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Modeling Soil Water Dynamics Based on the Approach of Compensatory Root Water Uptake

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Modeling Soil Water Dynamics Based on the Approach of Compensatory Root Water Uptake

Cong Li[1], Zhengfeng Hu[2] and Kefeng Zhang[3*]

[1] College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310058, China

[2] Design and Research Institute of Environmental Protection Sciences of Zhejiang Province, Hangzhou 310007, China

[3] Ningbo Institute of Technology, Zhejiang University, Ningbo 315100, China

[*]Corresponding author's e-mail: kfzhang@nit.zju.edu.cn

Abstract. Agro-hydrological models can not only be used to study water dynamics in the soil-crop system, but also be used for agricultural water management. Therefore, it is important to devise this kind of models. In this study, a new agro-hydrological model, based on the compensatory root water uptake approach, was proposed. A dataset from field experiments on cabbage was used to evaluate the reliability of the model. Results showed that the predicted soil water potential at various depths agreed well with the measurements. The Nash-Sutcliffe efficiency coefficient and the Willmott's index of agreement reached to 0.633 and 0.916, respectively, indicating that model was accurately constructed, and could potentially be used for optimizing water use in agriculture.

1. Introduction

It is well documented that agro-hydrological models have played a pivotal role in optimizing resources use in agriculture, and a great number of such models have been proposed [1].

Agro-hydrological models concern various processes [2], and one of which is the macro-level description of root water uptake. It assumes that root water uptake is determined by crop potential evapotranspiration, root length density and soil water potential. There are two commonly used ways, named non-compensatory and compensatory approaches, to describe root water uptake in the existing agro-hydrological models [3-6]. The non-compensatory approach calculates the actual root water uptake at a given depth based on the local root length density and soil water content/potential only, and the capacity of root water uptake reduces as a result of lacking water in the soil. The compensatory approach, on the other hand, takes the whole root system into consideration, and the reduction of root water uptake in dry soil regions can be compensated by the increased water uptake by roots in the wet regions. There is evidence that the simulated results from the compensatory approach are more reasonable, compared with the measurements [6].

In this study, an agro-hydrological model for water dynamics in the soil-crop system using the compensatory approach for root water uptake based on the work by Yang *et al.* [3] was first proposed. The model was then validated against measured data from field experiments on cabbage, and its performance was rigorously assessed by statistical analyses of the simulated results.

2. The model

2.1. Governing equations

For the 1-D situation in the soil-crop system, soil water movement can be described by the Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}[K(\theta)(\frac{\partial h}{\partial z}+1)] - \beta(h)S_{\max}(z) \tag{1}$$

in which   is the soil volumetric water content, z is the vertical coordinate, t is the time, h is the soil water pressure head, K is the soil hydraulic conductivity,   is the reduced coefficient of root water uptake, S_{max} is the maximum root water uptake, i.e. potential crop transpiration.

As mentioned early, the compensatory approach assumes that roots can take up more water in the wet regions to compensate the reduction of water uptake by roots in dry regions. Although there are different root water uptake models using such a principle [5-8], the method proposed by Javis [5] was widely used. With this method, S_{max} at a specific depth z is calculated as follows:

$$S_{\max}(z) = \frac{T_{pot}\beta(h)L_r(z)}{\int_0^{R_z}\beta(h)L_r(z)dz} \tag{2}$$

in which T_{pot} is the crop potential transpiration, which can be computed according to the FAO56 [9]. $L_r(z)$ is the relative root length density at z [10]. The calculation of   can be seen elsewhere [3].

2.2. Assessment of model performance

Four statistical indices are used for evaluating the simulated results. They are: the root of the mean squared errors (*RMSE*), the mean error (*ME*), the Nash-Sutcliffe efficiency coefficient (*NSE*) [11] and the Willmott's index of agreement (*d*) [12]

3. Field experiments

The field experiments were carried out on the farm at the International Horticulture of Warwick University, UK (latitude: 52°12' N, longitude: 1°37' W). The soil was sandy loam, and the soil particular distribution and its associated soil hydraulic properties can be seen in Zhang *et al.* [13]. The fully randomised block method was used in the experiments. The crop, cabbage (*cv. Eminence*, Tozer seeds, UK), was transplanted on 29 April, 2009, and harvested on 28 September in the same year. The experimental plot size was 5.0 x 2.0 m, and the spacing within and between rows was 0.5 m. The soil was irrigated with 6.4 mm of water on 5 May, 9.6 mm on 12 May and 3.1 mm on 2 June. The above-ground crop dry weight at harvest was 13.2 t/ha, and the maximum rooting depth was 140.0 cm. Watermark 200SS-v sensors (Irrometer Company, USA), which could measure soil water potential in the range of -10 to -200 kPa with reasonable accuracy, were used. The sensors were placed at the depths of 10, 30, 50, 70, 90 cm on 10 June, 2009. A data logger (DL2e, Delta-T devices, Cambridge, UK) was used for recording the measured sensor data, and the recorded time interval was 1 h. The initial soil water content was measured on 1 May, 2009 in the layers of 0-30 cm, 30-60 cm and 60-90 cm, and the measured values were 0.20，0.21 and 0.24 cm3 cm-3, respectively. The weather data during the experiments were collected from an onsite weather station. Figure 1 shows part of the measured weather data. A detailed description of the experiments can be found in [13].

4. Results and discussion

4.1. Overall comparison of the simulated results

Figure 2 and Table 1 show the comparison of soil water potential at various depths between measurement and simulation and the statistical analyses of the simulated values. It is clear that the value of R^2 of the fitted line between measurement and simulation reaches 0.745 with the number of

samples of 188. The gradient of the fitted line is 0.756 which is close to 1.0, and the intercept is small (Figure 2). This indicates that the simulated values are highly correlated with the measurements. The calculated statistical indices of *RMSE* and *ME* are small, whilst both *NSE* (0-1) and *d* (0-1) are relatively high (Table 1). The negative value of *ME* suggests that the overall simulated values are smaller than the measurements. It is reasonable to conclude that the proposed model performed satisfactorily for the studied case.
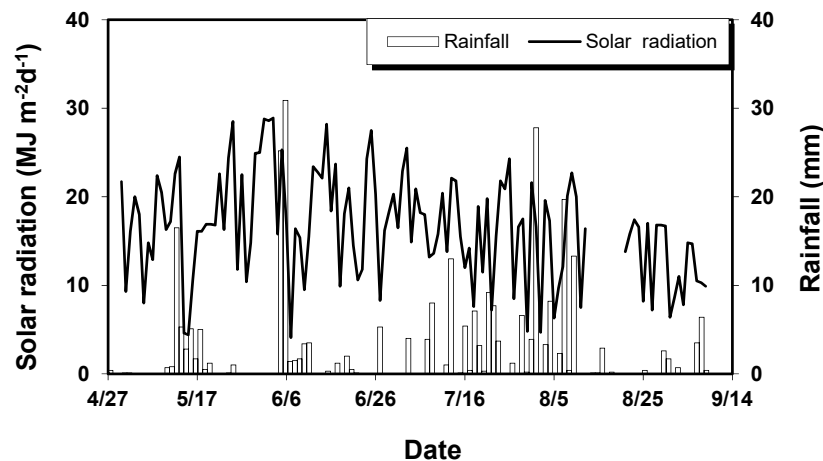

Figure 1. Measured daily solar radiation and rainfall during the experimental period

Table 1. Statistical analyses of simulated values of soil water potential

No of samples	RMSE (kPa)	ME (kPa)	NSE (-)	d (-)
188	17.86	-5.46	0.633	0.916

4.2. Soil water potential at various depths

Detailed comparisons of soil water potential at various depths were also carried out, and some of such comparisons are shown in Figure 3 as examples. It can be observed from Figure 3 that: (1) The simulated patterns of variation in soil water potential coincided with the measurements. There were two dry periods from 20 June to 12 July and 20 August to 8 September after the installation of soil sensors at 10 June. Soil water potential at the depths of 10 cm and 50 cm decreased markedly. (2) Soil water potential at the depths of 10 cm and 50 cm was greatly affected by both weather and root water uptake, leading to much bigger variations in the measured and simulated values. (3) No great change in soil water potential was observed at the depth of 90 cm. The model predicted a small decrease in soil water potential at the late stage of crop growth with the minimum value of -22.5 kPa. This suggests that the effect of crop growth on soil water below the depth of 90 cm was ignorable due to sparse root distributions in the region.

5. Conclusions

An agro-hydrological model was proposed for water dynamics using a compensatory approach for root water uptake in this study. Results showed that the measured soil water potential values at various depths could be reasonably re-produced by the model. Overall the model performed satisfactorily. This suggests that the model could be used for studying water relations and precise water management in crop production.
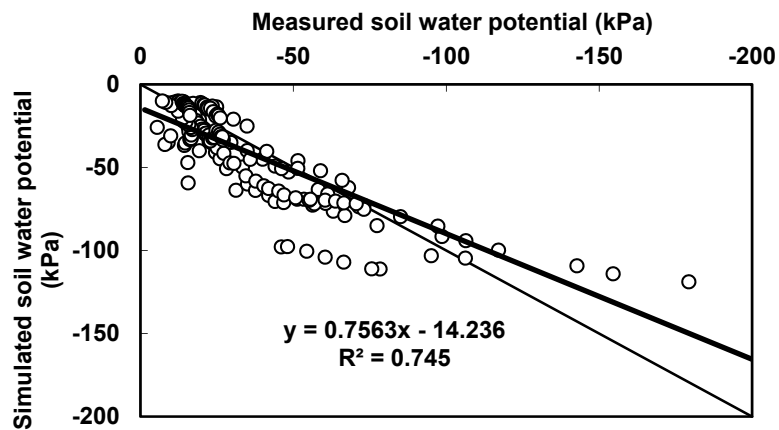
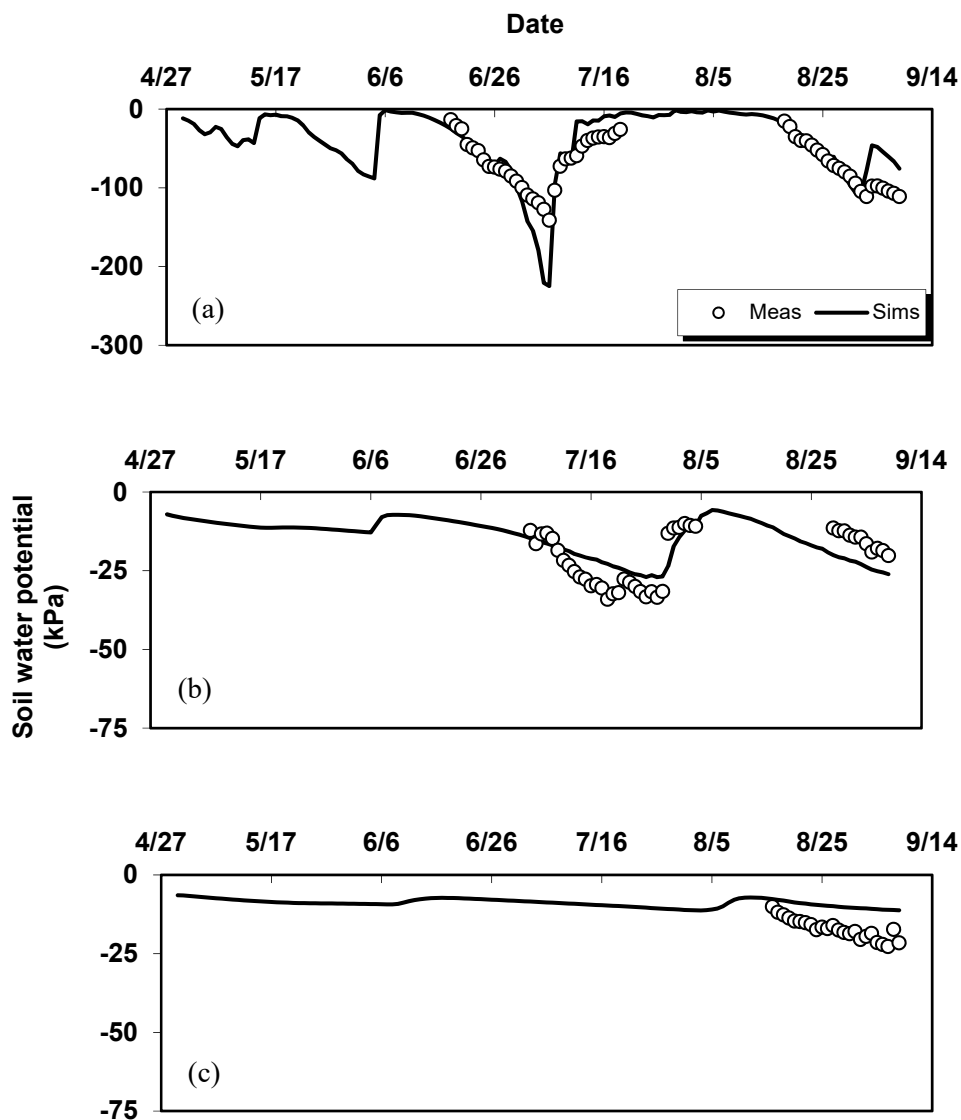Figure 2. Overall comparison of soil water potential between measurement and simulation

Figure 3. Comparison of soil water potential at different depths, (a) the 10 cm depth, (b) the 50 cm depth, (c) the 90 cm depth

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