Feasibility Study for Development of Statewide Evapotranspiration Network

John W. Nielsen-Gammon
Department of Atmospheric Sciences
Texas A&M University
n-g@tamu.edu

Guy Fipps
Department of Biological and Agricultural Engineering
Texas A&M AgriLife Extension Service
gfipps@tamu.edu

Todd Caldwell
Bureau of Economic Geology, Jackson School of Geosciences
University of Texas at Austin
todd.caldwell@beg.utexas.edu

D. Brent McRoberts
Department of Geography
Texas A&M University
mcrobert@tamu.edu

Don Conlee
Department of Atmospheric Sciences
Texas A&M University
dconlee@tamu.edu

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1 Executive Summary

Information was collected on existing mesonets, potential evapotranspiration networks, and stakeholder needs, in support of a comprehensive feasibility study for a Texas statewide evapotranspiration network. This report summarizes the data and information collected from interviews and online resources regarding the purpose, design, operation, and value of these mesonets. It analyzes existing network data within Texas and evaluates the costs and benefits associated with operating a more comprehensive or integrated network. Finally, it presents options for a sustainable Texas mesonet based on successes elsewhere and the specific needs and resources of Texas.

A mesonet here refers to a set of weather stations designed to detect and monitor weather phenomena ranging in size from several miles to hundreds of miles (the "mesoscale"). Such disturbances include flooding and thunderstorms (i.e. convective precipitation), high winds, droughts, and heatwaves. Instruments may be located as high as 10 m above the ground, and stations are generally located to avoid influences from urban landscapes, irrigation, forests, and large bodies of water. This report restricts the term mesonet to networks that serve a variety of needs or stakeholders.

ET (Evapotranspiration) networks differ in both their objectives and measurements. Their objective is to determine the atmospheric demand for water evaporation and transpiration from land covered by a well-watered reference crop – either alfalfa or clipped grass. Such data is valuable for irrigation scheduling for agricultural production and for improving efficiencies in landscape watering for homes and businesses. ET networks use specific instruments often at 2 m heights sited well within a homogenous field of a well-maintained reference crop. Requirements of growers and stakeholders often drive the siting and spacing. An ET network has a particular specialized use while a mesonet is more of a multi-purpose network.

Many existing mesonets in other states were originally established for agricultural purposes, while others were established in support of public safety. Most have been in operation for an average of twenty years and by now serve a broad range of sectors and constituencies.

In Texas, there are three mesonets that serve a variety of purposes: the West Texas Mesonet, the Lower Colorado River Authority (LCRA) Hydromet Network, and the TexMesonet. There is one dedicated ET network, the TexasET Network, and there are numerous other single-purpose networks.

All surveyed mesonets and ET networks measure air temperature, relative humidity, wind, and precipitation. Solar radiation is measured at all stations in the TexasET and TexMesonet networks, but only partially in the other two networks. In addition, many also measure soil temperature and soil moisture at a variety of subsurface levels as well as wind or temperature at multiple above-ground levels.

Data transmission from individual stations is predominantly by cellular network. Users access the data via web sites, text alerts, apps, and through retransmission of data to larger aggregation networks such as the Meteorological Assimilation Data Ingest System, the National Mesonet Program, and MesoWest. Most mesonets quality control their data to either World Meteorological Organization or National Weather Service standards.

Individual startup costs range from $6,200 to $25,000 per station, and network maintenance and operating costs range from $1,600 to $6,000 per station. Differences in cost largely reflect differences in instrumentation and maintenance needs. Maintenance costs for ET stations can be high due to irrigation infrastructure and land management required to maintain the reference grasses. Staffing needs depend on the mix of employees and outside contractors; labor-intensive tasks include station, instrumentation, and communication maintenance, calibration, product development, and administration.

The benefits gained from fully functional ET networks are substantial. Analyses of benefits of existing ET networks find typical water savings of several inches per year on irrigated cropland, implying potential water savings exceeding one million acre-feet per year within the agriculture sector alone. Overall, the potential economic return on investment is substantial, with one study estimating it at 20:1.

Mesonet business models range from comprehensive centralized networks with fully integrated operations to secondhand aggregators of data from existing networks. Most of the successful networks examined in this report operate on a partnership model with some centralized tasks and funding and some tasks and funding shouldered at the local level. Nearly all mesonets function through university or multi-university partnerships. In most cases, data is free of charge.

In Texas, an appropriate model would be a consortium model, consisting of the Texas Water Development Board, universities such as Texas Tech University, Texas A&M University, and the University of Texas, and other statewide or regional stakeholders/operators such as the the Texas A&M Agrilife Extension Service, Lower Colorado River Authority and the Electricity Reliability Council of Texas. Additional stakeholder participation can be formalized through an advisory board.

Successful mesonets elsewhere have avoided challenges which can potentially lead to failure of the network, including:

1. lacking an overall network vision;
2. failing to properly engage potential stakeholders;
3. misdiagnosing local needs;
4. lacking diversification in revenue streams;
5. not fully exploring potential government partners;
6. not properly budgeting for maintenance costs; understaffing;
7. lacking data and metadata standards;
8. insufficient communications infrastructure; and
9. not providing reliable web/automated dissemination of data.

2 Introduction

2.1 Mesonets and Evapotranspiration Networks

Automated meteorological observing systems with station spacings of a few miles to dozens of miles are called “mesonets”, short for *meso*scale *net*works. Mesonets can have multiple purposes and satisfy many needs simultaneously for residents, commercial operations, local, regional, and state agencies, farmers, educators, and emergency responders. This report specifically restricts the term "mesonet" to weather station networks that serve multiple needs for multiple stakeholders.

One primary need is for accurate information on precipitation and evapotranspiration (ET), essential for determining the irrigation requirements of various crops. Actual ET information is also vital for many other activities, including seasonal crop consumptive use for regional water planning, water availability and demand for design and management of infrastructure, and urban water management and planning. Actual evapotranspiration can only be measured directly using flux towers that detect the upward and downward motion of water vapor near the ground. This approach is useful for scientific research stations but is impractical over large areas and variable crops. However, ET can be determined with good accuracy from climatic data, specifically temperature, dew point, solar radiation and wind data, as long as such sensors are sufficiently accurate and located at specific elevations, and as long as the weather station is properly sited. These siting requirements frequently prevent many existing weather stations to be used for ET determination.

The economics of installing and maintaining weather stations benefit from multifunctionality. For example, the same instruments necessary for evapotranspiration, plus a simple wind direction sensor, are also useful for severe weather detection, weather forecasting, airborne chemical transport monitoring, energy load estimation, and transportation safety. Site acquisition, preparation, and maintenance, data logging, communication, and quality control have costs that accrue whether the resulting data is being used for one purpose or for many purposes. Multifunctionality of data maximizes the value of the data and value of the investment in the mesonet. Since multifunctionality is a key aspect of mesonet viability, and since many aspects of mesonet operation are quasi-independent of the specific uses of the data, this report also considers multifunction mesonets in addition to networks exclusively used for ET.

The uses of data partly drive the requirements for data accuracy. This, in turn, affects the acquisition costs of individual instruments, calibration, and maintenance.

2.2 Purpose of Report

The purpose of this report is to provide guidance to the Texas Water Development Board (TWDB) in the buildout and operation of a statewide evapotranspiration network, which TWDB has dubbed the TexMesonet. This study, which has been sponsored by TWDB, consists of four parts: a study of existing mesonets and ET networks in other states, an evaluation of existing networks within Texas, determination of potential water savings and other benefits, and a thorough description of how a statewide evapotranspiration network would function, expand, and be sustained.

There is special emphasis on ET because the data 1) measure key aspects of the water budget, 2) provide important agricultural and hydrological information, 3) assist in drought assessment, and 4) are derived from elements that can provide other types of useful information, i.e., are multifunctional. We will detail several factors that are important for the intelligent and cost-effective growth and sustainment of a successful mesonet and present options for future actions.

2.3 Current Status of TexMesonet

Currently, TexMesonet is a unified virtual network of high quality data to support flood monitoring and flood forecasting efforts by the National Weather Service (NWS), state and local authorities, and emergency responders. It includes stations installed and operated by TWDB as well as many stations operated by others from which data is transmitted in real time. Currently in Texas numerous local and regional weather monitoring systems are maintained by the federal, state, private and university partners – many feed directly into MesoWest (http://mesowest.utah.edu/) and MADIS, which aggregate meteorological observations from many sources. Additionally, there are citizen-cooperator sites or special-purpose networks measuring only one or two parameters.

Beginning in May 2016, TWDB installed the initial five stations of the network in Blanco and Kendall counties and plans to continue installing stations over the next several years with an informal goal of at least one primary station per county with the full suite of sensors and proper siting, plus secondary sites. Meteorological data collected at primary sites include air temperature, humidity, precipitation, wind speed and direction, barometric pressure, solar radiation, soil moisture, and soil temperature. Such data collection facilitates derivative products such as potential evapotranspiration. As of this writing, there is one program manager and two TWDB full-time staff working on the TexMesonet effort, with additional IT staff support. The online TexMesonet Viewer (http://texmesonet.org) currently includes data from about 1,000 stations provided from 12 mesonet systems across the state. The TexMesonet goal is to provide 1-minute data for emergency management in the near future, whereas present-day data latency is currently at 15 minutes.

2.4 Project Tasks and Timeline

This study consists of four tasks:

Task 1: Study of Existing Statewide Evapotranspiration Networks in Other States

Develop a comprehensive database of existing networks in other states that are designed specifically to measure evapotranspiration or that provide measurements of time-dependent meteorological or soil parameters crucial for determining evapotranspiration.

Task 2: Evaluation of Existing Evapotranspiration Networks in Texas

Develop a comprehensive database of existing networks within Texas similar to Task 1.

Task 3: Determination of Potential Water Savings and Other Benefits

The direct water savings benefit and other ancillary benefits of a statewide evapotranspiration network depend on the specific characteristics of it, including the number and distribution of stations, the data quality, the availability of decision-making tools, and the integration of network information into a comprehensive analysis and forecasting system. We will have collected data on the benefits of existing networks in Texas and elsewhere through Tasks 1 and 2. We use this information to estimate potential benefits for the entire state of Texas.

Task 4: A Thorough Description of How a Statewide Evapotranspiration Network Function, Expand, and Be Sustained

The survey of networks within and outside Texas reveals a wide variety of network design and operating strategies. We will examine the full range of existing network strategies and evaluate them for their viability in their current environments. We will also consider potential barriers or advantages inherent to Texas in implementing such strategies.

The project officially began in late September 2016. Progress was reported quarterly basis culminating in this feasibility report submitted in June 2017. In addition, we engaged Board staff and stakeholders in a workshop on February 17, 2017 at the Pickle Research Campus, UT-Austin. A workshop report was submitted to TWDB on May 15, 2017, which summarized the event (see Caldwell et al., 2017). This final feasibility report includes a summary of each scenario including costs associated with implementation, hardware, staff time, and training for implementation, required technical expertise for each method, accuracy and applicability of each technology, and time estimate for full implementation.

3 What is a Mesonet?

A network is an integrated or interconnected system of measurements taken for a common purpose or goal. This goal requires spatial and temporal data acquisition beyond that of a single location. In meteorology, mesoscale refers to weather events that range in size from about one mile to about 150 miles lasting from several minutes to several hours to several months. Mesoscale weather events are phenomenon that might go undetected without densely spaced observations. Thunderstorms, wind gusts, heatbursts, and drylines are examples of mesoscale events. A mesonet network is designed specifically to measure the size and duration of these mesoscale weather events in near real-time to primarily aid forecasters and emergency responders. In addition, many agencies, regulators, industries, citizens and educators rely on such data.

3.1 Is a Mesonet an ET Network?

ET (Evapotranspiration) networks differ in both their objectives and measurements, and have very detailed requirements for weather station siting, configuration of the station, and positioning and types of sensors employed. Their objective is to measure specific climatic parameters in order to determine the water requirements of crops and other plant materials. Such data is valuable for irrigation scheduling for agricultural production, as well as for natural resource modeling, water planning, among others. Two professional societies (the American Society of Agricultural and Biological Engineers and the American Society of Civil Engineers) have established a calculation method and weather station standards that are used throughout the world for ET purposes. ET networks use specific instruments often at 2 m heights sited well within a homogenous field of a well-maintained reference crop, referred to as ETo. An ET network has a particular specialized use while a mesonet is more of a multi-purpose network.

3.2 History

The history of weather observations in this country is as long as the history of the United States itself, dating back to the days of Benjamin Franklin. However, the history of mesonets only dates back a few decades. The technological advances in equipment in the 1980s led to the National Weather Service deploying a large number of automated weather stations across the country. This was combined with advances in computing, electronics, and communications capabilities that made the remote and automated acquisition of data operationally feasible. These advances drew interest from entities at the state-level, particularly research groups at universities in the Midwest, looking to set up their own automated weather networks. From a weather monitoring perspective, the three primary reasons for the explosion of state mesonets in the 1980s and early 1990s were 1) enhancing the density of observations provided by the NWS, 2) decreasing the latency of data acquisition, and 3) measuring additional meteorological variables, such as solar radiation and soil temperatures (Fiebrich 2007).

3.3 Components

The most important component for a mesonet to be successful is to have reliable and adequate mission-driven funding. This requires a common vision for network design, which includes the overall purpose of the network, the placement of stations, the types of measurements made, and the delivery of the data. Mesonets typically have a staff comprised of program managers that coordinates mesonet activities, research scientists that provide technical expertise and work in the field, computer programmers that maintain the network database, and administrative personnel to coordinate the financial and logistical activities of the mesonet. Most successful mesonets build partnerships in the public, private, and academic sectors and listen to and adapt to the needs of the citizens they serve.

Besides staff, the three primary components of mesonets are the 1) equipment placed at the station location, 2) a centralized database, and 3) communications of the measurements taken by the equipment to the database. The on-site equipment includes not only the meteorological instruments, but also the additional infrastructure needed to make quality observations. These additional considerations are a data logger to record observations, a tower or tripod for proper siting of the equipment, and a properly maintained environment around the equipment (e.g., no trees, no overgrown grass, and no obstructions). Personnel must regularly conduct site visits to maintain the on-site equipment and infrastructure. A database is housed at a central location where the majority of the core mesonet staff works. The database should have plenty of server space to store data, algorithms to QA/QC data, and a webpage for delivery of the data. Staff skills must include software expertise for overseeing database operations and electronics and equipment expertise to adequately address problems with equipment causing erroneous observations. Product generation and dissemination, preferably developed in collaboration with users of products, vastly increases the value of the data. A sound communications infrastructure provides the link between the on-site equipment and the centralized database. Communications components include a means for transmission of data and a data plan (usually cellular or wireless internet) for delivery to the database.

4 Evapotranspiration

4.1 Defining ET

Evapotranspiration (ET) is the conversion of liquid water to vapor from the soil and through transpiration by vegetation. In short, ET is the total amount of water it takes to grow crops and other plant material. While originally develop for agriculture, the ET concept has been adopted to cover most plant materials, including landscapes, athletic fields, nurseries, etc. The ET requirements depend upon the type of plant, its current growth stage and the local climate.

Potential or reference evapotranspiration (written as PET or ETo) is the amount of water used by a reference crop assuming no limits of soil water availability. ETo assumes a hypothetical reference crop with very fixed parameters (i.e. 12 cm tall, fixed surface resistance, 0.23 albedo, etc.). ETo is the maximum amount of atmospheric demand for water required by a crop given local climatic conditions. The reference crop, usually a cool season grass or alfalfa is assumed to be well maintained with growth not limited by water availability, nutrients, disease, etc.

The basic relationships are as follows:

PET ~ ETo = the water use of a specific reference crop, usually grass or alfalfa

ETc = ETo x Kc

Where: Kc = crop coefficient, which depends on plant type and stage of growth

ETc = the evapotranspiration of a specific crop

Many methods have been proposed for calculation of ETo; however, methods derived from a combination of energy balance and a mass transport or aerodynamic term have been found to be the most accurate (Burman et al., 1980). The first combination method was proposed by Penman (1948, 1963), which required local climatic data (temperature, dew point, solar radiation and wind). Since then, in order to improve the accuracy of ETo, several forms of the Penman method were developed. Due to the lack of local climatic data, numerous simpler, approximate methods have also been proposed, such as the Hargraves and Blaney-Criddle methods. While not as accurate, typically these methods rely upon only local measurements of temperature.

In 1999, American Society of Civil Engineers (ASCE) formed a Task Committee on Standardization of Reference Evapotranspiration. The purpose of this committee was to evaluate the results of evapotranspiration estimates calculated using 13 equations, and to develop a recommended Standardized Reference Evapotranspiration Equation. The resulting method is often referred to as the "standardized" or "ASCE Penman-Monteith Equation," or the "FAO-56" method. This method has since been adopted world-wide and is considered to be the most accurate ETo calculation. The standardized equation can be used to calculate hourly and/or daily ETo. All ET and related networks surveyed in this project calculate and post daily ETo using this method.

4.2 Sensor and Weather Station Requirements

Integral to the calculation of ETo with the standardized Penman-Monteith equation is the accuracy of the climatic data required (temperature, relative humidity, solar radiation and wind).

In a previous TWDB funded study, Marek et al. (2010) found that small errors in these measurements resulted in significant errors in seasonal ET calculations. In addition to sensor accuracy, the standardized Penman-Monteith method requires measurements to be taken at specific heights above the ground, certain sensors to be shielded appropriately, and that the weather station be properly sited and maintained. Siting requirements for ET stations are often much stricter than that of weather stations used in other applications. Siting requires a large well-maintained grassy area at least 30 times the height of the station, with additional requirements for distances away from obstacles.

Weather station requirements for calculation of ETo with the standardized method have been incorporated into the ASABE Standard for Measurement and Reporting Practices for Automatic Agricultural Weather Stations (ASABE, 2015). All ET and PET networks included in the survey here follow these standards.

Most ET and PET networks use similar equipment, Campbell Scientific data loggers, and sensors as are used in the TexasET Network. Table 1 lists TexasET equipment specifications and costs.

Table 4-1: Datalogger and sensors used in the TexasET Network

Datalogger/Sensor model	*Cost per station ($)*
CR800 Datalogger for Measurement and Control	1056
HMP60-L10 Vaisala Temperature and RH Sensor	288
6 Plate Gill Radiation Shield	115
TE525-L25 6" Rain Gauge	356
LI200RX-L15 LI-COR Pyranometer	470
LI2003S LI-COR Leveling Base	77
03002-L15 RM Young Wind Set	663
Tipping bucket Rain Gage TE525	355
Total cost for datalogger and sensors	3380

4.3 Benefits of ET Observations

In Texas, and many other regions, irrigation is the largest user of water. In Texas, agricultural irrigation accounts for 60% of all freshwater usage, and landscape irrigation accounts for 40-60% of municipal water usage during the summer months. ET based irrigation schedules typically can reduce water consumption by 20-30% in agricultural irrigation and 40-50% in landscape irrigation. Thus, the need for water conservation and to free up water for other uses is a major driver of ET observation and the establishment of ET networks.

The first state-wide PET Network established in the US was the California Irrigation Management Information System (CIMIS) which began operation in 1982 with the purpose to provide current and historical weather information for irrigation management, funded though the California Department of Water Resources. Parker et al. (1996) evaluated the costs and benefits of CIMIS and found that CIMIS was successful in promoting increases in agricultural production and lowering input water use. They estimated that it produces benefits valued at $64.7 Million per year to California, far exceeding its annual cost of $850,000. Other benefits include:

1. Reduced agricultural water consumption by 13% and increase crop yield by 8%,
2. Urban parks, cemeteries and golf courses showed the highest water use reductions, averaging about 8 inches reduction in irrigation use per site. Three municipal water

districts achieved annual water savings between 10-20% through irrigation management education programs with the use of hotlines for CIMIS data dissemination,

3. Through crop consultants, CIMIS saved their clients between 11 and 40% in annual water consumption,
4. The availability of CIMIS data allowed for adoption of advanced control systems for irrigation scheduling and water management.

The North Carolina Environment and Climate Observing Network (NC ECONET) is a state-supported mesonet that includes an ET Network. Duke (2003) conducted an analysis of the economic value of the mesonet to the state of North Carolina for varies aspects of the mesonet and climatic data services provided. In regards to agriculture, this paper states that $43.4 million dollars per year could be saved by use of the network's data just in the areas of crop management, pesticide application, and drought effect mitigation.

Marek et al. (2010) reported that areas with ET networks that are properly operated, maintained and implemented with a sound education/outreach program have reduced seasonally pumped water amounts by growers by 5 cm (2 inches) per year per acre without the loss of crop yield. That amount of water savings based on the regional acreage in Texas Water Planning Region A could save producers 18 million dollars annually in energy pumping costs alone. With over 6 million irrigated acres in Texas, the potential benefits of a state ET Network are significant.

The *WaterMyYard* Program is a Texas homeowner outreach program that informs participants if they need to water during the current week, and if so, how many minutes to run their irrigation systems. These runtimes are determined from ETo data collected as part of the TexasET Network and sent to users who set up a profile by email and text. The program was launched in 2013 in cooperation with select cities and water districts. Currently, there are about 9900 participants in the program, with estimated total water savings of 798 million gallons per year, which equates to a water-cost savings of $2.9 million.

The City of Frisco WaterWise program began in 2009 and uses ETo-based data in order to answer the question “Do we need to water at all?” This information is issued weekly through newsletters, social media, city websites, and a phone hotline. Frisco has seen consumption drop from 300 to 147 gallons per person per day since 2009, and attributes much of this to their WaterWise program.

5 Survey of ET Networks

5.1 Definition of ET Networks

Various terms are used to describe networks that calculate ETo, including PET Networks, ET Networks, Ag Crop Weather Networks, and Ag Weather Networks, among others. The Texas Groundwater Protection Committee (TGPC) defines an ET network as a network with the following characteristics: (http://tgpc.state.tx.us/POE/FAQs/TxETnetworks_FAQ.pdf):

1. Consists of special weather stations designed specifically to measure the parameters needed for the calculation of reference evapotranspiration (ETo);
2. Calculates and uses ETo to determine plant water requirements and irrigation watering recommendations, and
3. Disseminates this information to end users through on-line access, on-line tools, emails, and other methods.

In our survey of networks, we found that they can be classified as follows:

1. ET Network

- Calculates and posts near real-time reference ET data (ETo) following the standardized Penman-Monteith Method or with a closely related form of the Penman equation,
- Follows the ASABE Standard for weather station specifications, siting, and management, and
- Meets all three TGPC characteristics.

2. PET Network

- Calculates and posts near real-time reference ET data (ETo) following the standardized Penman-Monteith Method or with a closely related form of the Penman equation,
- Follows the ASABE Standards for weather station specifications, siting, and management, and
- Posts ETo data in near real-time, but does not calculate crop ET or have tools for users to do so.

3. Ag Weather Network

- Calculates and posts near real-time reference ET data (ETo) following the standardized Penman-Monteith Method or with a closely related form of the Penman equation,
- Follows the ASABE Standards for weather station specifications, siting, and management, and
- Posts ETo data in near real-time, but whose primary purpose is implementation of crop models and other crop management tools for decision support.

4. Other

- Does not calculate ETo using a form of the Penman Equation and/or
- Does not meet ASABE weather station standards
- Due to the expected amount of error in ETo values reported, these types of networks are of limited value.

5.2 Survey of State ET Networks

We used a similar process as in the survey of mesonets discussed in Section 6. To be included, the network must have an active website, and must post near, real-time data, typically daily summaries. The website then was reviewed, and basic information compiled. As needed, follow-up calls were made to the network managers for clarification or additional information.

Out of state networks were evaluated on their ease of use and potential to be a good model for Texas to reference. The identification of an out of state network as a good model for Texas means that the network has certain features that are well-designed and particularly useful for users. Ease of use was graded on a 1 to 3 scale, where:

- A score of 1 means the network website is very simple to navigate in order to find and access ET and climatic data. Generally, these websites are well organized with intuitive menus and links to follow.
- A score of 2 means the end user has to navigate through various pages or web tools in searching for ET data.

A score of 3 would be given to a network whose website was difficult to navigate and access ET data. Table 5-1 lists all out-of-state networks that were identified which meet one of the network definitions given above. All 15 networks post daily data. Table 5-2 lists the classification of the network into one of the four categories listed above. Table 5-3 lists key characteristics of each network. Two of the networks, Florida and Oklahoma, have features that would serve as a good model for a state-supported ET network in Texas. Of the 15 networks identified, only two of the networks are state funded, with all the remaining state networks a project of the land-grant university system. University-based networks use a combination of funding sources to support the network.

Table 5-1: State ET and related Networks included in our Out-of-State Survey

State	Network Name	URL
California	California Irrigation Management Information System	cimis.water.ca.gov
Colorado	Colorado Agricultural Meteorological Network (CoAgMet)	coagmet.colostate.edu
Florida	Florida Automated Weather Network (FAWN)	fawn.ifas.ufl.edu
Georgia	Georgia Automated Environmental Monitoring Network	weather.uga.edu/index.php
Iowa	ISU Soil Moisture Network	mesonet.agron.iastate.edu/agclimate/#tmpf
Louisiana	Louisiana Agriclimatic Information System (LAIS)	weather.lsuagcenter.com/Default.aspx
Minnesota	Ag Weather Network	agweathernetwork.com
Nebraska	Nebraska Agricultural Water Management Network (NAWMN)	water.unl.edu/cropswater/nawmn
New Mexico	New Mexico State Evapotranspiration	nmclimate.nmsu.edu/evapotr/home.php
North Carolina	North Carolina Environment and Climate Observing Network (ECONet)	climate.ncsu.edu/econet/
North Dakota	North Dakota Agricultural Weather Network (NDAWN Center)	ndawn.ndsu.nodak.edu
Oklahoma	Mesonet	www.mesonet.org
South Dakota	Mesonet at SDSTATE	climate.sdstate.edu
Utah	AgWeather Net	climate.usurf.usu.edu/agweather.php
Washington	AgWeatherNet	weather.wsu.edu/?p=88650

Table 5-2: Classification of State ET and related Out-of-State Networks

ET Network	PET Network	Ag Weather Network	Other
Colorado	California	Georgia	Minnesota
Florida	Iowa		Nebraska
North Carolina	Louisiana		New Mexico
Oklahoma	North Dakota		South Dakota
Washington	Utah		

Table 5-3: Characteristics of Out of State Networks.

State	Real Time ETo	ETc Tables	Ag Crops	Turf	Accumulated Soil Moisture-Water Balance Tools	Other/ Advanced Scheduling Tools	Runtimes Recom-mendations	ET Weather Data Available	Ease of Use (1-3)	Good Model?	Management Entity
California	X							X	1		State
Oklahoma	X		X	X	X			X	1	X	State
Washington State	X		X	X	X			X	2		University
Colorado	X	X	X	X				X	1		University
Georgia	X		X		X	Peaches		X	2		University
North Carolina	X					Turfgrass		X	2		University
North Dakota	X		X	X	X			X	1		University
Agrimet USBR	X	X	X	X				X	1		Federal
South Dakota	X		X					X	2		University
Arizona	X	X	X	X				X	2		University
Florida	X	X	X	X		Lawn Tools	X	X	1	X	University
Great Plains-USBR	X	X	X	X				x	1		Federal
Nebraska		X	X						2		University
Louisiana	X							X	2		University
Utah State	X							X	2		University

Table 5-4: Crop ET data or calculation tools included in each surveyed Network

ET Network	Agricultural Crops	Landscape/Horticulture
Oklahoma	Wheat, Grass Hay, Alfalfa, Corn, Cotton, Peanut, Sorghum, Soybean, Pecan, Peach, Grape, Watermelon, Tomato, Sweet Corn	Garden Vegetables, Turfgrass
Washington State	Alfalfa, Apples, Apricots, Dry Beans, Green Beans, Blueberries, Carrots, Cherries, Clover, Grapes, Corn, Sweet Corn, Crucifers, Cucumbers, Pasture Grass, Hops, Onions, Peaches, Pears/Plums, Peas, Peppermint, Potatoes, Radishes, Raspberries, Safflower, sorghum, Soybeans, Spearmint, Spinach, Spring Grains, Strawberries, Sugar Beets, Sunflower, Tomato, Wine Grapes, Winter Wheat	Turfgrass
Colorado	Alfalfa, Corn, Dry Bean, Small Grain, Sugar Beets, Potato, Onion, Winter Wheat	Cool Season Turfgrass
Georgia	Peaches	None
North Dakota	Alfalfa, Barley, Corn, Dry Bean, Potato, Soybean, Sugar Beets, Sunflower, Wheat	Turfgrass
Agrimet USBR	Alfalfa, Apples, Asparagus, Dry Beans, Sugar Beets, Blueberries, Broccoli, Cabbage, Grapes, Cherries, Cranberries, Carrots, Field Corn, Garlic, Fescue Hay, Hops, Melons, Mint, Onion, Orchards, Pasture, Pears, Peas, Peaches, Poplar Tree, Potato, Peppermint, Rapeseed/Canola, Safflower, Spearmint, Barley, Strawberry, Spring Grain, Spearmint, Trailing Berries, Winter Grain, Winter Grapes	Lawn Grass, Easter Lilies
South Dakota	Corn, Soybeans	Grass
Arizona	Alfalfa, Nuts & Apples, Corn, Chile, Wine Grapes, Cotton	Turfgrass
Florida	Beans, Cabbage, Carrot, Corn, Cotton, Cucumber, Sorghum, Peanut, Potato, Small Grain, Tobacco, Summer Squash, Tomato, Watermelon, Strawberry, Citrus	Turfgrass
Great Plains USBR	Alfalfa, Apples, Asparagus, Dry Beans, Sugar Beets, Blueberries, Broccoli, Cabbage, Grapes, Cherries, Cranberries, Carrot, Field Corn, Garlic, Melons, Mint, Onion, Orchard, Pasture, Pears, Peas, Peaches Poplar Tree, Potato, Peppermint, Canola, Strawberry, Sweet Corn, Spring Grain, Spearmint, Sunflower, Trailing Berries, Winter Grain, Wine Grapes	Lawns
Nebraska	Corn, soybeans, Wheat, Sorghum, Sunflower, Sugar Beets, Potato, Dry Bean	None

5.3 ET and Related Networks in Texas

The number of ET and related networks that still operate in the State has significantly declined since the last ET study contracted by the TWDB (Marek et al. 2010). The High Plains PET Network operated by Texas A&M AgriLife shut down in 2013 due to a lack of funding, as did the South Texas Crop Weather Network in January 2017. There remains only two networks in

Texas that meet one of the network definitions given above, have active websites, and post near real-time ETo and related data. These are listed in Table 5-5.

Table 5-5: ET and Related Networks in Texas

Network Name	Type/Classification	URL
TexasET Network	ET Network	texaset.tamu.edu
West Texas Mesonet	Other	mesonet.ttu.edu

The **TexasET Network**: Texas A&M AgriLife Extension Service.

Began in 1994 and currently with 56 weather stations located statewide. Data transfer for all but one station is by cell phone IP or direct internet transfer. TexasET is self-funded through revenue from short courses and contracts/grants, and it depends upon local sponsors to cover the costs of the weather stations. Local sponsors not only purchase the station itself, but also provide the location (site) for the station, perform all maintenance of the station and the site, and cover communication costs. However, future continuation is in doubt due to the lack of sustained funding sources. In recent years, there been an increase in interest from cities and municipal water districts, and extensive urban weather station networks have been established in the Dallas/Ft. Worth region, in the Austin area, and in the greater Houston area.

The TexasET Network displays daily weather and ETo data, heat units, and other data; offers interactive, easy-to-use calculators that allow users to determine the irrigation water requirements of crops and landscapes; and provides several other tools (e.g., for downloading data and setting up automatic email notifications of customized weather data and irrigation recommendations). This network is unique in that it is self-funded. The TexasET Network provides the "backbone" for the WaterMyYard program (http://WaterMyYard.org) that is becoming very popular among cities and water districts. http://TexasET.tamu.edu

West Texas Mesonet: Texas Tech University.

Initiated in 1999 to provide free real-time weather and agricultural information for residents of the South Plains region of western Texas. The network does post ETo data and is classified here as "other" as it does not use the standardized Penman Monteith Method for calculation of ETo and does not explicitly follow the ASABE standard for weather stations siting. However, some of their stations do appear to meet these siting requirements, and thus, show potential for use in an ET or PET Network. http://www.mesonet.ttu.edu/

6 Mesonets Outside Texas

6.1 Overview of Information Gathering Process

Most of the time and effort spent on this project was in the gathering of information from currently operating mesonets. The information received was recorded in an Excel spreadsheet template designed specifically for this project. Information was collected for each mesonet through two methods: semi-structured interviews and online resources.

Semi-structured interviews were scheduled over email with an appropriate point of contact for each mesonet (See Table 6-1). The interviews themselves were conducted over the telephone and typically lasted between half an hour and an hour and a half. As needed, answers to follow-up questions were solicited via email or obtained from documents provided by the interviewee or from online resources.

The semi-structured interviews were designed to elicit the information necessary to fulfill the information-gathering needs of the project while not being unduly burdensome to the person being interviewed. A standardized Excel spreadsheet was developed with interview questions and space for answers to be entered by the interviewer. Both the list of questions in text form and the Excel interview template is included in the Appendix. The interviewer used the list of questions as a rough guide, allowing the conversation to flow and entering responses into the appropriate boxes. Since these were interviews rather than comprehensive surveys, some questions were left unasked if they seemed irrelevant or inconsequential in the context of answers already received.

The interview responses were stored within the Excel document as one worksheet per mesonet. This enabled easy compilation and cross-referencing of topical responses.

This process can be broken down into a few distinct steps for each mesonet we studied:

1. Identify the person most capable to answer a comprehensive list of questions.
2. Send an email to the person(s) identified in Step 1 requesting a phone interview.
3. After an interview was setup, browse the mesonet webpage for information that could assist in the direction of the interview.
4. Interview the key person(s) at a convenient time and transcribe important information from the conversation. For information that was already documented, request that the interviewee provide access to the existing material.
5. Use any supplemental information provided by the interviewee to complete the Excel template.
6. Revisit the mesonet webpage to find information to help complete the Excel template.

Table 6-1: Mesonet personnel interviewed for this report

Network Name	State	Interviewee or Contact
Auburn University Mesonet	Alabama	Rodger Getz*
South Alabama Mesonet	Alabama	Sytske Kimball*
Arizona Meteorological Network	Arizona	Paul Brown
California Irrigation Management Information System	California	Bekele Temesgen
Colorado Agricultural Meteorological Network	Colorado	Zach Schwalbe
Delaware Environmental Observing System	Delaware	Kevin Brinson, Dan Leathers
ET Idaho	Idaho	Rick Allen
Florida Automated Weather Network	Florida	William R. Lusher*
Georgia Automated Environmental Monitoring Network	Georgia	Ian Flitcroft
Illinois Climate Network	Illinois	Jennie Atkins
Iowa Environmental Mesonet	Iowa	Daryl Herzmann
Purdue Automated Agricultural Weather Station Network	Indiana	Ken Scheeringa
Kansas Mesonet	Kansas	Chip Redmond
Kentucky Mesonet	Kentucky	Stu Foster
Louisiana Agriclimatic Information System	Louisiana	Randy Price
Michigan Enviro-Weather	Michigan	Jeff Andresen
Missouri Mesonet	Missouri	Pat Guinan
Nevada Integrated Climate and Evapotranspiration Network	Nevada	Justin Huntington
New Jersey Weather and Climate Network	New Jersey	Dave Robinson
New York State Mesonet	New York	Jerald Brotze
North Carolina Environment and Climate Observing Network	North Carolina	Sean Heuser
North Dakota Ag Weather Network	North Dakota	Daryl Ritchison
Oklahoma Mesonet	Oklahoma	Chris Fiebrich
University of Oregon Solar Radiation Monitoring Lab	Oregon	Frank Vignola*
South Dakota Mesonet	South Dakota	Nathan Edwards
Utah's Ag Weather Network	Utah	Robert Gillies
AgWeatherNet	Washington	Sean E. Hill*

*Denotes personnel not directly interviewed

6.2 Summary of Basic Mesonet Information

6.2.1 Size of Networks

A master list of mesonets was created from a variety of online resources and from personal knowledge. These online resources include a list of mesonets incorporated into the Meteorological Analysis Data Ingest Stream (MADIS; https://madis.noaa.gov/network_info.shtml), which is operated by and in support of the National Centers for Environmental Prediction, a branch of the National Weather Service (NWS), which in turn is part of the National Oceanic and Atmospheric Administration (NOAA). Another online resource is hosted by the National Center for Atmospheric Research's Earth Observing Laboratory (https://www.eol.ucar.edu/projects/hydrometnet/) in support of a Global Energy and Water cycle Exchanges (GEWEX) subproject, the GEWEX Americas Prediction Project (GAPP).

A set of stations may be considered to be a "loose" network if it shares a common means of data collection and dissemination, but station installation and maintenance is handled by different agencies. At a bare minimum, a set of stations is considered a network if the information is being collected and processed by the mesonet agency. At the other extreme, a uniform network shares consistent instrumentation, siting standards, quality control, maintenance, and product generation. Many of the mesonets described here are uniform networks, but some include stations with different instrumentation and siting standards. For such heterogeneous networks, this report focuses on what we call top-tier sites: those sites that are part of a uniform sub-network with preferred instrumentation. We define a top-tier sub-network as an agency's collection of stations with the consistencies of a uniform network. Table 6-2 lists the number of top-tier sites and the total number of sites within each network.

Table 6-2: Web addresses and configuration of statewide mesonets

State	Web Site	Stations	Top-Tier	TTStation Density (sq mi/stn)
AL	www.awis.com/mesonet/index.html	17	13	4000
AL-south	chiliweb.southalabama.edu	26	26	450*
AZ	ag.arizona.edu/azmet	28	28	4100
CA	www.cimis.water.ca.gov	152	152	1100
CO	www.coagmet.colostate.edu	93	75	1400
DE	www.deos.udel.edu	69	57	50**
FL	fawn.ifas.ufl.edu	42	42	1600
GA	weather.uga.edu	83	83	700
ID	data.kimberly.uidaho.edu/ETIdaho	126	17	4900***
IA	mesonet.agron.iastate.edu/agclimate	17	17	3300
IL	www.isws.illinois.edu/warm/datatype.asp	19	19	2900
IN	www.iclimate.org	8	8	4500
KS	mesonet.k-state.edu	56	56	1500
KY	www.kymesonet.org	68	68	600
LA	weather.lsuagcenter.com/Default.aspx	9	9	4800
MI	www.enviro-weather.msu.edu/homeMap.php	86	86	1100
MO	agebb.missouri.edu/weather/stations	34	24	2900
NV	nicenet.dri.edu	18	18	6100
NJ	www.njweather.org/maps/station-locations	65	40	200
NY	www.nysmesonet.org	163	115	500
NC	climate.ncsu.edu/econet	40	40	1200
ND	ndawn.ndsu.nodak.edu/current.html	85	85	800
OK	www.mesonet.org	121	121	600
OR	solardat.uoregon.edu/index.html	26	26	6200****
SD	climate.sdstate.edu/index.asp	46	26	2900
UT	climate.usurf.usu.edu/agweather.php	125	35	2300
WA	www.weather.wsu.edu	177	177	400

* AL-south density calculation includes 14 counties in southern Alabama (9), western Florida (2), and southeastern Mississippi (3)
** DE density calculation includes Chester Co., PA
*** ID density calculation includes only stations directly measuring evapotranspiration variables
**** OR density calculation includes only stations in Oregon

6.2.2 Purposes

Sixteen of the surveyed mesonets were established primarily to serve agricultural needs, either research or production. Thus, these mesonets tend to be housed at land grant universities, for which agricultural research and extension is a core mission. Four of the surveyed mesonets were specifically designed to monitor evapotranspiration. Five of the mesonets were established with a primary mission of public safety. The University of Oregon Solar Radiation Monitoring Lab (SRML) monitors different solar radiation measurements, but most SRML stations do not observe other meteorological parameters. This report will refer to three main categories of mesonets as 1) agriculture, 2) evapotranspiration (ET), and 3) public safety.

In general, the purpose of each mesonet arose from a need or multiple needs that were unmet with the meteorological monitoring networks that were in place. For the agricultural networks, the measurements and derived indices are commonly driven by the specific crops within the state. The primary benefit of the mesonets in these states is an increased availability of information to make decisions that will directly benefit crop yields and safety. There are several examples of the agricultural networks saving producers millions of dollars because the available observations allowed for an informed decision that otherwise wouldn't have been made. The location of the ET-specific networks are in western states that rely heavily on irrigated agriculture. The ET observations in these networks (and the others that compute ET) provide more informed and targeted watering information than would otherwise be available. The public safety mesonets were primarily started to aid government-based emergency management efforts and often resulted from a catastrophic event that affected the state. An example is the New York State Mesonet formed in the aftermath of Hurricane Sandy in 2012. The SRML was developed to serve as a center for the "planning, design, deployment, and operation of solar electric facilities in the Pacific Northwest."

Table 6-3: Statewide mesonets included in this study

Network Name	State	Primary Mission	Operator
Auburn University Mesonet	Alabama	Agriculture	Auburn Univ.
Colorado Agricultural Meteorological Network	Colorado	Agriculture	Colorado St. Univ.
Florida Automated Weather Network	Florida	Agriculture	Univ. of Florida
Georgia Automated Environmental Monitoring Network	Georgia	Agriculture	Univ. of Georgia
Illinois Climate Network	Illinois	Agriculture	Illinois St. Water Survey
Iowa Environmental Mesonet	Iowa	Agriculture	Iowa St. Univ.
Purdue Automated Agricultural Weather Station Network	Indiana	Agriculture	Purdue Univ.
Kansas Mesonet	Kansas	Agriculture	Kansas St. Univ.
Louisiana Agriclimatic Information System	Louisiana	Agriculture	Louisiana St. Univ.
Michigan Enviro-Weather	Michigan	Agriculture	Michigan St. Univ.
Missouri Mesonet	Missouri	Agriculture	Univ. of Missouri
North Carolina Environment and Climate Observing Network	North Carolina	Agriculture	North Carolina St. Univ.
North Dakota Ag Weather Network	North Dakota	Agriculture	North Dakota St. Univ.
South Dakota Mesonet	South Dakota	Agriculture	South Dakota St. Univ.
Utah’s Ag Weather Network	Utah	Agriculture	Utah St. Univ.
AgWeatherNet	Washington	Agriculture	Washington St. Univ.
Arizona Meteorological Network	Arizona	ET	Univ. of Arizona
California Irrigation Management Information System (CIMIS)	California	ET	California Dept. of Water Resources
ET Idaho	Idaho	ET	Univ. of Idaho
Nevada Integrated Climate and Evapotranspiration Network	Nevada	ET	Desert Research Institute
South Alabama Mesonet	Alabama	Public Safety	Univ. of South Alabama
Kentucky Mesonet	Kentucky	Public Safety	Western Kentucky Univ.
Delaware Environmental Observing System	Delaware	Public Safety	Univ. of Delaware
New Jersey Weather and Climate Network	New Jersey	Public Safety	Rutgers Univ.
New York State Mesonet	New York	Public Safety	State Univ. at Albany
Oklahoma Mesonet	Oklahoma	Public Safety	Univ. of Oklahoma
University of Oregon Solar Radiation Monitoring Lab	Oregon	Solar Radiation	University of Oregon

Because the networks discussed in this report constitute a selective sample, they should not be interpreted as representative of typical mesonets. At any rate, the purpose of this report is not to determine the characteristics of a typical mesonet. It is to identify the characteristics of a successful mesonet.

6.2.3 Consumers of Information

Despite the particular mission-driven origins of the surveyed mesonets, all of them now serve multiple user constituencies. Four of the agricultural mesonets now serve a public safety mission, at the state and/or federal level. All four ET mesonets and two of the public safety mesonets are noted to be utilized by agricultural interests. Eight of the mesonets (four agricultural and all four ET) are utilized for water supply monitoring or drought monitoring purposes. Seven provide essential data for research applications. Among the other uses mentioned by the surveyed mesonet operators are economic development, education, energy, tourism, transportation, engineering, construction, environmental protection, insurance, and news and information.

Perhaps the most avid consumers of the mesonet information are the producers and farmers that use the data to make decisions about their specific commodity. There are numerous examples of consumers deciding to become network sponsors because of their desire for localized information. This includes the Kentucky Mesonet, primarily a public safety mesonet, which has drawn praise from local and county governments within the state for its use in helping to provide valuable information in dangerous weather situations. Additionally, a few of the states surveyed offer sponsorship programs in their network to incentivize both public and private entities to donate and become more involved in their state's mesonet program, even without directly running a mesonet station. For example, Michigan Enviro-Weather has a tiered sponsorship program that gives consumers the options to 1) sponsor a weather station in exchange for advertising (two tiers), 2) sponsor a specific commodity, 3) sponsor the mesonet fully and appear on the home page (most expensive), and 4) sponsor a specific web product.

6.3 Summary of Mesonet Business Models

6.3.1 Startup Costs/Funding

The agriculture mesonets were established in the 1980s and 1990s, primarily with internal funding within university agricultural research and extension programs. Some received additional federal or state grant money to assist with installation and operations. Only two networks (Florida and Illinois) were funded initially with money allocated directly from the state.

The Arizona ET mesonet was started in 1986 using a collection of start-up funds. CIMIS (California) was originally funded in 1982 by state grants to UC Davis. ET Idaho was started in 2007 through federal funding and relies on the Pacific Northwest BOR, which provides most of the monitoring equipment. The Nevada mesonet was also originally funded by federal dollars, originating in 2010. The Oregon SRML was started in 1977 through funding by the now-defunct Pacific Northwest Regional Commission.

Three of the five public safety mesonets were initially established using federal grant money, either from the Federal Emergency Management Agency or the National Weather Service. New Jersey was established using state agency money, from the State Police and the State Department of Transportation. The South Alabama Mesonet was originally funded through grants and donations.

The reported costs for new stations vary considerably, depending on instrumentation. The New York State Mesonet stations, with a start-up cost of $40,000, were far and away the costliest in the mesonets surveyed. The initial generous appropriation by FEMA's Hazard Mitigation Grant Program ($23.6 million) allowed for a setup of state-of-the-art monitoring and communications equipment, secure infrastructure, and numerous redundant sensors that most networks would like to have if not hampered by budgetary restrictions.

The other two networks with a significantly higher start-up cost than the rest are those in the Illinois network (an agricultural network) and the Kentucky network (a public safety network). Both cost about $25,000 to establish a new station. At the lower end, three agricultural networks (Colorado, North Dakota, and Utah) cost between $6,200 and $7,000 per station installation. The cost per installation for the remaining nine networks is between $10,000 and $15,000.

6.3.2 Maintenance Cost/Funding

Funding for additional stations comes from a variety of sources. Eleven of the mesonets follow a model whereby individual local or state entities sponsor new stations, and a twelfth mesonet is planning to expand in that manner. Four build new stations through agriculture extension funding, five through state funding, one through both agriculture and state funding, and another through grants and donations. The remaining mesonets utilize federal funding from sources such as the National Mesonet Program and FEMA for network expansion.

The State University of New York applied for over $30 million in funding through FEMA's Hazard Mitigation Grant Program (HMGP) after Hurricane Sandy and was granted $23.6 million to build a 125-station network. Funding was secured by demonstrating this proposed network "can reduce risks to communities by improving the state's ability to provide better weather-related warnings. When dealing with potentially severe weather conditions, accurate forecasts are paramount to helping emergency managers plan."

Maintenance costs also vary across networks. The primary variables driving maintenance costs are the costs of the sensors and the amount of travel necessary. The amount of travel is primarily driven by the size of the state, the distribution of stations, the location of the main office(s), participation of individual station operators, and the site maintenance requirements.

North Dakota reports the lowest per-station maintenance cost, $1,000, while Illinois reports the highest per-station maintenance cost, $6,000. The median cost per station is about $2,500. Maintenance costs at 18 of the 26 mesonets are paid by individual station sponsors, either local or state entities, with state or federal funding utilized by the other eight mesonets.

Programmatic funding includes overall network operation, quality control, product generation, data dissemination, and data archival. Programmatic funding was provided by individual station sponsors at nine mesonets, by the state at five mesonets, by agricultural research and extensions at four mesonets, by the National Mesonet Program at one mesonet, and by FEMA at another. The other mesonets made use of various combinations of these funding sources.

Full-time-equivalent staff levels for each mesonet varied from 1 to 5, with 2 or 2.5 being most common. CIMIS employed the most full-time staff at five, while the New York mesonet have 11 scientists (including 10 PhDs) that spend extensive time on mesonet related activities. Most work was done in-house, with a few mesonets outsourcing site preparation, maintenance, calibration, or web services.

6.3.3 Financial Outlook

Three of the five public safety mesonets reported a financial outlook. One reported the situation excellent, the other reported the situation stable, and the third reported "Probably OK". One public safety network was the most rapidly growing network, so its financial situation can be assumed to be sound. The other appears to be relatively stable by outside appearances, based on recent activities. The agricultural networks generally reported a stable financial outlook, except for one excellent, one good, and one unsure. Several of the agricultural networks reported a stable funding situation only because of the additional funding provided recently by the National Mesonet Program. Of the three ET networks that reported, the mesonet operators reported the outlook to be "poor", "fine", and "solid." The outlook for the Pacific Northwest BOR network, which provides most of the observations for ET Idaho reported a "solid" financial outlook.

6.4 Summary of Mesonet Infrastructure

6.4.1 Equipment

Measurements at standard mesonet sites are listed in Tables 6-4 and 6-5. For mesonets with multiple configurations, the most common configuration is listed. In some cases, values were interpreted or adapted from the information originally provided. See original spreadsheet for detailed responses.

At least half of the networks follow the siting guidelines promulgated by the WMO (http://www.wmo.int/pages/prog/www/IMOP/SitingClassif/CIMO_Guide_2014_en_I_1-2_Annex_1B.pdf). Other guidance for siting mentioned by at least one network operator include manufacturer recommendations, the proposed guidelines by the American Association of State Climatologists (AASC), conventional agricultural network standards, and standards followed by the Climate Reference Network (CRN) and NOAA's Environmental Real-time Observation Network (NERON).

All of the surveyed mesonets (except the Oregon SRML) observe air temperature, relative humidity, wind speed, and solar radiation, the four parameters necessary for calculation of evapotranspiration. Two of the mesonets include direct ET measurements through evapotranspiration sensors (Indiana and Missouri). The heights above ground at which these quantities are measured vary from mesonet to mesonet, and some mesonets make some observations at multiple levels. All surveyed mesonets also measure precipitation. All surveyed mesonets measure soil temperature, and most measure soil moisture as well. There is currently no standard for soil moisture data collection; however, most networks install various sensor models at 2, 4, 8, 20 and 40+" depths, depending on need. Less common measurements include barometric pressure, wetness, and snow depth.

Table 6-4: Mesonet observed variables and heights (positive) or depths (negative) (if known and relevant). Italicized observables are commonly used to estimate evapotranspiration.

	Agricultural networks							
Observable	**AL**	**CO**	**FL**	**GA**	**IA**	**IL**	**IN**	**KS**
Air temperature	*5’*	*5’*	*6.5’*	*6.5’*	*6.5’*	*6.5’*	*6.5’*	*5’*
Air temperature			33’					
Relative humidity	*5’*	*5’*	*6.5’*	*6.5’*	*6.5’*	*6.5’*	*6.5’*	*5’*
Relative humidity								
Wind speed, direction	*6.5’*	*6.5’*		*10’*	*10’*		*10’*	*5’*
Wind speed, direction	*33’*		*33’*			*33’*		*33’*
Solar radiation	*yes*	*6.5’*	*10’*	*6.5’*	*6.5’*	*6.5’*	*10’*	*5’*
Precipitation	yes	3’	1’	1.5’	1.5’	3’	1.5’	33’
Snow depth								
Barometric pressure				yes				
Evapotranspiration								3’
Wetness								
Soil temperature								
Soil temperature	-2”	-2”		-2”	-1.5”			-2”
Soil temperature	-4”		-4”	-4”		-4”	-4”*	-4”
Soil temperature	-8”	-6”		-8”		-8”		
Soil temperature								
Soil temperature								
Soil temperature								
Soil moisture				-2”		-2”		
Soil moisture				-4”		-4”		
Soil moisture				-8”	-8”	-8”		
Soil moisture								
Soil moisture					-20”			
Soil moisture								
Soil moisture						-40”		
Soil moisture					-50”	-60”		

*Measured beneath both bare ground and sod

Table 6-4 (continued)

More Agricultural Networks

Observable	**LA**	**MI**	**MO**	**NC**	**ND**	**SD**	**UT**	**WA**
Air temperature	*10'*	*5'*	*5'*	*6.5'*	*5'*	*6.5'*	*6.5'*	*6.5'*
Air temperature	33'							
Relative humidity	*10'*	*5'*	*5'*	*6.5'*	*5'*	*6.5'*	*6.5'*	*6.5'*
Relative humidity	33'							
Wind speed, direction	*10'*	*yes*	*10'*	*20'*	*10'*	*10'*	*10'*	*10'*
Wind speed, direction	*33'*			*33'*				
Solar radiation	*yes*	*3'*	*10'*	*6.5'*	*6.5'*	*yes*	*10'*	*yes*
Precipitation	yes	3'	1.5'	3'	3'	yes	6.5'	yes
Snow depth								
Barometric pressure			yes	yes	yes			yes
Evapotranspiration				yes				
Wetness								
Soil temperature	-0.5"							
Soil temperature	-2"	-2"	-1.5"			-2"		-2"
Soil temperature	-4"	-4"	-4"	-4"	-4"*	-4"	-4"	
Soil temperature				-8"		-8"	-8"	-8"
Soil temperature	-12"			-12"				-10"
Soil temperature				-16"		-20"		
Soil temperature						-40"		
Soil moisture						-2"		
Soil moisture		-4"			-4"	-4"		
Soil moisture		-8"		-8"	-8"	-8"	-8"	
Soil moisture					-12"			
Soil moisture					-20"	-20"		
Soil moisture					-30"			
Soil moisture					-40"	-40"		

*Measured beneath both bare ground and sod

Table 6-4 (continued)

Other Networks

Observable	AL-south	AZ	CA	DE	ID	KY	NV	NJ	NY	OK	OR
Air temperature	6.5’	5’	6.5’	6.5’	6.5’	5’	6.5’	6.5’	6.5’	5’	
Air temperature	33’								30’	30’	
Relative humidity	6.5’	5’	6.5’	6.5’	6.5’	5’	6.5’	6.5’	6.5’	5’	
Relative humidity	33’										
Wind speed, direction	6.5’	10’	6.5’	10’	10’		10’			6.5’	
Wind speed, direction	33’					33’		33’	33’	33’	
Solar radiation	30’	8’	6.5’	10’	10’	10’	6.5’	10’	6.5’	6.5’	yes
Precipitation	3’	1.4’	3’	1.5’	6.5’	3’	3’**	yes	6.5’	yes	
Snow depth									yes		
Barometric pressure	5’				6.5’		yes	yes	6.5’	yes	
Evapotranspiration											
Wetness						yes					
Soil temperature					-1”						
Soil temperature	-2”	-2”		-2”	-2”	-2”		-2”	-2”	-2”	
Soil temperature	-4”	-4”			-4”	-4”	-4”	-4”		-4”*	
Soil temperature	-8”		-6”		-8”	-8”	-8”	-8”	-10”	-10”	
Soil temperature	-20”				-20”	-20”	-20”	-20”	-20”	-24”	
Soil temperature	-40”				-40”	-40”					
Soil moisture	-2”					-2”		-2”	-2”	-2”	
Soil moisture	-4”			-4”		-4”	-4”	-4”			
Soil moisture	-8”					-8”	-8”	-8”	-10”	-10”	
Soil moisture	-20”					-20”	-20”	-20”	-20”	-24”	
Soil moisture	-40”					-40”					

*Measured beneath both bare ground and sod
** Also measured at 10’

Table 6-5: Mesonet observed variables: expected or required accuracy

Agricultural Networks

Observable	CO	FL	GA	IA	IL	IN	KS	LA	MI	MO	NC	ND	SD	UT	WA
Air temperature (°F)	0.4	0.4		0.7	0.4	0.9	0.4	0.4	0.1	1	0.5	0.4	0.5	0.4	0.2
Relative humidity (%)	2	2		1	2	2	2	1	1	2	3	2	2	2	1
Wind speed (mph)	1	0.1		1	0.5	0.2	0.6	0.6		1	0.6	1	1	0.6	1
Wind direction (°)	5	2		5	3	4	3	1		5	3	5	5	3	5
Solar radiation (%)	3	3	3	3	5	3	5	3			5	3	3	5	
Precipitation (%)	1	3		1	5	1	2	2	1		2	1	1	1	1
Snow depth (in)															
Barometric pressure (mb)							2		2		0.5	0.2			0.5
Evaporation (%)															
Evapotranspiration (%)						1									
Wetness (in^2)															
Soil temperature (°F)	0.7	0.4		0.9	0.7	0.7	0.3	1.8			0.4	1.8	0.6	0.9	0.7
Soil moisture (%VWC)				3	3		1		3		1	3	3	1	3

Other Networks

Observable	AL-south	AZ	CA	DE	ID	KY	NV	NJ	NY	OK	OR
Air temperature (°F)	0.5	0.9	0.4	0.5	0.2	0.4	0.4	0.9	0.5	0.9	
Relative humidity (%)	2	2	2	1	1	2	2	2	1	3	
Wind speed (mph)	0.5	0.5	0.8	1	0.5	0.6	0.5	1	0.5	0.7	
Wind direction (°)	0.3	5	5	5	0.3	1	3	5	3	3	
Solar radiation (%)	3	3	3	3	3	5	5	3	3	5	2
Precipitation (%)	2	1	1	1	2	*	1	1	**	5	
Snow depth (in)				0.4					0.4		
Barometric pressure (mb)					2		0.5	2	0.1	0.4	
Evaporation (%)					0.3						
Evapotranspiration (%)											
Wetness (in^2)						0.1					
Soil temperature (°F)	0.4	1.8	0.7	0.4	0.2	0.6	0.9	1.6	0.5	0.9	
Soil moisture (%VWC)	3			1		1	1	2.5	1		

* Reported as 0.5 mm for precipitation events.
** Reported as 0.1 mm for precipitation events.

6.4.2 Communications

Each mesonet surveyed had a system of electronic communications that allowed for transmission of observations from the individual stations to the primary database, allowing for dissemination. The vast majority of communications from the individual stations is through cellular transmissions. Interviewees providing specific information mostly used a Verizon data plan and a Raven XTE cellular modem. Two of the mesonets use radio transmission, one uses satellite transmission, one uses a combination of cellular and satellite transmissions, and three use a combination of cellular and internet. A few respondents mentioned that positioning stations in the vicinity of schools not only provides educational benefits, but also cuts down on communications costs. Most schools will allow free internet access in exchange of the benefit of housing a weather observing station.

6.4.3 Maintenance Requirements

Most of the mesonets surveyed had specific maintenance schedules in place (Table 6-6), with an allowance for unscheduled visits for problems in the sensors and/or infrastructure. While most had maintenance standards expressed as a desired number of site visits per year, a few had seasonal variations in their requirements. A few of the mesonets have the information pertaining to the site visits, such as maintenance logs, available for on the web.

Some agricultural mesonets typically required more frequent visits during growing seasons, with at least one requiring weekly site visits. In addition to site visits, a few of the mesonets had strict standards for sensor replacement and calibrations. For example, the North Carolina mesonet (ECONet) requires calibration of equipment every two years and replacement every five years, at minimum.

A few of the interviewees expressed the benefits of placing stations at agricultural experiment stations. Placement of these stations allows for more frequent visits, more technically savvy personnel on hand, and more frequent communications about the status of the equipment.

6.5 Summary of Mesonet Data Stewardship

6.5.1 Data Collection

Nearly all of the mesonets reported having a Campbell Scientific data logger for on-site storage of observations before transmission. The models ranged from the older CR10X newer versions including the CR3000, with most mesonets sampling every few seconds (Table 6-6).

Table 6-6: Mesonet sampling, reporting, and maintenance visit frequency

Agricultural Networks

Metric	AL	CO	FL	GA	IA	IL	IN	KS	LA	MI	MO	NC	ND	SD	UT	WA
Sampling (sec)			5-15	1			3		3			60		3		5
Aggregation (min)	60	60	15	15	15	5	30	1	2	5	5		5	5		15
Reporting (min)		60	15	15	60	5	60	3	2	60	5	5	5	5	5-15	15
Visits (per year)		1		5	1*	3**	2	2	1-2	2-4	2-4	2-3	1	1		

*Experiment farm research sites maintained once per week.
**Sod & bare soil at agricultural sites maintained every six weeks during growing season.

Other Networks

Metric	AL-south	AZ	CA	DE	ID	KY	NV	NJ	NY	OK	OR
Sampling (sec)	3	10	60	20		3		2	3-30	3	
Aggregation (min)	1	60	60	5	15	5	30	5	5	5	1
Reporting (min)	1	*	60	5	60	5	30	5	5	5	
Visits (per year)	12	6-8	10	4	1	3		1	3	4	

* Data transmission is done just after midnight.

6.5.2 Data Dissemination

At most mesonets, all data is free. A few disseminate some data freely or disseminate free only to selected users. Some charge for large requests for archived data, but the red tape associated with charging for data seems in some cases not to be worth the effort of collecting the cost reimbursements.

All surveyed mesonets use web pages for data and product delivery, with some also maintaining FTP or XML access. Cell phones are increasingly being used for data delivery, either via text message alerts or smartphone apps.

Data is also incorporated into larger networks in most cases. Ten networks are included in the Meteorological Assimilation Data Ingest System (MADIS), where it can be used directly to improve weather forecasts. Three more are moving in that direction, while one has been frustrated with the requirements MADIS imposes on data availability, formatting, and certification. The frustration stems from the difficulty of integrating the MADIS XML format (Starfish Fungus Language) into the current metadata systems already in place. Most have their data disseminated via the National Mesonet Program, which, as noted above, provides some support funding for network maintenance. See Table 6-7 for a list of the mesonets directly participating in MADIS and the National Mesonet Program.

Nearly all of the agricultural networks receive some funding from the National Mesonet Program, while Utah's Ag Weather Network receives funding from the Bureau of Reclamation. The Purdue network (IN) is the only known agricultural network without federal funding, though it is unclear whether or not the Alabama Mesonet receives federal dollars. About half of the non-agricultural stations receive federal funding through sources like the National Mesonet Program and FEMA whereas the others rely upon state funding, private stakeholders, and donations.

Almost all mesonets also generate products from their data, with one noting that the computing part of mesonet operation requires as many resources as the maintenance of the network itself. These products can include generic products such as graphs and maps as well as specialized products for specific crops and pests and for water monitoring. At least half the mesonets permit or encourage specialized product generation by third parties.

All mesonet operators archive data, and those data archives are available to users, mostly free of charge, as discussed in the next section. One mesonet operator reported that their organization's IT services accidentally deleted their entire archival database. This experience highlights the value of redundant, off-site backup of irreplaceable data and information.

Table 6-7: Inclusion in MADIS and the National Mesonet Program (NMP)

Agricultural Networks

Metric	**AL**	**CO**	**FL**	**GA**	**IA**	**IL**	**IN**	**KS**	**LA**	**MI**	**MO**	**NC**	**ND**	**SD**	**UT**	**WA**
MADIS	N	N	Y	N	Y	N	N	N	Y	N	Y	Y	N	N	N	Y
NMP	*	Y	Y	Y	Y	Y	*	Y	Y	Y	Y	Y	Y	Y	*	Y

* Cannot confirm/deny membership in NMP based on available information.

Other Networks

Program	**AL-south**	**AZ**	**CA**	**DE**	**ID**	**KY**	**NV**	**NJ**	**NY**	**OK**	**OR**
MADIS	Y	N	N	Y	N	Y	N	Y	N	Y	N
NMP	Y	*	*	Y	*	Y	*	Y	Y	Y	*

* Cannot confirm/deny membership in NMP based on available information.

6.5.3 Example of Exceptional Web-Based Delivery

The New Jersey Weather and Climate Network (NJWCN) has a web delivery system (http://www.njweather.org/) that is aesthetically pleasing and both thorough and efficient in its dissemination of data. The home page features direct access to statewide maps of the most popular products (e.g., temperatures, winds, etc.) and data for a single station, which can be set by the user. Maps are available for several pre-defined geographic regions for each of the several variables measured by NJWCN. Values for weather elements such as air temperature, barometric pressure, precipitation, relative humidity, soil water content, evapotranspiration, soil temperature, solar radiation and winds are mapped with an appropriate color table. Clicking on a map value will take you directly to that station's "home page."

In addition to the maps, tools to create tables and charts are directly available from the home page. Clicking on "Tables" gives the user the option to look at 5-minute, hourly, and daily data tables. Clicking on a single station will allow you to go to the station's homepage or to display a time series of conditions from that station. Users have the option of creating customizable data tables by varying the weather elements, stations, and time spans of data requests. By clicking on the "Charts" tab on the home page, users can create time series using the latest data of any variable, and can choose 24 hours of 5-minute data, 7 days of hourly data, or 30 days of daily data.

Each station's "home page" contains the latest National Weather Service Forecast, tabular summaries of the latest observations, and charts of key variables. In addition to the data, a comprehensive list of metadata, names of the deployed sensors, and photos of the site are available. Each listed sensor is hyperlinked to a page that gives a thorough description, specifications, and photo of the equipment.

Other mesonets with exceptional web delivery are Michigan Enviro-Weather (http://www.enviro-weather.msu.edu/homeMap.php) and the Washington AgWeatherNet (http://www.weather.wsu.edu). Both offer an easy-to-use web interface, detailed observational data, an extensive record of metadata, and a wide variety of agricultural-based specialty products. Many of products produced by Enviro-Weather were encouraged to be developed and are currently paid for by station sponsors.

6.5.4 Quality Control

Quality control of real-time data was quite variable. Six (GA, IA, IL, MI, ND, NY) networks employed full or part-time workers whose primary responsibility was data quality control. Another three reported inspecting data products more informally, while seven (AL-south, CO, DE, FL, KY, NV, WA) reported using some automated tools for quality control. Although it was difficult to ascertain specific details on each network's QA/QC procedures during our interview process, it was evident that most networks performed at least basic sanity checks on the observations entered into the database and disseminated to the public.

Problems with data quality are often much easier to detect after the fact, particularly in the case of gradual sensor deterioration. Only seven (AL-south, FL, ID, MO, ND, NV, NY) networks reported a formal program of quality control of archived data. Another two (IL, KY) reported minimal but nonzero archival quality control activities.

6.5.5 Metadata

Station metadata is essential for proper interpretation of observations. In addition to basic instrumentation and observing characteristics discussed in the previous section, comprehensive metadata can include records of instrument changes, calibrations, maintenance logs, and site descriptions and photos.

Twenty-one of the mesonets reported maintaining metadata that went beyond the basic information. There was no conventional metadata framework being followed. Metadata archival formats ranged from paper documents to computer files to spreadsheets, and only in a few cases were the metadata posted on the web for easy user access. Table 6-8 details some of the advanced metadata that was made available on the web pages for the networks surveyed.

Table 6-8: Metadata information included

Agricultural Networks

Metric	AL	CO	FL	GA	IA	IL	IN	KS	LA	MI	MO	NC	ND	OK	SD	UT	WA
Instrumentation		Y	Y		Y	Y		Y				Y	Y	Y		Y	Y
Maintenance logs	Y				AL					Y		Y		Y			
Site photos		Y		Y		Y		Y		Y	Y	Y	Y	Y		Y	Y
Sponsorship information			Y*	Y						Y	Y	Y	Y		Y		Y

* Not available on an individual station basis

Other Networks

Metric	AL-south	AZ	CA	DE	ID	KY	NV	NJ	NY	OR
Instrumentation	Y	Y	Y			Y	Y	Y		Y
Maintenance logs	Y									
Site photos	Y		Y				Y	Y	Y	
Sponsorship information						Y				

6.6 Examples of Successful Statewide Networks

This section provides a more in-depth look at two of the statewide, university-based mesonets we investigated: the North Dakota Ag Weather Network (primarily agriculture) and the Kentucky Mesonet (primarily public safety). A third network, ET Idaho, is not a typical mesonet, but rather is a database that provides estimates of ET, net irrigation requirement (NIR), and precipitation for supporting the water needs of Idaho. Though it is not particularly unusual for mesonets to measure ET, the ET Idaho database is the most comprehensive found in our survey.

Following a more in-depth examination of the three aforementioned statewide networks, a shorter summaries of other networks are included. Many of the operating principles foundational to the successes of these networks are shared by other mesonets and should be considered for implementation into a Texas statewide evapotranspiration network.

6.6.1 North Dakota Ag Weather Network

The North Dakota Ag Weather Network (NDAWN), operated by North Dakota State University originated in 1989 by way of a grant from the High Plains Regional Climate Center (HPRCC). The information presented is courtesy of an interview with Daryl Ritchison, interim director of NDAWN, supplemental files sent by Ritchison, and the NDAWN webpage (http://ndawn.ndsu.nodak.edu/).

The original NDAWN consisted of six stations at agricultural research stations throughout North Dakota and has since grown to 85 stations in Minnesota, Montana, and North Dakota. A major focus and perhaps the biggest strength of NDAWN since its inception has been to provide detailed weather observations for crop-specific models. These models proved to be of great value during the 1993 Great Midwest Flood as several farmers commented that NDAWN was responsible for saving their crops. This 1993 flood sparked a tremendous period of growth in the network, which currently has excellent spatial coverage across most of North Dakota, as most locations in the state are within 20 miles of a station. Several of the mesonet operators stressed the importance of extreme events (not always weather-related) for highlighting the need to either start a new observational network or improve an existing one.

After the initial HPRCC startup grant, NDAWN has a business model of funding new stations through sponsorship. Sponsors include a variety of government agencies and private businesses (e.g., HPRCC, University of North Dakota Regional Weather Information Center, Red River Valley Potato Growers Association). This sponsorship model has been bolstered by relatively low startup costs (~ $7,000) with equipment that is both inexpensive and reliable (i.e., each piece of equipment NDAWN uses is used in several other networks). Network growth has been slow in recent years thanks to a diminishing need for new stations, so much of the annual operating budget is allocated for maintenance and infrastructure upgrades. The state of North Dakota covers NDAWN salaries and most of the funding comes from state and government agencies. The cost of NDAWN station maintenance is the lowest out of all networks studied (~ $1,000). The most important cost reducer has been the hiring of a network engineer, which has reduced the annual costs by $700/station. Much of the savings comes from the ability of the engineer to perform direct maintenance and calibrations instead of sending equipment to the manufacturer.

NDAWN uses primarily Campbell Scientific equipment and World Meteorological Organization (WMO) standards for observations. A major strength of NDAWN is its high standards for siting, which are explicitly detailed on their webpage at https://ndawn.ndsu.nodak.edu/help-equipment.html. This includes placing sites to minimize the effects of obstructions (horizontal distance from nearby obstructions at least 20-25 times the height of the obstructions) in flat, locations not subject to localized effects from cold air drainage. Grass is maintained in the vicinity of the 10 ft. tripod that houses most of the equipment, except for a 4 ft. × 5 ft. patch of bare ground used for soil temperature and moisture observations. Another desirable characteristic of NDAWN is standardization of the equipment used at each site. This homogenization minimizes the effects of equipment-related biases and allows easier detection of sensors that may need troubleshooting.

A mission of Ritchison (and most of the mesonet operators interviewed) is to maintain relationships with the individual station operators. This includes getting people to buy into the idea that the equipment is "their station." For researchers, this point is easy to get across since the quality of their results is directly tied to the quality of the observations. For producers, decision points for applications of water, sprays, pesticides, etc. may hinge on razor-thin margins of error. The willing participation of station operators in maintenance has reduced the frequency with which NDAWN staff needs to visit each site. Currently each site is visited a minimum of once each year, with recalibration of the instrumentation done every other year.

Observations are taken every 5 minutes and a cellular communication modem allows for online data displays to be updated every 10 minutes. The only issue is that the modem is a power drain, particularly in the cold season. In recent years, this has limited the transmission of data to once an hour during winter nights, but this issue is expected to be remedied for the upcoming winter with an equipment upgrade. In addition to raw data, NDAWN provides summaries for several pre-defined time intervals for easy download.

The webpage provides a detailed description of the network, which includes the NDAWN history, mission, and funding sources. Additionally, each measurement type, each variable type, each piece of observational equipment and the NDAWN siting standards are thoroughly explained. Of particular importance to this study, users have the capability to compute time series of Jensen-Haise and Penman potential evapotranspiration time series.

All data is freely available to the public, with the stated reason being that "all equipment and non-labor costs are funded by sponsors." NDAWN employs a quality control specialist whose job is to catch errors in real-time before ingestion into larger data systems, such as the HPRCC online data repository. This includes replacing erroneous or missing data with estimates to ensure that any crop models depending on a continuous flow of real-time data continue to function properly when issues arise.

Because much of the focus is on agriculture, there are tutorial web pages for using the weather data to make decisions for several important crops (e.g., barley, canola, corn, soybeans, sugarbeet, wheat). Also, there are links to numerous agricultural prediction models that use NDAWN observations to determine risks associated with specific crops in specific locations. Ritchison has continuous contact and meetings with the agricultural researchers on the NDSU campus to help in the development of indices to mitigate important problems, such as insects and fungal diseases.

According to NDAWN, North Dakota has a wider variety of crops than anywhere in the US outside of Florida and California (D. Ritchison, personal communication). Therefore, it is easy to see the impacts of NDAWN in the agricultural sector. One researcher estimates the NDSU wheat scab model could save producers in excess of $25 million annually. The Red River Valley Sugarbeet Growers Association estimates that the use of the NDAWN data-driven models to avoid a single spraying of fungicide each year would produce savings equivalent to $9 million.

NDAWN is a great example of successfully integrating a mesonet into the agricultural research community. The use of NDAWN data and crop-specific products has brought tangible financial benefits to North Dakota producers. Ritchison stated in our interview, "No agricultural sponsor has lamented financing the operation of a station." Application of the data to beneficial agricultural-based initiatives has allowed NDAWN to flourish, and more importantly, has justified its existence to the North Dakota state legislature that is responsible for much of its funding.

6.6.2 Kentucky Mesonet

The Kentucky Mesonet (KYM) originated in 2006 and is headquartered at Western Kentucky University (WKU). The information presented is courtesy of an interview with Stuart Foster, Kentucky State Climatologist and director of the Kentucky Climate Center (KCC), supplemental files sent by Foster, and the KYM webpage (http://www.kymesonet.org/). The KYM was originally funded by the National Weather Service (NWS) and a $2.9 million grant to the KCC. In less than a decade of existence, the KYM has become an integral part of the NWS forecasting operations, helping to fulfill the KYM mission "to improve local forecasts and severe weather warnings, aid emergency response efforts, enhance agricultural productivity, assist local utility providers, and support business and industry." The KYM has excellent spatial coverage around Kentucky with 68 stations strategically placed around the state with a nominal spacing of about 20 miles. Only Warren County (where WKU is located) has more than one station, though future plans include pairing stations in complex terrain to sample the diversity of conditions (e.g., eastern Kentucky where local relief can be several hundred feet).

Perhaps the most impressive accomplishment of the KYM has been its ability to secure steady state and local funding. After repeatedly demonstrating the network's importance to promote public safety, funding for the KYM is currently a line item in the state budget after the Kentucky General Assembly recently approved a budget of $750,000 a year through 2018. This stability follows a period after the startup of KYM in which Foster was scrambling for money to cover operating costs. These efforts have included working with county judges, sending letters to local government officials, working to find local sponsors for existing stations, and forming an advisory board consisting of people who can "advise regarding strategic initiatives and be champions for the Kentucky Mesonet." The advisory board is made up of members from a variety of backgrounds, such as the Kentucky Transportation Cabinet, the Kentucky Rural Water Association, the National Weather Service, Kentucky Farm Bureau, dean of the Western Kentucky College of Science and Engineering, the Kentucky County Judge Executive Association, and the Kentucky Council of Area Development Districts. This broad base of advisors is in charge of marketing the mesonet and the Kentucky Mesonet sponsorship program.

The long-term funding model that KYM hopes to achieve is to maintain its status as a line item in the state budget to receive general funds to cover operating cost. This top-down approach would be paired with a bottom-up approach in which each station is sponsored by a local entity, whether it is local government or a private partner. Although the state funding reduces the stress related to scrambling around for operating costs, it is typically rigid. Finding local "champions" makes operations more agile, resilient, and helps to drum up political support and goodwill for the network. New station operators are expected to sign a site license agreement (SLA), with a commitment to pay $25,000 in start-up costs and properly maintain the station equipment and site. Although the startup cost is the highest (along with the Illinois Climate Network) among all the mesonets interview thus far, this SLA provides an incentive for local station operators to take ownership of "their" station.

The KYM carefully surveys potential sites to ensure compliance with the WMO standards for monitoring temperature, precipitation, and winds. The instrumentation for temperature/relative humidity (Vaisala), winds (R.M. Young), and solar radiation (Apogee pyranometer) are relatively inexpensive but is equipment that is widely used and proven reliable. The exception is precipitation is measured by an Ott weighing bucket precipitation gauge and alter shield, which costs more than $6,000 and measures precipitation with an accuracy of 0.1 mm. Thanks to recent federal funding, the KYM is installing soil temperature and soil moisture probes to support drought-monitoring efforts. Overall, the consistency of the KYM equipment gives users confidence that the data are homogeneous from station to station.

What distinguishes the KYM from most of the other networks is that it spends more money initially to ensure a sound infrastructure, which includes a 10 m tower, concrete slab, and chain-link fencing around the site. A trained KYM technician visits each site at least 3 times annually in the fall (adding antifreeze to the gauge bucket), spring (removing antifreeze), and summer. Foster emphasized the need to continually test and calibrate the instrumentation to ensure a continual stream of high-quality data.

A reason the KYM stresses data quality is it is difficult for the KCC to compete with the data coverage made available by private entities (e.g., WeatherBug, Weather Underground). Unlike KYM, these networks are reliant upon personal weather stations that often fall far short of published standards. Foster has done an exceptional job at selling the overall quality of the KYM, which has given consumers of the data confidence of its reliability.

The KYM disseminates this data free of charge in the form of real-time, daily, and monthly summaries and 5-minute data for the current day. Access to the raw data for all users, except for the NWS, may incur a charge depending upon the size of the request. Consumers of the real-time data include media, local public safety officials, energy maintenance crews, and folks in the agricultural community.

The webpage has a simple layout, is easy to navigate, and provides ample information about the network architecture, site selection, equipment, and site maintenance. Perhaps the best feature is the ability to customize the web page to set any station of your choosing as the "default" station. Future plans include a cell phone application that is currently under development, customized products for the energy and agricultural sectors. The University of Kentucky Agricultural Weather Center uses KYM data to compute reference evapotranspiration using the Penman-Monteith method (http://weather.uky.edu/php/cal_et.php).

In addition to the calibration and replacement of instruments, data quality is assured through automated, real-time quality control and manual quality assurance checks. KYM keeps detailed notes on site visits (including photographs) and is working toward digitizing metadata through a real-time mobile GPS application. Foster noted the importance of properly collecting and documenting metadata and that the American Association of State Climatologists Mesonet Committee (Foster is the chair) is working to develop open-source software to standardize metadata collection.

The viability of the KYM is excellent thanks to the leadership of Foster, who has done a remarkable job of demonstrating the value of a well-run mesonet to the citizens of Kentucky. Fostering relationships with local businesses, local government, county and state agencies, and the agricultural research community has secured several different revenue streams to ensure continued maintenance and development of the network. From a scientific perspective, the data quality standards instituted from the start of the KYM has been the most critical components to its success.

6.6.3 AgriMet

AgriMet is a network of 70 automated agricultural ETo weather stations operated and maintained by the Bureau of Reclamation out of Boise, ID. The stations are located in irrigated agricultural areas throughout the Pacific Northwest and are dedicated to regional crop water use modeling, agricultural research, frost monitoring, and integrated pest and fertility management.

The AgriMet program is funded by a combination of federally appropriated dollars through the Bureau of Reclamation's Water Conservation Field Services Program, along with contributions from a variety of sponsors outside of the BOR. The funding from Reclamation supports the salary and support costs of the AgriMet Program Manager position, while the sponsor funding supports all other activities, such as the salary of a part time student position, travel, equipment and supplies, maintenance of the weather station network, and support of the satellite receive site. The contributions from the various sponsors are pooled into a "sponsor account" from which all operation and maintenance activities of the weather station network are funded. Operational costs are averaged over a several year period, and adjustments to the annual operation and maintenance assessment are made as required. http://www.usbr.gov/pn/agrimet/

6.6.4 Short Summaries of Other Successful Statewide Mesonets

Arizona Meteorological Network (AZMET): Operated by the University of Arizona, AZMET provides meteorological data and weather-based information to agricultural and horticultural interests operating in southern and central Arizona. Meteorological data is collected from a network of 27 automated weather stations located in both rural and urban production settings. Meteorological data collected by AZMET include temperature (air and soil), humidity, solar radiation, wind (speed and direction), and precipitation. AZMET also provides a variety of computed variables, including heat units (degree-days), chill hours, and ET_o. The original 1986 start-up funds allowed for the purchase of 10 weather stations and hiring of two people. Due to recent state budget cuts, AZMET is currently relying on private donations to support its operations. These funding uncertainties make long-range planning difficult at best; it might be necessary to remove or relocate stations as funding and logistical needs require. http://ag.arizona.edu/azmet

California Irrigation Management Information System (CIMIS): A program of the Office of Water Use Efficiency (OWUE), California Department of Water Resources (DWR) that manages a network of over 120 automated weather stations in the state of California. CIMIS was developed in 1982 by DWR and the University of California, Davis to assist irrigators in managing their water resources efficiently. Estimated parameters (such as ETo, net radiation, dew point temperature, etc.) and measured parameters (such as solar radiation, air temperature, relative humidity, wind speed, etc.) are stored in the CIMIS database for unlimited free access by registered CIMIS data users. The CIMIS weather stations are randomly distributed throughout the State of California. CIMIS is a state agency serving the public free of charge. Some of the CIMIS stations are owned by the State while local cooperators own others. The list of local cooperators includes water agencies, universities, cities, U.S. Department of Agriculture, U.S. BOR, conservation districts, and private agricultural related industries. http://wwwcimis.water.ca.gov/

Colorado Agricultural Meteorological Network (CoAgMet): PET. A program between Colorado State University and USDA-ARS. The network of 86 automatic weather stations distributed across the state date back to 1992 and produce hourly, daily and monthly estimates of ETo. http://www.coagmet.colostate.edu/

Georgia Automated Environmental Monitoring Network (GAEMN): PET, soil moisture, and climate data. Established in 1991 by the College of Agricultural and Environmental Sciences of the University of Georgia, it has since grown to include 81 stations. The objective of the GAEMN is to collect reliable weather information for agricultural and environmental applications. Each station monitors air temperature, relative humidity, rainfall, solar radiation, wind speed, wind direction, soil temperature at 2, 4, and 8 inch depths, atmospheric pressure, and soil moisture every 1 second. Stations are individually sponsored. http://www.georgiaweather.net/

Illinois Climate Network (ICN): PET, soil moisture, climate. A 19-station array of automated weather stations. The network provides enhanced temporal weather observations on numerous weather and climate variables including: temperature, precipitation, relative humidity, barometric pressure, wind speed, wind direction, and solar radiation. Values of potential evapotranspiration and dew point temperatures are computed and added to the data set. Sites are located primarily at university agricultural experimental farms and community colleges across the state. http://www.isws.illinois.edu/warm/datatype.asp

Nevada Integrated Climate and Evapotranspiration Network (NICE Net): PET and soil moisture. Consists of 18 agricultural weather station located throughout the state of Nevada and operated by Desert Research Institute, Nevada State Engineer's Office, and U.S. Bureau of Reclamation. Types of data collected at each station include solar radiation, air temperature, relative humidity, wind speed, precipitation, barometric pressure, soil temperature, and soil moisture. http://www.nicenet.dri.edu/

Oklahoma Mesonet: This collaboration between Oklahoma State University and the University of Oklahoma, was initially funded in 1990, and had rapid buildout to 108 stations during 1991-1993. Today, 121 stations are located across the state, including at least one in all 77 counties. These stations are very complete for most meteorological and agricultural purposes, and the network has been the example followed to some degree by many of the statewide networks in this report. All aspects of the program are very well documented. The related Oklahoma Climatological Survey handles the data from the network and provides excellent web-based data and derived-product delivery and displays. Deep into its third decade, the Oklahoma Mesonet remains stably funded and has been referred to as the “gold standard” for statewide networks. http://www.mesonet.org/index.php

6.6.5 Considerations for Avoiding Failure

The common factor mentioned by all the successful mesonets in our study is the existence of reliable and adequate funding sources. Without steady revenue streams, the complicated infrastructure needed for recording and disseminating observations cannot be properly maintained, data quality will suffer, users will diminish, and the network will fail. Therefore, it is critical to strategically target stakeholders that will most benefit from the network’s existence and properly demonstrate the need for steady and adequate funding. Most mesonet failures can be attributed to a lack of funding, but it is possible to fail with sufficient money if network operators are not good stewards of stakeholder money. Here is a summary of some key mistakes mesonet operators should avoid.

- **Lacking an overall network vision:** There should be a clear top-level vision for the network prior to deployment, with all members of the mesonet team on the same page. This includes the initial placement of stations, personnel, equipment, infrastructure, standards and the purpose of the network’s existence (i.e., agriculture, public safety, evapotranspiration, hybrid, etc.). Several of the networks interviewed stressed the vision as vital to succeeding. Properly scoping the growth of the network is an essential component of this vision. If the vision is unclear, there is a great potential for money to be wasted and the network to fail. One network in particular has a great deal of financial strain based on quickly spending startup funds and not adequately planning for maintenance of the network.
- **Failing to properly engage and educate potential stakeholders:** There are a variety of methods for engaging potential stakeholders (e.g., electronic, talks, etc.) It is important to educate the public and private sectors about the importance of reliable, local weather information. There are numerous unmet needs for weather data in the commercial,

governmental, and educational sectors, but often times these groups need to be educated on how to find and use weather data for their applications. Although it is impossible to meet each and every group's demands, failing to engage and educate potentially beneficial stakeholders is important for keeping mesonets operational and thriving. Several of the network operators interviewed expressed an interest in expanding their outreach programs.

- **Misdiagnosing local needs:** For a large state like Texas, the monitoring needs are diverse and equipment should be strategically placed to maximize efficiency. If the observations made at a site are not of particular interest to local users and, in particular, local stakeholders, interest in the station will likely be insufficient to garner financial support. The foundation of properly meeting local needs is greatly enhanced by developing local partners that can advocate on the network's behalf. The concept of meeting local needs is particularly important in agriculture, as key decisions are often made based on weather-related tipping points. Mesonets may be able to withstand isolated cases but a systematic failure to properly address local needs will likely lead to the network failing. None of the operators interviewed expressed this as a shortcoming, but a few mentioned this was a problem after taking over their networks from previous operators.
- **Lacking diversification in revenue streams:** A major concern of several mesonet operators was that their network's existence hinged on the persistence of a single funding mechanism. Given the relatively unstable funding climate, it is strategic to acquire as many stakeholders as possible to decrease the volatility of available funds. Maintaining a diverse portfolio of investors will increase the likelihood of a given network's survival. The most successful networks had a variety of funding sources, whereas several network operators interviewed were pessimistic about their futures because of funding concerns.
- **Not fully exploring potential government partners:** There are many opportunities to partner with local, state, and national agencies to secure funding. Perhaps the most obvious is the National Mesonet Program, which a few network operators rely on to keep their networks afloat. Several of the thriving networks maintain close relationships with local government stakeholders and with the state government, who in turn, are able to provide funds to anchor the network's stability. None of the operators interviewed expressed any regrets about this potential pitfall but there were certainly networks that were more skillful at securing government funds than others and they seemed to be in better shape.
- **Not properly budgeting for maintenance costs:** A common theme in our interviews with network operators was a systematic underestimation of how expensive it is to properly maintain station, communications, and database infrastructures. Although none of the networks interviewed had failed, this pitfall was a common reason for inhibiting network growth and even losing stations.
- **Understaffing:** Staffing considerations are often limited due to budget constraints, but a failure to construct a proper staff is a potential pitfall that is essential to avoid. In many of the larger states interviewed, network operators stressed the need to build up good relationships with local experts so that maintenance work could be outsourced and the travel budget could be minimized. Most of the network operators interviewed expressed

interest in adding one or more missing components to their staff. The wish lists included personnel ranging from technical experts to help with maintenance to IT for help managing the database and content delivery.

- **Lacking data and metadata standards:** From a scientific perspective, the easiest way to network failure is to gain a reputation for not delivering high-quality data and lacking proper metadata standards. Nearly all of the network operators said the value proposition of their mesonet relative to other data sources was the quality and reliability of the data. Many of the operators expressed interest in more stringent metadata standards but none of those interviewed lamented about the quality of their data.
- **Insufficient communications infrastructure:** Among all the network operators interviewed, the most common annoyances expressed related to difficulties in electronic communications with remote stations. All of the mesonet operators interviewed had workable communications infrastructures in place, with most opting to outsource communications to cellular networks (e.g., Verizon). This pitfall is purely hypothetical based on the mesonets we interviewed but is a challenging obstacle to overcome.
- **Not providing reliable web/automated dissemination of data:** Web delivery of mesonet information is the most direct method for engaging with both current and potential stakeholders. Having a modern-looking web portal is essential for maintaining a strong public profile and demonstrating the feasibility of your network. In most cases, operators that expressed concern about their network's future viability had out-of-date web portals and lacked systematic ways to deliver large data requests.

6.7 Examples of Successful Mesonets in Other Countries

6.7.1 Australia

The Australian Government Bureau of Meteorology (BoM) was established with the *Meteorology Act 1906* and centralized Australia's weather operations and services. This was replaced by the *Meteorology Act 1955* that more clearly defined the BoM role and more closely aligned Australia's observational standards with the World Meteorological Organization (WMO), which Australia joined in 1950 as one of the first members. The climate of Australia is tropical in the north, temperate in the populated south and southwest coastal regions, and mainly arid and semi-arid across the Australian Outback, which presents challenges for a nationwide network with common equipment.

The BoM operates largely as a line item in the Australia government and received nearly 214 million Australian dollars (AUD) from 1 July 2015 through 30 June 2016. Additional revenue of 82.6 million AUD was generated through sales, the vast majority of which were data and services. However, the BoM reported a net operating loss due to expenditure of 372.5 million AUD (BoM 2016), with the vast majority of expenditures on employee benefits, improvements in infrastructure, and a decrease in the exchange rate with the US Dollar (USD). The United States supplied much of the equipment for a new Supercomputer.

Of particular interest to this project, the BoM maintains an extensive, centralized database of agriculture-based station observations on their web page (http://www.bom.gov.au/watl/). Several of these stations are BoM "Automatic Weather Stations" (AWSs), which were first installed in the early 1990s to enhance Australia's meteorological monitoring capabilities (BoM 2005). The network is set up similarly to the US COOP network, with both AWS and human observations taken by contract or volunteer observers, with some of the earliest records date back to the 1830s. National standardization of observation instruments was undertaken in 1910, which serves as the starting point of the BoM official data record.

In the mid-1990s, the BoM began actively searching for hosts of the automated AWS from groups interested in environmental monitoring. The initial cost for an AWS conforming to BoM standards is listed as 40,000 AUD and includes equipment (BoM 2017a) for measuring temperature, humidity, and precipitation. Over the last 10 years or so, the exchange rate has varied from about 1 AUD to 0.75-1.0 USD (currently closer to 0.75).

In 1997, BoM released a document that required siting and exposure standards for the AWS stations (BoM 1997), in line with WMO standards. The purpose was to "endeavor to take into consideration financial and practical limitations whilst preserving the scientific quality of the observations." This document makes clear to those who may be interested in the equipment and infrastructure necessary for startup and the maintenance responsibility operators are expected to fulfill. Major strengths of the BoM weather network are the comprehensiveness of the siting and observational requirements for potential station operators and the clear communication of this information. The BOM stresses several different requirements for AWS operators:

1. Siting in a manner that is spatially and temporally representative
2. Using high-quality sensors
3. Using meaningful and widely-used algorithms for computation of derived variables
4. Regularly maintaining equipment in a manner that does not disrupt the climate record
5. Carefully documenting equipment and siting
6. Providing output data that is flexible, simple, and human-readable
7. Having a reliable communications infrastructure in place
8. Permanently storing observed data

From the perspective of someone interested in operating a network of weather stations, perhaps the most impressive feature of the BoM network is the documentation of metadata at each site, which is not surprising given the rigor expected of the station operators. Station metadata files are freely available (BoM 2017b), which provides a complete history of the station and detailed schematics of the surrounding environment.

In addition to the detailed location schematic, the metadata document contains a detailed description of the instrumentation history for each observation type. The full metadata file for the Sydney Airport station is 28 pages and is available online (BoM 2017c).

Overall, including the AWS network, there are several thousand stations reporting basic meteorological parameters, including more than 6,700 precipitation stations, 5,300 hydrological monitoring stations, and 5,000 volunteer observers. Overall, there are more than 18,000 precipitation stations in the BOM database, with records going back to the push for standardization that occurred in 1910. A comparison to the US shows that US Geologic Survey (USGS) maintains a database with roughly 15,000 real-time streamflow, lake level, and groundwater level monitoring sites (Hirsch and Fisher 2014). The Applied Climate Information System has about 20,000 stations reporting precipitation in their database and the COOP network currently includes about 9,000 volunteers.

The main climate data and metadata portal is rather archaic looking relative to newly restructured National Centers for Environmental Information webpage (http://www.ncei.noaa.gov/). However, most data and metadata requests on the BoM page (either small, large, or somewhere in between) are freely available in a few clicks. The agricultural services data is designed similarly to the main climate data page, but provides more specialized products such as solar radiation and ET.

In the past 10 years or so there has been an added emphasis on observing agriclimate information such as evaporation, evapotranspiration (ET), and solar radiation. The Australia *Water Act 2007* (Parliament of Australia 2007) was a key driver, calling for a national framework to manage water monitoring resources and information. Under this mandate, the BOM administered the Modernization and Extension of Hydrologic Monitoring Systems Program, which had funding of 80 million AUD for upgrading Australia's national water monitoring capabilities. Funded projects focused on upgrades in observations, databases, and visualization (BoM 2010).

In 2014, an independent panel released a report on *Water Act 2007* and concluded that although its passage has increased the comprehensiveness of hydrologic information in a centralized database (Commonwealth of Australia 2014), more effort was need in educating stakeholders and collaborating with other government agencies to deliver better end products. The BoM provides an "Environmental Information Explorer" page (http://www.bom.gov.au/jsp/eiexplorer/) that is a great tool for obtaining metadata and information about specific sites, but this tool does not allow for direct data access. A very user-friendly web interface is available for the roughly 200 "Hydrologic Reference Stations", with access to charts and numerous customized data products.

All weather data recorded at each station is stored in the BoM climate database known as the Australian Data Archive for Meteorology (ADAM), with up-to-date daily files are available via an FTP server. More specific and customizable data requests are freely available at the Australian climate data online portal (http://www.bom.gov.au/climate/data/). To help digitize more than 30,000 station-years of records, the BoM asked for public volunteers to assist add these data to the ADAM database. The BoM charges a cost recovery fee for the data that have not already been digitized. For long-term climate monitoring, Australia has the Australian Climate Observations Reference Network (ACORN), which is similar to the US Climate Reference Network and maintains a database of 112 long-term, homogeneous temperature records. A manifestation of the ACORN is a dataset of about 60 high-quality pan-evaporation stations. For all the observing networks, the density of stations is much higher outside of the Outback region, in the major population centers spanning along Australia's southern and eastern coastlines.

Perhaps the main lesson to be learned from the BoM environmental observation program is that the ease of web access to both data and metadata is as good or better than observational networks operating on a national scale in the US. Additional features of the BoM networks that stood out were:

1. Level of detail in the metadata reports
2. High standards of siting and observational required by station operators
3. Multiple levels of data regionalization on the web page

The BoM philosophy of using the web interface is to first determine your geographic region of interest (ranging from national to single site) before seeing a list of available products.

6.7.2 Switzerland

The Federal Office of Meteorology and Climatology in Switzerland was established in 1863 as the Central Meteorological Institute, and currently operates as MeteoSwiss (renamed in 2000 after being renamed the Swiss Meteorological Institute in 1979) as an office of the federal administration in Switzerland. The Swiss weather service has been regulated by the government since 1881 and on 18 June 1999, the Federal Act on Meteorology and Climatology was passed. A byproduct of this legislation is that MeteoSwiss is legally required to "record meteorological and climatological data continuously" (MeteoSwiss 2014).

Although it is a rather small country (at nearly 16,000 sq mi. is a bit larger than Maryland), there is a large contrast in the prevailing climate from north to south, highlighting the need for a relatively dense network of observing stations. In the more populated northern region, the Köppen climate classification is mostly Oceanic (Köppen *Cfb*; similar to coastal Massachusetts) with a mostly progressive weather pattern year-round. In the mountainous southern region, which contains the Swiss Alps, the climate is mostly Alpine (Köppen *ET*; similar to the very high-altitude mountains in the Western US) with temperatures largely a function of elevation.

Based on open financial documents, MeteoSwiss operates at a deficit of about 70 to 75 million Swiss Francs (CHF) annually, which is presumably supplemented by the Swiss government (MeteoSwiss 2017a). For reference, there is currently close to a one-to-one exchange rate between the CHF and the USD. There has been an increase in both the demand and profitability of weather and climate data from 2014 to 2015 and for both years a higher rate of return for the data relative to the weather and climate services MeteoSwiss provides. These two conclusions should be accepted with caution though, as a more detailed breakdown of the earnings and expenses was unavailable.

The Swiss set up an observational network of 88 stations upon the founding of the Central Meteorological Institute and began recording data in 1864, six years prior to the establishment of the US Weather Bureau. The original purpose of the network was to provide the Swiss with an understanding of climatological variations over time and space but in time became the foundation of daily weather forecasts. Soon after the network commenced, the Swiss saw the need for additional precipitation stations and installed 50 additional precipitation-only sites in the following 20 years. By 1960, there were more than 300 precipitation-only stations.

By the late 1970s, there was a transition toward fewer long-term climate stations with the introduction of automated weather stations. In 1981, the Swiss had deployed 60 such stations and established the ANETZ network, one of the first automated weather networks in the world and a full decade before the ASOS network was deployed in the US. Even with advances in technology, the Swiss Meteorological Institute recognized need to keep continuity in the climate record and has maintained a "manual precipitation monitoring network" (including 100 automatic rain gauges) and has 50 "totalizers" in remote areas of the Swiss Alps and are visited at the end of each hydrologic year (MeteoSwiss 2017b).

In the late 1990s, as the technology of the ANETZ station aged and the equipment failed without the existence of replacement parts, the Swiss determined a total overhaul of the network was necessary. MeteoSwiss launched a new national reference monitoring network that commenced observations in 2003, referred to as "SwissMetNet" (Suter et al. 2006). Some major needs that were seen as necessary for the upgraded network were:

1. Standardization of the network.
2. Partnerships with other existing weather network operators.
3. Taking over stations if not properly maintained.
4. Installing a separate network for visual observations.
5. Installing state-of-the-art and consistent internet-based communications at all sites.
6. Placing the Federal Office of Communications (OFCOM) in charge of all data transmissions to make use of any technological advances.

The network was configured to provide relatively homogeneous coverage (MeteoSwiss 2016). In regions with a need for higher density monitoring (e.g., Swiss Alps), precipitation-only and manual stations provide increased spatial coverage.

The MeteoSwiss has a comprehensive listing of equipment on their webpage (MeteoSwiss 2017c) with the equipment at each individual station based on the observational needs at that location. MeteoSwiss puts a great deal of emphasis on the quality of observations and this is reflected in other choices made in the network design. To maintain consistency with the previous generation of automated stations, some of the important and reliable sensors were retained (e.g., air temperature sensors). For new equipment, SwissMetNet uses top-of-the-line sensors, housing, and shielding and maintains consistency of the equipment across the network, including the equipment layout and spacing between instruments (Heimo et al. 2006). This includes a strategic division of the network into 3 station-types to provide sufficient coverage for different applications based on available resources:

1. High-quality, comprehensive (in terms of parameters measured) stations
2. High-quality, less comprehensive stations
3. Lower-quality, less comprehensive stations

The emphasis on quality standards led MeteoSwiss to adopt a rigorous certification procedure in 2013, which uses about 80 quality control checks put forth by the WMO Commission for Instruments and Methods of Observations (WMO 2014). The rigor of examination is based on the category of station, with a plan to perform the check once every five years. Currently, the results are only for internal consumption, but the certification procedure was deemed a necessity due to the integration of non-MeteoSwiss operated stations into the SwissMetNet dataset. The five basic groups of criteria answer these questions:

1. Is there an adequate frequency of data transmission?
2. Are the metadata complete and accurate?
3. Are the instruments up to the WMO guidelines and is the housing and ventilation adequate?
4. Is there an adequate maintenance schedule and is there a plan in place for dealing with faulty equipment?
5. Is the data record complete and meet WMO quality standards?

For data delivery, MeteoSwiss offers a wide range of web content, including a data portal for expert users, another data portal for teaching and research, scientific reports, professional consulting, and a hotline for weather and climate questions. Responding to the increased need for specialized climate services and responding to WMO recommendations for providing climate services, the National Centre for Climate Services (NCCS) was launched in 2015 at MeteoSwiss. The NCCS works as a collaborative partner to provide expert guidance for natural hazards, agriculture, health, energy, forestry, and water resources.

MeteoSwiss data are stored in a centralized data warehouse, which operates on a simple four-tier structure from ingestion to processing to storage to dissemination (MeteoSwiss 2017d). MeteoSwiss data storage efforts have strongly benefitted from strong partnerships with the university sector (Swiss Federal Institute of Technology), the Swiss National Supercomputing Centre.

Data users should benefit from a relatively new mandate put forth by the Swiss government, referred to as “liberalization of data.” The broad goal of the directive is to encourage innovative research to benefit the business, scientific, and public sectors (MeteoSwiss 2017d). Although the response to the initiative has been mostly positive, there has yet to be a strategic response from the private weather services industry, which employs more than 400 people in Switzerland.

MeteoSwiss places a great deal of emphasis on climate change and the role of the organization to be both educators and scientists that advance knowledge of impending changes. This has driven the organization to place a large emphasis on producing quality data at each station so that heterogeneities in spatiotemporal analyses are minimal. The results of the MeteoSwiss efforts have produced a relatively high-resolution, homogeneous dataset going back more than 150 years and the implementation of the SwissMetNet, which has not only improved climatological monitoring, but also real time applications such as forecasting and flood monitoring.

7 Existing Weather Observations in Texas

7.1 Statewide or Smaller Networks

7.1.1 Hydrometeorological Networks

ATX Flood Early Warning System monitors rainfall and water levels at 130 locations and 15 low water crossings in and around Austin, TX. Data is used for predictive models and mapping for emergency managers to plan effective and timely response. https://hydromet.lcra.org/coa/coa.aspx

Edwards Aquifer Authority operates 13 weather stations used to calculate PET needed in aquifer recharge models. Data are collected every 15 minutes and transmitted hourly through a cellular network. They also operate rain gages for Nexrad calibration, as well as soil moisture, stream gages, and groundwater level recorders. http://www.edwardsaquifer.org/scientific-research-and-data/aquifer-data-and-maps/weather-stations

Harris County Flood Warning System measures rainfall and water levels in bayous and major streams at 142 locations. When rain is detected, stations transmit rainfall amounts via radio frequency every time 0.04 inches of rain is measured. Sensors report bayou/stream levels every 0.10-foot rise in water levels. The data is monitored daily by Harris County Flood Control District staff to ensure the gages are properly functioning and transmitting accurate data during storm events. Recently, soil moisture sensors have been added. https://www.harriscountyfws.org/

LCRA Hydromet: The Lower Colorado River Authority's network consists of >275 stream and precipitation gauges. Some include air temperature and humidity while new additions through the WaterMyLawn program also include PET stations. The Hydromet gauges send a continuous stream of data over an emergency radio network to their central River Operations Center in Austin. LCRA hydrologists, engineers and other experts use the data to develop forecasts, analyze trends and share information with the public. The network is hoping to add more wind, temperature and soil moisture sensors in the coming years. http://hydromet.lcra.org/

Texas A&M Forest Service Remote Automated Water Stations (RAWS): Following the 1998 fire season, the Texas Forest Service established the Predictive Services Department as a permanently staffed unit to provide short and long-term forecasts and analysis. The program produces information and products that are utilized at the national, state and local level by firefighters, election officials and public administrators. Most of the products (daily fire danger, drought indices, fuel dryness) have been developed as automated, online and publically available resources through a partnership with Texas A&M's Spatial Sciences Laboratory. Over 80 RAWS station monitor 2m air temperature and humidity, 6.1m wind speed and direction, solar radiation hourly. This data is pushed to MesoWest. http://ticc.tamu.edu/predictiveservices/texasraws.htm

Texas Soil Observation Network (TxSON): University of Texas at Austin. The primary goal of this network is to calibrate and validate NASA's Soil Moisture Active/Passive satellite by providing spatially scaled soil moisture data at 3, 9 and 36 km. The dense monitoring network is located in eastern Gillespie County and has since evolved to cover many other regions of the state including Travis, McCulloch and Presidio Counties with one weather station and 4-6 satellite soil moisture and rain gauge stations. TxSON also includes 3 eddy covariance stations in

Bexar County and 18 soil moisture and groundwater wells in Haskell, Kent, and Stonewall counties. The network was originally launched through private donations to the Jackson School of Geosciences and is now subsidized by several water foundations, Texas Parks and Wildlife Department, the Edwards Aquifer Authority, the Nature Conservancy, and NASA's Jet Propulsion Laboratory. The network primarily consists of > 70 stations measuring soil moisture at 5, 10, 20, 50 and 100 cm depth and precipitation in real-time. Seven stations currently report ETo using Penman-Monteith and ASCE method for rangelands.
http://www.beg.utexas.edu/research/programs/txson

7.1.2 Other Networks Operating in Texas

There are a number of other networks operating in Texas, including:

- The Brazos River Authority operates three reservoirs, each with weather stations that include an automated evaporation pan.
- The Guadalupe-Blanco River Authority operates rain gauges mostly in their upper basins.
- The San Antonio River Authority operates a network of rain gauges and measures water elevations for dam operations in reservoirs and rivers.
- The Trinity Regional Water District operates a few weather stations, mainly at reservoirs and stage gauges on the Trinity River for flood operations. Their data is used by NWS. They are hoping to add wind speed and direction and peak gusts to their network.
- The Texas Alliance for Water Conservation Project at Texas Tech University has several PET stations and develops irrigation scheduling models.
- The Texas Water Observatory, run by TAMU and in partnerships with USDA, operates eddy covariance stations in the Lower Brazos River Basin. Many of these stakeholders are in need of assistance and training with proper maintenance, calibration, etc., of their equipment but are also willing to push their data to TWDB.
- The Texas A&M AgriLife Research Center at Weslaco operates a 4-station network in the Lower Rio Grande Valley region and posts daily weather summaries at http://southtexasweather.tamu.edu/
- The Texas A&M AgriLife Research Center at Beaumont helped develop iAIMS (integrated Agricultural Information System) which ties into, downloads and posts on-line data from over 28,000 weather stations worldwide. In Texas, iAIMS includes many temperature and rainfall stations not included in other networks. https://beaumont.tamu.edu/climaticdata/WorldMap.aspx
- The Brazos County Groundwater Conservation District operates a 3-Station network used to support the Brazos Valley Water Smart program, which informs users if yard watering is needed each week. https://bvwatersmart.tamu.edu/ .

Particular sectors in Texas do not collect any data but do rely heavily on weather data. The Electric Reliability Council of Texas (ERCOT) operates the electric grid and manages the deregulated market for 75 percent of the state. There are over 570 generation units that feed into the ERCOT grid. Many of these units have on site weather stations; however, the data is proprietary of the unit and used to price energy based on potential demands. Although ERCOT uses a substantial amount of weather data to forecast energy demands state-wide, they do not operate any stations. Likewise, there are many obvious weather stations located along Texas roadways managed by the Texas Department of Transportation (TxDOT) but none of these are managed by them. TxDOT simply provides the right-of-way to put instrumentation along their roads. The instrumentation is managed more locally by city and county agencies responsible for road conditions.

The Atmospheric Sciences Department at Texas A&M maintains a Mesonet-level site at the University's Research Farm. The site was an original site of a 1990's era attempt at a Mesonet with 5 primary stations and some 15 rainfall-only stations for satellite sensor/algorithm validation. This site includes all common Mesonet variables including solar radiation as well as soil temperature and moisture at 6 depths. Data is disseminated via website and CWOP/MesoWest. This site is an excellent candidate for immediate inclusion into the existing TWDB data infrastructure.

7.2 Federally Operated Networks

Automated Surface Observation Systems (ASOS) are federally-funded meteorological stations that are part of a nationwide joint program of the National Weather Service, the Federal Aviation Administration, and the Department of Defense. They are the nation's primary meteorological sites with extensive additional cloud, precipitation, and visibility sensors to support aviation. These stations do not have soil temperature, soil moisture, or solar radiation measurements. Texas has 57 ASOS stations. https://www.faa.gov/air_traffic/weather/asos/

Automated Weather Observation System (AWOS) stations are found at smaller airports without ASOS stations, and may be funded by the FAA or by state or local governments or private aviation interests. Many AWOS stations in Texas are funded by the Texas Department of Transportation. The stations are similar to ASOS, but do not generally have the precipitation type or present weather sensing capability. Like ASOS, these stations do not have soil temperature, soil moisture, or solar radiation measurements. There are approximately 112 AWOS stations in Texas. https://www.faa.gov/air_traffic/weather/asos/

US Climate Reference Network (CRN): Soil moisture and climate data, The National Oceanic and Atmospheric Administration collects comprehensive climate and soil moisture data at 115 stations nationwide with 8 residing in Texas. This network is located outside agricultural areas and wind measurements are made at 1.5m. Soil moisture depths are the same as SCAN, however, each depth is triplicated, as is air temperature and humidity. https://www.ncdc.noaa.gov/crn/

Soil Climate Analysis Network (SCAN): soil moisture and ETo, the USDA Natural Resources Conservation Service provides comprehensive soil moisture and climate data from over 200 stations in 40 states. There are currently 14 SCAN sites operating in Texas. This network has a standardized depth profile of soil moisture sensors at 5, 10, 20, 50, and 100 cm along with standard meteorological sensors cable of calculating ET_O. Stations are located in agricultural lands and natural vegetation. http://www.wcc.nrcs.usda.gov/scan/

US Geological Survey under partnerships with local and regional agencies primarily operates streamflow network with 508 sites in Texas. Many stations also collect rainfall and other meteorological parameters. http://waterdata.usgs.gov/tx/nwis/

7.3 National Mesonet Program

Marshall (2016a; 2016b) provides excellent and comprehensive overviews of the National Mesonet Program (NMP) in two talks given in early 2016. Additional content is provided from a NOAA research-funding proposal (NOAA 2016) solicitation for a private contractor to handle the NMP data streams and subcontracting. These two sources provide most of the content for this section.

The NMP is a federally funded initiative to collect and maintain a comprehensive database of data and metadata records from local, state, and regional weather networks (i.e., mesonets) in the US. In the NMP, the term *mesonet* describes an observational network with sufficient spacing to observe mesoscale weather phenomena in real-time. Momentum for the NMP was generated by a National Research Council report (2009) that outlined a strategy for the design, deployment, and operation of a nationwide “Network of Networks” (NoN). The NRC report resulted in a funding mandate by Congress. The Oklahoma Mesonet, under the leadership of Ken Crawford, was seen as the “gold standard” and participated as a pilot member of the NMP.

The NMP began as a mechanism for the National Weather Service (NWS) to purchase from non-federal observational networks to enhance the overall NWS activities. Over time, this evolved into the centralized NoN envisioned by the program’s pioneers and has been instrumental in the NWS mission to provide “protection of life and property and enhancement of the national economy” (NOAA 2017). The NMP mesonets provide a much-needed enhancement to the spatial density of available, quality observations. Also, many of the NMP members measure elements that are not routinely gathered by typical NWS stations, such as soil moisture, solar radiation, and evapotranspiration.

The NMP was made a formal part of the Presidential Budget request to Congress in FY2012 after several years as an earmark, with funding of 18 million USD in FY2016. Each year, the funding is delegated to a private contractor that makes subcontracting agreements with the individual mesonets. Global Science & Technology (GST) was awarded a 14.8 million USD contract for FY2016. For the 2017 trough 2019 fiscal years, a contract worth 45 million USD over three years was awarded to Stinger Ghaffarian Technologies (SGT). In this and other projects, the SGT mission is to “provide technology solutions and services to the United States government… that yield high-performing and cost-effective government programs” (SGT 2017). The NMP contract requires the purchase of observational data from participating networks that can use the funds to cover operational and infrastructure costs.

Members of the NMP are required to provide comprehensive and accurate metadata records that fall in line with WMO standards. Because the NWS plans to implement the NMP observations as part of its core observational tools, both the data and metadata should be provided “via a systems approach, using established and consistent processes and protocols.” The NWS now uses a centralized database called the Meteorological Analysis and Data Ingest System (MADIS) to store incoming data and metadata. NMP members are required to meet minimum data and metadata transmissions standards (quality and frequency) for ingestion into MADIS. Membership may also require alternative data streams, such as NWS local and regional offices.

The metadata requirements for the physical attributes of each mesonet station include station name, unique identifier, location, parameters, network and site data providers, and distribution restrictions, all in a specified format. Additional metadata requirements (not shown) include specific attributes about data transmission, siting, exposure, instruments, data loggers, quality control, and maintenance.

From all indications, joining the NMP requires signing a subcontract with the main NMP contractor (currently SGT) or one of the private partners. For example, the Oklahoma Mesonet is a subcontractor of Earth Networks, who is a direct subcontractor of SGT. Potential members must provide proof that their mesonet is capable of fulfilling the membership obligations, which include several data, platform, and performance requirements. It's worth explicitly stating that members are subcontractors of SGT or partner of SGT and funds are provided in the form of a contract and not a grant. From a NOAA perspective, there a big legal difference between the direct purchase of data rather than providing operating funds through a grant. For a potential NMP member (especially in academia), selling data (or services if more convenient) contractually can potentially eliminate the overhead charges that are typically associated with government grants. It is not clear what, if any, mechanisms are in place to pass this funding on to mesonet partners.

8 Network Design for Texas

8.1 End-user Needs by Regional Water Planning Groups

In 1997, Senate Bill 1 (SB1) was enacted by the Texas Legislature to develop, manage and conserve water resources and preparedness for drought. It further provided regulatory decisions to Texas Commission on Environmental Quality (TCEQ) and financing discretion to the TWDB who in turn divided the State into 16 Regional Water Planning Groups (RWPG). Regional water plans are submitted by each RWPG every five years to determine best practices to conserve water supplies, meet future water supply demands, and respond to potential flood and/or drought. Each group has different mesonet needs based on their respective climate, population, agricultural productions, drought resiliency, and emergency preparedness. PET stations clearly can aid irrigation management. Other needs may require different data. For example, lake evaporation from reservoirs is currently estimated from pan evaporation data. Weather stations could improve these estimates if properly sited near reservoirs. Similarly, lakes provide recreational opportunities and weather data can be useful for people planning visits.

Table 8-1 summarizes potential users' needs for each RWPG according to the executive summaries in each Region's 2016 Water Plan. The table is not intended to be a comprehensive needs assessment, but instead to reflect the priorities stated by each RWPG. Many RWPG have some ongoing weather data collection for either agricultural water conservation (e.g. Regions A and O) or for emergency response (e.g. Regions H and K).

Table 8-1. Potential needs for each Regional Water Planning Group (identified by letter)

Irrigation Management	A	B			E	F			I		K	L	M		O	P
Water Supply	A	B	C	D	E		G	H			K	L	M		O	
Flood Control							G	H		J	K	L	M	N		
Reservoir Management		B	C				G				K	L				P
Energy and Industry	A		C	D		F	G	H				L	M	N		
Drought Mitigation	A	B	C	D	E	F				J	K	L	M		O	
Existing Mesonet	A						G	H			K				O	

8.2 Specific End-user Needs and Instrumentation

8.2.1 Flood Warning

Mesonet data can assist with flood warning in three ways. First, mesonet stations provide direct measurements of precipitation rate during flood events. These data can be used directly in flood forecasting or used in real time to calibrate radar data to provide reliable estimates of the distribution of heavy rainfall throughout the area. Second, high-quality meteorological mesonet data can be utilized by weather forecasting models and forecasters to identify locations where heavy rainfall is likely to develop or intensify. Third, soil moisture measurements provide direct observations of water present in the ground. This makes it possible to determine how much additional rainfall can be absorbed by the soil before runoff occurs, and also improves the calibration and accuracy of land surface models for assessment of soil moisture conditions between stations, and other measurements of land surface energy exchange processes are also helpful for model calibration.

Several flood control districts operate their own high-density automated precipitation networks, with data available in real time to public safety officials and, often, the general public. Elsewhere, real-time precipitation data is medium to low density and is typically located in and around urban areas rather than in watersheds upstream of populated areas, where floods form. The National Weather Service is responsible for flood warnings, and detailed real-time flood information is essential for local public safety officials.

Flooding is an issue throughout the state of Texas, so improved flood warnings would be beneficial everywhere. The greatest benefit would be in highly populated flood-prone areas such as the Hill Country, the I-35 Corridor, and southeast Texas.

8.2.2 Tornado and Severe Thunderstorm Warning

For other types of hazardous weather associated with severe thunderstorms, such as tornadoes, hail, and microbursts, the primary tool for detection and warning is presently Doppler weather radar. Mesonet data can be extremely valuable for improving the lead time of severe weather warnings. Meteorologists can use surface mesonet data to detect where thunderstorms are likely to form and whether existing thunderstorms are moving into environments that are more or less favorable for severe weather development. Observations of conditions above the ground provide additional valuable information by allowing meteorologists to predict changes in storm structure and tornadic potential. Improved weather warnings provide a substantial safety benefit by giving people enough time to take shelter and by narrowing down the warning areas to only those locations most likely to be affected.

The National Weather Service is the agency responsible for severe weather warnings. For mesonet data to improve weather warnings, the data must be of sufficiently high quality and must be available within seconds to minutes of being collected. The National Weather Service presently relies on airport weather stations and data from a few other trusted networks available in real time. National Weather Service personnel have noted that high-quality, high-density mesonets such as the Oklahoma Mesonet provide substantial benefits to severe weather warnings.

Severe weather is possible throughout the state of Texas. The combination of Texas's size and location causes it to receive more severe weather than any other state in the United States. The risk of severe weather tends to be higher in northern Texas than in southern Texas, but severe weather in southern Texas can be less predictable because of a lack of upstream observations.

8.2.3 Fire Weather

Fire behavior is strongly affected by meteorological conditions. Fire intensity and spread are enhanced by low atmospheric moisture, strong winds, and dry fuels. Knowledge of meteorological and fuel conditions is essential both for the implementation and management of controlled burns and for suppression of uncontrolled or unplanned fire.

Persons who would utilize fire weather information include controlled burn operators such as farmers, ranchers, and land managers, and firefighters and emergency responders. The Texas A&M Forest Service operates a specialized network of Remote Automated Weather Stations targeted toward wildland fire susceptibility and suppression.

Both wildfire and controlled fires are common throughout the state of Texas, from the marshes near Beaumont to the Davis Mountains.

8.2.4 Agriculture

The purpose and benefits of an evapotranspiration network were discussed earlier. In summary, ET networks provide scientific estimates of water use by plants, which can be essential to proper crop management activities such as irrigation and other applications.

However, there are many other agricultural applications of an ET network or a mesonet. Almost all aspects of a crops development are intimately related to meteorological conditions and their effect at the field level. Likewise, most management activities depend critically upon proper monitoring of weather conditions. Monitoring conditions such as temperature, solar radiation, humidity and wind not only affect irrigation decision making, but influence decisions regarding planting and harvesting, plant diseases and pest management. These applications for weather driven decisions would make mesonet data extremely valuable any agricultural operation.

Intensive farming activities are found in many areas of the state. In other areas ranching and forestry activities are common. In other states, mesonet data is used to monitor livestock comfort. Many small landowners and urban residents practice agriculture on a small scale in their own gardens, and, as discussed in Chapter 5, meteorological information can reduce water use, particularly in landscape/yard irrigation. Thus, there is no part of the state that would not benefit agriculturally from a mesonet. Existing agriculturally-oriented networks, as discussed previously. provide insufficient coverage in Texas.

8.2.5 Water Supply: Recharge

Streamflow into reservoirs can be measured directly using stream gauges. However, recharge of aquifers and prediction of changes in streamflow require reliable measurements or estimates of soil moisture. Declines in soil moisture can serve as leading indicators for declines in streamflow and subsurface recharge. If soil remains saturated, base flow and subsurface flow will remain high. If the soil dries out, base flow and subsurface flow decline. Diagnoses of the causes of changes in recharge are facilitated by soil moisture information. Soil moisture, in turn, changes in response to precipitation and evaporation, so measurements of those processes supply supporting information.

Network distribution needs in support of recharge monitoring are highly situation specific. In general, observations at a few key locations would be adequate, and are only useful for water suppliers with the technical capability to make good use of the information.

8.2.6 Water Supply: Storage

Lake evaporation is presently estimated indirectly from measurements of temperature, moisture, and wind at conventional stations. Lake evaporation estimates can be made more accurately if the meteorological measurements are taken immediately upwind and downwind of the lakes. Measurement pairs are needed to provide reliable estimates of wind speed over the lake and upwind temperature and moisture conditions. Upwind and downwind GPS-based precipitable water measurements can be used to validate the lake evaporation calculations over the long run, but changes in atmospheric moisture caused by the lake on any given day are probably too small to be detected directly. Conventional measurements should be supplemented by a radiometer that measures the surface temperature of the lake.

With the likely application of lake evaporation measurements as a check and calibration of conventional lake evaporation calculations, only a small number of lakes would need to be outfitted with station pairs. While a station close to a lake would have its weather influenced by the lake and thus be of limited value for other applications, the use of a station pair virtually guarantees that one of the two stations will be upwind of the lake and measuring representative large-scale conditions.

8.2.7 Drought Monitoring

Drought is one of the most costly natural disasters for Texas. Both local drought response and federal drought relief require accurate spatially-resolved understanding of drought severity and conditions. Many drought monitoring tools are available, including high-resolution mapping of precipitation and surface soil moisture. Ultimately, though, drought affects dryland agriculture and nonriparian ecosystems through changes in the soil moisture of the root zone. Direct measurements of soil moisture would complement satellite-based measurements, which only detect moisture at the very top of the soil, and precipitation-based estimates, which cannot assess the lingering effects of past precipitation or its absence.

Because drought is a problem throughout the state, comprehensive soil moisture measurements would be valuable. The limitation on number of stations would be driven by cost rather than utility, since both precipitation and soil texture are highly spatially variable and a dense network is needed for a comprehensive picture of drought conditions.

8.2.8 Education

Other networks have found that the educational benefits of a "backyard" high-quality weather station are a welcome accompaniment to the network itself. The availability of free data from local and more remote weather stations enables a wide range of educational opportunities involving analysis of data and relating that data to personal experiences. The educational benefits require no additional cost, unless educational modules are developed in collaboration with educational material providers. A side benefit of educational applications is the increased awareness of a mesonet and its uses and benefits among students and their parents.

There are no specific instrumentation or station location requirements for educational applications. However, synergies are possible if stations are established on the grounds of schools. The schools can take ownership of the station, conducting routine site maintenance and troubleshooting problems.

8.2.9 Energy

The rapid expansion of renewable power in Texas has created new challenges for meteorological information. Wind energy is obviously sensitive to wind speed, and solar energy is sensitive to solar radiation. Long-term measurements of wind speed and solar radiation would help identify optimal locations within the state for renewable power generation. On the short term, power production by wind and solar is highly sensitive to meteorological conditions, and improved short-term forecasting of sunlight and wind speed would yield direct improvements in load balancing and efficient power generation. Finally, power consumption is also sensitive to meteorological conditions, and improved forecasting and monitoring of extreme heat and cold would also yield benefits to grid resiliency.

Renewable producers are weather-sensitive but competitive, so they collect lots of meteorological information but generally treat it as proprietary. Additional data would benefit renewables operations and potentially serve as a source of revenue given the close relationship between meteorological conditions and energy prices. Additional data may also facilitate expansion of renewable power facilities into additional locations determined to be economically viable.

Both wind and solar are favored in west and south Texas. Tropospheric wind profile observations would be particularly valuable along the fenceline of west and north Texas (for example, near Pecos, Muleshoe, and Stratford), detecting changes in weather conditions as they enter the state but before they have affected renewable power generation.

8.2.10 Tourism

Texas ranks in the top five among the United States for the size of its tourism industry. Much of Texas's tourism is focused around outdoor activities, including hunting, bird watching, fishing, rafting, and wildflower viewing. Mesonet observations and dedicated web pages focused on particular outdoor tourism destinations can simultaneously serve as advertisements for the good weather Texas has to offer and enable tourists and residents alike to plan their outdoor activities for optimal weather conditions. Web cams provide additional information and allow visitors to visualize themselves participating in outdoor activities in Texas.

A handful of mesonet sites might be chosen specifically with tourism in mind. Some examples include South Padre Island, the Guadalupe River, Aransas National Wildlife Refuge, and Santa Elena Canyon.

8.2.11 Engineering and Construction

Texas infrastructure is distributed throughout the state, from oil wells and pipelines to skyscrapers. Comprehensive monitoring of weather hazards throughout Texas would be valuable for the design and construction of infrastructure. At the design phase, weather data is useful for optimizing both energy efficiency and resiliency to natural hazards. During the construction phase, weather data is essential to the safety of construction workers, avoiding hazards such as excessive heat, strong winds, and lightning.

There are no special instrumentation or siting requirements associated with this mesonet application. The application is a side benefit of whatever mesonet is installed.

8.2.12 Environmental Quality

The Texas Commission on Environmental Quality operates a mesonet (both surface stations and radar wind profilers) designed for monitoring of pollutant concentrations and transport. The network is well suited for monitoring and tracking pollution within the largest urban areas of Texas. A more comprehensive mesonet would fill in the gaps and provide much better ability to assess the trajectories of pollutants or plumes in more rural areas of the state. Examples include the West explosion and the Arkema chemical plant explosion, both of which occurred outside the high-density network of TCEQ stations. Better data coverage would permit more precise assessments of the downwind transport of potentially hazardous airborne chemicals or smoke plumes and would alert first responders to sudden changes in weather conditions before they occur.

As with engineering and construction, there are no special instrumentation or siting requirements associated with this application. Perhaps mesonet stations or even radar wind profilers might be sited adjacent to very high risk facilities so as to provide convenient specific, localized data should it ever be needed.

8.2.13 Insurance

A comprehensive mesonet would benefit both insurance companies and their customers. As with engineering, long-term environmental monitoring would permit more accurate determination of the risks of weather-related hazards, thereby enabling insurance pricing to more accurately reflect real risk and benefiting companies and customers alike. In the case of a damaging meteorological event, meteorological data may be useful in determining the cause of the damage and hence the applicability of insurance.

As with the previous two items, there are no special instrumentation or siting requirements associated with this application. This particular use would be best served by a mesonet whose density is high where infrastructure is most valuable.

8.2.14 Summary

A summary prioritization of the instrumentation needs is provided in Figure 8-1. For some applications and instruments, a dense network is needed with multiple stations per county. For other applications and instruments, a broad network is needed with something like one station per county. For the remaining applications and instruments, only a few instruments need to be deployed in special locations. For example, for flood warning, a few radar wind profilers would be valuable along the coast, while for severe weather and fire warning, a few profilers in western Texas would be valuable.

	Precip	Air temp	RH	Wind speed	Wind direction	Soil M	Solar radiation	wind profiles	GPS PW	Soil T	Pressure	Evap	Evapotrans	Wetness	Snow	Benefit to Cost Ratio
ET	EB	EB	EB	HB		MB	EB			EB	EB	LB	LB	LB		High
Other Ag	EB	EB	HB	EB	EB	EB	HB			EB		MB	MB	LB		High
Flood warning	ED	MB	MB	MB	MB	HD	LD	MS	MS			LD	LD			High
Recharge	HS	LS	LS	LS	LS	ES	LS			LS		LS	LS	LS	MS	Low-Medium
Storage		ES	ES	ES	ES		ES		HS			LS	LS			Low-Medium
Drought	ED					ED						LD	LD		MD	Low-Medium
Severe	LB	EB	EB	EB	EB	LB		ES	ES		MB					High
Energy		EB	HB	EB	EB		EB	ES			MB					High
Fire	MB	HB	HB	EB	EB	LB		HB	MB		MB	LB	LB	HB		Medium
Engineering	EB	HB	HB	EB	EB		HB									Medium
Environment	MB	MB	MB	EB	EB			MB								Low-Medium
Insurance	EB	LB	LB	EB	EB											Low-Medium
Tourism	HS	ES	HS	ES	ES		ES									Low-Medium
Education	HB	HB	HB	HB	HB	LB	MB			LB	MB	LB	LB	LB		Low

LEGEND

	Dense	Broad	Specialized
Essential	ED	EB	ES
High priority	HD	HB	HS
Medium priority	MD	MB	MS
Low priority	LD	LB	LS

Figure 8-1: Instrumentation priorities for various network uses. As indicated in the legend, each instrument is evaluated on the basis of priority (Essential, High, Medium, or Low) and required spatial coverage (Dense, Broad, or Specialized locations). Abbreviations: Precip = precipitation, Air temp = air temperature, RH = relative humidity, Soil M = soil moisture, GPS PW is precipitable water from global positioning system methods, Soil T = soil temperature, Evap = evaporation, Evapotrans = evapotranspiration, Wetness = leaf wetness, and Snow = snow depth.

8.3 Recommendations for Network Design

A framework modeled after Table 8-1 and Figure 8-1 could be used by TWDB for a master plan network design. The priority applications of the TexMesonet should be selected based on agency needs and public benefit. Once applications are determined, Table 8-1 and Figure 8-1 can be used to determine the appropriate station locations spacing, and instrumentation. While some instruments may be low priority, the small incremental cost of adding them to a station may make such instruments worthwhile. Other factors, such as spatial gaps, land access, etc., would also need to be considered when identifying needs on a regional and local basis. For a TexMesonet to remain feasible over the long-term, such data must feed into RWPG plans as they are critical stakeholders.

For example, if the first nine uses listed in Figure 8-1 are adopted as network priorities, the planned network could consist of comprehensive stations measuring precipitation, air temperature, humidity, wind speed and direction, solar radiation, air pressure, and soil temperature. These stations would be broadly deployed throughout the state and supplemented by additional stations measuring precipitation and soil moisture in high-impact locations. Also, budget permitting, a small number of radar wind profilers and a greater number of GPS precipitable water instruments would be deployed in key locations.

Once a master plan is established, informed choices may be made for prioritization of station installation. If a station sponsorship model is followed, sponsors may wish to site stations at locations not recommended by the master plan. Approval of such requests should take into account whether the core missions of the mesonet would be degraded (such as if a station in a poor location would make it unlikely a later station would be added in a nearby good location) or whether the station simply provides additional information.

9 Cost Analysis of Mesonet Components

9.1 Common Network Staff Requirements

Network staff requirements are dependent on the sizes of the network and customer bases. The staffing requirements listed here are for a typical multi-use network of 100 stations. Additional research/extension associates and system analyst/programmers would be needed if the network also incorporates and synthesizes data from other networks.

Research/Extension Scientist or Program Manager (1 FTE): This is commonly a PhD level position or someone with significant experience in monitoring networks. Perhaps his/her most important tasks are securing sustainable funding and public outreach. The scientist also provides oversight of support staff on systems, users, programs, etc., and QA/QC (data acquisition and quality control, monitoring, telecommunications, trouble-shooting, sensor evaluations/calibrations). This person should have experience/education in sensors, statistics, climatology (weather data), applications of the data (environmental science, engineering, agricultural applications, etc.), and telecommunications. The scientist will interact with stakeholders and end-users, respond to special requests, and provide technical expertise and interpretation, as needed. This person will supervise and work closely with the Research/Extension Associate and Field Technicians on needed trouble-shooting, and instrumentation replacement and repairs. Some operations will require two or more people.

Research/Extension Associate (1-2 FTE): The associate will have QA/QC responsibilities (data acquisition and quality control, monitoring, telecommunications trouble-shooting, sensor evaluations and calibrations). This person should have experience/education in sensors, statistics, climatology (weather data), applications of the data (environmental science, engineering, agricultural applications, etc.), and telecommunications. This position will back up the scientist, and therefore will interact with stakeholders and end-users, conduct product development, respond to special requests, and provide technical expertise and interpretation as needed. This person will direct the Field Technicians and provide support as needed.

Field Technician (1-2 FTE) would be responsible for much of the on-ground operations and maintenance of stations. Field installation requires general knowledge of both construction (e.g. concrete, electrical, telecommunications) and meteorological equipment. Under direction of the research/extension associate, the field technician would be responsible for maintaining sensor calibrations and field logs that would be included in each station's metadata.

System Analyst/Programmer (1-2 FTE) will set up databases and configure the network in the first year, and be responsible for continuing programming, software upgrades, security and network support. If existing networks are brought into the mesonet, their acquisition and processing (including QA/QC) software may include antiquated programs and languages that are no longer supported by modern computer operating systems. This means that programs must be converted/updated into modern languages. Additionally, some automation of QA/QC statistical operations is needed to ensure timely identification and correction of data issues. Ongoing data security, system maintenance, programming and other operations will be needed to maintain the database and to ensure the system stays in compliance with security regulations. The programmer will also be expected to make needed adjustments and develop new code to accommodate changing data acquisition/dissemination expectations. The programmer will need to work initially with ET Network leadership and the new Research/Extension Scientist to ensure the programs are working satisfactorily.

Administrative assistant (0.5 FTE) that could also be shared between programs or paid to another program for access to assistance with hardware acquisition, office management, and travel.

9.2 Equipment

This subsection covers the costs of instruments and associated hardware in a mesonet based upon the survey of mesonets and ET networks. These cost estimates are simply that – an estimate. Every station has a suite of sensors, and each instrument has several configurations that can influence the final price. Therefore, the costs listed below should be viewed as a rough estimate rather than an absolute reference.

Each network's equipment purchases are a balance between competing factors. These include the available budget for each station, the quality of the equipment, site acquisition and non-equipment costs, and the purpose of the network stations. The latter factor dictates the relative amount of money that will need to be spent on different types of equipment. For instance, an ET network will place a higher value on solar radiation sensors than will one designed primarily for public safety.

Before installing the equipment, network operators must negotiate rights to a site to place the equipment if one is not readily available. For installing the equipment at a site, there are three different options: 1) complete installation without any outsourcing, 2) outsource only specific components of the installation (e.g., fencing), or 3) outsource all of the installation except the parts requiring specific scientific expertise.

Equipment maintenance in most networks is done by members of the mesonet staff that travel to the site to conduct repairs and/or replacement of equipment. However, several operators mentioned the benefit of maintaining a close relationship with the station sponsors, so that emergency maintenance can be done locally (either by the sponsor or a local subcontractor). A few networks (e.g., North Carolina EcoNet) have designed certificate programs to assist in equipment maintenance. The TexasET Network requires each station to have a local manager that works to correct problems, with remote support by network staff. AgriLife Extension Service offers a class for such managers on Agricultural Weather Station Operation and Management at no charge.

An important component of any weather station is the tower. Each surveyed mesonet used either a 10 ft (3 m) tripod or 30 ft (10 m) tower. ET networks standardize measurements at 2 m, while mesonets generally take measurements at 10 m. A taller tower allows greater flexibility in measuring multiple levels of wind speed, as well as air temperature and humidity gradients. A 3 m tripod ranges in price from $500-1000 while a10 m tower can cost well over $1000. In addition, taller towers require more infrastructure including guy-wires and concrete bases to keep the system stable.

9.2.1 Air Temperature and Relative Humidity

In the surveyed mesonets, the cost of combined air temperature and relative humidity sensors ranged from $300 to $800 per sensor. Table 9-1 lists different sensor options and the manufacturer's claimed accuracy. All sensors listed require radiation shielding. A simple 6-

plate shield is approximately $200. Aspirated shields are more accurate in low winds, but are considerably more expensive in both initial costs and power requirement. These sensors should be re-calibrated every two years. Many have removable chips that make this process very simple.

Table 9-1: Estimated cost and accuracy of combined air temperature and relative humidity sensors

Instrument	Price	Temperature Accuracy	RH Accuracy
CS215 temperature and relative humidity probe	$500	+/- 0.7°F	+/- 2%
Vaisala 50Y temperature and relative humidity probe	$300	+/- 0.9°F	+/- 1%
Rotronic HygroClip HC2-S3	$600	+/- 0.2°F	+/- 0.8%
Vaisala HMP155 temperature and relative humidity probe	$800	+/- 0.4°F	+/- 1%
Vaisala HMP35C temperature and relative humidity probe	$600	+/- 0.4°F	+/- 2%
Vaisala HMP45C temperature and relative humidity probe	$800	+/- 0.4°F	+/- 2%
Vaisala HMP50L temperature and relative humidity probe	$800	+/- 1.1°F	+/- 2%
Vaisala HMP60 temperature and relative humidity probe	$800	+/- 0.5°F	+/- 2%
Vaisala HMP60L temperature and relative humidity probe	$800	+/- 1.1°F	+/- 2%
Vaisala HMT337 humidity and temperature transmitter	$300	+/- 0.4°F	+/- 1%

9.2.2 Wind Speed and Direction

In surveyed mesonets, the cost of wind sets containing a vane and anemometer ranged from $500 to around $1,000 per set. Table 9-2 shows the different options and the manufacturer's stated accuracy. Most wind sensors have replaceable bearings that should be changed every 3-5 years.

Table 9-2: Estimated cost and accuracy of anemometers

Instrument	Price	Wind Speed Accuracy	Wind Direction Accuracy
Met One 014A (speed)/024A (direction)	$700	+/- 1.0 mph	+/- 5°
Met One 034A-L wind set	$500	+/- 0.2 mph	+/- 4°
Met One 034B-L wind set	$600	+/- 0.2 mph	+/- 4°
R.M. Young 03001 wind monitor set	$1,000	+/- 1.1 mph	+/- 5°
R.M. Young 03001 wind sentry set	$700	+/- 1.1 mph	+/- 5°
R.M. Young 03002 wind monitor set	$1,000	+/- 1.1 mph	+/- 5°
R.M. Young 03002-L wind sentry set	$700	+/- 1.1 mph	+/- 5°
R.M. Young 05103 wind monitor set	$1,000	+/- 0.7 mph	+/- 3°
R.M. Young 05103-5 wind sentry set	$1,000	+/- 0.7 mph	+/- 0.3°
R.M. Young 05103-L wind sentry set	$1,000	+/- 0.6 mph	+/- 0.3°
R.M. Young 05106 wind monitor set	$1,000	+/- 0.7 mph	+/- 3°

9.2.3 Solar Radiation

Most of the surveyed ET networks and mesonets use Apogee or LI-COR silicon (photodiode) pyranometers that can detect the portion of the solar spectrum between 350 nm and 1100 nm. These sensors are relatively inexpensive, costing between $300 and $500. Such sensors are good for ET purposes but readings may need to be extrapolated to the total shortwave band for other applications. The Illinois Climate Network and TxSON use more expensive, full-band/full-view pyranometers from Eppley and Hukesflux which have a greater accuracy than silicon pyranometers, have higher accuracy particularly for longer wave lengths, and are designed for applications that require high measurement accuracy in demanding applications such as scientific meteorological observation networks and utility scale solar-energy-power production sites. These cost approximately $1200-1500. Like all sensors, the wide range in prices reflect the technology and accuracy of the instrument. Photodiode sensors (Apogee, LI-COR, SP Lite2) are relatively inexpensive ($200-500) for measuring a narrow band of incoming shortwave radiation, but they do not meet ISO standards. More accurate instruments use a thermopile and have ISO 9060 designations of Second Class, First Class, or Secondary Standard. Table 9-3 lists e different solar radiation equipment, including those used by the Oregon SRML. Recalibration of pyranometers is often done every 2 years.

Table 9-3: Estimated cost and accuracy of pyranometers

Instrument	**Price**	**Accuracy**
Apogee SP-110 pyranometer	$300	+/ 5%
CS300 pyranometer	$400	+/ 5%
Licor LI-200X pyranometer	$400	+/- 3%
Kipp & Zonen SP Lite2 pyranometer	$700	+/- 2%
Hukesflux LP02 Pryanometer	$900	+/- 1.8%
Kipp & Zonen CMP3	$2,200	+/- 1 %
Eppley Diffue Pyranometer(8-48)	$2,200	+/ 1%
Eppley Standard Precision Pryanometer (SPP)	$2,700	+/ 0.5%

9.2.4 Barometric Pressure

Only about half of the mesonets in the survey had specific barometric pressure equipment available. Relative to the equipment used for the meteorological variables used to compute ET, the prices of the barometers was variable, with most costing around $1,000 (Table 9-4). For TWBD, barometric pressure could be very useful for correcting non-vented pressure transducers in groundwater wells.

Table 9-4: Estimated cost and accuracy of barometers

Instrument	Price	Accuracy
Setra 278 Barometer	$600	+/- 0.05 inHg
Peet Brothers 2000 ultimeter	$1,000	+/- 0.05 inHg
Peet Brothers 2001 ultimeter	$1,000	+/- 0.05 inHg
Vaisala CS106 barometer	$900	+/- 0.02 inHg
Vaisala PTA247 barometric pressure sensor	$300	+/- 0.01 inHg
Vaisala PTB110 barometric pressure sensor	$1,000	+/- 0.06 inHg
Vaisala PTB101B barometric pressure sensor	$1,000	+/- 0.06 inHg
Vaisala PTB330 barometric pressure sensor	$2,000	+/- 0.003 inHg
*Vaisala WXT520 weather transmitter	$2,500	+/- 0.02 inHg

* Equipment also measures wind speed and direction, precipitation, air temperature and relative humidity

9.2.5 Precipitation

Precipitation gauges had the largest variance in cost among the instruments surveyed in this study. Four of the gauges mentioned cost between $300 and $600. The other seven gauges cost $1,000 or more with three of the gauges costing $6,000 or more (Table 9-5). Tipping bucket gauges tend to be less expensive and routinely used in ET Networks where only daily rainfall totals are needed, not rainfall intensity. As "effective rainfall" is used in irrigation demand calculations (a measurement of the amount of rainfall which becomes available to the plant), errors caused by the inability of tipping buckets to record very high intensity rainfall events are not significant. For other applications, such errors during both light and heavy precipitation may require calibration and application of correction curves in order to meet WMO accuracy standards (WMO, 2014). More expensive weighing gauges tend to perform better under high intensity rainfall but also require more data processing and maintenance. Heated options are available to melt solid precipitation. These are more expensive and require more power. Rain gauges are often calibrated annually either in the lab or once installed.

Table 9-5: Estimated cost and accuracy of precipitation sensors

Instrument	Price	Accuracy
Texas Electronics TE-525 tipping bucket rain gage	$500	+/- 1%
Hydrological Services TB-4 tipping bucket rain gauge	$1,300	+/- 2%
Hydrological Services TB-3 tipping bucket rain gauge	$1,900	+/- 2%
Belfort storage precipitation gauge	$6,000	+/- 1%
Geonor T-200 B precipitation gauges	$6,000	+/- 0.1%
OTT Pluvio rain gauge	$4,000	+/- 5%
OTT weighing bucket precipitation gauge and alter shield	$6,300	+/- 0.004 in
SDI12 Tipping bucket rain gauge	$2,400	+/- 3%
Sierra Misco RG2501	$400	+/- 0.04 in
Standard 8 inch diameter rain gauge	$300	+/- 0.01 in

9.2.6 Soil Moisture and Soil Temperature

The soil moisture and soil temperature probes used by mesonets in the survey were typically priced less than $500, with a few costing less than $100. Soil temperature is seldom calibrated. However, inexpensive thermocouples require very high precision differential voltage measurements by the data acquisition system. Many of the more expensive sensors are ‘smart’ sensors using SDI12 communication that require only a communication port to read the sensor. Generally, more expensive sensors operate at a higher frequency and are less influenced by soil texture and salinity. Thus, a lower cost sensor requires a site-specific calibration and manufacturers' specifications are often exaggerated. Mesonets measuring soil moisture and soil temperature typically did so at multiple depths (Table 6-4). The costs listed in Tables 9-6 (soil moisture) and 8-7 (soil temperature) are for a single sensor. Note, these costs are also dependent on the length of sensor wires. Once installed, soil sensors are typically left untouched and require no further calibration. However, there are other soil moisture sensor technologies that are used in research and agricultural applications and which provide greater accuracy than those listed in Table 9-6. Additional analysis of operational requirements is recommended before choosing a soil moisture sensor for use in a Texas statewide ET network or mesonet.

Table 9-6: Estimated cost and accuracy of soil moisture and temperature probes

Instrument	Price	Water Content Accuracy	Temperature Accuracy
Campbell Scientific 105T thermocouple	$75		+/- 1.8°F
Campbell Scientific 109 thermistor probe	$100		+/- 0.5°F
YSI Soil Temperature 44030	$25		+/- 0.2°F
Type T Thermocouple	$200		+/- 1.8°F
CS616 water content reflectometer	$125	+/- 5% VWC	
Delta-T ML3 soil moisture sensor	$200	+/- 3% VWC	
CS229 heat dissipation sensor	$180	+/- 3% VWC*	+/- 0.2°F
Acclima TDT sensor	$150	+/- 4% VWC	+/- 0.9°F
Acclima TDR-315	$300	+/- 2% VWC	+/- 0.5°F
Decagon ECTM	$200	+/- 5% VWC	+/- 0.5°F
CS65x soil water content reflectometer	$220	+/- 3% VWC	+/- 0.5°F
Stevens Hydraprobe II sensor	$400	+/- 3% VWC	+/- 0.5°F

*CS229 used by the OK Mesonet measures soil matric potential and must be converted to VWC by a site specific equation.

9.2.7 Data Loggers

While it is important to have reliable instruments , it is equally important that the observations are properly measured and logged for transmission to the database. Each network that specified the data logger used Campbell Scientific, which includes older models: the CR10X ($1000, discontinued) and CR23X ($1500, discontinued), and newer versions: CR300 ($600), CR1000 ($1,500), CR6 ($1900) and the CR3000 ($2,900). Although mesonets used various data loggers, there was not any obvious correlation between equipment cost and the frequency of sampling (Table 9-7). Costs are generally proportional to the number of available channels, processing and write speeds, memory, and control ports. Today, smart sensors using SDI12 communication protocols have reduced the need for the data logger to read and process analog signals from most sensors. Overall, data loggers are robust and tend to last beyond nearly all sensors. Data loggers operating in harsh environments will need servicing and possibly recalibration every 3-5 years.

Table 9-7: Survey of Mesonet Data Loggers

Metric	**FL**	**GA**	**IN**	**LA**	**NC**	**SD**	**WA**
Data logger	CR10X	CR1000	CR10X	CR23X	CR1000	CR10X	CR1000
Sampling (sec)	5-15	1	3	3	60	3	5

Metric	**AL-S**	**AZ**	**CA**	**DE**	**KY**	**NJ**	**NY**	**OK**
Data logger	CR3000	CR10X	CR1000	CR1000	CR3000	$2,000*	CR3000	CR10X and CR23X
Sampling (sec)	3	10	60	20	3	2	3-30	3-30

* Didn't specify specific instrument but noted data logger cost was around $2,000.

9.2.8 Additional Site Infrastructure

Each site must have infrastructure to mount the instruments, house the data logger and communications equipment, provide for power, and in some cases, provide security. These costs varied widely in the surveyed networks, and were generally higher for stations with instrument mounting at 10m, significant fencing, and concrete pads. Costs for enclosure, solar panel(s) and charge controller, battery, instrument mounting attachments and tower (10m) would typically be in the range of $2000-$3000. Cost for fencing, concrete pad, and any AC electrical infrastructure will vary with location and complexity.

9.3 Communications

There are two primary costs associated with communications from a weather station to the main computer and database. The first is the one-time cost of the communications hardware, which is typically a cellular data modem, or an antenna and equipment for radio transmissions. Other communication options include hard-line telephone, satellite systems, and direct internet transfer, all with associated equipment requirements. Cellular networks are the most common means of communication. The second cost for those using cellular (and some internet) communications is a monthly data charge. Some mesonet operators have lowered costs by bundling the charges for several stations or through the host institute. For example, both Verizon and ATT have group discounts with universities in Texas. Monthly cellular data charges for stations on the TexasET Network typically cost about $25/month each. In some cases, radio is used to transfer the data from several weather stations to a central location in order to reduce data charges. One disadvantage of cellular communications is that the cellular network configuration may change. For example, both ATT and Verizon upgraded their networks to only support GSM and 4G, respectively, for data services. Many older modems are no longer compatible on these networks so they must be replaced with a newer technology. Ultimately, coverage at the field site usually dictates the choice of carrier.

Direct internet transfer is a simple and reliable choice in situations where the weather station is located close enough to a computer with internet access so that they can be connected by cable.

Radio communications are primarily used to transmit data over relatively short distances from a weather station to a computer with internet access. Radios operating at lower frequencies (public bands) require no permitting and have no monthly data charges. These frequencies require line-of-sight and are subject to interference. Licensed bands reduce these problems. Satellite communication systems are primarily used for stations in remote locations. Data transmission costs are higher per single station than other options, but may be comparable to cellular for networks with a large number of weather stations. Table 9-8 lists costs of some of the communications-related equipment from surveyed mesonet operators.

Table 9-8: Estimated cost of communications equipment

Instrument	Price
Sierra Wireless RV50 (ATT or Verizon)	$550
NL240 Wireless Network Interface (CSI)	$400
Campbell Scientific RF407 radio	$400
GOES Transmitter	$2,800
Air Link Raven XT (discontinued)	$450
Sierra Wireless LS300 (ATT only, discontinued)	$500
Verizon Raven XE Modem (Verizon only, discontinued)	$500

9.4 Data Processing and Archival

The operational handling of real-time data, verifying its quality assurance and control, processing the data into usable products, and ultimately archival are considerable efforts that require both qualified staff, software, and hardware.

In mesonets, data are generally posted to a website at 30- or 60-minute intervals after collection from stations in the network. In addition, weather data are commonly pushed to national collectors such as Regional Climate Centers (NOAA) or MADIS, as well as university systems like MesoWest (University of Utah). These data are further processed and standardized for use in various weather and hydrological forecasting models. ET and ag weather networks typically post data daily.

The whole process requires computing hardware such as servers and commercial software. It also involves many custom applications to both validate the data and move it, requiring custom scripts and programming. Data acquisition systems typically combine commercial software with custom programming. One commonly used commercial software package is Loggernet or Loggernet Admin ($590/$1135, Campbell Scientific), which is used for automatically downloading data and transmitting it to a central computer. Quality control functions are sometimes done by the networks themselves, requiring custom programming Costs for this function will vary by sophistication of web sites, dissemination, product generation, and QC efforts, but typically would include web server class hardware assets. Customized programming is used in the TexasET Network, for example, to ensure quality of data by automatically flagging of data that is outside of expected bounds and preventing it from being publically posted until reviewed by network personnel. Such automatic processing reduces personnel time in reviewing data and troubleshooting problems.

Data, including raw signals and metadata, are generally kept by the network operators for the life of the network, so an archival scheme and an expanding and robust storage system and database is implied. While this might initially be accomplished with relatively inexpensive disk storage such as a RAID system, the long-term value of the data may need to be protected with more sophisticated backup arrangements including tape, optical, or external cloud architecture. Costs vary by the sophistication of data preservation, network size, accessibility of data streams, and length of time. A successful statewide Mesonet system will have to eventually pay serious attention to long-term data stewardship, and the software aspects of data stewardship are easiest to implement from the beginning.

9.5 Maintenance

Inability to obtain long-term maintenance funding has been the end of many well-intentioned observing efforts, including a mesonet installed by Texas A&M in the 1990s. Experience of our surveyed mesonets, as well as those of the authors, show that installed mesonet stations must be constantly monitored and actively maintained to achieve the desired measurement accuracy and data return rate. These activities include inspection, site maintenance and mowing, and sensor/equipment servicing and recalibration. Routine inspection is particulary important. Common problems are birds building nests in rain gages, rain gages becoming clogged by debris, and solar panel surfacing becoming covered.

9.5.1 Maintenance Personnel

Field technicians are responsible for maintenance of both the site and equipment. This includes replacing sensors and general site maintenance (mowing, basic electrical work, fence and structures maintenance, etc.). This position requires mechanical skills (for wiring, basic mechanical repairs, machinery and other equipment maintenance, etc.), potentially significant travel (some sites are remote), and working in all weather conditions.

Field technician costs vary substantially from network to network, depending on whether local partners have been identified to assist with site maintenance. A technician may be able to make between two and five site visits per day if the stations are nearby. With a state as large as Texas, multiple field technicians would be needed in different parts of the state.

9.5.2 Instrument Maintenance

Sensors require periodic maintenance and recalibration to maintain accurate observations. Notably, all mechanical anemometers and wind vanes (or combination instruments) have bearings which will eventually fail or otherwise degrade the measurement. RH sensors are subject to drift and failure, and manufacturers generally recommend recalibration every one to two years, along with temperature recalibration for combined sensors. Depending on the type of sensor, needed maintenance can either be performed by mesonet personnel or by returning the sensor to a recalibration facility, usually the manufacturer. A large mesonet program would likely invest in its own calibration equipment for some parameters, such as temperature, if the cost-benefit of equipment purchase vs. vendor calibration is favorable.

Table 9.1 shows the recommended budget for sensor recalibration used in the Texas ET Network. These costs do not include personel time or shipping charges. All sensors must be recalibrated every one to two years. . Other instrumentation types have longer periodic calibration cycles, but also will eventually require return to a calibration facility. Rain gauges require periodic testing to verify proper operation, but in-house personnel can usually maintain these with vendor part kits such as reed switches. This still will require replacement part procurement.

Table 9-9 Sensor replacement and calibration costs budget recommendations for stations on the TexasET Network (excluding personnel time and shipping).

Sensor	Recommended Recalibration Schedule	Replacement Cost ($)	Recalibration Cost ($)
Datalogger CR800	Three years plus, depending on environmental conditions*	1056	230 (270 if calibration documentation is needed)
Temperature/Relative Humidity HMP60	once every two years	288	95 (installed replacement chip)
Solar Radiation (pyranometer) LI 200R	once every two years	466	130
Wind Speed and Direction 03002-L	once every two years	663	175 (refurbish bearings)
Rain Gage TE525	once every year	356	125 (calibration only)
Total		**2829**	**755**

- Dataloggers properly sealed and with desiccant replaced annually will not normally need recalibration unless operating under harsh conditions

Although proven sensor systems are usually robust, eventually failure out-of-warranty will demand a replacement. A pool of replacement sensors is required to reduce down-time of stations, and must be budgeted for. Often, the strategy is to replace a sensor at one site with one from the ready-spare pool, repairing, calibrating, or purchasing a replacement as needed, and placing that sensor in the pool.

9.5.3 Site Maintenance Visits and Infrastructure

In order to repair or replace failed or failing sensors, to do maintenance on site infrastructure, or to simply inspect facilities on a periodic basis, visits by network personnel to observation sites/stations are required. In addition to the personnel costs, travel costs must be budgeted for and are clearly dependent on the distance from the home base of maintenance technicians. In some instances, the surveyed networks use partner personnel to perform routine maintenance such as mowing.

Some infrastructure parts are prone to failure or are consumables, such as batteries and desiccant. Battery replacement in a properly sized solar system can be expected every 2-4 years. Solar panels are generally robust, but may be more prone to theft and/or breakage than other infrastructure elements. Tower hardware should last perhaps 20 years, but eventually elements such as grounding and guy-line parts may need to be replaced.

10 Organization and Governance

10.1 TexMesonet Challenges

A successful, sustainable mesonet must overcome several challenges to ensure long-term operation at reasonable cost. In general, surveyed mesonets received funds to cover initial costs of equipment and infrastructure, requiring that funds for maintenance and upkeep costs come from different sources. There are four types of challenges noted by most networks: financial, spatial distributions, data and meta-data management, and standardization. Reliable funding, stability of qualified technical support staff and retention, recurring costs (sensor recalibrations, communications) are common challenges. Inadequate spatial distribution in order to meet the requirements of all the various stakeholders may result if there are insufficient funds to establish the network.. Database management, data uploads to websites, technical support for end users and specific applications require additional resources. When existing stations are incorporated into a mesonet, the sensors, data QA/QC, siting requirements, maintenance and upkeep, and measurements are likely not standardized in regards to the location of sites, measurement heights and depths, units of output or time integration (cumulative, mean, instantaneous), among others.

This section describes three possible models for a sustainable TexMesonet. These models are not the only three options available, but they include components that span the range of viable options. Some mixing and matching of options is possible, but the report specifies those aspects of the model that are interdependent. The common issues considered here are network objectives, network heterogeneity, the role of a central network operator, capital and maintenance costs, and the nature of the operating entity. Partial funding may be available through the National Mesonet Program.

10.2 Comprehensive Centralized Model

At one end of the spectrum of mesonets is the Oklahoma Mesonet. The Oklahoma Mesonet developed out of a collaboration between Oklahoma State University, whose primary interest was in agricultural applications, and the University of Oklahoma, whose primary interest was in public safety. They recognized that a single network could accomplish both missions. There were also political benefits to a collaboration between the two major public universities in the state. Initial funding came from the state legislature in 1990, supplemented by university contributions, for a total startup cost of $5M in today's dollars. The sensor suite has been expanded over the years, and presently the Oklahoma Mesonet serves as a national model for high-quality, comprehensive mesonet operation.

Although the Oklahoma Mesonet is operated as a two-team partnership, it is treated here as a centralized mesonet because it possesses many key characteristics of a top-down network: standardized, uniform equipment; central operations, quality control, maintenance and archival; a statewide funded mandate; and a comprehensive set of products and outreach activities. Stations are well sited and sensors are high quality. Similar characteristics apply to the mesonets in Australia and Switzerland discussed earlier.

10.2.1 Translation to Texas

The primary objectives of the TexMesonet as originally conceived are agriculture and public safety, similar to what initially inspired the Oklahoma Mesonet. With Texas being five times the size of Oklahoma, startup costs for an Oklahoma-style network with its current sensor suite could be $25M to $40M. While the Oklahoma Mesonet has operated effectively with a centralized shop for maintenance and calibration, the sheer geographical size of Texas makes a centralized facility challenging The operating body would need to be either a statewide agency with substantial local presence or a consortium of regional entities. The Texas A&M System, including Agrilife Research and the Agrilife Extension Service is one example of such a statewide agency with a presence in 52 of Texas' 254 counties.

With its initial installation of mesonet stations, TWDB has taken a first step in this direction, though its network coverage is presently limited to a few counties. TCEQ operates the largest centralized network in Texas, but this network is single-purpose, and instrumentation, siting, and quality-control practices are all optimized for that specific purpose.

10.2.2 Advantages

10.2.3 The Oklahoma Mesonet benefits from uniformity of equipment, which facilitates quality control, calibration, maintenance, and use and interpretation of data. With substantial attention having been paid to data quality, the Oklahoma Mesonet is able to serve multiple constituencies, including public safety. Special effort has been paid to assisting emergency managers and other public safety officials with data, software, and education. The operating entity maintains complete control over station siting and requirements for instrumentation and operation. Disadvantages

The business model for the Oklahoma Mesonet requires substantial sustained core funding from the State of Oklahoma for maintenance and operations. Sustainability is difficult in the absence of such core funding. Strict uniformity discourages flexibility in siting requirements, station density, and sensor selection. Operation of a comprehensive centralized mesonet may be challenging for a state government entity whose mission is sector-specific rather than comprehensive unless the mesonet benefits to that sector justify the effort. A centralized mesonet fails to leverage existing networks of varying quality that already exist within Texas.

10.3 Clearinghouse of Mesonets Model

At the other end of the spectrum is the concept of a clearinghouse of mesonets, or network of networks, in which the network operator does not directly operate weather stations but instead collects observations from third-party networks. An example of such a network is MesoWest, operated by the University of Utah. MesoWest collects data from 221 local, regional, and national weather networks ranging in size from one station to over 8000 stations. MesoWest passes the data stream through some automated quality control checks and makes the data available in real time. Its website presents a variety of analysis/display options and other products, and archived data is also available. Users can choose among several options for which networks to include in MesoWest products.

10.3.1 Translation to Texas

The TWDB already operates a clearinghouse of mesonets, pulling data from MesoWest and from individual network operators in Texas, aggregating it, displaying it, producing a limited suite of products, and archiving the data. As discussed earlier in this report, the state of Texas is so large as to contain many weather networks, and TWDB estimates that data from about 2000 stations are already included in their clearinghouse. TWDB does not perform any additional quality control, instead relying on that performed by MesoWest and other data providers.

10.3.2 Advantages

A network of networks leverages existing single-purpose networks or multi-purpose mesonets, so that there are no costs for station sensors, installation, and maintenance. The low operational costs make such a clearinghouse highly sustainable for TWDB. In some areas of Texas, the density of available stations in Texas is high enough to provide coverage similar to that of other mesonets elsewhere. Aggregation maximizes data availability and ease of access for a variety of users, in particular making single-purpose network data available for other uses even when those other users are beyond the scope of the single-purpose network operator. A clearinghouse is well suited to operation by a single agency or other entity. Incentives (e.g. monetary or in-kind) to participate could give network operators greater sustainability or ability to expand.

10.3.3 Disadvantages

While easily sustainable for TWDB, the data collection networks are not. Stations will likely come and go, as will entire networks. Furthermore, data coverage is high in some parts of the state, but other parts of the state have relatively few stations available. More importantly, the available stations are not necessarily suitable for particular purposes. ET networks have rigorous standards for siting and sensor placement that render almost all stations within Texas unsuited for that purpose. Many stations also do not have the frequency, data standards, or quality control needed for most public safety applications. The value added from mere aggregation of data is small, since aggregation is already being performed by sites such as MesoWest. The inclusion of otherwise unavailable data is beneficial but requires information on suitability of data for particular purposes that may not be readily available to the aggregator. There is no mechanism for growing the network or resolving deficiencies in the network beyond including whatever other measurements are already being made by others.

10.4 Partnership Models

Most existing mesonets operate within the spectrum bounded by the two models described above: a centralized model with no compilation and inclusion of external data, and a clearinghouse model with no generation of internal data. There are two important aspects of this spectrum: the station level and the aggregation level.

At the station level, the necessary tasks are the establishment of specifications, the capital costs of equipment purchase, the acquisition of sites, the installation of stations, the transmission of data, and the maintenance of stations. In the centralized model, a single entity is responsible for all of these functions. In the clearinghouse model, the operator of the network of networks is not responsible for any of these functions. Other models exist in which the top-level network operator is responsible for some but not all functions. For example, the operator may promulgate specifications for stations and leave it to individual station operators to meet those specifications as a condition for inclusion in the network. Or the operator may carry out some or all of these functions in exchange for local sponsorship. An example within this spectrum is the North Dakota Ag Weather Network, described in Section 6, which establishes specifications and assists with site selection, installation, and maintenance. For such a model to work, there must be a clear benefit for the station sponsor to meet the specifications for inclusion in the network.

At the aggregation level, the necessary functions are data ingestion, quality control, product generation, data and product distribution, data archival and stewardship, and provision of archived data. Most of these functions are common to the centralized and clearinghouse models, except that in the clearinghouse model, data is obtained from network hubs rather than the actual stations and quality control may be performed by the individual networks.

An example of this model in coastal meteorological and oceanographic observations is the National Data Buoy Center (NDBC). NDBC initially was the operator of a network of primarily coastal buoys and coastal meteorological stations. However, other data sources and networks began to observe on smaller spatial scales, most notably the efforts of regional coastal ocean observing networks (so-called regional COOS networks) under the umbrella of NOAA's Integrated Ocean Observing System (IOOS) program. Other data sources also became available, such as data from oil platforms in the Gulf of Mexico. NDBC now serves as a national aggregator and QC provider for both its own physical assets and those of others who observe the ocean and atmosphere on and near the coast, notably inserting data into the Global Telecommunications System (GTS) for worldwide availability. A relatively seamless interface, regardless of provider, is provided via NDBC's web presence and other product dissemination pathways. https://www.ndbc.noaa.gov

10.4.1 Translation to Texas

Because of the size of Texas and the uneven coverage provided by existing stations for various purposes, a compelling case can be made that existing mesonets (such as the West Texas Mesonet and the LCRA Hydromet network) and other specialized networks need to be incorporated in any statewide mesonet. If so, this precludes a full-blown centralized model and requires at least some clearinghouse functionality. Likewise, there are needs for additional stations in key locations that are undersampled for purposes such as agriculture and public safety, so some additional activity at the station level seems appropriate as well.

The TWDB, as noted, is engaged already in both centralized and clearinghouse activities. In fact, our study indicates that TWDB's own initial stations and centralized operation have evolved to most of the best practices (and sensors) of the programs surveyed in this report. However, it has not yet engaged in the hybrid station-level activities that fit under the partnership model. Because new stations might be necessary in many remote areas of Texas, a formal partnership of operating entities may be necessary to provide station maintenance and oversight.

An even broader consortium would facilitate the incorporation of existing data into a comprehensive mesonet. Existing network operators would benefit from products and services that target their networks' core purposes. Such products and services may be developed by an existing network operator and incorporated into the broader mesonet, or they may be developed by the consortium to benefit the customers of several network operators. The local network operators also benefit from the integration of data from other stations within their service area. Such activities are best performed by a consortium organization including some combination of

TWDB, other state agencies, universities, and major network operators rather than by a single agency whose core mission may have little overlap with that of the local network operators and stakeholders. A consortium would also have greater flexibility in obtaining funding from federal and private sources.

Individual station sponsorship by local entities has been a successful model for many mesonets in other states. If the same level of per capita local funding is available in Texas as in North Dakota, Texas can support over 2000 stations at the North Dakota station quality level. If the same level of mesonet funding per unit GDP is available in Texas as in North Dakota, the number of viable stations rises to 3500.

With a hybrid network, a statewide database of high quality, documented and maintained data and sources should be electronically warehoused and made readily available for use in research, education and water planning. The Texas Natural Resources Information System (TNRIS – Texas Water Development Board's clearinghouse for natural resources and GIS data) may be an appropriate location / group to maintain the database. The database clearinghouse group and the participating network operators should be supported through adequate and stable funding to maintain physical infrastructure, telecommunications, operations and maintenance, and data management, storage and delivery. Lastly, networks should be supported with technically competent personnel at all levels.

10.4.2 Advantages

A hybrid model maximizes the potential value of a TexMesonet, by utilizing existing stations and creating new ones. At the station level, costs are lower than for the centralized model because many stations already exist and are being funded for specific purposes.

New stations can be tailored to specific needs. For example, precipitation-only measurements have less-restrictive siting requirements than temperature measurements, so relatively inexpensive precipitation-only stations can be used to supplement more comprehensive stations. This makes sense because precipitation in Texas tends to be highly variable over short distances. Likewise, other types of stations can be considered, such as GPS-based atmospheric humidity measurements or radar wind profiler measurements.

A hybrid model is the most common model for successful, sustained networks. Local sponsorship literally creates buy-in to the network. The broader the constituency that consider themselves to be contributing to the overall network and utilizing its benefits, the greater the long-term viability of the network.

10.4.3 Disadvantages

While there are cost savings over the centralized model at the station level, there is greater effort required to work with the data at the aggregation level than with either of the other models. Since the mesonet includes some of its own stations, quality control must be performed on the data from those stations. There is generally less information available as input for quality control for data from outside networks, so neither station siting, instrumentation, or quality control can be standardized throughout the network. Adequate metadata must be gathered and made available to data users so that they can utilize stations of the appropriate quality.

11 Recommendations for Texas

11.1 Choices and Benefits

The expenses associated with the various options must be weighed against the benefits of various configurations of a statewide mesonet. Substantial benefits have been documented for the agriculture sector, for whom the benefits accrue through more efficient use of water, better weather-appropriate crop management decisions, and so forth.

Beyond the benefits of outreach, research, education, and safety, the Oklahoma Mesonet claims a conservative annual economic value of $2.8 to $5.4 million dollars from the agriculture sector alone.

The California Irrigation Management Information System (CIMIS), developed and operated by the California Department of Water Resources, was assessed using a UC Cooperative Extension survey and the CIMIS user database. They found that the benefits of the program far outweigh the state cost of about $850,000 per year. Statewide, 363,816 agricultural acres are under CIMIS, with annual estimated benefits of $64.7 million. Fresno and Kern counties receive the largest net benefits, while Santa Barbara and Ventura counties have the highest benefits per acre. According to their calculation, statewide agricultural water applications are reduced by 107,300 acre-feet annually. http://ucanr.edu/repository/cao/landingpage.cfm?article=ca.v054n03p21&fulltext=yes

More broadly, a conservative cost-benefit analysis suggests that the ECONet network of local weather stations could save the people of North Carolina nearly $90 million in a year. https://www.nc-climate.ncsu.edu/econet/value.html

These valuations apply to a sustainable statewide network with ET-quality observations. Presently, Texas does not have a network that provides statewide data with ET-quality observations that is sustainable.

Another sector with large benefits from a statewide mesonet is public safety. Even stations that do not meet evapotranspiration network standards can be extremely valuable for weather warning and hazard response if the station data is available in real time and is of known, high quality. For public safety purposes, a network that leverages good existing data with gap-filling sensors would provide the maximum benefit. Given the population density of Texas and its susceptibility to a broad array of natural hazards, the citizens of Texas would greatly benefit from the improved protection against natural disasters that a comprehensive mesonet would provide.

Ultimately, the mission of TWDB is centered on the conservation and responsible development of water for Texas. We conclude this report with rough estimates of water savings available through implementation of the various mesonet models.

11.2 General Comments on Water Savings

The Texas climate is characterized by extremes and agriculture depends on reliable timing and availability of water. Plants need water for photosynthesis where it is exchanged for atmospheric carbon and used to build biomass. As crops grow, water in the root zone is depleted leading to stress and reduced productivity. Irrigation is often used to supplement rainfall and increase soil moisture storage. Irrigation is the largest water consumer in the State, using 7.83 million acre-feet in 2014 with 82% of that coming from groundwater [*TWDB*, 2014]. This feasibility study is an appraisal of the current state-of-the-science weather networks including both multi-purpose mesonets and potential evapotranspiration networks comparable in scale to Texas, the goal being to guide TWDB's TexMesonet Program and ultimately improve water conservations statewide.

Studies of successful ET networks indicate that water savings on irrigated cropland on the order of inches per acre per year are to be expected. Extrapolated to all of Texas's irrigated agriculture, the water savings on croplands alone would exceed a million acre-feet per year. A more precise estimate of water savings requires knowing station locations, sensors, and products that would be made available to agricultural producers. Other water savings can accrue in urban areas through products designed to provide guidance on lawn and garden watering timing and amounts.

Municipal water use is the second largest user of water in Texas after agricultural irrigation and is quickly rising, and landscape irrigation accounts for 40-60% of municipal water consumption during the lawn irrigation season. As seen in the WaterMyYard program and the City of Frisco Waterwise program, significant amounts of water can be saved through ET Networks accompanied by public outreach programs. For example, water savings in the WaterMyYard program are estimated to average 80,000 gallons a year per residence. In 2018, the Houston Galveston Subsidence District and AgriLife Extension are initiating a study to actually track the reduction in water use by homeowners who sign up for the program. This study will provide more definitive data on actual water savings achievable.

The authors of this report are committed to the development of techniques to improve agricultural and other water conservation. However, this was a research-based effort and not directly related to any demonstration project with tangible water savings. Our results, if implemented would benefit efficiency of water conservation plans and/or programs, and to enhance the value of future water conservation programs. For example, Bonneville Power in Oregon provides farmers rebates of $5.25/acre for using science-based irrigation scheduling. A network such as TexMesonet could provide near real-time irrigation scheduling for farmers and consultants, further reducing demand.

Reliable weather data are desperately needed to improve weather forecasts by the National Weather Service and to more accurately assess the state's surface and groundwater supplies. Such data would also improve crop ET estimates and reduce irrigation demand. Crop ET is the major consumptive user of water resources both in Texas and across the globe. Its quantification along with each component of the water balance is critical to assess water conservation.

12 Acknowledgments

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13 Acronyms

AASC	American Association of State Climatologists
ACORN	Australian Climate Observations Reference Network
ADAM	Australian Data Archive for Meteorology
ASABE	American Society of Agricultural and Biological Engineers
ASCE	American Society of Civil Engineers
ASOS	Automated Surface Observing System
ATX	Austin, Texas
AUD	Australian Dollars
AWS	Automated Weather Stations
AZMET	Arizona Meteorological Network
BoM	Bureau of Meteorology (Australia)
BOR	Bureau of Reclamation
CIMIS	California Irrigation Management Information System
CoAgMet	Colorado Agricultural Meteorological Network
CRN	Climate Reference Network
COOP	Cooperative Observer Network
COOS	Coastal Ocean Observing System
CWOP	Citizen Weather Observing Program
DWR	California Department of Water Resources
EAA	Edwards Aquifer Authority
ERCOT	Electric Reliability Council of Texas
ET	Evapotranspiration (combined water loss to atmosphere through evaporation and transpiration, a measurement of the amount of water needed to grow crops
ETc	The actual water requirement of a specific crop or plant, such as cotton
ETo	The potential evapotranspiration for a particular reference crop, usually grass or alfalfa under observed weather conditions if ample soil moisture is available.
FAWN	Florida Automated Weather Network
FEMA	Federal Emergency Management Agency
FTE	full-time equivalent
GAEMN	Georgia Automated Environmental Monitoring Network
GAPP	GEWEX Americas Prediction Project
GBRA	Guadalupe-Blanco River Authority

GEWEX	Global Energy and Water cycle Exchanges
GTS	Global Telecommunications System
HGMP	Hazard Grant Mitigation Program
HPRCC	High Plains Regional Climate Center
ISU	Iowa State University
ICN	Illinois Climate Network
IOOS	Integrated Ocean Observing System
IT	Information Technology
KCC	Kentucky Climate Center
KYM	Kentucky Mesonet
LAIS	Louisiana Agriclimatic Information System
LCRA	Lower Colorado River Authority
MADIS	Meteorological Assimilation Data Ingest System
NASA	National Aeronautics and Space Administration
NAWMN	Nebraska Agricultural Water Management Network (NAWMN)
NC ECONet	North Carolina Environment and Climate Observing Network
NCCS	National Centre for Climate Services (Switzerland)
NDAWN	North Dakota Agricultural Weather Network
NDBC	National Data Buoy Center
NDSU	North Dakota State University
NERON	NOAA's Environmental Real-time Observation Network
NEXRAD	Next Generation Weather Radar
NJWCN	New Jersey Weather and Climate Network
NICE Net	Nevada Integrated Climate and Evapotranspiration Network
NMP	National Mesonet Program
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
OSU	Oklahoma State University
OU	University of Oklahoma
OWUE	Office of Water Use Efficiency

PET	Equivalent to ETo; the potential evapotranspiration of a particular reference crop, usually grass or alfalfa under observed weather conditions if ample soil moisture was available)
QA/QC	Quality Assurance / Quality Control
RAWS	Remote Automated Weather Stations
RWPG	Regional Water Planning Groups
SCAN	Soil Climate Analysis Network
SDSTATE	South Dakota State University
SGT	Stinger Ghaffarian Technologies
SRML	Solar Radiation Monitoring Laboratory
TAMU	Texas A&M University
TAMUS	The Texas A&M University System
TCEQ	Texas Commission on Environmental Quality
TGPC	Texas Groundwater Protection Committee
TNRIC	Texas Natural Resources Information System
TxDOT	Texas Department of Transportation
TxSON	Texas Soil MOisture Observation Network
TWDB	Texas Water Development Board
USDA-ARS	United States Department of Agriculture - Agricultural Research Service
USGS	United States Geological Survey
UT-Austin	The University of Texas at Austin
UT-BEG	The University of Texas at Austin, Bureau of Economic Geology
WKU	Western Kentucky University
WMO	World Meteorological Organization

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ASABE. 2015. Measurement and Reporting Practices for Automatic Agricultural Weather Stations. American Society of Agricultural and Bilogical Engineers, ASAE EP505.1 APR2015.

BoM, 1997. *Guidelines for the siting and exposure of meteorological instruments and observing facilities.* Observation Specification No. 2013.1, 86 pp. [Available online at http://www.bom.gov.au/climate/cdo/about/observation_specification_2013.pdf]

BoM, 2005. *Automatic weather stations for agricultural and other applications.* Commonwealth of Australia Bureau of Meteorology. [Available online at http://www.bom.gov.au/inside/services_policy/pub_ag/aws/aws.shtml]

BoM, 2010. *Modernisation and Extension of Hydrologic Monitoring Systems Program.* Commonwealth of Australia Bureau of Meteorology. [Available online at http://www.bom.gov.au/water/about/publications/document/modexfund-01.pdf]

BoM, 2016. *2015-16 Bureau of Meteorology Annual Report.* Commonwealth of Australia Bureau of Meteorology, 224 pp. [Available online at http://www.bom.gov.au/inside/eiab/reports/ar15-16/doc/Bureau-Annual-Report-2015-16.pdf]

BoM, 2017a. About weather station data. [Available online at http://www.bom.gov.au/climate/data/stations/about-weather-station-data.shtml]

BoM, 2017b. About data and observations. [Available online at http://www.bom.gov.au/climate/data-services/about-data-observations.shtml]

BoM, 2017c. Basic climatological station metadata at Sydney Airport AMO. [Available online at http://www.bom.gov.au/clim_data/cdio/metadata/pdf/siteinfo/IDCJMD0040.066037.SiteInfo.pdf]

Caldwell, T, B.D. McRoberts, G. Fipps, and J.W. Nielsen-Gammon, 2017, Workshop Notes – A statewide evapotranspiration monitoring network: TexMesonet and beyond. Texas Water Development Board contract number 1613581995, May 15, 2017, Austin, TX, 59 pp.

Commonwealth of Australia, 2014. *Independent Review of the Water Act 2007*. Commonwealth of Australia, 117 pp. [Available online at http://www.environment.gov.au/system/files/independent-review-water-act-2007.pdf]

Duke, S.M.R. 2003. The ECONet/NC CRONOS Database: Its Value to the State of North Carolina. On-line paper at http://climate.ncsu.edu/econet/value.html

Fiebrich, C. A., 2009: History of surface weather observations in the United States. *Earth Sci. Rev.*, **93,** 77–84. doi:10.1016/j.earscirev.2009.01.001.

Frei, T., 2003: Designing meteorological networks for Switzerland according to user requirements. *Meteorol. Appl.*, **10**, 313-317.

Heimo, A., B. Calpini, T. Konzelmann, and S. Suter, 2006: SwissMetNet: The New Automatic Meteorological Network of Switzerland. *WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation*, Geneva, Switzerland, P1(16). [Available online at http://www.wmo.int/pages/prog/www/IMOP/publications/IOM-94-TECO2006/P1(16)_Heimo_Switzerland.pdf]

Hirsch, R. M., Fisher G. T., 2014. Past, present, and future of water data delivery from the U.S. Geological Survey. *J. Contemp. Water Res. Educ.*, **153**, 4–15. doi: 10.1111/j.1936-704X.2014.03175.

Jensen, M.E. Editor. 1980. Design and Operation of Farm Irrigation Systems. ASAE Monograph No. 3. American Society of Agricultural Engineers.

Marek, T., D. Porter, P. Gowda, T. Howell, and J. Moorhead. 2010. Assessment of Rexas Evapotranspiration (ET) Networks. Final Project Report. TWDB Contract No. 0903580904. December 21.

Marshall, C. H., 2016: The National Mesonet Program. *22nd Conference on Applied Climatology*. New Orleans, LA, Amer. Meteor. Soc, 2.4.

Marshall, C. H., 2016: Data Rights and Sharing: National Mesonet Paradigm. *Network of Networks Forum*. Washington, DC, Amer. Meteor. Soc.

MeteoSwiss, 2014. *Federal Law on Meteorology and Climatology.* Swiss Federal Office of Meteorology and Climatology, 15 pp. [Available online in German at http://www.admin.ch/ch/d/gg/pc/documents/2433/MetG-OGD_Erl.-Bericht_de.pdf]

MeteoSwiss, 2016. *SwissMetNet: The MeteoSwiss reference monitoring network.* Swiss Federal Office of Meteorology and Climatology, 2 pp. [Available online at http://www.meteoswiss.admin.ch/content/dam/meteoswiss/en/Mess-Prognosesysteme/Bodenstationen/Automatisches-Messnetz/doc/SwissMetNet_The_MeteoSwiss_Reference_Monitoring_Network.pdf]

MeteoSwiss, 2017a. Facts and figures. [Available online at http://www.meteoswiss.admin.ch/home/about-us/portrait/facts-and-figures.html]

MeteoSwiss, 2017b. Manual precipitation monitoring network. [Available online at http://www.meteoswiss.admin.ch/home/measurement-and-forecasting-systems/land-based-stations/manual-precipitation-monitoring-network.html]

MeteoSwiss, 2017c. Measurement instruments. [Available online at http://www.meteoswiss.admin.ch/home/measurement-and-forecasting-systems/land-based-stations/automatisches-messnetz/measurement-instruments.html]

MeteoSwiss, 2017d. Data management. [Available online at http://www.meteoswiss.admin.ch/home/measurement-and-forecasting-systems/datenmanagement.html]

National Research Council, 2009: *Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks*. National Academies Press, 234 pp.

NOAA, 2016: *Federal contract opportunity EA-133W-16-RP-4036 for data processing, hosting, and related services at National Oceanic and Atmospheric Administration (NOAA) Eastern Region Acquisition Division*.

NOAA, 2017: National Weather Service Mission Statement. [Available online at http://www.nws.noaa.gov/mission.php]

Parker, D., D. Zilberman, D. Cohen and D. Osgood. The Economic Costs and Benefits Associated with the California Irrigation Management Information System (CIMIS). Report to the California Department of Water Resources. University of California, Berkeley, Department of Agricultural and Resource Economics. May 1996.

Parliament of Australia, 2007. *An Act to make provision for the management of the water resources of the Murray-Darling Basin, and to make provision for other matters of national interest in relation to water and water information, and for related purposes*. Water Act 2007, 234 pp. [Available online at http://www.legislation.gov.au/Details/C2007A00137]

Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc.. A 193.

Penman, H.L. 1963. Vegetation and hydrology. Tech. Commication No. 53. Commonwealth Bur. Of Soils, Harpenden, England.

SGT, 2017: SGT Awarded NOAA Mesonet Program. [Available online at http://www.sgt-inc.com/sgt-awarded-noaa-mesonet-program/]

Suter, S., T. Konzelmann, C. Mühlhäuser, M. Begert, and A. Heimo, 2006: SwissMetNet – The new automatic meteorological network of Switzerland: Transition from old to new network, data management and first results. *Proc. of the 4th International Conference on Experiences with Automatic Weather Stations*, Lisbon, Portugal, 24. [Available online at https://www.researchgate.net/profile/Michael_Begert/publication/228564872_SwissMetNet-the_new_automatic_meteorological_network_of_Switzerland_transition_from_old_to_new_network_data_management_and_first_results/links/5689354a08ae1e63f1f8cb25.pdf]

WMO, 2014. *Guide to Meteorological Instruments and Methods of Observation.* World Meteorological Organization, WMO-No. 8, 1128 pp. [Available online at http://library.wmo.int/opac/doc_num.php?explnum_id=3121]

17 Draft Comments

The Texas Water Development Board review team provided the following comments to the contractor after reviewing the draft final report. The comments and page numbers are based on the paper version of the draft report dated June 15, 2017, as submitted by the contractor. These comments were taken into consideration during preparation of the final version of the final report.

Overall, the review team thought this was a thorough and well-written draft report. Excellent job!

General comments:

1) Please ensure that the various evapotranspiration acronyms (ET, ET_c, ET_o, and PET) are used appropriately throughout the document.
    a. Consider moving the list of acronyms on page 68 to a definition of terms section at the beginning of the report.
    b. PET and ET are mentioned in the Executive Summary, but not defined in the report until page 11. Please include definitions of any acronyms where they are first used in the report.
    c. ET_c and ET_o are also variously printed with different fonts for the "c" or "o". Please consider changing these to subscript text, which seems most appropriate for these terms.
2) Please add bullet points to the Executive Summary on the major components of a successful network as well as considerations and concerns for avoiding network failures.
    a. Add any appropriate TexMesonet recommendations to the body of the report (consortium and advisory board, National Mesonet Program, etc.). Include specifics on who, what, when, and how the advisory board might function.
    b. Include a section in the report about the considerations and concerns for avoiding network failure. Include examples of networks that have failed and why.
3) Include a section on the regional differences in end user needs (irrigation scheduling in major agricultural regions and urban areas, lake evaporation, flood forecasting in certain areas, public safety, power generation, etc.).
4) Consider drawing further distinctions between a mesonet and a network specifically dedicated to ET, with particular focus on the different siting and maintenance requirements.
5) If possible, please explain how different networks handle equipment purchases, installation, and maintenance, as well as their contracting and subcontracting practices.
6) Add the figures shown in the initial version of the draft report (but omitted from the paper copies) back into the final report, along with a List of Figures section similar to the List of Tables.

7) The suggestion about including LiDAR data, as discussed at the meeting on the August 11, 2017, warrants inclusion in the final report. Include the benefits to public safety, water modeling, etc.
8) Consider also including any suggestions about how to improve upon the TexMesonet website, such as how to deal with the different latency issues amongst the wide-range of datasets. Also include any decision-making tools for end-users that would help to establish support from various stakeholders.

Specific comments:

1) Page 4, paragraph 2, sentence 3: Missing a "to" between "located" and "avoid".
2) Page 4, paragraph 3: Data from the ET networks are useful in providing irrigation recommendations for the average homeowner as well as irrigation scheduling for agricultural production. Consider mentioning this additional end-user benefit.
3) Page 5, paragraph 1, sentence 2: in the phrase "that sector alone," you might want to be explicit and say the agricultural sector if that is what you mean.
4) Page 5: Consider adding the main takeaways to the Executive Summary. For example:
    a. What are the range of costs for each weather station?
    b. How many staff members and what experience are needed to operate a statewide network?
    c. How might the TexMesonet best function (centralized, clearinghouse, or partnership model)?
5) Page 5: Consider adding the key considerations, findings, and components of a successful network, for example:
    a. Stable funding via diverse revenue streams,
    b. Broad support from a wide variety of end users,
    c. Dedicated source of funds for ongoing maintenance,
    d. QA/QC protocols and metadata standards, and
    e. Role / importance of partnerships in successful networks at the local, state, and national level.
6) Page 6, paragraph 2, sentence 5: Correct "determining" to "determined".
7) Page 6, paragraph 3, sentence 1: Please clarify if you are discussing the installation and maintenance when you refer to "the economics of "; benefits should be singular.
8) Page 6, paragraph 3, sentence 3: It seems like the list of tasks "have" costs rather than "are costs" that accrue…
9) Page 7, paragraph 2, sentence 2: Correct "other" to "others".
10) Page 7, paragraph 3, sentence 2: TexMesonet collects wind speed "and direction".
11) Page 7, paragraph 3, sentence 2: There should be a semicolon after soil moisture.
12) Page 7, paragraph 3, sentence 3: This should be "is one program manager, and two full-time staff working…"
13) Page 11, paragraph 1, sentence 4: Correct "develop" to "developed".
14) Page 11, paragraph 3, sentence 2: There is an extra "by" in this sentence.
15) Page 11, paragraph 4, sentence 4: Should be "adopted" instead of "adapted".

16) Page 12, paragraph 1, last sentence: Correct “well-maintain” to “well-maintained”.
17) Page 12, paragraph 3, sentence 1: Campbell Scientific is misspelled.
18) Page 12, Table 4-1: Add table headings such as Components and Cost as well as an additional row at the bottom for the total cost per station.
19) Page 12, paragraph 4, sentence 3: Change “typical” to “typically”.
20) Page 12, paragraph 5, sentence 1: CIMIS should be spelled out for the first appearance.
21) Page 12, paragraph 5, last sentence: Correct “coats” to “costs”.
22) Page 13, item number 2: Correct “gold” to “golf”.
23) Page 13, item number 4: Please further explain what aspect you are referring to when you say “computers” such as “to control watering schedules”. Please also correct “advance” to “advanced”.
24) Page 13, paragraph 2: Please verify the water savings mentioned in the Region A Water Plan. Consider changing “has generally saved” to “could save” [if an ET network was funded and all producers in the region adopted irrigation scheduling based on the data from such a system]. Please also correct “ares” to “acres”.
25) Page 14, paragraph 1, sentence 2: Correction “projection” to “protection”.
26) Page 15, paragraph 1, sentence 3: Change “complied” to “compiled”.
27) Page 15, paragraph 2, sentence 5: This sentence should not include a colon after networks as it is currently written.
28) Page 15, paragraph 2: The text here indicates that two of the networks included in the survey were state funded, yet Table 5-3 only shows one network as being state funded.
29) Page 15, Table 5-1: Please include the appropriate info for the Oklahoma Mesonet in this table. The acronym for the South Dakota network also doesn’t seem to match with the network name provided in this table.
30) Page 16, Table 5-3: Please explain how the “Ease of Use (1-3)” and “Good Model?” factors were evaluated; also, consider changing “ETC” to “ETc” (should be “ET_c”, really).
31) Page 17, Table 5-4: Consider moving several [most] of the “Landscape/Horticulture” crops shown in the Oklahoma network to the “Agricultural Crops” column.
32) Page 17, paragraph 1: Change “High Plains PET Network” to “High Plains ET Network”.
33) Page 17, paragraph 1, sentence 3: Remove the word “one” from this sentence or revise, as appropriate.
34) Page 18, paragraph 2, last sentence: Correct “station” to “stations”.
35) Page 19, item 5: Include the word “information” after supplemental.
36) Page 20, Table 6-1: Include “or contact” after the word “Interviewee” in the last column.
37) Page 21, paragraph 1: There is an extra “th” in the second sentence; “sub-network” is introduced without including a clear definition. “Loose” network is not clearly

defined and does not seem helpful or necessary to explain the size of a network as written.

38) Page 22, Table 6.2: This table needs consistency in format. For example, some are hyperlinks, others are not.
39) Page 24, Table 6-3: Consider changing the “purpose” heading to “primary mission,” considering several of these networks fulfill multiple purposes. Explain who operates CIMIS (California Department of Water Resources and UC-Davis, correct?).
40) Page 24, last two sentences: Remove this section about the Oklahoma Mesonet being omitted from the surveyed networks. This network is included in the study according to Table 6-3. (It is paramount that the Oklahoma Mesonet be included in all appropriate sections throughout the report.)
41) Page 25, paragraph 2, sentence 3: Please finish the sentence; it looks incomplete.
42) Page 26, paragraph two, last sentence: Add further details about how FEMA might fund the mesonet, if possible.
43) Page 27, paragraph 1: Consider changing “mesonet operators” to “network operators” for the three ET networks.
44) Page 27, paragraph 2: Add “proposed guidelines” in the appendix if feasible or provide a web link.
45) Page 32, paragraph 1, second sentence: Remove the word “is”.
46) Page 32, paragraph 2, last sentence: Remove the word “for” and/or revise as appropriate.
47) Page 33, table 6-6: Resize the first column so that the other columns (state abbreviations and ranges) fit on one line, if possible.
48) Page 33, paragraph 3, first sentence: Add “networks” after “Ten”.
49) Page 33, paragraph 5, sentence 1: Change “archived” to “archive”.
50) Page 33, paragraph 3: Consider expanding upon or clarifying why one of the surveyed network operators was “frustrated with the requirements MADIS imposes on data availability, formatting, and certification”.
51) Page 34, Table 6-7: Consider seeking clarification on which networks are confirmed members of the National Mesonet Program, if possible.
52) Page 34, paragraph 2, sentence 2: Correct the spelling of “minue” to “minute”.
53) Page 35, paragraphs 1 and 2: The number of networks does not match the number of acronyms listed in the three parentheticals in both paragraphs. Also, the “USA” network is undefined and not mentioned anywhere else in the report.
54) Page 35, Table 6-8: The first column is not formatted properly. Please also consider including the Oklahoma Mesonet in this table.
55) Page 36, paragraph 4, sentence 3: Revise “commenting” to “commented”.
56) Page 36, paragraph 5, sentence 3: Remove the word “has”.
57) Page 37, last paragraph: Is this statement true? “North Dakota has a wider variety of crops than anywhere in the US (outside of Florida and California).” Verify, if possible.
58) Page 38, Section 6.6.2 states that Mr. Foster formed an “advisory board”, but does not clearly explain its impacts on the Kentucky Mesonet. Please elaborate on the

make-up, role, and function of the advisory board. Explain how the Kentucky Mesonet benefits from having an advisory board.

59) Page 39, paragraph 3: Statement is missing a second "is" in the first sentence: "A reason the KYM stresses data quality is it is difficult…".
60) Page 40, paragraph 3, sentences 1 and 2: Sentence 1 ends abruptly and sentence 2 starts abruptly; this looks like it should be one sentence.
61) Page 40, paragraph 4, last sentence: U.S. BOR is called simply "Reclamation" in section 6.6.3, make sure you use the same acronym in all references.
62) Page 41, paragraph 5, last sentence: Correct "as" to "and".
63) Page 42, end of sentence at the top of the page: Sentence is incomplete.
64) Page 42, paragraph 4, sentence 3: Insert the word "in" after the word "interested".
65) Page 42, last paragraph: Correct "operation" either to "operating" or "the operations of".
66) Page 43, paragraph 2, sentence 2: Change "the occurred" to "that occurred".
67) Page 44, paragraph 1, sentence 2: Remove "is a high quality", or revise as appropriate.
68) Page 44, paragraph 2, sentence 1: Correct "less" to "lesson" and consider ending the sentence/starting a new sentence after the word "metadata", or revise as appropriate.
69) Page 46, paragraph 4, last sentence: There should be a reference to what specific type of private industry is being described. It does not seem possible that only 400 people are employed in private industry in Switzerland.
70) Page 47, paragraph 2, sentence 1: Take out "aquifer" between "recharge" and "models".
71) Page 47, paragraph 3, last sentence: Add an "s" to "soil moisture sensors".
72) Page 47, paragraph 4, sentence 3: Change "central their" to "their central".
73) Page 47, paragraph 5: Consider revising/removing the word "AgriLife" from the name of the "TAMU Spatial Sciences Laboratory" (if appropriate).
74) Page 48, paragraph from previous page: Jayton is a town in Kent County. Why it is included in the list of counties is unclear. It is not clear what is meant by "Edwards Aquifer Associations"; please clarify. "Penman-Monteith" is also misspelled in the last sentence.
75) Page 48, first full paragraph, sentence 1: If appropriate, revise end of sentence to "including automated evaporation pans." Sentence 3: Add an "a" before "network" and the word "and" before "measures". Sentence 4: Add "the" before "Trinity River". Sentence 6: add "The" before "Texas Alliance for Water Conservation".
76) Page 48, paragraph 2, sentence 1: Change "heavy" to "heavily".
77) Page 49, paragraph 3, sentence 1: Nationwide does not need to be hyphenated.
78) Page 49, paragraph 4, sentence 1: Remove the word "in" from "climate data in at 200…"
79) Page 51, paragraph 2, last sentence: Add "a" to "critical component of [a] successful network".

80) Page 51, paragraph 3: Add "to" to the sentence "…will be needed [to] maintain the database". Please also change the word "program" to "programmer" in the next sentence.
81) Page 51: Consider adding a section explaining the field technician needs of a statewide network.
82) Page 52, paragraph 3, first sentence: Remove the "s" from "weather stations". Last sentence: should be "concrete" instead of "cement".
83) Page 52, paragraph 4, sentence 4: Spell out "approximately".
84) Page 53, paragraph 2, sentence 2: Remove "that" from "…extrapolated that to the total…" Sentence 4: remove "the" from "…TxSON use the a more expensive…"
85) Page 54, first line: the sentence about the Photodiode sensors appears to be incomplete. Please correct.
86) Page 54, last sentence: States "Tipping bucket gauges tend to be less expensive but are not WMO certified" without citation. Please add citation.
87) Page 55, first full paragraph, sentence 7: Correct "manufacture" to "manufacturer's specifications".
88) Page 56, Table 8-6: There is a blank row that seems extraneous.
89) Page 56, paragraph 1, sentence 2: There is no dollar amount listed after CR6, please include a dollar amount if available.
90) Page 56, Table 8-7: Consider adding the Oklahoma Mesonet to the table.
91) Page 57, paragraph 2, sentence 10: Correct "oftern" to "often".
92) Page 63, paragraph 3, sentence 1: Add an "and" between "Mesonet" and "the" in the parentheses.
93) Page 65, last paragraph, sentence 1: Change from "per year" to "per acre, per year".
94) Page 66: Consider including a discussion on the water savings potential for landscape water use programs, with examples from existing partners in the Water My Yard program, if available. Any known results/benefits reported by those partners regarding how the program has helped to promote municipal water conservation would also be beneficial, especially considering municipal water use represents the second largest demand sector in the state (and is projected to surpass irrigation as the largest demand sector in the coming decades).
95) Page 68. Add any other acronyms used in the report to this list (e.g. NDAWN, CIMIS, HPRCC, KYM, OTT, CWOP, NCCS).