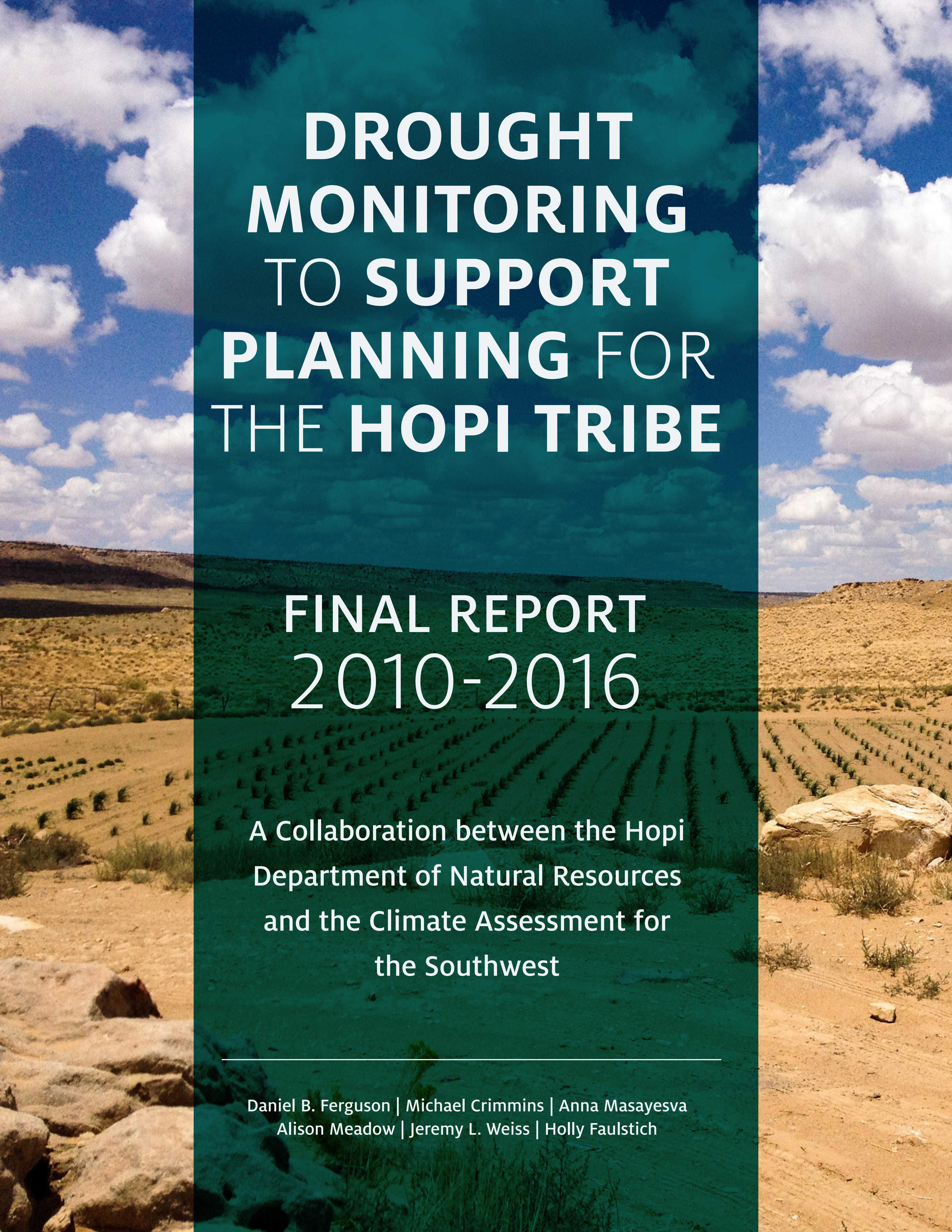

DROUGHT MONITORING TO SUPPORT PLANNING FOR THE HOPI TRIBE

FINAL REPORT 2010-2016

A Collaboration between the Hopi Department of Natural Resources and the Climate Assessment for the Southwest

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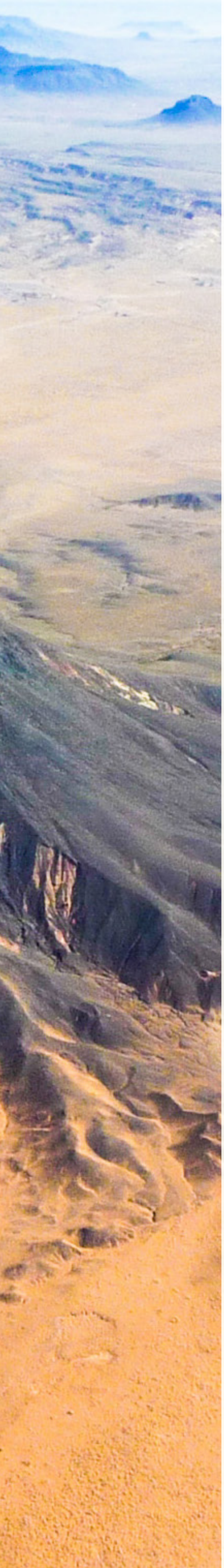


AERIAL PHOTOGRAPH OF THE HOPI BUTTES AREA. PHOTO CREDIT: JON MASON AND JODI NORRIS

OVERVIEW OF THIS REPORT

The six sections of this report represent a summary of much of the work that the University of Arizona's Climate Assessment for the Southwest (CLIMAS) research team has carried out since our collaboration with the Hopi Department of Natural Resources (DNR) began formally in 2010.

Section 1—Project Overview provides a short description of how the CLIMAS/Hopi DNR collaboration came about and a summary of what the work has been focused on.

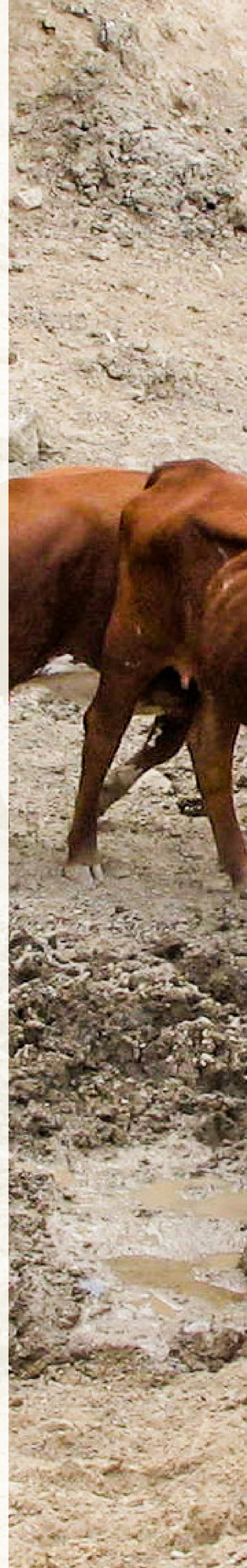
Section 2—Recommendations to Develop a Local Drought Information System summarizes what we believe is a viable strategy for improving drought monitoring across the Hopi Reservation. Within this section is the rationale for why drought monitoring is important, our understanding of why the current drought monitoring section of the Hopi drought plan is insufficient, and our suggested strategy for the continued development of the local drought information system we began to pilot with the DNR in 2014 with the Quarterly Hopi Drought Status reports.

Section 3—Summary of 2013-2014 Interviews contains a detailed synthesis of the 21 interviews Anna Masayesva—at that time a member of the CLIMAS research team—conducted with Hopi drought stakeholders. While these interviews inform the recommendations in Section 2 and are the basis of much of what is reported in Section 5, the interview summary contains considerably more information that also may be of interest to Hopi DNR staff and tribal leaders.

Section 4—Hopi Climate: An Overview to Support Drought Monitoring and Management provides a detailed analysis of climate patterns on the Hopi Reservation and a brief explanation of short- vs. long-term drought and how the Standardized Precipitation Index can be a useful tool for examining the different time scales of drought. We developed this section at the request of the Hopi DNR as potential input to drought planning and to provide basic information that could be included in climate-related grant applications the Tribe may write.

Section 5—Rain Gauges to Range Conditions: Collaborative Development of a Drought Information System to Support Local Decision Making is a 2016 peer-reviewed manuscript the CLIMAS research team published. This manuscript provides an overview of the project, the context for drought and drought-related decision making on the Hopi Reservation, the rationale for developing a local drought information system, and a basic description of the drought information system the research team has envisioned.

Section 6— Helping a Community Develop a Drought Impacts Reporting System is a 2013 article published in the magazine *Rural Connections* by the UA project team It provides a short overview of the challenge of drought monitoring in the Four Corners and the initial plan for developing a local drought information system with the Hopi Tribe.



COWS SEEKING WATER IN A DRY WASH ON THE HOPI RESERVATION. PHOTO CREDIT: DANIEL FERGUSON

SECTION 1: PROJECT OVERVIEW

This report is based on work carried out by researchers from the Climate Assessment for the Southwest (CLIMAS) program at the University of Arizona (UA) in collaboration with the Hopi Department of Natural Resources (DNR). The CLIMAS/ Hopi DNR collaboration began informally in 2009 when DNR leadership contacted Dan Ferguson and Mike Crimmins from CLIMAS with concerns about drought conditions on the Hopi Reservation. Initial discussions between the CLIMAS researchers and the DNR focused on the limited availability of climate data across the Hopi Reservation and surrounding lands, the kinds of regional climate information that is available, and DNR 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 the DNR with little information about drought conditions across the reservation to inform tribal leaders and citizens. Drought monitoring on the reservation essentially was not being carried out and the Tribe was relying on regional drought information (e.g., the U.S. Drought Monitor) that the DNR staff felt did not accurately represent local conditions.

After several visits to meet with the DNR staff, the CLIMAS research team pursued grant funding from the National Oceanic and Atmospheric Administration (NOAA) to enable collaborative work with the DNR to both address the drought monitoring challenges the Tribe had identified and allow the research team to conduct studies to better understand regional drought patterns and impacts. The CLIMAS researchers received an initial grant from NOAA's Sectoral Applications Research Program (SARP) in 2010 and a second grant from the Regional Integrated Sciences and Assessments (RISA) program in 2013. All the work contained in this report was supported by those SARP and RISA grants. The overarching goal of the project was to help the DNR staff and leadership devise an improved drought monitoring strategy to support development of an updated drought mitigation and response plan. The work primarily was focused on addressing three related challenges that CLIMAS researchers and DNR staff identified at the outset of our collaboration:

1. Weather and climate data that accurately and reliably capture local drought conditions on the Hopi Reservation are limited, which impedes the ability of DNR management and tribal leadership to make decisions in response to drought conditions and hinders the ability of the Tribe to proactively plan for drought.
2. The drought monitoring component of the 2000 Hopi drought plan has proven to be ineffective for supporting decision making by the DNR and the Hopi Tribe's leaders.
3. No consistent, reliable source of information exist about drought conditions on the Hopi Reservation.

The majority of our work with the DNR therefore focused on understanding:

- the kinds of data and information collected and utilized by the DNR;
- key concerns that the DNR and Hopi stakeholders had about drought impacts, tribal drought response, the information currently informing drought decisions, and information that may be useful if it were available;
- processes that may be useful for improving drought monitoring;
- processes that may be useful for improving the availability of drought information across the Hopi Reservation.

SECTION 2: RECOMMENDATIONS TO DEVELOP A LOCAL DROUGHT INFORMATION SYSTEM

Drought Information System Goals

The rationale and strategy for developing a local drought information system is based on our work to understand the climatic context for drought on Hopi lands (much of which is represented in Section 4 of this report), how Hopi citizens and resource managers experience drought (reflected in Sections 3 and 5 of this report), and how the DNR produces and consumes data and information that may be relevant to drought monitoring (a central part of the published paper included here as Section 5). The local drought information system we describe below is meant to:

- work within the existing human, technical, and financial resources of the DNR;
- incorporate local observations of environmental conditions on the Hopi Reservation;
- incorporate available regional climate data and information either produced by CLIMAS or otherwise available to DNR staff;
- provide a platform for collecting and presenting locally important information about drought conditions, including systematic observations from Hopi drought stakeholders who are not part of the DNR;
- provide a consistent, reliable source for drought information to those concerned about drought on the Hopi Reservation; and
- help foster a community-wide, ongoing dialogue about local and regional drought conditions that can support local drought planning and policymaking.

Why Focus on Monitoring?

Throughout the collaboration with the DNR, our work remained focused on improving drought monitoring on the Hopi Reservation for two reasons. First and foremost, the initial conversations we had with DNR leadership and staff revolved around the lack of instrumental data (e.g., long-term, reliable weather stations) on the reservation. The fact that weather and climate data from official U.S. observation networks are extremely limited across Hopi lands led us to look at non-traditional sources of data and information—including a variety of routine observations by DNR technicians—to bolster the regional hydrometeorological data that are available.

We also remained focused on improving drought monitoring because we found that DNR management and tribal leadership felt they did not have sufficient information about local weather and climate and lacked a consistent stream of data and information about the status of drought-vulnerable systems (e.g., ranching, farming, water resources, cultural resources) on the reservation. Our understanding was that the DNR wanted to update and improve the existing Hopi drought plan. We felt it would be difficult for any drought plan or policy to fully succeed without a simpler, more reliable, and more useful strategy for routinely monitoring the various ways Hopi social and ecological systems were being impacted by and responding to dry conditions. In particular, both DNR staff and Hopi drought stakeholders we interviewed expressed a general desire for more proactive planning (rather than simply responding to drought events as they happen), which requires a systematic approach to tracking the evolving status of conditions, trends, and changes in vulnerabilities so that any policies triggered by the plan reflect on-the-ground ways that drought-vulnerable systems change over time. Without a feasible, useful, and reliable drought monitoring system in place, proactive planning would be difficult to achieve.

Limits to the Existing Drought Monitoring Plan

The existing Hopi drought plan (first approved by the Hopi Tribal Council in August 2000) includes a complex drought monitoring strategy. We found two related challenges confronting the DNR in its efforts to implement that monitoring strategy. First, the original drought plan assumed that a significant amount of funds would become available for instruments and more elaborate data collection and analysis to track drought conditions. Those funds never materialized, leaving the DNR in the difficult position of having to monitor drought conditions with existing resources. Because the 2000 drought monitoring strategy relied on new resources that did not arrive, much of the data required for tracking drought conditions and triggering various actions essentially does not exist, severely undermining the utility of the plan for decision making. The second challenge we identified with the existing monitoring plan relates to human resources within the DNR. Even if all the data in the plan were available, the limited number of staff and data-processing capacity within the DNR would make full implementation of the monitoring strategy—and therefore the plan itself—difficult.

Central to the current drought monitoring strategy is the weather station network on the reservation (called for in the 2000 drought plan) run by the Hopi Water Resources Program. Our initial conversations with the DNR leadership at the outset of this project revolved around questions about the best way to upgrade that network. By visiting the existing weather stations with DNR technicians, talking to DNR staff, and generally assessing the challenges of operating and maintaining a network of weather stations, we ultimately suggested that DNR defer upgrading their network pending the availability of significantly more financial and human resources. Our suggestion was based on several observations: 1) many of the existing instruments were in poor working order (compromising data quality and therefore utility); 2) the data processing capacity within the DNR was limited; and 3) the cost of new instruments, operation and maintenance, and staff time to collect, reduce, and analyze the data was prohibitive. While there is clearly value in having a high-quality weather observing network on the Hopi Reservation to inform local decisions, our impression throughout our collaboration with the DNR was that the challenges that come with operating and maintaining such a network exceeded the value for the DNR.

After reviewing the existing drought monitoring plan, informally assessing the existing network of weather stations, and having many conversations with DNR staff, we came to the conclusion that a simpler monitoring strategy that used existing knowledge, skills, data, information, and technical capacity was a reasonable and tenable approach for characterizing local drought conditions. Our guiding assumption, therefore, for the rest of our collaboration was that routinely synthesized local observations combined with the available regional climate data would provide an effective stream of information to inform DNR and Hopi Tribe decisions about drought.

Why a Local Drought Information System?

Our interactions with DNR leadership and staff, our analysis of the existing drought plan, and our analysis of the existing regional climate data led us to pursue the idea of working with the Hopi DNR to develop what we call a local drought information system. The components of the system we envisioned are described below, but here we briefly explain our rationale for suggesting such a system.

First, the cost of purchasing, operating, and maintaining a functional climate monitoring network across the Hopi Reservation, combined with the human resources challenges of data processing and management, led us to focus on ways the DNR could utilize existing data, information, and human resources to effectively monitor drought conditions. As we looked closely at the kinds of observations the DNR already was making, we concluded that much of the information already being collected had significant potential for tracking drought status. By routinely synthesizing *existing* drought-relevant information for DNR management, tribal leadership, and citizens, we feel the DNR can provide sufficient, locally-relevant information about drought without incurring the significant new expenses of building out and maintaining an instrumental network.

Aside from avoiding these costs, we believe that focusing on developing a local drought information system that utilizes existing information offers a significant advantage for tracking *specific concerns* tribal leaders, DNR management, and citizens have about drought. Drought is a notoriously difficult climate hazard to track, primarily because the impacts that come from precipitation deficits are so varied, are dependent on how long a drought lasts, and are dependent on specific stakeholder concerns. A drought information system built around observations that the DNR or citizens were already making or are interested in starting to make would provide the flexibility to focus on specific issues of concern (e.g., impacts on farming or ranching) and potentially cover more area more efficiently than an instrumental network. This kind of system—if it is designed to *systematically* capture observations of drought conditions most relevant to the community—could provide a richer characterization of drought conditions than a typical drought monitoring strategy built around weather stations.

Finally, development of a local drought information system may help foster dialogue about drought concerns and perceived vulnerabilities, identify critical impacts that should be monitored, and provide a basis for all drought stakeholders on the reservation to not only track conditions, but also provide input. Such a system would therefore allow for ongoing, community-focused conversations about drought conditions as they evolve through seasons, years, and decades. For robust drought planning focused on long-term community resilience, this type of continuous community engagement may be highly beneficial.

What Do We Mean By Local Drought Information System?

The local drought information system we envision would provide a means to collect, synthesize, and communicate data and information about drought. Ideally managed by the DNR, it would nevertheless be flexible enough to capture information collected by anyone willing and able to report routinely on conditions that are deemed relevant by the communities for monitoring drought on the Hopi Reservation.

As we initially conceptualized and piloted this system with the Hopi DNR in 2014, it would involve several inputs and outputs and facilitate multiple outcomes related to improved planning for drought on Hopi lands.

STORM MOVING ACROSS THE HOPI MESAS. PHOTO CREDIT: DANIEL FERGUSON

Inputs

The backbone of the local drought information system we envision would be local data and information. In the initial pilot system we created with the DNR in 2014, these local observations were limited to data from rain gauges the Office of Range Management (ORM) maintains across the reservation and some information about range conditions. From our work with the DNR, however, we identified other potentially useful data and information sources that already are being collected that may be useful inputs to the local drought information system. These include 1) hydrologic information, including data from monitoring wells that track shallow aquifers that may be responsive to seasonal precipitation and ORM observations of flow from springs and seeps; and 2) water levels (or presence/absence of water) behind earthen dams on the ranges, also observed by ORM technicians. This type of system could also include information not typically associated with drought monitoring that nonetheless could indicate how drought conditions are intensifying or abating, including reports of wildlife trespass that the DNR deems related to drought conditions or law enforcement reports of trespass at windmill sites.

Aside from data and information the DNR could contribute, this type of system would allow for contributions from citizens and non-DNR professionals on the reservation. From the interviews we conducted (see Section 3 for a detailed summary), we found some interest in an open system that would allow for drought observations from those outside the DNR. Reports about local drought conditions and impacts from farmers, ranchers, and Community Service Administrators (CSAs) could provide important information about drought on Hopi lands and how it is impacting Hopi people. This type of community-based system could even include input from health care professionals about what they identify as drought-related health impacts on community members.

This type of information system, however, must be designed in such a way that reports are made *consistently* and *routinely* to track evolving conditions as accurately as possible through time. The strength of this kind of system is the diversity of information it could provide. The major weakness—reliance on consistent and routine reporting from multiple sources—could result in a system that provides only ad hoc information that is therefore unreliable for tracking drought. Our work with the DNR and our interviews with Hopi drought stakeholders suggests potential for such a system to work given sufficient buy-in from the communities and the DNR and clear agreement about what should be included and in what form and how frequently data and information would be contributed.

To provide a broader climate context for local observations, the local drought information system would include *regional* data and information (e.g., information about conditions across the Four Corners states). In the pilot system we created with the DNR, the CLIMAS research team contributed drought information about the broader Southwest region. Though the data that contributes to these drought assessment products come from instruments outside the boundaries of the Hopi Reservation, they are sufficient to provide a larger-scale perspective on drought in the region.

Outputs

The primary output for the local drought information system we envision is a local drought summary document that would be produced four times per year by the DNR. In collaboration with the DNR, we piloted this idea by producing a Quarterly Hopi Drought Status Report in 2014 that included a subset of the inputs described above (the four 2014 reports are included at the end of this section). Our work on this pilot output and the interviews we conducted during that period suggest such a report could be quite useful for many Hopi drought stakeholders, including the CSAs, wildfire professionals, public health workers, farmers, ranchers, the DNR itself, and the tribal government. The piloted drought status summary was a simple two-page document that was distributed as a PDF via email in March, June, September, and December and reflected observations during the prior three months. Producing the report every three months seemed to balance the information needs of the DNR with the effort required for the DNR staff to produce the report. The first page included local observations while the second page included regional drought assessment information. This type of simple report allows for almost any routinely collected, relevant drought information to be included. Ideally, the local information portion of the report would grow as the DNR and Hopi drought stakeholders identify drought indicators they feel are important to consistently monitor.

In addition to the quarterly report, our interviews suggested that regular presentations by the DNR staff about drought conditions may be an important element of a Hopi local drought information system. We did not explore in depth what form these presentations may take or detailed analysis of what Hopi drought stakeholders wanted, but our interviews did suggest that perhaps using existing structures (e.g., the routine meetings of the CSAs) for communication between the DNR and communities may be beneficial for keeping everyone apprised of evolving drought conditions. Specifically, our interviews pointed to a general interest in more community-based education about drought conditions, how the reservation plans for and deals with drought, and what citizens may be able to do to cope with dry conditions. This type of community outreach by the DNR could provide an important means for creating routine dialogue about drought on the reservation that could contribute to improved proactive planning.

Outcomes

The purpose of the local drought information system described above is to assist the DNR, the Hopi Tribe, and Hopi citizens to achieve several drought-resilience outcomes. These outcomes range from short-term (i.e., over the next year or two), to medium term (i.e., over the next five years), to long-term (i.e., beyond the next five years).

Three short-term outcomes:

1. Consistently monitored drought-vulnerable systems that lead to routine characterization of conditions across the Hopi Reservation.
2. Better information about drought conditions that equips DNR leadership and tribal leaders for more informed drought decision making.
3. Increased engagement between the DNR and villages/ citizens about drought.

Three medium-term outcomes:

1. Development of data and information that could support efforts to seek funding for drought planning, mitigation, and response.
2. More ongoing community dialogue about drought impacts, responses, and mitigation strategies.
3. Development of an updated drought plan that reflects DNR and community concerns and includes a feasible monitoring plan.

Two long-term outcomes:

1. The Hopi Tribe and citizens would be better prepared for severe drought.
2. Hopi communities increase their long-term resilience in the face of persistently dry conditions in the coming decades.

Suggested Next Steps

Though funding for the collaboration between CLIMAS and the Hopi DNR expired in 2016, the UA team welcomes the opportunity to contribute, however we are able, to implementing the system described above. Below is a summary of our suggested next steps.

Continue producing Quarterly Hopi Drought Status Reports

Based on our interviews and the fact that the tribal government appeared to use the Quarterly Hopi Drought Status reports to inform a decision in the fall of 2014 about stocking on specific drought-impacted ranges, continuing to produce the quarterly summary of conditions is a clear next step if the DNR is able to do so. Should the DNR choose to produce the quarterly status report, we identified several decisions that should be addressed to help ensure it is an effective output of the information system: 1) identify all existing information that is most important to include; 2) identify any new information that the DNR, tribal leaders, and citizens deem important to include; 3) ensure that all data and information to be included in the status reports are consistently reported; and 4) ensure that someone within the DNR is tasked with compiling and producing the report.

RICK NASAFOTIE (HOPI OFFICE OF RANGE MANAGEMENT) AND DANIEL FERGUSON(UNIVERSITY OF ARIZONA) DISCUSS RANGE CONDITIONS IN SUMMER 2013 ON THEHOPI TRIBE'S LANDS IN NORTHERN ARIZONA. PHOTO: MICHAEL CRIMMINS

In terms of including the regional climate conditions as part of the quarterly status reports, CLIMAS already produces a monthly summary of regional conditions that could be used in the quarterly status report. Beyond existing CLIMAS products, we can continue to provide quarterly information tailored to the Hopi drought report if that is of interest to the DNR and the Tribe.

Finally, we recommend that if the DNR chooses to continue producing the quarterly drought reports, they consider distributing it as widely as possible across the Hopi Reservation. Our interviews suggested that Hopi drought stakeholders are interested in receiving periodic information, and some are willing to contribute data and information. Our work indicated that email may be the most effective means for wide distribution, though the DNR may have other more effective communication tools.

Decide on a Village/Community Engagement Strategy

The interviews we conducted with Hopi drought stakeholders indicated an interest in more communication from the DNR about drought, including presentations about conditions and how the Tribe's drought plan works. Several people also specifically mentioned their interest in participating in drought education efforts.

If the DNR chooses to continue to produce the quarterly drought status reports, that process may provide the basis for regular engagement between DNR and villages. Soliciting input from citizens and non-DNR professionals about what should be included, identifying people who are willing to contribute routine information, and periodic community briefings about the information in the summaries all appear to be tractable ways to use the quarterly drought status reports as a means for opening dialogue about drought with Hopi communities.

Finally, our interviews suggested potential to engage non-DNR professionals (e.g., CSAs) and citizens as contributors to a Hopi local drought information system. Though we did not identify specific individuals who are willing to contribute data and information, our work indicates that this may be a viable strategy should the DNR be interested in pursuing it. This level of engagement would need to be carefully designed to ensure observations were aligned with drought-vulnerable systems that the DNR and the communities are interested in monitoring and that reporting conditions could be done systematically, but it has potential to be an important component of a community-based drought information system.

Quarterly Hopi Drought Status Report
January-March 2014

THE HOPI TRIBE

THE UNIVERSITY OF ARIZONA | CALS COOPERATIVE EXTENSION

CURRENT RANGE CONDITIONS – HOPI RESERVATION

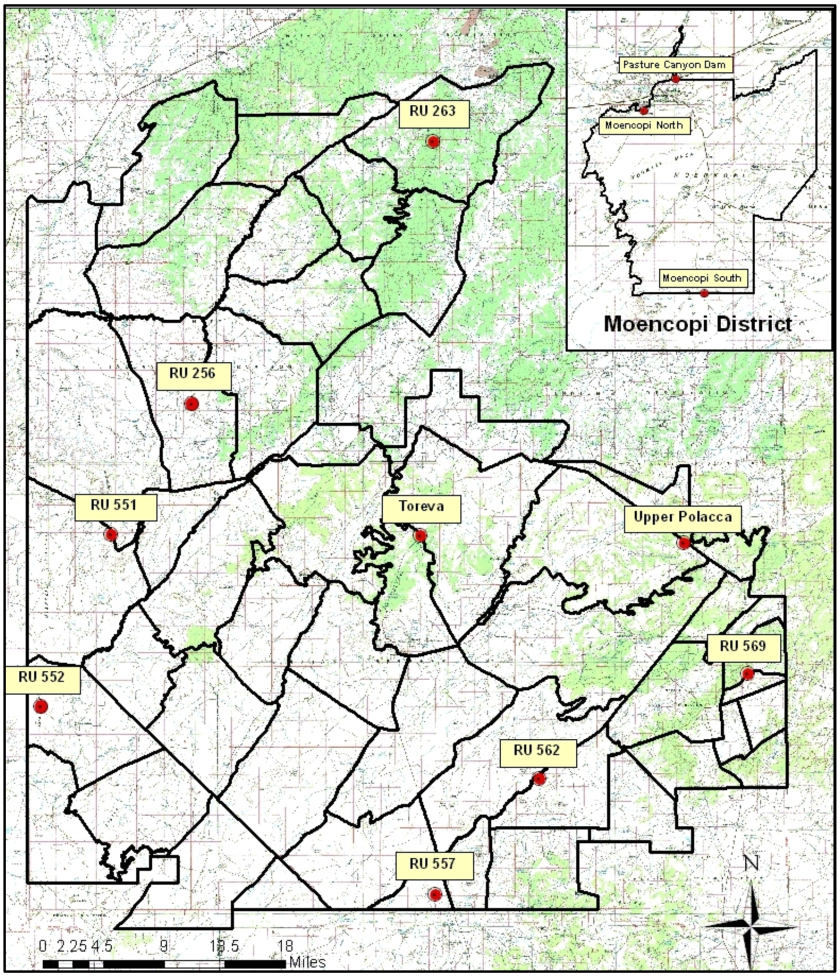


Figure 1. 2014 Rain Gauge Locations

Range Condition Notes:

The current condition of the rangeland is generally fair for this time of year. Soil moisture depth ranged from 4-21 inches throughout the winter months in the northern ranges. Although precipitation was sparse this quarter, the following vegetation has been observed to be in bloom:

Grasses – Cheatgrass, Squirrel tail, Needle and thread.

Forbes - Tansy mustard, Little twist flower, Princess plume.

The winter annual vegetation seems to have begun germination earlier than usual, which may be a result of the high winter temperatures.

Table 1. January – March 2014 Precipitation (inches)

Rain Gauge Location	January	February	March	TOTAL
Range Unit 263	**.54**	**.30**	**.24**	**1.08**
Range Unit 256	**0**	**.03**	**.15**	**.18**
Range Unit 551	No data			**-**
Range Unit 552	No data			**-**
Range Unit 557	No data			**-**
Range Unit 562	No data			**-**
Range Unit 569	No data			**-**
Upper Polacca	**0**	**.17**	**.72**	**.89**
Toreva	**0**	**0**	**1.5**	**1.5**
Pasture Canyon Dam	**.73**	**.06**	**.05**	**.84**
Moencopi North	**.70**	No data	**0**	**.70**
Moencopi South	**.60**	No data	**.20**	**.80**

Quarterly Hopi Drought Status Report
April-June 2014

CURRENT RANGE CONDITIONS – HOPI RESERVATION

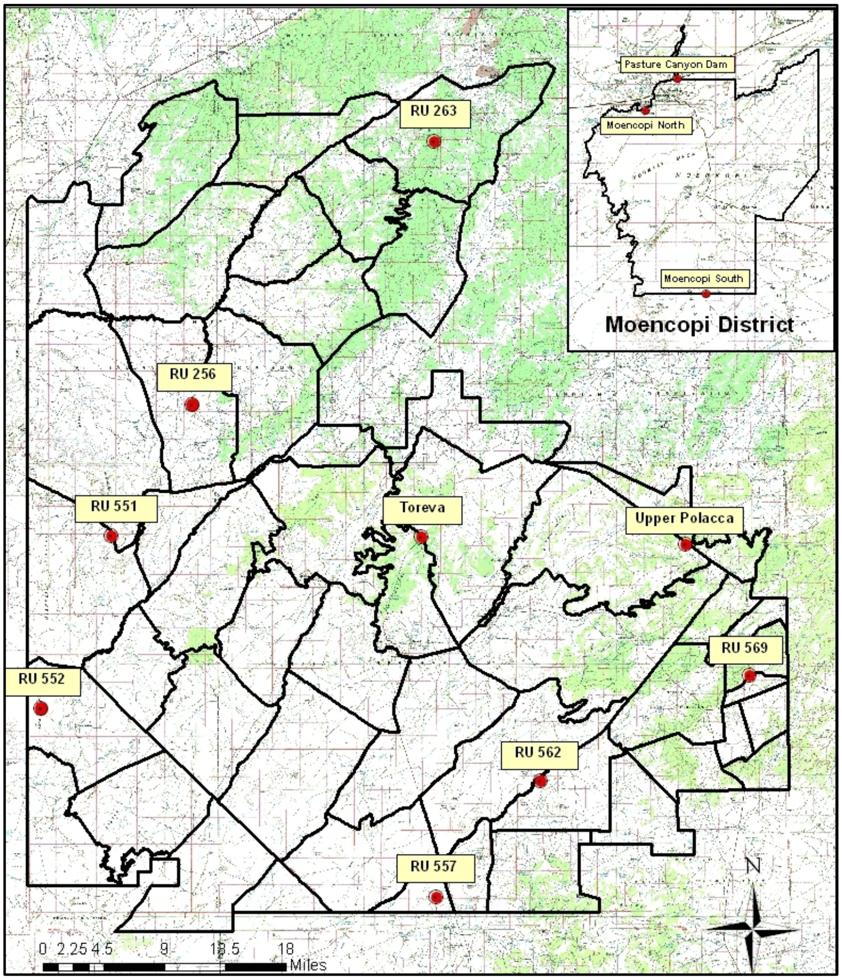


Figure 1. 2014 Rain Gauge Locations

Range Condition Notes:

The current condition of the rangeland is generally poor for this time of year. The cool season annual vegetation has seeded and completed it's life cycle. Warm season annual grasses such as Sand dropseed and Alkalai sacaton should be abundant during this time of year but appear to be dormant. This may be due to the lack of moisture and the extensive windy conditions that persisted during the past quarter. Perennial forbs such as Globemallow are now in the flowering stages. The warm season annual grasses should respond at the start of the monsoon rains.

Table 1. April – June 2014 Precipitation (inches)

Rain Gauge Location	April	May	June	TOTAL
Range Unit 263	.05	No Data	No Data	.05
Range Unit 256	0.0	No Data	0.0	.00
Range Unit 551	0.0	.02	0.0	.02
Range Unit 552	0.0	0.0	0.0	0.0
Range Unit 557	0.0	0.0	0.0	0.0
Range Unit 562	.07	0.0	0.0	.07
Range Unit 569	.12	.30	.22	.64
Upper Polacca	.13	.12	.19	.44
Toreva	No Data	No Data	No Data	-
Pasture Canyon Dam	.02	.10	.05	.17
Moencopi North	No Data	No Data	No Data	-
Moencopi South	No Data	No Data	No Data	-

Quarterly Hopi Drought Status Report
July-September 2014

CURRENT RANGE CONDITIONS – HOPI RESERVATION

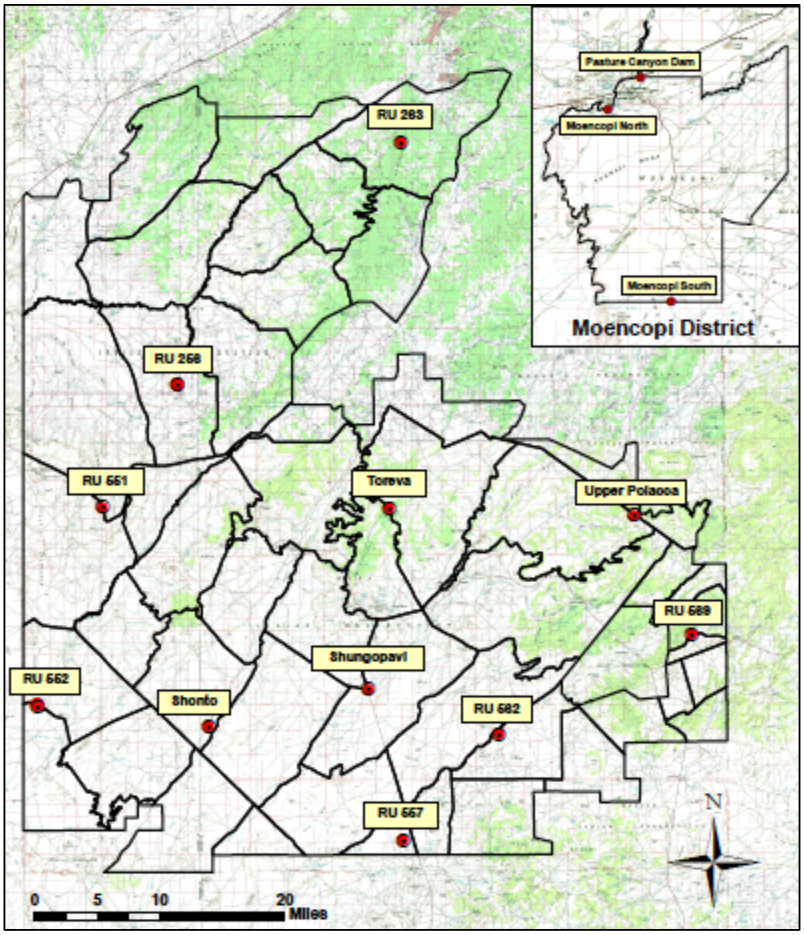


Figure 1. 2014 Rain Gauge Locations

Range Condition Notes:

The general condition of the range is poor to fair depending on the amount of precipitation received this monsoon season.

The monsoon rains arrived late (August) this summer and was very spotty throughout the reservation. The warm season annual grasses that are located in areas that received rain responded to the moisture and grew to maturity and are now in the seeding stage. The vegetation in areas that did not receive rain did not respond and only old growth vegetation (grey color) is present.

Table 1. July – September 2014 Precipitation (inches)

Rain Gauge Location	July	August	September	TOTAL
Range Unit 263	No Data	.83	.02	**.85**
Range Unit 256	No Data	.06	.20	**.26**
Range Unit 551	No Data	1.0	.08	**1.08**
Range Unit 552	.24	.26	.18	**.68**
Range Unit 557	.12	.36	.27	**.75**
Range Unit 562	.10	.45	.10	**.65**
Range Unit 569	0.0	.72	.18	**.90**
Upper Polacca	0.0	1.35	.63	**1.98**
Toreva	.03	1.0	.04	**1.07**
Shungopavi	.13	.60	.39	**1.12**
Shonto	.05	.40	.28	**.73**
Pasture Canyon Dam	.71	.61	.96	**2.28**
Moencopi North	1.0	0	.17	**1.17**
Moencopi South	.15	0	.26	**.41**

Quarterly Hopi Drought Status Report
October-December 2014

CURRENT RANGE CONDITIONS – HOPI RESERVATION

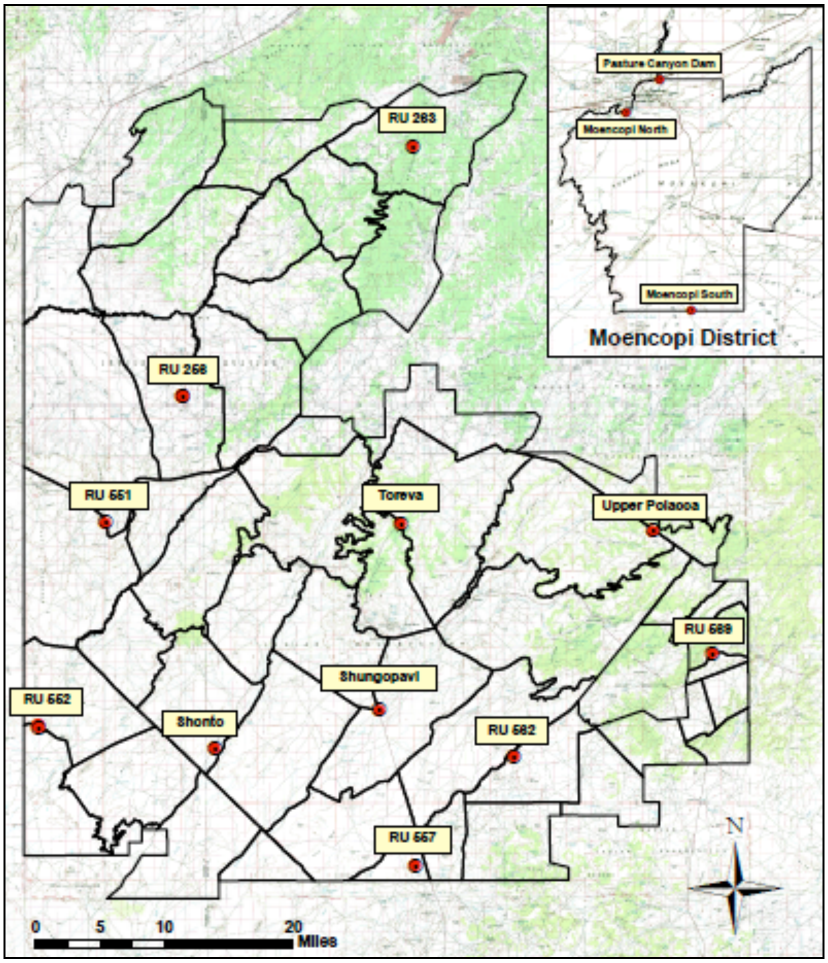


Figure 1. 2014 Rain Gauge Locations

Range Condition Notes:

The general condition of the range is fair. Although a few grasses (e.x. Indian ricegrass) and forbs (e.x. Filaree) have begun to sprout, most cool season rangeland vegetation is currently dormant due to the freezing temperatures caused by recent winter storms. Once temperatures begin to rise, the cool season vegetation should respond normally. If the warm winter temperatures persist, the vegetation that we would normally see on the range in early spring will prematurely begin to sprout and may be damaged by any future freezing events.

Table 1. October – December 2014 Precipitation (inches)

Rain Gauge Location	October	November	December	TOTAL
Range Unit 263	No Data	No Data	No Data	**-**
Range Unit 256	.15	.16	.10	**.41**
Range Unit 551	.02	.05	.38	**.45**
Range Unit 552	No Data	0	No Data	**0**
Range Unit 557	No Data	.20	No Data	**.20**
Range Unit 562	No Data	.20	No Data	**.20**
Range Unit 569	.68	.12	1.70	**2.50**
Upper Polacca	.46	.46	1.65	**2.57**
Toreva	No Data	No Data	.50	**.50**
Shungopavi	No Data	No Data	1.25	**1.25**
Shonto	No Data	No Data	1.24	**1.24**
Pasture Canyon Dam	.03	.07	.52	**.62**
Moencopi North	.05	.03	No Data	**.08**
Moencopi South	.06	.02	No Data	**.08**

SECTION 3: SUMMARY OF 2013-2014 INTERVIEWS

A primary goal of the collaboration between CLIMAS and the Hopi DNR was to develop a local drought information system that was feasible within human and financial resource constraints and could produce useful information for tribal government leaders, resource managers, and citizens, to better understand drought issues experienced by Hopi stakeholders. To help understand those drought issues Anna Masayesva, a Hopi community member, conducted 21 interviews throughout 2013 and into early 2014. Interviews were not recorded, but for each interview a set of detailed notes was used to capture the ideas people shared.

The goals of the interview were:

1. To better understand how drought is experienced by Hopi people, including the impacts that people are experiencing, how they currently deal with drought, and how they expect to deal with drought if severe conditions continue into the future;
2. To identify sources and types of information people currently access or want; and
3. To understand the expectations citizens have of the tribal government and villages in terms of drought planning and monitoring.

The stakeholders interviewed consisted of farmers, ranchers and officials from public health, law enforcement, transportation, wildfire management, village water resource administrators, and the U.S. Bureau of Indian Affairs. During the interviews, Masayesva gathered information about impacts, adaptations, and responses that people were directly attributing to drought and noted comments about many secondary impacts and responses.* Many of these, such as increased soil erosion across range units, are difficult to ascribe solely to drought because land use clearly has played a role. Our goal was to understand how drought was experienced so we could suggest a viable 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 and responses that could definitively be attributed to drought, instead focusing on local perceptions and experiences of drought.

*The interview questions are included at the end of this summary.

HOPI PALE GREY SQUASH. PHOTO CREDIT: PETER BAER

Perceived Drought Impacts

Through the course of the interviews, we captured a variety of perceptions about how drought conditions are impacting individuals, families, the overall Hopi landscape, and cultural fabric of the people. We sorted these comments into the seven categories below. Within each category we further sorted the comments by the types of impacts those interviewed said they have observed or believe are happening.

Farming

Twelve of the 21 people interviewed commented on how drought is impacting Hopi farming. The most common farming impact mentioned was related to drought conditions ***causing reduced crop yield or total failure of crops*** for the individuals interviewed, for members of their family, or for other community members. Specific comments about reduced yields and crop failure touched on the length of time that the soil stays moist during the planting season, the planting season coming earlier, high winds helping to dry out soils in the spring, and total failure of precipitation after plants were in the ground.

Three of the people interviewed mentioned that ***wildlife***

trespass on farm fields was a significant drought impact. Specific comments related to insects, rabbits and other small animals, and large animals such as elk causing impacts to crops during drought years.

The other primary farming impacts people reported were ***poor soils*** and ***insufficient flow in washes***.

Infrastructure

Twelve of the 21 people interviewed described what they perceived as drought impacts on infrastructure across the Hopi Reservation. The most frequently discussed impacts were associated with ***earthen dams*** and ***windmills***. The most common observation from the interviewees was insufficient surface water to fill the existing catchments behind earthen dams across the ranges. The related problem people reported was the failure of several windmills on the reservation. Specifically, people mentioned the problem of dry catchments leading to more pressure on the windmills for stock water. One person also mentioned damage that has been sustained by some of the windmills as a result of high winds and dust storms. Several people noted that, in general, many of the windmills across the reservation are not operational, which is causing more stress on village water systems as ranchers are forced to haul water from those systems.

Two people mentioned drought-related impacts to ***roads***. Specifically, the concerns were related to soil erosion impacting roadways; sediment build-up in washes (attributed to thriving tamarisk during the drought), which causes problems with bridges; and sand dunes overrunning roadways.

Other drought-related infrastructure impacts mentioned included sand inundating ***fences***, ***cattle guards***, and ***culverts***. In the case of fences, one concern was that tumbleweeds choke fence lines, causing sand dunes to form and bury the fences. Other concerns arose from more pressure on village wells, which leads to more frequent failure of well pumps.

Springs

Nine people mentioned that drought conditions were impacting springs across the Hopi Reservation. Four interviewees attributed the drying of springs to a lack of precipitation. Three people noted that springs were drying but did not mention a direct cause. One person attributed springs drying to groundwater pumping by Peabody, and another suggested the springs were dry as a result of neglect by Hopi citizens who would normally maintain them. Another person suggested that the springs across the reservation were unchanged by recent drought.

Ranching

Eight people we interviewed mentioned drought impacts on ranching. The most common impact reported was ***reduced forage***. One person also reported that ***soil erosion*** was being driven by the lack of precipitation preventing rangelands from growing sufficient grass to hold topsoil down. One person mentioned ***livestock mortality*** due to poor range conditions and water availability being limited by drought. Another person described local conflicts with Navajo ranchers over ***trespass*** on Hopi ranges during extremely dry times.

Wildlife

Five people described what they perceived to be impacts on wildlife from drought. The main observation—reported by three people—was related to ***changes in animal behavior*** as a result of dry conditions, specifically changes in migratory patterns, fewer birds and other animals near declining springs, and wildlife trespass on farm fields. One person also said hunters are reporting ***more scarce wildlife***, including prey species like rabbits.

Social Conflicts

Seven people described social conflict related to farming and ranching that they felt was an impact of dry conditions. Specific farming-related conflicts included rumored crop theft from corn fields, fights within families over the use of fields, and conflict in Moenkopi between farmers and other users of water from the reservoir. Ranching conflicts that people reported were related to competition for range and water resources during especially dry times.

Cultural Impacts

Six people described cultural impacts from drought. Five of the comments were related to ***disruption of cultural practices or beliefs***. One person noted that the lack of corn and other cultural resources from dry conditions was disrupting Hopi ceremonial life. Another described problems with using non-Hopi corn for making piki and the related problem of having non-Hopi seed stock corrupt the genetic integrity of Hopi corn. One person reported that with multiple years of low precipitation, some people are starting to question their faith in Hopi cultural practices meant to bring rain. Two people also described emergent cultural tension associated with sharing, as reduced crops may lead to reduced sharing of important resources like corn and beans, which was described as running counter to Hopi teachings.

ADAPTING TO DROUGHT NOW AND IN THE FUTURE

During our interviews, Masayesva asked people to describe how they are currently adapting to or coping with drought conditions. We have divided the summary of responses below into ***Current Adaptations*** to reflect what people said they or their family or neighbors are doing now and ***Future Adaptations*** for ideas people offered about what may be necessary if drought conditions persist for several more years. Within each of the Current and Future categories, we have further grouped comments by the common themes that emerged: water, farming, ranching, and infrastructure.

Current Adaptations

Water

Twelve of those interviewed described ways in which they are currently dealing with drought in terms of their use of water. The most common current drought response related to water—mentioned by 10 people—was ranchers ***hauling water*** for cattle. In the context of drought response, most people talked about hauling as an expensive adaptation that put an additional burden on village water systems. Five of those interviewed also talked about ***increasing water conservation*** as something either they personally are doing or their villages have been doing. Two people also described their own efforts to ***retain water*** either through berms in fields to help keep water from running off or by using household greywater.

Farming

Eight of the people interviewed talked about ways in which farmers are coping with drought conditions. Most of the comments about farming adaptations were related to ***changing farming practices***. These included cultivating smaller fields, planting later, foregoing the use of tractors to help retain soil, using cover crops to hold down soil, limiting planting to specific types of soil where soil moisture remains higher in dry times (e.g., higher clay content), and shifting to only planting corn in a household vegetable garden, where it can be easily watered. Three people also talked about either themselves or others ***irrigating fields*** to try to keep them productive. One person suggested that during the recent drought, farmers had to be more vigilant about keeping pests away from their crops. Another suggested that successful farmers were able to keep track of specific seed stock that has thrived through dry years and continue to plant those varieties. One person also suggested that some farmers were choosing not to plant as a way to cope with dry conditions. Closely related to farming adaptations, four people specifically made comments about how their use of culturally important foods have changed during drought conditions. Three of those we spoke to talked about drought forcing them to ***reduce the practice of sharing traditional foods***, including corn. Two mentioned people ***purchasing corn*** off the Hopi Reservation in order to have enough for traditional uses. These adaptations to drought were described as impacting the economic health of families (i.e., buying corn rather than raising it) and driving cultural tension, as not sharing goes against Hopi teachings.

Ranching

Aside from hauling water, six people described three other ways in which ranchers are currently adapting to dry conditions. Four people said that when conditions are as dry as they have been over recent years, ranchers have to ***reduce herd size***. Three people mentioned that some ranchers are being forced to haul ***supplemental feed***, an adaptation that they noted is expensive. Two people described specific ranching ***innovations*** that they are either doing now or would like to do. Those innovations were experimenting with raising smaller bulls, which will result in smaller cattle eating less grass, and rotating stock through pastures (though the interviewee who noted range rotation mentioned that his range unit has insufficient fencing to allow for rotation).

Infrastructure

Two people told us about infrastructure improvements they have made to help alleviate impacts of recent drought conditions. One of them described a fairly sizable investment made as the result of a grant to ***upgrade range water*** by installing a larger stock tank and plumbing a long line to a new drinker to ensure cattle had sufficient water. Another person talked about ***building berms*** to help direct water and retain it in fields.

Future Adaptations

Water

In terms of water issues, the most common future adaptations to persistently dry conditions we heard about related to ***conservation***. Of the 12 people who discussed future conservation measures that might be needed, six of them talked about village-level conservation measures, including water metering, rate increases, strict conservation policies to be implemented during especially dry times, and limits on irrigation. Five people described household-scale conservation as an important element of future conservation. Three interviewees mentioned more ***rainwater or greywater harvesting*** as a means to adapt to future dry conditions, and three described the need for the tribe to secure ***alternative water sources*** to mitigate future drought.

Farming

The most common future adaptation the interviewees offered with regard to farming was to ***increase irrigation***. Six people discussed the potential need for farmers to adopt some form of irrigation if Hopi agriculture is to continue through persistent drought conditions in the future. Five people talked about persistent drought forcing farmers to return to more ***traditional farming techniques***, including smaller fields, traditional soil and water conservation practices, and reducing or eliminating use of tractors. One person suggested that ***abandoning Hopi farming*** entirely may be necessary if drought conditions persist and another suggested the need for carefully ***conserving existing seed stock*** to ensure enough exists to continue planting in the face of severely dry conditions.

Ranching

The future ranching adaptations offered by our interviewees were stark: either ***abandon ranching*** altogether or s***everely reduce herd sizes***. The four people who addressed future ranching described the economic challenges of continuing to ranch as well as the impact that ranching has on the landscape. One person perceived current stocking rates to be too high, which means exacerbated range impacts if drought persists, and talked about reducing herd size as a necessary adaptation the Hopi Tribe should consider now.

Infrastructure

Four people mentioned some sort of infrastructure improvements that would need to happen to buffer against future drought, including ***more cattle tanks on the ranges***, potentially ***damming washes*** to retain surface water, ***fencing to reduce dune impacts*** on roads and ranges, and implementing a ***tribal water utility system*** to ensure stable water supplies and maintenance of the water system.

DROUGHT INFORMATION

During the interviews, people were asked about the kinds and sources of information they currently consult related to drought, sources of information they knew about on the Hopi Reservation that may be able to provide information on drought conditions, how individual Hopi citizens or the communities might be able to contribute to drought monitoring, and the kinds of drought information they would like to have but cannot currently access.

Information Currently Consulted

Eleven of the 21 people interviewed said they got drought-related data and/or information from a ***non-tribal government source*** and 11 also said they got information from ***Hopi Tribe government sources***. The table below identifies the government sources interviewees cited.

Information Source	Government
Department of Emergency Services	Hopi Tribe
Water Resource Program	Hopi Tribe
Hopi Tribe Executive Offices	Hopi Tribe
Hopi Tutuveni	Hopi Tribe
Office of Range Management	Hopi Tribe
Bureau of Indian Affairs	Federal
Indian Health Service	Federal
National Oceanic and Atmospheric Administration	Federal
National Weather Service	Federal
Natural Resources Conservation Service	Federal
US Drought Monitor	Federal
US Geological Survey	Federal
Coconino County	County
Navajo County	County
Arizona Department of Transportation	State

In addition to the government sources above, four people cited the ***farmer's almanac*** as an information source, while three said they received information from ***non-governmental*** organizations, including tribal grassroots environmental groups and non-tribal groups like the Sierra Club and the Quivira Coalition. Two people mentioned consulting ***historic data and information*** (e.g., old Arizona Cooperative Extension reports) and one interviewee talked about getting information from a ***private sector*** cattle company.

In terms of how people are accessing data and information related to drought, 12 said they use the ***Internet***, 11 cited ***television***, and seven mentioned the ***radio***.

Potential Sources of Drought Information

Interviewees also were asked to identify any entities they knew of that could provide Hopi communities with information about drought conditions on the Reservation. The table below lists the sources identified.

Potential source for drought information	Category
Regional universities	Academic
Hopi Agency Wildland Fire Program	Government, Tribal
Hopi Department of Natural Resources	Government, Tribal
Hopi Office of Range Management	Government, Tribal
Hopi village water operators	Government, Tribal
Navajo Nation	Government, Tribal
Environmental Protection Agency	Government, Federal
Federal Emergency Management Agency	Government, Federal
Federal Highway Administration	Government, Federal
Indian Health Service	Government, Federal
U.S. Department of Housing and Urban Development	Government, Federal
Arizona Department of Agriculture	Government, State
Arizona Department of Transportation	Government, State
Coconino County	Government, County
Navajo County	Government, County
Inter Tribal Council of Arizona	Nonprofit
Northern Arizona Council of Governments	Nonprofit
Rural Community Assistance Corporation	Nonprofit
Rural Water Association of Arizona	Nonprofit
Sierra Club	Nonprofit
Pharo Cattle Company	Private

Information Wanted

Those interviewed were asked what kinds of drought information they want but do not currently get. The responses ranged across the 10 topics in the table below. For each topic, we highlighted the common themes and in some cases included a quote from an interviewee as an example of the kinds of information desired or why that information is desired.

Topic (number of respondents)	Themes and example quotes from responses
Range (8)	***Vegetation***: basic information about the range conditions; results of ORM/NRCS range inventories ***Range water***: where to haul water from, what windmills and tanks are operational; monitoring information from the Hopi Water Resources Program ***Example quote***: "Would like information on the range conditions, so that we can anticipate when community members with livestock will potentially start putting pressure on the [village water] system and reducing our water storage. If we got information, we could in turn send it out to the community members. Like if we know which windmills are working and which aren't. We can help get that information out within our community."
Wind info (6)	High wind warnings; regional wind patterns
Local weather info (5)	Local weather ***forecasts***; current and historic ***local weather data*** (temperature, precipitation, humidity, wind); ***local warnings*** for high winds, heavy rain events, road conditions, unusually dry conditions, winter storms.
Fire info (4)	Fire danger ***warnings***, local fire ***conditions***, including fuel conditions on the range.
Current drought status (4)	**Example quote #1**: "I think that there is a big communication gap when it comes to getting [information about drought conditions] out to the Hopi Community." **Example quote #2**: "The drought status reports that you have been sending out are very helpful, any kind of information that reports current conditions on the reservation." **Example quote #3**: "I want to have information about current drought conditions so I can have my resources ready, like making sure my truck is working if I know I have to haul water."
Historic responses (3)	Information about how Hopis dealt with ***past droughts, traditional conservation practices***
Aquifer status (2)	Information on aquifer ***levels***; how drought is affecting the ***groundwater quality/quantity***
Soils status (1)	Soil type/quality on the Hopi Reservation and the impacts of drought on those soils
Sand dunes info (1)	Sand dune ***monitoring*** information
road hazard info (1)	***Signage and warnings*** about high wind, dust storms, and floods

Information That Could Be Contributed

Four of the 21 people commented about the potential of citizens to contribute information to help monitor for drought conditions across Hopi lands. One person suggested they would be willing to provide information about their ***village water system***, one said they would provide information about the ***condition of the range unit*** they utilize, and one said they would be willing to provide stock tank water levels for a tank they use. Another person also suggested that they did not think volunteer monitoring would work unless the those contributing data and information were paid.

DROUGHT RESPONSES

Masayesva concluded the interviews by asking interviewees to offer their opinions about how the Hopi community can be more involved in drought planning and monitoring and what responses to drought they would like to see from the Hopi Tribe. Responses fell into the categories described below.

Education

The most common theme in response to questions about both community involvement in drought planning and preferred responses by the tribe—touched on by 13 people—was education. The general idea that emerged from multiple respondents was that improving drought response on the Hopi Reservation first required more education about ***what drought*** *is*, what ***the impacts*** are, ***why people should be concerned***, and ***what can be done*** by individuals, the villages, and the tribal government. Most of the interviewees suggested these education efforts be broadly aimed at citizens, though a few people offered specific groups that could participate in drought education: farmers, ranchers, village water administrators, and tribal leaders. One respondent—expressing the logic offered by multiple people—suggested that once people understand the issues related to drought they can make more informed decisions about how they farm, ranch, or use domestic water. Another told us that tribal leadership should be well-educated about drought and its effects on tribal resources so that when they seek funding they can speak to all the issues and effects on areas like transportation, natural resources, and law enforcement.

SAND DUNES ALONG THE SOUTHERN BOUNDARY OF THE HOPI RESERVATION.
PHOTO CREDIT: DANIEL FERGUSON

The topics our interviewees suggested that might be covered by a drought education effort included ***water conservation*** (e.g., drip irrigation, rainwater harvesting, what other tribes in the region have done successfully), ***erosion control***, ***sustainable harvesting techniques for cultural resources*** (e.g., yucca), ***customary methods for cleaning and maintaining the springs***, ***best practices for mechanical dryland farming*** (e.g., "how to use a tractor"), and the types of ***soil and nutrients*** in typical Hopi fields. Our interviewees suggested these types of efforts could be conducted as workshops in the villages and/or offered by the Hopi Department of Natural Resources either in person or as webinars. Several people mentioned that whatever education efforts take place, they need to be conducted in such a way that they easily can be understood by anyone participating. One person suggested that the ideal person to lead a drought education effort is a Hopi who is well educated in both Hopi ways and the relevant western science. Another recommended that the tribe develop a "train-the-trainer program" specifically about Hopi drought issues.

Public outreach

Closely related to the theme of drought education, 12 of 21 respondents indicated an interest in more public outreach from the tribe about drought. Ten people said they would like to see more routine reports from the Department of Natural Resources about ***current and expected drought conditions***. Though a few respondents mentioned wanting information about range conditions and availability (or not) of water on ranges (e.g., which windmills are functional and which stock tanks have water), most people simply called for more regular reports or presentations from the tribal government about local conditions to help inform decisions. The overall idea that emerged from these comments was a desire to have more routine outreach—both in person and in written reports—from the Hopi DNR about conditions across the reservation. Two people also specifically said they wanted the DNR to routinely let citizens know what types of resources are available from the tribe (e.g., the Office of Range Management) and the federal government.

Five respondents mentioned wanting more outreach from the tribe on existing ***planning*** efforts related to drought. Three people specifically said they wanted to know more about the ***drought plan*** and related efforts, and two wanted more information about how the tribe is planning to deal with drought-related ***emergencies*** (e.g., potential water shortages). One person called for more outreach about how the tribe is ***enforcing range management plans***.

As with the request for more drought education, there were several comments about the need to make any drought outreach from the DNR or the tribal government more broadly accessible to all citizens (e.g., not technical).

Proactive planning

Ten of the 21 people touched on their desire to see more proactive planning within both the tribal government and the villages. In general, the interviewees called for more future-oriented, community-based planning for ongoing drought and acute drought-related emergencies (e.g., water shortages and insufficient forage). Four respondents specifically mentioned the need for more proactive planning related to ***water sustainability***, three called for more robust range permitting, and two people mentioned the need for ***updating the existing Hopi drought plan***. One quote in particular summarizes much of what was noted related to planning: "Need to be more proactive and less reactive."

Improve monitoring

Eight people mentioned the need for better drought monitoring on Hopi lands. Most of these comments were about keeping track of ***local conditions*** (e.g., temperature, precipitation, wind, forage conditions, surface and shallow groundwater resources) to inform decisions. One person specifically mentioned the need for this kind of data and information to support grants and other funding requests.

Infrastructure improvements

Six respondents identified improved infrastructure as a necessary response to drought conditions, including ***upgrading range water infrastructure*** (e.g., windmills, earthen dams, and stock tanks) and ***improving plumbing for domestic water*** in the villages to reduce leakage.

Community engagement

An overarching theme that was woven through many of the comments was the idea that the DNR could be more directly engaged with citizens and the villages on drought issues. Several people pointed out that the villages—and in some cases individual citizens—could provide data and information that might be useful for drought planning and monitoring, with one suggesting that since "local area people…know the area and the conditions" their knowledge could be better utilized. Several others pointed out that villages have the means to disseminate information to citizens (e.g., through Community Service Administrators) about drought, though that is not generally happening now. As mentioned above in the "Education" section, several people suggested that villages could host workshops on a range of topics related to drought impacts, farming/ranching practices, traditional Hopi drought-response practices, and water conservation. The general idea that emerged from all of these comments was that more engagement between the DNR, the villages, and individual citizens is a promising path forward for drought monitoring and planning.

Consistent water policies

Another overarching theme that emerged throughout the interviews was a desire for clearer water policies across the Hopi Reservation. These comments about water policy arose in response to multiple questions, but in general they touched on the lack of clarity about how the tribal government could assist villages in the event of water shortages, the perceived need for more consistent water conservation planning, and more focus on understanding existing and potential future supplies. Three people specifically mentioned the idea of developing a tribal water utility program—as opposed to the current village-scale water management—that could address these and other concerns across the reservation. Regardless of the particular means for achieving more consistent water planning, the message that arose from these comments was that many of those we interviewed felt that more clear and consistent water policies were needed on the Hopi Reservation.

INTERVIEW QUESTIONS

About Drought

1. What is your definition/understanding of "drought"?

Current Drought Response

2. Have drought conditions impacted you, your family, or your community? If yes, in what way?
    a. Economic Impacts.
    b. Social Impacts.

3. Have you observed the impacts of drought on the natural resources of the Hopi Tribe?

4. How do you, your family, or community members cope with the drought impacts you have listed above?

5. What ways can we cope/adapt to the impacts of drought if the conditions worsen/persist in the long-term (beyond 10 years +)?

Drought Information (Present and Future)

6. What sources, if any, do you rely on to obtain information related to climate or drought conditions?

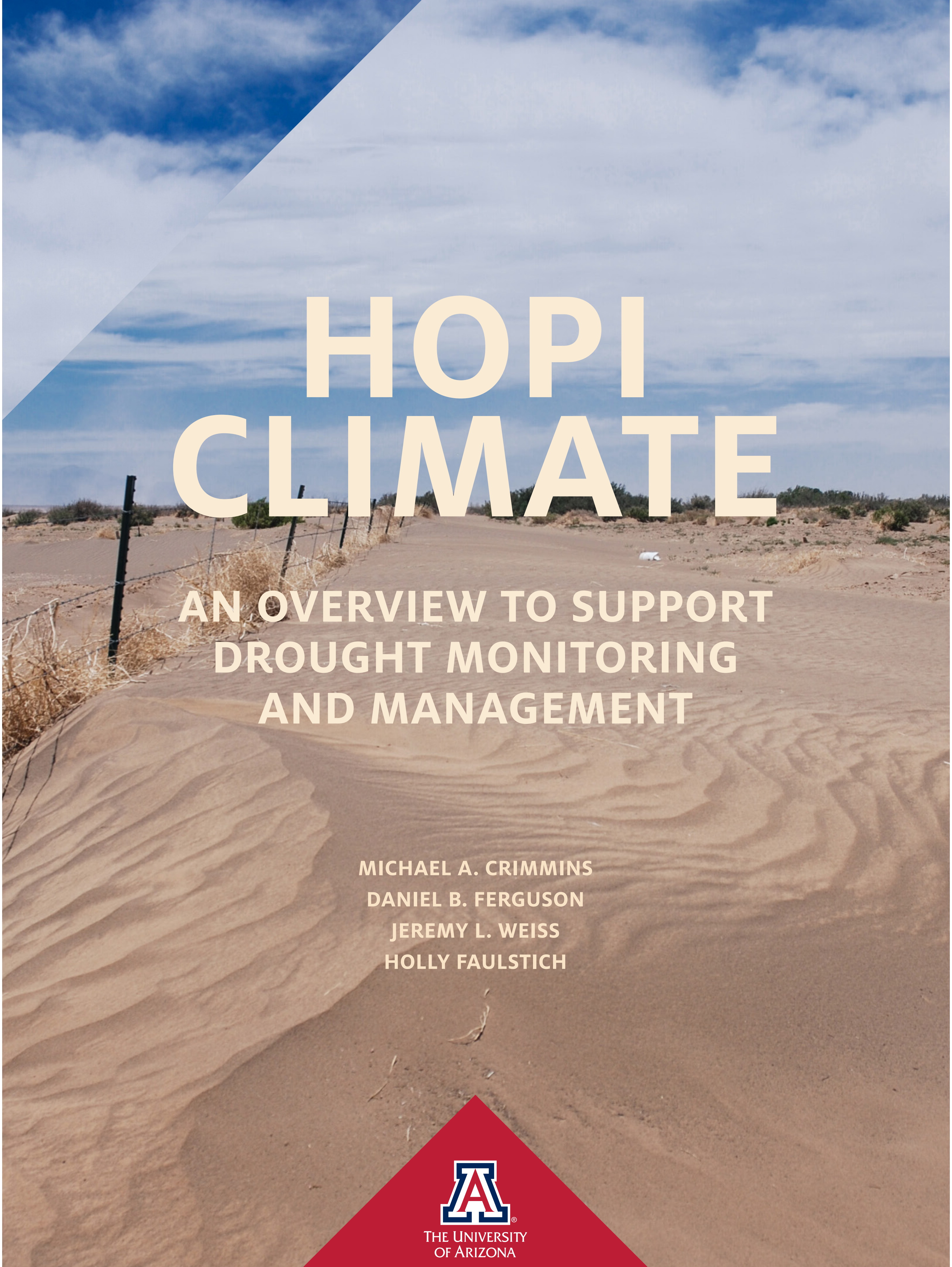
7. What kind of information about drought conditions on the Hopi Reservation would be useful to have?

8. Are you aware of any entities that can provide information to the Hopi community regarding drought conditions on the Hopi Reservation?

Drought Policy/Planning

9. How can communities/individuals become involved in drought planning and monitoring efforts on the Hopi Reservation?

10. What kind of information and responses to drought would you like to see from the Hopi tribal government?



HOPI CLIMATE

AN OVERVIEW TO SUPPORT DROUGHT MONITORING AND MANAGEMENT

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HOPI CLIMATE: AN OVERVIEW TO SUPPORT DROUGHT MONITORING AND MANAGEMENT

The climate of the Hopi Reservation is one of extremes. Situated on the Colorado Plateau in northeastern Arizona (Figure 1) it can experience very cold winters, hot summers, and exceptional variability in precipitation amounts across the reservation and between seasons and years. The landscape reflects the climate, with vegetation communities varying from conifer (i.e., piñon-juniper) woodlands at cooler and wetter higher elevations to grasslands and desertscrub communities at warmer and drier lower elevations

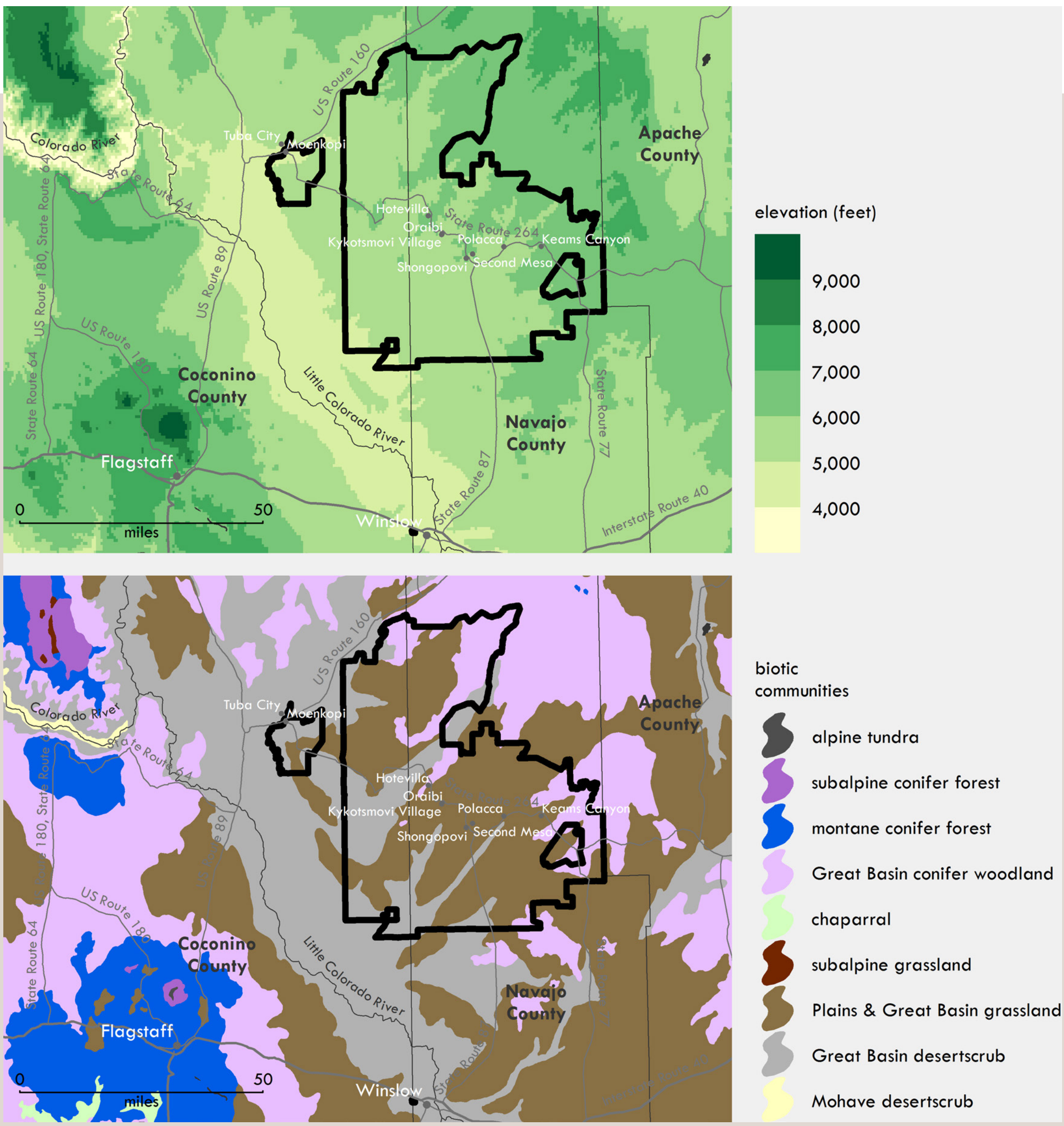

Figure 1. Elevations (top) and biotic communities (bottom) within and around the Hopi Reservation. Elevation data are available at http://www.prism.oregonstate.edu/normals/ (Daly et al. 2002). The Nature Conservancy provided biotic community (i.e., biome) data that are based on Brown (1994).

CLIMATOLOGY OF MONTHLY TEMPERATURE AND PRECIPITATION

On average, the Hopi Reservation receives about 8.5 inches of precipitation each year with higher elevation areas typically receiving more and lower elevation areas less (Figure 1.). Temperatures also vary with topography and throughout the year, but the annual average high temperature is 67°F and the annual average low temperature is 37°F, a climate pattern typical of a cool, high desert location.

Another unique feature of the climate of the Hopi Reservation is that it varies seasonally between winter and summer wet seasons and dry intervening seasons in the spring and fall. This seasonal-transitional climate is unique to the southwest U.S. where winter storms from the west and northwest bring much of the cool season precipitation to the region and the North American Monsoon System brings moisture and convective thunderstorm activity from the south into Arizona and New Mexico. Figure 2 shows the long-term average monthly precipitation and temperature for the Hopi Reservation for each month of the year. The bars depict higher precipitation from December through March and drier conditions in the spring (April-June) as the winter storm track shifts to the north away from the region. A dramatic increase in precipitation is observed at the onset of the monsoon season in early July that typically lasts through late September (Crimmins 2006). A shift towards climatologically drier conditions occurs again in October and November, which are transition months away from monsoon and tropical-type precipitation back into a winter storm pattern. The two wet seasons of December–March and July–September are a key feature of the region's seasonal-transitional climate. The characteristics of precipitation between the two seasons is also dramatically different. Winter storms typically bring precipitation in the form of snow or long duration, low intensity precipitation events that can recharge soil moisture reserves and contribute to replenishing local water resources. Summer precipitation typically arrives as highly localized, intense convective storms that can produce high levels of runoff and erosion, but also is important moisture for warm season range grasses. This seasonality in precipitation can drive both short and long term drought cycles and requires careful monitoring to track potential impacts at different timescales.

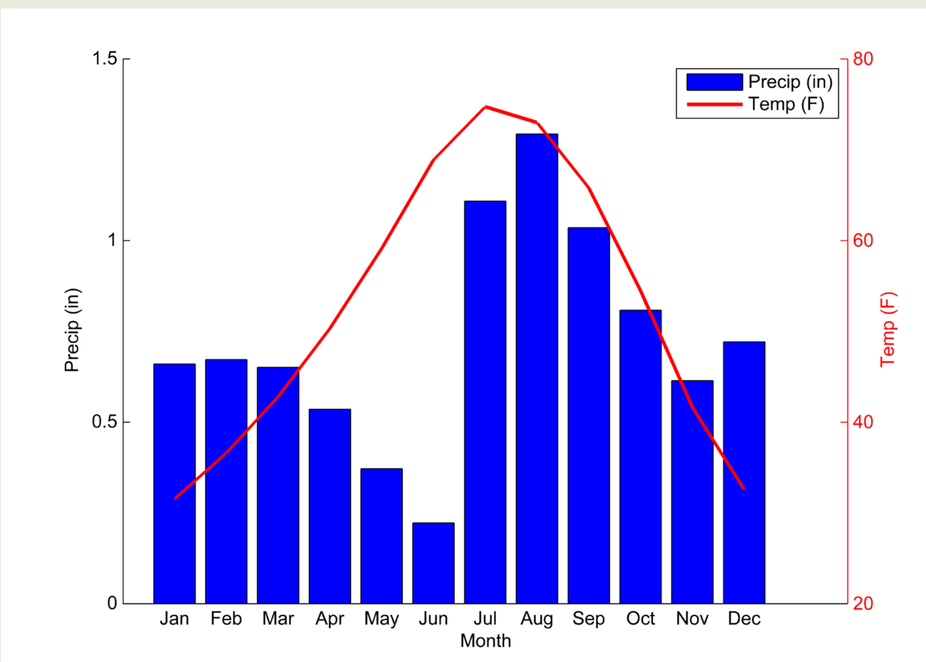

Figure 2. Monthly average temperature and precipitation for Hopi (calculated from PRISM gridded climate data, Daly et al. 2002)

A CLOSER LOOK AT CLIMATE EXTREMES

Data from two long-term weather stations on and around the Hopi Reservation allow for a closer examination at what types of climate extremes may be expected for this region. Figure 3 shows climate summary plots for Tuba City (4,988 ft. above sea level), and Keams Canyon (6,205 ft. above sea level) both with data extending back to the late 1800s. These plots show the daily averages and extremes for several climate variables including temperature (top plots) and precipitation (bottom). These stations are only 60 miles apart and have very similar climates, but the data reveal important differences as well. For example, Tuba City (at a lower elevation) observes much warmer temperatures and fewer cold extremes than Keams Canyon. Many of Tuba City's record temperatures are well above 100 °F in the months of June and July (red bars in top-left plot), while Keams Canyon has observed many record lows below 0 °F (blue bars in top-right plot). These record highs and lows for these two relatively close locations represent a temperature range of over 120 °F. More statistics for these stations can be found at http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?az4586 for Keams Canyon and http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?az8792 for Tuba City.

The seasonality of precipitation between the winter and summer seasons is also evident in the bottom two plots that show daily average (very small green bars) and record precipitation amounts (blue bars) for the two stations. As expected, winter precipitation amounts and extremes are slightly higher for the higher elevation Keams Canyon station with daily record amounts regularly above 0.5 inches and several instances of total daily precipitation in excess of 1.5 inches. This is less the case during the summer and fall seasons when convective thunderstorms bring extreme precipitation to both stations. Keams Canyon has observed several days during the summer season with total precipitation in excess of 1.5 inches, but so has Tuba City. Interestingly Tuba City has observed much higher precipitation extremes in the summer than Keams Canyon with several daily precipitation amounts in excess of 2 inches. All of these daily records occurred in the month of September and were most likely associated with late monsoon season thunderstorm activity and tropical storm systems (Hereford and Webb 1992).

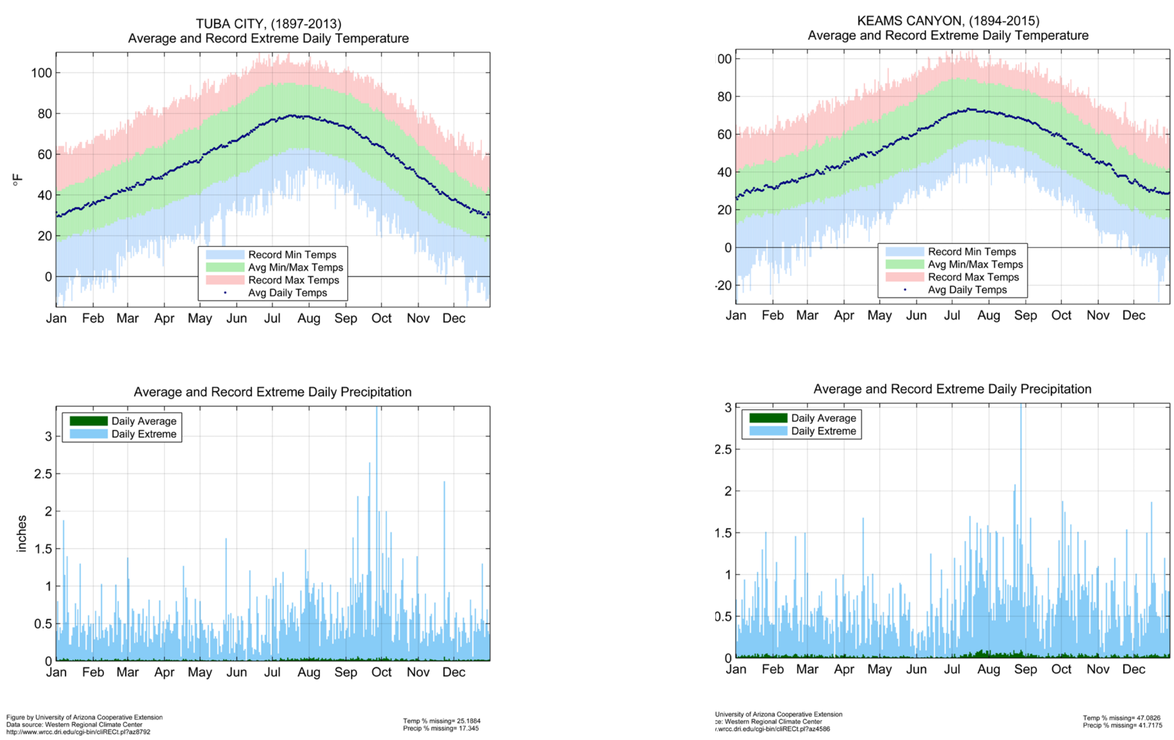

Figure 3. Daily temperature and precipitation summary plots for Tuba City and Keams Canyon, AZ.

MEASURES OF ARIDITY

Another subtle difference related to elevation differences between these two stations and the seasonality of precipitation is in the levels of the aridity these two locations experience. Aridity is the degree of dryness a location experiences and is a typical feature of desert locations. The level of aridity is controlled by the interplay between local levels of precipitation and levels of potential evapotranspiration throughout the annual cycle. Potential evapotranspiration is a measure of the amount of water that would evaporate from soils and water bodies and transpire from plants if sufficient water were available (which is almost always never present in an arid climate). The level of potential evapotranspiration is controlled by several factors including amount of sunshine, relative humidity levels, wind speed, and temperatures. High amounts of sunshine, high wind speeds, low relative humidity, and high temperatures can drive high levels of potential evapotranspiration. The plots in Figure 4 show estimates of average daily potential evapotranspiration (calculated only from temperature values) through the calendar year for Tuba City and Keams Canyon. The light tan bars in both of the top plots indicate the average daily potential evapotranspiration (PET) amounts for each day of the year. Note how PET values peak at over 0.25 inches per day in the June and early July period, the hottest and driest part of the year. These values can be totaled over the year (bottom plots) to get a rough estimate of the average water balance between incoming precipitation and atmospheric demand on this water through evaporation and transpiration from plants. On average Tuba City observes 6 inches of precipitation each year, but given its hot and dry climate through the spring and early summer has a total estimated PET value of 57 inches indicating a huge climatological water deficit or high level of aridity (bottom-left plot). Keams Canyon which is slightly higher in elevation and slightly wetter and cooler observes about 11 inches of precipitation on average each year and a PET value of 52 inches; a slightly lower deficit, but still indicative of an arid climate. A basic understanding of aridity and the interplay between temperature and precipitation can be a useful tool in tracking potential drought impacts. **Drought events accompanied by temperatures that are much above-average can have much higher levels of PET as well. This could drive higher levels of stress on vegetation and water resources much more quickly than simple precipitation monitoring may indicate.**

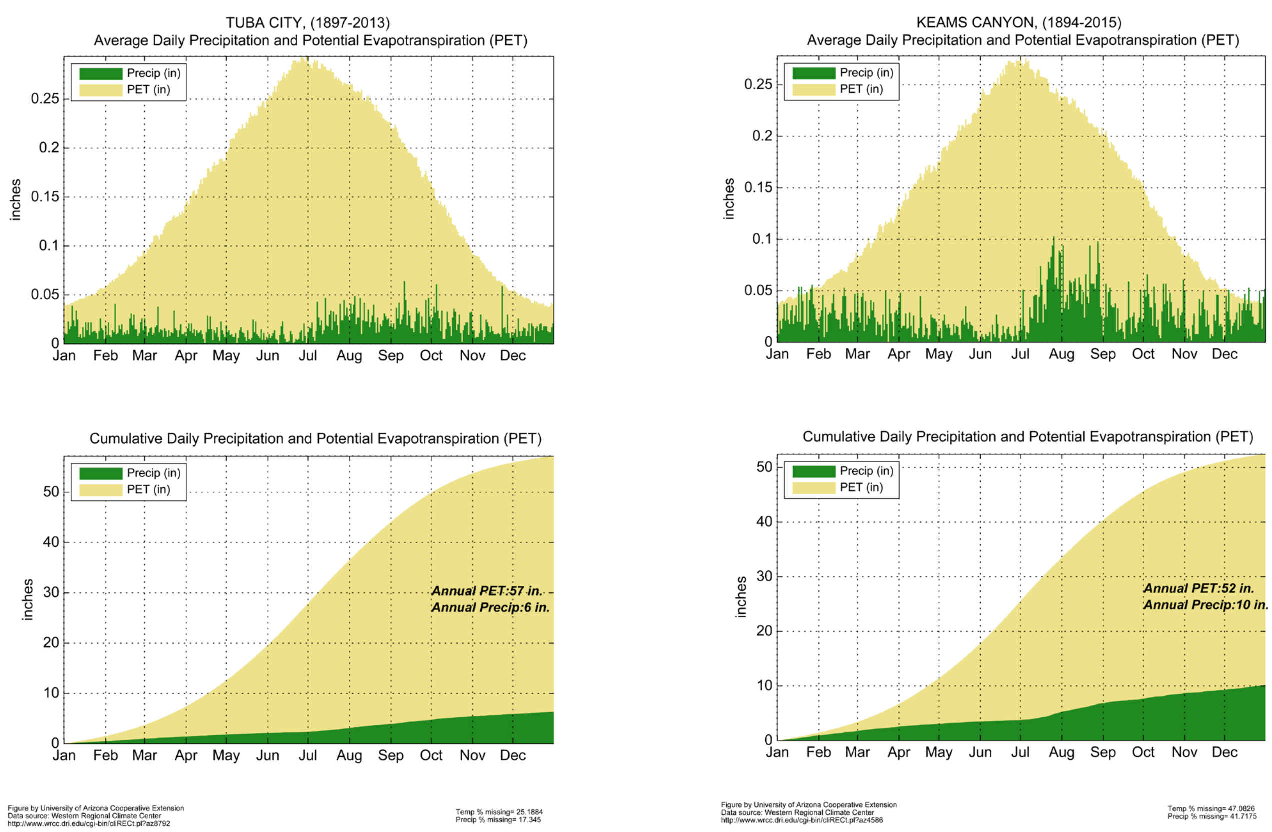

Figure 4. Daily precipitation and potential evapotranspiration summary plots for Tuba City and Keams Canyon, AZ.

PALEOCLIMATE VARIABILITY

The southwest U.S. is subject to large amounts of natural variability in precipitation amounts from year to year (Woodhouse et al. 2010). This is especially true for the Hopi Reservation when considering the importance of winter and summer precipitation separately and how these seasons vary over time. A recent study (Faulstich et al. 2013) examined tree-ring based reconstructions of both cool (October-April) and warm (July-August) season precipitation for the Four Corners region. By examining the width of tree ring samples collected across northeast Arizona and northwest New Mexico they were able to estimate seasonal precipitation amounts for the period of 1597-2008. A key finding from this study was that drought occurring in both the winter and following summer, or dual-season droughts, was more common over the past 400 years than has been observed over the past 100 years. In this study dual-season droughts were also linked to historical and archaeological evidence of major impacts to Native American communities across the Four Corners region including famines and migrations. The fact that dual-season droughts were more common in the extended precipitation record than in more recent records suggests that the risk of dual-season droughts is much higher than has been typically expected and requires special attention in planning and preparedness efforts.

YEAR-TO-YEAR VARIATIONS IN ANNUAL TEMPERATURE AND PRECIPITATION, 1900-2014

Over the past century, the lands that now make up the Hopi Reservation have experienced two distinct wet periods comprised of several consecutive years of above-average precipitation, one starting in 1905 and running through the early 1910s and again in the late 1970s through the late 1980s. Droughts were also very common over the past century with a pronounced dry period in the early 1900s, deep drought conditions through the 1950s and early 1960s, and again in the late 1990s up through the end of the data record in 2014. The data in Table 1 shows that the two driest years in the 115-year record are 2009 with only 4.6 inches of precipitation observed (53% of average) and 1989 with 4.65 inches of total precipitation observed.

Precipitation variability over the past two decades (i.e., 1990s and 2000s) is somewhat different than the patterns observed earlier in the record. Since the wet period observed in the 1980s, annual precipitation amounts have switched rapidly between above-average and below-average levels leading to rapid swings between intense short-term drought conditions and unusually wet conditions. Overall, 11 of the 15 years between 2000 and 2014 were below average indicating the extended duration of the current drought even with intervening near-average or above-average precipitation years. The 24-month Standardized Precipitation Index (SPI) time series depicts this rapid switching between unusually wet and dry conditions especially evident between 1990 and 2014 with increasing drought intensity and duration (Figure 6). Note how the cumulative effect of multiple dry years from 1999 to 2003 led to the most intense drought conditions observed in the entire period of record. Even though 2002 wasn't the driest year on record, it was the peak of the driest multi-year drought in the past 115 years across the region.

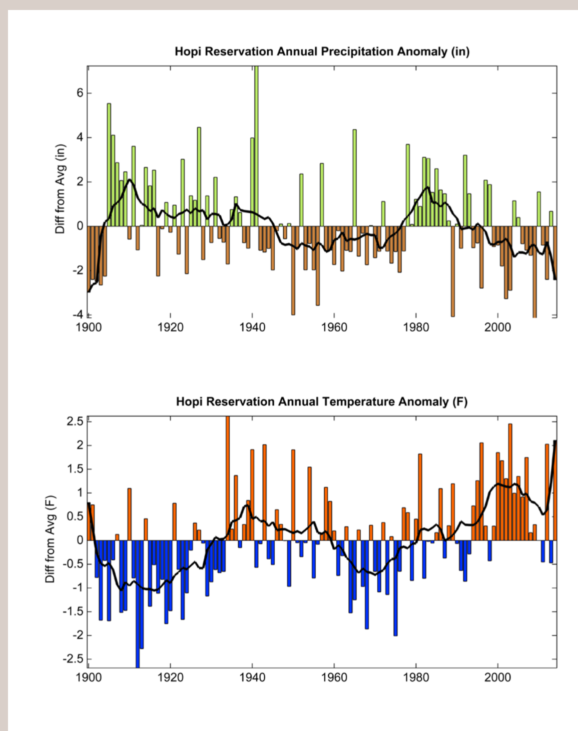

Figure 5. Annual precipitation and temperature differences from long-term averages

Much of the inter-annual variability and longer-term wet and drought cycles are related to the El Niño-Southern Oscillation or ENSO (see http://www.climas.arizona.edu/sw-climate/el-ni%C3%B10-southern-oscillation for more information) and its well-known impact on influencing the winter weather pattern across the southwest U.S. (e.g. Hereford et al. 2002). Strong El Niño events typically bring wetter than average winter conditions while La Niña events tend to bring the opposite with drier winters. The relationship between ENSO and summer precipitation is much weaker and less clear. Overall the most recent drought conditions (since the late 1990s) are well connected with several strong La Niña events (e.g., 2011 and 2012) that predictably led to drier than average conditions, reinforcing the nearly two decades-long drought.

This period has also been much warmer than any other period in the past 115 years (bottom panel, Figure 5) with 12 of 15 years between 2000 and 2014 logging above-average temperatures. Four of the top five warmest years on the Hopi Reservation (Table 2) all occurred since the late 1990s with two near the end of the record. This warming observed at the regional level is consistent with trends related to human-caused global warming and is expected to continue well into the future (Garfin et al. 2013). As discussed earlier, warmer temperatures lead to higher rates of evapotranspiration creating additional water stress on plants and water resources. Several studies focusing on the southwest U.S. have demonstrated that the above-average temperatures observed in the past decade coincident with recent drought conditions have exacerbated drought stress and impacts across the region (Breshears et al. 2005, Weiss et al. 2009, 2012).

Year	Total precipitation (in.)	Difference from average (in.)	Percent of average
2009	4.60	-4.13	52.7
1989	4.65	-4.07	53.3
1950	4.73	-3.99	54.2
1956	5.15	-3.57	59.1
2002	5.46	-3.26	62.6
1900	5.75	-2.97	65.9
2003	5.84	-2.89	66.9
1996	5.94	-2.79	68.0
1903	6.08	-2.65	69.7
1902	6.24	-2.49	71.5

Table 1 Top ten driest years for Hopi Reservation from 1900-2014.

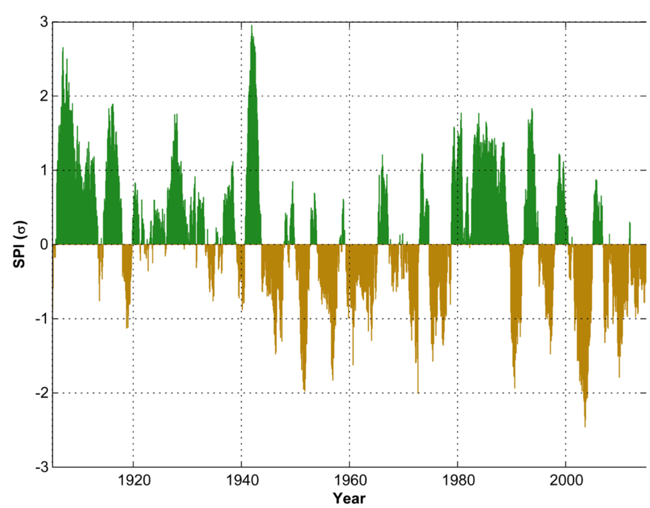

Figure 6. Long-term drought conditions depicted by the 24-month Standardized Precipitation Index.

SHORT- VS. LONG-TERM DROUGHT

Long-term cycles in wet and dry periods, the constant seasonal shift from wet to dry seasons, and different characteristics of precipitation between winter and summer can create a complex picture with respect to drought impacts and drought monitoring. Drought is typically tracked at timescales of seasons to years, but given the nature of the seasonal-transitional climate of the region, drought impacts may emerge or disappear at different timescales, necessitating tools that can track both short and long timescales of drought. For example, multiple years of below-average precipitation during the winter may impact local water resources and are indicative of a longer-term drought impact. During this same time period, plentiful summer rains may lead to average or even above-average range conditions, but may not improve the longer-term deficits impacting water resources. In other words, long-term drought conditions may exist even when short-term drought conditions may not. An index that can capture different timescales of precipitation variability, like the SPI, can help detect and track situations when short- and long-term drought do not necessarily match.

Figure 4 is an illustration of how short- versus long-term drought conditions can differ at any given point in time. The graphic depicts monthly SPI values calculated from 1 to 60 months with longer time scales (longer-term drought) towards the top of the graphic. Green colors indicate wet conditions and yellows and browns indicate drought conditions. The color patterns lean to the right because immediate changes in monthly precipitation, either unusually wet or dry (Figure 4, bottom panel), impact slowly varying systems like surface water systems and ecosystems. With this drought index, what matters most is both the intensity of the monthly anomaly (whether a given month was above- or below-average) and how many months were above or below average in a row. Note how intense drought conditions developed in 2002 over many months leading to very low SPI values at short and long timescales. This intense drought period was followed by the very wet winter season of late 2004 and 2005. The monthly precipitation values (bottom plot) show several months of above-average precipitation which undoubtedly brought short-term drought relief as indicated by the positive SPI values and green colors at timescales less

Year	Average annual temperature (F)	Difference from average (F)
1934	55.3	2.6
2003	55.1	2.5
2014	54.8	2.1
1996	54.7	2.1
2012	54.7	2.0
1943	54.7	2.0
1940	54.6	1.9
1950	54.6	1.9
2000	54.5	1.9
1981	54.5	1.8

Table 2. Top ten warmest years for Hopi Reservation from 1900-2014.

WHAT IS THE STANDARDIZED PRECIPITATION (SPI) INDEX?

The SPI takes precipitation data (typically at the monthly timescale) and converts it into standard deviation units and can do so for different window lengths of time. For example, a 1-month SPI for January 2014 is the value of the total precipitation observed for that month converted into standard deviation units. If the total precipitation was exactly the average, the SPI value would be 0 or positive if above-average and negative for a below-average value. This can also done at longer timescales (multiple months to years) to track longer-term drought conditions. For example the 12-month SPI ending on December of 2014 would represent the annual total precipitation and whether it was above-average (SPI>0) or below-average (SPI<0). Since SPI values are standard deviation units, they communicate additional information about the intensity or rareness of drought conditions. Values above or below 2 standard deviations would be expected to be very rare events (less than 3% of the time in the historical record), indicating very wet or dry conditions when examining a long data set.

than 20 months, but did fully erase drought at longer timescales. Long-term drought conditions remained at longer timescales that integrated the earlier deep drought conditions that developed in 1999 and peaked during 2002. These longer-term drought conditions may have been further relieved if wet conditions would have continued beyond 2005, but both the monthly plot (bottom) and SPI values show that drought conditions returned later in the year and continued for the next several years. The plot of SPI values provides a visual depiction of how multiple timescales of drought and no-drought can coexist and why tracking at least two timescales of drought (e.g. 6 month for short-term drought and 24 month for long-term drought) can provide important insight into why differential drought impacts may exist. See http://cals.arizona.edu/climate/misc/spi/spicont_Arizona2.png for a near-real time monitoring product at the climate division scale.

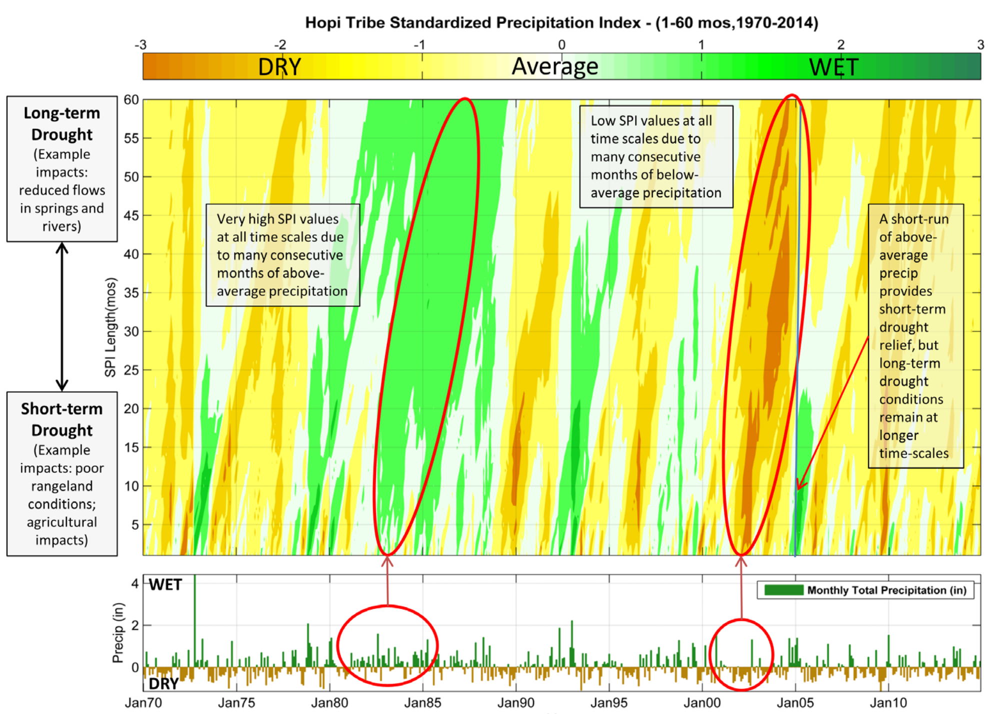

Figure 7. Multi-scale Standardized Precipitation Index plot for Hopi - 1970-2014

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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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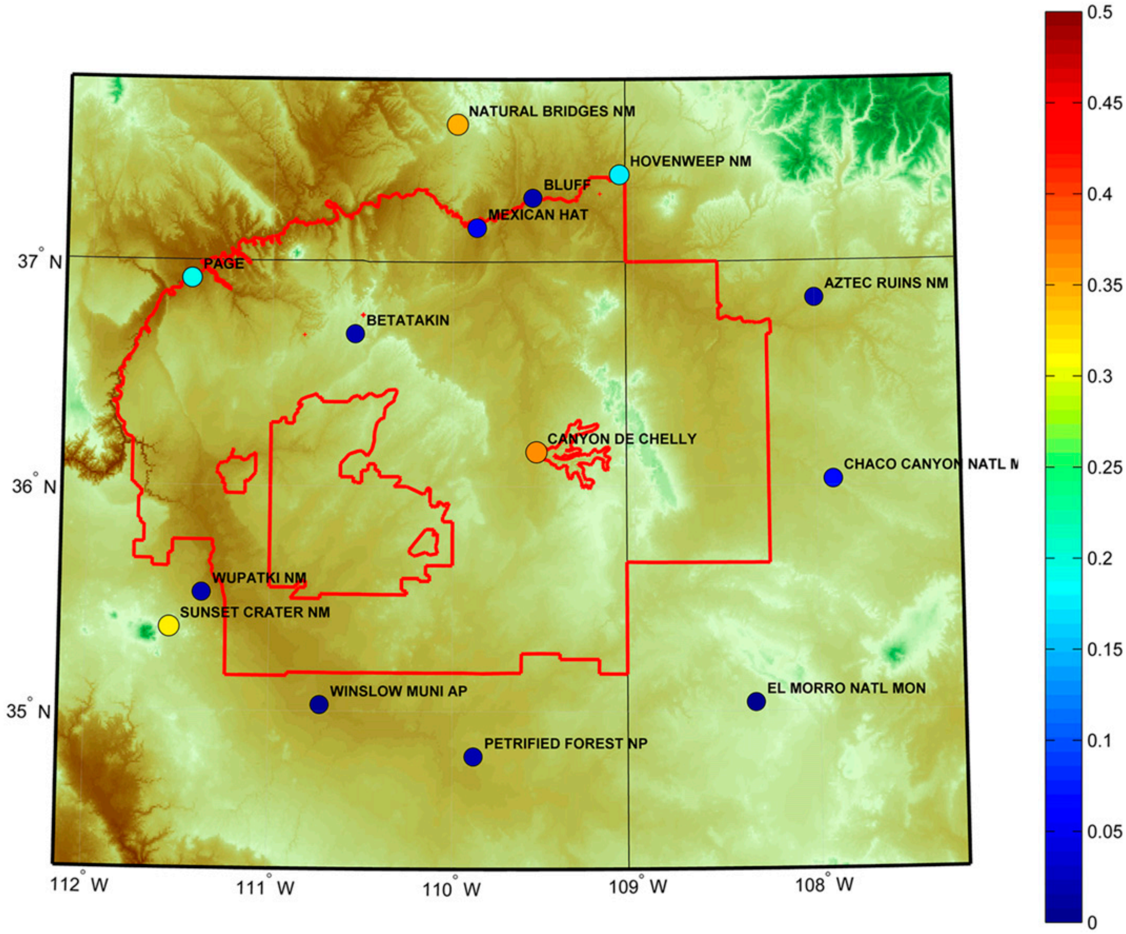

FIG. 1. The study region is shown with the periods of record for National Weather Service COOP network stations indicating the lack of high-quality climate data available on the Hopi reservation (indicated by the red polygon between 111° and 110°W longitude).

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 (Masayesva) 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 documents[1] 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. Masayesva 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.

[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.

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[ying] 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 mi^2 in two parcels: the main reservation is made up of three mesas

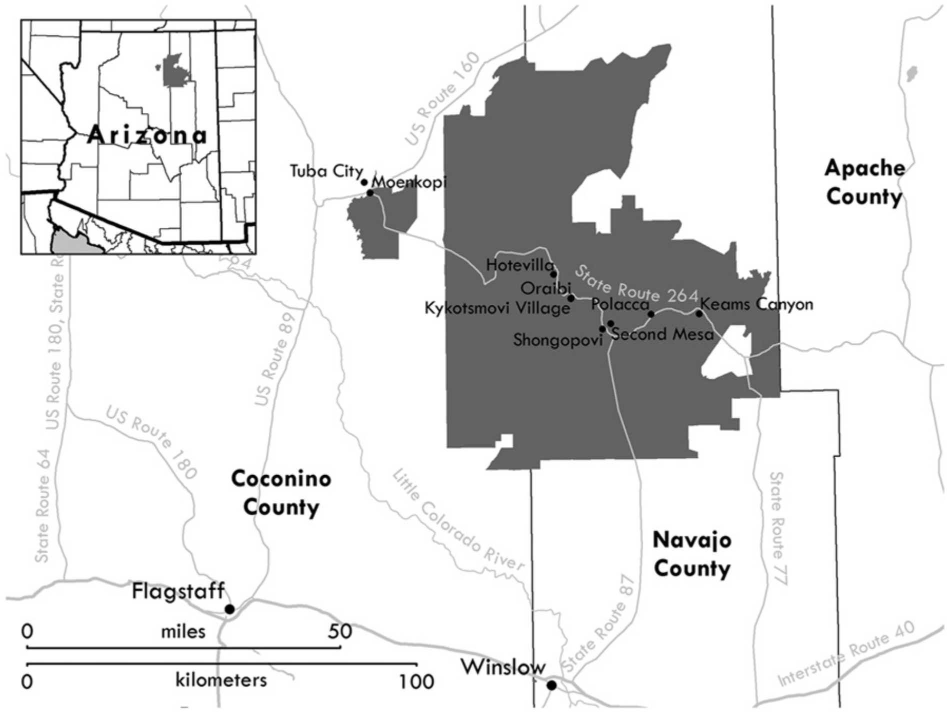

FIG. 2. The lands of the Hopi reservation (indicated in gray). Figure courtesy of Jeremy Weiss, University of Arizona.

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	• High costs of supplemental feed • Increased erosion
	Loss of surface water for livestock	• 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	• Reduced carry capacity of ranges • High costs of repairing and maintaining infrastructure (e.g., fences, roads)
Farming	Reduced crop yields and complete crop failures	• 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	• Reduced number of prey species • More wildlife encounters with people
	Increased presence of invasive species	• Many invasives inedible for stock and wildlife
	Reduced availability of edible, medicinal, other traditional plants	• 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	• Villages losing traditional water sources • Impacting irrigation practices at Lower and Upper Moenkopi
	Reduced recharge of aquifers	• Concern over loss of small seeps and springs throughout reservation that provide water for stock, wildlife
	Reduced flow in ephemeral washes	• 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's[2] use of groundwater is having

[2] The 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	Near normal	Initiate public awareness program and increase frequency of monitoring activities
		% normal	Near normal	
		SPI	0 to −0.99	
		PDSI	−1.00 to −1.99	
	Agriculture/range	Soil moisture	Near normal	Evaluate use of less productive fields, maintain forage reserve, and ensure rotation of livestock
		Vegetation index	Near normal (41%–70% relative greenness)	
		Range condition	Good (50%–75% climax)	
	Hydrology	Standard soil moisture index (SSI)	0 to −0.99	Increase frequency of monitoring activities
		Surface water storage	Near normal	
		Groundwater supply–demand ratio	Good (110%–130%)	
Moderate drought	Meteorology	Climate	Below normal	Increase public information activities by relaying status of water supply and measured impacts, and notify drought relief agencies of potential need
		% normal	Below normal	
		SPI	−1.00 to −1.49	
		PDSI	−2.00 to −2.99	
	Agriculture/range	Soil moisture	Near normal to below normal	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
		Vegetation index	Below normal (1%–40% relative greenness)	
		Range condition	Fair to good (25%–75% climax)	
	Hydrology	SSI	−1.00 to −1.49	Rehabilitate water storage structures, springs, and wells, seek voluntary limits on nonessential use, and require audits for high-volume users
		Surface water storage	Near normal to below normal	
		Groundwater supply–demand ratio	Fair to good (90%–130%)	
Severe drought	Meteorology	Climate	Below normal	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
		% normal	Below normal	
		SPI	−1.50 to −1.99	
		PDSI	−3.00 to −3.99	
	Agriculture/range	Soil moisture	Near normal to below normal	Request financial assistance, reduce livestock numbers, lease additional grazing areas, improve water conveyance efficiencies, and begin conjunctive uses of surface and groundwater
		Vegetation index	Below normal (<40% relative greenness)	
		Range condition	Poor to fair (0%–50% climax)	
	Hydrology	SSI	−1.50 to −1.99	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
		Surface water storage	Near normal to below normal	
		Groundwater supply–demand ratio	Fair (90%–110%)	

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	
		PDSI	−4.00 or less	
	Agriculture/range	Soil moisture	Below normal	All of the above severe drought actions, plus increase enforcement activity in regard to range codes and permit condition violations
		Vegetation index	Below normal (<40% relative greenness)	
		Range condition	Poor to fair (0 to 50% climax)	
	Hydrology	SSI	−2.00 or less	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
		Surface water storage	Below normal	
		Groundwater supply–demand ratio	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 is 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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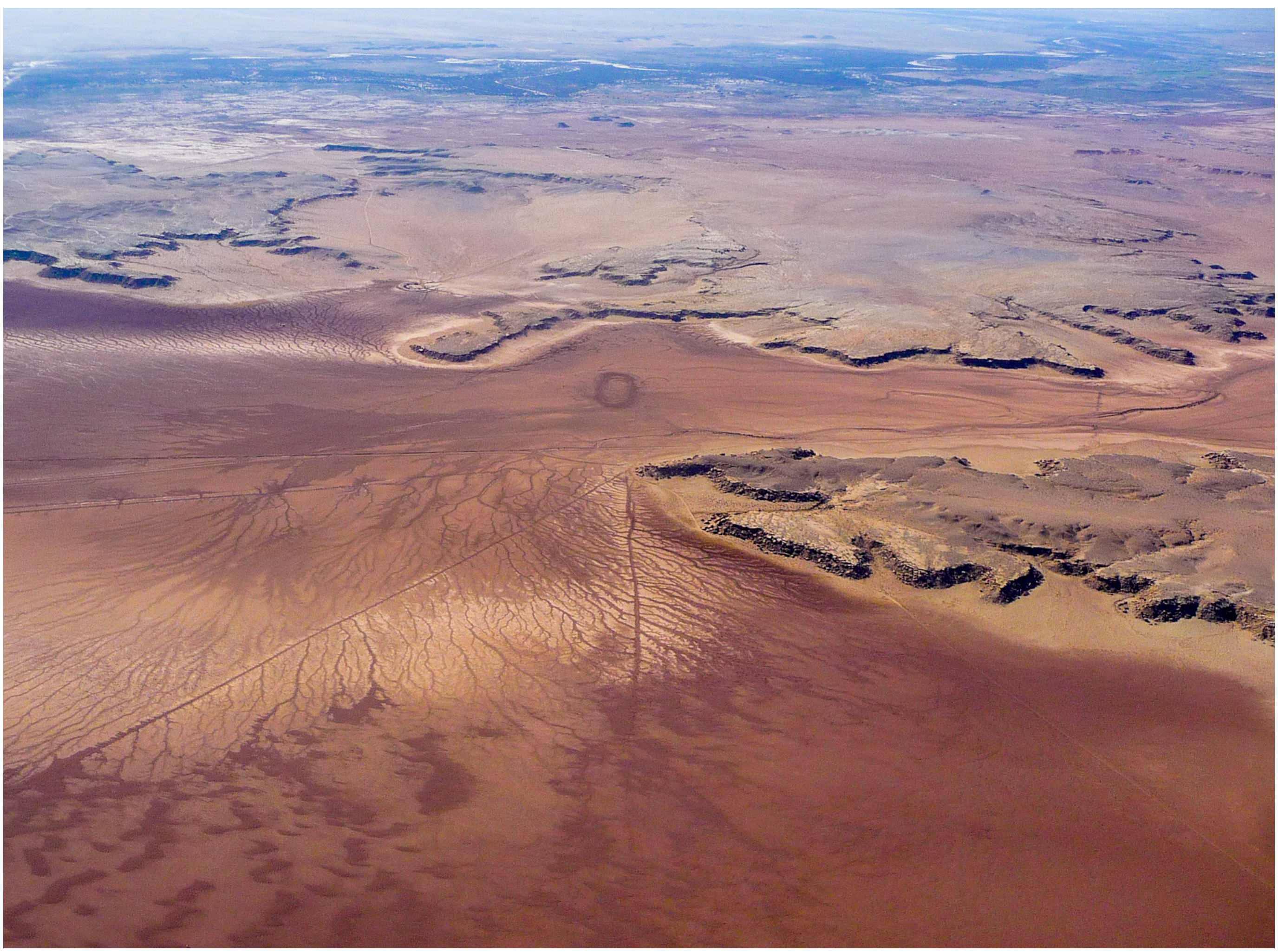

AERIAL PHOTOGRAPH OF THE LITTLE COLORADO RIVER FLOODPLAIN NEAR HOPI BUTTES. PHOTO CREDIT: JON MASON AND JODI NORRIS

HELPING a Community DEVELOP a Drought Impacts REPORTING SYSTEM

BY ALISON M. MEADOW, DANIEL B. FERGUSON, AND MICHAEL CRIMMINS

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Can Monitoring the Impacts of Drought Improve Planning for Drought?

Unlike most weather, or climate-related hazards, drought does not have an easy or universal definition. Drought is, of course, simply a shortage of precipitation, but shortage for whom and by how much? Arguably, those who experience its impacts best define drought. Monitoring for drought, one might then assume, would rely heavily on observations of the impacts of drought. In fact, standard drought monitoring relies primarily on measurements of precipitation and streamflow to determine drought status in a particular region. Most experts in drought monitoring, planning, and response recognize the need for a greater focus on monitoring drought impacts, but such information remains a relatively small portion of drought status assessments due to the complex nature of drought impacts and the difficulty in ascribing a particular impact directly to drought – particularly if the observer is not specifically trained in resource management or monitoring.

Our recent work with the Hopi Tribe's Department of Natural Resources (HDNR), however, has helped convince us that depending on the circumstances of a particular community, impact observations can be at least as important as hydroclimatic data in determining drought status and selecting appropriate responses.

Community Sustainability

The Hopi people have lived in the Four Corners region of the southwest (Figure 1) for at least 1000 years (with some notable periods of absence during previous severe droughts[1]). This region has been experiencing frequent deep drought events over the past several decades with brief excursions back to average or even wet conditions (Figure 2). Overall this pattern of recent climate variability has produced acute short-term drought impacts in certain seasons (e.g., poor forage for livestock) and longer-term impacts to water resources (e.g., drying of near-surface springs) across the region. Persistent drought conditions negatively affect Hopi livelihoods by diminishing crop production from traditional farming, reducing the growth and abundance of culturally significant wild plants, and stressing livestock, which in some cases is driving ranchers to reduce herd size.

In conversations with tribal natural resource managers a clear message has emerged: this region is their home, they have neither the intention or the ability to move away, and they must, therefore, make the best possible resource management decisions to maintain the land and Hopi livelihoods. As one tribal resource manager told us, "We're not going anywhere, so we need to take care of what we have."

Over the last three years we have been working with the Hopi Department of Natural Resources to develop a drought status-monitoring program based largely on a diverse set of environmental indicators relevant to the region. In this case, impacts monitoring

[1]Oral and written histories of the region note that many Hopi people migrated to the Rio Grande region in the mid-1800s to escape severe drought. They returned to their traditional homelands once conditions improved (see for example Clemmer).

is a better choice than hydroclimatic data because it allows the community to: 1) work around the limited availability of long-term and readily available climate data in the region, 2) characterize drought status according to local needs and for local decisions, and 3) create a monitoring program that fits the current technological and resource capacities of the community. The following summarizes our process and some of our lessons-learned. We present it here in hopes of inspiring others to consider the role of locally relevant and consistently collected impacts data in drought monitoring and drought status assessment.

Hopi Drought Monitoring

As a complex natural hazard, drought affects different people and different communities in vastly different ways that are not always captured by hydroclimatic data. Sparse rains may lead to immediate drought impacts in one community without water storage capacity and have little-to-no impact on another community with ample water storage. Many Hopi people are dryland farmers and ranchers who rely on seasonal rains to support their crops and forage for their livestock. In this semi-arid region, the timing and form of precipitation matters as much as the amount. For example, a heavy rain that simply runs off parched soils is of little value to agriculture or ecosystems desperate for soil moisture, while a lighter, gentler storm may allow moisture to sink into the soil where it will be of greater benefit.

The unique sensitivity of the Hopi people to drought conditions has been especially acute in recent years. In 2009, the then-manager of the HDNR approached researchers at The University of Arizona with a problem. Tribal natural resource managers knew that drought conditions were severe, yet did not see their perception of conditions reflected in any of the national drought monitoring products, in particular the US Drought Monitor. Because drought monitoring is primarily focused on instrumental data, the fundamental problem for places like the Four Corners is a lack of reliable, long-term weather stations to generate that data (Figure 3 - see next page). The lack of data in turn hindered the HDNR's ability to declare and undeclare drought, take appropriate mitigation steps, or engage in public education about drought status and opportunities for drought aid. While the glaring lack of formal precipitation and temperature monitoring on reservation lands is a problem, this is a longer-term issue of funding for basic monitoring without an immediate solution. Through our partnership with the HDNR we have devised what we hope will provide a more immediate solution: utilize the existing resource management and technical staff within HDNR to develop a stream of monitoring information based on impact observations. By developing a local drought impacts monitoring program, the HDNR can tailor drought indicators to their own decision needs as well as their existing capacity for data management.

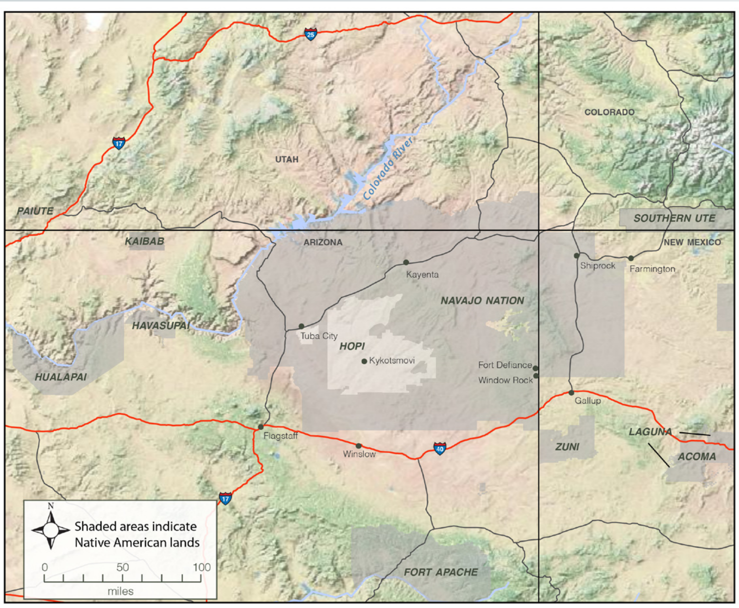

FIGURE 1. THE FOUR CORNERS REGION OF THE US SOUTHWEST WITH NATIVE AMERICAN LANDS HIGHLIGHTED.

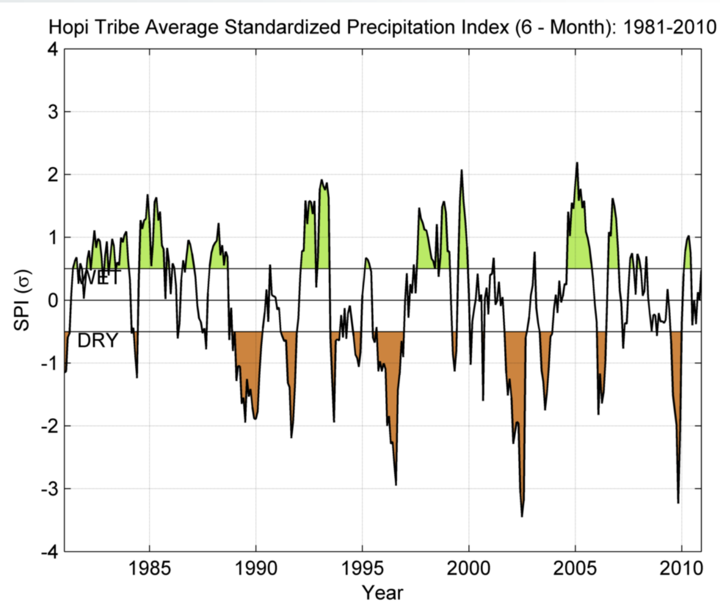

FIGURE 2. DROUGHT INDEX FOR HOPI TRIBE SHOWING INCREASING FREQUENCY OF DEEP DROUGHT EPISODES OVER THE PAST THIRTY YEARS (BROWN FILLED AREAS INDICATE SHORT-TERM DROUGHT CONDITIONS; CREATED USING AVERAGE MONTHLY PRECIPITATION DATA EXTRACTED FROM PRISM CLIMATE DATABASE).HIGHLIGHTED.

Process of Establishing an Impacts Monitoring Program

Identify community's needs

We began our collaboration with the HDNR with an assessment of their observations, concerns, wishes, and capacity related to drought monitoring. Among the tools we used was a focus group with resource managers that centered on a seasonal calendar to prompt discussion of when during the year precipitation is most important to Hopi livelihoods and whether managers have perceived any changes in the precipitation regime in recent memory. We also discussed pressing concerns about drought conditions including the potential for loss of traditional farming methods and crops; the requirement to reduce herd sizes placing an enormous burden on households with little other income; and the loss of culturally important plants that do not grow well under recent drought conditions.

Identify community goals

Our next step was to determine what a Hopi drought monitoring system would be used for. In many agricultural communities in the US, drought status is used as the basis for federal drought assistance. However, our preliminary assessment suggests that Hopi drought monitoring is used internally to guide tribal planning and mitigation activities such as providing financial support for ranchers who need to haul water for their livestock, to determine whether livestock reductions are necessary, and to inform the general public and elected officials about the state of the community's land and resources.

Identify key impacts for that community

To guide the development of a drought-monitoring program, we attempted to determine drought impacts that were most detrimental to the community. The concerns about drought consistently raised by HDNR staff included: poor forage for livestock, insufficient water for livestock (in springs or impoundments), and not enough precipitation (or at the wrong time) for the dryland agriculture.

Identify community assets

An important consideration in designing a monitoring program was that it fit the capabilities and resources available in HDNR. As with many resource management agencies at all levels of government, the HDNR are financially strapped and lack the technological resources to manage a data-intensive monitoring program. The HDNR is fortunate, though, to have resource technicians who are intimately familiar with the landscape and are regularly surveying the land as part of the tribe's resource management and grants reporting responsibilities. Because these technicians were out on the land, collecting ecological status information regularly, and were familiar with the landscape, we determined that implementing a drought impact monitoring program would essentially mean just tweaking the system already in place to incorporate a focus on drought impacts.

What's already being done in the community?

Identify gaps in best practices.

Our next step was to engage with the resource technicians and their managers to determine what kind of monitoring they were doing already, how they were recording the information, and how that information was managed and used within HDNR. Through this process we learned that different parts of HDNR were charged with monitoring different resources, collected data in different ways, and had differing levels of expertise. By examining the data collection forms for each branch of DNR, interviewing technicians from each branch, and going out in the field with technicians, we were able to compile a list of resources that are regularly monitored, those that are not, and how that data is used. For example, springs are checked and flow-rates measured monthly, but water levels in earthen dams, which provide water for livestock, were not systematically assessed on the same schedule.

Based on these insights, we are currently in the process of developing a short drought monitoring protocol for HDNR resource technicians. Not all technicians will answer every question (for example, water resources technicians are not expected to contribute rangeland status observations), but the format is the same for all technicians, meaning that the data can be assimilated in one main database by the HDNR. Our recommended drought impacts monitoring protocol for Hopi DNR will draw on their concerns, is based on existing monitoring practices, and fits the resources available within the HDNR.

Consider data management issues

A key lesson for our team was the need to carefully assess the data management and technological capacities of our partners. In the case of HDNR, both are limited due to funding and the relative isolation of the community (which limits internet bandwidth and cellular connections). While there are many technological tools that could be applied to monitoring drought conditions in an area with few weather stations—such as remote sensing technology—those were not an effective solution to the problems at

Hopi because they could not be easily integrated into existing technological or data management frameworks. By keeping the impacts monitoring list as short as possible (and still remain useful for decision makers), we hope to allow the HDNR to quickly integrate this data into their management structures.

Provide training to reporters

In addition to the drought impacts monitoring protocols, we are also developing a training module for the technicians who will be collecting the data. Although most are familiar with other ecological monitoring practices, our assessments demonstrated the need to provide some additional background on the importance of consistency in monitoring for drought. We will use a scenario-based approach to training in which the technicians are presented with a range of realistic situations so that we can all come to better understand how drought impacts data could be used to support resource management decisions. We will test the use of these protocols by accompanying resources technicians to the field to see how they work on-the-ground. We will also work with the data managers to see how information coming from the technicians is being uploaded to the drought database as well as what kinds of reports can and are generated based on the impacts data. Once the monitoring protocols have been implemented in the Hopi DNR, we will periodically return to evaluate how well they are being followed, whether more protocols have been added to the program, and how drought impacts data are being used in decision making.

This collaborative project has provided us with ample opportunities to explore the importance and practicality of monitoring drought through systematic collection of impacts data. We are at a relatively early stage in this experiment. We hope the new monitoring protocols will prove useful to and useable by the Hopi Department of Natural Resources and will strengthen their drought planning and response program. We also hope this work will provide lessons for other communities struggling to better characterize and track drought in their region.

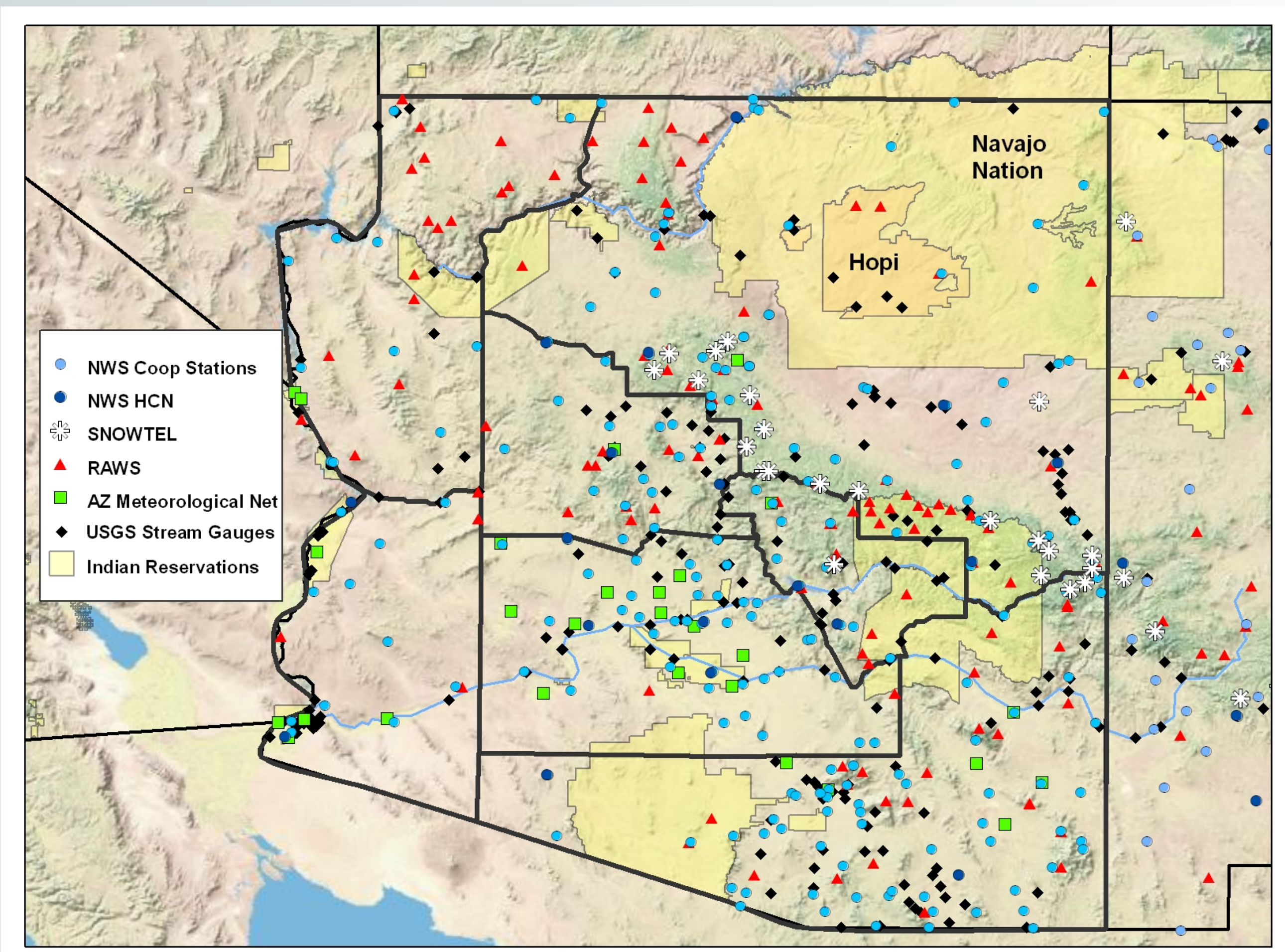

FIGURE 3. THIS MAP OF WEATHER AND STREAMFLOW INSTRUMENTS ACROSS ARIZONA HIGHLIGHTS THE RELATIVE DEARTH OF INSTRUMENTAL DATA AVAILABLE FOR TRIBAL LANDS (INDICATED BY YELLOW SHADING). MAP BY ZACK GUIDO, CLIMATE ASSESSMENT FOR THE SOUTHWEST, UNIVERSITY OF ARIZONA.

PHOTO: DANIEL B. FERGUSON