Title: Estimating Groundwater Recharge Using the Oklahoma Mesonet

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Publications/Presentations:


Problem and Research Objectives:

Statement of critical regional or State water problem

Oklahoma water resource managers need accurate information on groundwater recharge rates to allow more effective water management and planning and to reduce groundwater related conflicts, but no functional recharge monitoring network exists in Oklahoma, or anywhere else to our knowledge. The statewide Oklahoma Mesonet provides a uniquely rich set of long-term data on hydro-meteorological variables which are relevant for recharge estimation, most notably soil moisture. When soil moisture, hydraulic conductivity, and hydraulic gradient are known, drainage from the soil profile can be calculated based on unsaturated flow theory (Nolan et al., 2007). Groundwater withdrawals that exceed the rate of drainage from the soil profile are not sustainable in the long term, unless the aquifer receives inflows from adjacent aquifers or surface water bodies. We have recently completed an intensive measurement campaign in which we estimated soil hydraulic conductivity functions for the stations of the Oklahoma Mesonet. These new data have enabled us, for the first time, to calculate drainage rates using Mesonet data. In our preliminary work for this proposal, we calculated Mesonet-based drainage rates for five sites in Oklahoma and discovered a remarkable level of agreement between the average annual drainage rates at those sites and previously published groundwater recharge estimates for the corresponding aquifers. This exciting discovery suggests that the Mesonet has real potential as a tool for estimating groundwater recharge across Oklahoma. However, we currently lack any
independent estimates of groundwater recharge directly co-located with Mesonet sites, so the site-specific level of agreement between recharge and Mesonet-based drainage rate is unknown. Also, we have no knowledge about the extent to which regional scale spatial variability in groundwater recharge is reflected in Mesonet-based drainage rates. There is a critical need for both site-specific and regional scale research to fill these two knowledge gaps.

**Nature, scope, and objectives of the project**

The long-term goal for this team of collaborators is to improve scientific understanding about and inform sustainable management of Oklahoma’s groundwater resources by creating powerful new tools for recharge estimation and mapping. The objective of this proposal is to clarify the relationship between Mesonet-based drainage rates and groundwater recharge rates in western Oklahoma. This is an essential next step in a logical progression of research that will lead us toward our long-term goal. The timing is right to pursue this research because it aligns with state priorities for improved groundwater monitoring. Specifically, this research will complement and be coordinated with the new groundwater monitoring and assessment program being developed by the Oklahoma Water Resources Board (OWRB). We have chosen to focus on western Oklahoma because groundwater is the predominant source of water in that region of the state, and several aquifers in western Oklahoma are expected to face major water supply challenges in the near future. Our team is well-qualified to lead this research because the proposed work builds directly on our recent improvements to Mesonet soil moisture monitoring. Furthermore, we have compiled preliminary data from five Mesonet sites, and those data demonstrate the feasibility of the proposed methods (Table 1). With strengths in soil physics, hydrogeology, and meteorology, and years of experience with Mesonet management and groundwater monitoring, our team has the expertise needed to ensure the project’s success. To accomplish our objective we propose two specific aims, to be completed over two years:

1. **Determine the site-specific level of agreement between Mesonet-based drainage rates and independent estimates of recharge in selected aquifers.** Our working hypothesis is that Mesonet-based drainage rates are not significantly different from independently determined groundwater recharge rates. Site-specific, independent recharge estimates will be obtained for three locations in the Rush Springs aquifer and four in the Ogallala aquifer. The unsaturated zone chloride mass balance method will be applied to core samples collected from these locations to determine recharge for comparison with drainage estimates from co-located Mesonet stations.

2. **Determine the regional level of agreement between Mesonet-based drainage rates and independent regional recharge estimates for western Oklahoma.** Drainage will be calculated for the decade from 2000-2009 for all Mesonet stations in western Oklahoma having the necessary soil moisture data. An average annual soil drainage rate map will be created for western Oklahoma and compared with a new regional recharge map based on chloride concentrations in groundwater sampled from existing OWRB monitoring wells.

**Methodology:**

Specific aim #1: Determine the site-specific level of agreement between Mesonet-based drainage rates and independent estimates of recharge in selected aquifers.
1.1 Introduction: Although Mesonet-based drainage rates demonstrate strong agreement with prior recharge estimates (Table 1), no co-located, site-specific recharge estimates currently exist with which to directly compare the Mesonet estimates. Therefore, in this specific aim our objectives are to produce such recharge estimates and determine how they relate to the Mesonet-based drainage estimates. Our working hypothesis is that Mesonet-based drainage rates are not significantly different from independently determined groundwater recharge rates. We will focus our efforts initially on two significant “at-risk” aquifers in Oklahoma, the Rush Springs aquifer in west-central Oklahoma and the Ogallala aquifer in north-west Oklahoma. The well-established unsaturated zone chloride mass balance method (McMahon et al., 2003; Scanlon et al., 2002; Wood and Sanford, 1995) will be applied to estimate recharge using core samples collected from locations within each aquifer near existing Mesonet stations. This work is an important next step toward supporting or refining our working hypothesis because these data will provide a more robust test of the Mesonet-based drainage rates than is possible using existing literature data. The outcome of this aim will be new knowledge about the relationship between Mesonet-based drainage rates and groundwater recharge, knowledge that is crucial for developing a statewide recharge estimation system using the Oklahoma Mesonet.

1.2 Research design: Drainage at the 60 cm depth will be calculated on a daily time step for the ~15-yr period of record for four Mesonet sites above the Ogallala aquifer (Boise City, Goodwell, Hooker, and Slapout) in the Oklahoma Panhandle and three Mesonet sites above the Rush Springs aquifer (Putnam, Hinton, and Ft. Cobb). We will follow previous studies (Keese et al., 2005; Nolan et al., 2007; Wang et al., 2009) in using hydraulic conductivity functions estimated by the Rosetta pedotransfer function (Schaap et al., 2001), but we will improve on these studies in two important ways. First, we will use daily measurements of soil moisture as the independent variable in the hydraulic conductivity functions rather than modeled soil moisture values or infrequent measurements of soil moisture as employed in prior studies. Soil moisture will be calculated from the output of the Mesonet’s Campbell Scientific 229-L heat dissipation sensors (Illston et al., 2008) using newly developed soil water retention curves which improve the accuracy of the resulting soil moisture values by >30% relative to the pre-existing curves (unpublished data). Drainage events can be highly episodic and the importance of having daily soil moisture measurements should not be underestimated. Second, we will use the H5 model within Rosetta which requires more input data (i.e., water retention at -33 and -1500 kPa) and is known to produce more accurate results than the H3 model within Rosetta (Schaap et al., 2001), the one used in previous recharge studies.

In preliminary work for this project we explored a variety of methods for estimating the hydraulic gradient at the 60 cm depth, including methods that used data from sensors at the 5 and 25 cm depths. We found that the most reasonable recharge estimates in all cases examined resulted from assuming a unit-gradient (i.e. gravity driven flow) at 60 cm. This unit-gradient assumption has been widely used in previous recharge estimation studies (Keese et al., 2005; Nolan et al., 2007; Wang et al., 2009), although not in connection with daily soil moisture measurements and not at such a relatively shallow depth. In summary, our drainage calculation methods have two significant advantages over prior studies and one disadvantage. The advantages are the use of daily soil moisture measurements from the Mesonet and the use of the most accurate sub-model within Rosetta. The disadvantage is that the 60 cm depth we will use is shallower than that used in most prior studies creating some potential for errors (e.g. violation of unit gradient assumption or plant water uptake below 60 cm). However, our preliminary data
(Table 1) provide exceptionally strong support for our methods, indicating that the advantages of our methods overcome this disadvantage.

The unsaturated zone chloride mass balance approach (uz-CMB) will be used to obtain site-specific recharge estimates at the seven Mesonet sites listed in the first paragraph of this section following the methods of Scanlon et al. (2010b). Core samples from the surface to a depth of ~15 m will be collected using a direct-push drill rig (e.g., Model 6620DT or similar, Geoprobe, Salina, KS) or by direct-rotary drilling (Shuter and Teasdale, 1989) at sites with consolidated subsurface materials impenetrable by the direct push system. Cores will be divided into ~0.5 m segments and sealed to prevent water loss during transport. In the laboratory the water content and bulk density of the segments will be determined, and the segments will be leached with double-deionized water and the extracts analyzed for chloride concentrations using flow injection analysis colorimetry by the mercuric thiocyanate method (e.g. Zalesny et al., 2008). Extract chloride concentrations will be converted to pore water concentrations, which will then be used in the uz-CMB calculations to estimate the site-specific recharge rate corresponding to each core following Scanlon et al. (2010b). Chloride concentrations in precipitation, required in the CMB method, will be obtained from the National Atmospheric Deposition Program (http://nadp.sws.uiuc.edu/). A paired t-test will be used within each aquifer to test our working hypothesis that Mesonet-based drainage rates are not significantly different from independently determined groundwater recharge rates. Linear regression of Mesonet-based drainage versus uz-CMB recharge estimates across all eight sites will also be performed to clarify the relationship between these two variables.

1.3 Expected outcomes: The research proposed under specific aim #1 is expected to result in new knowledge about site-specific recharge rates in two significant aquifers in Oklahoma, the Ogallala and the Rush Springs, which serve regions facing the prospects of serious water supply shortfalls. This research is also expected to provide the foundation for a Mesonet-based, statewide groundwater recharge estimation system by revealing new insights into the relationship between Mesonet drainage rates and site-specific groundwater recharge values.

1.4 Potential problems and alternative approaches: Sites which have undergone significant land cover or climate changes can have complex chloride profiles which do not conform with the steady-state assumption in the uz-CMB method. In the event that one of our sites displays such behavior we will apply the displacement velocity approach (Scanlon et al., 2010b). The velocity-based approach is well-established and proven to be effective for sites which have undergone significant changes in recharge rates. In the event that the results from this specific aim lead us to reject our working hypothesis, we will follow the statistical modeling approach of Kim and Jackson (2012), refining their existing stepwise regression model, which estimates recharge based on soil, climate, and vegetation parameters. An advantage with this method is that we can include the Mesonet drainage rates as an additional independent variable in the recharge estimation model, whereas Kim and Jackson were limited to only precipitation and potential ET data to represent the climatic control on recharge. Even without drainage rate information, they were able to explain 75% of the variance in recharge data around the world.

Specific aim #2: Determine the regional level of agreement between Mesonet-based drainage rates and independent regional recharge estimates for western Oklahoma.

2.1 Introduction: Water resource managers need not only site-specific recharge information but also an accurate understanding of regional recharge patterns in order to determine sustainable aquifer withdrawal rates. Therefore, in specific aim #2, our objective is to compare spatial
patterns of recharge determined by an independent method to the patterns in Mesonet-based drainage rates. Drainage will be calculated for the decade from 2000-2009 for all Mesonet stations in western Oklahoma having the necessary soil moisture data. An average annual soil drainage rate map will be created for western Oklahoma and compared with a new regional recharge map based on chloride concentrations in groundwater. This work is necessary because the site-specific comparisons described in specific aim #1 are not sufficient to determine if the Mesonet drainage rates can accurately represent spatial variability of recharge at the regional scale. The key outcomes of this specific aim will be 1) a first-glimpse of the Mesonet’s potential as a regional recharge estimation tool and 2) much needed new information about regional recharge rates across western Oklahoma.

2.2 Research design: Daily drainage will be calculated for 2000-2009 for the ~50 Mesonet stations in western Oklahoma which have 60 cm soil moisture data throughout that time period. Calculation procedures were described under specific aim #1. Annual drainage totals and average annual drainage rate for the decade will be calculated for each station. Ordinary kriging (Ahmadi and Sedghamiz, 2007) will be applied to create a drainage map for western Oklahoma using the station latitude and longitude coordinates together with the average annual drainage rates. In the second year of the project (pending additional funding), groundwater samples from existing OWRB monitoring wells in western Oklahoma will be collected in conjunction with the startup of the new OWRB groundwater monitoring and assessment program. These groundwater samples will be analyzed for chloride and sulfate as in the work of Scanlon et al. (2010b). Existing groundwater chloride and sulfate data for Oklahoma will also be obtained from the USGS National Water Information System database (waterdata.usgs.gov/nwis). While the unsaturated zone soil samples indicate site-specific recharge conditions, groundwater samples indicate recharge conditions for the local region up-gradient of the sampling site with spatial scales up to several kilometers (Scanlon et al., 2002). Therefore, the chloride concentrations in the groundwater samples will be used in the saturated zone CMB approach (sz-CMB) to estimate regional recharge rates across western Oklahoma. Ordinary kriging will be used to interpolate these estimates and create a regional recharge map for western Oklahoma similar to the one recently produced for the Texas Panhandle (Scanlon et al., 2010b). Spatial patterns in the Mesonet-based drainage map will be qualitatively compared with those in the sz-CMB recharge map, and the magnitudes of the mapped variables will be compared in order to determine the regional level of agreement between Mesonet-based drainage rates and independent regional recharge estimates for western Oklahoma.

2.3 Expected outcomes: The research proposed under specific aim 2 will result in important new knowledge about spatial patterns of groundwater recharge across western Oklahoma, a region heavily dependent on groundwater. The western Oklahoma recharge map produced here will be the first large-scale recharge map produced for Oklahoma in thirty years. This research will provide a key first indication of the Mesonet’s ability to represent spatial variability in groundwater recharge at the regional scale, thus this work is an important step toward an operational statewide groundwater recharge estimation system based on the Oklahoma Mesonet.

2.4 Potential problems and alternative approaches: The sz-CMB approach assumes that the chloride is not derived from underlying saline aquifers or from dissolution of chloride-bearing minerals (Wood and Sanford, 1995). In western Oklahoma, these processes likely affect the Blaine aquifer in far southwestern Oklahoma and northern portions of the Cimarron River aquifer near the Kansas border, both of which are known to have elevated chloride levels. Other localized cases of chloride contamination may be encountered due to oil and gas production
activities and other miscellaneous sources. To prevent erroneous recharge estimates, chloride to sulfate ratios will be used to identify any wells that are impacted by chloride contamination, whether from upward movement of saline water or other sources. Ratios of chloride to sulfate which are >1 accurately delineated regions impacted by saline water from deeper formations in the Texas Panhandle (Scanlon et al., 2010b), and a similar threshold is expected to apply for Oklahoma. In the event that the work in specific aim #1 leads us to reject the working hypothesis of that aim and adopt instead a statistical modeling approach, we will then use the Kim and Jackson model as refined under specific aim #1 (see section 1.4) to calculate recharge for the Mesonet sites across western Oklahoma, using the drainage rate as an input to the model. These modeled recharge values would then be mapped at the regional scale and compared with the regional recharge map produced from the sz-CMB approach.

**Principal Findings and Significance:**

Through two previous OWRRI projects (2010-2011) we created a comprehensive database of soil hydraulic properties at the Mesonet stations. Using year one funds from our 2013 proposal, we have merged these soil properties with daily soil moisture measurements and the Buckingham-Darcy equation for unsaturated flow to calculate drainage below 60 cm, which is the standard depth of the deepest Mesonet soil moisture sensors. *For the aquifers summarized thus far, median annual drainage at 60 cm demonstrates an exceptional level of agreement with previously published recharge rates (Table 1).* Furthermore, in a recent global review of groundwater recharge, the recharge rate under grasslands represented 8.3% of precipitation on average (Kim and Jackson, 2012). For all the Mesonet sites evaluated thus far, the median ratio of drainage at 60 cm to precipitation was 0.078, or 7.8%. The agreement between these two percentages provides further compelling evidence for our working hypothesis. For fractured near-surface aquifers like the Arbuckle-Simpson aquifer (Christenson et al., 2011) where transit times from the surface are expected to be relatively short, we expect that spikes in the Mesonet-based soil drainage rates will be reflected in seasonal changes in groundwater levels. Again, this expectation has been substantiated in our results to date, lending additional support to our approach.

**Table 1: Median annual precipitation and median annual drainage at 60 cm for the Mesonet sites above the Rush Springs and Ogallala aquifers from 1996 through 2012.** For comparison, prior published estimates of groundwater recharge for these aquifers are also shown.

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