J1.2 ANALYSIS AND VERIFICATION OF SOIL MOISTURE MEASUREMENTS FROM THE OKLAHOMA MESONET

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1. INTRODUCTION

The need for accurate and robust measurements of soil water content has grown as numerical weather models have increasingly incorporated soil moisture variables into simulations of land-atmosphere interactions. To meet this need, measurements of soil moisture have been collected since 1996 by the Oklahoma Mesonet (McPherson et al. 2007). Currently, automated soil moisture sensors are installed at over 100 of the Mesonet sites at depths of 5, 25, and 60 cm. From the output of the sensors, observations of variables such as soil matric potential (MP), fractional water index (FWI; Fig. 1), and volumetric water content (WC) are calculated.

During the summer of 2007, soil cores were manually extracted from over 20 Mesonet locations at various intervals. Each sampled location was chosen specifically for its soil texture classification. The soil cores were divided into 5 cm increments from the surface to a depth of 30 cm, and 10 cm increments from 30 to 60 cm. From these cores, the volumetric water content of the cores was determined and compared to the values reported by the automated sensors at the Mesonet sites. A similar dataset collected during the 2003 Soil Moisture Experiment (SMEX) was also included in the analysis.

The goal of this project was to determine the correlations between the WC calculated from Mesonet observations and the manually obtained WC. Once fully determined, these correlations will be used to find a more practical and accurate method for automated calculation of WC across the Mesonet.

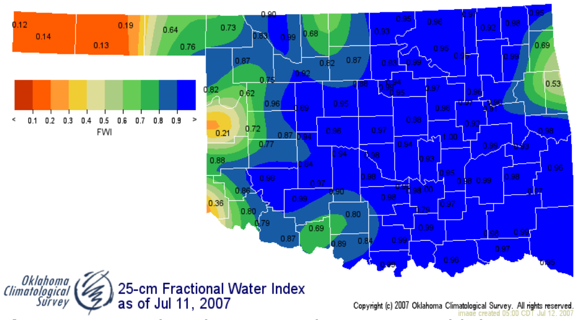

Figure 1. Fractional Water Index across Oklahoma on July 11, 2007 at a depth of 25 cm. The blue areas indicate extremely wet soil.

2. DATA AND METHODS

To obtain a data set of manually determined WC, Mesonet employees visited numerous Mesonet locations multiple times to extract soil cores. Using an auger, soil cores were taken from each side of a Mesonet site for redundancy (Fig. 2). Each Mesonet site has four sides oriented North, East, South, and West. The first core removed on each side spanned a depth of 30 cm and was cut into 5 cm sections (0-5 cm, 5-10 cm, etc . . .). The second spanned a depth of 60 cm and was cut into 10 cm sections (30-40 cm, 40-50 cm, 50-60 cm). Each section of each core was placed into a small metal can and sealed with electrical tape to ensure a minimum loss of water from the sample during transport and processing back at the OCS laboratory. There were 9 cans used for each side of the Mesonet site, 6 for the first core to 30 cm, and 3 for the second core to 60 cm. Thus, 36 cans were collected during each visit to a Mesonet site.

Figure 2. A Mesonet researcher obtains a soil core on the East side of the ACME Mesonet site.

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In the laboratory, the cans were unsealed and placed on an electronic mass balance to find the total mass of the sample. With the lids removed, the cans were then placed inside an industrial oven for a period of no less then 72 continuous hours at a constant temperature of 120 °C. This insured that all water within the cores was fully evaporated before the cans were removed from the oven. Once cooled and with the lids replaced, the cans were measured again on the mass balance. The change in mass due to baking the cores was the mass of water in the sample. The mass of each can without a soil sample was also found on the mass balance.

Over 1600 soil cores were collected during May, June, July, and early August of 2007 for inclusion in the analysis. Surveys to more than 22 Mesonet locations across Oklahoma ensured that 8 different soil textures were included in the analysis.

The incorporation of soil core data collected during the 2003 SMEX greatly enhanced the scope of the project by adding 1300 more cores taken from over 30 Mesonet sites. The cores from 2003 also better reflected overall drier conditions across Oklahoma.

3. ANALYSIS

a. Field Samples

Two separate techniques were employed to determine WC for this project. The first technique calculated WC from the soil core data using several simple relationships and conversion factors. The Mesonet calculated WC from the automated sensor's observations using the equation for matric potential and another equation employing site and depth-specific coefficients based on the percentage of clay, silt, and loam found in the soil (Illston et al. 2008).

WC from the manually acquired data was calculated as follows:

$$WC = \frac{g_{water}}{g_{soil}} \cdot \frac{1cm^3_{water}}{1g_{water}} \cdot \frac{g_{soil}}{cm^3_{soil}} \qquad (1)$$

The first term of the equation had already been determined by direct measurement in the laboratory. The inverse density of water is the second term of the equation. The third term of the equation is the density of the soil sample itself. Unfortunately, the third term introduced error into the calculation of WC from the soil cores. Unfortunately, not every soil core yielded the exact shape of a cylinder. Human error, holes in the ground from animals or other causes, and soil compaction all contributed to a lack of cylindrical shape for some of the soil cores. In an effort to reduce this error, the third term of the equation was designated the mean bulk density, where all the masses of all the cores at a particular site and depth were averaged and divided by the ideal volume of the soil sample. The ideal volume was found using the formula for the volume of a cylinder, the radius of the auger, and the height of the core (either 5 cm or 10 cm). Thus, via equation (1), the g_{water} terms in the equation cancel, as do the g_{soil} terms, leaving cm^3_{water}/cm^3_{soil}. This is the volumetric water content of the soil sample.

b. Automated Measurements

The soil moisture sensors installed at Oklahoma Mesonet sites do not directly measure WC. Rather, they measure the ΔT_{ref} value which is a variable that determines the temperature change in a porous ceramic matrix after the matrix has been heated for a specific period of time (Illston et al. 2008). A large ΔT_{ref} indicates a lack of moisture in the soil around the sensor, whereas a small ΔT_{ref} points to the presence of a large amount of moisture in the soil. The theoretical minimum and maximum values of ΔT_{ref} are 1.38 °C and 3.98 °C, respectively.

The Mesonet then calculates the soil matric potential of the soil using the ΔT_{ref} measurement. Soil matric potential is defined as the capillary force needed to retain water in the soil (Dingman 1994). It has units of kilopascals. MP is found with the following equation:

$$MP = -c \cdot \exp(a \cdot \Delta T_{ref}) \qquad (2)$$

where *c* is a calibration constant equal to 0.717 kPa and *a* is a calibration constant equal to 1.788 $°C^{-1}$ (Illston et al. 2008).

With MP calculated, the Mesonet uses an additional equation to compute WC. Each of the four coefficients in the following equation is site and depth specific. Thus, hundreds of different relationships exist for calculating WC by the Oklahoma Mesonet. The form of the equation is:

$$WC = WC_r + \frac{WC_s - WC_r}{\left(1 + \left(\alpha \cdot \frac{-MP}{100}\right)^n\right)^{\left(1-\frac{1}{n}\right)}} \qquad (3)$$

where WC_r is the residual water content of a soil sample (cm^3_{water}/cm^3_{soil}), WC_s is the saturated water content of a soil sample (cm^3_{water}/cm^3_{soil}), α is an empirical constant (kPa^{-1}), n is an empirical constant (unitless), and MP is the matric potential of the soil sample found by (2; Arya and Paris 1981). A WC value of 0.0 cm^3_{water}/cm^3_{soil} would indicate a completely dry soil sample, whereas a WC value of 0.5 cm^3_{water}/cm^3_{soil} would refer to a saturated soil sample.

4. RESULTS

With all data gathered and analysis completed, correlations were drawn between the WC found by the manual method and the method the Mesonet uses to calculate WC.

Ideally, a perfect correlation between the manual and automated WC should exist (Fig.3), with an R-squared correlation coefficient of 1. However, for most of the soil types the correlations were not this strong. The loam soil type was fairly representative of most of the other soil types in the correlation between automated WC and manual WC (Fig. 4). WC values range from 0.0 to 0.5 on both axes, and an R-squared value of 0.6115 indicates a moderate degree of correlation. In the lower left portion of the graph automated WC was consistently higher than manual WC; conversely, in the upper right portion of the graph automated WC was less than the reported manual WC. This problem was also seen in the sandy clay loam soil type (Fig. 5). Automated WC was higher than manual WC for dry soil samples and lower than manual WC for wet samples. With an R-squared correlation of 0.4756, the sandy clay loam WC had a lesser degree of association than the loam soil. This problem was most clearly demonstrated with the loamy sand soil type (Fig. 6). With a correlation coefficient of only 0.1016, the automated WC and manual WC had very little relationship to each other.

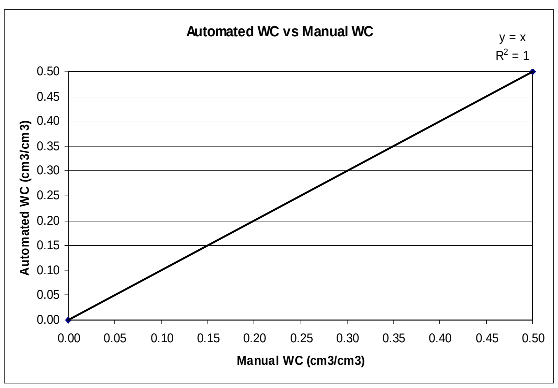

Figure 3. The ideal correlation between the Mesonet WC and the manually determined WC.

The relationships between all automated WC and manual WC for every soil type were not particularly well linked (Fig. 7). The R-squared value of 0.4621 indicates only a limited degree of correlation between the two sampling techniques. The automated WC generally had values 0.05-0.15 cm^3/cm^3 higher than manually reported WC for dry soil samples. The opposite was true for wet soil samples.

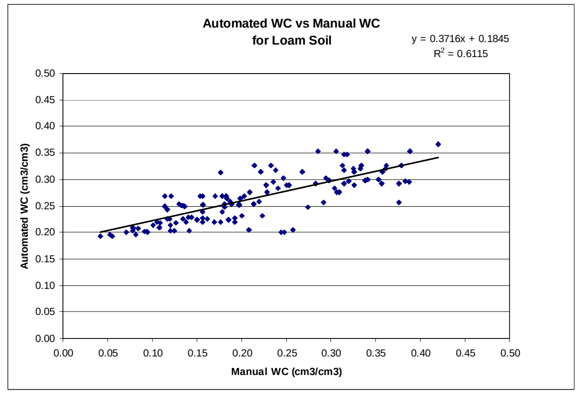

Figure 4. Correlation between automated WC and manual WC for loam soil.

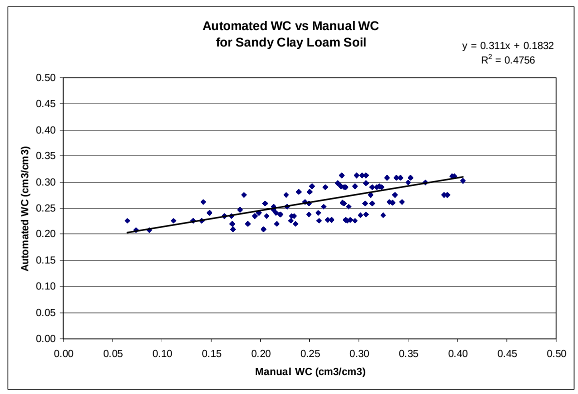

Figure 5. Another comparison of WC, this time for sandy clay loam soil.

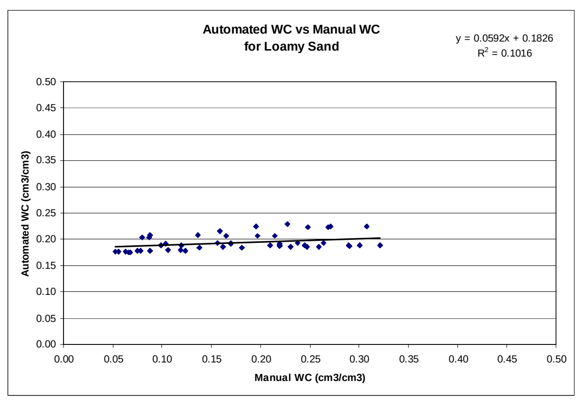

Figure 6. The correlation between automated WC and manual WC is practically nonexistent for the loamy sand soil type.

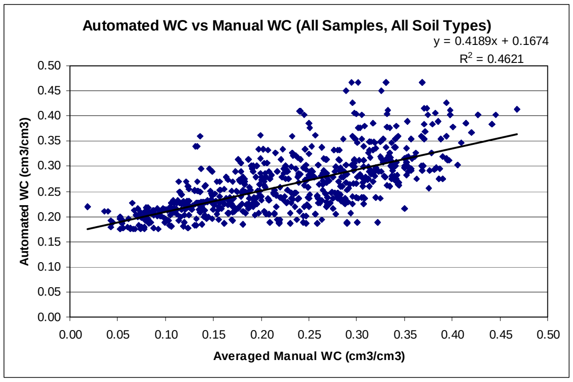

Figure 7. A plot of every manual value of WC matched against corresponding WC values calculated by the Mesonet.

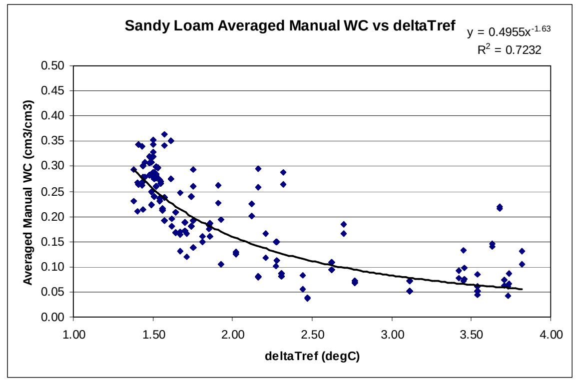

Figure 8. The relationship between the manual samples of WC and ΔT_{ref} observed at Mesonet sites for sandy loam soils.

One of the goals of this project was to improve the accuracy of automated WC calculations of the Oklahoma Mesonet. To this end, volumetric water content retention curves were found for each soil type. Initial results concerning these curves look promising, especially for sandy loam (Fig. 8). On the y-axis manual WC is plotted and on the x-axis ΔT_{ref} is plotted. The result is a plot of the relationship between manually obtained WC and the ΔT_{ref} measurement found by the Mesonet. This curve has a fairly strong correlation with $R^2 = 0.7232$.

This curve, along with the other WC retention curves for the remaining soil types, may eventually replace the current method of calculating WC for the Mesonet. The current method for calculating water content, as described in the previous section, is somewhat complicated and site and depth specific. Furthermore, several of the terms used in the calculation of WC by the Mesonet are subject to change during extremely wet conditions and extended droughts. By using only one water retention curve per soil type rather than hundreds, the calculation of WC would be simplified and much less labor intensive. However, additional modification and analysis of these retention curves is necessary before such a change could occur.

5. SUMMARY AND CONCLUSIONS

During the summers of 2003 and 2007 soil cores were manually extracted from numerous Mesonet sites to determine the correlations between the automated calculation of volumetric water content by the Oklahoma Mesonet and the water content found from the manual extraction of the soil cores. Analysis found that the correlations were limited for most of the soil types. The calculated values of WC by the Mesonet was usually higher than the manual WC values for dry samples and considerably lower than the manual WC for extremely wet soil samples.

Additionally, the comparison between the observed values of ΔT_{ref} and the manual soil samples revealed overall direct relationships based solely on soil type. Such retention curves could be used to improve the accuracy and ease of the automated calculation of WC for all soil types of the Oklahoma Mesonet in the future.

6. ACKOWLEDGEMENTS

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7. REFERENCES

Arya, L.M., and J.F Paris, 1981: A physicoempirical model to predict the soil moisture characteristic from particle-size distribution and bulk density data, *Soil Sci. Soc. Am. J.*, **45**, 1023-1030.

Dingman, S.L., 1994: *Physical Hydrology*. Prentice Hall, Upper Saddle River, NJ. 575 pp.

Illston, B.G., J.B. Basara, D.K. Fisher, R.L. Elliot, C.A. Fiebrich, K.C. Crawford, K. Humes, and E. Hunt, 2008: Mesoscale monitoring of soil moisture across a statewide network, *J. Atmos. Oceanic Technology*, In press.

McPherson, R.A., C.A. Fiebrich, K.C. Crawford, R.L. Elliott, J.R. Kilby, D.L. Grimsley, J.E. Martinez, J.B. Basara, B.G. Illston, D.A. Morris, K.A. Kloesel, S.J. Stadler, A.D. Melvin, A.J. Sutherland, H. Shrivastava, J.D. Carlson, J.M. Wolfinbarger, J.P. Bostic, and D.B. Demko, 2007: Statewide monitoring of the mesoscale environment: A technical update on the Oklahoma Mesonet, *J. Atmos. Oceanic Technology*, **24**, 301-321.