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PREDICTION OF SOIL MOISTURE CONTENT IN A SKELETAL-CALCAREOUS SOIL OF SOUTH FLORIDA BASED ON SHALLOW GROUNDWATER LEVELS

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RESUMEN. *La zona agrícola adyacente al Parque Nacional de Everglades en el Sur de la Florida (EEUU) está sujeta al incremento del nivel freático para restaurar el flujo natural de los humedales. Para comprender la variación del contenido de humedad y su relación con el acuífero somero, ésta fue estudiada en una plantación de lychee (Litchi chinensis) en zanjas con suelo Krome. El objetivo principal fue interpretar el efecto de capilaridad del nivel freático en la zona no saturada. Se utilizaron 32 sensores de capacitancia distribuidos en cuatro profundidades y se registró el nivel freático mediante cuatro piezómetros con transductores de presión. Se desarrolló una curva característica del suelo obtenida con datos de campo asumiendo condiciones hidrostáticas de un perfil drenado al equilibrio y se ajustó al modelo de van Genuchten. Los resultados mostraron distintos parámetros y tendencias de retención de agua para cada profundidad del suelo. El modelo hidrostático permitió buenas predicciones en general de la humedad del suelo basado en lecturas del nivel freático somero (coeficientes de eficiencia de Nash y Sutcliffe >0,75 en todos los casos), aunque la precisión del modelo es mayor frente a las fluctuaciones generales del nivel freático. Dicha técnica resulta práctica para comprender la dinámica de humedad en la zona no saturada de los suelos Krome debido a su alta permeabilidad y fácil recuperación del estado de equilibrio.*

ABSTRACT. *The agricultural area adjacent to the Everglades National Park in South Florida (USA) is influenced by the rise in groundwater levels as part of the efforts to return to a more natural flow pattern in the Everglades. To understand this scenario, soil moisture and its relationship with the shallow groundwater were studied in a lychee (Litchi chinensis) orchard planted in trenches of Krome soil. The objective was to interpret the effect of shallow groundwater capillarity in the unsaturated zone. Soil moisture was recorded using 32 capacitance sensors distributed at four depths and groundwater was monitored with pressure transducers located in four piezometers. A field soil water characteristic curve was developed assuming hydrostatic conditions in a profile drained to equilibrium and fitted to van Genuchten model. The fitted curves showed different parameters and retention patterns at each depth. The hydrostatic model offered good predictions of soil moisture variation based on shallow groundwater observations (Nash Sutcliffe coefficients of efficiency >0.75), although these were more accurate in representing the long term trend changes of water table fluctuations. The technique is practical to interpret the soil water dynamics in the vadose zone of Krome soils in response to the shallow groundwater changes. However, its application is limited to scenarios like the one study for Krome, where the high permeability of the soil allows for a fast recovery of the hydrostatic equilibrium state.*

1. INTRODUCTION

During the last decades, Southeast Florida has been subject to a comprehensive plan to restore natural flow of wetlands in Everglades National Park (ENP).To achieve these goals, the South Florida Water Management District (SFWMD) is required to raise canal levels which have strong hydraulic connections to the extremely shallow Biscayne aquifer characterized by its high permeability and fairly response to storm events (Pitt, 1976; Ritter and Muñoz-Carpena, 2006). According to Minkowski and Schaffer (2001), 88% of the tropical fruit crops in this region are in Miami-Dade County's Redland agricultural area adjacent to the ENP and 91 % of Miami-Dade County's fruit crop agricultural land is located on Krome soils. Thus, understanding the hydrological interactions in the unsaturated zone can help translate the benefits and problems of water management into an agronomical perspective according to the local grower's water necessities and plant's physiological flood tolerance resistance.

Calcareous soils in Miami-Dade Country are derived from limestone. Krome soils are classified as loamy skeletal, carbonatic, hyperthermic Lithic Udorethents (Noble et al., 1996) made of rock plowed oolitic limestone (Colburn and Goldweber, 1961). Muñoz-Carpena et al. (2002), found that Krome soils present a complex bimodal water retention pattern, where the gravel fraction contributes to drainage and the loamy fraction controls the soil water retention. Previous anecdotal evidence has been reported in the region suggesting that groundwater may be contributing to plant water requirements in this soil type. Al-Yahyai et al. (2005) and Al-Yahyai et al. (2006) suggested shallow groundwater capillary rise and Migliaccio et al. (2008) irrigation studies nearby this area identified soil water diurnal patterns during the dry season. In case the shallow groundwater is contributing a certain amount of plant water requirements (through capillarity), its hydrological significance should be explained to improve water management and model soil water status in the unsaturated zone.

The relationship between soil water content and shallow groundwater level is a dynamic process of alternate cycles of wetting and drying. In a field scale situation, this relationship is more simply evaluated considering hydrostatic conditions. Hydrostatic conditions refer to soil water in equilibrium (without movement) typically with a shallow groundwater, and may also be referred to as "drain to equilibrium" conditions. If the conditions described occur, water pressure potential is determined by the distance of a specific point in the soil to the water table, with positive values when the point is below the water table (saturation and hydraulic head) and negative when the point is above the water table due to its matric potential in terms of suction (Buckingham, 1907; Klute and Page, 1982). Thus, a soil water characteristic in a homogenous soil profile drained to equilibrium can be obtained through a series of observations of water table decline where its point of saturation reached at the water table is zero, and its moisture content may be equal to the effective porosity.

The objective of this study was to test the validity of the drain to equilibrium hydrostatic assumptions to interpret the soil moisture variation based on shallow groundwater elevation in a trenched gravelly, skeletal calcareous soil. The analysis was conducted in three steps: (i) monitoring soil moisture and groundwater level in a synchronized manner to identify when hydrostatic conditions developed; (ii) determination of soil water characteristic curves of a profile drained to equilibrium; (iii) construction of a simple hydrostatic model to predict soil moisture based on groundwater observations.

2. MATERIALS AND METHODS

2.1. Experimental site

The study was conducted in Homestead south Miami-Dade, Florida, in a Lychee (*Litchi chinensis*) field at the University of Florida (UF) Tropical Research and Education Center (TREC) (80.5^{0}W, 25.5^{0}N). The site has a mean elevation of 3.12 m National Geodetic Vertical Datum (NGVD) 1929 and is identified by a subtropical, marine climate. Annual rainfall is 1,448 mm/yr (Ali et al., 1999) with 80% occurring during the wet season (June to October) and the dry season (November to May) is characterized by a general declining trend of groundwater levels. The lychee field (as most of the tropical fruit crops in the area) is planted in trenches 0.40 to 0.45 meters wide and 0.45 to 0.60 meters deep (Figure 1); this practice is needed to increase the soil depth for rooting growth and tree stability (Crane et al., 1994).

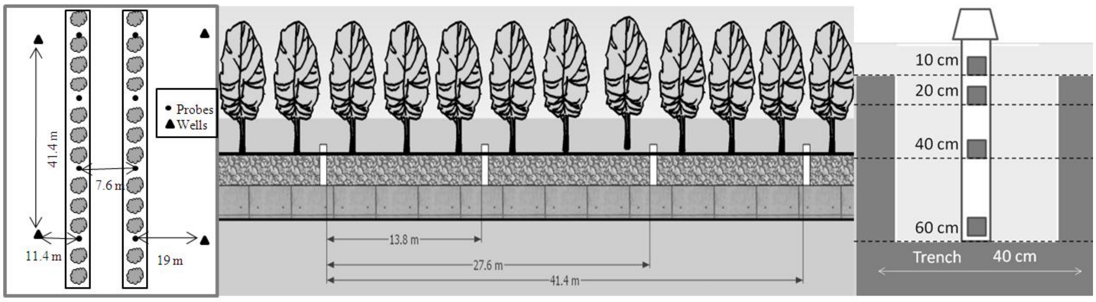

Figure 1. Schematic of wells and capacitance probes installed along a lychee trench in the experimental site and distribution of a probe and its capacitance sensors in the soil profile.

2.2. Equipment: soil moisture and groundwater monitoring

To track soil moisture, eight EnviroSCAN multi sensor capacitance probes (Sentek Ltd. Pty., Stepney, Australia) were installed in two rows of lychee trees planted in trenches of Krome soil. Each row had four probes and each probe had sensors positioned at 10, 20, 40 and 60 cm depth (Figure 1). The system measured soil water content as a function of the apparent bulk dielectric constant of the soil, imposed frequency and electrode configuration, as described in detail by Paltineanu and Starr (1997). These sensors are capable of measuring volumetric water content values ranging at a resolution of 0.1% (Buss, 1993). Sensor normalization procedure was used to incorporate raw frequency readings in soil with frequency readings of air and water. A calibration equation (Equation 1) for Krome soils previously developed by Al-Yahyai et al. (2006) was used to adjust the measured scaled frequency (*SF*) with the absolute volumetric water content (θ).

$$\theta = \left(\frac{SF - C}{A} \right)^{1/B} \quad (1)$$

where θ is the volumetric water content and *A*, *B*, and *C* are coefficients fitted through a nonlinear regression of SF versus θ. For the case of Krome very gravelly loam soils *A* is 0.011, *B* is 1 and *C* is 0.5206.

The distance between the sensors and the water table (pressure potential) required the measurement of groundwater table elevation. Piezometers were installed at four different points adjacent to the study site. Levelogger LT 3001 (Solinst Ltd., Ontario, Canada) pressure transducers were suspended and submerged at 3.6 meters depth and used for measuring the water level (accuracy = 0.1% -10^{o}C to 40^{o}C). Water levels were compensated using data collected by Barologger air barometric pressure readings. Groundwater levels were also adjusted based on weekly manual water table depth readings.

Both soil moisture and groundwater monitoring devices were synchronized to collect readings every 15 minutes from 16 September 2008 to 23 March 2009. Irrigation practices were suspended during the study to promote drained to equilibrium conditions, although irrigation for freeze protection was allowed to protect the trees. Daily rainfall and reference evapotranspiration (ET_o) were collected from the Florida Automated Weather Network (FAWN) station located at UF TREC, within 100 m of the site. Data for events likely to alter drain to equilibrium conditions (e.g., storms, freeze protection events and remaining moisture greater than daily evapotranspiration) were discarded from the analysis.

2.3. Data Interpretation: soil water characteristic curves

The filtered data set collected was summarized to daily means. Soil moisture was categorized according to the installed depth. Pair wise comparisons among means using Tukey test ($\alpha = 0.05$) determined the sensors with no significant differences and box plot comparisons verified similar distributions among the selected sensors.

Groundwater data from the four piezometers were averaged and summarized to daily means. Water table depth (WTD) was adjusted to soil moisture sensor distance to the water table or distance to soil moisture (DSM). Hence, each sensor depth had an adjusted DSM equivalent the WTD difference with the sensor’s depth.

The relation from the drained to equilibrium soil moisture from each selected sensor with its correspondent DSM was fitted with a polynomial equation of fourth order to represent 10 points from the filtered scatter. Van Genuchten et al.(1991) RETC program was used to fit the 10 points and represent a soil water retention curve through least squares parameter optimization. Soil hydraulic parameters were described using the van Genuchten (1980) equation:

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1+(\alpha h)^n\right]^m} \quad (2)$$

Where θ is the volumetric water content; h is the pressure head; θ_s and θ_r represent the saturated and residual water contents, respectively; and α, n and m are empirical shape parameters.

2.4. Modeling soil moisture based on groundwater observations

The fitted parameters (θ_s, θ_r, α, n and m) estimated from the soil water retention data at each depth were used to predict soil moisture according to the DSM daily observations. The difference between observed values and model predictions goodness of fit was evaluated using the Nash and Sutcliffe (1970) coefficient of efficiency (C_{eff}) described in Equation (3).

$$Ceff = 1.0 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (3)$$

Where O_i are the observed values, P_i is predicted values; and $\bar{O}$ is the mean of the measured data; values for C_{eff} range between 1.0 (perfect fit) and negative infinity. C_{eff} values lower than zero indicates that the mean value of the measured time series would be a better predictor of the model (Nash and Sutcliffe, 1970).

3. RESULTS AND DISCUSSION

3.1. Soil moisture and groundwater monitoring

During the study period more than 580,000 readings of soil volumetric water content (θ) were collected from 32 capacitance sensors and about 72,500 water level readings were collected from four pressure transducers. Ranges and variances found among sensors installed at the same depth varied. This required some review of the data so that sensor datasets that were inconsistent could be discarded to prevent fitting inconsistencies. Thus, Tukey test (α = 0.05) and box plot comparison of distributions were useful criteria to select representative sensors for each depth. The possible reasons related to the differences found in the same sensor category (or profile depth) are contact interference of the probe with the soil due to air gaps, technical deficiencies of instrumentation and/or site specific conditions of soil moisture. The selected, representative sensors datasets are shown in Figure 2, as well as the soil water dynamic response to rainfall events and mean water table elevation (WTE) fluctuations. Storms identified from the end of September 2008 to the beginning of October 2008 are part of the wet season; data collected from the beginning of dry season (November) until March 2009 provided a period of fewer rain events. This dry period offered the conditions to collect more data representing a soil water state of equilibrium. The sensors located at 10 and 20 cm depths had greater ranges and changes of soil water content due to direct response to storm events. Sensors at 40 and 60 cm depths had trends similar to the water table fluctuations, which are strongly related to the canal levels as concluded in previous work by (Ritter and Muñoz-Carpena, 2006). The spikes of soil moisture during January 2009 were related to freeze protection, certain sensors responded differently according to its location and distance from the sprinklers. The remaining moisture dynamics after freeze protection were not related to capillarity and therefore discarded.

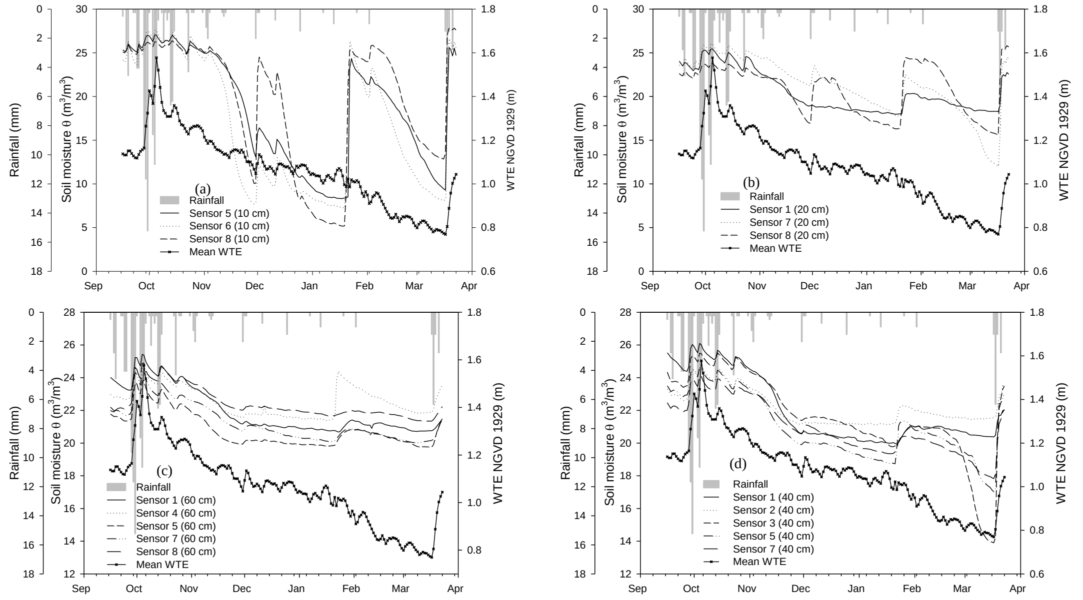

Figure 2. Soil moisture sensors selected to model the response to groundwater levels.

3.2. Characterizing soil water characteristic curves of a soil profile drained to equilibrium

Differences among soils in terms of retention and water movement depend to a large extent on pore size and shape distributions. The interpretation of the drain to equilibrium data as a field soil water characteristic curve using van Genuchten model (1980) instead of a polynomial fit adds meaning to the evaluation because the van Genuchten model is considered an analytical expression with fitted hydraulic parameters that have a physical basis. Results of fitted curves and parameters shown in Figure 3 and Table 1 confirm previous findings by Muñoz-Carpena et al. (2002) in soil water holding capacity, where large changes in suction respond to small changes in soil water content for the loamy fraction of the soil. The range of soil water encountered during the study corresponds to water contained in the loam fraction. The gravel fraction of the soil that corresponds to very rapid soil water depletion would be found at closer DSM observations (< 0.1 m), unusual for the dry season of the study. Therefore, it was not possible to capture the inflection point where the water retention switches from gravel to loam fractions. It is important to consider the fitted characteristic curve could be better described by a bimodal porosity model that requires description of more than one inflection point. For this, multimodal retention functions as described in detail by Durner (1994) could be used.

Table 1 Van Genuchten fitted parameters using RETC software for daily mean observed values at depths 10, 20, 40 and 60 of trenched Krome soils.

	Depth (cm)			
Parameter	10	20	40	60
θ_s (m^3/m^3)	0.2701	0.2711	0.4905	0.3741
θ_r (m^3/m^3)	0	0	0	0
α(cm^{-1})	0.0053	0.0050	0.0106	0.0112
n	28.7893	9.9850	2.3209	1.8685
m	0.9653	0.8999	0.5691	0.4648

The heterogeneity of the soil profile was confirmed by differences found for most of the fitted parameters (Table 1) among depths. Bruce and Luxmoore (2003) explain situations where the curves may vary more with depth than with area in response to compaction. For this case study, soil water characteristics for individual layers were required. Skaggs et al. (1978) remarked about this heterogeneity feature and explained that superficial profiles tend to have higher porosity than the deeper layers. For the analyzed results, this is not the case, since θ_s (understood as effective porosity) was lower at 10 and 20 cm than 40 and 60 cm. However, curve shapes might be influenced by other field factors such as root distribution, transpiration and weather factors that influence shallower layers more so than deeper layers. Effective porosity, θ_s parameters at 40 and 60 cm have more similarities with Al-Yahyai et al. (2006) laboratory curve (θ_s = 0.47) as well as the n and m parameters (1.46 and 0.32 respectively) which stand for the dimensionless measure of the pore size distribution. The alpha (α) parameters were found similar between 10 and 20 cm depths and between 20 and 40 cm depths. Dispersion of observations was greatest for the 10 cm depth, where a hysteric shape of the curve can be seen (Figure 3).Hysteresis is a trend difficult to distinguish between the drying of wetting process with field data. In many circumstances, the soil's water holding characteristics make difficult to capture the drain to equilibrium condition. Nonetheless, the aquifer high permeability and the soil's low water holding capacity where the main driving factors to obtain such consistent drained to equilibrium conditions in this study.

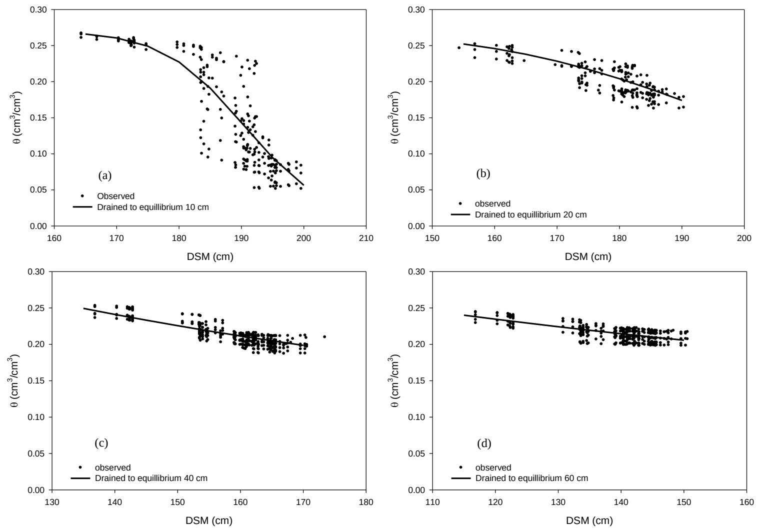

Figure 3 Trenched Krome soils drained to equilibrium soil water characteristic curve fitted with van Genuchten parameters at depths:(a) 10 cm (b) 20 cm (c) 40 cm and (d) 60 cm.

3.3. Predicting soil moisture based on groundwater level observations

The models proposed for each depth were determined by fitting the parameters shown in Table 1 to Equation 2. The model's capacity to explain the relationship between groundwater level and soil volumetric water content was estimated using the C_{eff} accuracy of predictions which is greater than the mean value of the observed data at all depths (Figure 4). Time series comparisons of the four models predicted results versus filtered observations indicate that groundwater level has a greater influence on the soil water content of the deepest layers of the trench (40 and 60 cm) as compared to the shallower layers of the trench (10 and 20 cm). At the beginning of the time series between the months of November and December 2008, model predictions tend to underestimate soil water content compared to the predictions at the end of January, where soil water observations were not directly in function of the groundwater fluctuations. This situation is more evident in the 10 and 20 cm depths where a greater exposure to seasonal weather and evapotranspiration fluctuations was observed in FAWN data resulting in an increase in evapotranspiration during the last two months of the study. Greater evapotranspiration rates are associated with greater plant water uptake and therefore lower observed soil water content.

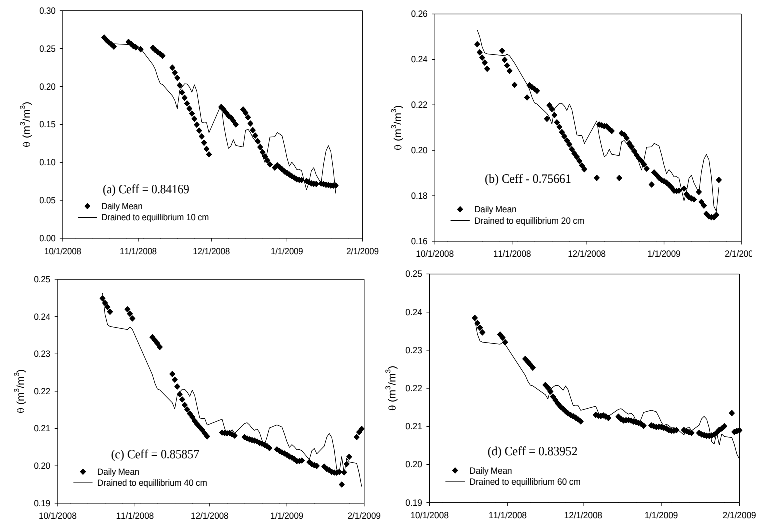

Figure 4. Observed daily mean values and soil water content predictions using the adjusted water table depth (DSM) as reference at depths: (a) 10 cm (b) 20 cm (c) 40 cm and (d) 60 cm depth.

In order to extend the model's capacity of prediction beyond the range of the filtered points, the parameters were tested to predict soil moisture during the whole study period. The results were not as satisfactory compared to the C_{eff} found in Figure 4. The C_{eff} values were -1.121, -0.898, 0.466, and 0.428 for 10, 20, 40, and 60 cm depths, respectively. The accuracy of the predictions in all the depths was reduced between the third week of January and the second week of February 2009 coinciding with the time period of freeze protection events. During the described term, all model predictions were underestimating observations because the sensors were reporting remaining soil water from the freeze protection event that obeyed a drying pattern with similar shape to the fitted curves but from a different water source than groundwater. This point highlights the importance of properly identifying drain to equilibrium for an accurate prediction.

As a result, the relationship found between soil water content and groundwater level using this simple and practical one-dimensional model is maintained when hydrostatic assumptions fit with the weather conditions. In this study, this corresponds to periods when water table is declining and low rainfall is reported, matching with the dry season. This season corresponds to the period when capillary rise has the potential to supply a part of the irrigation requirements, or if in excess damage the crop roots. The simple model presented offers the opportunity to help to determine possible outcomes when raising the water level to restore natural flow in the ENP. It is important to understand that the values of the parameters obtained from retention models are based on field observations of water content and matric head. The model reliability remains only within the limits of the observed results (DSM range). Extrapolation of model values outside the range of input (DSM) are not reliable and should only be used as an indication of the trends. To extend the model, future research should focus on gathering field data for conditions when the water table is closer to the installed sensors. This way the retention curves can capture the points of inflection of the fitted curves and lead to a better defined picture of the capillary fringe (0 to 1 meter) level of influence, Finally, our results clearly indicate that groundwater level is an important factor to consider to explain the soil water content variation in this area and that this effect needs to be considered in CERP management alternatives.

4. CONCLUSIONS

Characterizing a field soil water characteristic curve for a Krome trenched soil based on the drained to equilibrium concept is a simple and useful technique to build a one-dimensional model able to predict groundwater influence on the unsaturated zone. Van Genuchten equation permitted the representation of an empirical soil water retention model using parameters that have a physical basis. The application of the fitted curves through the hydrostatic model confirmed the variation of soil water retention patterns that exists in short depth intervals. The points of inflection in the curves were not identified on the data range of observations for any of the models and water retention was characterized to have small changes of moisture for relatively large changes of suction potential. Although the model predictions were generally good (C_{eff} = 0.76 to 0.86), the fit strongly depends on if the conditions for the period of record are close to the drained to equilibrium assumptions. The proposed model was able to capture the general and most representative trends of soil water content changes in response to the shallow groundwater fluctuations confirming the importance of this relationship.

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REFERENCES

Al-Yahyai, R., B. Schaffer, F.S. Davies and J.H. Crane, 2005. *Four levels of soil water depletion minimally affect carambola phenological cycles. Horttechnology, 15*: 623-630.

Al-Yahyai, R., B. Schaffer, F.S. Davies and R. Munoz-Carpena, 2006. *Characterization of soil-water retention of a very gravelly loam soil varied with determination method. Soil Science, 171*: 85-93.

Ali, A., W. Abtew and South Florida Water Management District, 1999. *Regional rainfall frequency analysis for central and south Florida.* Hydrologic Reporting Unit, South Florida Water Management District Water Resources Evaluation, West Palm Beach, FL.

Bruce, R.R., and R.J. Luxmoore. 2003. *Water Retention: Field Methods*. Soil Science Society of America Book Series 5: 663-686.

Buckingham, E., 1907. *Studies on the movement of soil moisture*. Govt. print. off., Washington.

Buss, P., 1993. *The use of capacitance based measurements of real time soil water profile dynamics for irrigation scheduling*. National Conf. of the Irrigation Assoc., Australia and the National Committee on Irrigation and Drainage, Launceston, Tasmania.

Colburn, B. and S. Goldweber, 1961. *Preparation of oolitic limestone soil for agricultural. Proc. Fla. State Hort. Soc., Vol. 74*, pp. 343-345.

Crane, J., C. Balerdi, R. Campbell, C. Campbell and S. Goldweber, 1994. *Managing Fruit Orchards to Minimize Hurricane Damage. HortTechnology, 4*: 21-27.

Durner, W., 1994. *Hydraulic conductivity estimation for soils with heterogeneous pore structure. Water Resources Research, 30*: 211-223.

Fares, A. and A.K. Alva, 2000. *Soil Water Components Based on Capacitance Probes in a Sandy Soil. Soil Science Society of America Journal, 64*: 311-318.

Klute, A. and A.L. Page, 1982. *Methods of soil analysis. American Society of Agronomy : Soil Science Society of America*, Madison, Wis.

Migliaccio, K.W., B. Schaffer, Y.C. Li, E. Evans, J.H. Crane and R. Munoz-Carpena, 2008. *Assessing benefits of irrigation and nutrient management practices on a southeast Florida royal palm (Roystonea elata) field nursery. Irrigation Science, 27*: 57-66.

Minkowski, K. and B. Bruce Schaffer, 2001. *Section 1: A Geographic Information System for Miami – Dade County Agriculture. Miami-Dade County agricultural land retention study, Vol. 2*, Florida Agricultural Market Research Center, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, Fla., p. 110.

Muñoz-Carpena, R., Y. Li and T. Olczyk, 2002. *Alternatives of Low Cost Soil Moisture Monitoring Devices for Vegetable Production in South Miami-Dade County*. University of Florida Cooperative Extension Service, Institute of Food and Agriculture Sciences, EDIS ABE333, Gainesville, Fla.

Nash, J.E. and J.V. Sutcliffe, 1970. *River flow forecasting through conceptual models part I -- A discussion of principles. Journal of Hydrology, 10*: 282-290.

Noble, C.V., R.W. Drew and J.D. Slabaugh, 1996. *Soil Survey of Dade County Area, Florida*. USDA/NRCS, Washington, D.C.

Paltineanu, I.C. and J.L. Starr, 1997. *Real-time Soil Water Dynamics Using Multisensor Capacitance Probes: Laboratory Calibration. Soil Science Society of America journal., 61*: 1576.

Pitt, W.A.J., D. Central and Southern Florida Flood Control and S. Geological, 1976. *Response of ground-water levels to flood control operations in three basins*, southeastern Florida. U.S. Dept. of the Interior, Geological Survey, Tallahassee.

Ritter, A. and R. Muñoz-Carpena, 2006. *Dynamic factor modeling of ground and surface water levels in an agricultural area adjacent to Everglades National Park. Journal of Hydrology, 317*: 340-354.

Skaggs, R.W., L.G. Wells and S.R. Ghate, 1978. *Predicted and measured drainable porosities for field soils. Transactions of the Asae, 21*: 522-528.

Van Genuchten, M.T., 1980. *A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal, 44*: 892-898.

Van Genuchten, M.T., F.J. Leij, S.R. Yates and S.K.E.R.L. Robert, 1991. The *RETC code for quantifying the hydraulic functions of unsaturated soils*. Robert S. Kerr Environmental Research Laboratory, Office of Research and Development, U.S. E.P.A., Ada, Okla.