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Satellite-Based Drought Reporting on the Navajo Nation

A.J.K. McCullum, C. McClellan, B. Daudert, J. Huntington, R. Green, V. Ly, A.R.G. Marley, N.R. Tulley, C. Morton, K.C. Hegewisch, J.T. Abatzoglou, and D. McEvoy

Research Impact Statement: The Drought Severity Evaluation Tool (DSET) combines remote sensing, modeled, and in-situ data in a user-friendly web interface to meet the unique water management challenges of the Navajo Nation.

ABSTRACT: In data scarce regions of the world, co-produced management tools that combine remote sensing, modeled, and in situ data provide the information needed to support ground-based monitoring systems for improved water and natural resource management. On the Navajo Nation (N.N.), in the Four Corners of the southwestern United States, there is a need for data-driven management of water resources as the region is prone to water scarcity and emergency drought declarations, which have become more common under a changing climate. The current tools used by the N.N. Department of Water Resources largely lack the spatial detail, consistent measurements, and political and administrative information specific to their needs for determining appropriate response actions. The Drought Severity Evaluation Tool (DSET), a cloud-based web application that harnesses the capabilities of Google Earth Engine, is a user-friendly tool that pairs remotely sensed, modeled, and in situ data on the N.N. The DSET computing capabilities include on-the-fly generation of regional to field scale maps, time series figures, and reporting metrics that can assist in drought emergency declarations and the assistance to local communities through the subsequent allocation of relief dollars across the N.N. to the regions that need it most.

(KEYWORDS: remote sensing; water resource management; drought monitoring; cloud-computing.)

INTRODUCTION

The proliferation of satellite remote sensing applications and products for drought monitoring has provided unprecedented amounts of information on precipitation, evapotranspiration, snow cover, soil

moisture, and vegetation conditions. These data are integral to the identification and evaluation of drought severity, particularly in regions where ground-based monitoring is scarce, where resources are limited, and where topography is highly variable (Wardlow et al. 2012; AghaKouchak et al. 2015; Beck et al. 2019; West et al. 2019). While the availability

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of Earth Observations (EO) has increased rapidly in recent years, data products from these observations are generally underutilized by water managers for decision-making activities (Franklin 2001; Kansakar and Hossain 2016; Pettorelli 2019; Prados et al. 2019; Calders et al. 2020; Hatfield et al. 2020). This is particularly evident within sovereign tribal nations of the United States (U.S.), where although EO data have the unique ability to fill data and resource gaps, they are infrequently used (Kalluri et al. 2003). Barriers to the use of these data for decision making include large computational requirements, limited technical knowledge, numerous complex tools and data portals, lack of time and resources, minimal training and capacity building, and limited availability of operational products (Thakur et al. 2018; Prados et al. 2019). When operational remote sensing products and decision support tools are developed, they often do not meet the spatial and temporal resolution requirements necessary for supporting water management decisions. Additionally, these tools rarely provide the flexibility for users to create custom data requests that are specific to administrative boundaries, time periods of interest, or climatological summaries used in reporting.

In order to increase the use and adoption of remote sensing data and applications for water resource management, stakeholder engagement and co-production of knowledge between researchers and end-users during tool development is necessary and important. Sustained relationships, adaptive approaches, and continued stakeholder feedbacks provide an opportunity to tailor tools for decision making. Relationship building and informed, adaptive, and respectful consultation is particularly important when partnering with Indigenous communities (McGrath and Phillips 2008; Marcus 2010; Bureau of Reclamation 2012; Fordham and Montour 2015; Fitzpatrick et al. 2016). Partnerships and the co-production of tools regarding their land and natural resources is essential for respectful acknowledgment of multiple knowledge systems. For Indigenous communities, there exists a cherished connection between the people and their physical environment that must be considered (Chief et al. 2016). One such relationship-building effort is the Tribal Climate Tool, co-developed by the Climate Impacts Group at the University of Washington and Indigenous leaders, to help tribes in the Pacific Northwest and the Great Basin understand how climate change may affect their lands (Krosby et al. 2018). These considerations, when paired with a user-friendly tool design, trainings, and capacity building, provide an opportunity to increase the effective and continued use of EO for natural resource management (Prados et al. 2019). This iterative and engaged development process emphasizes the mission

of National Aeronautics and Space Administration's (NASA) Western Water Applications Office (WWAO), which tackles water resource issues in the western U.S. through the empowerment of decision makers with useful, accessible, and sustained remote sensing-based information.

In order to increase the operational use of EO data for water management, the Drought Severity Evaluation Tool (DSET) was co-developed by NASA and the Desert Research Institute in partnership with the Navajo Nation Department of Water Resources (N.N. DWR). This tool, based on Climate Engine (Huntington et al. 2017), allows users to perform on-demand cloud-based calculation and visualization of satellite remote sensing, modeled, and in situ climate variables, drought indices, and vegetation condition datasets. The DSET (<https://app.climateengine.org/dset>) includes administrative boundaries, ground-based precipitation data, and analysis and visualization capabilities specific to the needs of the N.N. The co-production process involved engagement with the partner prior to the start of the project, feedback/listening sessions during regular meetings and trainings, and adaptive modifications to the tool. Multiple training sessions with the partner during and after tool development occurred, in addition to the development of an online interactive User Guide with step-by-step tutorials and video demonstrations to facilitate sustainable use of the DSET. Thus, the DSET reduces the computational barrier of large and complex geospatial data, provides EO data at actionable spatial scales, and meets the needs of project partners. In this paper, we provide multiple case studies to demonstrate the applications of DSET for monitoring (1) drought, (2) snowpack, (3) high elevation lakes, and (4) agriculture.

BACKGROUND AND USER NEEDS

The N.N. is the largest sovereign tribal nation in the U.S. in total land area, with boundaries in Arizona, New Mexico, and Utah. The N.N. has an arid climate, with frequent and extended droughts that have been exacerbated by warming temperatures and precipitation deficits in recent years (Navajo Nation Department of Water Resources 2003, 2011; Woodhouse et al. 2010; Ferguson et al. 2011; Crimmins et al. 2013; Garfin 2013; Cook et al. 2015; Gonzalez et al. 2018; Tom et al. 2018; Williams et al. 2020). With a large land area of over 70,000 km², a population of nearly 200,000, and between 25–40 percent of the N.N.'s homes lacking direct access to public

drinking water systems, there are multiple and varied challenges to water management during long-term widespread droughts (Navajo Nation Department of Water Resources 2003, 2011). Natural resource management challenges are primarily related to agriculture and livestock management (e.g., overgrazing, dry-land farming water needs, feral horse populations) and ecosystem health (e.g., desertification, invasive species, watershed restoration). During periods of prolonged drought, these natural resource management issues are intensified.

The Water Management Branch (WMB) of the N.N. DWR is responsible for monitoring and reporting drought conditions. The current network of water resource monitoring includes eighty-five precipitation gauges, nine stream gauges, twelve weather stations, and eight snow courses. Limited funding, staff, and infrastructural constraints have made consistent and accurate data collection difficult. To determine the N.N.'s drought status, the N.N. DWR uses multiple data products: (1) six-month Standardized Precipitation Index (SPI) values from the Western Regional Climate Center (WRCC), (2) drought summaries from the U.S. Drought Monitor, (3) climate summaries from the Climate Assessment for the Southwest (CLIMAS), and (4) interpolated maps of precipitation from the network of gauge stations across the N.N. These maps and summaries are combined into monthly drought status reports that are provided to water resource managers in the region, the N.N.'s Commission on Emergency Management, the N.N. Council (akin to the U.S. House of Representatives), and the N.N. President. These parties use drought status reports to (1) make an emergency drought designation and to (2) disseminate emergency drought funding allocations across the N.N.'s five Agencies (akin to U.S. states) and 110 Chapters (akin to U.S. counties). However, drought status reports often contain data with coarse spatial resolution that result in single drought designations for large swaths of diverse landscapes. For example, the WRCC provides SPI values for the 344 climate divisions of the U.S. The entire N.N. is encompassed in three climate divisions, with the majority of the land encompassed in the largest climate division in the country, the Arizona climate division 2 (over 90,000 km²). The N.N. had previously used drought summaries for the states of Arizona, New Mexico, and Utah for drought reporting, and recent advancements in U.S. Drought Monitor maps now provide climate summaries for the entire N.N. Additionally, the U.S. Drought Monitor and the CLIMAS maps do not provide Agency and Chapter-specific summaries for drought indices.

Due to the N.N.'s size and geographic variability, administrative areas are often times more or less impacted by drought when compared to drought

status reports. However, emergency relief resources are evenly distributed across affected administrative boundaries. With the introduction of the DSET, the N.N. DWR now has the ability to generate more spatially resolved drought information and summaries for each Agency and Chapter, alongside their ground-based data, to assess drought status and variability within administrative areas in order to allocate resources to the areas that need it most.

TOOL DEVELOPMENT AND METHODS

DSET Overview

The DSET is a spin-off of Climate Engine (CE), a Google Earth Engine (GEE) (Gorelick et al. 2017) based web application that enables users to process, visualize, download, and share global and regional climate and remote sensing products on-demand (Huntington et al. 2017). The parallel cloud-computing of GEE is used to overcome data storage and processing limitations that are especially burdensome to stakeholders. The user-centric design focuses on the ability to conduct analyses and generate visualizations, such as customizable maps and time series, that can be used directly for drought analysis and reporting (Huntington et al. 2017). The DSET has dual-purpose mapping and time series analysis functionality. In the mapping view, climate and remote sensing variables can be displayed with common calculations (climatologies or anomalies) and statistics (mean, median, maximum, minimum, and total) for specific time periods. Additional mapping features such as color palette and transparency adjustment, and the ability to overlay common vector layers such as watershed boundaries make results and figures customizable. In the time series view, users can conduct one or two variable analyses and display data from a point location or area average, daily values, or annual summaries over a defined time period (e.g., month(s), seasons, calendar year, or water year [WY]). The time series figures are dynamic, allowing the user to interact with the display to identify values at each data point, zoom into a specific time period, and download the image or associated data in different formats. Most importantly, the DSET interface allows for data downloads in various formats including GeoTIFF and CSV, to allow users to further evaluate and publish results using existing software tools and workflows. This type of functionality has been shown to increase the ability of the partner to access and depict data for decision making (Sheffield et al. 2018).

N.N. DWR Specifications

While the DSET has the functionality of the standard CE user interface, additional features were added through an iterative process with the partner agency (N.N. DWR) and personnel from other N.N. natural resources departments (Figure 1). Additional features include (1) in situ precipitation data from the network of eighty-five N.N. rain gauges, (2) N.N. administrative boundaries and high elevation region layers, (3) on-the-fly area-averaged calculations of precipitation and the SPI from satellite/modeled sources, (4) previously unincorporated NASA data such as precipitation from the Tropical Rainfall Measurement Mission (TRMM) and from the combined TRMM/GPM Integrated Multi-satellitE Retrievals (GPM/IMERG v6), (5) removal of unnecessary datasets (for N.N. DWR) currently available in the CE interface, and (6) inclusion of N.N. Seal and WWAo logo on main page display and on map images.

First, the primary modification of DSET from CE is the inclusion of datasets associated with the N.N. network of eighty-five precipitation gauges,

maintained by the N.N. DWR WMB. This key attribute of the DSET allows direct comparisons of in situ measurements and remote sensing and modeled precipitation data sources. In situ data from the N.N. precipitation gauge network are collected on a quasi-monthly basis and includes the cumulative precipitation component included in the DSET along with other variables collected by the N.N. DWR such as ambient air temperature, wind direction, maximum wind speed, and average wind speed. Observations from the N.N. network date back several decades and are valuable for the analysis of historical climatologies, trends, and changes in the region. The quasi-monthly precipitation totals for the N.N. rain gauge network is manually updated in a Google Sheet by the N.N. DWR and displayed on the DSET as grid cells with values only represented at rain gauge locations. With the inclusion of these data into the DSET, the user can compare in situ measurements, as part of their previous workflow, directly with remotely sensed data that could be added to the future processes, such as from the integrated IMERG products (11 km spatial resolution) available from NASA

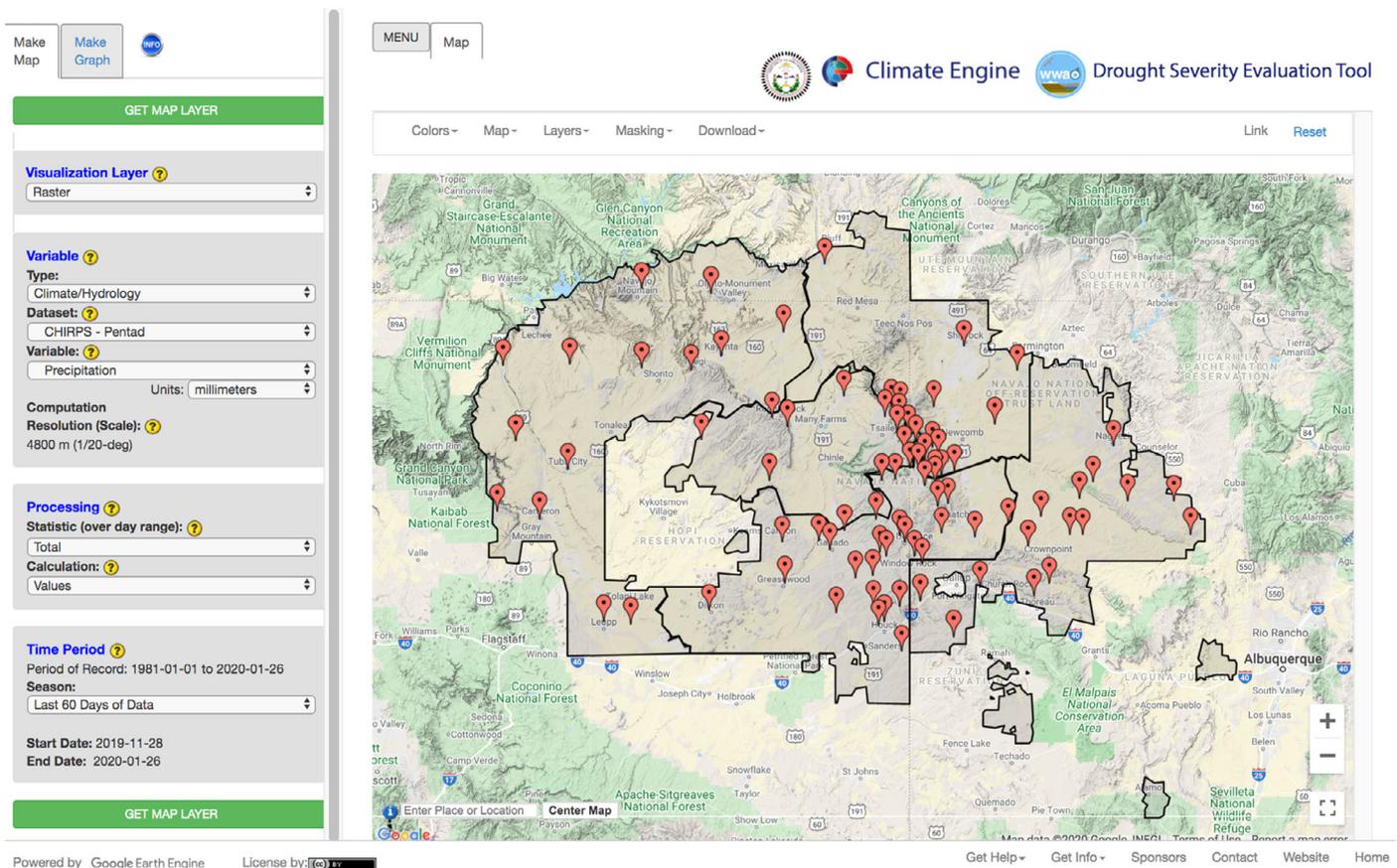


FIGURE 1. The Drought Severity Evaluation Tool (DSET) main mapping interface. The Navajo Nation Agency boundaries and the network of rain gauges are displayed. The visualization panel on the left allows the user to define the data, statistic, and time period of interest.

(Huffman et al. 1997, 2017) or the modeled products such as the include Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data (4.8 km spatial resolution) (Funk et al. 2015). These comparisons can be conducted in the map or time series interface. Secondly, the addition of the N.N.'s administrative boundaries and areas of interest provides stakeholders with the unique ability to select and calculate statistical summaries of regions that are identified in drought mitigation activities. These layers include (1) five Agencies, (2) 110 Chapters, (3) N.N. precipitation gauge locations, and (4) mountain ranges where wintertime snowpack is commonly observed. The default map image illustrates the Chapter boundaries, where the user can click and view each Chapter name. In the *Make Graph* tab of the DSET, the user can also select a specific Chapter

(Agency, precipitation gauge station, or high elevation region) to obtain spatially and/or temporally summarized data from selected areas of interest. While gridded data are useful for drought reporting purposes, precomputed area-averaged precipitation and drought datasets are needed for rapid access and visualization for Agency, Chapter, and high elevation region areas of interest. This is an improvement over previously used data sources that do not provide explicit values for each of these administrative boundaries. These include CHIRPS Pentad precipitation (Funk et al. 2015), and 3-, 6-, 9-, or 12-month SPI area-averaged values via gridMET (4 km spatial resolution) (Abatzoglou 2013) (Figure 2). These pre-computed area-averages are stored in the Google cloud and are automatically updated through time. Area averages over the N.N. boundaries are

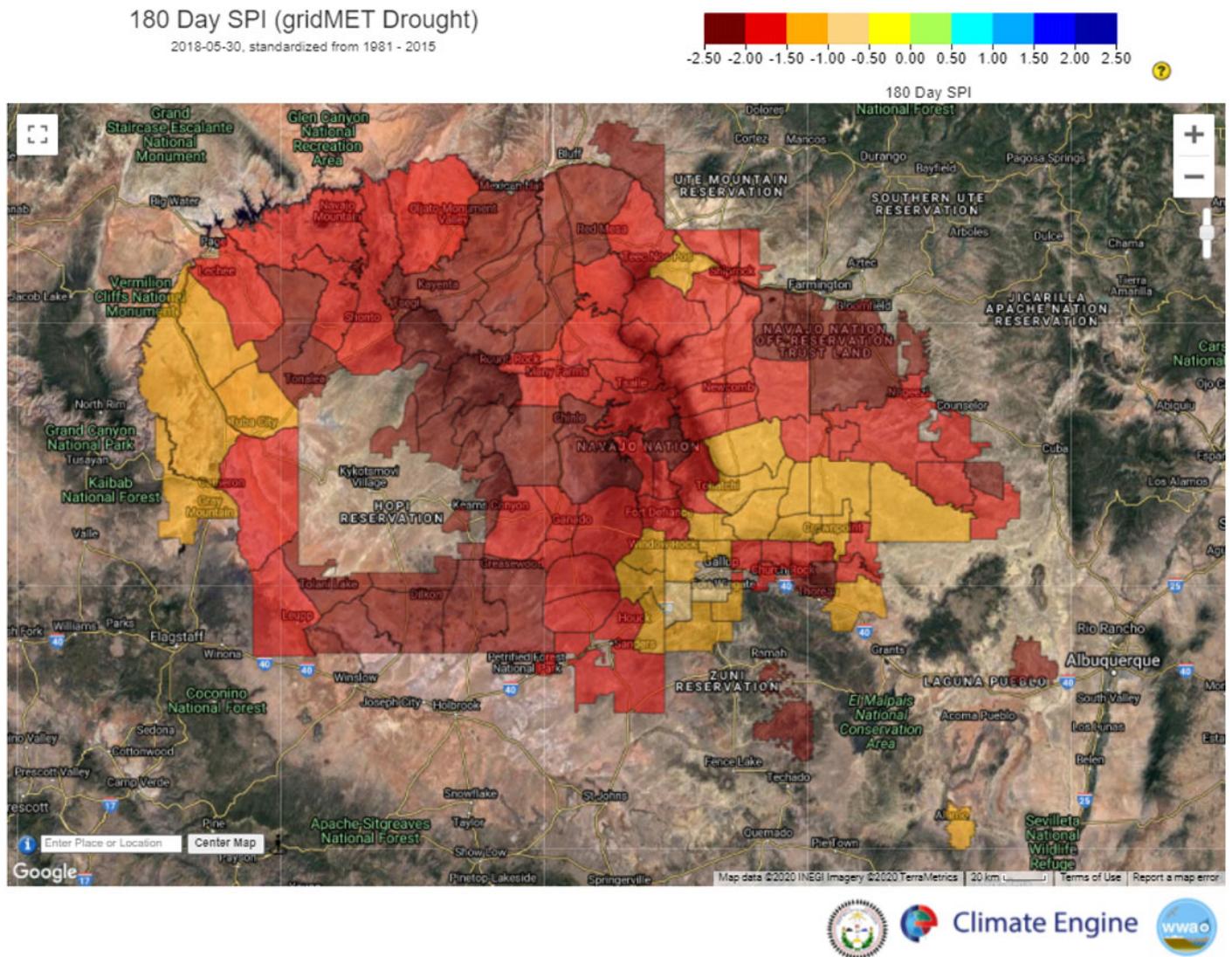


FIGURE 2. Area-averaged polygons indicating the six-month (180 day) Standardized Precipitation Index (SPI) for each of the Nation’s 110 Chapters, leading into the summer monsoon season of 2018 (end date of May 30, 2018), where much of the Nation experienced extreme or exceptional drought.

computed daily in the Google cloud using the CHIRPS and gridMET Earth Engine raster assets.

Precomputed mapping functionality is important for the incorporation of the DSET outputs in drought reporting, complementing spatially interpolated precipitation gauge summaries, and allowing stakeholders to evaluate spatial average conditions and variability for areas of interest. In cases where there are different SPI estimates within an Agency, the N.N. DWR will give preference to dataset (s) with finer resolution, and/or will be addressed on a case-by-case basis. These additional functions and features are particularly useful for efficiently communicating with a broad audience, ranging from the public to political leaders, managers, and scientists.

NASA Data Specifications

The DSET provides data processing and visualization for multiple gridded remote sensing and

climate/modeled datasets (Table 1), including NASA EO datasets of TRMM and IMERG (Huffman et al. 1997, 2017) from 1998 to present. TRMM is a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA) designed to monitor and study tropical rainfall. The 34B2 product contains a gridded, TRMM-adjusted, merged infrared precipitation (mm/h) and RMS precipitation-error estimate, with a three-hour temporal resolution and a 0.25-degree spatial resolution. TRMM data are provided within the DSET at a daily temporal resolution (Huffman et al. 1997). The DSET also includes the most recent version of IMERG (v6) which intercalibrates, merges, and interpolates all satellite microwave precipitation estimates, together with microwave-calibrated infrared (IR) satellite estimates, precipitation gauge analyses, and potentially other precipitation estimators at fine temporal and spatial scales for the TRMM and GPM eras over the entire globe (Huffman et al. 2017). The incorporation of NASA EO datasets within DSET provides the ability to more easily

TABLE 1. Satellite and climate datasets and their respective variables currently available in DSET. Assets available in the Google Earth Engine catalog <https://developers.google.com/earth-engine/datasets>.

Data	Variables	Spatial resolution	Temporal resolution	Duration	References
Satellite					
GPM/IMERG (V06)	<i>P</i>	11 km	Daily	2000–present	NASA/Huffman et al. (2017)
TRMM	<i>P</i>	28 km	Daily	1998–2015	NASA/Huffman et al. (2017)
Landsat (4, 5, 7, 8)	<i>NDVI, EVI, NDSI, NDWI, NBRT, TC, FC, Blue, Green</i>	30 m	16 days	1984–present	NASA/USGS
Aqua-Terra/ MODIS	<i>LST, NDVI, EVI, NDSI, BAI, NDWI, FSC</i>	500 and 1,000 m	8–16 days	2000–present	NASA
Sentinel-2	<i>NDVI, EVI, NDSI, NDWI, NBRT, TC, FC, Blue, Green</i>	10, 20, and 60 m	10 days	2015–present	ESA
Modeled/climate					
CHIRPS	<i>P</i>	4.8 km	Daily, and five days	1981–present	Funk et al. (2015)
gridMET	<i>T, R_s, q, T_d, U, ET₀, P, P – ET₀, BI, ERC, FM100, FM1000, PDSI, EDDI, SPI, SPEI</i>	4 km	Daily	1979–present	Abatzoglou (2013)
CFS Reanalysis	<i>T, R_s, R₁, R_n, q, U, PET, P, LE, H, SM</i>	~19–29 km (0.2-deg to 0.3-deg)	Daily	1979–present	Saha et al. (2010)
MERRA-2	<i>P, T, ET₀, ET_r, EDDI, SPI, SPEI</i>	~50 km (0.5-deg × 0.625-deg)	Daily	1980–present	Gelaro et al. (2017)
SNODAS	<i>SWE, SD</i>	~1 km (0.008-deg)	Daily	2003–present	Barrett (2003)

Note: (a) Data acronyms: IMERG, Integrated Multi-satellite Retrievals for GPM; TRMM, Tropical Rainfall Measurement Mission; CHIRPS, Climate Hazards Group InfraRed Precipitation with Station data; CFS, The Climate Forecast System; MERRA-2, The Modern-Era Retrospective analysis for Research and Applications, Version 2; SNODAS, Snow Data Assimilation System; MODIS, Moderate Resolution Imaging Spectroradiometer. (b) Satellite variables: *EVI*, Enhanced Vegetation Index; *NDWI*, Normalized Difference Water Index; *NBRT*, Normalized Difference Burn Ratio Thermal Index; *TC*, True Color composite; *FC*, False Color composite; *Blue*, blue reflectance; *Green*, green reflectance; *FSC*, Fractional Snow Cover; *LST*, Land Surface Temperature; *NDVI*, Normalized Difference Vegetation Index; *NDSI*, Normalized Difference Snow Index; *BAI*, Burn Area Index. (c) Climate variables: *T*, temperature; *R_s*, downward solar radiation at the surface; *q*, specific humidity; *T_d*, dewpoint temperature; *U*, wind speed; *P*, precipitation; *P – ET₀*, potential water deficit; *BI*, burning index; *ERC*, Energy Release Component; *FM100*, 100-h dead fuel moisture; *FM1000*, 1,000-h dead fuel moisture; *PDSI*, Palmer Drought Severity Index; *EDDI*, Evaporative Demand Drought Index; *SPEI*, Standardized Precipitation Evapotranspiration Index; *R₁*, downward longwave radiation at the surface; *R_n*, net radiation; *H*, sensible heat flux; *SWE*, Snow Water Equivalent; *SM*, soil moisture at 5, 25, 70, 150 cm; *PET*, Potential Evapotranspiration; *LE*, latent heat flux. (d) Reference acronyms: NASA, National Aeronautics and Space Administration; USGS, U.S. Geological Survey; ESA, European Space Agency.

access these data, and easily make comparisons with N.N. DWR in situ data.

The DSET tool was further customized by removing global CE datasets such as TerraClimate and the Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (McNally et al. 2017; Abatzoglou et al. 2018) that were not of interest to N.N. users, allowing them to more readily choose relevant datasets for N.N. drought and vegetation monitoring and reporting needs. In addition, the inclusion of the N.N. Seal in the web interface and on map images allows the N.N. DWR to generate maps directly from the DSET to include within drought reports with acknowledgment to N.N. DWR.

CASE STUDY EXAMPLES

Drought Background

Due to the size of the N.N., droughts are not uniform across the region. According to analysis conducted by the N.N., from 1895 to 2000, 32 years are classified as moderate, severe, or extreme drought years (Navajo Nation Department of Water Resources 2003). For half of those years, the entire N.N. experienced similar severity. However, during the 32 drought years, the western region experienced more severe drought for eight of the years, and the eastern region experienced more severe drought for nine of those years (Navajo Nation Department of Water Resources 2003). This necessitates regionally explicit drought indices that provide the level of spatial detail to identify these differences.

Two of the most severe recent droughts on the N.N. occurred in the 2002 and 2018 WYs. During the 2002 drought, a relatively dry 2001 monsoon season was followed by abnormally low snowpack conditions in the winter months (DJF). The N.N.'s drought status shifted to alert level during October 2001, and reached emergency levels by February 2002 (Crimmins et al. 2013). Similar conditions can be observed for the N.N. with six-month (May 2001–October 2001) SPI via the WRCC's West Wide Drought Tracker (WWDT) (Abatzoglou et al. 2017), which uses 1895–present Precipitation-elevation Regressions on Independent Slopes (PRISM) data (Daly et al. 1993), and DSET, which uses (among other datasets) daily CHIRPS data. For each of the subsequent case study examples, drought conditions for the 2002 and the 2018 WYs are highlighted to showcase some of the capabilities of the DSET.

While there are various drought indices used to examine onset, extent, and severity, the N.N. DWR uses the six-month SPI for drought declarations in the region (Navajo Nation Department of Water Resources 2003). The SPI, developed by McKee et al. (1993), is the most commonly used index to characterize meteorological drought. SPI can be interpreted similarly to the number of standard deviations the observed value is from the mean of the same time period for the entire record length. Positive SPI values are related to higher than average precipitation over the time period and negative SPI values are related to lower than average precipitation. On the N.N., SPI values are categorized as no drought ($SPI \geq 0$), drought alert ($-1 \leq SPI < 0$), drought warning ($-1.5 \leq SPI < -1$), and drought emergency ($SPI < -1.5$) (McKee et al. 1993; Navajo Nation Department of Water Resources 2003; Crimmins et al. 2013) (Figure 3).

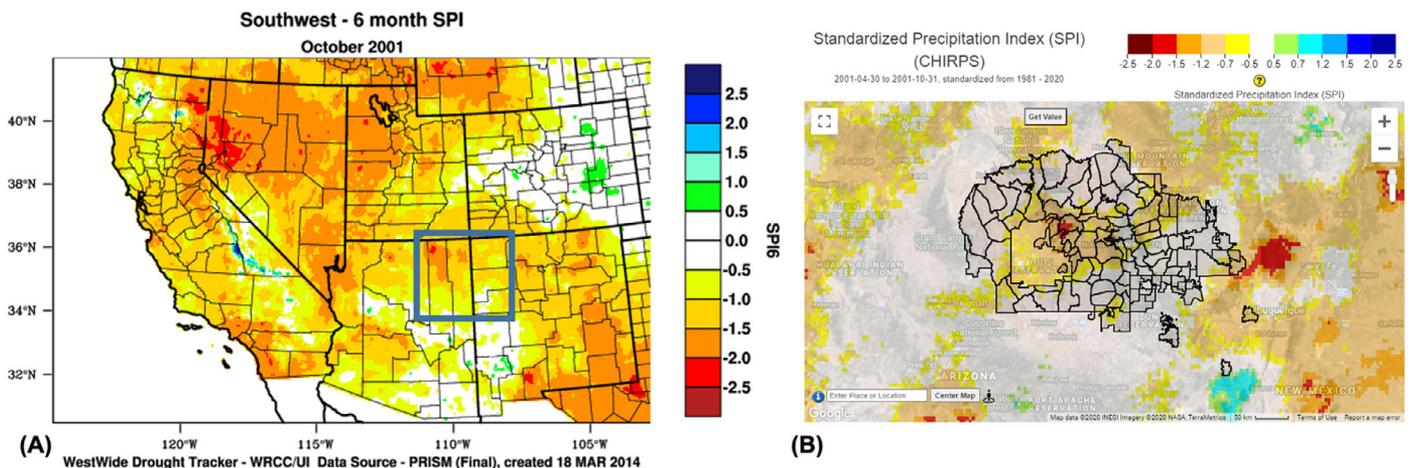


FIGURE 3. (a) October 2001 six-month SPI generated using PRIMS data from the Western Regional Climate Center (WRCC) West Wide Drought Tracker for the entire southwestern United States (U.S.) with the county boundaries identified; (b) October 2001 six-month SPI generated using daily Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) from DSET with the Navajo Nation Chapter boundaries displayed.

The DSET includes two other multi-scalar drought indices, including the Evaporative Demand Drought Index (EDDI) and the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010; Hobbins et al. 2016). The Palmer Drought Severity Index (PDSI) (Palmer 1965) is also provided via gridMET (Daly et al. 1993; Xia et al. 2012; Abatzoglou 2013) and represents approximately a 9- to 12-month time scale (e.g., Vicente-Serrano et al. 2010). The particular benefit of EDDI and SPEI is the incorporation of evaporative demand (i.e., potential evapotranspiration), a key indicator for identifying the onset and progression of drought, especially in the southwestern U.S. (Trenberth et al. 2007; Vicente-Serrano et al. 2010; Hobbins et al. 2016). EDDI can identify rapid demand-based drying droughts or “flash droughts” driven by rapid changes in meteorological conditions, such as a decrease in humidity and increases in wind speed with little to no substantial changes in precipitation (Hobbins et al. 2016; McEvoy et al. 2016; Otkin et al. 2018). The ability to monitor flash droughts, provides a unique perspective for monitoring early warning and drought development that is independent of precipitation, particularly to help explain origins of drought when long-term precipitation conditions may be at or above normal.

While the N.N. DWR currently relies solely on quasi-monthly precipitation via the N.N. rain gauges for short-term monitoring, and the six-month SPI values for longer term drought reporting, an evaluation of the data accuracy is not explicit in the decision-making process for two datasets that report the same metrics (e.g., precipitation or SPI). However, this could be modified for future drought reporting with revisions to the N.N. Drought Contingency Plan (DCP), which may incorporate additional metrics including EDDI and anomalies in satellite-derived Normalized Difference Vegetation Index (NDVI) and surface temperature. By using additional indices and anomalies of EDDI, NDVI, and surface temperature, the N.N. will be better equipped to monitor drought and early warning.

The DSET complements the existing drought tools such as WWDT by including the ability to (1) display and download datasets with N.N. boundaries (Agencies or Chapters) in one map, (2) select any point on the map to obtain the value for a given time period, (3) select a specific Agency or Chapter and generate a time series of a drought metric along with user-selected variables such as precipitation or evaporative demand, and (4) generate area-averaged SPI values for each Agency or Chapter and download the data as a map, time series, or table (as a CSV or Excel file). Visualizing different time scales of drought with other metrics (using either the predefined 3-, 6-, 9-, or 12-month SPI, or a user-specified time period)

within the boundaries of the N.N. provides resource managers a more nuanced understanding of hydrologic vs. vegetative drought and can assist in improved response. Resource managers can track the progress with bi-monthly maps of the six-month SPI that show drought development across the N.N.

Drought Monitoring

As outlined in the N.N. DCP, the N.N. relies on the six-month SPI index from the three climate divisions (North East Arizona, North West New Mexico, and South East Utah) from the WRCC (Navajo Nation Department of Water Resources 2003). When any of these regions experience a drought alert, the Executive Director of Natural Resources, the Director of Emergency Management, the Drought Task Force and the Emergency Management Commission are notified (Navajo Nation Department of Water Resources 2003). During a drought warning, the Resources Committees, the affected grazing and soil and water conservation districts, the farm boards, and the Chapters are notified and limited mitigation resources are used. During a drought emergency, tribal programs can utilize drought resources including drought emergency insurance funding.

Drought conditions within one specific Chapter can also be assessed with the DSET. For example, the time series of six-month SPI for the Black Mesa Chapter, located in the north-central portion of the N.N. approximately 40 km west of Canyon De Chelly National Monument in AZ is illustrated in Figure 4, and shows the onset of drought in 2001–2002, and rapid recovery during the summer and fall of 2002 due to monsoon rains over the Chapter.

The climate on the N.N. is highly variable both seasonally and yearly, punctuated by two distinct wet seasons, making drought management difficult. Inter-annual variability related to modulations of the El Niño-Southern Oscillation also impacts both the frontal storm systems in the winter and the monsoonal moisture flow in the summer (Cayan et al. 1999; Barlow et al. 2001; Hendon et al. 2007). The variability in precipitation necessitates examining drought indices that represent different time scales of drought (Cayan et al. 2010; Ferguson et al. 2011; Crimmins et al. 2013). While the six-month SPI is a practical drought index for the region, additional metrics and time scales may improve drought identification and response times. The limitations of the six-month SPI include: (1) the inability to identify long-term drought that may be affecting groundwater, (2) the inability to capture shorter seasonal or monthly trends that may impact vegetation management or farming decisions, and (3) the exclusion of other climate variables

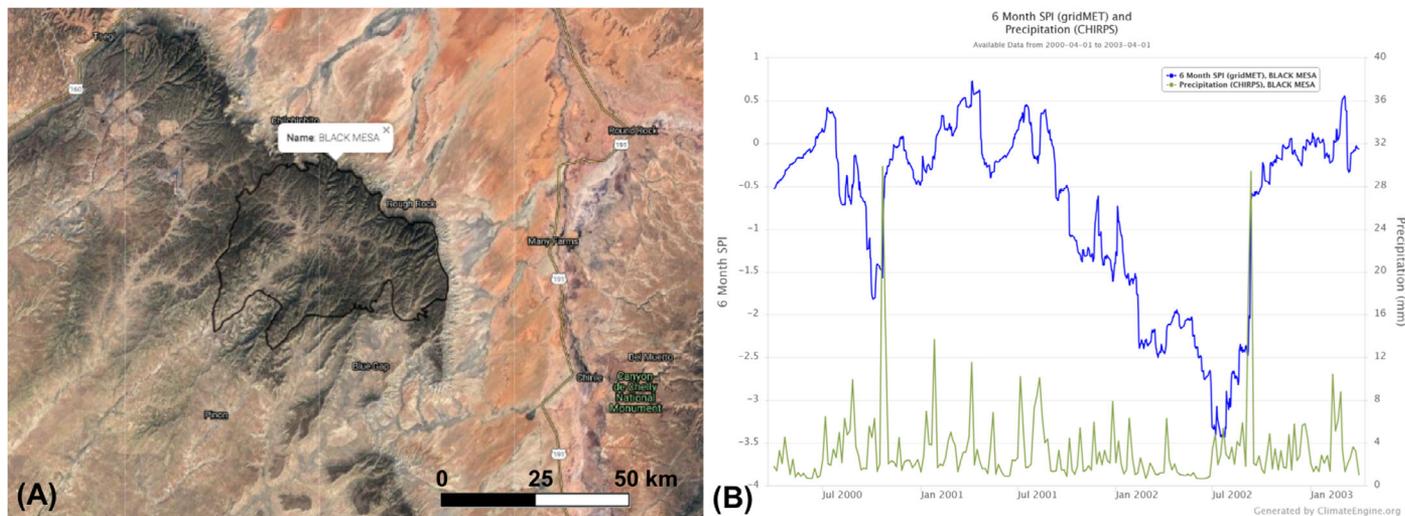


FIGURE 4. (a) The Black Mesa Chapter, located in the central portion of the Navajo Nation, approximately 50 km west of Canyon De Chelly Nation Monument, Arizona (b) The gridMET six-month SPI for the Black Mesa Chapter in blue and the CHIRPS pentad precipitation in green from January 2000 to January 2003.

such as temperature and evaporative demand. To address these issues, the DSET has the capability for the user to specify time scales of interest to calculate SPI, and includes precomputed datasets for 3-, 6-, 9-, and 12-month gridMET and CHIRPS SPI as area-averaged values for the Agencies and Chapters that can be visualized both as maps and time series.

The utility of EDDI is highlighted through a comparison of the six-month SPI (gridMET), six-month EDDI (gridMET), and the monthly difference from average land surface temperature (LST) (via the eight-day Terra Moderate Resolution Imaging Spectroradiometer product) across the N.N. during the onset of the 2018 drought. The six-month SPI values across the N.N. ending November 2017, were largely normal or above normal (wetter than normal), whereas the six-month EDDI values ending in November 2017 indicated above average evaporative demand in portions of the northeastern N.N. and within the Hopi lands. Simultaneously, the November LST was well above normal (nearly 5°C) across the entire N.N. (Figure 5). These trends continued into December 2017, where the EDDI indicated drought conditions developing and worsening during this period of above average LST, and the SPI continued to indicate nearly normal conditions. As drought conditions were beginning to develop according to the SPI in January 2018, EDDI indicated moderate to extreme drought conditions. By the time, moderate conditions are evident across much of the N.N. with SPI (February 2018), the entire N.N. appears to be in a drought emergency, and was later declared. This example illustrates how the rapid development of drought can be tracked within DSET through the use of multiple drought indicators like EDDI and LST

anomalies. The feedbacks between precipitation and evaporative demand are demonstrated here through the rapid change in SPI and EDDI. Having multiple complementary drought indicators provides the N.N. with new early warning capabilities that may be useful in responding to droughts earlier with more lead time.

Snowpack

Snowpack contributes to approximately 50%–70% of the freshwater resources in the southwestern U.S. (Hunter et al. 2006; Ajay et al. 2008). Declines in snowpack have been observed from 1985 to 2010, with further declines projected regionally over the twenty-first century (Novak 2007; Garfin 2013; Scalzitti et al. 2016). On the N.N., the Chuska Mountains serve as the largest fresh water reservoir, containing 80% of the wintertime Snow Water Equivalent (SWE), however, few ground-based measurements are made due to limited resources and remote terrain. Across the N.N., there are eight snow course sites, including two co-located with SNOpack TELemetry (SNOTEL) sites (Natural Resources Conservation Service 2017; Tsinnajinnie et al. 2018). DSET includes daily snow depth and SWE via the SNOW Data Assimilation System (SNODAS) (National Operational Hydrologic Remote Sensing Center 2004), and can be used to create wintertime (November–April) SWE anomalies, and pair those anomalies with other drought indices such as SPI. For example, in 2018 the N.N. declared a drought emergency and implemented multiple mitigation activities. Figure 6 illustrates that SNODAS November 1–April 1

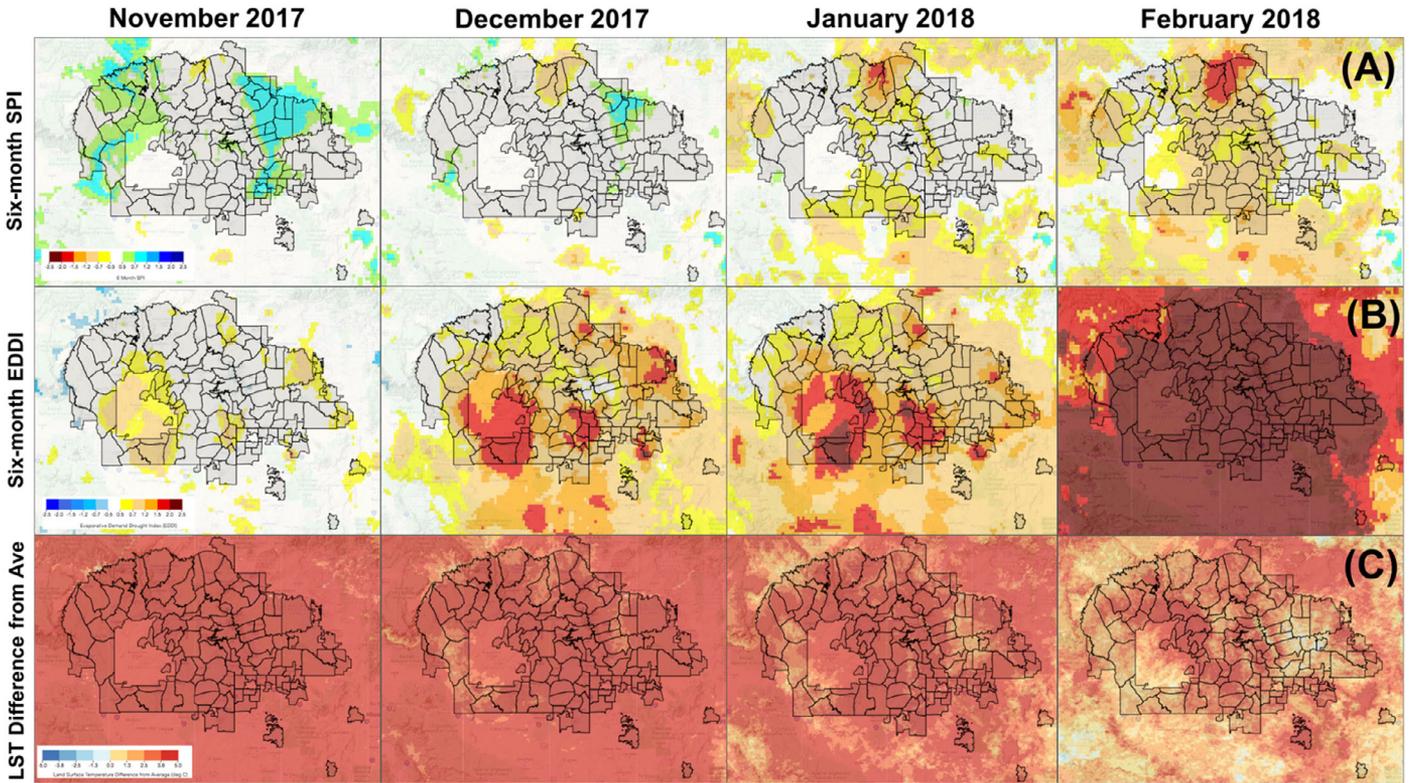


FIGURE 5. The progression of drought and climate conditions from November 2017 to February 2018 from (a) The six-month SPI via gridMET, (b) the six-month EDDI via gridMET, and the (c) difference from average land surface temperature via MODIS.

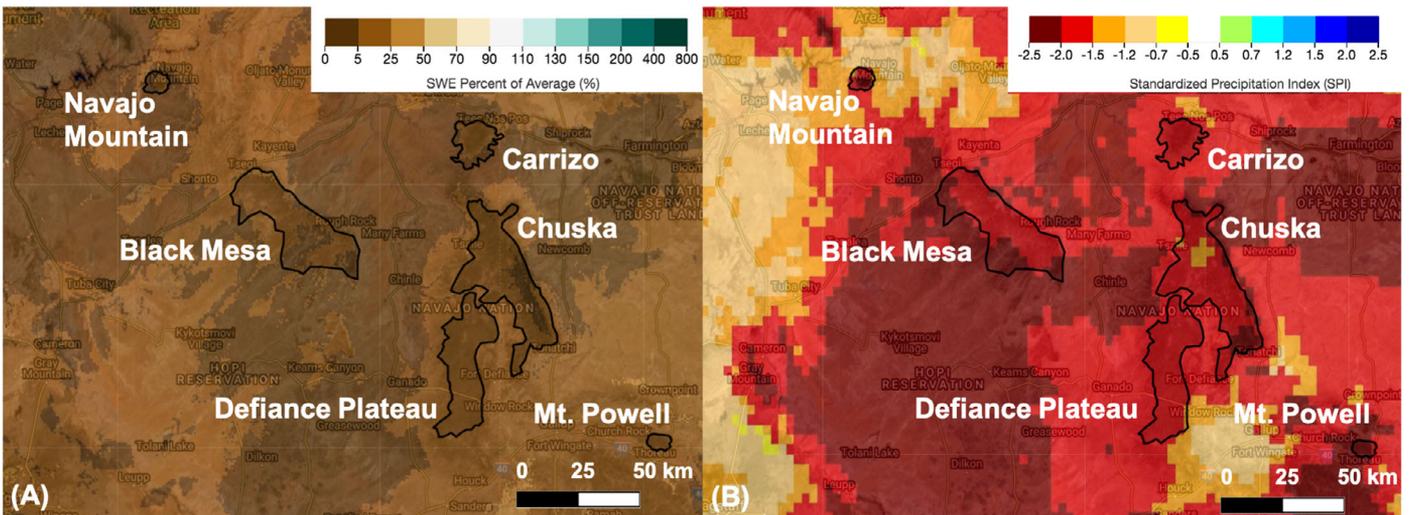


FIGURE 6. (a) SWE percent of average from SNODAS for November 2017–April 2018 with the six high elevations regions displayed. (b) Subsequent six-month SPI values from gridMET (ending June 1, 2018) for the same regions.

average SWE was anomalously low, with portions of the Chuskas at only 3.8% average SWE during this time, and contributed to extreme and exceptional drought across much of the N.N. as indicated by the six-month SPI ending in June (Figure 6).

High Elevation Lakes

In the Chuska Mountains, high elevation lakes and meadows support agriculture, livestock, wildlife, and culturally relevant activities. Lake level responses are

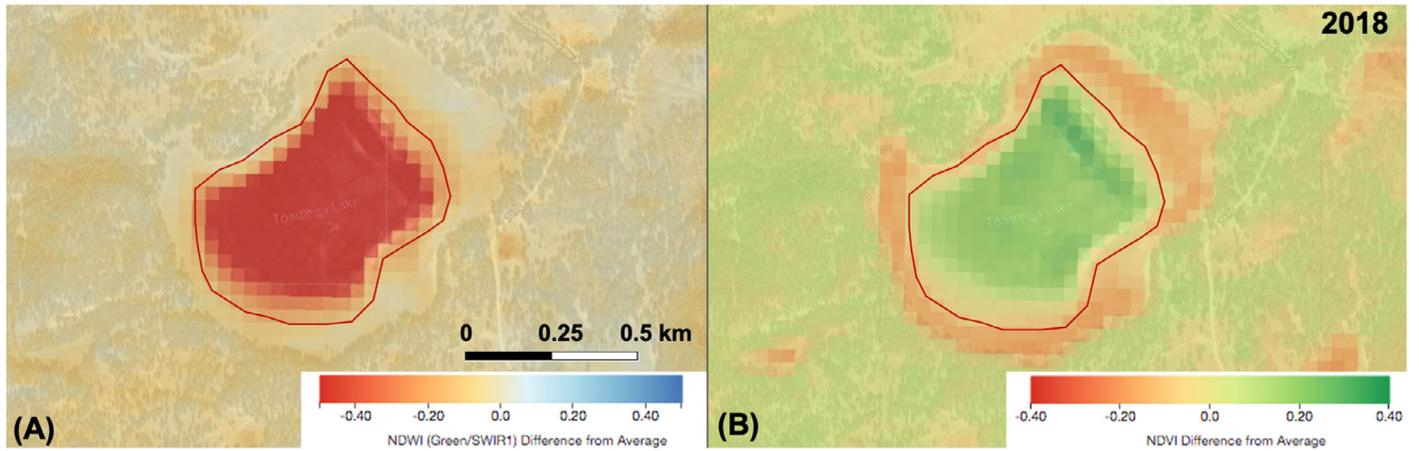


FIGURE 7. (a) NDWI (Green/SWIR1) Difference from Average (baseline of 1985–2010) from Landsat for the northern growing season (April–October) from 2018 in Toadlena Lake (b) NDVI Difference from Average from Landsat for the northern growing season (April–October) from 2018 in Toadlena Lake. The red line indicates the area chosen for Figure 8 time series analysis. During the 2018 drought period there is less water and increased vegetation in this snowmelt-fed lake.

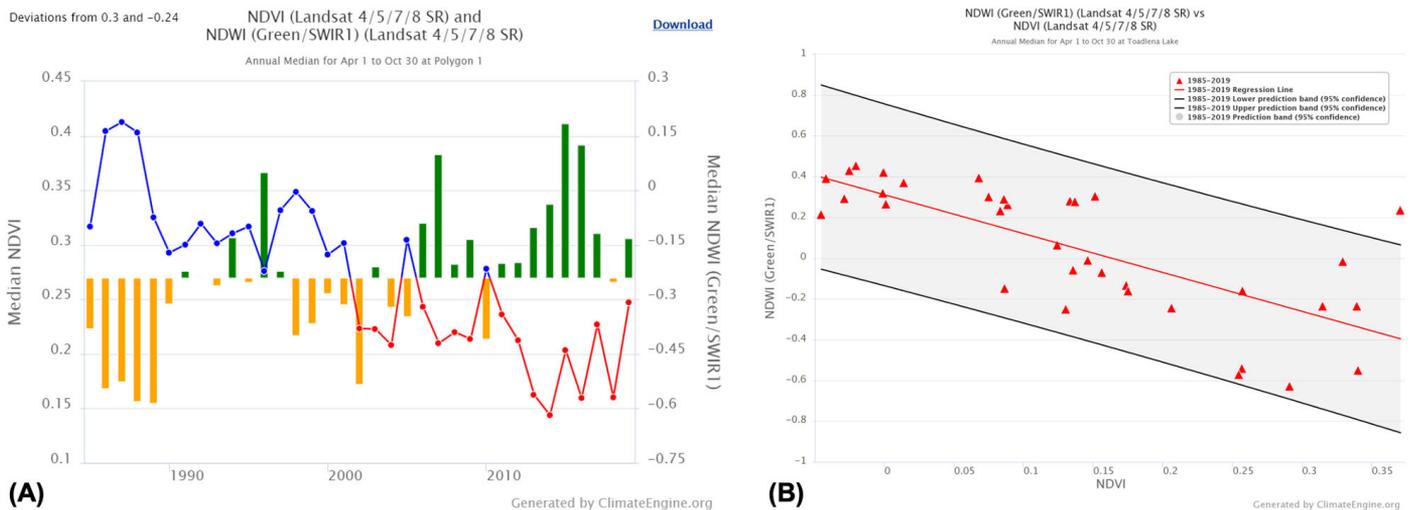


FIGURE 8. (a) Median NDVI within Toadlena Lake for the northern growing season (April–October) from 1985 to 2019, where yellow bars indicate below average conditions and green bars indicate above average conditions plotted with Median NDVI for the same time period, where blue line represents above average conditions and red line indicates below average conditions. (b) Scatter plot of Median NDWI and NDVI for the northern growing season (April–October) from 1985 to 2019, with red linear regression, and 95% confidence intervals for the same region.

tied to hydroclimatic variables, such as snowpack, temperature, and monsoonal rainfall (Brice 2018). The Water Occurrence Change Intensity product, available via the European Space Agency’s Global Surface Water Explorer, indicates declines in many of these snowmelt-fed lakes (Pekel et al. 2016). Declines can be examined in detail through the use of multiple Landsat-derived indices, such as the Normalized Difference Water Index (NDWI) (Gao 1996). The DSET contains multiple NDWI calculations including a modified NDWI, which uses the green and the shortwave or middle infrared bands of Landsat, and is commonly used to identify open water (McFeeters 1996; Xu 2006). Similarly, the NDVI and

the Enhanced Vegetation Index (EVI) are common metrics for monitoring vegetation vigor (Tucker et al. 1973; Rouse et al. 1974; Liu and Huete 1995; Matsushita et al. 2007). Toadlena Lake, located approximately eight km west of Toadlena, NM, is one example where lake levels have been in decline, potentially due to less overall precipitation and/or earlier snowmelt timing. These declines are highlighted in Figure 7 which illustrates a comparison of median northern growing season (April–October) Landsat NDWI for periods of 1985–2000 and 2001–2019.

To assess the impacts of the 2018 drought on Toadlena Lake surface water extent, the growing season

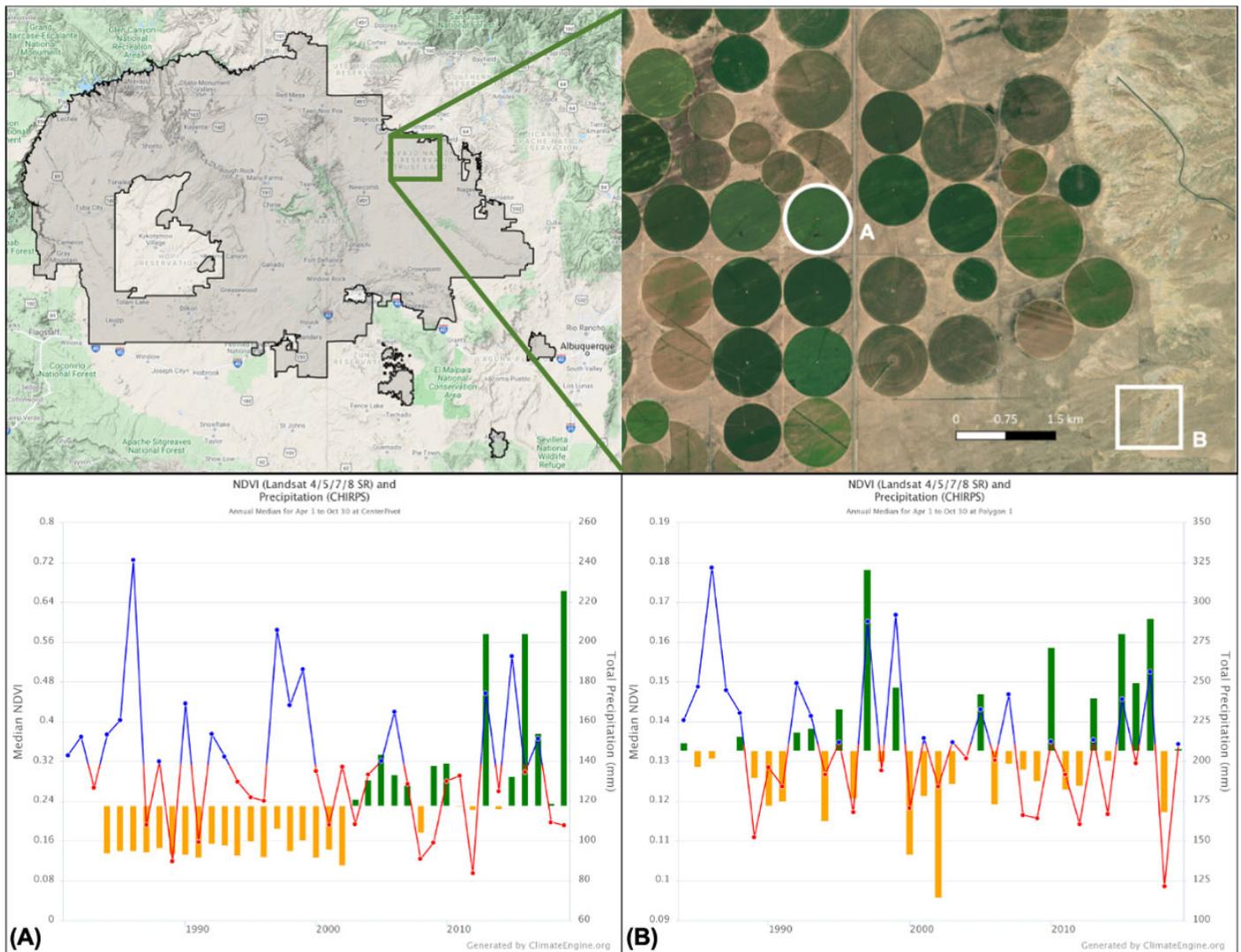


FIGURE 9. Navajo Agricultural Products Industry (NAPI) region south of Farmington, New Mexico (top left), with the selections of a center-pivot irrigation field (a) and a nonirrigated region (b) (top right). Time series of median NDVI (bars) and total precipitation (lines) during the northern growing season (April–October) from 1984 to 2019 in the center pivot irrigated field (a, bottom left) and a nonirrigated area (b, bottom right). Years with below average NDVI are indicated as orange bars, and years with above average NDVI are indicated with green bars. Years with above average precipitation are identified as blue dots/lines and years with below average precipitation are identified with red dots/lines.

NDWI and NDVI difference from average (1984–2010) was used. The dry lake region displays anomalously low NDWI, anomalously high NDVI within the lake bed, and anomalously low NDVI around the perimeter, indicating water level declines. Subsequently, using the *Draw Polygon* feature of the *Make Graph* tab within the DSET, a time series (Figure 8a) or a scatterplot (Figure 8b) of the median NDVI and the NDWI can be generated over the entire lake. These user-generated figures within the DSET efficiently identify the inverse relationship of NDWI and NDVI in declining lakes in the Chuska Mountains and can be easily made for additional regions. Here, as the lake levels drop (declines in NDWI), vegetation

encroaches (increases in NDVI) into the areas that were once submerged.

These types of analyses are especially useful to identify changes in high elevation lakes or meadows that are difficult to reach, and where time and resources are limited. Priority areas for restoration and management of fish populations can also be identified, for example, in the nearby stocked Wheatfields Lake.

Agriculture

The N.N. manages over 212,000 acres of farmland with \$92 million in agricultural products produced

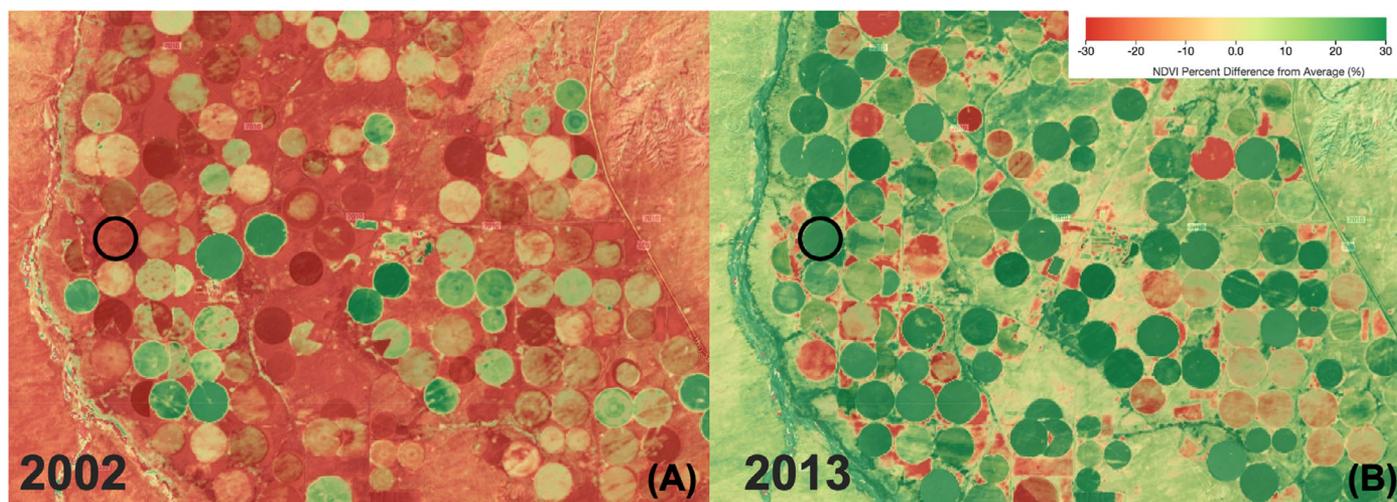


FIGURE 10. Percent difference from average (baseline of 1985–2010) of NDVI via Landsat in northeastern portion of NAPI farmland during the northern growing season (April–October) of 2002 (a) and 2013 (b). The black circle highlights the variation in NDVI for a specific field, where the percent difference from average value in 2002 was -27.6% and in 2013 was 39.3% .

annually (U.S. Department of Agriculture 2019). The N.N.'s largest farming operation, Navajo Agricultural Products Industry (NAPI), with an estimated 72,000 acres of developed farmland, produces alfalfa, corn, small grains, potatoes, and beans near Farmington, New Mexico (Roberson 2006; U.S. Department of Agriculture 2019). NAPI is highly dependent on water deliveries from the San Juan River via the San Juan-Chama Diversion Project for irrigation management (Navajo Indian Irrigation Project 1962). NAPI is an economically and culturally important resource for the Nation, therefore reviewing water rights, assessing water use, irrigation performance, crop yields, and drought impacts are crucial. Agricultural remote sensing has increased in recent years, especially with the advent of cloud computing resources (Allan 1984; Atzberger 2013; Steven and Clark 2013; Huntington et al. 2017; Weiss et al. 2020). The DSET can be used to assess and monitor crop health, phenology, harvests, and fallowing at the field-level.

While NAPI has been in operation since the 1970s, from 2002 to 2004 irrigated land increased (Roberson 2006) and is highlighted by computing the maximum NDVI during the growing season (April–October) year. This increase in irrigated acreage occurred during a period of drought. The DSET can be used to generate and assess field-level annual time series of vegetation vigor by drawing polygons around features of interest and selecting the time period of interest. Figure 9 illustrates an annual time series of growing season median NDVI and cumulative precipitation from 1984 to 2019 for irrigated and nearby nonirrigated areas, where it is evident that irrigation began in 2003 due to the large increase in NDVI during below average

precipitation. For the nonirrigated area, close correspondence between growing season cumulative precipitation and median NDVI is observed.

Vegetation vigor relative to long-term average conditions can easily be assessed spatially by generating and visualizing Landsat NDVI percent difference from average maps (Figure 10), and new and fallowed fields identified can be compared against NAPI irrigation management or crop rotation information to inform future planning activities. Maps and time series could also be used to identify the impact of decreased water deliveries during drought periods on agricultural productivity in this region.

CONCLUSIONS

Combining the technological advancements of cloud computing with multiple data types (i.e., remote sensing, modeled climate and weather, and ground-based observations) and a stakeholder-driven tool design has increased the uptake and use of advanced data products for drought and land management decision making. On the N.N., granular-scale drought monitoring using remote sensing data is a work in progress. Previous drought declarations have usually been made from six-month SPI values, U.S. Drought Monitor designations (D3 and D4), and impact reports from local communities.

While no single drought index will provide the N.N. with a comprehensive view of drought extent and severity, the DSET provides the ability to

conduct more advanced and spatially resolved monitoring of drought severity and land cover status and change via a web application. Functionality of the DSET includes on-demand generation of customizable maps of point and gridded datasets, multivariable time series analysis of satellite, modeled, and ground-based data, direct downloads of data and figures in multiple formats (e.g., CSV, PDF, PNG, GeoTIFF), precomputed summary statistics of precipitation and drought indices for administrative boundaries, URL link sharing for quickly reproducing results, and partner acknowledgment via logos in map results. The DSET, through the CE platform, helps the user overcome barriers to the use of NASA EO through on-the-fly computing, predefined analyses, point-and-click functionality, and has resulted in new opportunities to more easily generate management-relevant results under time and resource constraints.

Co-production of the DSET with the N.N. DWR provided a unique opportunity to showcase the importance of engagement with the management community in the design and delivery of technical tools. Leveraging the capabilities of a pre-existing platform and tailoring that tool with a specific partner in mind has increased the effectiveness of our product. Successful delivery of the DSET required a focus on partner needs prior to tool creation. Long-term tool sustainability requires buy-in from the partner agency for continued maintenance and modification. Thus, establishment and continued relationships among scientists and natural resource managers are essential for effective data-driven decision making. Co-production of tools, knowledge sharing, and capacity building through training activities with natural resource managers will lead to increases in data used as service to society.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: This includes four supplemental figures and one supplemental table. These figures include (1) the ability to generate a two-variable times series with the DSET of precipitation from N.N. rain gauge data and the GMP/IMERG (v6) dataset, (2) the progression of the 2002 drought via the gridMET six-month SPI across the N.N., (3) NDWI and NDVI data for Toadlena Lake in the Chuska Mountains, (4) the expansion of agricultural production near Farmington, NM, and (5) a table of the drought indices highlighted in the case study analyses.

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AUTHORS' CONTRIBUTIONS

A.J.K. McCullum: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing-original draft; writing-review & editing. **C. McClellan:** Conceptualization; data curation; supervision; writing-review & editing. **B. Daudert:** Data curation; investigation; software; validation; visualization; writing-review & editing. **J. Huntington:** Conceptualization; data curation; project administration; resources; software; supervision; visualization; writing-review & editing. **R. Green:** Investigation; methodology; validation; writing-review & editing. **V. Ly:** Formal analysis; investigation; validation; writing-review & editing. **A.R.G. Marley:** Formal analysis; investigation; validation; visualization; writing-review & editing. **N.R. Tulley:** Formal analysis; investigation; writing-review & editing. **C. Morton:** Software; visualization; writing-review & editing. **K.C. Hegewisch:** Software; writing-review & editing. **J.T. Abatzoglou:** Software; writing-review & editing. **D. McEvoy:** Software; writing-review & editing.

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