Final Report – Ochsner et al. OWRRI Project FY2014

Title: Estimating Groundwater Recharge Using the Oklahoma Mesonet

Start Date: 03/01/14

Original End Date: 02/28/15 **No-Cost Extension Until:** 12/31/15

Congressional District: 3rd

Focus Category: GW, WQN, MET

Descriptors: groundwater, recharge, soil moisture

Students:

Student Status	Number	Disciplines
Undergraduate	1	Environmental Science
M.S.	1	Plant and Soil Sciences
Ph.D.		
Post Doc		
Total	2	

Principal Investigators:

Tyson Ochsner, Assoc. Prof., Plant and Soil Sciences, Oklahoma State University
Chris Fiebrich, Assoc. Director, Oklahoma Climatological Survey, University of Oklahoma
Chris Neel, Water Resources Geologist, Oklahoma Water Resources Board

Publications:

Wyatt, B.M., T.E. Ochsner, C.A. Fiebrich, C.R. Neel, and D.S.Wallace. *in review*. A simple method for estimating drainage through long-term soil moisture monitoring. Vadose Zone J.

"Drainage Mapping." soilmoisture.okstate.edu. Oklahoma State University Soil Physics Group, Accessed Feb. 25, 2016. http://soilmoisture.okstate.edu/

Presentations:

1. Ochsner, T.E., B.M. Sallee, C. Fiebrich and C. Neel. 2014. Estimating Groundwater Recharge Using the Oklahoma Mesonet. Oklahoma Water Research Symposium, Oklahoma City, Oklahoma. Oct. 22-23, 2014. Invited.
2. Sallee, B.M. and T.E. Ochsner. 2013. Estimating Groundwater Recharge Using the Oklahoma Mesonet. Oklahoma Water Resources Research Symposium, Midwest City, Oklahoma. Oct. 22-23, 2013.

3. Sallee, B.M. and T.E. Ochsner. 2014. Estimating Groundwater Recharge Using the Oklahoma Mesonet. 3rd Annual Student Water Conference, Stillwater, Oklahoma. Apr. 10-11, 2014.
4. Sallee, B.M., T.E. Ochsner, C. Fiebrich and C. Neel. 2014. Estimating Groundwater Recharge Using the Oklahoma Mesonet. Oklahoma Water Research Symposium, Oklahoma City, Oklahoma. Oct. 22-23, 2014.
5. Sallee, B.M., T.E. Ochsner, C. Fiebrich and C. Neel. 2014. Estimating Groundwater Recharge Using the Oklahoma Mesonet. ASA-CSSA-SSSA International Annual Meeting, Long Beach, California. November 2-5, 2014.
6. Wyatt, B.M., T.E. Ochsner, C. Fiebrich and C. Neel. 2015. Estimating groundwater recharge using the Oklahoma Mesonet. Soil Science Society of America Annual Meeting, Minneapolis, MN. Nov. 15-18, 2015.
7. Wyatt, B.M., T.E. Ochsner, C. Fiebrich and C. Neel. 2015. Estimating groundwater recharge using the Oklahoma Mesonet. Oklahoma Water Resources Advisory Board, Ada, OK.
8. Wyatt, B.M., T.E. Ochsner, C. Fiebrich and C. Neel. 2015. Estimating groundwater recharge using the Oklahoma Mesonet. Oklahoma Water Research Symposium, Norman, OK. Dec. 2-3, 2015.
9. Wyatt, B.M., T.E. Ochsner, C. Fiebrich and C. Neel. 2015. Estimating groundwater recharge using the Oklahoma Mesonet. The 2015 Workshop at Marena, Oklahoma, In Situ Sensor Testbed (MOISST), Stillwater, OK. Jun. 2-3, 2015.

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 suggested that the Mesonet had real potential as a tool for estimating groundwater recharge across Oklahoma. However, we lacked 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 had no knowledge about the extent to which regional scale spatial variability in groundwater recharge is reflected in Mesonet-based drainage rates. There was 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* was to clarify the relationship between Mesonet-based drainage rates and groundwater recharge rates in western Oklahoma. To accomplish our objective we proposed 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.** Site-specific, independent recharge estimates were obtained for selected locations in the Rush Springs aquifer and in the Ogallala aquifer. The unsaturated zone chloride mass balance method was 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 was calculated for the decade from 1998-2014 for all Mesonet stations in Oklahoma having the necessary soil moisture data. An average annual soil drainage rate map was created for Oklahoma and compared with a pre-existing recharge map based on the stream baseflow separation method.

Methodology:

Specific aim #1: Determine the site-specific level of agreement between Mesonet-based drainage rates and independent estimates of recharge in selected aquifers.

Research design: Drainage at the 60 cm depth was calculated on a daily time step for the ~15-yr period of record for Mesonet sites above the Ogallala aquifer and the Rush Springs aquifer. We followed 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 improved on these studies in two important ways. First, we used 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 was 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 (Scott et al., 2013). Drainage events can be highly episodic and the importance of having daily soil moisture measurements should not be underestimated. Second, we used 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.

The unsaturated zone chloride mass balance approach (uz-CMB) was used to obtain site-specific recharge estimates at the Arnett, Boise City, Freedom, Goodwell, Hooker, Slapout, and Woodward Mesonet sites in northwest Oklahoma and the Fort Cobb Mesonet site above the Rush Springs aquifer following the methods of Scanlon et al. (2010). Core samples were collected from the surface to maximum depths ranging from 1 to 8 m. Cores were 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 was determined, and the segments were 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 were converted to pore water concentrations, which were then be used in the uz-CMB calculations to estimate the site-specific recharge rate corresponding to each core following Scanlon et al. (2010). Chloride concentrations in precipitation, required in the CMB method, will be obtained from the National Atmospheric Deposition Program (http://nadp.sws.uiuc.edu/).

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

2.1 Research design: Daily drainage was calculated for 1998-2014 for all Mesonet stations in Oklahoma which have 60 cm soil moisture data. Calculation procedures were described under specific aim #1. Annual drainage totals and average annual drainage rate were calculated for each station. Ordinary kriging (Ahmadi and Sedghamiz, 2007) was applied to create a drainage map for Oklahoma using the station latitude and longitude coordinates together with the average annual drainage rates. Groundwater samples from existing OWRB monitoring wells in western Oklahoma were collected in conjunction with the startup of the new OWRB groundwater monitoring and assessment program. These groundwater samples were analyzed for chloride and sulfate as in the work of Scanlon et al. (2010). 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 were used in the saturated zone CMB approach (sz-CMB) to estimate regional recharge rates for aquifers in western Oklahoma. Spatial patterns in the Mesonet-based drainage map were also qualitatively compared with those in a pre-existing statewide recharge map (Pettyjohn et al., 1983), and the magnitudes of the mapped variables were compared in order to determine the regional level of agreement between Mesonet-based drainage rates and independent regional recharge estimates for western Oklahoma.

Principal Findings and Significance:

Mean annual soil moisture-based drainage rates across the state ranged from 6 mm yr^{-1} at Boise City, OK to 266 mm yr^{-1} at Bristow for the period from 1998-2014 (Figure 1). A similar range of recharge values has been found by prior studies in Oklahoma, with reported recharge rates ranging from 0.8 to 333 mm yr^{-1}. The state-wide median value of the mean annual soil moisture-based drainage rate for the years 1998-2014 was found to be 67 mm yr^{-1} (2.6 in yr^{-1}), which is approximately 7.7% of the median state-wide rainfall of 870 mm yr^{-1} for the same period. A similar percentage was found by Kim and Jackson (2012), who observed that an average of 8% of rainfall became recharge under grassland systems in their global analysis. Soil moisture-based drainage rates generally followed the precipitation gradient of the state, as expected, decreasing from east to west (Figure 1).

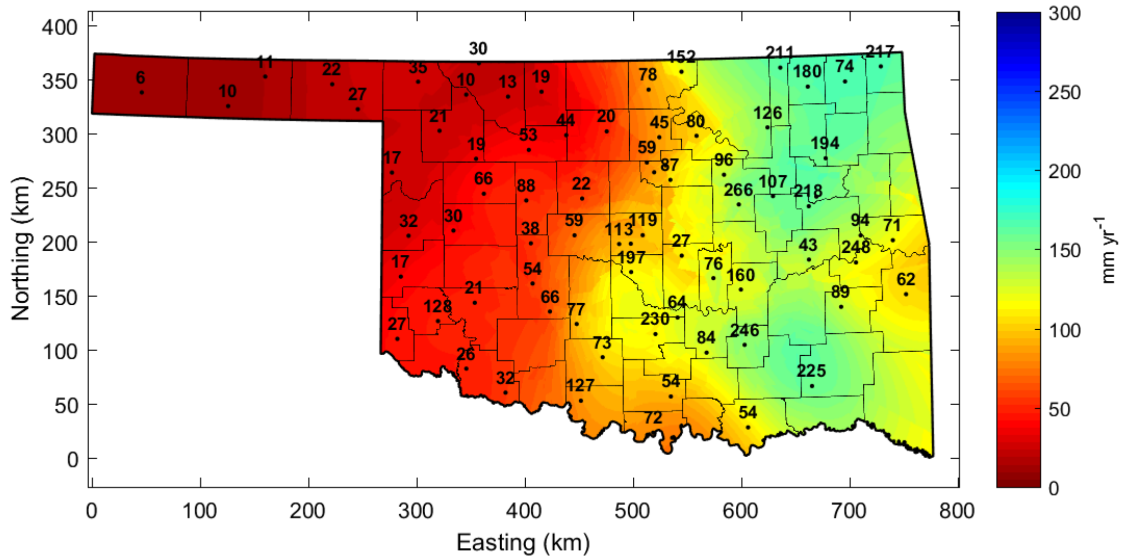

Figure 1. Statewide mean annual soil moisture-based drainage rates for the years 1998-2014 in mm per year. Drainage rate labels for the Stillwater, Oklahoma City East, Porter, and Marena sites were excluded for clarity, but were 214, 82, 166, and 66 mm yr^{-1}, respectively.

The most recent prior state-wide recharge rate map for Oklahoma (Fig. 2), published by Pettyjohn et al. (1983), corresponds fairly well with the map of soil moisture-based drainage rates. Although Pettyjohn et al. (1983) used the baseflow separation method and data from the 1970's, the maps are similar in several ways, including the trend that drainage and recharge rates decrease from east to west. Additionally, the maximum soil moisture-based drainage rate (266 mm yr^{-1}) and maximum Pettyjohn et al. (1983) recharge rate (254 mm yr^{-1}) are comparable. However, there are also some differences between the two maps. For instance, our calculated drainage rates in the Oklahoma Panhandle range from 6 to 27 mm yr^{-1} and are higher than the recharge rate of 2.5 mm yr^{-1} or less estimated for this region by Pettyjohn et al (1983). This difference is reasonable, given that the baseflow method used by Pettyjohn et al. (1983) underestimates recharge when there are upstream water losses due to groundwater evapotranspiration in riparian areas or groundwater pumping, both of which likely influence streamflow in the semi-arid, groundwater-irrigated Panhandle region (Scanlon et al., 2002). Also, there is a difference in the location of the maximum estimated drainage and recharge rates between the two studies. Pettyjohn et al. (1983) estimated that the greatest rates of groundwater recharge occur in the southeast portion of the state, near the Oklahoma-Arkansas border (Figure 3), while the maximum soil moisture-based drainage rates occurred in two areas: one in the northeast and one in the southeast (Figure 2). This may be caused, in part, by a relative lack of soil moisture sensors at the 60-cm depth in the far southeastern part of the state due to shallow bedrock, which leads to a lack of drainage rate estimates in that region.

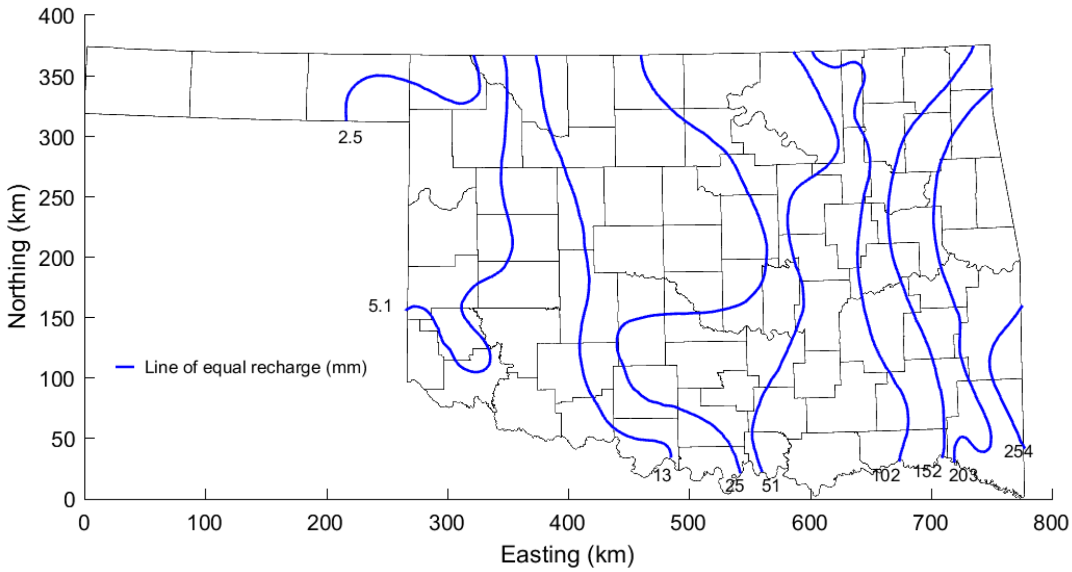

Figure 2. Previously published state-wide recharge map made using the stream baseflow method of recharge estimation. Adapted from original publication by Pettyjohn et al. (1983).

Soil moisture-based drainage estimates summarized by aquifer compare well with previous recharge estimates for major Oklahoma aquifers (Table 1). These drainage values were found by computing the median value of the mean annual drainage rate for aquifers with a minimum of three Mesonet sites above them, resulting in aquifer-scale drainage rate estimates for six Oklahoma aquifers. All aquifer-scale median soil moisture-based drainage rates fall within the range of previous recharge estimates, with the exception of the Arkansas River alluvial aquifer, which has only one prior recharge estimate. Though only one other study has estimated recharge for the Arkansas River alluvial aquifer, the soil moisture-based drainage estimate is within 30% of the estimated recharge rate found by that study. These results provide evidence that drainage estimates from a large-scale soil moisture monitoring network can be indicative of potential recharge rates at the spatial scales of an individual aquifer and an entire state.

Table 1. Summary of soil moisture-based drainage rates by aquifer. Aquifer name, number of Mesonet sites located above the aquifer, median value of the mean annual soil moisture-based drainage rate, a range of previous recharge estimates, and the number of publications contributing to that range.

Aquifer	Sites	Drainage	Recharge	Sources
		mm yr^{-1}	mm yr^{-1}	
Boone	3	74	2.3-267	4
Arkansas River	5	165	127	1
Garber-Wellington	3	113	0.8-211	4
Rush Springs	5	66	5.1-89	4
Antlers	4	63	7.6-76	3
Ogallala	8	19	1.5-56	4

Measured mean chloride concentrations found by CMB_{uz} analysis of soil cores taken at the eight focus sites ranged from 39 mg L^{-1} at the Goodwell site to 1529 mg L^{-1} at the Freedom site (Table 2). These chloride concentrations led to estimated recharge rates ranging from 0.12 mm yr^{-1} at Boise City to 2.5 mm yr^{-1} at the Arnett site. CMB_{uz} analysis of soil cores taken at the eight focus sites gave a median recharge rate of 0.3 mm yr^{-1}, a significantly lower value than the 19 mm yr^{-1} median estimate made from Mesonet soil moisture data. The reasons for this discrepancy between Mesonet drainage rates and CMB_{uz} recharge values are not clear. One possibility is that the unit-gradient assumption made in our analysis of Mesonet drainage rates does not reflect actual conditions at these sites. Another possibility is that chloride inputs not reflected in the NADP data could have affected chloride concentrations in the soil, leading to an underestimation of recharge from the CMB_{uz} analyses. A third possibility is that significant root water uptake may occur beneath the 60 cm depth such that the Mesonet-based drainage rates overestimate recharge.

Table 2. Site name, mean annual precipitation, mean chloride concentrations in precipitation, depth-weighted mean chloride concentration beneath the root zone from soil cores, and CMB_{uz} recharge estimates for the eight Mesonet focus sites.

Mesonet Site	**Precipitation**	**Cl_P**	**Chloride**	**Recharge**
	mm yr^{-1}	mg L^{-1}	mg L^{-1}	mm yr^{-1}
Arnett	561	0.19	81	2.5
Boise City	386	0.1	624	0.12
Fort Cobb	712	0.19	961	0.27
Freedom	655	0.19	1529	0.16
Goodwell	410	0.1	39	2.0
Hooker	436	0.1	687	0.13
Slapout	530	0.1	516/76	0.20/1.4
Woodward	630	0.19	127	1.8

Analysis of groundwater data from the OWRB's GMAP program by the CMB_{sz} method yielded aquifer-scale recharge rates for five Oklahoma reservoirs (Table 3). A total of 54 groundwater samples from the GMAP program had chloride concentrations below the detection limit of 10 mg L^{-1}, while 19 samples had sulfate concentrations beneath this limit. These samples were assumed to have chloride and sulfate concentrations of 5 mg L^{-1}, which would also create an upper limit on recharge rates. For the Ogallala aquifer, this assumed concentration results in the highest recharge rate possible being 18.9 mm yr^{-1}. The removal of samples with a $Cl:SO_4$ ratio greater than one led to the exclusion of 32 of the 155 groundwater samples taken. Recharge rates from this analysis ranged from 4.8 mm yr^{-1} for the Canadian River alluvial aquifer to 25.4 mm yr^{-1} for both the Elk City and Gerty Sand aquifers. Because groundwater samples are representative of a large area and not specific to a certain location, recharge estimates found by the CMB_{sz} method are only comparable to Mesonet-based drainage rates summarized by aquifer (Table 3). The only aquifers that were tested under the GMAP program which also have an adequate number of Mesonet sites located above them to produce a reliable aquifer- scale median drainage rate are the Ogallala and Rush Springs aquifers. Aquifer-scale median Mesonet estimates of drainage and recharge estimated by CMB_{sz} show a high level agreement for the Ogallala aquifer, with rates of 21 and 17.8 mm yr^{-1}, respectively. However, the median Mesonet-based drainage rate and CMB_{sz} -estimated recharge rate for the Rush Springs aquifer vary by an order of magnitude, with rates of 74 mm yr^{-1} and 7.6 mm yr^{-1}, respectively. The cause of this discrepancy between the CMB_{sz} and Mesonet-based estimates for the Rush Springs aquifer is unclear. One reason could be that groundwater samples used in the CMB_{sz} calculations reflect chloride concentrations over only one year of sampling, while drainage estimates calculated using Mesonet data are given as the median of mean drainage rates for sites above the aquifer for the years 1996-2012. Recharge estimates from this analysis of groundwater chloride seem to be intermediate between the Mesonet-based drainage rates, which are slightly higher, and the CMB_{uz} recharge rates, which are much lower.

Table 3. Mean annual precipitation, number of samples, mean groundwater chloride concentrations, and recharge estimates calculated by the CMB_{sz} method for select Oklahoma aquifers sampled in the 2013 portion of the GMAP program.

Aquifer	Precipitation	No. Samples	GW chloride	Recharge
	mm yr^{-1}		ppm	mm yr^{-1}
Gerty Sand	894	5	11	25.4
Canadian River	770	34	52	4.8
Rush Springs	714	64	31	7.6
Elk City	683	13	9	25.4
Ogallala NW	587	39	11	17.8

We have written and submitted a manuscript describing these results for peer-reviewed publication in Vadose Zone Journal, a high quality journal in hydrologic sciences. That manuscript is designed to disseminate the result of the project to the international scientific community. We have also created a new web portal to deliver annual drainage maps to the public and end users such as the Oklahoma Water Resource Board. These annual and long-term mean drainage maps are at http://soilmoisture.okstate.edu/. Thus, this project has leveraged the existing Mesonet infrastructure to provide a continual flow of valuable new information relevant for understanding and managing groundwater resources in Oklahoma. Furthermore, the methods developed and demonstrated in this project can be applied to a number of other large-scale soil moisture monitoring networks around the world. Doing so is likely to produce new information about potential groundwater recharge rates that will be valuable for advancing hydrologic understanding with the ultimate goal of improving management of groundwater resources, resources that are increasingly critical for societies worldwide.

References:

Ahmadi, S. and A. Sedghamiz. 2007. Geostatistical Analysis of Spatial and Temporal Variations of Groundwater Level. Environ. Monit. Assess. 129: 277-294. doi:10.1007/s10661-006-9361-z.

Illston, B.G., J.B. Basara, D.K. Fisher, R. Elliot, C.A. Fiebrich, K.C. Crawford, K. Humes and E. Hunt. 2008. Mesoscale monitoring of soil moisture across a statewide network. J. Atmos. Ocean. Tech. 25: 167-182. doi:10.1175/2007JTECHA993.1.

Keese, K.E., B.R. Scanlon and R.C. Reedy. 2005. Assessing controls on diffuse groundwater recharge using unsaturated flow modeling. Water Resour. Res. 41: W06010. doi:10.1029/2004wr003841.

Kim, J.H. and R.B. Jackson. 2012. A Global Analysis of Groundwater Recharge for Vegetation, Climate, and Soils. Vadose Zone J. 11. doi:10.2136/vzj2011.0021RA.

Nolan, B.T., R.W. Healy, P.E. Taber, K. Perkins, K.J. Hitt and D.M. Wolock. 2007. Factors influencing ground-water recharge in the eastern United States. J. Hydrol. 332: 187-205. doi:10.1016/j.jhydrol.2006.06.029.

Pettyjohn, W.A., H. White and S. Dunn. 1983. Water Atlas of OklahomaUniversity Center for Water Research, Oklahoma State University, Stillwater, OK.

Scanlon, B., R. Healy and P. Cook. 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol. J. 10: 18-39. doi:10.1007/s10040-001-0176-2.

Scanlon, B.R., R.C. Reedy, J.B. Gates and P.H. Gowda. 2010. Impact of agroecosystems on groundwater resources in the Central High Plains, USA. Agr. Ecosyst. Environ. 139: 700-713.

Schaap, M.G., F.J. Leij and M.T. van Genuchten. 2001. ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. J. Hydrol. 251: 163-176.

Scott, B.L., T.E. Ochsner, B.G. Illston, C.A. Fiebrich, J.B. Basara and A.J. Sutherland. 2013. New Soil Property Database Improves Oklahoma Mesonet Soil Moisture Estimates. J. Atmos. Ocean. Tech. 30: 2585-2595. doi:10.1175/JTECH-D-13-00084.1.

Wang, T., V.A. Zlotnik, J. Simunek and M.G. Schaap. 2009. Using pedotransfer functions in vadose zone models for estimating groundwater recharge in semiarid regions. Water Resour. Res. 45: W04412. doi:10.1029/2008wr006903.

Zalesny, J.A., R.S. Zalesny Jr, A.H. Wiese, B. Sexton and R.B. Hall. 2008. Sodium and chloride accumulation in leaf, woody, and root tissue of Populus after irrigation with landfill leachate. Environ. Pollut. 155: 72-80. doi:10.1016/j.envpol.2007.10.032.