Modeling The Water Balance For Aerobic Rice: A System Dynamics Approach

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EXTENDED ABSTRACT

A field soil water balance model is developed for non-ponded "aerobic rice" in North China Plain. Increasing water scarcity necessitates the development of irrigated rice systems that require less water than traditional flooded rice. The aerobic rice is an effort to save water in response to growing worldwide water scarcity with the pressure to reduce water use and increase water productivity in irrigated agriculture. Aerobic rice is not ponded and irrigated similar to other crops and is suitable for water-scarce environments and can stand being periodically flooded.

In any water harvesting and recycling systems, accurate estimation of different water balance components in a cropped field is essential to achieve effective use of limited irrigation water. Soil water balance models are helpful to develop appropriate strategies for efficient management of irrigation water.

The conceptual model is firstly presented. Based on the analysis and integration of existing information available on hydraulic processes occurring in an aerobic rice field, this paper outlines the general components of the water balance. The hydraulic dynamics is analyzed from the feedback relations among the components (Figure 1). Referring to existing knowledge and information, the model is formulated using mathematical equations and implemented using the Vensim simulation tool. The model simulates various water balance components such as actual evapotranspiration, percolation, surface runoff, and capillary rise in the field on a daily basis. The model parameters are validated with the observed experimental field data from Huibei Irrigation Station, Kaifeng. A statistical test (t-test) is carried out to determine the significance between the observed and simulated values of the parameters and the results show that the simulated and observed values are the same at 95% confidence level. The R^2 are found to be high and root mean square error low. Thus the presented model can perform the simulation of soil water balance system for aerobic rice.

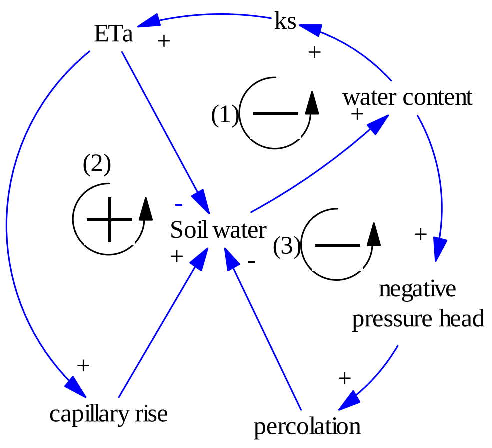

Figure 1. Causal loop diagram for the dynamic soil water system

The system dynamics technique proved to be an efficient approach for the simulation of a complex water resource system. Its merits include the increased speed of model development, ease of model improvement, ease of model improvement and its inherent flexibility And transparency. Scenarios, other than those treatments simulated in this study are being evaluated (not reported in this study) by using the existing framework.

1. INTRODUCTION

Increasing water scarcity necessitates the development of irrigated rice systems that require less water than traditional flooded rice. Since the late 1990s, aerobic rice has been grown in the North China Plain as a supplementary-irrigated upland crop to cope with water scarcity. In irrigated aerobic rice systems, rice grows in non-flooded and non-saturated soil under supplemental irrigation. Aerobic rice is not ponded and irrigated similar to other crops and is suitable for water-scarce environments, and can stand being periodically flooded (Yang et al. 2005).

In any water harvesting and recycling systems, accurate estimation of different water balance components in a cropped field is essential to achieve effective use of limited irrigation water (Agrawal et al., 2004). Soil water balance models are helpful to develop appropriate strategies for efficient management of irrigation water. The existing soil water balance models for rainfed rice and low land rice (e.g. Agrawal et al., 2004; Panigrah and Panda, 2003, Wopereis et al, 1993); however, a soil water balance model for aerobic rice has not been seen in literatures.

This study attempts to develop a dynamic model for addressing soil water balance associated with hydrological processes. System dynamics (Sterman 2000) is applied as a methodology that provides an inside view of endogenous feedback structures relating to hydraulic processes in a soil water balance system in an aerobic rice field. The system dynamics tool, Vensim is used as it provides a fully integrated simulation system to conceptualize, document, simulate, analyze, and optimize models of dynamic systems.

The conceptual model is firstly presented, and then, based on the analysis and integration of existing information available on hydraulic processes occurring in an aerobic rice field, this paper outlines the general components of the water balance. The hydraulic dynamics is analyzed from the feedback relations among the components. Referring to existing knowledge and information, the model is formulated using mathematical equations and implemented using the Vensim simulation tool (Ventana Systems, Inc., 2004). The model simulates various water balance components such as actual evapotranspiration, percolation, surface runoff, and capillary rise in the field on a daily basis. The model parameters are validated with the observed experimental field data from Huibei Irrigation Experiment Station, Kaifeng.

2. MODEL DEVELOPMENT

2.1. Conceptual model

Field experiment for the year of 2003 was established in the upland of Huibei Irrigation Experiment Station, Kaifeng, China. The water balance model is formulated for aerobic rice with supplemental irrigation. Because the soil is coarse and there was no dyke around the field, there was no standing water during the growth season and only unsaturated condition is taken into consideration. Plots were divided with plastic to avoid lateral seepage between them.

Schematically, the root zone can be conceptualized as a box in which the water content fluctuates over time (Figure 1). The water content is expressed as the crop root zone fraction. It makes the adding and subtracting of losses and gains straightforward as the various parameters of the soil water budget are usually expressed in terms of water depth. Rainfall, irrigation and capillary rise of groundwater towards the root zone add water to the root zone and decrease the root zone depletion. Soil evaporation, crop transpiration, surface runoff and percolation losses remove water from the root zone and increase the depletion (Allen et al., 1998).

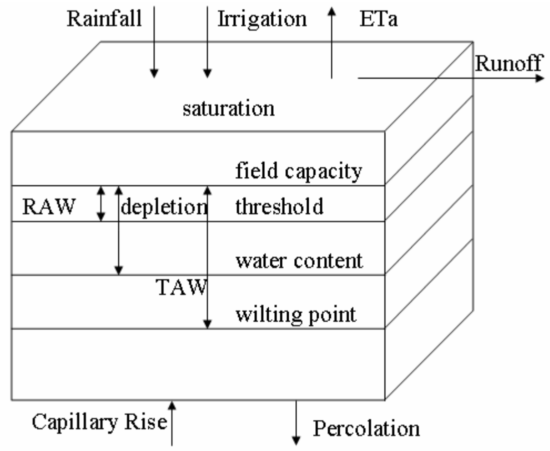

Figure 1. Conceptual model of soil water balance (Allen et al., 1998)

2.2. Model formulation

Considering the effective root zone as a single layer, the soil water balance at the field level can be expressed in terms of storage as given below:

$$S_j = S_{j-1} + I_j + R_j + CR_j - ET_{aj} - P_j - SR_j \quad (1)$$

Where S_j, S_{j-1} are the soil water storage at the end of day j and $j-1$; I_j is the irrigation on day j; R_j is the rainfall on day j; CR_j is the capillary rise from the underlying watertable on day j depending on the depth to watertable; ET_{aj} is the evapotranspiration on day j; P_j is the percolation on day j; and SR_j is the runoff on day j.

Under unsaturated conditions, actual evapotranspiration (ET_a) is calculated by:

$$ET_{\text{a}} = K_c \cdot K_s \cdot ET_0 \qquad (2)$$

Where K_s is a dimensionless factor expressing the effects of limiting soil moisture conditions on crop evapotranspiration; and K_c is the single crop coefficient (Allen et al., 1998).

The soil moisture coefficient used in Equation 2 is calculated by:

$$K_s = \begin{cases} 1 & D \le RAW \\ \dfrac{TAW\text{-}D}{TAW\text{-}RAW} & RAW \le D \le TAW \end{cases} \qquad (3)$$

Where D is the root zone depletion; RAW is the readily available soil water in the root zone; TAW is the total available soil water in the root zone. According to Figure 1, we have:

$$K_s = \begin{cases} 1\text{¡¡¡¡¡¡¡¡¡¡¡¡¡¡} & \theta \ge \theta_{threshold} \\ \dfrac{\theta - \theta_{wp}}{\theta_{threshold} - \theta_{wp}}\text{¡¡} & \theta_{wp} \le \theta < \theta_{threshold} \end{cases} \qquad (4)$$

Where θ is the volumetric water content; θ_{wp} is the water content at wilting point; and $\theta_{threshold}$ is the threshold water content when water stress occurs.

$$\theta_{threshold} = (1-p) \cdot \theta_{fc} + p \cdot \theta_{wp} \qquad (5)$$

Where p is the fraction of total available water that a crop can extract from the root zone and θ_{fc} is the water content at field capacity.

Under unsaturated conditions, the well-established empirical soil water retention function proposed by Brooks and Corey (1964) is used:

$$h(\theta) = \frac{h_b}{\left(\dfrac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{1/\lambda}} \qquad (6)$$

Where $h(\theta)$ is negative pressure head; h_b is bubbling or air entry pressure head; θ is volumetric soil water content; θ_r is residual water content; θ_s water content at saturation; and λ is pore size index.

Darcy's Law was used to calculate the percolation from soil water to groundwater:

$$K(\theta) = K \cdot e^{-\alpha / h(\theta)} \qquad (7)$$

Where K is the saturated vertical hydraulic conductivity; and α is texture-specific empirical constant, which is 1.0 for sandy loam soil (Tindall et al., 1999).

Darcy's Law was used to calculate the percolation from soil water to groundwater:

$$P = \frac{(h(\theta) - h) \cdot K(\theta)}{T} \qquad (8)$$

Where h is the groundwater head; and T is the soil thickness between rooting zone and groundwater table.

Upward capillary fluxes from the groundwater are ordinarily evaluated using empirical formulas that involve some soil-related parameters and consider the depth of groundwater table below the root zone. Capillary rise is evaluated using the following exponential relationship (Li and Dong, 1998):

$$CR = ET_c \cdot e^{-\sigma \cdot d} \qquad (9)$$

Where CR is the capillary rise; ET_c is the crop evapotranspiration; σ is a parameter that relates to the capacity of the soil to transmit capillary fluxes; and d is the depth of the groundwater table below the bottom of the root zone.

Throughout the aerobic rice growth season, no standing water occurred. When the soil becomes saturated after irrigation, redundant water is discharged as surface runoff. Surface runoff from the field is given as:

$$SR_j = \begin{cases} 0 & \theta \le \theta_s \\ S_j - \theta_s \cdot D_r & \theta > \theta_s \end{cases} \qquad (10)$$

Where θ is the saturated water content; D_r is the root depth and the other are the same as above.

2.3. The system dynamics model

System dynamics is a theory of system structure and a set of tools for representing complex systems and analyzing their dynamic behavior (Forrestor, 1961). The most important feature of system dynamics is to elucidate the endogenous structure of the system under study, to see how the different elements of the system actually relate to one another, and to experiment with changing relations within the system when different decisions are included. In system dynamics, the relation between structure and behavior is based on the concept of information feedback and control (Simonovic, 2002).

In system dynamics modeling, causal loop diagrams represent the major feedback mechanisms, which reinforce (positive feedback loop represented by '+') or counteract (negative feedback loop represented by '-') a given change in a system variable (Sterman, 2000). The first negative feedback loop in Figure 2 represents the interaction between actual evapotranspiration "ETa" and soil water storage: the larger the ETa, the less the water storage, then the less the soil water content and soil moisture coefficient "ks", which in turn decreases ETa, completing the negative loop. The second feedback loop represents the interaction between ETa and capillary rise: the larger the ETa, the larger the capillary rise, then the larger the soil water content and ks, which in turn increases ETa, completing the positive loop. The third feedback loop represents the interaction between soil water storage and percolation: the larger the storage, the larger the water content, then the larger the negative pressure head and percolation, which in turn decreases soil water storage, completing the negative loop.

From the above analysis, system dynamics is a suitable approach for modeling the hydrological processes that are non-linear and occur in feedback form.

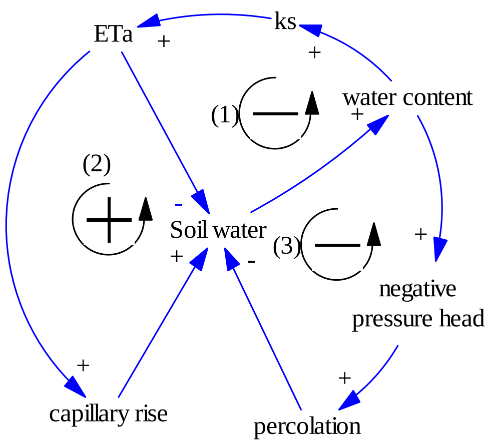

Figure 2. Causal loop diagram for the dynamic soil water system

The model is implemented using the system dynamic tool, Vensim. Vensim provides a simple and flexible way of building simulation models from causal loop or stock and flow diagrams. By connecting words with arrows, relationships among system variables are entered and recorded as causal connections. This information is used by the Equation Editor to help form a complete simulation model. Modeler can analyze your model throughout the building process, looking at the causes and uses of a variable, and also at the loops involving the variable (Ventana Systems, Inc., 2004). The model structure is shown in Figure 3.

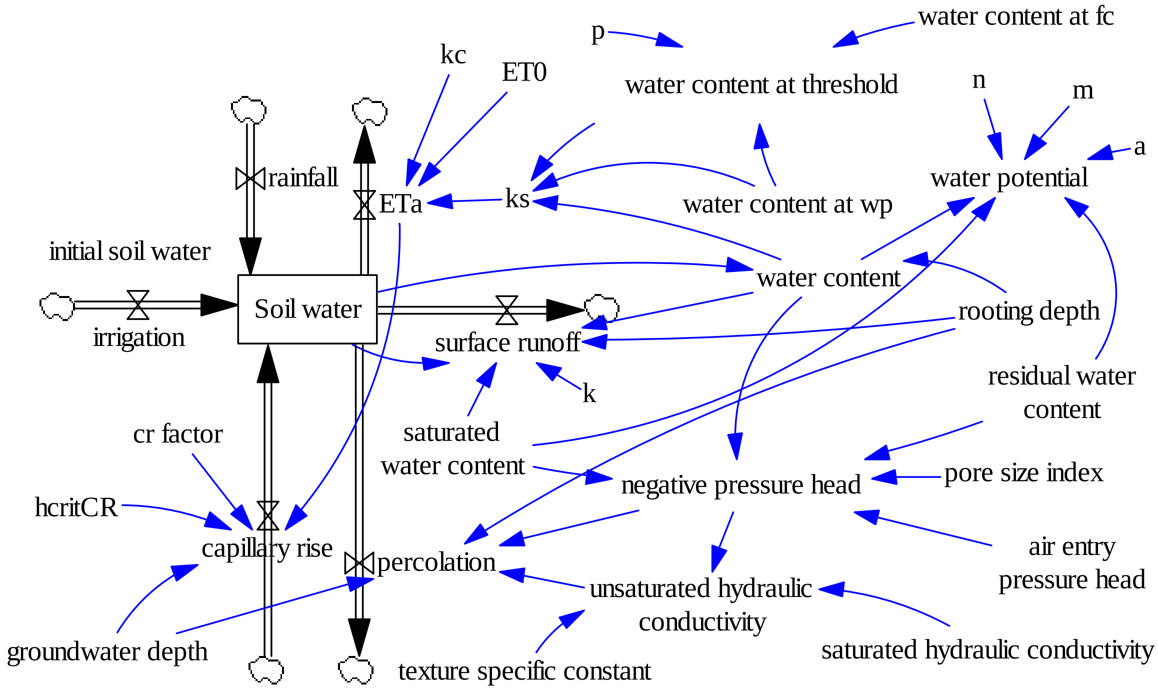

Figure 3. The stock-flow structure of the dynamic soil water balance model

In Figure 3, soil water potential is calculated by the following equation derived from van Genuchten's model (van Genuchten, 1980):

$$\psi = \frac{\left[\left(\frac{\theta_s - \theta_r}{\theta - \theta_r} \right)^{1/m} - 1 \right]^{1/n}}{a} \qquad (11)$$

Where ψ is the soil water potential, Kpa; a , m and n are dimensionless coefficients; and the others are the same as above.

3. RESULTS AND DISCUSSION

The results collected from the field experiments were used to validate the model, and graphical (e.g. visual adequacy of observed vs. simulated soil water potential) as well as statistical tests were conducted. The statistical tests include the t-test, coefficient of Determination (R^2) and root-mean-square error (RMSE).

Field experiment was carried out in 2003 in Huibei Irrigation Experiment Station. Supplemental irrigation was applied when soil water tension reached at -30 and -70 Kpa for two different water treats (T1 and T2). Daily rainfall, irrigation, reference crop evapotranspiration were measured as the model input data. The values of other parameters of the model were abstracted from previous study (Li et al, 2004). Daily soil tensions at four depths (10cm, 25 cm, 50 cm and 75 cm) of root zone were measured and average root zone soil water tensions were obtained for model validation.

The graphical results Figures 4 and 5 show the daily variation of the observed values of soil water potential for the experimental field for two different water treatments, along with the simulated values. The figures show that in most of the cases, observed and simulated values are following the same trend. As for the simulated results of the components of water balance, such as evapotranspiration, percolation capillary rise and surface runoff, there were no observed data to compare with, but the simulated values appear reasonable based on authors' experience in this area. Figure 6 shows the simulated percolation for T 1 as an example.

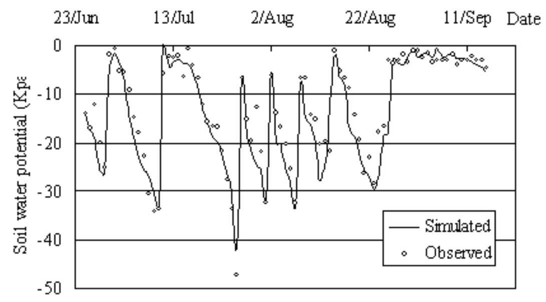

Figure 4. Simulated and observed water content for Treatment 1

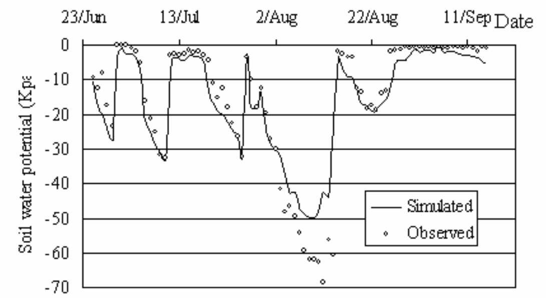

Figure 5. Simulated and observed water content for Treatment 2

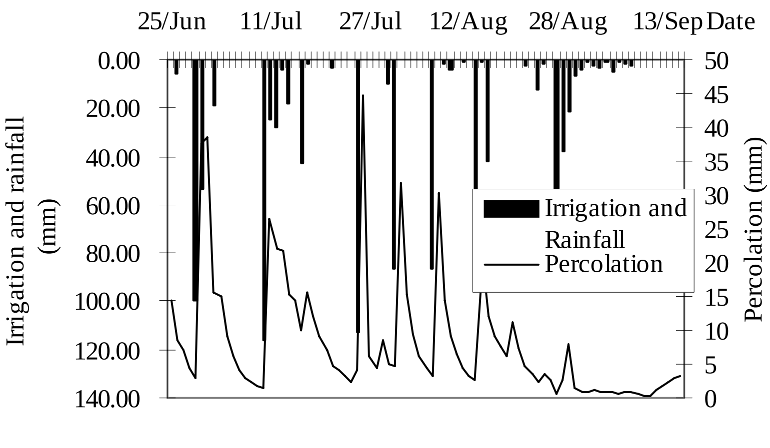

Figure 6. Simulated percolation for Treatment 1

Results of statistical comparison between observed and simulated soil water potential are presented in Table 1. Values of the coefficient of determination (R^2) between the observed and simulated values of water potential are found to be high (more than 0.85 for two treatments), which satisfies the prediction ability of the developed model. The Root Mean Square Error (RMSE) between the daily observed and simulated water content for the two water treatments are 3.96 Kpa and 7.21 Kpa. The t-test indicates that the simulated and observed values are the same at 95% confidence level (Table 1). Thus it may be concluded that the model presented in the paper can perform the simulation of water balance.

Table 1. Results of statistical comparison between observed and simulated soil water potential*

	N	X_{mean} (SD)	Y_{mean} (SD)	P(t)	α	β	R^2	RMSE
T 1	83	-12.5(10.5)	-14.1(10.7)	0.167	0.96	-2.1	0.89	3.96
T 2	83	-15.6(19.1)	-16.0(14.4)	0.444	0.711	-4.9	0.89	7.21

*In this table, N is the data pairs; X_{mean} is the mean of observed values, Kpa; Y_{mean} is the mean of simulated values, Kpa; SD is the standard deviation, Kpa; P(t) is the significance of paired t-test; P(t)>0.05 means simulated and observed values are the same at 95% confidence level; α is the slope of linear relation between simulated and observed values; β is the intercept of the linear relation between simulated and observed value; R2 is the coefficient of determination of $Y=\alpha X+\beta$; and RMSE is the root mean square error.

4. CONCLUSIONS

The present study was carried out to simulate the water balance in a rice field on a daily basis under an aerobic condition with provision of supplemental irrigation based on soil water tension at -30 and -70 KPa. The objectives were accomplished by developing a physically based conceptual water balance model and then the conceptual model was implemented using the system dynamic tool, Vensim. The water balance model was formulated to simulate the percolation, actual evapotranspiration, surface runoff, and capillary rise as these processes occur in the field water balance system. The model was validated using the experimental data of two water treatments. A statistical test (t-test) was carried out to determine the significance between the observed and simulated values of the parameters. The t-test indicates that the simulated and observed values are the same at 95% confidence level.

The system dynamics technique proved to be an efficient approach for the simulation of a complex water resource system. Its merits include the increased speed of model development, ease of model improvement, the ability to simulate the interactions between the model components. Scenarios, other than those treatments simulated in this study are being evaluated (not reported in this study) by using the existing framework. It should be pointed out that some of the present parameters in the presented model were assumed. With more effort on refining the parameters, it is expected that the model would become a more practical tool for irrigation management for aerobic rice.

5. ACKNOWLEDGMENTS

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