USING THE VAN GENUCHTEN MODEL TO ESTABLISH IRRIGATION SCHEDULING THRESHOLDS

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Abstract

An efficient irrigation system requires information on soil water status to determine irrigation application quantity and timing. Knowledge of the boundary of the lower and upper limits of soil water content is necessary to optimize irrigation applications by avoiding crop drought stress and nutrient leaching. However, *in situ* measurements of soil water characteristics needed to establish these boundaries are labor and time intensive. The objectives of this study were thus 1) to propose a new method of calculating field capacity (FC) from the van Genuchten Model (vG Model), 2) to utilize the calculated FC in irrigation scheduling, and 3) to evaluate the developed irrigation scheduling. Physical property data of nine typical soil series in Tift County, Georgia were input into the RETC (RETention Curve) program for parameters of the vG Model. Soil volumetric water content (VWC) and water tension (SWT) at FC calculated in the current study were consistent with previous results in soils with similar textures. Irrigation needed to bring the soil profile to FC was calculated. The water balance calculated from the vG Model was equal to or higher than that calculated from the Water Balance Equation, but they were linearly correlated (R^2 = 0.67-0.83). Therefore, the vG Model can be calibrated for utilization in irrigation management in the aspects of the upper limit accuracy and irrigation scheduling.

Introduction

Fresh water has become a scarce resource, and the situation has been predicted to be worse considering global climate change and the increasing global population (IPCC, 2013). Among the uses of fresh water, water consumption in agricultural production takes up a large proportion worldwide (WWDR, 2014). In the U.S., irrigation withdrawals in 2005 accounted for 37% of total freshwater withdrawals (USGS, 2014). The corresponding total energy expense for irrigation pumping is also high, approximately 1.5 billion in 2003 and 2.7 billion in 2008. However, the increase of irrigated acreage was only 4.6% from 52.5 million in 2003 to 54.9 million in 2008 (USDA-NASS, 2013). To meet the challenge of feeding more people with less resource inputs, irrigation water should be used more efficiently in a long run, and one of the strategies is to improve irrigation management.

Efficient irrigation systems require the information of soil water status to determine irrigation application quantity and timing. The accurate boundary of lower and upper limits of soil water content is the premise to avoid the occurrence of crop drought stress and nutrient leaching. The *in situ* FC refers to the relatively stable soil water content with negligible downward drainage, after saturation by rainfall or irrigation and fast downward drainage (Nemes et al., 2011). This situation would be attained in several days as indicated by the method of fluxed-based estimation (Brito et al., 2011; Twarakavi et al., 2009). For example, 52-205 hours were needed to reach soil water drainage flux density of 1.0 mm day^{-1} for FC measurements in different soils (Brito et al., 2011). In another study, drainage reached the flux of 0.01 mm d^{-1} after 83 h for sand and 303 h for clay (Twarakavi et al., 2009). Thus, the *in situ* measurement is labor and time consuming. Lab measurements of FC usually determine the soil water content at SWT of 10 to 33 kPa. Soil water tension of 10 kPa is used as a benchmark for coarse-textured soils, and 33 kPa for loams or clays (USDA-NRCS, 2004). However, the thresholds are till vague in defining FC in soils with different textures, and FC should be defined for each specific soil instead of by a universal SWT (Nemes et al., 2011; Zacharias and Bohne, 2008). On the other hand, FC is usually determined in the 12 USDA textual classes ((Nemes et al., 2011; Twarakavi et al., 2009), overlooking unique characteristics that each specific soil within a certain textual class might possess and their impact on soil FC. For example, within sandy soils, textural variability in silt and clay content leads to variability in FC (Zettl et al., 2011). It is therefore imperative to develop alternative methods to determine soil-specific SWT to best estimate FC.

Furthermore, FC and permanent wilting point (PWP) can only provide the information of the amount of available water content (AWC) for crop growth, but fail to characterize the process of soil water release. For example, 50% FC is a widely used threshold for irrigation application. It is much faster for the soil water content of a sandy soil dropping from 100% FC (<20 kPa) to 50% FC (approximately 33 kPa) than a clay soil (Irmak et al., 2006). Available water content dropped from 0.08 to 0.04 cm^3 cm^{-3} corresponding to 5 to 15 kPa of SWT in a Florida sandy soil (Morgan et al., 2001). That range of SWT is much lower than the SWT at FC for clay soils in general even when they exhibit similar AWC (Teepe et al., 2003). Soil water release curves thus plays an important role in estimating available soil water at different stages of the soil drying process and irrigation management. The objectives of this research were thus to propose a new method of calculating parameters of soil water status from vG Model, to utilize the parameters and the soil water release curves in irrigation scheduling, and to evaluate the accuracy the proposed irrigation scheduling.

Materials and Methods

Generating parameters of soil water status using van Genuchten Model

Van Genuchten Model (van Genuchten, 1980) has been widely used to describe soil water release process. Soil water content at inflection point of vG Model is assumed to be the situation of texture-dominant pores (large and small) filled with water (Reynolds et al., 2009). At the initial stage of soil water release, the rapid decrease in soil water content is the depletion of soil water contained in large pores due to gravity. After the rapid depletion, soil water content decreases at a slower rate, and the depleted soil water is assumed to come from small pores due to plant water use (Brady and Weil, 2008) (Fig. 1a). Therefore, in the process of soil water release the point at which the slope changes from a rapid to a slower decrease in soil water content can be defined as FC (Zotarelli et al., 2009). The rapid decline stage could be expressed as the tangent line with inflection point, and the slow decline stage could be described as the tangent line with PWP. The intersection of the two tangent lines is the FC and the corresponding SWT (Fig. 1b).

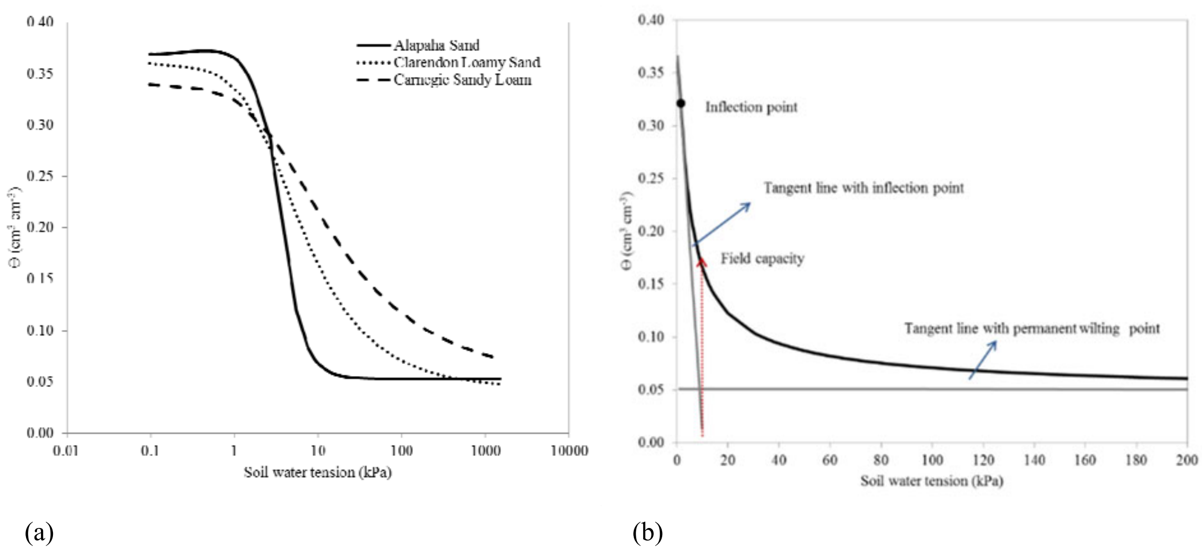

Fig. 1 Soil water release curves (a) of soil series Alapaha sand, Clarendon loamy sand, and Carnegie sandy loam with soil tension was expressed on a logarithmic scale; (b) with inflection point, PWP, and tangent lines with inflection point and PWP (using Clarendon series as an example)

Soil texture was assumed to be homogenous through the soil profile. Particle size distribution into sand, silt, and clay, and bulk density at soil profiles of 0-15 and 0-30 inch were thus averaged in a soil-depth weighted way, and the weighted means were shown in Tables 1 (Perkins et al., 1986). The selection of 0-15 and 0-30 inch was designated for shallow- and deep-rooted crops, respectively. Parameters of vG Model (θ_s, θ_r, n, and α) (van Genuchten, 1980) (Table 2) were generated from RETC software (RETC, 2009) based on soil physical characteristics indicated in Table 1.

Table 1 Weighted average of soil particle distribution into sand, silt and clay, and bulk density (BD) of typical soil series at Tift County, GA in soil profiles of 0-15/0-30 inch

Soil type	Sand				Loamy sand		Sandy loam		Sandy clay loam
Soil series	Alapaha	Fuquay	Troup	Pelham	Leefield	Tifton	Clarendon	Dothan	Carnegie
Sand (%)	96/93	90/88	91/91	88/89	85/83	81/73	78/70	82/71	76/65
Silt (%)	1.6/4.7	7.0/8.3	7.0/7.0	9.3/8.3	11/13	9.8/9.7	14/14	9.6/10	8.6/9.0
Clay (%)	2.4/2.3	2.8/3.4	1.6/2.2	2.5/2.6	3.3/4.5	9.2/18	7.8/16	7.9/19	15/26
BD (g cm^{-3})	1.6/1.6	1.5/1.5	---	1.6/1.6	1.6/1.6	1.7/1.6	1.6/1.6	1.6/1.6	1.7/1.7

Table 2 Parameters of vG Model of typical soil series at Tift County, GA in soil profiles of 0-15/0-30 inch

	Sand				Loamy sand		Sandy loam		Sandy clay loam
Parm	Alapaha	Fuquay	Troup	Pelham	Leefield	Tifton	Clarendon	Dothan	Carnegie
α	.03/.03	.04/.04	.04/.04	.04/.04	.04/.04	.04/.03	.04/.03	.04/.03	.03/.03
n	3.6/3.1	2.7/2.4	2.9/2.8	2.5/2.6	2.2/1.9	1.7/1.4	1.6/1.4	1.8/1.4	1.4/1.2
θ_s	.37/.36	.39/.40	.38/.38	.36/.36	.34/.35	.35/.36	.36/.36	.37/.37	.34/.35
θ_r	.05/.05	.05/.05	.05/.05	.04/.04	.04/.04	.05/.05	.04/.05	.05/.06	.05/.06

Van Genuchten Model (van Genuchten, 1980) describes how soil VWC decreases with increasing soil pressure head: $\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha h)^n]^{1-\frac{1}{n}}}$

where θ is soil VWC ($cm^3\ cm^{-3}$), and h is pressure head (cm). θ_s and θ_r are the saturated and residual VWC ($cm^3\ cm^{-3}$), respectively; and α and n are adjustable coefficients.

The first derivative of vG Model is: $\frac{d\theta}{dh} = \alpha^n(1-n)(\theta_s - \theta_r)\frac{h^{n-1}}{[1+(\alpha h)^n]^{2-\frac{1}{n}}}$

The second derivative of vG Model is:

$$\frac{d\theta^2}{dh^2} = \alpha^n(1-n)(\theta_s - \theta_r)\{(n-1)\alpha^{n-2}[1+(\alpha h)^n]^{\frac{1}{n}-2} - h^{2n-2}\alpha^n(2n-1)[1+(\alpha h)^n]^{\frac{1}{n}-3}\}$$

The inflection point of vG Model is obtained by setting its second derivative to zero. Therefore, the pressure head (h_i) and soil VWC (θ_i) at the inflection point can be calculated. The tangent line with inflection point of vG Model is using its first derivative as the slope (S_i) and crossing its inflection point (h_i, θ_i). The slope is: $S_i = \theta'(h_i)$

The tangent line with inflection point is: $\theta - \theta_i = S_i(h - h_i)$ or $\theta = S_i(h - h_i) + \theta_i$

Similar to the tangent line with inflection point above, the tangent line with PWP of vG Model is using its first derivative as the slope (S_{PWP}) and crossing its PWP (h_{PWP}, θ_{PWP}). The slope is: $S_{PWP} = \theta'(h_{PWP})$

The tangent line with PWP is: $\theta - \theta_{PWP} = S_{PWP}(h - h_{PWP})$ or $\theta = S_{PWP}(h - h_{PWP}) + \theta_{PWP}$

The soil pressure head at PWP is assumed as 15310 cm (pressure head) or 1500 kPa (SWT) (Tolk, 2003) and the corresponding VWC can be calculated from vG Model.

Intersection of the tangent line with inflection point and the tangent line with permanent wilting point is:
$S_i(h - h_i) + \theta_i = S_{PWP}(h - h_{PWP}) + \theta_{PWP}$
The pressure head at the intersection is: $h_{inter} = \frac{\theta_{PWP} + S_i h_i - S_{PWP} h_{PWP} - \theta_i}{S_i - S_{PWP}}$
The corresponding soil VWC at the intersection (or FC) is: $\theta_{FC} = \theta(h_{inter})$
Available water capacity (AWC) is calculated as $\theta_{AWC} = \theta_{FC} - \theta_{PWP}$. For convenience, pressure head h (cm) is converted to SWT (kPa) by $SWT = -\frac{h \times 9.8}{100}$

The calculated FC was compared to the FC generated from HYDRUS-1D software (HYDRUS-1D, 2012). HYDRUS-1D is a software for analysis of water flow and solute transport. Field capacity can be defined as the soil water content when the drainage flux from the initial saturation decreases to a predefined negligibly small value, such as 0.001, 0.01, and 0.1 cm d^{-1} (Twarakavi et al., 2009). The drainage flux of 0.1 cm d^{-1} was selected in the current study for coarse-textured soils.

Irrigation scheduling development

Irrigation quantities to bring the soil water status back to FC were calculated at 10, 20, 30, 40, 50, 60, 80, 100, 150, and 200 kPa in each soil series. The FC used in the calculation was the ones generated from vG Model as described above.

Irrigation scheduling evaluation

Six cotton fields in the southwestern Georgia were selected for the evaluation of irrigation scheduling generated from vG Model. WaterMark soil moisture sensors (Irrometer Company, Riverside, CA) for continuous measurements of SWT were installed at 8, 16, and 24 inch in the fields right after planting in the spring of 2014. The SWT of the 24-inch profile was calculated on a weight basis as:

$$h = \frac{1}{2} h_{8\ inch} + \frac{1}{3} h_{16\ inch} + \frac{1}{6} h_{24\ inch}$$

Soil water release curves were developed using the soil physical properties from Web Soil Survey (USDA-NRCS, 2013). The simulated water balance (the irrigation needed to bring soil water content from a lower SWT to higher one) using vG model and using Water Balance Equation was compared. The water balance from vG Model was calculated as follows:

A high SWT (h_1) was input into vG Model: $\theta(h_1) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h_1)^n]^{1 - \frac{1}{n}}}$

After rainfall or irrigation, SWT dropped to a lower level (h_2): $\theta(h_2) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h_2)^n]^{1 - \frac{1}{n}}}$

The soil water content difference between the two SWT values was calculated as $\Delta\theta = \theta(h_2) - \theta(h_1)$ and $\Delta\Theta = \Delta\theta \times depth$. $\Delta\theta$ and $\Delta\Theta$ are soil VWC difference in $cm^3\ cm^{-3}$ and mm, respectively.

On the other hand, the soil water balance was also calculated using the Water Balance Equation: $\Delta S = P + I - ET - D - R$, where ΔS is the change in soil water storage. P, I, ET, D and R represent precipitation, irrigation, evapotranspiration, drainage, and runoff, respectively. It was assumed that no runoff or drainage occurred during the experiment. Precipitation was measured using rain gauge in the field or close meteorological stations. Irrigation quantity and application dates were recorded. Cotton evapotranspiration was calculated on a daily basis using reference evapotranspiration and crop coefficients (data from Dr. Vasilis Liakos).

During the growth season, events of rainfall and irrigation application resulted in changes of SWT were selected. The change of soil water storage was calculated using vG Model and Water Balance Equation in each selected events, and the calculated results from the two methods were compared.

Results and Discussion

Parameters of soil water status generated from van Genutchen Model

Field capacity calculated from vG Model ranged from 0.12 to 0.14 cm^3 cm^{-3} for sand, 0.14 to 0.23 cm^3 cm^{-3} for loamy sand, 0.18 to 0.23 cm^3 cm^{-3} for sandy loam, and 0.20 to 0.26 cm^3 cm^{-3} for sandy clay loam (Table 3). Permanent wilting point was from 0.04 to 0.05 cm^3 cm^{-3} for sand, 0.04 to 0.08 cm^3 cm^{-3} for loamy sand, 0.05 to 0.09 cm^3 cm^{-3} for sandy loam, and 0.07 to 0.13 cm^3 cm^{-3} for sandy clay loam (Table 3). Field-measured FC in sandy soils ranged from 0.08 to 0.21 cm^3 cm^{-3} using capacitance probe (Zettl et al., 2011). The results in the current study were also close to measured FC in a sandy loam using gravimetric method and neutron probe 0.21 and 0.22 cm^3 cm^{-3}, respectively (Jabro et al., 2009).

Calculated PWP was close to parameter θ_r in vG Model (Tables 2 and 3), which was consistent with the definition of θ_r in vG Model (van Genuchten, 1980). Permanent wilting point generally ranges from 0.05 cm^3 cm^{-3} in sand, to 0.30 cm^3 cm^{-3} in clay (Czyz and Dexter, 2013; Teepe et al., 2003), and does not differ greatly from different studies or methods, as indicated as 0.04-0.05 cm^3 cm^{-3} for sand, 0.06 cm^3 cm^{-3} for loamy sand, and 0.071-0.092 cm^3 cm^{-3} for sandy loam (Czyz and Dexter, 2013; Dunne and Willmott, 1996; Twarakavi et al., 2010).

Available water content at FC ranged from 0.07 to 0.10 cm^3 cm^{-3} for sand, 0.10 to 0.13 cm^3 cm^{-3} for loamy sand, 0.12 to 0.14 cm^3 cm^{-3} for sandy loam, and 0.12 to 0.13 cm^3 cm^{-3} for sandy clay loam (Table 3). Soil water tension at FC was from 5 to 6 kPa for sand, from 6 to 15 kPa for loamy sand, from 8 to 15 kPa for sandy loam, and 13 to 17 kPa for sandy clay loam (Table 3). The results from the calculation were consistent with those from previous research in similar soil texture. Estimated SWT at FC was 18 and 27 kPa for a sandy loam and a clay loam respectively (Jabro et al., 2009). From field samples of two Florida sandy soils, FC was 0.11-0.16 cm^3 cm^{-3}, AWC 0.08-0.09 cm^3 cm^{-3} at alternative tension of 5-8 kPa (Obreza et al., 1998). In another sandy soil, AWC was 0.08 cm^3 cm^{-3} at soil matric potential of 5 kPa (Morgan et al., 2001).

Table 3 Field capacity (FC, cm^3 cm^{-3}), soil water tension at FC (SWT, kPa), permanent wilting point (PWP, cm^3 cm^{-3}), and available water content at FC (AWC, cm^3 cm^{-3}) generated from vG Model at depths of 0-15/0-30 inch of soil series of Tift County, GA.

	Sand				Loamy sand		Sandy loam		Sandy clay loam
	Alapaha	Fuquay	Troup	Pelham	Leefield	Tifton	Clarendon	Dothan	Carnegie
FC	.12/.12	.14/.14	.13/.13	.13/.13	.14/.15	.18/.23	.18/.22	.16/.23	.20/.26
SWT	5/5	6/6	5/5	6/5.5	6.5/6.5	10/15	9/14	8/15	13/17
PWP	.05/.05	.05/.05	.05/.05	.04/.04	.04/.04	.05/.08	.05/.08	.05/.09	.07/.13
AWC	.07/.07	.09/.10	.08/.08	.09/.08	.10/.11	.12/.13	.13/.14	.12/.14	.13/.12

In addition, the calculated FC were close to those generated from HYDRUS-1D at a drainage flux rate of 0.1 cm per day (Fig. 2). Field capacity estimated using HYDRUS-1D at drainage flux of 0.1 mm d^{-1} was 0.08 cm^3 cm^{-3} for sand, 0.17 cm^3 cm^{-3} for loamy sand, 0.22 cm^3 cm^{-3} for sandy loam, and 0.29 cm^3 cm^{-3} for sandy clay loam in general (Twarakavi et al., 2009). Compared to previous results, the calculated FC in the current study was close to those obtained from field measurements and estimation using different models, and thus this mathematic method is reliable in estimating FC.

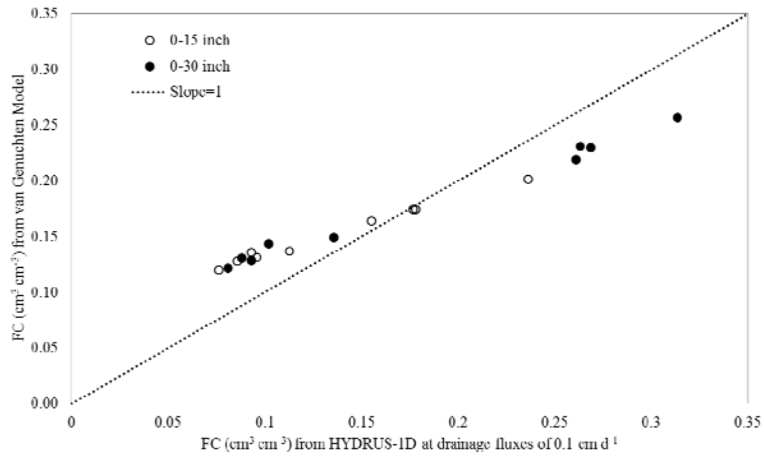

Fig. 2 Calculated FC from vG Model and from HYDRUS-1D at a drainage flux of 0.1 cm d^{-1}

Irrigation scheduling using van Genuchten Model

Table 4 Irrigation quantity to bring soil water status back to FC (inch) at depths of 0-15/0-30 inch

	Sand				Loamy sand		Sandy loam		Sandy clay loam
SWT	Alapaha	Fuquay	Troup	Pelham	Leefield	Tifton	Clarendon	Dothan	Carnegie
0 (kPa)	0	0	0	0	0	0	0	0	0
10	0.8/1.5	0.8/1.4	0.8/1.6	0.7/1.4	0.6/0.9	0.1/0	0.1/0	0.2/0	0
20	1.0/2.0	1.2/2.4	1.1/2.3	1.1/2.1	1.0/1.9	0.6/0.4	0.8/0.6	0.9/0.4	0.4/0.2
30	1.0/2.1	1.2/2.6	1.2/2.4	1.2/2.3	1.2/2.3	0.8/1.0	1.1/1.2	1.2/1.1	0.6/0.6
40	1.0/2.2	1.3/2.7	1.2/2.5	1.2/2.4	1.2/2.5	1.0/1.3	1.2/1.6	1.2/1.5	0.8/1.0
50	1.0/2.2	1.3/2.7	1.2/2.5	1.2/2.4	1.3/2.6	1.1/1.6	1.3/1.9	1.3/1.8	1.0/1.2
60	1.0/2.2	1.3/2.8	1.2/2.5	1.3/2.4	1.3/2.7	1.1/1.8	1.4/2.1	1.4/2.0	1.0/1.4
80	1.0/2.2	1.3/2.8	1.2/2.5	1.3/2.4	1.3/2.8	1.2/2.1	1.5/2.4	1.5/2.3	1.2/1.7
100	1.0/2.2	1.3/2.8	1.2/2.5	1.3/2.5	1.4/2.9	1.3/2.3	1.6/2.6	1.5/2.5	1.3/1.9
150	1.0/2.2	1.3/2.9	1.2/2.5	1.3/2.5	1.4/3.0	1.4/2.6	1.7/2.9	1.6/2.9	1.4/2.2
200	1.0/2.2	1.3/2.9	1.2/2.5	1.3/2.5	1.4/3.0	1.5/2.8	1.7/3.1	1.6/3.1	1.5/2.5
Water holding capacity	1.0/2.2	1.3/2.9	1.2/2.6	1.3/2.5	1.4/3.2	1.7/4.0	1.9/4.1	1.7/4.2	2.0/3.7

Irrigation scheduling was built based on the FC and soil release curves of each soil series (Table 4). For soil series of sand, soil water depletion is very fast. Even at 10 kPa, irrigation quantity was more than 50% of water holding capacity. When the soil texture became denser, soil water depletion was slowed down. The irrigation of 50% of water holding capacity occurred at 50 kPa or higher. The irrigation scheduling in the current study was similar to the soil water depletion and available water capacity in sand, loamy sand, and sandy loam in Nebraska in the study of Irmak et al. (2006).

Comparing irrigation scheduling from van Genuchten Model to Water Balance Equation

The evaluation was separated into two scenarios: water balance from vG Model was either higher than or equal to water storage from Water Balance Equation (Fig. 3). But they were closely correlated with the determination coefficients of 0.65 and 0.86, respectively.

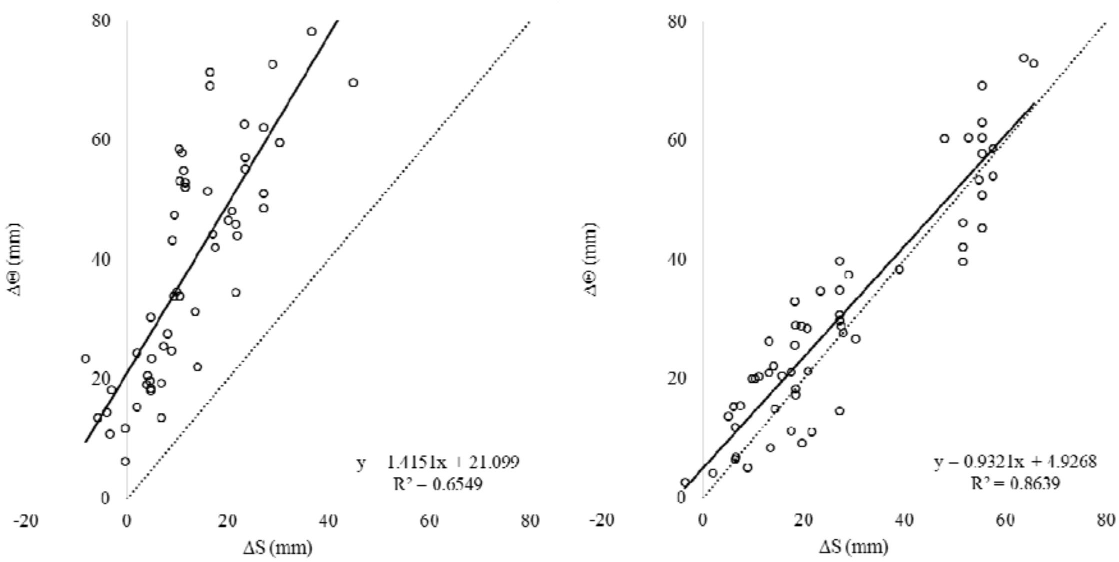

Fig. 3 Comparison of the difference of soil VWC derived from vG Model and Water Balance Equation. ΔΘ represents the water balance calculated from vG Model, and ΔS is the change of soil water storage calculated from the Water Balance Equation.

Summary

A new method was proposed in the current study to obtain FC from vG Model. Soil FC and SWT at FC calculated in the current study were consistent with previous results in soils with similar textures, and were also close to those generated from HYDRUS-1D. Due to the accuracy of the calculated FC, it was utilized as the upper limit in irrigation scheduling, and the irrigation quantities needed to bring the soil profile to FC was calculated at different SWT. The developed irrigation scheduling was similar to those developed in soils with similar textures. In the evaluation of the developed irrigation scheduling, the water balance calculated from the vG Model was equal to or higher than that calculated from the Water Balance Equation, but they were linearly correlated. With further calibration, it is possible to utilize the vG Model in FC calculation and irrigation scheduling.

Acknowledgements

The work was funded through grants awarded to the Southeast Climate Consortium Southeast Climate Extension project funded by USDA-NIFA and NOAA's Regional Integrated Sciences and Assessments (RISA) Program. We gratefully acknowledge Mr. Michael Tucker, Mr. Herman Henry, and Mr. Rodney Hill for installing and maintaining the sensor network.

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