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Modelling of Soil Water Movement and Its Application of Citrus Garden in Hilly Area of Jiangxi Province

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Abstract

The soil water movement in citrus garden in the region of low hilly area is highly concentrated. It’s necessary to develop water-saving agriculture along gentle slope upland in southern China. The numerical modeling of soil moisture content was established, based on Richard movement equitation. The simulated soil moisture was in good agreement with measured data. Modeling analysis showed that the soil hydraulic parameters are more sensitive than other kind of parameters. The simulation also demonstrated that the cumulative evapotranspiration in the 150 cm soil profile at upper slope is higher than lower slope. In conclusion, it’s advantageous for tillage soil at the lower slope to keep soil moisture and resist the drought in the citrus garden during dry season in southern China. The numerical modeling of soil moisture has practical significance to improve the management of water capture and retention and development of water-saving agriculture.

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Keywords: Soil water movement; dynamic modeling; citrus garden; water balance
1. Introduction

Southern China's low hilly area of red soil, including Hainan, Guangxi, Guangdong, Fujian, Hunan, Jiangxi, Zhejiang, Hubei, Anhui and Sichuan provinces of the 619 counties, has land area of 1,133,300 km². It accounts for 11.8% of total national area. Its rich biological and climatic resources play an important role in China's agricultural and economic development. With a combination of traditional agricultural and valley agriculture, the hilly region of red soil will become an important base for agricultural production in China.

Richards equation-based simulation of soil moisture dynamics is a relatively fast and inexpensive means of studying the effects of slope upland on root zone water storage and the difference of slope positions. Analytical or numerical models (Noborio et al., 1996; Zhang et al., 1999; Dahiya et al., 2007) have been developed to simulate and manage the transport of water, heat and salt through the variably saturated soil zones. Application and accuracy of these models depend upon the specific field conditions. Most methods for estimating the hydraulic parameters are tedious and time consuming. An increasing alternative to direct measurement of soil hydraulic parameters is the use of inverse modeling (Van Genuchten, 1980; Dahiya et al., 2007, Schadler, 2007). However, little information is available on inverse modeling of red soil along gentle slope upland in southern China.

Based on the theory of fluids dynamics and the soil moisture data of gentle slope, the dynamic model of red soil moisture was established during the growth stage of citrus growth in southern China in the paper. Additionally, we used model calculation to assess water balances for upper slope and lower slope under different hydrological years.

2. Materials and Methods

2.1. Field measurements

Field experiments were carried out at the field of the third Liu Ken farm from 2001 to 2003 in Yujiang County, Jiangxi Province. Experiment area is 25.2 ha. The altitude is 45.0 m, and the slope gradient is 5 degree. The parent material is the Quaternary red clay, where selected area is typical distribution hilly region of red soil.

Experimental area has plenty of rainfall, adequate sunshine, four remarkable seasons, and long frost-free period. The total average amount of solar radiation is 108.5 kal cm-2 over years. The average annual sunshine is 1868.5 h while the average annual temperature is 17.7 °C. The averaged annual rainfall reaches 1788.4mm. All meteorological data were from the weather station in the vicinity.

Soil moisture was measured by tensiometers and data logger (U.K.). The measure depths were designed repeatedly as 20-, 40-, 60-, 85-, 150-cm at the middle slope of citrus. The retention curve of soil samples was determined by pressure plate chamber.

2.2. Numerical modeling

2.2.1. Model description

Assuming a homogeneous and isotropic soil under the condition of root water uptake, the governing equation for water flow is the Richards equation:
\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ K(\theta) \frac{\partial h}{\partial z} - K(\theta) \right] - S(z,t)
\] (1)

Where \( \theta \) is the volumetric water content \((\text{cm}^3\text{cm}^{-3})\), \(K(\theta)\) is the hydraulic conductivity \((\text{cmd}^{-1})\), \(h\) is the soil water pressure head \((\text{cm})\), \(S(z,t)\) is the rate of root water uptake \((\text{d}^{-1})\), \(t\) is the time \((\text{d})\), \(z\) is the vertical space coordinate \((\text{cm})\). Due to deep level for underground water, the initial and boundary conditions of water flow can be written as:

\[
\theta(z,t) \mid _{t=0} = \theta_0(z), \quad \theta(z,t) \mid _{z=L} = \theta_0(L)
\] (2)

\[
\left. k(\theta) \frac{\partial h}{\partial z} - k(\theta) \right| _{z=0} = E_{\text{s}(t)} - P_{(t)}
\] (3)

where \(L\) is depth of the soil profile, \(E_{\text{s}(t)} \) \((\text{mm d}^{-1})\) is the maximum potential rate of evaporation under the prevailing atmospheric conditions, and \(P_{(t)} \) \((\text{mm d}^{-1})\) is rainfall intensity at local situations.

### 2.2.2. Root Water Uptake of citrus

The expression of root water uptake model was specified according to Belmane et al. (1983):

\[
S(z,h) = \alpha(h) S_{\text{max}}
\] (4)

where \(S(z,h)\) represents the volume of water removed per unit time from a unit volume of soil due to plant water uptake, \(\alpha(h)\) is a prescribed dimensionless function of the soil water pressure head, \(S_{\text{max}}\) is the potential water uptake rate.

### 2.2.3. Soil evaporation and crop transpiration

The potential evaporation \((ET_p, \text{mm d}^{-1})\) was estimated from Penman Monteith equation (Monteith, 1981). Since the ratio of potential evaporation \(E_p\) to potential transpiration was directly related to \(LAI\) describing the crop situations, and \(LAI\) of crop changes with the developing stages, therefore they were expressed by the following equation:

\[
E_p = ET_p e^{-\beta LAI}
\] (5)

\[
T_p = ET_p - E_p
\] (6)

\[
LAI = \begin{cases} 
-0.188 + 0.22 JD - 0.004 JD^2 + 0.000015 JD^3 & JD < 33 \\
4.6315 JD^{0.1065} & JD \geq 33
\end{cases}
\] (7)

where \(\beta\) is a coefficient related crop species, the value is 0.6 for citrus. \(JD\) is the day after citrus sowing.

### 2.2.4. Hydraulic functions

The soil water retention curve and the hydraulic conductivity function were expressed by the following equations (Van Genuchten, 1980; Sobieraj et al., 2002) as (9)–(10). where, \(\theta_r\) and \(\theta_s\) are residual and saturated water content \((\text{cm}^3\text{cm}^{-3})\), respectively, \(\theta_s\) is estimated from its total porosity; \(\alpha\) is inverse of bubbling pressure \((\text{cm}^{-1})\); \(n\) is a fitting constant reflecting the steepness of retention curves; parameter \(m = 1 - 1/n\); \(K_s\) is saturated conductivity \((\text{cm d}^{-1})\); \(S_e\) is effective water saturation.
\[ S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \left[ 1 + (\alpha h)^n \right]^m \]  

(9)

\[ K(\theta) = K_S S_e^{0.5} \left[ 1 - (1 - S_e^{1/m})^m \right]^2 \]  

(10)

3. Results and Discussion

3.1. Simulation results

Three layers of the soil profile were considered for simulation due to uneven nature of soil profile. Fig. 1 describes the measured and simulated soil moisture during the growth period of citrus from 2001 to 2003. The simulation showed that the simulated curves have same trends as measured changes in the field. The averaged relative error is 3.3% at the citrus garden. The maximum value is 5.6% occurring in the 0-30 cm soil layer, while the minimum value is 1.7% in the 50-70 cm soil (Table 1).

![Fig.1. Comparison between simulated and measured soil water content at the citrus field from 2001 through 2003](image-url)
Table 1. Relative error (%) of simulated value of soil moisture with measured value by tensiometer in different horizons

<table>
<thead>
<tr>
<th>Year</th>
<th>0-30 cm</th>
<th>30-50 cm</th>
<th>50-70 cm</th>
<th>70-100 cm</th>
<th>100-200 cm</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>4.86</td>
<td>3.42</td>
<td>3.64</td>
<td>3.58</td>
<td>4.56</td>
<td>4.01</td>
</tr>
<tr>
<td>2002</td>
<td>5.12</td>
<td>3.14</td>
<td>2.32</td>
<td>1.69</td>
<td>2.3</td>
<td>2.91</td>
</tr>
<tr>
<td>2003</td>
<td>4.12</td>
<td>4.73</td>
<td>2.56</td>
<td>2.93</td>
<td>6.54</td>
<td>4.18</td>
</tr>
</tbody>
</table>

3.2. Sensitivity analysis

The sensitivity of the modeling depends not only on the internal structure, but also on the soil and plant factors. The change of soil moisture was taken into account as the increase value of 5%, 10%, 25%, 50% for main parameters (Table 2). Different parameters under same situations changed as non-linear, indicating that the sensitivity of the parameters is different in the model. The more sensitive parameters are the soil hydraulic parameter of $\theta_s$, $n$ and $\theta_r$ while the sensitivity for LAI of crops is smaller. The parameter sensitivity is the smallest for root density of Rd.

Table 2. The values from sensitivity analysis of model parameters

<table>
<thead>
<tr>
<th>$\theta_r$</th>
<th>$\theta_s$</th>
<th>$K_s$</th>
<th>$\alpha$</th>
<th>$n$</th>
<th>$K_c$</th>
<th>LAI</th>
<th>$R_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[cm$^3$cm$^{-3}$]</td>
<td>[cm$^3$cm$^{-3}$]</td>
<td>[cmd$^{-1}$]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[cmcm$^{-3}$]</td>
</tr>
<tr>
<td>+5%</td>
<td>0.127</td>
<td>0.922</td>
<td>-0.0124</td>
<td>0.0073</td>
<td>-0.2498</td>
<td>-0.0357</td>
<td>0.0031</td>
</tr>
<tr>
<td>+10%</td>
<td>0.1236</td>
<td>0.9192</td>
<td>-0.0126</td>
<td>-0.0268</td>
<td>-0.2394</td>
<td>-0.0343</td>
<td>0.002</td>
</tr>
<tr>
<td>+25%</td>
<td>0.1286</td>
<td>0.9426</td>
<td>-0.0128</td>
<td>-0.0081</td>
<td>-0.2061</td>
<td>-0.0321</td>
<td>0.001</td>
</tr>
<tr>
<td>+50%</td>
<td>0.1367</td>
<td>0.9765</td>
<td>-0.012</td>
<td>-0.01</td>
<td>-0.1207</td>
<td>-0.0318</td>
<td>0.0012</td>
</tr>
</tbody>
</table>

3.3. Model application under different hydrological years

In order to compare the differences of water balance between upper slope and lower slope under different years, the analysis of hydrological frequency local from rainfall data and evapotranspiration was carried out from 2001 to 2003. The evapotranspiration increased with rainfall at upper and lower slope during the citrus growing season under different hydrological years. But the cumulative evapotranspiration at upper slope is little smaller than the lower slope for the 150 cm soil profile. The maximum difference reached 23.4 mm of calculation in 2002. But, the maximum difference reached 13.6 mm of simulation in 2003. The reason is that the average amount of water storage at upper slope is slightly smaller than lower slope during the growth of citrus (Table 3). The cumulative evapotranspiration difference depends on rainfall, land use, slope position and calculation.

4. Conclusions

The numerical modeling of soil water dynamics was established for the citrus garden along gentle slope upland. It could be adapted to crop water use and water management for the field of the red soil in southern China. Soil moisture at the fields with gentle slope was affected by season, soil type, crops and other factors. Modeling analysis showed that the soil parameters have greater sensitivity.

The established modeling was found to be a useful tool to determine field scale hydraulic properties using experimental data for analyzing soil moisture dynamics and water balance under gentle slope
conditions. Next step is attempting to create a two-dimensional model of water movement along gentle slope based on further investigated data and improved experimental design.

Table 3. Slope difference of cumulative evapotranspiration in the 150 cm depth in different year

<table>
<thead>
<tr>
<th>Position</th>
<th>Rain [mm]</th>
<th>Calculation [mm]</th>
<th>Simulation [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>Upper</td>
<td>1614.5</td>
<td>794.9</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>1614.5</td>
<td>812.8</td>
</tr>
<tr>
<td>2002</td>
<td>Upper</td>
<td>1697.8</td>
<td>804.1</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>1697.8</td>
<td>828.7</td>
</tr>
<tr>
<td>2003</td>
<td>Upper</td>
<td>1555.4</td>
<td>764.5</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>1555.4</td>
<td>754.2</td>
</tr>
</tbody>
</table>

Cumulative evapotranspiration at upper slope is smaller than lower slope while the arable layer at lower slope is favorable to resisting the drought from citrus garden. The numerical modeling of soil moisture has practical significance to improve the management of water capture and retention and development of water-saving agriculture.

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References