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**The Oklahoma Mesonet:
A Multi-Purpose Network for Water Resources Monitoring and Management**

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Abstract

The Oklahoma Mesonet, a statewide automated network of more than 110 environmental monitoring stations, has proven to be very useful to the state's water management functions at both the wet and dry ends of the hydrological spectrum. Now in its 14th year of operation, this highly successful network is operated jointly by Oklahoma State University and the University of Oklahoma. Mesonet data are used for real-time decisions on short time scales by flood forecasters at the National Weather Service, for reservoir management decisions by the U.S Army Corps of Engineers, and for flood response by the state's emergency management community. During dry periods, information provided by the Mesonet is an important part of the state's assessment of water resources. Officials at the Oklahoma Water Resources Board track the Mesonet's array of real-time drought monitoring products and advise key decision-makers on drought status by region. National assessments by the authors of the U.S. Drought Monitor are also informed by the Oklahoma Mesonet's suite of climate-scale products.

Overview of the Oklahoma Mesonet

The University of Oklahoma (OU) and Oklahoma State University (OSU) operate more than 110 surface observing stations comprising the Oklahoma Mesonet (McPherson et al 2007; Brock et al. 1995; Elliott et al. 1994). Remote stations send data every 5 minutes to an operations center, located at the Oklahoma Climatological Survey (OCS), for data quality assurance, product generation, and dissemination. The Oklahoma Mesonet (<http://www.mesonet.org>) was established as a multi-purpose network to provide research-quality data in real time. The mission of its personnel is to operate a world-class environmental monitoring network, to deliver high-quality observations and timely value-added products to Oklahoma citizens, to support state decision makers, to enhance public safety and education, and to stimulate advances in resource management, agriculture, industry, and research. Since 1994, the Oklahoma Mesonet has collected 3.5 billion weather and soil observations and produced millions of decision-making products for its customers.

Scientists and engineers at OSU and OU planted the seeds of the Oklahoma Mesonet during the early to mid-1980s and joined forces in 1987, beginning the partnership to design, implement, maintain, and fund the Oklahoma Mesonet. In late 1990, with the endorsement of Oklahoma's governor, the U.S. Department of Energy (USDOE) awarded \$2.0 million in oil-overcharge funds to support the design and implementation of the network. OSU and OU provided an additional \$0.7 million. The first operational stations were installed in December 1991, and the last of the original 107 stations was installed in July 1993. After testing and troubleshooting, network-wide data collection and dissemination began on January 1, 1994. Core operations of the Oklahoma Mesonet are supported primarily by legislative funding through the Oklahoma State Regents for Higher Education.

An Oklahoma Mesonet station occupies a 100-m² plot of land and comprises a datalogger, solar panel, radio transceiver, lightning rod, and environmental sensors located on or surrounding a 10-m tower. Remote stations measure more than 20 environmental variables. In terms of hydrologic variables, these measurements include rainfall at all sites and soil moisture at most

sites. Data are transmitted every five minutes by VHF radio link to the Mesonet operations center in Norman via the Oklahoma Law Enforcement Telecommunications System (OLETS).

Since inception, the Oklahoma Mesonet has used a 30.5-cm diameter MetOne tipping bucket rain gauge with a resolution of 0.25 mm. The gauge has been modified substantially by Mesonet staff. Station power constraints prohibit the use of any heating device that would allow for measurement of frozen precipitation. As a result, snow and ice are measured as liquid equivalent after melting occurs. In 1996, the Oklahoma Mesonet installed Campbell Scientific's 229-L soil moisture sensors at approximately half of its sites. Since then, additional sites have received soil moisture sensors, creating a real-time statewide network. The 229-L senses heat dissipation, which can be related directly to the soil-water potential. Volumetric water content of the soil is calculated via an empirical relationship that uses soil-water potential and the soil characteristics.

The primary focus of network operations and maintenance is to obtain research-quality observations in real-time. From the receipt of a sensor from a vendor to the dissemination of real-time and archived products, the Oklahoma Mesonet follows a systematic, rigorous, and continually maturing protocol to verify the quality of all measurements. Quality-assurance consists of (1) proper site selection and configuration to minimize network inhomogeneities; (2) calibration and comparison of instrumentation before and after deployment to the field; (3) three scheduled annual maintenance passes; (4) automated quality assurance procedures performed as data are collected (repeated several times throughout the day and through subsequent days); and (5) manual inspection of the data (Shafer et al. 2000).

During each of three, scheduled annual maintenance passes, Oklahoma Mesonet technicians perform standardized tasks, including cleaning and inspecting sensors, verifying depth of subsurface sensors, cutting and removing vegetation, taking photographs, and conducting on-site sensor calibrations (Fiebrich et al. 2006). In addition, technicians may upgrade equipment, rotate sensors, and perform communications testing and maintenance. Site visit forms and photo-documentation are posted on the Mesonet website to make it easy for anyone using the data to investigate a site's maintenance history.

The automated quality assurance software of the Oklahoma Mesonet is designed to detect significant errors in the real-time data stream and to incorporate manual QA flags that capture subtle errors in the archived dataset. Observations are never altered; each datum is flagged as 'good,' 'suspect,' 'warning,' or 'failure.' Only 'good' and 'suspect' data are delivered in real-time to users. For real-time data, up to eight QA tests are run per observation, operating on the past six hours of data. Once per day, up to 13 QA tests are run on each variable, operating on the past 30 days of data. As a result, more than 111 million calculations are completed daily. Currently, real-time QA completes within approximately one minute.

Human intervention can override any automated QA flag. The QA meteorologist determines whether automated flags mark real events by analyzing the results of a web-based, daily QA report. To detect subtle problems in the rainfall dataset, a meteorologist compares a station's accumulated rainfall to that of nearby sites using double mass analysis. To aid in the analysis, the QA meteorologist uses complementary data sets, including soil moisture observations, rain gauge data from the U.S. Geological Survey, NWS surface observations, radar data, and terrain

maps. For example, OCS software calculates storm-total rainfall from Oklahoma Mesonet data for the time interval corresponding to the NWS storm-total precipitation product. A resultant map is generated and the QA meteorologist compares the values to find any malfunctioning gauges.

Examination of monthly data supplements daily and event-driven manual QA to detect slight biases or drift in sensors. Monthly statistics for each variable (e.g., averages, differences, accumulations) are computed, plotted, and analyzed both spatially and temporally. Data from similar instruments at different heights or depths allow the diagnosis of sensor biases, small amplitude noise in the data, and anemometer starting-threshold problems. After analyses are complete, the meteorologist prepares a monthly QA report that documents any problems as well as repairs and activities performed by field technicians that may have affected data quality during the previous month.

River and Flood Forecasting

Located in Tulsa, Oklahoma, the Arkansas-Red Basin River Forecast Center (ABRFC) is one of thirteen River Forecast Centers in the National Weather Service (<http://www.srh.noaa.gov/abrfc>). The mission of the ABRFC is to “provide technical support to the National Weather Service's efforts to provide river and flood forecasts and warnings for protection of life and property and to provide basic hydrologic forecast information for the nation's economic and environmental well-being.” The ABRFC area of responsibility includes the drainage area of the Arkansas River above Pine Bluff, Arkansas, and the drainage area of the Red River above Fulton, Arkansas. This comprises over 208,000 square miles including all of Oklahoma and portions of six other states.

Primary operational duties at the ABRFC include hydrologic forecasting, hydrometeorologic analysis and support (HAS) functions, and the monitoring/quality control of associated data sets which are input/output to/from operational computer models. Other operational functions performed on a seasonal or as needed basis include production of water supply forecasts, flood outlooks and drought summaries.

At the ABRFC, extensive use is made of radar-based estimates of precipitation. Rain gauge data are invaluable in providing the “ground truth” for calibrating and verifying the radar estimates. For example, on an hourly time scale, ABRFC forecasters use Oklahoma Mesonet rainfall data to help calibrate gridded estimates of rainfall developed from radar data. The calibrated data are fed into a hydrologic model that is used to predict main stem river levels. Daily river forecasts are used mostly for economic reasons (e.g., barge traffic on the lower Arkansas River), or for recreational purposes (e.g., floating on the Illinois River). During flooding situations, forecasts of river and stream levels are provided much more frequently and at more locations.

Mesonet data are also used in real-time as reference measurement points for excessive rains that can trigger flash flood events. Since the Mesonet data are transmitted in very near real-time, and at five-minute intervals, the data are extremely valuable in determining if storms really are producing the rainfall amounts estimated by the radar. The Mesonet gauge data provide an immediate ground-truth capability.

At the ABRFC, the Oklahoma Mesonet is viewed as the best of several sources of rain gauge data (GOES, ALERT, etc.). This reputation has been earned primarily due to the Mesonet's outstanding system of quality assurance including gauge maintenance and calibration. On the rare occasions when a gauge appears to be malfunctioning, the data are quickly flagged as questionable or missing, and the gauge is usually repaired or replaced within a few days.

Other information from the Mesonet's suite of sensors proves useful to the meteorologists and hydrologists at the ABRFC. For example, high spatial and temporal temperature data help forecasters to define the freezing line for a heavy freezing rainfall event, which can have a significant impact on the amount of runoff generated by the event. Research work is currently being done to compare Mesonet soil moisture readings with model-calculated estimates. This may eventually lead to real-time "calibration" of hydrologic model states.

Finally, the Mesonet has been used by the Oklahoma Water Resources Board as a platform for real-time monitoring and reporting of stream levels. As part of a test deployment, five stream gauges have been installed on various streams in the state, with the Mesonet infrastructure being used to collect and disseminate the resulting data.

Emergency Management

Oklahoma Mesonet data are used in real-time by 192 public safety agencies in and around Oklahoma, through the OK-First program (Morris et al 2001). OK-First is the Oklahoma Mesonet's decision support system that provides data service and ongoing training to emergency management and public safety professionals. Decision support is categorized by hazard, such as severe thunderstorms and tornadoes, winter weather, or extreme temperatures. Public safety officials must plan for, and respond to, hazards related to both ends of the hydrologic spectrum: drought and flooding. Drought planning and response involves the use of daily Mesonet data such as is provided for the Oklahoma Water Resources Board (described later in this paper).

What makes OK-First successful is its combination of data, training, and decision-support. Representatives from each of the authorized jurisdictions are required to complete a training course where they learn the basics of meteorology and applications and limitations of radar data, and become familiar with the data and products provided by the Oklahoma Mesonet and other sources. Public safety officials gain increased confidence in their own abilities to make decisions affecting their local communities, including when to close bridges for potential high water, more effectively deploying storm spotters, and pre-positioning equipment in advance of a potentially hazardous event. This empowerment of local officials led Harvard University's John F. Kennedy School of Government to present the OK-First Program with an Innovations in American Government award in 2001.

For flood response, public safety officials have access to a combination of real-time Mesonet data and county-by-county flash-flood guidance (FFG) from the National Weather Service River Forecast Center. FFG provides the estimated rainfall necessary to cause localized flash flooding over a one-, three- or six-hour period. When any Mesonet station within the county exceeds 50% of the projected flood-causing rainfall, a map is highlighted indicating a rising threat of flash-

flooding. Colors elevate sequentially (yellow, orange, red) as observed values surpass 75% and 100%. An example is shown below.

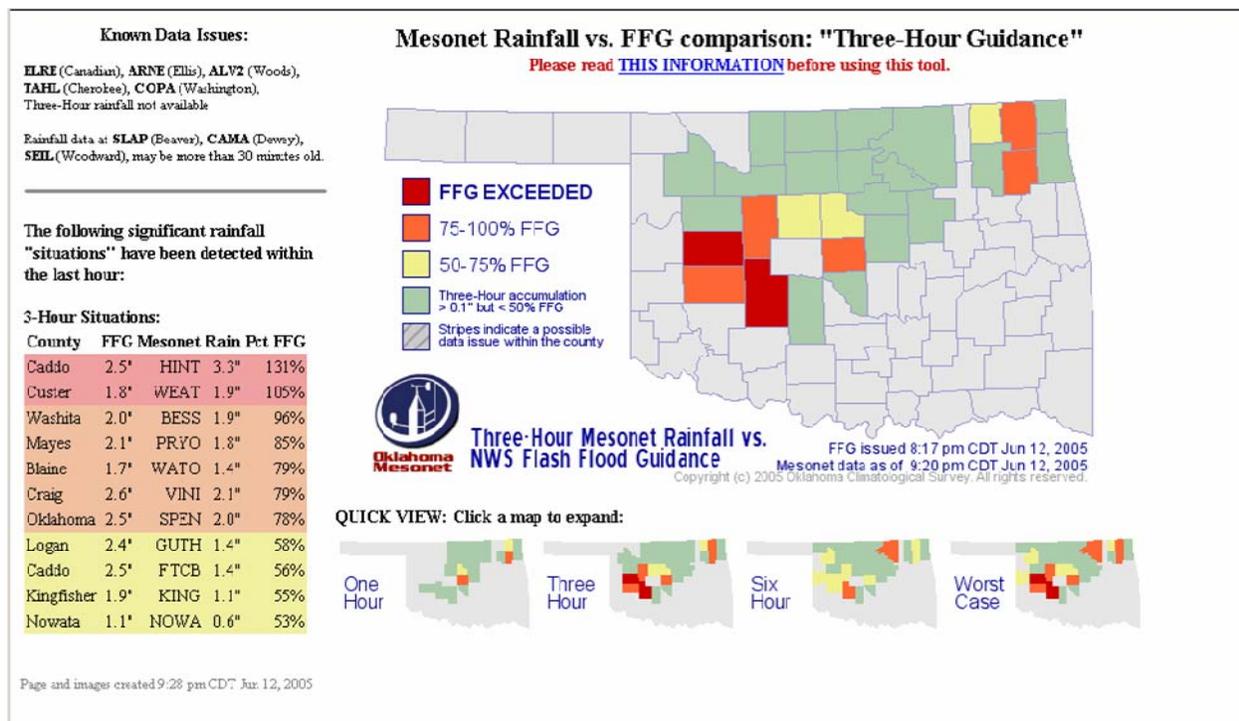


Figure 1. Example of an OK-First graphic integrating Oklahoma Mesonet rainfall information and flash flood guidance from the National Weather Service River Forecast Center.

Drought Monitoring

The Oklahoma Water Resources Board (OWRB) is the lead agency for monitoring the state's water resources (<http://www.owrb.ok.gov>). The OWRB has come to rely on an automated drought monitoring website (http://climate.ocs.ou.edu/rainfall_update.html) provided by the Oklahoma Mesonet. The Mesonet's drought monitoring information has been available to decision-makers since 1996 and was developed collaboratively through interaction with officials at the OWRB, other state agencies, and U.S. Drought Monitor authors. Online help is available for each element of the drought monitoring package, and Mesonet personnel provide additional support via telephone or face-to-face conversation.

The drought monitoring system incorporates real-time rainfall data from the Mesonet with historical surface observations to provide contextual information on current precipitation departures. This includes statewide maps of precipitation totals and departures; regional (climate division) tables showing relative rankings and a variety of drought indices, soil moisture readings at three levels, and related resources including the Oklahoma Fire Danger Model (<http://agweather.mesonet.org/models/fire/>).

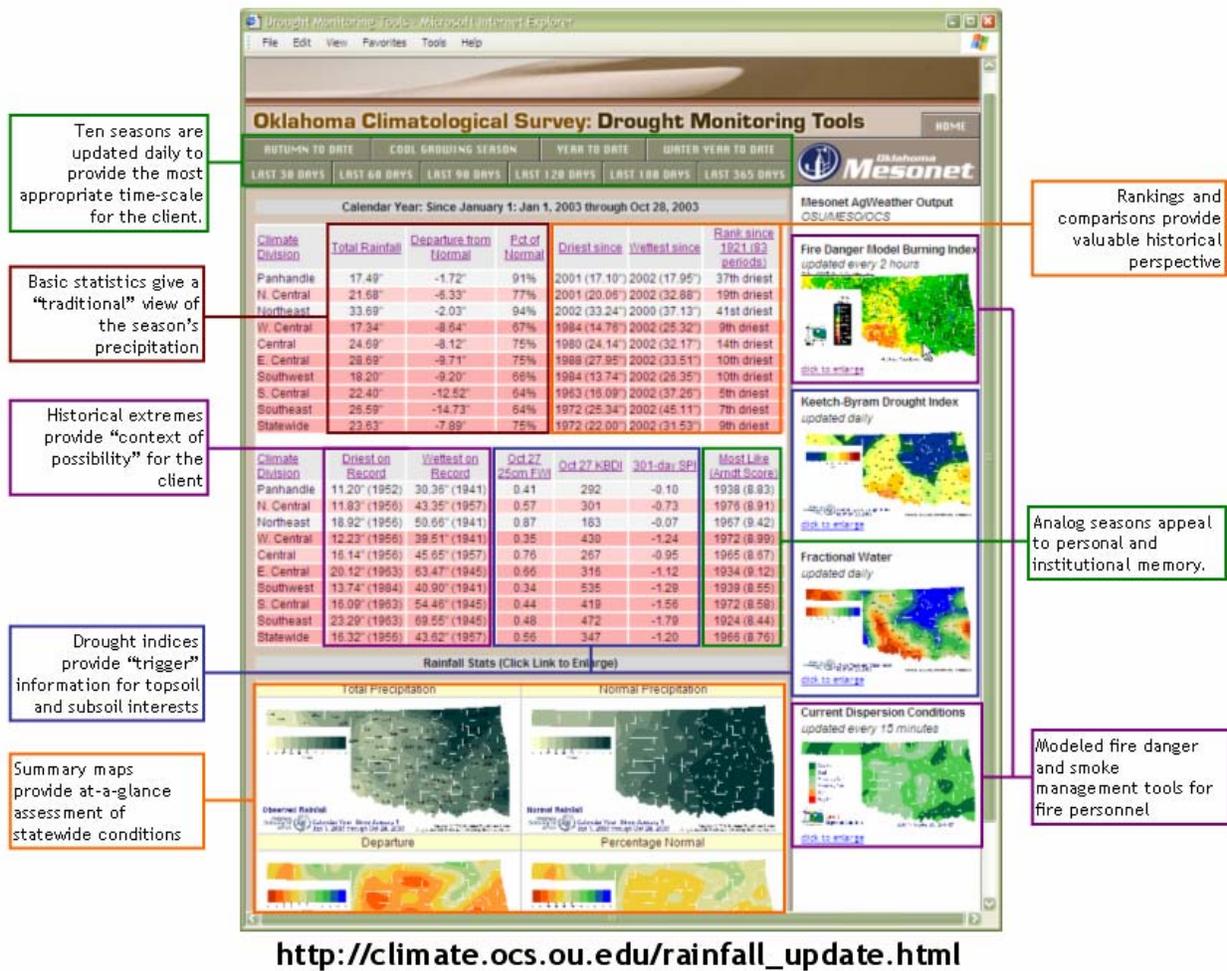


Figure 2. The Oklahoma drought monitoring website. Information is presented as regional tables of indices, maps of precipitation and departures, and specialized models.

Data from the Mesonet website are routinely included in the *Water Resources Bulletin*, which is published monthly by the OWRB (more frequently during drought conditions). The *Water Resources Bulletin* is the key vehicle for communicating drought conditions to the leadership of other state agencies, the Governor's office, and state legislators. Much of the content from the first few pages of the *Bulletin* comes from the Mesonet drought monitoring pages.

To improve drought monitoring efforts related to groundwater, the OWRB, in cooperation with the Oklahoma Mesonet and the USDA Agricultural Research Service (ARS), has conducted a pilot study for continuous monitoring of groundwater levels at several Oklahoma Mesonet stations. The wells are equipped with continuous water level recorders that provide real-time groundwater level data on the Internet. Such monitoring can provide insights on short-term variability and long-term trends in groundwater levels, and can help in determining the effects of climatic variability on groundwater resources. Water level measurements are collected in conjunction with other meteorological data (such as precipitation, temperature, soil moisture, and

soil temperature) that aid in the interpretation of water level changes and potential drought conditions.

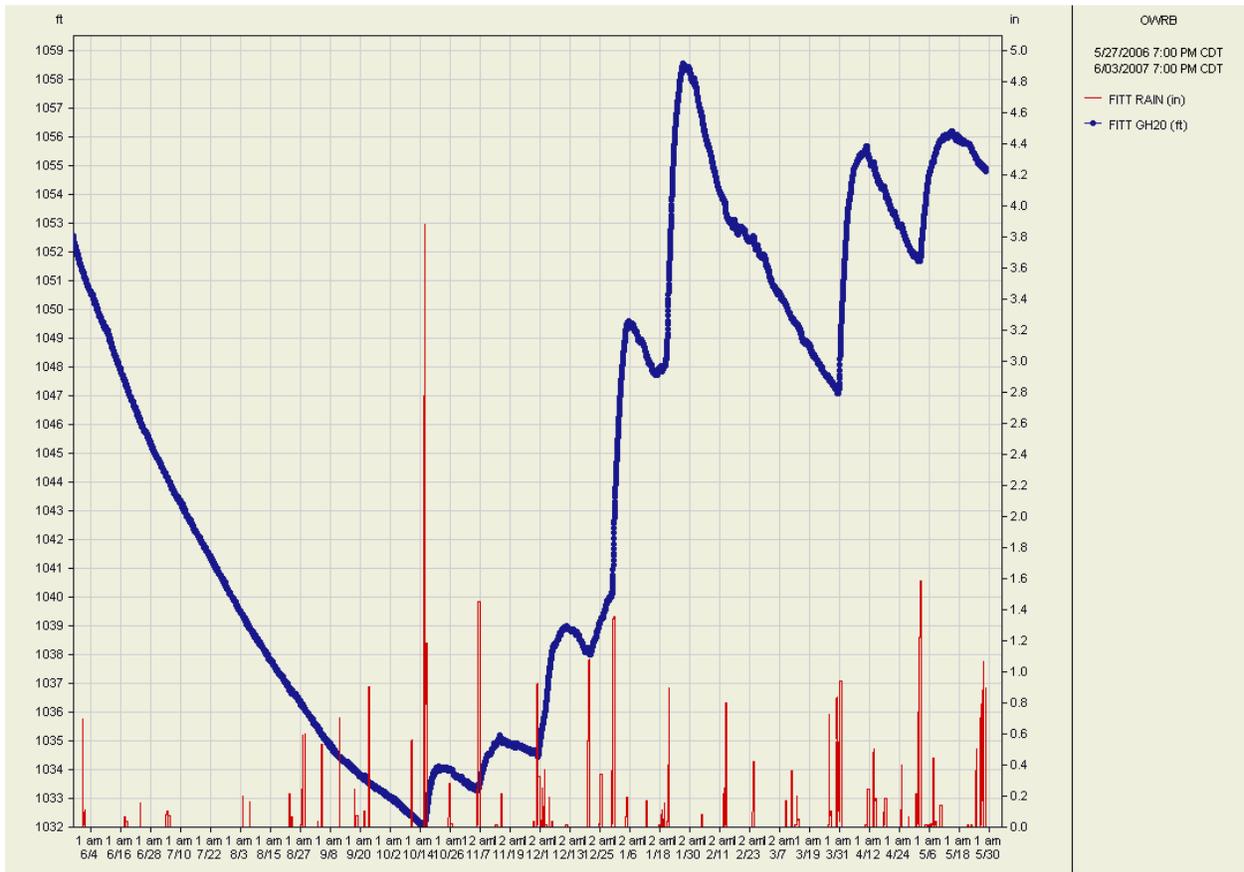


Figure 3. Water level elevations (feet) recorded at the groundwater well at the Fittstown, OK Mesonet site. Red bars indicate daily rainfall totals according to the scale on the right side of the diagram (inches). An extended drought lasting more than 18 months ended in Fall 2006, with subsequent recovery of groundwater levels over a 3-month period.

The Oklahoma Mesonet drought monitoring tools are used routinely by U.S. Drought Monitor authors during their assessments of Oklahoma conditions. The Mesonet tools provide an “always on” report of precipitation conditions and anomalies over ten periods of varying length. The authors consult these reports directly, or indirectly through “expert” testimony from state officials.

Hydrologic Investigations

The OWRB routinely uses climatic data in conducting hydrologic investigations of groundwater basins. For example, climatic data from the Oklahoma Mesonet are being applied to a variety of analyses for the Arbuckle-Simpson Hydrology Study. As part of this study, a new Mesonet station was commissioned in 2005, with an accompanying 78-m observation well. The well is

equipped with a pressure transducer and data logger, which record continuous water level measurements. Real-time daily water level measurements and hydrographs are available on the Mesonet website, along with the other meteorological data. These data provide researchers with information essential to understanding the aquifer and how it responds to variations in precipitation, evaporation, temperature, soil temperature, soil moisture, and wind speed. Barometric pressure data collected at the Mesonet station will be used in evaluating diurnal water-level fluctuations for earth tide effects. Earth tide effects can be used to calculate the specific storage and porosity of the aquifer.

Mesonet data are also being used by the OWRB in determining the water budget for the Arbuckle-Simpson aquifer. A distributed rainfall-runoff model is being developed to quantify the hydrologic water balance at gauged locations in terms of surface runoff, aquifer discharge, and other components such as evapotranspiration and precipitation. Mesonet precipitation data are being used to ground-truth radar rainfall data used in the model. To determine the water balance of specific watersheds, data were gathered for precipitation, recharge, runoff, and actual evapotranspiration. Results from the rainfall-runoff model will be coupled with a groundwater flow model to estimate recharge to the aquifer and to simulate base flow to streams. Researchers at Oklahoma State University, the University of Oklahoma, and the USDA-ARS Grazinglands Research Laboratory all have used the Mesonet as a key data source for various studies involving hydrologic and water quality modeling. The availability of a statewide, real-time, weather and soil monitoring network has also been a key factor in attracting a number of large, multidisciplinary, field research studies to Oklahoma. Several of these multidisciplinary campaigns have focused on remote sensing of soil moisture.

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An extensive Mesonet-related bibliography can be found online at:
<http://www.mesonet.org/bibliography>