# Technical Overview of the TexMesonet—A Network of Networks for Improved Water Management and Prediction in Texas

BRIANA M. WYATT,[a] NATHAN LEBER,[b] AND MARK OLDEN[b]

[a] *Department of Soil and Crop Sciences, Texas A&M University, College Station, Texas*
[b] *Texas Water Development Board, Austin, Texas*

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ABSTRACT: Accurate, timely, and accessible meteorological and soil moisture measurements are essential for a number of applications including weather forecasting, agricultural decision-making, and flood and drought prediction. Such data are becoming increasingly available globally, but the large number of networks and various data reporting formats often make utilization of such data difficult. The TexMesonet is a "network of networks" developed within the state of Texas to collect, process, and make public data collected from more than 1700 monitoring stations throughout the state. This paper describes the TexMesonet, with special attention paid to monitoring sites installed and managed by the Texas Water Development Board. It also provides a case study exemplifying how these data may be used and gives recommendations for future data applications.

KEYWORDS: Agriculture; Hydrology; Soil moisture; Wildfires; Drought; Water resources

## 1. Introduction

Accurate, timely, and accessible meteorological and soil moisture measurements are essential for a number of applications including weather forecasting (Ford et al. 2015; Sobash and Stensrud 2015), agricultural decision-making (Ziolkowska 2018; Marek et al. 2020), flood and drought prediction (Elliott et al. 2007; Illston and Basara 2002), air travel safety (Kulesa et al. 2003), and air quality prediction (Carmichael et al. 2008), among others. In recent years, many nationwide and statewide meteorological and soil moisture monitoring networks have been created to provide information necessary for these applications in the United States (McPherson et al. 2007; Schroeder et al. 2005; Diamond et al. 2013; Schaefer et al. 2007). In Texas, a number of disparate environmental monitoring networks have existed for various lengths of time, each collecting measurements of variables deemed most useful to the network manager or their target end user. However, monitoring sites across these networks often measure different variables at different temporal frequencies using different equipment and quality control and dissemination methods. Because of this, and despite the ~1700 existing environmental monitoring stations installed in the state of Texas [Texas Water Development Board (TWDB); TWDB 2022a], there remains a lack of openly available, high-quality environmental data for water managers, decision-makers, and the public in the state. A number of reasons may account for the lack of a unified monitoring system throughout Texas including the size of the state. Based on the experience of the authors, some of those reasons include the amount of funding needed to maintain and oversee the large number of sites required, disagreements about the purpose or goal of the network, difficulty in locating installation sites due to lack of public land and willingness of private landowners, and a perceived lack of benefits of such a monitoring network.

However, support for a statewide monitoring network has grown in recent years due to a variety of factors, including anticipated climate change impacts, a rapidly increasing state population, and growing water and energy resource demands (Greene 2020). Most notably, extreme flash floods in central Texas that were responsible for the destruction of 350 homes and 13 deaths in May 2015 led to the creation of a state government-supported fund to create a unified meteorological "network of networks" (Greene 2020). The TexMesonet, operated and overseen by the Texas Water Development Board, was created in response to this funding. Since 2016, the TexMesonet has become a "one-stop shop" for those seeking to access the variety of meteorological and soil monitoring data collected throughout the state. This online resource is the only place where meteorological and soil moisture data from many of the state's disparate monitoring networks are integrated into a single repository and platform. This paper is intended to provide an overview of the TexMesonet, including the various networks included in it, the measurement types collected by each network, and planned and potential uses and applications of TexMesonet data for the benefit, safety, and prosperity of the citizens of Texas. Special attention is paid to sites installed and managed by the Texas Water Development Board, whose instrumentation, site layout, quality control procedures, and maintenance protocols are described below. Additionally, a case study is presented that demonstrates a potential application of soil moisture data for wildfire prediction.

## 2. Networks and available data

To date, the TexMesonet consists of 14 independent state-level networks or U.S. national networks with sites located within the state of Texas, one network in Mexico, as well as

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*Corresponding author*: Briana M. Wyatt, briana.wyatt@tamu.edu

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two coastal water level monitoring networks located in the Gulf of Mexico. The names of networks included in the TexMesonet and measurement types available from each network are shown in Table 1. The "network of networks" approach entails gathering real-time data reported from each of these individual networks, storing it in a centralized location, and making it available from a single source. This method is especially useful when integrating data from sparse networks spread over large areas and is expected to increase the utility and applicability of data from all networks for research applications and decision-making.

Because each partner network was designed, and is managed, by a different entity for various purposes, these monitoring networks vary with respect to the type and frequency of measurements that are available. Data from each monitoring location are gathered and posted on the TexMesonet web page (www.texmesonet.org) every 5 min, though some networks provide data less frequently (e.g., hourly). Currently, the only quality control procedures carried out on data are those defined by each individual network. No quality control is done after retrieving data from these networks, with the exception of sites managed by the TWDB, though the creation of rigorous, standardized, TWDB-managed quality control procedures is a primary goal moving forward. Available measurements include air temperature, relative humidity, atmospheric pressure, wind speed and direction, incoming solar radiation, river flow and stage, precipitation, soil moisture, and soil temperature. Of course, each variable is only available for sites and networks that collect those data types. Currently available derived data products include variables such as the wind chill, heat index, and dewpoint temperature.

### *Sites managed by the TWDB*

In an effort to create a single unified statewide monitoring network and to fill in spatial gaps between existing networks' monitoring sites, the TWDB has been installing their own monitoring stations since 2016. As of July 2023, 100 such sites have been installed (Figs. 1 and 2), with 99 sites currently operational and one decommissioned. Of these operational sites, 82 are primary, with a 10-m tower measuring variables at both 2 and 10 m above the ground surface, and 17 are secondary, with a 3-m tower measuring air temperature, relative humidity, wind speed and direction at 2 m above the ground surface, as well as rainfall (TWDB 2022b). The use of primary and secondary sites is related to the "network of networks" approach and existing data availability. In some areas, a full 10-m tower is necessary because no such data exist in that area. In other instances, those data do exist, and a secondary site is adequate to fill in the data gap. This network managed by the TWDB will eventually include more than 300 monitoring locations with an average distance of 32 km (20 mi) between sites (Greene 2020). If this goal is met, the TexMesonet sites managed by the TWDB will compose the largest state-level environmental monitoring network in the United States, both in terms of spatial coverage and number of sites. Below, we describe the layout and instrumentation of TWDB monitoring

TABLE 1. List of networks, number of sites in each network, and measured data types with symbols for measurements that are collected by each network (x = available at all sites, xx = available at select sites, blank = not available). Coastal water level networks and stations outside Texas are not included here. Freq = measurement frequency, $P$ = precipitation, $T_{air}$ = air temperature, RH = relative humidity, DP = dewpoint temperature, $P_{atm}$ = atmospheric pressure, WS/D = wind speed and direction, SR = incoming solar radiation, SM = soil moisture, ST = soil temperature, and $Q$ = streamflow; NA indicates not available.

| Network | No. sites | Freq (min) | $P$ | $T_{air}$ | RH | DP | $P_{atm}$ | WS/D | SR | SM | ST | $Q$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| City of Austin Flood Control | 78 | 15 | x | | | | | | | | | x |
| USDA Climate Reference Network (Diamond et al. 2013; Bell et al. 2013) | 8 | 5 | x | x | x | x | | x | x | x | x | |
| Edwards Aquifer Authority | 75 | 30 | x | xx | xx | xx | | xx | xx | xx | | |
| Guadalupe-Blanco River Authority | 67 | NA | x | | | | | | | | | |
| City of Grand Prairie | 28 | 15 | x | | | | | | | | | |
| Hydrometeorological Automated Data Systems (Kim et al. 2009) | 476 | 5 | x | | | | | | | | | |
| Harris County Flood Control District | 125 | 15 | x | | | | | | | | | |
| Jefferson County Drainage District No. 6 | 76 | 15 | x | | | | | | | | | |
| Lower Colorado River Authority Hydromet (Clarke et al. 2007) | 245 | 15 | x | xx | xx | xx | | | | | | xx |
| National Weather Service/Federal Aviation Administration (Kuligowski 1997) | 193 | Variable | x | x | x | x | | x | | | | |
| Remote Automated Weather Stations (Horel and Dong 2010) | 96 | 10 | x | x | x | x | | x | x | | | |
| San Jacinto River Authority | 13 | 15 | x | | | | | | | | | |
| Texas Water Development Board | 98 | 5 | x | x | x | x | x | x | x | x | x | |
| Texas Soil Observation Network (Caldwell et al. 2019) | 32 | 60 | x | xx | xx | xx | | xx | xx | x | x | |
| West Texas Mesonet (Schroeder et al. 2005). | 146 | 1[a];15[b] | x | x | x | x | x | x | x | x | x | |

[a] Frequency of above-ground measurements.
[b] Frequency of below-ground measurements.

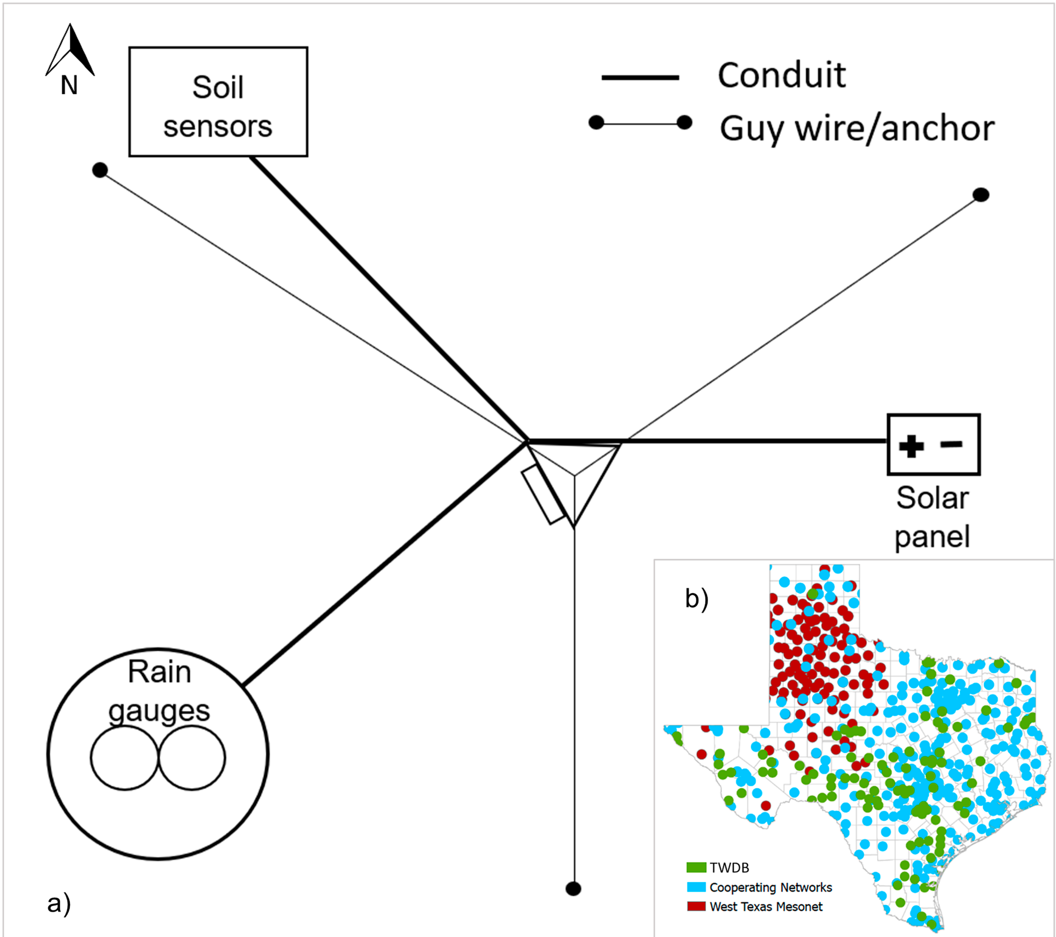


FIG. 1. (a) Aerial site diagram (not to scale) showing the locations of enclosures, solar panels, rain gauges, and soil sensors at primary TWDB sites, and (b) locations of TexMesonet sites installed and maintained by the TWDB (green circles), the West Texas Mesonet (red circles), and select sites from the FAA and U.S. Forest Service RAWS cooperating networks (blue circles). Each TWDB site measures approximately 11.6 m × 11.6 m. Circles in (b) have a radius of 16 km (10 mi). The locations of all >1700 monitoring sites included in the TexMesonet can be viewed online (https://www.texmesonet.org).

sites, communication and data processing procedures, calibration and maintenance procedures, and potential applications.

#### 1) PRIMARY STATION LAYOUT AND SITING REQUIREMENTS

The site layout is the same for all primary sites and is shown in Figs. 1 and 2. Installation sites are selected based on several factors, including, but not limited to, analysis of gaps in spatial coverage; population centers and risk potential; and availability of partners such as groundwater districts, state agencies, and private landowners. Sites are intended to be representative of the area in which they are located, with minimal impacts from obstructions such as trees and buildings. When possible, sites are installed in open areas where such obstructions are not present, which leads most sites to be installed in areas of grassland or pasture, though there are no specific vegetation or land-cover requirements for the sites (e.g., no vegetation height/type requirements as when measuring evapotranspiration). Vegetation at the sites is trimmed in certain locations within the fenced area as is necessary for routine maintenance, but the entirety of vegetation in or around the site is never removed.

Site ratings for measurements of air temperature and relative humidity, precipitation, and wind speed at TWDB monitoring locations have been classified following recommendations laid out by the World Meteorological Organization for sites on land (WMO 2014). These recommendations indicate that each measurement type should be classified separately, with class-1 sites meeting the strictest requirements and class-5 sites meeting minimal requirements. Ratings for each site and measurement type are shown for the 99 operational stations in Table S1 in the online supplemental material. For 2-m height air temperature and relative humidity data, 52 sites meet class-1 requirements, 42 meet class-2 requirements, and 4 sites meet class-3 requirements. For precipitation measurements, 81 sites meet class-1

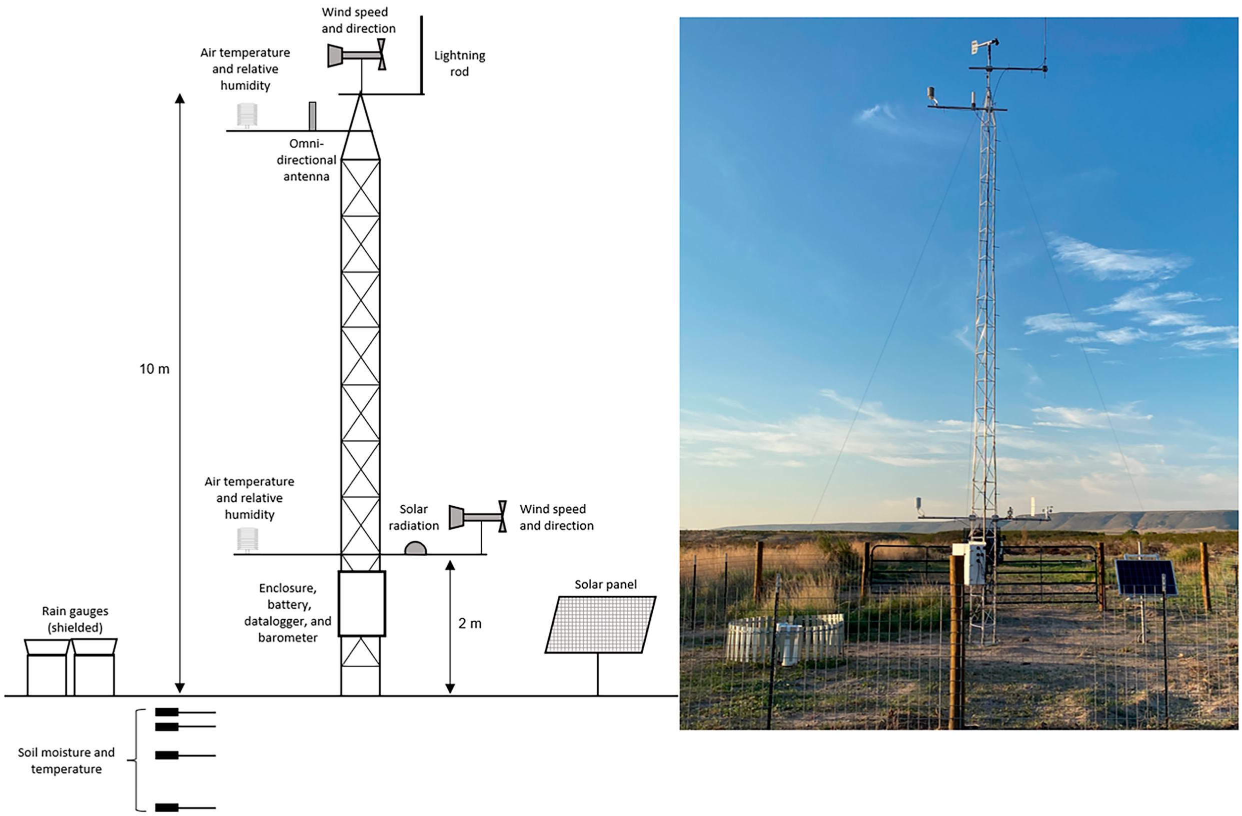


FIG. 2. Site profile of a primary monitoring site managed by the Texas Water Development Board.

requirements, 14 sites meet class-2 requirements, and 3 sites meet class-3 requirements. For 10-m wind speed measurements, 29 sites meet class-1 requirements, 8 sites meet class-2 requirements, 31 sites meet class-3 requirements, 8 sites meet class-4 requirements, 5 sites meet class-5 requirements, and all 17 secondary sites are classified as class 4S, indicating stations with wind speed and direction measurements at only 2 m.

### 2) MEASURED VARIABLES AND INSTRUMENTATION

Air temperature data are measured every 5 min at 2 and 9 m above the ground surface. Measurements at 2 m are collected using a shielded two-in-one air temperature and relative humidity probe (HMP60; Vaisala Oyj) instrument. This instrument has a measurement range from −40° to 60°C with a manufacturer-specified air temperature accuracy of ±0.5°C in the 10°–30°C range and ±0.6°C outside that range. Relative humidity measurements from this instrument have a manufacturer-specified accuracy of ±3% when relative humidity is less than 90% and temperatures are 0°–40°C and ±5% when relative humidity is greater than 90%. Measurement accuracy is lower outside the 0°–40°C range, with accuracies of ±5% below 90% relative humidity and ±7% when relative humidity is above 90%. Air temperature measurements at 9 m are collected using a CS109 temperature probe (Campbell Scientific), which has a measurement range from −50° to 70°C with a measurement tolerance of ±0.2°C within the range of 0°–70°C. Relative humidity is measured every 5 min at a height of 2 m above the ground using a Vaisala HMP60 (Vaisala Oyj) instrument.

Precipitation data are recorded every 5 min at ~60 cm above the ground surface using two types of rain gauge at primary sites, one a tipping-bucket model and the other a weighing model. Secondary sites use only the tipping-bucket style. The tipping-bucket rain gauges are MetOne380 (MetOne Instruments) instruments, which measure precipitation in 0.254-mm increments and have a manufacturer-specified accuracy of ±0.5% at a rainfall rate of 12.7 mm $h^{-1}$ and ±2.0% at a rainfall rate of 76.2 mm $h^{-1}$. Weighing precipitation gauges are the OTT WAD200 model (OTT HydroMet), which measure in intervals of 0.001 mm and a manufacturer-specified accuracy of ±0.1 mm. All precipitation readings are summed over each 5-min measurement period and reported as a cumulative value.

Wind speed and direction are measured every 5 min at both 2 and 10 m above the ground surface. Measurements at the 2-m height are made using a MetOne O34E (MetOne Instruments) wind sensor. This device records wind speeds from 0 to 269 km $h^{-1}$, with manufacturer-specified accuracies of 0.40 km $h^{-1}$ at wind speeds below 36.5 km $h^{-1}$ and ±1% at greater speeds. Wind direction measurements are provided in degrees, with a specified accuracy of ±3° and resolution of <0.5°. Measurements at 10 m are made using a heavy-duty wind monitor (R. M. Young 5108). This device has a wind speed measurement range of 0–360 km $h^{-1}$ and an azimuth reading of 360°, with a manufacturer-specified wind speed accuracy of ±1.08 km $h^{-1}$ and azimuth accuracy of ±3°.

Incoming solar radiation is measured every 5 min at 2 m above the ground using a digital thermopile pyranometer (Model CS320; Campbell Scientific). This instrument measures net shortwave irradiance in the range from 385 to 2105 nm, with measurement capabilities up to 2000 W $m^{-2}$ and a calibration uncertainty of ±2.6%.

Barometric pressure is measured every 5 min at 2 m above the ground surface using a CS106 barometer (Campbell Scientific). This device records measurements within the range of 500–1100 hPa with a manufacturer-specified accuracy of ±0.3 hPa at 20°C, ±0.6 hPa from 0° to 40°C, ±1.0 hPa from −20° to +45°C, and ±1.5 hPa from −40° to +60°C.

Soil moisture and temperature are measured at depths of 5, 10, 20, and 50 cm below the surface every 5 min using either TEROS 12 (METER Group) or CS655 sensors (Campbell Scientific). TEROS 12 sensors have a manufacturer-reported accuracy of ±0.03 $m^3$ $m^{-3}$ for volumetric water content measurements and ±0.3°C from 0° to 60°C. TEROS 12 sensors have 5.5-cm length probes, have been installed at 40 sites, and are primarily installed in locations with rocky or hard soils where the longer 12-cm probes of the CS-655 are difficult to insert. CS-655 sensors have a reported accuracy of ±0.03 $m^3$ $m^{-3}$ using a factory calibration and up to ±0.01 $m^3$ $m^{-3}$ accuracy with a site-specific calibration for volumetric water content measurements, and a reported accuracy of ±0.1°C from 0° to 40°C. These sensors are currently installed at 59 monitoring locations.

All data are collected using a CR1000/CR1000X datalogger (Campbell Scientific). Sites are powered using a WN 100W (Windy Nation) or GMA 100W (GMA Solar) solar panel and an SS-10-21V Morningstar charge controller (Morningstar Corp.). Data are reported in text files that are transferred from each station every 5 min to a web server managed by the TWDB. This server converts text data to an SQL database that is stored via Amazon Web Services. Communications with TWDB stations are handled by the AT&T FirstNet Control Center. This service is primarily intended for use by first responders during disasters and thus has a higher priority over other cellular networks and high level of reliability (estimated at 95+% network uptime). Sites using this communications system have been fully operational with no down time through multiple natural disasters in the state, including “Winter Storm Uri,” tornados, heat waves, and several hurricanes.

#### 3) Derived variables

Derived variables at TWDB monitoring sites include the heat index, wind chill, and dewpoint temperatures. Heat index or apparent temperature values are estimated by the datalogger at each site when air temperatures are ≥80°F and relative humidity levels >40% (Campbell Scientific 2001a) using the methods described by Steadman (1979a,b). Wind chill temperature values are estimated using the updated method developed by the National Weather Service in 2001 as described by Osczevski and Bluestein (2005). This index is calculated internally within the datalogger at each site for temperatures less than 1.7°C and assumes a wind speed greater than 4.8 km $h^{-1}$ (Campbell Scientific 2001b). Dewpoint temperature values are also estimated internally within the datalogger at each site using relative humidity and temperature measurements according to the methods described by Goff and Gratch (1946), Lowe (1977), and Weiss (1977). These variables are also calculated for Federal Aviation Administration (FAA) and Remote Automated Weather Stations (RAWS) monitoring sites shown in Fig. 1b, but those networks may use other estimation methods (see references for each network below Table 1).

#### 4) Station maintenance and sensor rotation

To ensure proper sensor function and to allow for regular maintenance and recalibration, above-ground sensors are regularly rotated on a schedule based on manufacturer-recommended maintenance times. Presently, site visits occur at least twice per year, though visit frequency will likely increase in the future as additional personnel are hired. Decommissioned sensors are sent to the manufacturer for recalibration before being redeployed. Rain gauges are tested each time a maintenance visit is performed. Wind speed and direction sensors at the 2-m height are rotated every three years while 10-m wind speed and direction sensors are rotated every 5 years. Dataloggers are rotated every 10 years, 9-m height air temperature sensors are rotated every 3 years, and 2-m air temperature and relative humidity sensors are rotated every 4 years. Barometric pressure sensors are rotated every 2 years.

#### 5) Quality assurance and control procedures

Data from sites managed by the TWDB have several quality assurance and quality control (QA/QC) procedures in place. An administrative tool developed by the TWDB conducts persistence and range checks on all incoming data (Table 2). If data are outside the prescribed range or are missing, those data points are flagged and reported to the TWDB staff, who are responsible for reviewing flagged data before removing them or permitting them to remain in the database. Given the goal of the TexMesonet to be utilized for informing real-time natural disaster response, there is some tension between real-time data reporting and applying thorough QA/QC protocols. Currently all data are made available immediately with relatively few QA/QC restrictions. Potential future plans to resolve this issue include providing provisional datasets with quality control flags, with finalized datasets published after review and revision later.

Data from partner networks not managed by the TWDB are gathered using the MesoWest API, a product of Synoptic Data (Synoptic Data, Inc.), which collects data from partner networks for inclusion on the TexMesonet web page. Data from partner networks are not currently processed for QA/QC prior to inclusion in the TexMesonet database, although many networks perform their own QA/QC procedures within the Synoptic Data system. Currently, QA/QC procedure details are not available for most local networks since many of these networks do not report that information. This highlights the need for improved documentation of QA/QC procedures for each

TABLE 2. Variable name, height/depth of measurement, units associated with each measurement (1 ft = 30.5 cm), and upper and lower limits of variable values outside of which data are flagged.

| Variable | Height/depth | Units | Lower limit | Upper limit |
|---|---|---|---|---|
| Precipitation | — | mm min$^{-1}$ | 0 | 40 |
| Wind speed | 10 m | m s$^{-1}$ | 0 | 90 |
| Wind gust | 10 m; 2 m | m s$^{-1}$ | 0 | 75 |
| Wind direction | 10 m; 2 m | ° | 0 | 360 |
| Wind speed | 2 m | m s$^{-1}$ | 0 | 75 |
| Air temperature | 9 m; 2 m | °C | −30 | 60 |
| Relative humidity | 2 m | % | 0 | 100 |
| Barometric pressure | 1 m | hPa | 500 | 1100 |
| Solar radiation | 2 m | W m$^{-2}$ | −1 | 1600 |
| Soil temperature | 5, 10, 20, and 50 cm | °C | −30 | 60 |
| Soil volumetric water content | 5, 10, 20, and 50 cm | cm$^3$ cm$^{-3}$ | 0 | 100 |
| Water level | — | ft | −500 | 10 000 |
| Water temperature | — | °C | 0 | 60 |

network as well as standardized QA/QC practices in Texas and nationwide. Federal networks included in the TexMesonet have reported QA/QC standards (NWCG 2019; NWS 2017; Diamond et al. 2013) and West Texas Mesonet standards are discussed in Schroeder et al. (2005). Future steps include the development and implementation of universal QA/QC standards for all networks, automated data processing features, and feasibility checks using data from neighboring sites and regional climate records. The long-term goal of the TexMesonet is to bring all data from partner networks up to American Association of State Climatologists (AASC) mesonet data quality standards.

## 3. Data access and download

Since its inception in 2016, the TexMesonet has become the state's "one-stop shop" for viewing and downloading meteorological and soil monitoring data. All collected data are freely available on the TexMesonet website. Current conditions for each site may be viewed on an interactive map, or past data records for each site may be downloaded directly. Preprocessed state-level maps of certain key variables, such as precipitation and air temperature, are also available for download at various time scales ranging from the past 24 h to the past year (e.g., Fig. 3). Users are also able to use a direct download function to select sites and variables of interest for time series downloads, though this type of download is limited to .csv files of a certain size. For larger data downloads, an application program interface (API) is available for select variables. In addition to currently available maps and data, there are plans in place to provide value-added products in the future as the network develops and to extend the API functionality to include all available variables. Potential value-added products include statewide estimates of evapotranspiration, high-resolution soil moisture products, and human and cattle comfort and safety indicators.

## 4. Benefits of the TexMesonet

In addition to the scientific benefits of a statewide monitoring network, there are numerous potential economic benefits as well. For example, the Oklahoma Mesonet utilizes meteorological and soil moisture information to derive seven agricultural decision-support products that support the state's agricultural productivity, including both crops and livestock (Ziolkowska et al. 2017; Klockow et al. 2010). The economic benefits of the Oklahoma Mesonet were estimated to be over $183 million for the 2006–14 period (Ziolkowska et al. 2017). Given the size and agricultural production capacity of the state of Texas, the economic impacts of similar decision-support products in the state have the potential to exceed a billion dollars for a single event, if those products are made available and utilized widely.

The scientific and economic benefits of the proper application of TexMesonet data have the potential to provide social benefits as well. Because agriculture regularly contributes in excess of $20 billion annually to the Texas economy (NASS 2022), the use of measured data to improve agricultural management practices will likely provide direct social benefits including improving food security and maintaining the well-being and mental health of producers. Outside of agriculture, the TexMesonet has potential to be used to improve human health and reduce suffering and loss of life and property (Na-Yemeh et al. 2022, 2023; Hocker et al. 2018) due to extreme weather events including hurricanes, flash floods, droughts, severe thunderstorms, and wildfires that are expected to increase in frequency and severity as a result of climate change. It is also likely to provide benefits such as minimizing the negative effects of extreme weather events on a broad range of economic sectors, the Texas power grid, and the state and national economies (e.g., Na-Yemeh et al. 2022, 2023). These benefits are likely to have widespread positive impacts for the general population, but even greater positive effects in reducing the disproportionate impacts of such events on vulnerable communities.

One example of how TexMesonet data may have been used to provide public benefit is so-called Winter Storm Uri, an extreme winter storm in February 2021 that was responsible for the deaths of more than 200 Texans. This multistate, 10+-day storm froze the majority of power sources in the state, causing a decrease in power supplies that cascaded into an electricity shortage that nearly collapsed the electrical grid of the entire state (Glazer et al. 2021). The extreme temperatures and lack of power led to a statewide water shortage as wastewater treatment plants lacked energy to supply potable water and as residential faucets were left dripping to avoid frozen pipes. While data from

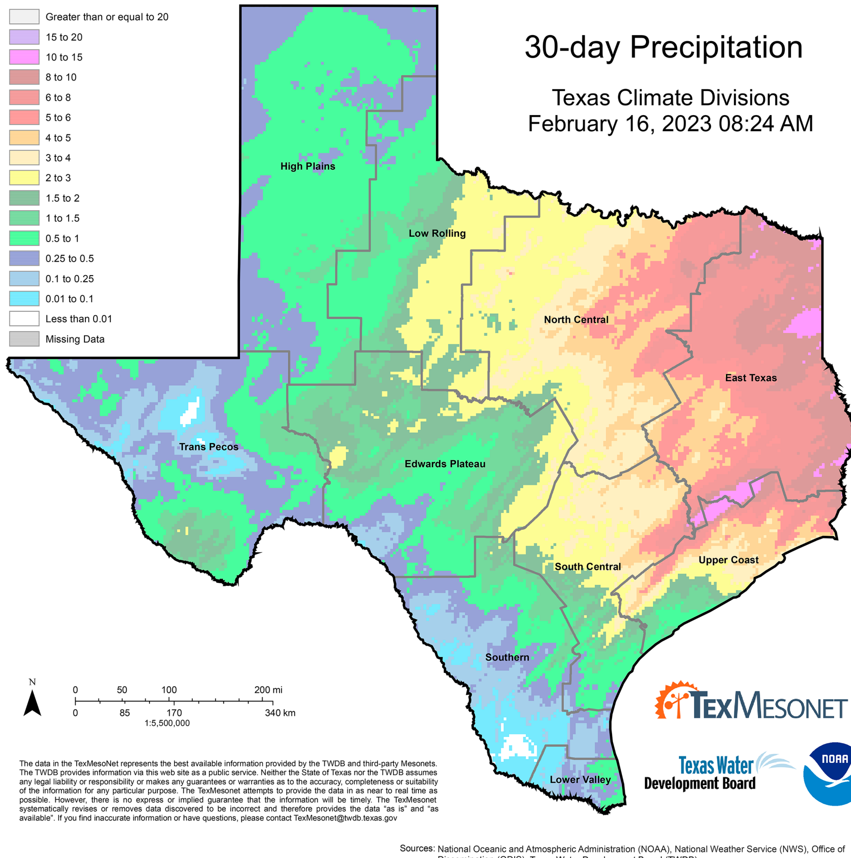


FIG. 3. Example of mapped products available online (https://www.texmesonet.org/DataProducts/SurfaceMaps).

the TexMesonet were freely available during this time, they were not utilized by state government officials to prepare citizens or to inform decision-making before or during Winter Storm Uri. This is only one recent example of how data from the TexMesonet may have been utilized to improve both preparation for and response to extreme weather events.

*Case study*

Because TexMesonet data are easily accessible, they are able to be used by scientists in the state to study a wide variety of topics. One example is the potential use of TexMesonet data to inform wildfire danger ratings. Here we provide a case study of the Borrega fire, which broke out in Kleberg County, Texas, on 25 March 2022 and burned more than 20 800 ha over a period of 10 days (Texas A&M Forest Service 2022). This fire broke out during abnormally dry conditions, including low precipitation and soil moisture as measured by the Los Machos Farm TWDB TexMesonet station, that began in August of 2021 and persisted through the spring of 2022 (Fig. 4). On 18 August 2021 soil moisture values at this site dropped below the permanent wilting point (USDA 2023) and did not rise above that level until more than eight months later on 25 April 2022. Despite low precipitation and soil moisture levels, this area was not categorized as being in drought according to the U.S. Drought Monitor.

Below-average rainfall, low plant water availability during the winter months, and a sudden increase in evaporative demand set the stage for an outbreak of fires in the region. Further, this dry spell was preceded by period of above average rainfall, with January–July 2021 precipitation in Kleberg County measuring 484 mm, which is 123 mm above average for those months of the year (1901–2000 base period; NCEI 2022). This above-average rainfall likely allowed for increased vegetation growth in the spring and summer of 2021 (as indicated by high NDVI values), enhancing the fuel load available to be combusted by a fire in the following spring. This case study aligns well with the findings of Krueger et al. (2016), who demonstrated that dormant season wildfire occurrence in the Southern Great Plains is positively correlated with high soil moisture conditions nine months prior. This is further supported by the observed conditions at the Los Machos Farm, where soil moisture levels were above average in June 2021, nine months prior to the Borrega fire outbreak in March 2022. These high soil moisture levels likely created a large fuel load that, combined with abnormally dry conditions in the spring of 2022, led to one of the top 25 largest fires in Texas history (Texas A&M Forest Service 2022).

The availability of soil moisture information is growing (Ochsner et al. 2013), and it has been clearly demonstrated that soil moisture impacts wildfire probability (Krueger et al. 2016), size (Krueger et al. 2015), and behavior (Chaparro et al. 2016).

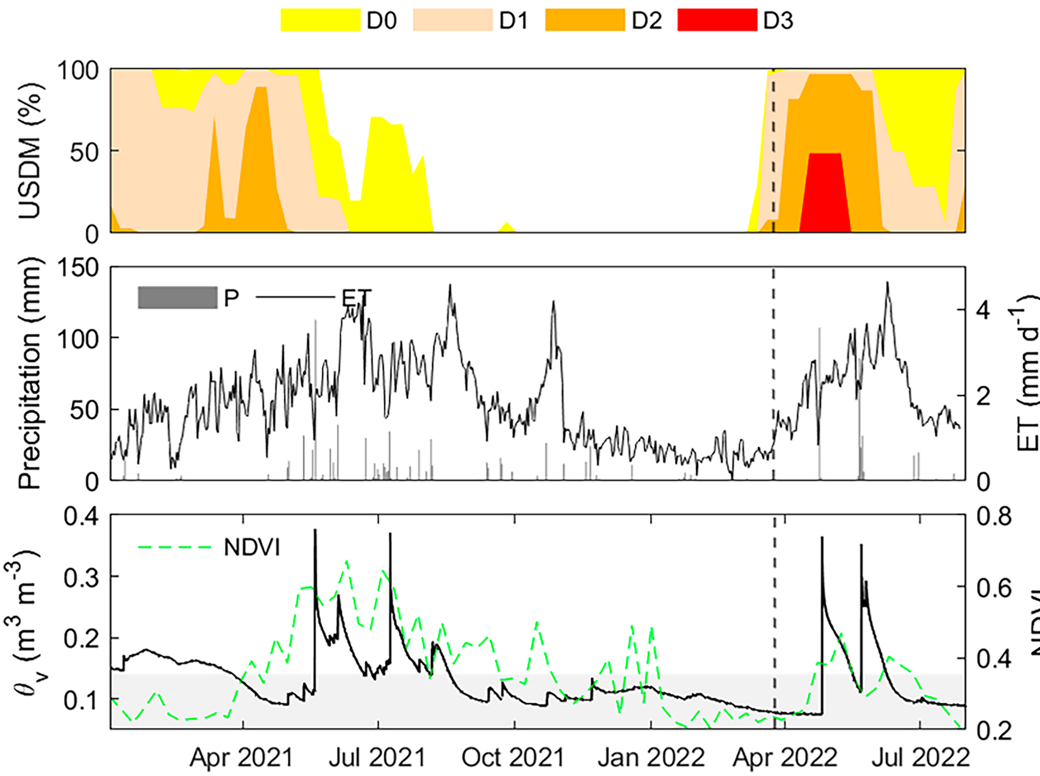


FIG. 4. (top) U.S. Drought Monitor (label USDM) categories, (middle) precipitation measured at the Los Machos Farm TWDB TexMesonet station and actual ET from the OpenET database, and (bottom) depth-weighted mean volumetric soil water content $\theta_v$ measured at the Los Machos Farm TWDB TexMesonet station from 1 Mar 2021 through 15 Aug 2022. The lightly shaded area in the bottom panel represents $\theta_v$ values below the permanent wilting point at this location according to the NRCS web Soil Survey. The vertical dashed line marks the start date of the Borrega fire on 25 Mar 2021.

Further, evidence suggests that soil moisture data may be a better wildfire predictor than currently used drought indices (Krueger et al. 2017). Despite this information, soil moisture measurements are not routinely used in wildfire prediction models or in real-time decision-making by the Texas A&M Forest Service or by the U.S. Forest Service (Krueger et al. 2022). Work is ongoing in Texas and in the United States to improve fire prediction models and to incorporate soil moisture data, which have a demonstrated relationship with wildfire occurrence and size (Krueger et al. 2015), and soil moisture data from the TexMesonet have the potential to provide valuable information in this effort.

## 5. Limitations

Despite the ongoing work of the TWDB to unify the many existing networks in the state, the TexMesonet faces several challenges. First, many of the existing monitoring networks incorporated into the TexMesonet only measure one variable, usually precipitation (Table 1). These sites and networks lack measurements of the other meteorological and soil variables necessary for developing many of the value-added products mentioned above, which limits the applicability of the TexMesonet data in certain areas of the state. Second, each network included in the TexMesonet uses different instrumentation, measurement frequencies, sensor calibrations, sensor types, installation heights, and installation depths (for soil sensors, where applicable). This level of variability poses a significant challenge when attempting to apply data from these networks in a unified way. Third, currently there are no rigorous quality assurance or quality control procedures performed on data collected from non-TWDB networks prior to their inclusion in the TexMesonet online database. This presents another significant challenge, as data quality is of great importance in any type of scientific research application, and also serves to increase the reliability of monitoring data in the eyes of policymakers and the public (Shafer et al. 2000). Finally, similar to other large-scale monitoring networks, the majority of TexMesonet monitoring locations are located primarily in grassland ecosystems due to the need for sites to be located away from obstructions such as trees. As such, these data do not represent conditions in other land-cover types, although work is actively ongoing to install monitoring sites in forested areas managed by the U.S. Forest Service.

## 6. Future of the network

Financial support for the TexMesonet is expected to continue in the future under funding provided to the TWDB by the state legislature and by the National Mesonet Program, into which the TexMesonet was accepted in April 2023. Additional recent work has been done to solidify the TWDB's ability to fund, manage, and maintain core TexMesonet stations into the future, with state legislation (Texas House Bill 2759) effective in September 2023 codifying the TWDB's role in serving as the lead agency in developing statewide monitoring efforts, providing a statewide resource for hydrometeorological data and summary information benefiting weather forecasting, flood preparedness, drought monitoring, wildfire management, water resources planning, water conservation, agricultural readiness and productivity, industrial readiness, and related business readiness and productivity across Texas. This legislation also codified the creation of a TexMesonet Advisory Board, a group of experts identified by the TWDB to provide guidance for the future of the network. However, it may be said that the primary support needed to ensure the future success of the TexMesonet is not only financial, but also includes a social component. Buy-in from the public and from policymakers is necessary to ensure the longevity and success of this type of network (Ziolkowska et al. 2017). This also means that it is essential that scientists within the state clearly demonstrate the scientific, social, and economic benefits of the data collected by the TexMesonet. To date, few studies have been carried out using TexMesonet data.

Additional future work includes installing TexMesonet stations under a greater variety of landscape and vegetation conditions. A major limitation of the TexMesonet, like many other networks, is that the vast majority of stations are located under vegetation types that are relatively easy to maintain and access—namely, grassland. This is a common issue with large-scale mesonets (Wyatt et al. 2021; Patrignani and Ochsner 2018), but also means that there are large areas of the state under forest and agricultural croplands that are not represented by available data. Work is under way to address this issue, with potential for collaboration with the U.S. Forest Service to retrofit existing monitoring sites with soil moisture sensors or install new monitoring sites within national forests in Texas.

As mentioned above, public and policymaker support is key in sustaining a large-scale monitoring network such as the TexMesonet. However, for stakeholders to value the information from the TexMesonet, they need to be aware of the data and able to easily use those data to benefit themselves and others. One of the best ways to get such data into the hands of the public is through a mobile application ("app"). By providing real-time, local weather data and benefit-added products to citizens, people will begin to know, understand, and value information being delivered by the TexMesonet. For example, the Oklahoma Mesonet has a mobile app for iOS and Android that has been downloaded more than 20 000 times. In 2022, the iOS version of the app was used on average 4000 times per day across the state, with uses increasing up to 30 000 per day during adverse weather conditions (C. Fiebrich, Oklahoma Climatological Survey, 2023, personal communication). This puts real-time data and knowledge in the hands of citizens, who are then able to use that information to make decisions about safety during adverse weather, irrigation scheduling, land management, planting and harvest decisions, livestock management, and so on. Given its importance in disseminating data and increasing public awareness of the TexMesonet, the development of a mobile application is currently one of the primary goals of the TWDB.

## 7. Conclusions

The TexMesonet is a network of networks for environmental monitoring created in 2016 and overseen and managed by the Texas Water Development Board. In addition to monitoring sites from 14 diverse local, state, and national networks, the TWDB has installed and maintains 99 additional sites, which are described in detail here. Data from the TexMesonet have potential to be utilized for such applications as irrigation scheduling, cattle and human comfort and safety indices, surface water and flood forecasting, and improving wildfire danger ratings, providing a significant value for improving the health, safety, and economy of the state. However, little work has been done at present to properly utilize these data for that purpose. Future work should aim to utilize the growing amount of environmental data available across the state in fundamental research, applications, and decision-making tools for the benefit, safety, and prosperity of the citizens of Texas.

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