8.4 A SOIL MOISTURE ANALYSIS OF DROUGHT CONDITIONS USING THE OKLAHOMA MESONET

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1. INTRODUCTION

The droughts of the summer of 1998 and fall of 2000 brought elevated temperatures and reduced rainfall over parts of Texas and Oklahoma. During these periods, the maximum temperature in many locations exceeded 100ºF for extended periods of time, and nearly the entire state of Oklahoma received less precipitation than average. The droughts had severe impacts on both states in a variety of areas. Over 100 deaths were attributed to the heat in 1998, as well as significant economic loss to crops and livestock (Basara et al. 1998).

While researchers have analyzed surface characteristics (air temperature, rainfall, etc.) of the droughts, limited analyses of subterranean characteristics, such as soil moisture, have been conducted to determine their impacts from the drought. This is due, in part, to a limited number of soil moisture observations (Emmanuel et al. 1995). A clearer understanding of the hydrological drought at all soil levels, as well as the recovery times of soil moisture following the end of the meteorological drought, remains a crucial topic for the modeling of land-atmosphere interactions (Entekhabi et al. 1999).

The most dramatic drought conditions in both droughts were located in southwest Oklahoma and parts of Texas. As a result, analyses of the soil moisture trends at different depths were conducted for locations in southwest Oklahoma using data collected by the Oklahoma Mesonet.

2. INSTRUMENTATION

The Oklahoma Mesonet (Brock et al. 1995) provides real-time data from 114 stations across Oklahoma with at least one station in every county. Data are recorded every 5 minutes and include meteorological variables such as air temperature, wind speed and direction and rainfall.

In 1996, Campbell Scientific 229-L (CSI 229-L) soil moisture sensors were installed at 60 Mesonet sites at depths of 5, 25, 60 and 75 cm. These sensors measure a temperature difference (DeltaT), which is a change in the sensor temperature after a heat pulse is introduced (Basara and Crawford 2000).

3. CALCULATED QUANTITIES

From the measured DeltaT values, hydrological variables such as soil water content, soil matric potential, and Fractional Water Index (FWI) can be calculated. Unfortunately, soil water content depends heavily upon soil texture and soil matric potential is exponentially related to soil wetness. Since FWI has no impedance from these factors, it is an ideal variable for analyzing soil drought conditions.

The Fractional Water Index is a normalized version of the 229-L sensor response (Schneider et al. 2001). This unitless value ranges from very dry soil having a value of 0, to soil at field capacity illustrated by a value of 1. It is given by the formula:

$$FWI = \frac{\Delta T_d - \Delta T_{ref}}{\Delta T_d - \Delta T_w} \qquad (1)$$

where, ΔT_{ref} represents the sensor response (ºC), ΔT_d represents the response when the sensor is dry (ºC) and ΔT_w represents the response when the sensor is wet (ºC). (Schneider et al. 2001).

4. CLIMATOLOGIES AND DEVIATIONS

Because of limited continuous observations of soil moisture, climatological averages of soil moisture values have rarely been calculated. These averages would benefit the meteorological, climatological and agricultural communities.

4.1 Climatologies

Data from the soil moisture sensors installed at the Oklahoma Mesonet have allowed monthly, seasonal and yearly averages of soil water content, soil matric potential and FWI to be calculated.

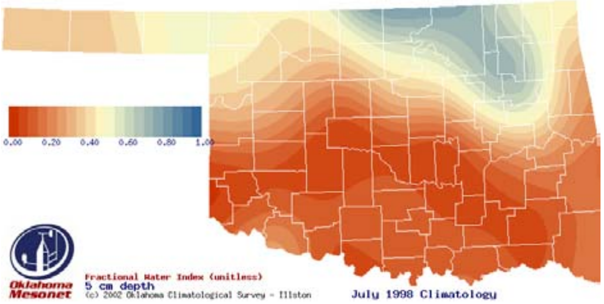

Figure 1 - 5 cm Fractional Water Index for July of 1998

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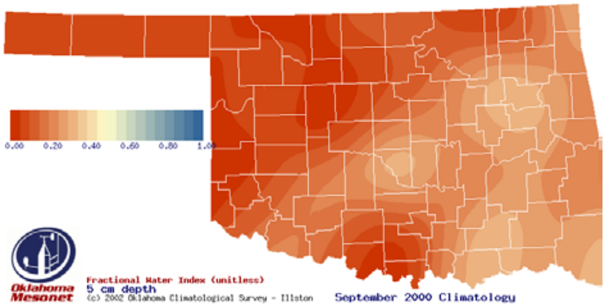

Figure 2 - 5 cm Fractional Water Index for September of 2000.

Figures 1 and 2 display the FWI at 5 cm for July of 1998 and September of 2000. These months correspond to the peak intensity of the droughts for their respective years. The western part of Oklahoma typically has lower FWI values due to both the warmer and drier climate and reduced vegetation.

4.2 Deviations

Once yearly mean values were determined, deviations from the mean were calculated to determine the severity of the drought conditions in Oklahoma. FWI is on a linear scale, so linear deviations were calculated.

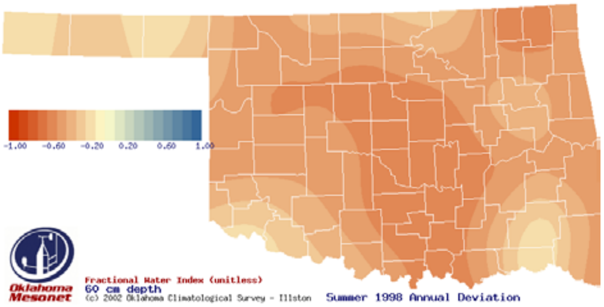

Figure 3 - 60 cm Fractional Water Index Summer 1998 Annual Deviation

While it is understandable that the summer is typically drier than the yearly average, the magnitude and spatial variability of the dry deviations are useful. Currently rainfall (or lack thereof) data is our best guess for this information.

Figures 3 and 4 show the summer deviations of FWI at 5 and 60 cm for 1998. During the drought of 1998, the central portion of Oklahoma deviated further (towards the drier end of the spectrum) than did other regions. The 60 cm depth, which corresponds closely to root zone depth, deviated further than the near surface (5 cm).

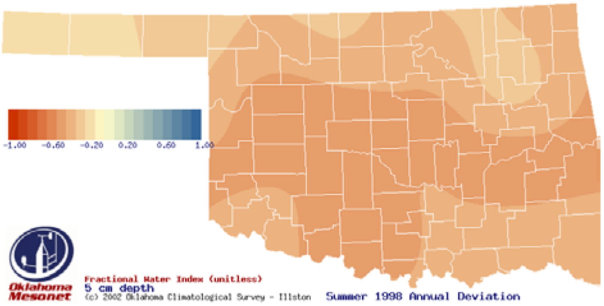

Figure 4 – 5 cm Fractional Water Index Summer 1998 Annual Deviation

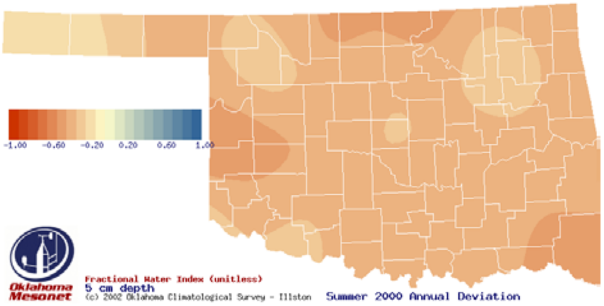

Figure 3 - 5 cm Fractional Water Index Summer 2000 Annual Deviation

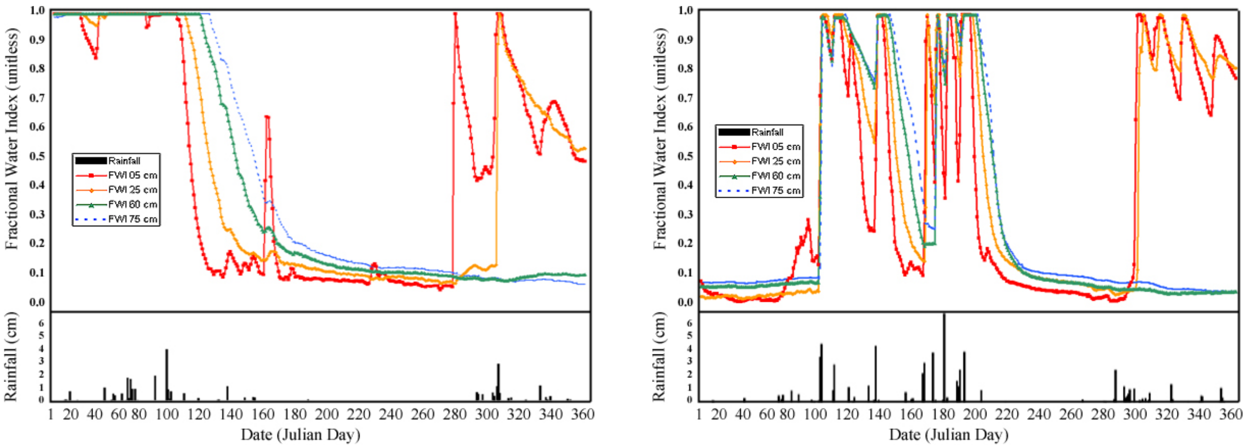

Figure 6 - Fractional Water Index and rainfall meteograms for Hollis during 1998 (left) and 2000 (right).

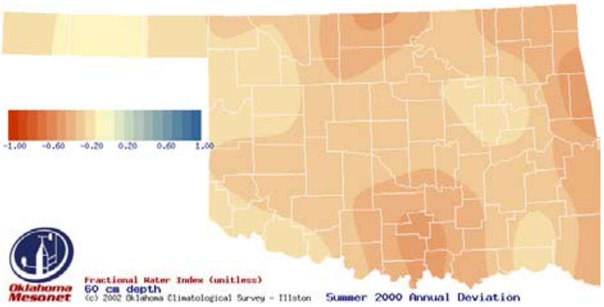

Figure 7 - 60 cm Fractional Water Index Summer 2000 Annual Deviation

Figures 5 and 7 show the summer deviations of FWI at 5 and 60 cm for 2000. Conversely to 1998, the central portion of Oklahoma did not deviate as far from the annual mean as did other portions. Also, throughout most of Oklahoma the 60 cm depth did not deviate as much as the near surface (5 cm).

Unfortunately, deviations only demonstrate how much a particular area deviated from its annual mean. However, monthly averages show that the FWI in the southwest portion of Oklahoma were the driest compared to the rest of the state. As a result, special attention was paid to the Hollis Mesonet station, one of the stations in the southwest part of the state. This station was chosen because it was ideally affected by the meteorological drought and was best suited for hydrologic drought analysis at the point-measurement scale.

5. LAG AND RECOVERY TIME

Analyzing the lag and recovery times of the subterranean moisture is key to understanding how drought conditions affect soil moisture. Figure 6 shows the FWI and rainfall at the Hollis Mesonet site during 1998 and 2000. The rain gauge at Hollis was inaccurate from June through October in 1998. However, almost no rain fell during this span, except for one occasion in mid-July. Thus, the figure is still representative of the meteorological conditions.

5.1 Lag Time

The lag time relating soil moisture as a function of depth is defined as the time from which the 5 cm Fractional Water Index value is 0.5 or less to when the respective depths (25, 60 and 75 cm) reach a FWI value of 0.5 or less. A value of 0.5 was chosen because it exists during the middle of the drying trend. This alleviates problems due to fluctuations during initial drying at the site. The slope of this decline in FWI may vary due to variations in soil texture, soil type and vegetation cover.

The magnitude of the drought also varied by depth during both years. During 1998, the 5 cm FWI at sites in the southwest part of Oklahoma reached 0.1, while in 2000 they reached values closer to 0.05. In addition, the deeper depths did not reach as low of a FWI as did the more shallow layers. However, the key point is that all of the FWI values were well below the wilting point for vegetation. While small rain events did occur during the droughts, only the 5 cm and the 25 cm depths responded minimally to the additional moisture.

Upon receipt of rainfall, the Fractional Water Index "spikes" upward. However, a much steeper downward slope follows due to continued heating and evapotranspiration (Basara et al. 1998).

5.2 Recovery Time

The recovery time is defined as the time between when the 5 cm FWI has returned to at or near field capacity and the deeper depths reach a FWI of 0.8 or more. A level of 0.8 represents soil moisture conditions that have sufficient moisture in the soil to support agricultural needs.

Normally, the winter precipitation recharges the soil moisture at the deeper layers. However, the droughts of 1998 and 2000 were so severe that even the heavy rains during the winter did not fully recharge the soil at the deepest depths. At best, the 60 cm FWI at some of the sites in the southwest part of Oklahoma reached a value of 0.25 after the drought, with no sign of further recharging by the end of the year.

6. POROSITY

The soil porosity is the proportion of pore spaces in a volume of soil (Dingman 1994). It is given by the formula:

$$\phi = \frac{V_a + V_w}{V_s} \qquad (2)$$

where V_a is the volume of the air in the soil, V_w is the volume of the water in the soil and V_s is the total volume of the soil. Porosity in soil varies very little on a temporal scale, but does tend to decrease with depth due to the compaction of soil. This unitless value usually ranges from 0.30 to 0.55.

7. POROSITY VERSUS LAG/RECOVERY TIME

Because porosity represents open air spaces for water to move through, an analysis about how the lag and recovery times are related to porosity was conducted. Correlations between each of the deeper depths (25, 60 and 75 cm), as well as the entire soil column, were calculated.

7.1 Lag Time

Figure 8 shows a scatter plot of the soil porosity values versus the lag time of the FWI during 1998. There is a moderate negative correlation (-0.6) between the two variables. Furthermore, this correlation strengthens with depth.

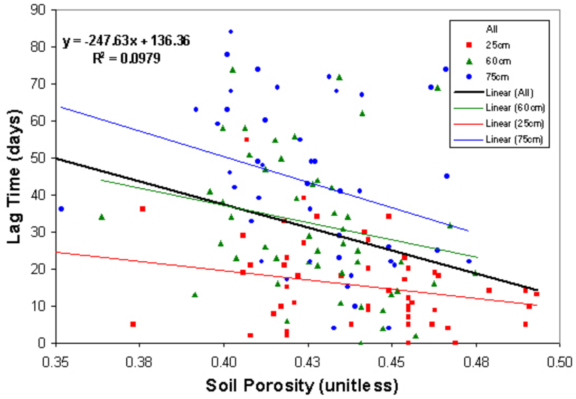

Figure 8 - Scatter plot of soil porosity versus lag time of soil moisture in 1998.

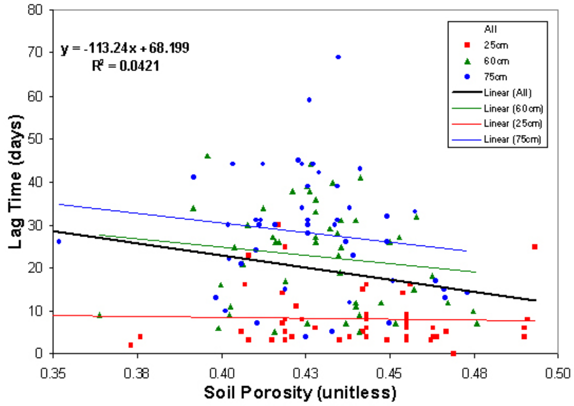

Figure 10 - Scatter plot of soil porosity versus lag time of soil moisture in 2000.

Figure 10 shows a scatter plot of the soil porosity values versus the lag time of FWI during 2000. Similar to 1998, there is a moderate negative correlation between the two variables. This correlation is not as strong as in 1998, but like 1998, it strengthens with depth.

7.2 Recovery Time

Figure 9 shows a scatter plot of the soil porosity values versus the recovery time of the FWI during 1998. Almost no correlation exists in this data. This is due, in part, to the bi-modal (seen at 0-7 days and ~30 days) distribution of the recovery time. The 0-7 day recovery time corresponds to stations in the eastern half of the state, while the ~30 days recovery time corresponds to the western half of the state. This demonstrates that the recovery time is more correlated with location than it is with the porosity of the soil.

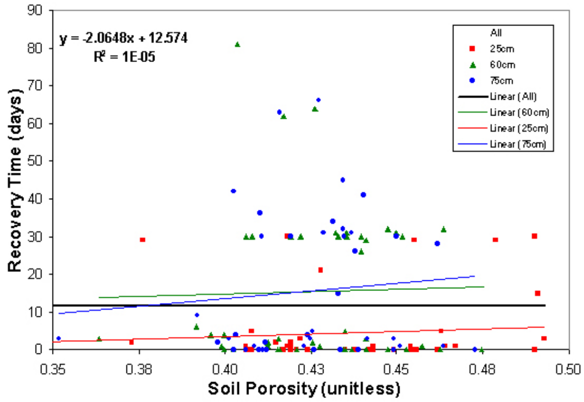

Figure 9 - Scatter plot of soil porosity versus recovery time of soil moisture in 1998.

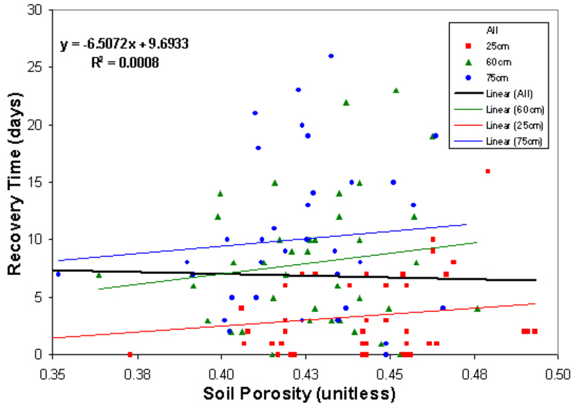

Figure 11 - Scatter plot of soil porosity versus recovery time of soil moisture in 2000.

Figure 11 shows a scatter plot of the soil porosity values versus the recovery time of FWI during 2000. Unlike 1998, the recovery time data is more uniformly distributed. While slight positive correlations do exist, they are very minimal. Similar to 1998, there is a stronger correlation between location than there is with soil porosity.

Overall, the data reveals that there is a moderate negative correlation between soil porosity and lag time of the soil moisture. This correlation increases with depth. The data also shows that the recovery time of soil moisture is more correlated with the physical location of the station than the porosity of the soil.

7.3 Comparison of the Two Droughts

In addition to comparisons between drought and soil characteristics, comparisons between the droughts of 1998 and 2000 were performed.

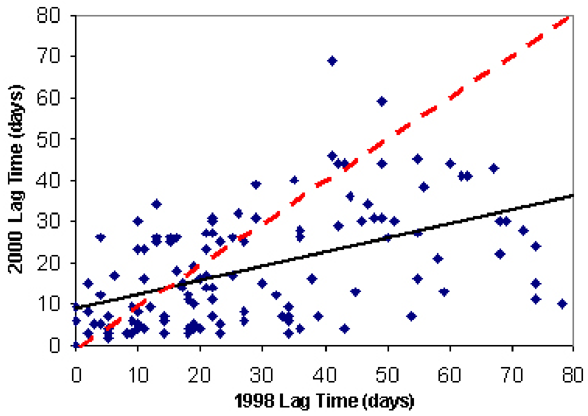

Figure 12 - Scatter plot of lag time between 1998 and 2000.

Figure 12 shows a scatter plot of the lag time in 1998 versus the lag time in 2000. The solid line represents the correlation between the two years, while the dashed line represents a perfect correlation. The data reveals that a moderate correlation exists between the two years and that a stronger correlation exists at shorter lag times.

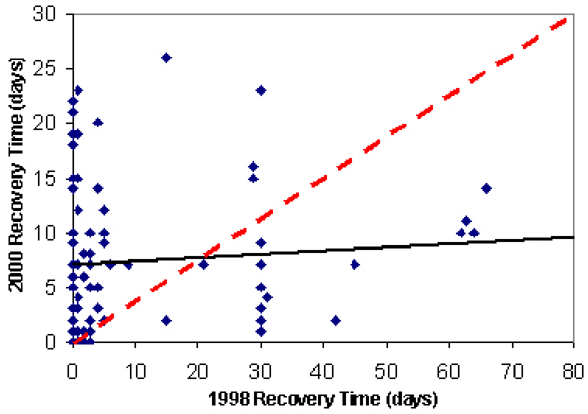

Figure 13 - Scatter plot of recovery time between 1998 and 2000.

Figure 13 shows a scatter plot of the recovery time in 1998 versus the recovery time in 2000. Almost no correlations exist between these two droughts with respect to recovery time. This is due to the lack of correlation in the recovery time and soil characteristics.

8. CONCLUSION

The droughts of 1998 and 2000 had a severe impact on Oklahoma and parts of Texas. Subterranean hydrological characteristics of the drought were observed and analyzed through the use of the soil moisture sensors installed in the Oklahoma Mesonet. These observations demonstrated how the drought impacted soil depths down to 75 cm. Furthermore, the winter rainfall was unable to replenish the soil depths at or below 60 cm.

Results from this study show how vegetation cover, soil texture and soil type all affect the rate at which soil moisture values are depleted at deeper depths. While not evident due to lack of agricultural crops during the winter, this study found that the soil moisture at the 60 cm and 75 cm depths did not recharge by the end of the year. Thus, the hydrologic drought continued even though the meteorologic drought had ended.

Further analyses showed that moderate correlations exist between soil porosity and the drying of soil moisture. The results also showed these correlations strengthen with depth. The recovery time was found to be more correlated with location than with soil porosity.

9. REFERENCES

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