Rain Gauges to Range Conditions: Collaborative Development of a Drought Information System to Support Local Decision-Making

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ABSTRACT

Drought monitoring and drought planning are complex endeavors. Measures of precipitation or streamflow provide little context for understanding how social and environmental systems impacted by drought are responding. Here the authors report on collaborative work with the Hopi Tribe—a Native American community in the U.S. Southwest—to develop a drought information system that is responsive to local needs. A strategy is presented for developing a system that is based on an assessment of how drought is experienced by Hopi citizens and resource managers, that can incorporate local observations of drought impacts as well as conventional indicators, and that brings together local expertise with conventional science-based observations. The system described here is meant to harness as much available information as possible to inform tribal resource managers, political leaders, and citizens about drought conditions and to also engage these local drought stakeholders in observing, thinking about, and helping to guide planning for drought.

1. Introduction

Drought is a prominent feature of the early 2000s climate of the U.S. Southwest. The first decade of the twenty-first century was the warmest, had the second-largest areal extent of drought, and was the fourth driest in the 1901–2010 instrumental record (Hoerling et al. 2013). Although projecting future precipitation is challenging, an assessment of recent research indicates that the overall warming trend across the Southwest is likely to lead to more frequent, more intense, and longer-lasting droughts in the Colorado basin (Gershunov et al. 2013). In addition to the

challenges associated with the warming trend, paleoclimate research has demonstrated that the Southwest has experienced drought conditions that are significantly more severe, long lasting, and spatially extensive than anything in the instrumental record (Woodhouse et al. 2010).

This climatic context suggests that planning for drought is necessary to increase the resilience of social–ecological systems in the Southwest. Drought planning in the United States has made strides over the last 20 years, as evidenced by the growing number of tribal, state, local, county, and watershed-scale drought plans (NDMC 2016). However, as of 2015, only 13 of the 47 U.S. state drought plans completed or under development were designated as mitigation-based by the National Drought Mitigation Center (Fu et al. 2013). The limited number of plans that focus on mitigating drought risk suggests that—at least at the state level—drought planning is still primarily focused on responding to the hazard rather than on addressing the underlying conditions that lead to significant impacts when drought occurs. An agreed upon set of drought indicators and a strategy to monitor them is a central feature of a drought plan. Monitoring and routine communication of that information are critical for plans meant to anticipate drought because they allow

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FIG. 1. The study region is shown with the periods of record for National Weather Service COOP network stations indicating the lack of high-quality climate data available on the Hopi reservation (indicated by the red polygon between 111° and 110°W longitude).

resource managers and decision-makers to continually assess conditions and take management and policy actions to mitigate drought impacts. However, in a review of western U.S. state drought plans, [Steinemann \(2014\)](#) found that indicators were often chosen poorly and were frequently not evaluated for their usefulness and that adequate monitoring was often perceived as lacking. Also, in reviewing western U.S. drought plans, [Fontaine et al. \(2014\)](#) report that the absence of indicators and data to support them at temporal and spatial scales that match drought decision-making contexts is a challenge. The absence of indicators and data at the right scale is especially acute for Native American communities in the semiarid U.S. Southwest, where instrumental climate data are sparse ([Fig. 1](#)) and dry conditions are the norm.

Here we report on a collaborative project between the University of Arizona (UA) and the Hopi Tribe Department of Natural Resources (HDNR) to develop a local drought information system—including monitoring, periodic presentation of conditions on the reservation to Hopi drought stakeholders, and a plan for engaging the

Hopi communities about drought—that is responsive to the climate-relevant decisions of tribal leaders and citizens. The project addresses three local problems related to planning for and responding to drought: 1) Hopi reservation lands are poorly monitored (instrumentally) for weather and climate; 2) the drought monitoring component of the existing Hopi drought plan relies on indicators and data that are mismatched in scale and scope to the actual experience of drought in Hopi communities; and 3) on the Hopi reservation there is currently no reliable source for local information about drought conditions.

This work has a local application—a drought information system for the Hopi Tribe—but it also makes a contribution to the broader literature on drought planning, especially in arid and semiarid regions of the world. Our work demonstrates an approach for conceptualizing drought with the affected community first, then developing a plan for monitoring and information delivery that reflects local experiences of and concerns about drought. Typical drought monitoring starts with hydrometeorological data, then considers local impacts

and observations as a secondary means to assess drought conditions (Svoboda et al. 2001). Our approach—driven by the social and climatic context, data constraints, and institutional realities—is to reverse this typical emphasis by placing impacts and locally available observations at the forefront and using available hydrometeorological data as a secondary means to assess drought conditions. This approach recognizes the local nature of a hazard like drought, accepts the limits of existing instrumental data to fully characterize local conditions across heterogeneous landscapes, and emphasizes the value and power of local observations as a source of information for making difficult climate-relevant decisions. Our work, therefore, offers a model for developing a locally responsive drought information system to support community resilience in the face of a socioclimatic hazard like drought.

2. The challenge of monitoring drought to support local decisions

To plan for drought, conditions in the systems most impacted must be well characterized at the scales at which decisions are made and that information must be broadly communicated to impacted stakeholders. Drought is typically characterized by analyzing current hydrological (e.g., snowpack, streamflow) and meteorological (primarily precipitation) conditions in relation to average conditions found in those data. This approach has at least two potential pitfalls. First, it assumes data of sufficient resolution and quality are available to accurately capture drought as it is experienced. Second, as a top-down, climatology-oriented perspective on drought, it provides only limited insight into drought as a hazard and therefore how it may be best planned for and mitigated. To meet the challenges of twenty-first century social and climate complexity, more integrative drought information systems are necessary.

Drought monitoring, planning, and response in the United States have been dominated by a “quasi-scientific management” approach. Scientific management, born from the late-nineteenth- and early-twentieth-century U.S. industrial interest in efficiency and technocratic solutions (Brunner 2010), relies on “science as the foundation for efficient policies made through a single central authority” (Brunner and Steelman 2005, p. 2). Without a national drought policy and without a coherent central technocratic infrastructure for managing drought, the United States has never been capable of implementing a true scientific management approach for drought, though there are characteristics of scientific management in the current system. Drought in the United States is characterized using indices derived

primarily from hydrometeorological data that are often not available at spatial and temporal scales adequate to inform regional and local drought decisions. The current system is largely embodied by the U.S. Drought Monitor (USDM), which is now used to directly inform important policy decisions like which regions of the United States are eligible for drought-relief funding (Farm Service Agency 2014). The USDM process recognizes the complexity of characterizing drought by blending multiple data sources and indices, relying on the expert judgment of the weekly author, and allowing for review by approximately 350 local, regional, and national experts before it is released each week (Wood et al. 2015, p. 1642). In practice, however, the USDM is primarily the product of a small group of scientists assessing available data to arrive at a characterization of drought that has important policy implications. Steinemann (2014, p. 844) found ambivalence with the USDM as a means of communicating drought conditions among state-level drought planners, many of whom did not use it or found it failed to adequately capture local conditions or provide locally useful information.

The need for monitoring the *impacts* of drought (not simply hydrometeorological indicators) as a means to more nuanced and policy-relevant drought characterization has been noted by drought experts, but the challenges associated with measuring impact are generally cited as a barrier to implementing such a system (see, e.g., Wilhite and Glantz 1985, p. 119; Hayes et al. 2011, 486–487; Meadow et al. 2013). Much of the problem with incorporating drought impacts into characterizations of drought is rooted in the complexity of drought as a hazard and the fact that as a practical matter, a precise, common definition of drought is essentially impossible to develop (Kallis 2008; Redmond 2002; Wilhite and Glantz 1985). Despite the commonly used definitions of meteorological, agricultural, and hydrological drought (Mishra and Singh 2010; Wilhite and Glantz 1985), there is little uniformity or consensus on how to define drought as it more broadly impacts social systems. In the literature “socioeconomic drought” is commonly discussed as a category, but it is essentially a catch-all phrase for dry conditions that impact anything people care about, which arguably would be any drought (Kallis 2008, p. 87). In many ways, the simplest drought definitions—for example, “when precipitation is insufficient to meet the needs of established human activities” (Hoyt 1936)—allow for more context-sensitive considerations of what makes drought socially relevant (Wilhite and Glantz 1985, p. 116).

Here we describe a strategy for developing a local drought information system that is based on an assessment of how drought is experienced by Hopi citizens and

resource managers; can incorporate local observations of drought impacts and more conventional indicators available locally like precipitation, groundwater levels, and the flow of persistent springs; and brings together local (HDNR and Hopi citizens) expertise with conventional science-based observations (currently via UA researchers). Our goal is to design a system that harnesses available information to inform tribal resource managers, political leaders, and citizens about drought conditions, but that also engages these local drought stakeholders in observing, thinking about, and helping to guide planning for drought. If fully implemented, this system will also provide a mechanism for the HDNR and the Hopi Tribe—if they so choose—to share their characterization of drought conditions across tribal lands with other local and state drought stakeholders as well as USDM authors.

3. Project background and methods

Our work began informally in 2009 when leadership from the HDNR contacted two of the authors (Ferguson and Crimmins) with concerns about drought conditions on the Hopi reservation. Initial discussions between the UA team and the HDNR focused on the dearth of climate data across the Hopi reservation and surrounding lands, the kinds of regional climate information that is available, and HDNR concerns about severe drought impacts across the reservation over the preceding decade. Through this process the UA team recognized that the drought monitoring strategy embedded in the existing Hopi drought plan was not useful and therefore not used, leaving them with little information to provide tribal leaders and citizens about drought conditions across the reservation. On-reservation drought monitoring essentially was not being carried out and the tribe was relying on regional drought information (e.g., the USDM) that the HDNR staff felt did not accurately represent local conditions.

By the fall of 2009 the UA and HDNR had agreed to collaborate to address the drought monitoring problem facing the tribe. Our collaboration was guided by the principles of transdisciplinary research: the problem we scoped was socially relevant and too complex to be easily addressed by either the HDNR or researchers alone, was based on collaborative work between interdisciplinary UA researchers and nonacademic partners in the HDNR, had as a central goal mutual learning, and ultimately sought the integration of different types of knowledge (Weichselgartner and Truffer 2015; Jahn et al. 2012).

The overarching goal of the project was to help the HDNR develop a local drought information system that was feasible within the constraints of existing human and

financial resources and could yield information useful for tribal leaders, resource managers, and citizens. The primary data collected and reported here came from two sources: interviews, focus groups, and participant observation within the HDNR and semistructured interviews with non-HDNR Hopi drought stakeholders.

The project design was based on rapid appraisal (Beebe 1995) because 1) we needed a systems view of drought as a modern social phenomenon on the Hopi Reservation (e.g., the biophysical and social impacts, tribal decision-making, and the role of the HDNR); 2) at the outset little information about the full system existed, so we needed to quickly generate as much information as we could; and 3) we knew that we would need to continually iterate what we found and refine our understanding as we proceeded (Beebe 1995, p. 42).

Data collected within the HDNR focused on building our understanding of how the organization operated, what information is generated, and how information is used so that the local drought information system we eventually developed would have the best chance of matching the institutional environment of the HDNR. To do this, we generally followed Taylor's (1991, p. 218) "information use environment" framework, which he defines as "the set of those elements in an organization that a) affect the flow and use of information messages into, within, and out of any definable entity; and b) determine the criteria by which the value of information messages will be judged." We therefore focused on understanding what affects the circulation and use of information into, within, and out of the HDNR and tried to understand how that information will be seen as valuable or not within both the HDNR and with the broader tribal leadership.

The goals for the interviews with non-HDNR drought stakeholders were 1) to better understand how drought is experienced on Hopi lands, 2) to identify sources and types of information people want or currently consult, and 3) to understand the expectations citizens have of the tribal government and community in terms of monitoring and planning.

Finally, a significant element of the project's design was the addition of a community member researcher as the onsite project lead for approximately 18 months (2013–14). Anna Masayesva is a member of the Hopi tribe who had previously worked within the office of the tribe's vice chairman, had worked for the HDNR, and—at the time the bulk of the research reported here was taking place—was a member of her community's water sanitation committee. Masayesva provided an expert insider perspective and became the integrator of information as we proceeded to pilot the Hopi quarterly drought summary described in section 6 below.

TABLE 1. Sectoral breakdown of non-HDNR interviews.

Farmer	9
Village administration	7
Rancher	6
Health	4
Water	4
Transportation	2
BIA administration	1
Law enforcement	1
Wildfire	1

We carried out a total of 31 semistructured interviews: 10 with members of the HDNR staff (essentially everyone who had some duties related to drought) and 21 non-HDNR Hopi drought stakeholders. For the 21 non-HDNR interviews, we used a purposive sampling strategy (Teddlie and Tashakkori 2009) to talk with drought stakeholders from across a spectrum of Hopi society: farmers and ranchers; officials from public health, law enforcement, transportation, wildfire management, and the U.S. Bureau of Indian Affairs (BIA); and village water resource administrators. Most of our non-HDNR interviewees represented more than one sector. For example, several people have paid jobs on the reservation but are also farmers and/or ranchers. Table 1 shows the sectoral breakdown of our non-HDNR interviewees.

At the outset of the formal project, we secured a permit from the Hopi Cultural Preservation Office to proceed with our research. A condition of our research permit was that we would not record any interviews conducted outside of the HDNR, relying instead on detailed notes taken during interviews. To ensure the notes sufficiently captured the interviews, we first developed a simple 10-question semistructured interview protocol (see supplemental materials). Then the researcher who carried out the non-HDNR interviews (Masayessa) took careful notes during the interviews, reviewed and amended them immediately after each interview, and contacted the interviewee again if clarification was needed. Interviews with HDNR staff were recorded and transcribed (as allowed by our tribal research permit). Focus groups were not recorded, though team members took detailed notes and collectively summarized the main points immediately following them. All interview and focus group notes, transcripts, and relevant tribal documents¹ were analyzed using an ethnographic content analysis (ECA) approach (Altheide 1987). ECA allowed us to reflexively and

iteratively review and rereview the material we were gathering in a process of ongoing discovery and comparison of the themes that emerged to ultimately create a grounded narrative about contemporary Hopi drought useful for developing a local drought information system. Qualitative analysis software (MAXQDA and Dedoose) was used to organize, code, sort, and query all the data we gathered. Coding of the HDNR interviews was carried out by Meadow. Masayessa did initial thematic groupings of the non-HDNR interview data, which was then systematically coded by Ferguson. To further ground and help validate findings, we periodically briefed HDNR leadership and staff on our progress and received their feedback and additional insights.

4. Study context

a. Hopi governance

The Hopi tribe is a sovereign, federally recognized Native American community whose lands are on the Colorado Plateau in northeastern Arizona (Fig. 2). According to the 2010 census, the current population of the reservation is approximately 7200 (Arizona Rural Policy Institute 2016). The tribe is a confederation of 12 semiautonomous villages with a central government formed after the U.S. Congress passed the 1934 Indian Reorganization Act, which recognized tribal self-governance. Although several villages send no representatives to serve on the tribal council and the constitution has been contested by village leaders for generations, in its current form it “is best conceived, as a contract between the [constitutionally] specified, self-governing villages...embod[y]ing a necessary compromise by these once independent villages” (Sekaquaptewa 2000, p. 765). The governance in place at Hopi is complex, but in the modern era “Hopi people look to the tribal constitution, the tribal council, and the tribal courts to lobby for the needs of the villages and Hopi people, to provide basic governmental services...and to resolve disputes” (Sekaquaptewa 2000, p. 765). The governance of Hopi communities is relevant to our goal for developing a local drought information system because the HDNR is an agency of the central tribal government and therefore not directly connected to village governance. One aim of the drought information system we describe in section 6 is to use that system as a means to increase engagement between the HDNR and the villages about drought conditions.

b. Physical geography

The reservation covers approximately 2500 mi² in two parcels: the main reservation is made up of three mesas

¹ Documents we analyzed included the existing tribal drought and integrated resource management plans, tribal drought declarations, tribally developed information about range conditions, and several years of BIA range conditions surveys.

FIG. 2. The lands of the Hopi reservation (indicated in gray). Figure courtesy of Jeremy Weiss, University of Arizona.

and surrounding lands and the Moenkopi District, which is approximately 40 mi west of the main reservation near the town of Tuba City, Arizona (Suderman and Loma'omvaya 2001, p. 14). Reservation lands range from approximately 4500 to 7500 ft above sea level. The climate of the reservation is typical of the high deserts in the Southwest. Average annual rainfall across the whole reservation is approximately 8.5 in., with higher-elevation areas typically receiving more and lower-elevation areas receiving less. Temperatures also vary with topography and throughout the year, but the annual average high temperature for the reservation is about 68°F, with an annual average low temperature of about 37°F. The instrumental record for the region shows that droughts were common over the past 120 years, with a pronounced drought at the end of the nineteenth century and severe drought in the 1950s and early 1960s and again in the late 1990s through to the end of the record in 2015.

c. Land use

The 2012 U.S. Census of Agriculture shows the entire 1.6-million-ac. Hopi reservation as farmland, with the vast majority of that being rangelands and only 1688 ac. in cropland (National Agricultural Statistics Service 2014). Hopi farming is composed of small family fields—typically <10 ac.—that are almost entirely rain fed (Singletary et al. 2014, 9–13). Of the 1688 ac. in croplands, only 279 ac. are designated as irrigated (National Agricultural Statistics Service 2014).

The Hopi have lived on and around current reservation lands for at least a millennium (Sekaquaptewa 2008, p. 27; Singletary et al. 2014, p. 16) and are descended from populations dependent on maize agriculture since at least AD 700 (Adams 1979, p. 285). The terraced fields near the Hopi village of Bacavi are believed to have been farmed since at least AD 1200 (Wall and Masayesva 2004, p. 437). Dryland farming, which is central to Hopi life, is rooted in their origins in this world, with corn described as “the soul of the Hopi people” (Singletary et al. 2014, p. 1). Corn is crucial to Hopi ceremonial life, but it is also a practical part of modern Hopi diet and social life. Cultivars of corn are highly adapted to the semiarid climate of the region. As Wall and Masayesva (2004, p. 440) note, “seeds used now to plant blue, red, white, and yellow Hopi corn arise from a lineage that reaches back for many centuries.”

Livestock was introduced to the region with the Spanish in the sixteenth century (Pavao-Zuckerman and Reitz 2006); sheep were the primary stock for approximately 350 years. In the early twentieth century cattle began to dominate Hopi ranching. In the 1930s the BIA encouraged and supported ranching by digging wells, installing windmills, and building surface water impoundments across the reservation for watering livestock (Singletary et al. 2014, p. 22). For most Hopis, ranching and farming are not primarily economic activities, with 76% of producers on the reservation

yielding annual sales in 2012 of less than \$5000 (National Agricultural Statistics Service 2014).

Consumptive water on the reservation comes almost entirely from subsurface aquifers (Suderman and Loma'omvaya 2001, 30–37). Although current per capita water use on the reservation is estimated to be only 37 gallons per day, there is concern on the reservation that population increases, higher water consumption by modern houses, and commercial development will increase that rate enough that consumptive use will outstrip reliable supply by the mid-twenty-first century (Suderman and Loma'omvaya 2001, p. 33). Although impounded surface water is currently used only for watering livestock (from precipitation captured in earthen dams) and for irrigating small farm plots near the village of Moenkopi, the loss of surface water due to drought conditions impacts Hopi groundwater supplies as described in more detail in section 5a. To ensure reliable water for future generations, the tribe has been in negotiations to settle their claim to the Little Colorado River for decades, but a contentious settlement tentatively agreed to by all the parties in 2012 failed to be passed by the U.S. Congress in 2012 (Lee 2013, p. 643).

5. Results

The HDNR–UA collaboration was designed to develop a drought information system that could yield information useful for tribal leaders, resource managers, and citizens and that is feasible within the constraints of existing human and financial resources. Here we summarize some of the key considerations for such an information system based on interviews with community drought stakeholders as well as interviews, focus groups, and participant observation with HDNR staff and our analysis of tribal documents.

a. Contemporary experiences of drought

Through our interviews with community drought stakeholders, we gathered information about impacts that people were directly attributing to drought as well as many secondary or tertiary impacts. Many of these, for example, increased soil erosion across many of the range units, are difficult to ascribe solely to drought since land use clearly has played a role. Our goal was to understand how drought was experienced so we could develop an information system that allowed for ongoing community dialogue about conditions that can contribute to a more community-based planning effort. Therefore, we did not try to parse impacts that could definitively be attributed to drought, instead focusing on local understandings and experiences of drought. Table 2 synthesizes the major concerns we heard both from our

HDNR partners as well as the Hopi drought stakeholders we interviewed. Although most of the drought concerns are related to ranching and farming, we found no evidence that recent drought conditions have impacted the primary food sources for citizens. Ranching and farming, though important socially and culturally, typically only supplement store-bought foods.

1) RANCHING

The primary drought impacts reported by ranchers are obvious: loss of forage, increased soil erosion, and loss of surface water developed for livestock. We also found two less obvious, but socially important, ways that drought impacts on ranching affect Hopi society more broadly. First, one of the most commonly cited responses to the current drought (nine of the 21 non-HDNR interviews) was hauling water for livestock on the ranges because surface water impoundments normally filled by precipitation were absent. Water hauling as a drought response is costly for the rancher (in terms of fuel and time) as well as the tribal government and community water systems because it strains groundwater resources and the infrastructure that supports them (i.e., windmills and well pumps). Second, we found that the loss of surface water for livestock has spurred local conflicts. As one HDNR land manager told us, “I noticed every year about June or July we fight over water—everyone wants to protect their own distribution area, but people go out in the middle of the night and take water.” Over the last several years, the HDNR and Hopi Police have frequently responded to complaints of neighboring Navajo ranchers filling their water tanks at Hopi wells. Five of the 21 non-HDNR interviewees also mentioned that conflicts over ranchers hauling water for livestock were a concern they have had with recent drought conditions.

2) FARMING

The most common drought impacts on farming and gardening we recorded were reduced crop yield or crop failure (seven of 21 non-HDNR interviewees), drought causing poor soil conditions (four of 21 non-HDNR interviewees), and issues with wildlife trespass in cultivated fields or gardens that were attributed to drought (three of 21 non-HDNR interviewees). In addition to direct impacts, we found that farmers in particular discussed drought impacts on Hopi culture. These ranged from simply not having enough crops for ceremonial purposes to a creeping sense of cultural apathy as some Hopi farmers perceive the persistent drought as a failure of Hopi traditions meant to bring precipitation. We also found concern about loss of transmission of cultural knowledge that would usually come from multiple generations working in the fields together. One farmer

TABLE 2. Summary of current concerns about drought on the Hopi reservation.

	Primary impact	Indirect impacts
Ranching	Loss of forage for livestock	<ul style="list-style-type: none"> • High costs of supplemental feed • Increased erosion
	Loss of surface water for livestock	<ul style="list-style-type: none"> • High costs (financial and time) of hauling water • Conflicts with Navajo ranchers • Overpumping of wells on ranges is causing damage to pumps, windmills
	Increased erosion and accumulation of sand dunes	<ul style="list-style-type: none"> • Reduced carry capacity of ranges • High costs of repairing and maintaining infrastructure (e.g., fences, roads)
Farming	Reduced crop yields and complete crop failures	<ul style="list-style-type: none"> • Conflict (e.g., theft of crops) • Changes in traditional farming techniques • Cultural apathy • Health impacts from less exercise • Loss of transmission of cultural knowledge • Threats to Hopi drought-resistant seed stock • Impacting ceremonial life (loss of traditional foods for weddings, births, etc.)
Ecosystems	Loss of surface water for wildlife	<ul style="list-style-type: none"> • Reduced number of prey species • More wildlife encounters with people
	Increased presence of invasive species	<ul style="list-style-type: none"> • Many invasives inedible for stock and wildlife
	Reduced availability of edible, medicinal, other traditional plants	<ul style="list-style-type: none"> • Loss of transmission of cultural knowledge • Health impacts from loss of medicinal plants • Health impacts from loss of nutritious wild plants
Water resources	Reduced flow of traditional springs	<ul style="list-style-type: none"> • Villages losing traditional water sources
	Reduced recharge of aquifers	<ul style="list-style-type: none"> • Impacting irrigation practices at Lower and Upper Moenkopi • Concern over loss of small seeps and springs throughout reservation that provide water for stock, wildlife
	Reduced flow in ephemeral washes	<ul style="list-style-type: none"> • Loss of traditional fields • Some farmers starting to haul water

discussed his concern about losing local corn cultivars, as repeated crop losses have reduced local strains passed down through Hopi families for generations. See [Rhoades \(2013\)](#) for an in-depth study of the impacts of drought on modern Hopi agriculture.

3) ECOSYSTEMS

Many of the concerns about how ecosystems are impacted by drought closely relate to the ranching and farming concerns described above (e.g., increasing erosion, loss of surface water, decreased vegetation). We also found some concern that loss of surface water and vegetation across the reservation is responsible for declining numbers of prey, in particular fewer rodents for eagles (an important cultural resource). There is also concern about reduced abundance of culturally important plant species used for food, medicines, ceremonies, and crafts. Increased abundance of invasive plant species is also perceived to have come about since the beginning of the current drought. In particular, Russian thistle was repeatedly mentioned as a problem. As one HDNR manager told us, “the Russian thistle is getting bad and big—it’s like they are [absorbing]

all our moisture.” Finally, both farmers and HDNR staff reported an increase in the number of wildlife trespass incidents, particularly in farm fields and gardens.

4) WATER RESOURCES

Although potable water supplies for the villages are drawn from deep aquifers that are not tightly coupled with seasonal or annual precipitation, there are water resources challenges associated with drought on the reservation. Across the landscape, springs have historically been abundant and reliable. Seven of the 21 non-HDNR interviewees expressed concern that the drying of springs—particularly those that have been used by villages for generations—over the last two decades is tied to drought conditions. There is considerable political debate about the impact that an economically important local coal mine’s² use of groundwater is having

²The Hopi tribe receives approximately 80% of their annual budget from coal royalties, bonuses, and water fees paid by the Peabody Company, who run the Kayenta Mine ([Hurlbut et al. 2012](#)).

on springs. Groundwater is closely monitored for impacts from the mine, though those data are contested, so it is difficult to assess exactly what is driving the drying of springs. Less contentious is the relationship between some historically reliable seeps and springs that are tied to shallow aquifers and unlikely to be impacted by groundwater pumping. There have also been impacts on farming, as some ephemeral washes on the reservation have remained dry for multiple seasons. These alluvial plains have historically been ideal farm lands because periodic flows deliver nutrients and relatively high soil moisture.

b. Drought decision-making

At the scale of the tribal government, drought decisions are limited to a few possible actions, but they have the potential for substantial impact on Hopi people now and in the future. The tribe periodically restricts open fires when conditions are dry, can reduce the number of livestock on the ranges, and can completely close ranges and restore them if the conditions warrant such action. The tribe is also working to settle surface water rights so that the Hopi people will have reliable water supplies beyond their current groundwater systems. Additional tribal responsibilities include managing and maintaining infrastructure that is impacted by dry conditions (e.g., windmills and wells, roads that are damaged by blowing sand, fences that are periodically buried by dust storms), all of which can be costly. Decisions about prioritizing repair and replacement of infrastructure would ideally be informed by better characterization of drought on the reservation. The need to make these types of decisions is the main reason the HDNR wants improved drought-monitoring information.

In addition to government-level decisions, there are many short-term, drought-related decisions being made at the household scale. Ranchers are almost annually confronted with the difficult decision of whether to divest themselves of livestock, continue to haul food/water, or simply hope for the best and leave their animals to fend for themselves on the ranges. Farmers in our study reported altering their practices by planting earlier, later, or more frequently as soil moisture dictates, reducing field size, or hauling water in extremely dry times in order to provide moisture to individual seedlings.

Although drought decision-making related to farming and ranching in the United States is typically thought of in terms of seeking relief funds from government programs, our research shows that this is negligible on the Hopi reservation. Between 1995 and 2012, Arizona farmers and ranchers received a total of about \$94.3 million in USDA disaster payments, primarily from

drought. Of that \$94.3 million, less than \$28 000 went to farmers and ranchers in the Hopi zip code, with the average individual disaster payment being less \$200 over the entire 17-yr period.³ An official with the HDNR confirmed the extremely low rates of participation in USDA disaster-relief programs, noting that the majority of Hopi ranchers keep small herds (5–10 head) and only rarely file for relief funds.

The longer-term decisions confronting Hopi leaders and citizens are much more complex. When asked about best ways to cope with drought over the long term (i.e., if conditions remain warmer and drier for the foreseeable future), our interviewees discussed a range of potential challenges, including drastic livestock reductions, shifting from dryland farming to irrigated agriculture, imposing greater costs on water users, and developing a more systematic seed conservation program. These significant decisions will require political leadership, cooperation among the villages, and better environmental status information than the HDNR currently has.

c. Natural resource planning context

Current and future decisions regarding drought response and adaptation will be made in the context of traditional Hopi values. The tribal council approved an Integrated Resource Management Plan (IRMP) in 2001 that states that “the Hopi Tribe, in the interest of Hopi values shall reaffirm these stewardship responsibilities, *Tutavo*, which are rules by which the Hopi are to utilize natural resources and provide conservation efforts for environmental health” (Suderman and Loma’omvaya 2001, p. 3). The plan identifies the common interests of the Hopi people to be foremost in natural resource management decision-making (Suderman and Loma’omvaya 2001, p. 3). An HDNR resource manager in an early interview told us that “we’re not going anywhere, so we need to manage this land as best we can.” The overall goal is to maintain Hopi lands in such a way that they will remain useful and usable to support Hopi lifeways in perpetuity.

As a practical matter, decisions about which lifeways are most important and how to balance competing priorities for limited resources in the context of drought conditions are often reduced to conflicts over the primary land uses on the reservation. As noted in the 2001 IRMP, “the primary conflict is between livestock grazing and other land uses, specifically wildlife habitat,

³ The relief data presented here are based on the Environmental Working Group’s Farm Subsidy database available at <http://farm.ewg.org>. That database is compiled from USDA data on annual subsidies paid through their various programs.

TABLE 3. Potential response and mitigation actions for various drought stages from the 2000 Hopi drought plan.

Drought stage	Assessment index category	Assessment index	Index rating for area of interest	Potential response and mitigation actions for various drought stages
Mild drought	Meteorology	Climate % normal SPI PDSI	Near normal Near normal 0 to -0.99 -1.00 to -1.99	Initiate public awareness program and increase frequency of monitoring activities
	Agriculture/range	Soil moisture Vegetation index Range condition	Near normal Near normal (41%–70% relative greenness) Good (50%–75% climax)	Evaluate use of less productive fields, maintain forage reserve, and ensure rotation of livestock
	Hydrology	Standard soil moisture index (SSI) Surface water storage Groundwater supply–demand ratio	0 to -0.99 Near normal Good (110%–130%)	Increase frequency of monitoring activities
Moderate drought	Meteorology	Climate % normal SPI PDSI	Below normal Below normal -1.00 to -1.49 -2.00 to -2.99	Increase public information activities by relaying status of water supply and measured impacts, and notify drought relief agencies of potential need
	Agriculture/range	Soil moisture Vegetation index Range condition	Near normal to below normal Below normal (1%–40% relative greenness) Fair to good (25%–75% climax)	Increase soil moisture and vegetation monitoring activities, haul water, improve water distribution, adjust livestock numbers, and avoid unnecessary impacts to wildlife by controlling livestock access to sensitive areas
	Hydrology	SSI Surface water storage Groundwater supply–demand ratio	-1.00 to -1.49 Near normal to below normal Fair to good (90%–130%)	Rehabilitate water storage structures, springs, and wells, seek voluntary limits on nonessential use, and require audits for high-volume users
Severe drought	Meteorology	Climate % normal SPI PDSI	Below normal Below normal -1.50 to -1.99 -3.00 to -3.99	Increase community involvement and public education to establish importance of operational modifications within impacted sectors to protect human health and the environment, and streamline relief application and the funding process
	Agriculture/range	Soil moisture Vegetation index Range condition	Near normal to below normal Below normal (<40% relative greenness) Poor to fair (0%–50% climax)	Request financial assistance, reduce livestock numbers, lease additional grazing areas, improve water conveyance efficiencies, and begin conjunctive uses of surface and groundwater
	Hydrology	SSI Surface water storage Groundwater supply–demand ratio	-1.50 to -1.99 Near normal to below normal Fair (90%–110%)	Implement water use schedule for users of village water supplies, stockpile well equipment in case of failure, prohibit new water connections, and mandate commercial and industrial reductions in water use

TABLE 3. (Continued)

Drought stage	Assessment index category	Assessment index	Index rating for area of interest	Potential response and mitigation actions for various drought stages
Extreme drought	Meteorology	Climate	Below normal	All of the above severe drought actions, plus actively pursue financial assistance to reduce drought impacts
		% normal	Below normal	
		SPI	−2.00 or less	
	Agriculture/range	PDSI	−4.00 or less	All of the above severe drought actions, plus increase enforcement activity in regard to range codes and permit condition violations
		Soil moisture	Below normal	
	Hydrology	Vegetation index	Below normal (<40% relative greenness)	Install emergency wells to support agricultural and livestock needs, ration water through use of water trucks, allocate water to commercial uses, and establish monthly residential use
		Range condition	Poor to fair (0 to 50% climax)	
		SSI	Poor to fair (0 to 50% climax)	
		Surface water storage	−2.00 or less	
		Groundwater supply–demand ratio	Below normal	
			Poor (<90%)	

farming, rangeland plants and gathering, and wetlands plants and gathering” (Suderman and Loma’omvaya 2001, p. 4). Ranching is currently the dominant land use, with approximately 88% of reservation lands utilized as range for livestock, though as of the early 2000s, only about 5% of Hopi people had grazing permits (Suderman and Loma’omvaya 2001, p. 11).

The Hopi tribe adopted a drought plan in 2000, though we found that it has not been fully implemented. A significant barrier to having the drought plan used operationally is the complex monitoring and trigger system that inspired our HDNR–UA collaboration. The plan, developed by an off-reservation environmental consulting firm, characterizes drought according to conventional climatological definitions: meteorological, agricultural, and hydrological. There is also some discussion of socioeconomic drought vulnerabilities, but ultimately the monitoring and trigger protocol relies on the three conventional drought definitions. As the HDNR is currently constituted, there are not sufficient data available to support the identified monitoring categories and limited data handling capacity even if such data did exist, so in practice drought is nearly impossible for the tribe to declare by following the standards set out in the plan. In effect, drought decision-making at Hopi is not informed by the drought plan that is ostensibly meant to guide those decisions. Table 3, which is excerpted from the 2000 drought plan, shows the stages of drought, their triggers, and potential responses.

d. HDNR information use environment

To be effective, a local drought information system—or any other decision support system—must be responsive to the technical and human resource capacity constraints of those who develop the information as well as those of the intended users (Dilling and Lemos 2011; Moss et al. 2014). As we found with the Hopi drought plan’s monitoring protocol, when the decision support system does not match local technical capacity, it becomes impossible to use effectively. Our assessment of the information use environment of the HDNR yielded several insights about how to develop an information system that better fits the Hopi context.

We found that some of the most important resources within the HDNR are the technicians who work for multiple divisions within the agency. They regularly (typically on a monthly basis) produce information about environmental conditions across the reservation. In particular, the Office of Range Management (ORM), the Office of Hopi Lands Administration (OHLA), and the Water Resources Program (WRP) each collect

information likely to be useful for characterizing drought conditions.

Four ORM range technicians (though staffing levels fluctuate) continually assess the status of the 52 range units on the reservation and develop monthly reports on conditions within each unit. They also conduct annual range utilization surveys that provide a snapshot of forage conditions in each of the range units. Their reporting is primarily done to support stocking rate decisions, but it also supports decisions about infrastructure repair, overgrazed units, and trespass issues. ORM technicians also monitor a series of simple rain gauges placed in range units across the reservation.

The OHLA was developed as part of the resolution of the generations-long Navajo–Hopi land dispute (see, e.g., [Brugge 1999](#)) to administer what are called the Hopi Partitioned Lands. Four OHLA technicians, like their ORM colleagues, are continually out on the landscape and able to monitor evolving conditions, though their primary mission is to assure compliance with a variety of tribal land-use regulations. In the course of their regular duties, both the ORM and OHLA technicians are in routine contact with citizens across the Hopi reservation. As a result, they are an important conduit of information into and out of HDNR.

Water resources management is somewhat complex on the Hopi reservation. There are a total of 15 public water supply systems on the reservation maintained by seven independent village water committees, the BIA, and the Hopi Tribe Department of Facilities Management ([Hopi Tribe 2000](#), Attachment B, p. 13). The HDNR Water Resources Program does not manage any of the community water systems, but they do monitor surface water and groundwater across the reservation, including levels in a series of shallow wells and flow rates of a network of springs across the reservation, all of which can provide potentially useful information to assess drought conditions.

Finally, although farming is central to Hopi life, the HDNR has little to do with monitoring or managing farmlands. Ideally, a fully fledged Hopi drought information system will engage local farmers to both contribute and utilize the information produced. This is discussed more in [section 6](#).

We found that the technological limits of the HDNR—primarily a slow Internet connection and limited data-handling infrastructure—means that a local drought information system will require that relatively simple inputs collected across the HDNR (e.g., paper data sheets are still the norm), and eventually from the communities, will need to be compiled and synthesized, ideally by a single HDNR staff member. For distribution of information, we found that e-mail is a common and

useful way to share information within the HDNR as well as with community members.

6. Elements of a local drought information system

Based on the information presented above, we have been working with the HDNR on development and implementation of a drought information system that is capable of communicating drought conditions in local terms, but—perhaps as important—that can enable more communication between the HDNR and Hopi communities. The key elements of this system are that it 1) is based on information that reflects how drought is experienced by Hopi citizens and resource managers, 2) utilizes local observations of drought impacts either already collected for other purposes or that can be contributed by local observers (e.g., from agriculture, ecosystems, and culturally important uses of the land) as well as more conventional indicators available locally (e.g., precipitation, relevant hydrologic information), 3) brings together local expertise with conventional science-based observations, and 4) is capable of both informing and engaging a wide variety of local drought stakeholders (e.g., resource managers, political leaders, farmers, ranchers, community water managers, health professionals).

Our interviews with non-HDNR drought stakeholders revealed that many people (11 of 21) look to the tribal government for drought information, but most want more and different kinds of information about drought from the tribe. Some people want specific information (e.g., which windmills are operational on the ranges), but the majority (13 of 21) want the tribe to facilitate more community education about drought on the Hopi reservation. Therefore, we have been focused on developing a system that delivers information about drought conditions but that also can be a means for engaging stakeholders across the reservation.

Our vision is a local drought information system that incorporates observations that the community feels are relevant to drought status. In practical terms, the first step in developing the system is to routinely collect and synthesize the drought-relevant information from within the HDNR described above and distribute it to drought stakeholders across the reservation. In 2014 we worked with the HDNR to produce and distribute four quarterly Hopi drought summaries. In its initial form, the drought summary was a two-page PDF distributed via e-mail within the Hopi tribal government and to some non-HDNR stakeholders. The first page—produced by the HDNR—presented local information about range conditions and precipitation recorded by rain gauges located on the reservation. The second page—produced

by our UA team—contextualizes the local conditions with regional climate data and information, including recent temperature and precipitation data as well as the most recent USDM map. Even in this bare-bones form, this summary of drought conditions was used by the Hopi tribe to inform a decision in late October 2014 to impound some livestock on ranges on a part of the reservation shown to be in poor condition in the July–October 2014 drought summary.

Ideally, this type of drought summary will grow over time to include all the relevant information HDNR technicians already collect (as described in [section 5d](#)), but will also expand to include seasonal reports about crop conditions by farmers, reports from community water systems about water hauling, and any other drought-relevant information the HDNR or villages choose to routinely contribute. Our work so far suggests that there are willing contributors to and consumers of this kind of qualitative summary of recent conditions on the reservation.

Development of this information system is ongoing. As of spring 2016, the HDNR–UA team is working on a plan to collaboratively reach out to the Hopi villages to begin engaging them about the future of a local drought information system. Our immediate goals are to 1) share what we have learned so far in the HDNR–UA collaboration reported here, 2) gather feedback on the idea of a routine drought summary document similar to the four we produced in 2014, and 3) identify key partners outside of the HDNR who are interested in collaborating on the next stages of the information system envisioned here.

7. Conclusions

The local drought information system we describe here and the process we used to arrive at its development are an experimental solution to a set of challenges rooted in the basic fact that drought is a complex hazard. A scientific characterization of drought—particularly when data of sufficient spatial and temporal resolution do not exist—is always going to be limited in its ability to provide decision-makers and citizens the information they need to plan for an uncertain future. The local drought information system we are trying to build with our Hopi collaborators is meant to provide tribal leaders, HDNR managers, and citizens with information about current conditions and a platform to facilitate dialogue about drought on Hopi lands. This work contributes to a larger conversation among researchers, natural resources managers, and decision-makers globally about how to best conceptualize drought so that it can be better planned for and the impacts better

mitigated. A recent review by [Bachmair et al. \(2016\)](#) points to a significant gap between how drought is characterized by conventional drought indicators and how drought is experienced locally. They note that “citizen science initiatives and other social learning approaches that explore drought framing... offer opportunities to explore multiple understandings of drought impacts and improve indicator design and use” ([Bachmair et al. 2016](#)). Our work represents a transdisciplinary example of just this kind of effort. There are numerous challenges associated with including drought impacts observations into an overall drought-monitoring strategy ([Meadow et al. 2013](#); [Bachmair et al. 2016](#)), but our approach of partnering directly with the management agency responsible for drought monitoring and planning was aimed at limiting these challenges by codeveloping a drought information system that is flexible enough to integrate different kinds of data and information within the specific resource constraints and decision contexts of the community meant to use the system.

To date, our work has yet to directly tackle the hard questions about which indicators to use in a revised Hopi drought plan or which triggers make sense for particular actions by the tribe. This local drought information system is, however, ideally suited to helping facilitate discussions about those decisions among tribal leaders, the HDNR, and citizens. [Steinemann \(2014, p. 845\)](#) found that western state drought planners preferred having the flexibility to ground assessments with “hard triggers” [e.g., a particular standardized precipitation index (SPI) value], but also shade those assessments with “soft triggers” or nuanced assessments of drought conditions. A revised Hopi drought plan that relies on a simple hard trigger—for example, 6-month SPI based on gridded regional data—but that heavily values a soft trigger based on the local drought information system may be a reasonable solution when the time comes.

Our work demonstrates the complex nature of drought on the Hopi reservation. The topography means that local microclimates are an important feature of the Hopi landscape, and the ways that dry conditions impact the land are dependent on use and location. As [Dietz et al. \(2003, p. 1908\)](#) note, “highly aggregated information may ignore or average out local information that is important in identifying future problems and developing solutions.” Our work is meant to solve the challenges confronting the HDNR and the Hopi tribe more broadly, but it is also an attempt to implement a system that makes local information primary and larger-scale data secondary. Future work is needed to assess whether our approach is successful in helping the Hopi Tribe better plan for future droughts. Although this

work is tied to a specific geography and sociocultural context, the problems experienced by the Hopi tribe are not unique. Replicating our approach in other regions with communities with different social, economic, and cultural will be the best assessment of whether this kind of locally driven integrated drought information system is broadly applicable.

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