, and meteorological factors. Accumulating and comparing case studies from around the world can lead to integrated theories of drought.

Of course, this is much easier said than done. Causal factors may be incredibly hard to separate, and they can surpass the intellectual or resource capacities of individual researchers or interdisciplinary teams. Translating between disciplines is difficult; retreating back to disciplinary terrain will always be an easier option. Idiosyncratic case studies will not easily build up into integrated theories, especially as assumptions about desired adaptation states and associated vulnerabilities vary from analysis to analysis. But these are challenges to struggle with, rather than reasons to shy away from interdisciplinary work.

Collective scientific assessments: processes whereby scientists from different disciplines, together with policy makers and stakeholders deliberate and produce policy-relevant judgments on the state of knowledge

8.2. Collective Assessments

Collective scientific assessments (24) are characterized by broad participation of scientists from various disciplines; use of multiple models, methodologies, and sources of information; discursive learning among scientists; collective preparation and editing of products; and deliberation with policy makers, stakeholders, and the public. Drought monitoring, impact, and vulnerability assessments are—unconsciously—evolving toward this model (1, 23, 90, 93). This transformation should become explicit: Policy-oriented drought assessments should be designed in accordance with the attributes of successful collective scientific assessments. The United Nations provides a natural host for global and regional drought assessments. These, in turn, can spin off to continental, national, and local drought assessments, offering monitoring platforms and "juries" for drought-related policies. Collective scientific assessments are not without problems, which may concern rights to participation, rules of operation, resolution of differences, interfaces with hierarchical bureaucracies, and overriding political-economic dynamics. The drought literature has delayed engaging with these.

GROWTH, TECHNOLOGY, AND ADAPTATION

Debates concerning the role of technologies and markets in drought adaptation stumble upon greater questions concerning the sustainability of current growth. Water supply, food production, transportation technologies, and increasing agricultural trade have reduced vulnerability to drought and famine in the Western world. But is this pattern historically and geographically replicable? And is it environmentally sustainable? Whereas some blame drought disasters in the developing world on the substitution of local practices by Western technologies and the incorporation of local economies in global trade systems, others maintain that short-term increases in vulnerability will be followed by a decrease as economies modernize (an "inverted U hypothesis" between vulnerability, y-axis, and development, x-axis). An ecological criticism of inverted U-type arguments is that modern technologies reduce vulnerability in the short term, at the expense of the long term. The long-term resilience of energy-intensive food and water production is undermined by the displaced costs of technological and economic growth (climate change or fossil fuel exhaustion). Optimists, however, retain faith in the capacity of growth, technological advances, and markets to solve future environmental limitations. Which policies or practices are deemed adaptive, and which are not, is influenced by the position one takes in these debates.

8.3. Policies

Available science does not permit predictions of how climate change will alter the frequency and severity of droughts in specific places. The level of spatial and temporal resolution and certainty needed by planners is not likely to be available in the near future. But we do know that certain arid, semiarid, and snow-fed regions are likely to face more variable and drier conditions than experienced over the past 200 years, owing to anthropogenic climate change or natural, longer climatic fluctuations. We also know that the most vulnerable people are those who already suffer the most from droughts: low income farmers, the urban poor, pastoralists, and rain-dependant smallholders (Section 5). Support in these regions and for these people need not wait for more science.

Adaptation has to be local and context specific, and policy intervention should respect local complexities. Still some broad lessons can be drawn. Water and food production technologies may reduce vulnerabilities, especially in the developing world, but also may generate new vulnerabilities and be less resilient to a climatically unstable and energy scarce future (see sidebar). Access, rather than production, reduces vulnerability. Sound, low-regret policies include conservation, source diversification, appropriate low-scale technologies, economic diversification, and support for households'/communities' ongoing adaptation and coping strategies. Yet, relatively few investments go to these policies compared to new production technologies or postdisaster relief. This is not just a matter of public policy failure; as political ecology studies show, there are powerful interests who stand to lose from policy change. Economic globalization and related policies limit the capacity of states to intervene. They also favor specialization rather than diversification, and they direct investments to high-return technologies. Globalization-fueled inequalities exacerbate the vulnerability of the most vulnerable. Public action to counter such adverse effects is desirable.

SUMMARY POINTS

1. Droughts have climatic, hydrological, environmental, socioeconomic, and cultural causes that are very hard to separate.
2. It is not possible to derive a single drought severity metric. Collective processes of assessment, using multiple metrics and qualitative judgment, are necessary at global, continental, national, and local levels.
3. The capabilities of drought forecasts have improved, especially in areas where ENSO is active, but forecasts remain underutilized because they often do not fit user needs.
4. Climate change is likely to globally increase the area affected by droughts. Semiarid, coastal, and snow-fed basins are particularly exposed. Megadroughts, unseen in recent history, are part of the natural climate of western America, Africa, and perhaps other parts of the world.
5. Drought takes a heavy toll on human life in Africa, is a major source of social disruption in Asia, and causes significant economic losses in the agricultural sector in western countries.
6. Smallholder producers, herders, and destitute people in rural and urban areas, especially children, elders, and women, are particularly vulnerable to droughts. Economic globalization exacerbates their vulnerability and constrains state support policies.
7. Dominant public discourses of drought play into growth, supply expansion, and privatization politics.
8. Water and food production technologies do not necessarily reduce drought vulnerability, especially in the long term. Conservation is a lower-risk, lower-cost adaptation option, but regulatory frameworks and political-economic interests maintain a bias in favor of supply-side solutions.

FUTURE ISSUES

1. How should we organize and facilitate the collective scientific processes of assessing drought severity, impact, and vulnerability at different levels (global, continental, national, local)? How can such processes be integrated with institutional and public involvement processes?
2. How can interdisciplinary studies of specific drought events be designed? Is it possible to separate causal factors? How can disparate place-based, event studies be synthesized into integrated, interdisciplinary theories of drought?

3. What are the determinants of drought vulnerability in urban areas? How flexible are urban households in coping with supply cutbacks in the likely case of future megadroughts? How can their adaptive capacity be improved?
4. Standardized methods for drought impact accounting need to be developed.
5. Are existing drought policies and plans effective?

DISCLOSURE STATEMENT

The author is not aware of any biases that might be perceived as affecting the objectivity of this review.

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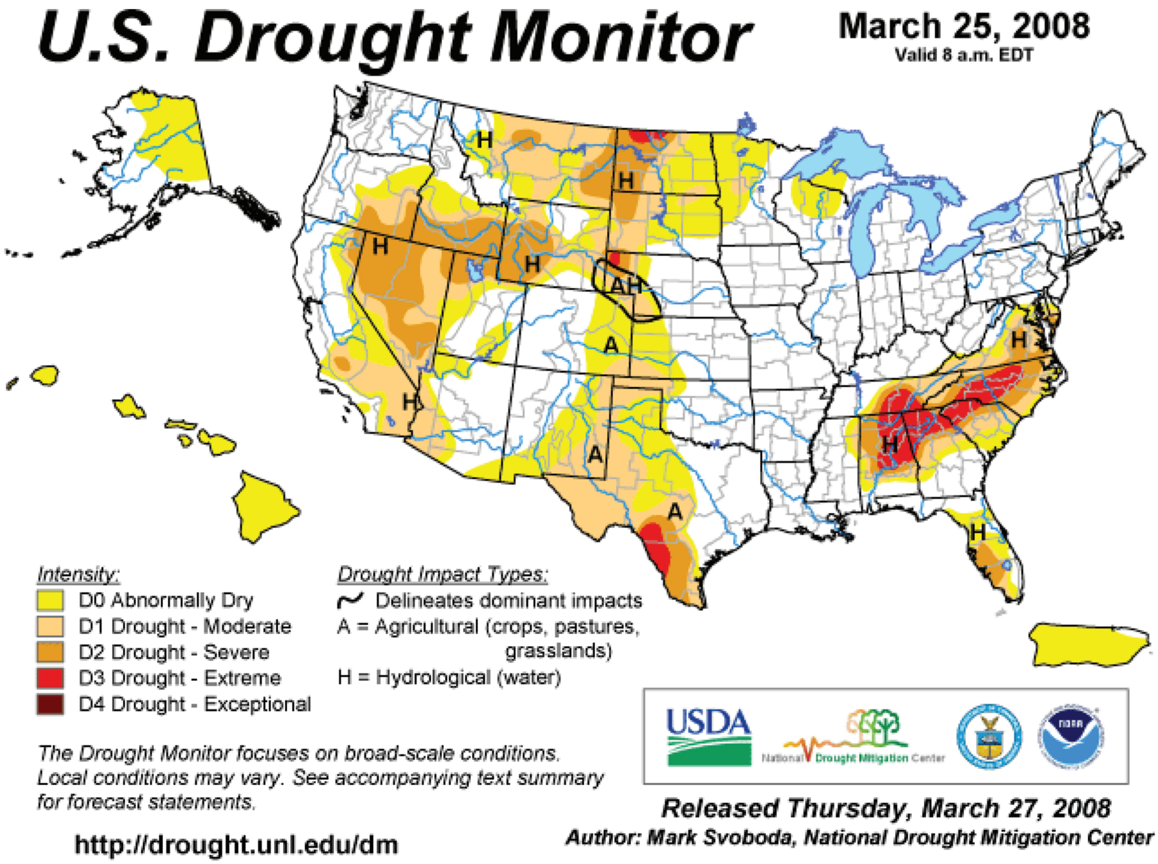

Figure 1

The U.S. Drought Monitor for the week of March 25, 2008. The map was downloaded from the Web site of the National Drought Mitigation Center, University of Nebraska, Lincoln (23a). See the text for an explanation of how the different drought intensity levels are derived.

Annual Review of
Environment
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Volume 33, 2008

Contents

III. Management, Guidance, and Governance of Resources and Environment

IV. Integrative Themes

Indexes

Errata

An online log of corrections to *Annual Review of Environment and Resources* articles may be found at http://environ.annualreviews.org