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Sensitivity Analysis of Hydraulic Parameters in the Simulation of Unsaturated Soil Water Dynamics

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ABSTRACT- Soil water content is one of the most important parameters for estimating irrigation frequency and providing the plant's water requirement. Since measurement of soil water content is both expensive and time consuming, water movement models are used to estimate these values. In this study, LEACHW model was used to estimate soil water content for two "dry" (20-29 Aug) and "wet" (1-6 Jul) periods during the 1995 growing season. Different values of hydraulic parameters were applied to investigate the sensitivity analysis of these parameters in the estimation of soil water content. Thus the values of b (pore distribution coefficient in Campbell's equation (2) were selected from 2 to 24, and $k(\theta)/k_S$ ratios of 0.1, 1, 10 and 100 were used. Finally 32 treatments were investigated for each period. Results showed that despite large variation for the hydraulic parameters, similar trends of results were obtained for all soil water content estimations. Statistical analysis comparing the estimated and measured results showed a systematic difference which can be adjusted using a few measured values of soil moistures. As an example, simulated results using b=24 and $k(\theta)/k_s$ =0.1 were calibrated to adjust the simulated results. The results of this study showed that a simple calibration method can be used for the estimation of soil moisture content without using extensive data required to represent hydraulic characteristics of soils.

Keywords: **LEACHW, Sensitivity analysis, Soil water content, Simulation, Soil hydraulic parameters**

INTRODUCTION

Soil water simulation models are used to provide guidance for agricultural and environmental management, such as the design of irrigation and drainage systems, and control of surface and ground water pollution (13).

Soil hydraulic characteristics, including soil water characteristic ($h(\theta)$) and soil hydraulic conductivity ($K(\theta)$) functions, play critical roles in the transport and retention of water in soils. These soil properties often exhibit significant spatial and temporal variation. Many models with different degrees of sophistication have been developed to

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describe soil water processes, all complicated by hysteresis (7 and 12), preferential flow (8), and temporal / spatial variability of soil properties (14). Difficulties in utilization of these models are mainly attributed to a lack of detailed information on soil characteristics. In many cases these functions are not adequately defined for the considered soil. Direct measurement of the nonlinear functions of $\theta(h)$ and $K(h)$ is time consuming and expensive. In addition, several measurements are required to accurately represent field soil conditions. On the other hand, soil hydraulic functions are often estimated from other more easily obtainable soil properties such as texture, bulk density and organic matter content (2, 9, and 12). However, these predictions can have high degrees of uncertainty and error, especially for the estimation of soil hydraulic conductivity (11 and 15).

Complex simulation models, such as LEACHW (13) and *ecosys* (4) attempt to present a theoretically rigorous representation of soil water processes. They require many input parameters that describe the properties of the soil water system. At the same time they provide many predictions about the soil water process, including evaporation, transpiration, infiltration, drainage, soil water distribution, etc.

Simulation models, however complicated, are still a simplified version of the physical reality. For example, many natural properties of soil such as heterogeneity and hysteresis are often ignored or greatly simplified in soil water models. Such simplifications make models less perfect; therefore, the models need to be validated. In many cases, required input parameters are estimated, which may result in errors in model's predictions. The effect of such prediction errors and the importance of increased accuracy in predictions from an improved estimation of input parameters, if available, need to be assessed. These depend on the particular process of interest.

Many water flow simulation models, such as LEACHW and *ecosys*, use Campbell's model (3) to represent hydraulic functions. In this study a sensitivity analysis is conducted on the importance of an accurate estimation of the parameters used in soil hydraulic functions described by Campbell for the simulation of soil water storage. Such study can provide guidelines on the level of accuracy necessary in obtaining measurements of soil hydraulic parameters prior to the simulation of various soil water attributes. In addition, it is discussed (i) whether simulation of volumetric water content would constitute proper evaluation of soil water flow models, and (ii) the limitations for the use of models such as LEACHW and *ecosys*.

MATERIALS AND METHODS

Simulation model

LEACHW is one of the five versions of the LEACHM model that simulates the water regime in unsaturated or partially saturated soils (6). LEACHW is based on a node-centered Crank-Nicholson finite difference solution of Richards' equation that simulates transient vertical flow in a heterogeneous soil profile. Vertical soil heterogeneity is represented by a number of horizontal layers of equal thickness, each with different hydraulic properties. This model was used in the present study for simulation of water flow for a range of hydraulic function parameters. Since many water simulation models use similar hydraulic functions (e.g. **ECOSYS)**, results of sensitivity analysis in this study could be used for evaluation of other models using the same hydraulic functions.

Campbell's empirical hydraulic functions (3) that represent the transient conditions of both soil water characteristic function and soil hydraulic conductivity function for $h < h_e$ are as follows:

$$h(\theta) = h_e\left(\frac{\theta}{\theta_s}\right)^{-b} \tag{1}$$

$$K(\theta) = K_s\left(\frac{\theta}{\theta_s}\right)^{m} \tag{2}$$

where $m = 2b + 3$, h is matric potential (m), h_e is air entry water potential (potential at which the largest water filled pores drain, or intercept of $ln\ h$ versus $ln(\theta)$) (m), b is the slope of $ln\ h$ versus $ln(\theta)$, θ is volumetric water content (m^3m^{-3}) and K is hydraulic conductivity (ms^{-1}). The subscript s denotes respective saturated values.

Although h_e and b are both empirical parameters obtained by fitting a straight line to the $ln(h)$ versus $ln(\theta)$ relation, they also have some physical significance (3).

Field experiment

The experiment was conducted on Breton rotation plots, located in the experimental station of the University of Alberta in Canada. Various soil physical properties (Table 1) are available from previous studies (1). Soil water was monitored continuously throughout the growing season of 1995. Using buried TDR probes, volumetric soil water content in two adjacent fallow plots was measured every half an hour. The probes were installed vertically to represent average water content of the uppermost 20 cm of soil surface.

Table 1. Soil properties of the Breton loam series (1)

Soil Properties	**Depth increments (cm)**					
	0-15	**15-30**	**30-76**	**76-112**	**112-150**	**150-170**
Bulk Density ($Mg\ m^{-3}$)	**1.35**	**1.40**	**1.50**	**1.50**	**1.50**	**1.50**
$\Theta^{\dagger}_{FC}$ (at 33 kPa) ($m^3\ m^{-3}$)	**0.251**	**0.286**	**0.317**	**0.296**	**0.268**	**0.272**
$\Theta^{\ddagger}_{WP}$ (at 1500 KPa) ($m^3\ m^{-3}$)	**0.095**	**0.158**	**0.208**	**0.19**	**0.154**	**0.159**
Silt (g g^{-1})	**0.62**	**0.37**	**0.35**	**0.36**	**0.38**	**0.40**
Clay (g g^{-1})	**0.12**	**0.29**	**0.33**	**0.33**	**0.27**	**0.28**
Organic C (g g^{-1})	**0.027**	**0.006**	**0.01**	**0.006**	**0.004**	**0.003**

†-Water content at field capacity, ‡- Water content at permanent wilting point

Measured water contents for the "wet" period of 1-6 July and the "dry" period of 20-29 August 1995 were used for this sensitivity analysis. Because of intense rainfalls during 1-6 July 1995, this period was selected to represent the dynamic state of soil water content in the upper 20 cm of the soil profile. In addition, the period of 20-29 August 1995 was used to represent the gradual drying of the soil.

Data Analysis

Sensitivity analysis on the importance of accurate hydraulic parameters for simulation of soil water contents was conducted by comparing measured water contents with simulated ones, produced by LEACHW, using a range of values for h_e, b, and K_s parameters.

A quantitative procedure adopted from Smith et al. (10) was used for this analysis. The procedure involved calculation of the average difference between the measured and simulated values (*ME*), the relative error (*RE*) as a proportion of the measurement and standard error of estimate (*SE*) root mean square of the difference between the predicted and the observed values, which is often proportioned against the mean observed value as relative standard error of estimate, *RSE* (10).

Simulation models generally divide the soils into a number of horizontal layers, having uniform physical characteristics throughout each layer. According to this assumption, predictions of water contents within a plot at a common depth would, then, be the same throughout the layer. The significance of variations among a number of observed water contents at common depths is used to examine the validity of this assumption. Furthermore, variability in the range of values of soil water measurements within a plot at different times is used to explore the temporal variability of soil condition during a growing season.

RESULTS AND DISCUSSION

Estimated soil hydraulic parameters

LEACHW represents the vertical heterogeneity of soils by a number of uniform horizontal layers. The soil profile from the surface to the lower boundary was divided into 5-cm increments in this study. Physical properties of soil, available from previous studies (1), were used in Campbell's equations to calculate the "estimated" values of h_e, b and K_s for each layer (Table 2).

Sensitivity of soil hydraulic parameters

Air entry value, h_e

To test for the sensitivity of variability in h_e values to the simulation of water content profiles, two possible extreme values of -0.6 kPa and -8.0 kPa (3), corresponding to maximum pore sizes of 500 μm and 38 μm respectively, were used for simulation of soil water during the "wet" period. The less negative values of h_e correspond to the larger pore size, which is assumed to be correlated to particle size. The simulated moisture contents were then compared with observed values (Table 3). Similar results were obtained for the two extreme values, which indicate that simulated water content results are lesssensitive to the values of air entry potential. The calculated h_e values ranged between -1.2 and -2.4 kPa for different depths (Table 2) and were used for the different scenarios throughout this study.

Table 2. Expected values of hydraulic parameters using physical properties of the soil

Soil Properties	Soil depth (cm)			
	0-15	15-30	30-110	110-150
h_e (*kPa*)	-2.4	-1.3	-1.9	-1.2
b	3.9	6.4	9.1	8.6
ρ_b (Mg m^{-3})	1.35	1.4	1.5	1.5
K_s (mm d^{-1})	123	62.7	17.7	18.5

Table 3. Statistical analysis of estimated vs. observed water contents, (m^3 m^{-3}) using two possible extreme values of h_e as compared with observed results, for the wet period of 1-6 July 1995

h_e (kPa)	-0.6	-8.0
ME	0.05	0.04
RE	0.17	0.14
SE	0.05	0.04
RSE	0.18	0.15

Slope of ln(h) versus ln(θ), or b value and saturated hydraulic conductivity

Campbell (3) stated that the expected range of *b* values would be from 2 to 24 in typical soils. The higher values of *b* represent soils with more widely distributed particle sizes. The expected values of hydraulic parameters, calculated from physical properties of distinct soil layers have been presented in Table 2.

From a number of measurements using undisturbed soil samples from the surface layer, Haderlein (5) developed least square equations of *K* (θ) for the Breton site with different tillage treatments. The general equation (not considering surface tillage treatments) for the site was:

$$-\log(K) = 14.7 - 15.7(\theta) \qquad R^2 = 0.72 \qquad (3)$$

where *K* is the hydraulic conductivity in m s^{-1}. Using this equation and the saturation water content of θ_s = 0.49 (1), the saturated hydraulic conductivity of $K_s \cong$ 10 *mm* d^{-1} is calculated. Haderlein (5) found a high level of variability among hydraulic conductivity data in Breton site, particularly near saturation. Many samples would, then, be required for a reliable estimate of K_s.

Therefore, the “estimated” value of $K_s \cong 123\ mm\ d^{-1}$ from Campbell’s equation seems to be reasonable. The calculated values of b and h_e, from the best fit line through measured $h(\theta)$ results for the Breton site (5), were 18.2 and -4.3 kPa, respectively. These values are within the range of b and h_e used in this study.

Saturated hydraulic conductivity (K_s) values of one order of magnitude smaller and also one and two orders of magnitude greater than the “estimated” value ($K_{s(est)}$), i.e. $0.1\,K_{s(est)}$, $10\,K_{s(est)}$ and $100\,K_{s(est)}$, were used in the analysis, to represent an extensive range of soils with variable ranges of physical and hydraulic characteristics. The $0.1\,K_{s(est)}$ value used in this analysis closely corresponds to the K_s value obtained by Haderlein (5). Each of these hydraulic conductivity values was combined with b values ranging between 2 to 24.

Simulated and observed results are compared graphically in figs.1-4 for the “wet” and the “dry” periods respectively. Despite the large range of values of hydraulic parameters used for simulations, the results indicated that, aside from “extreme” cases where saturated hydraulic conductivity values of 10 or 100 times greater than the estimated value were combined with b=2 (corresponding to a soil with extreme particle size uniformity) for any combination of hydraulic parameters the predicted results were similar, i.e. their responses to intense rainfalls and/or during drying periods were similar. In addition, predicted soil water contents deviated systematically from observed values, in other words, they result in nearly parallel lines. The overall shapes of the prediction and measured curves are similar. Water retention increases with b and decreases with K_s. Lower b values represent soils with higher pore size uniformity, i.e. most of the soil moisture is held within a smaller range of suction (close to h_e) and therefore drains easily. Similarly higher values of K_s correspond to soils with higher hydraulic conductivity, hence, lower retention capacity. As a result predictions of soil water retention with b = 2, especially when combined with higher hydraulic K_s, were consistently lower than the measured results. Other combinations of hydraulic parameters resulted in the overestimation of measured values, but to a lesser extent. Such deviations were observed for both “wet” and “dry” simulation periods.

Based on the measured results, no immediate response was observed to the major rainfall (13.8 mm) on 1st of July. Interestingly, prediction results using $K_s/K_{s(est)}$=0.1 reproduced a response lag (Fig. 1). This observation could be attributed to the presence of surface crusts, which is likely in Luvisolic soils.

During the “dry” period, the simulation of soil water content using lower values of b, indicated a higher rate and degree of water loss from the upper soil layer as compared with observed results.

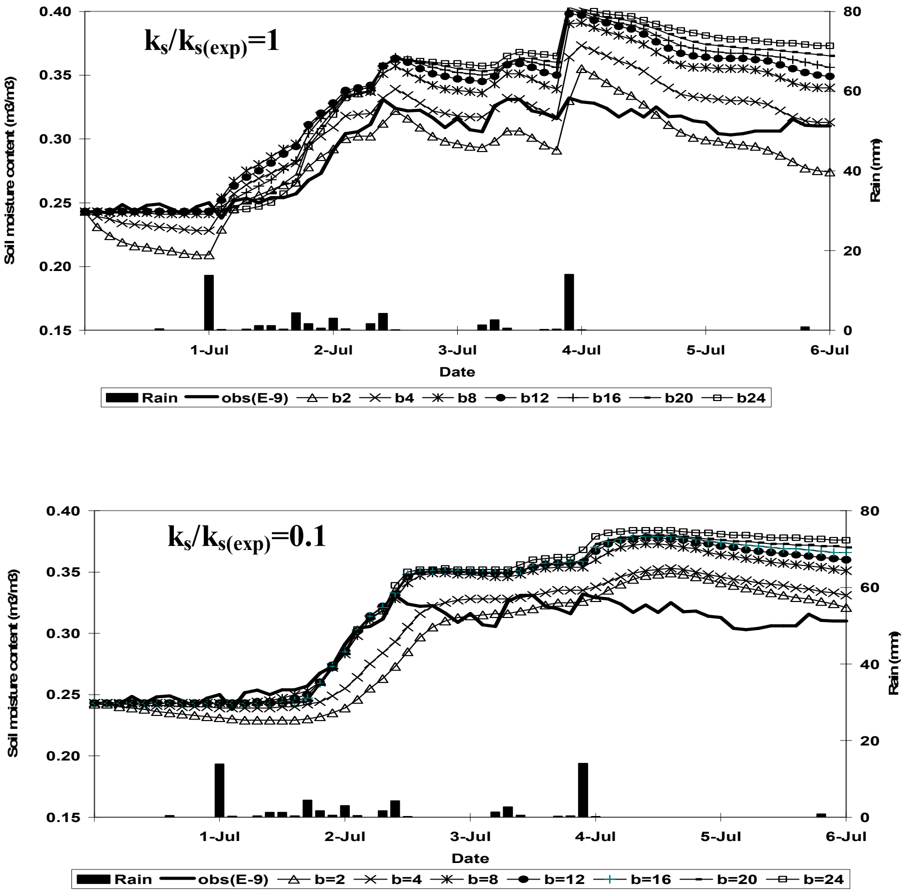

Fig 1. Observed soil-water contents as compared with simulated results using a range of b values between 2-24 and $K_s/K_{s(est)}$ =1, 0.1 for the period of 1-6 July 1995

Since the slope of water depletion is fairly linear following the rainfalls, indicating a constant rate of water loss, this deviation could be attributed to high prediction of evaporation, rather than drainage losses. The latter would have resulted in a higher rate of water loss immediately after rain.

Statistical comparisons of the estimated and observed results for the “wet” and the “dry” periods are presented in tables 4 and 5, respectively. According to the values of *ME* for the “extreme” cases the model greatly underestimated the observed soil water contents (Tables 4 and 5). For all other combinations of hydraulic parameters, predicted results showed an overestimation of 0 to 4% (*ME*) of the observed water contents. In addition, the similarity between absolute values of standard error (*SE*) and error of estimate values (*ME*), for every scenario, is an indication of a systematic under- or over-estimation of observed results for any individual scenario. This is in agreement with the generally parallel positions of the observed and predicted lines in Figs. (1-4).

Excluding the extreme cases described above, average values of *ME* and *SE* obtained for any combination of $K_s/K_{s(\exp)}$ with *b* were 0.025 and 0.035 for the “wet” period, and 0.02 and 0.04 for the "dry" period. These results are comparable with those obtained using the expected values of *b* and K_s (Table 2).

Table 4. Statistical analysis of estimated water contents *($m^3\ m^{-3}$)*, using different combinations of b and *Ks* values as compared with observed results, for the wet period of 1-6 July 1995

b	2	4	8	12	16	20	24	*b*	2	4	8	12	16	20	24
			$K_s/K_{s(exp)}$ =100								$K_s/K_{s(exp)}$ =1				
ME	-0.11	-0.03	0.02	0.03	0.03	0.03	0.03	ME	-0.01	0.01	0.03	0.03	0.04	0.04	0.04
RE	-0.59	-0.12	0.05	0.09	0.1	0.1	0.1	RE	-0.04	0.04	0.1	0.12	0.12	0.12	0.13
SE	0.12	0.05	0.03	0.04	0.04	0.04	0.04	SE	0.02	0.02	0.04	0.04	0.04	0.05	0.05
RSE	0.63	0.18	0.09	0.11	0.11	0.12	0.12	RSE	0.07	0.07	0.12	0.14	0.15	0.15	0.16
			$K_s/K_{s(exp)}$ =10								$K_s/K_{s(exp)}$ =0.1				
ME	-0.06	0.01	0.02	0.03	0.03	0.03	0.04	ME	0	0.01	0.02	0.03	0.03	0.03	0.03
RE	-0.24	0.02	0.07	0.1	0.1	0.11	0.11	RE	-0.01	0.02	0.07	0.08	0.08	0.08	0.09
SE	0.07	0.02	0.03	0.04	0.04	0.04	0.04	SE	0.03	0.02	0.03	0.04	0.04	0.04	0.04
RSE	0.28	0.07	0.09	0.11	0.12	0.12	0.13	RSE	0.09	0.07	0.1	0.11	0.12	0.12	0.13

Table 5. Statistical analysis of estimated water contents *($m^3\ m^{-3}$)*, using different combinations of b and *Ks* values as compared with observed results, for the dry period of 20-29 August 1995

b	2	4	8	12	16	20	24	*b*	2	4	8	12	16	20	24
			$K_s/K_{s(exp)}$ =100								$K_s/K_{s(exp)}$ =1				
ME	-0.1	-0.1	0	0.01	0.01	0.03	0.04	ME	-0	-0	0.01	0.03	0.04	0.05	0.05
RE	-0.5	-0.2	0	0.03	0.04	0.09	0.12	RE	-0.1	-0.1	0.02	0.09	0.13	0.16	0.18
SE	0.14	0.06	0.01	0.01	0.02	0.03	0.04	SE	0.06	0.04	0.03	0.04	0.05	0.06	0.07
RSE	0.48	0.19	0.03	0.04	0.06	0.1	0.13	RSE	0.18	0.13	0.11	0.15	0.18	0.21	0.23
			$K_s/K_{s(exp)}$ =10								$K_s/K_{s(exp)}$ =0.1				
ME	-0.1	-0	0	0.01	0.02	0.03	0.04	ME	-0	-0	0.02	0.03	0.04	0.05	0.05
RE	-0.3	-0.1	0	0.02	0.07	0.11	0.13	RE	-0.1	-0	0.06	0.11	0.14	0.15	0.16
SE	0.1	0.04	0.01	0.02	0.03	0.04	0.05	SE	0.04	0.03	0.04	0.05	0.06	0.06	0.07
RSE	0.34	0.12	0.04	0.05	0.09	0.13	0.15	RSE	0.13	0.11	0.14	0.18	0.2	0.22	0.22

Theoretically, values of *b* and K_s, using the physical properties of soil for every discrete soil layer (3), should be used for simulation. Due to the natural heterogeneity of soils, collection of such information is both expensive and time consuming. Still, our results using inaccurate values of these parameters were not substantially less accurate than the results obtained from "expected" hydraulic parameters using actual physical properties of each soil layer. These results suggest that factors other than *b* and K_s are more important in controlling the change in water content of upper soil horizons.

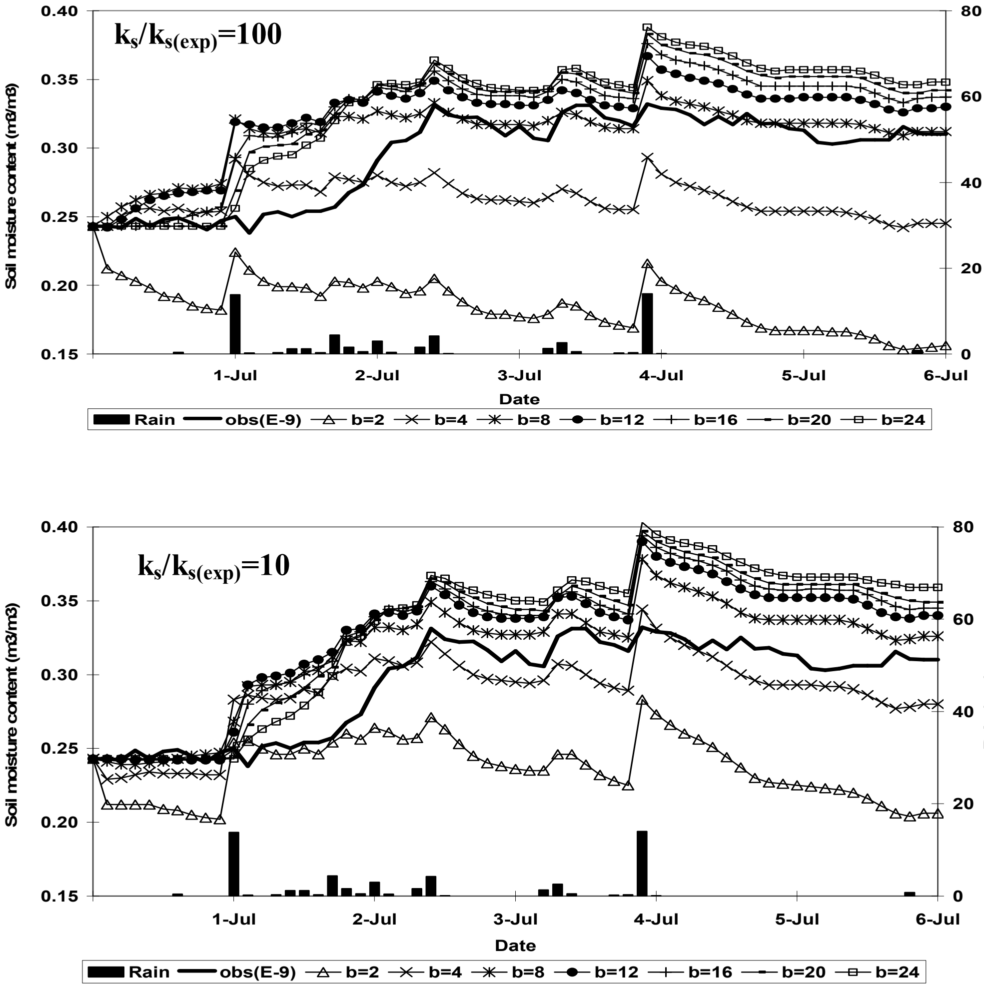

Fig 2. Observed soil-water contents as compared with simulated results using a range of b values between 2-24 and $K_s/K_{s(est)}$ =10, 100 for the period of 1-6 July 1995

As depicted in Figs.1-4, the predicted soil water contents for any combinations of hydraulic parameters are generally parallel with or systematically deviate from the observed values. In effect, any set of predicted results can be corrected to closely represent observed soil water content. Using only a few observations, the correction can be made by drawing a line through the observed values in a general trend with any set of predicted results.

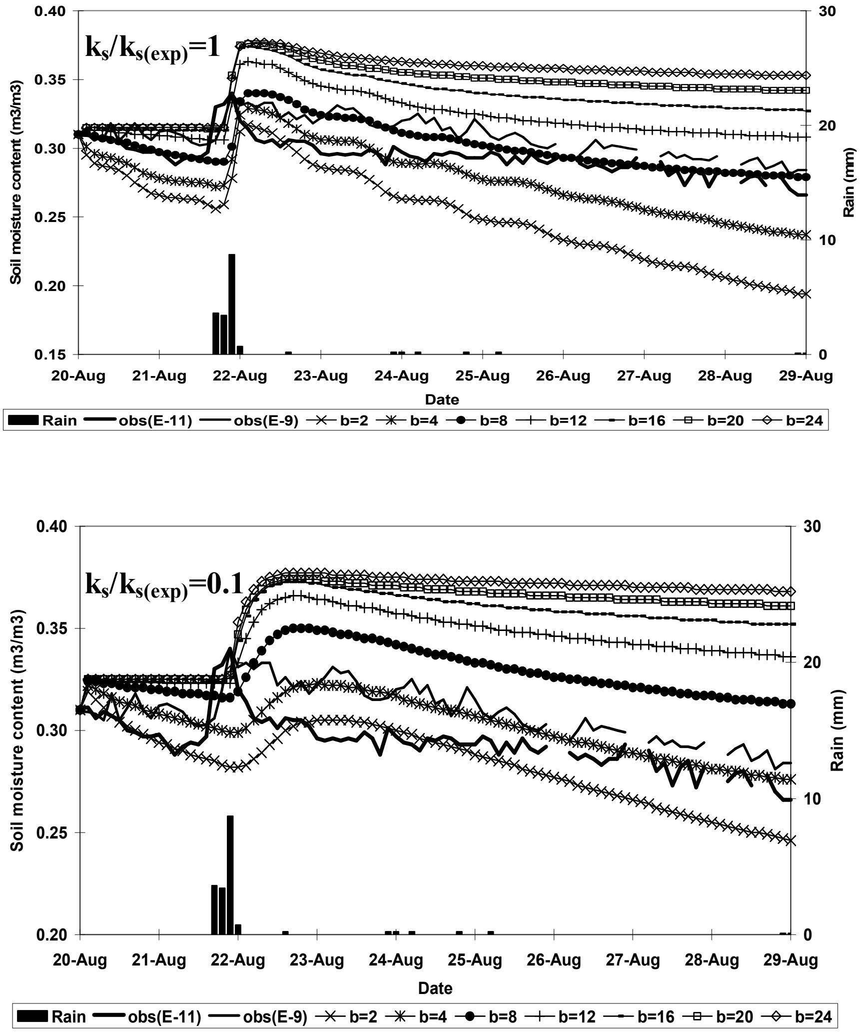

Fig 3. Observed soil-water contents as compared with simulated results using a range of b values between 2-24 and K/K(est) =0.1,1 for the period of 20-29 Aug 1995

Summary and Conclusions

In this study various combinations of hydraulic parameters were used to simulate the transient status of soil water content during a six-day wet period and a nine-day dry period. The simulated results were then compared with the observed values. For the entire range of possible b and h_e values, and a range of three orders of magnitudes of K_s values (similar to the range of possible values for K_s), the predicted water contents systematically deviated from the observed results, i.e. variation of predicted values over time generally resulted in parallel lines with respect to the observed values. In many cases, pedotransfer estimation of hydraulic parameters has shown to be uncertain, which has led to the calibration of predictions based on such methods. Alternatively it is proposed that the predicted results using any combination of hydraulic parameters could be easily "corrected" using a few observed values. An example of following this procedure is shown in Fig. 5. Statistical analysis of the calibrated results, represented in table 6, show they are in close agreement with the observed values. The correction procedure is much simpler than alternative methods which require parametric representation of the heterogeneous physical properties of soils.

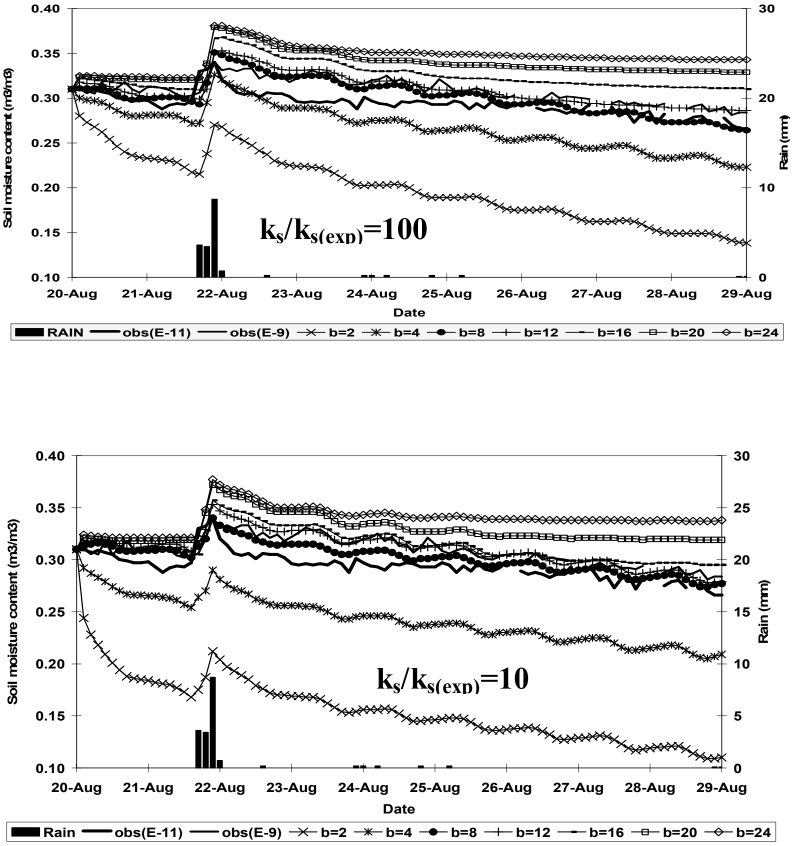

Fig 4. Observed soil-water contents as compared with simulated results using a range of b values between 2-24 and K/K(est) =10, 100 for the period of 20-29 Aug 1995

The results obtained in this study are limited to the simulation of soil water content, and should not be expanded to simulation of other components of the water balance equation. In the same context we propose that evaluation of models based on proper simulation of soil water contents alone should not be interpreted as validation of the model for simulation of other components of the water balance equation, such as drainage fluxes.

The importance of accurate predictions of soil water contents is not to be minimized here. Systematic deviation of predicted water content from actual conditions which results in consistently higher or lower soil water content predictions, even by a few percent, could have extensive implications for the growth of plants or may lead into huge amount of water in large scales. Therefore, irrigation designs, for example, which are based on such predictions could result in the over or under-application of water.

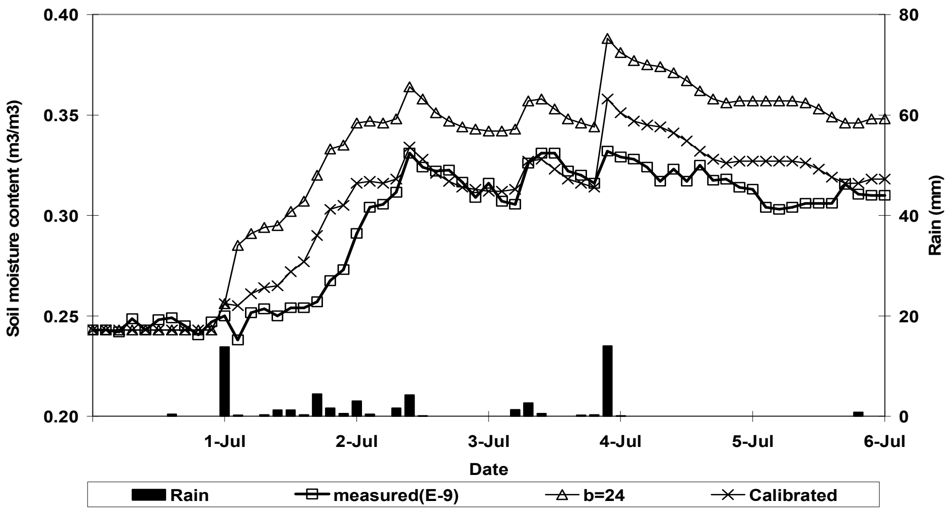

Fig 5. Observed soil-water contents as compared with calibrated results using a couple of observed soil moisture values to adjust estimated results from b= 24 and K/K(est)=0,1 for the period of 1-6 July 1995

Table 6. Statistical analysis of observed water contents (M^3M^{-3}) as compared with calibrated and estimated values using b=24 and $K/K_{s(exp)}$=0.1 , for the wet period of 1-6 July 1995

Criteria	b=24	Calibrated
ME	**0.03**	**0.01**
RE	**0.09**	**0.03**
SE	**0.04**	**0.015**
RSE	**0.13**	**0.05**

Finally, the results of this study showed that soil water simulation is not particularly sensitive to hydraulic properties. Large variations in hydraulic properties resulted in relatively small changes in simulated soil water contents. The deviations between predictions from observed results were systematic.

Differences in soil water fluxes, e.g. evaporation and drainage fluxes, resulted from the variability in hydraulic parameters could be substantial. This was not examined in the present analysis. However, for the purpose of predictions of soil water changes, the extra effort in obtaining more accurate hydraulic properties of soils may be expected to result in only minor improvements. Therefore, because of the insensitivity of simulated soil water content to hydraulic properties, it may be possible to substantially simplify the representation of the storage of water in soils without a detrimental effect on prediction accuracy.

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ارزیابی حساسیت شاخص های هیدرولیکی در شبیه‌سازی حرکت آب در خاک های غیر اشباع

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چکیده- رطوبت خاک یکی از پارامتر های مهم در تعیین دور آبیاری و تامین نیاز آبی گیاهان می باشد. از آنجائی که اندازه گیری این پارامتر در مزرعه نیازمند صرف وقت و هزینه بسیار می باشد، استفاده از مدل های حرکت آب در خاک بسیار مطلوب می باشد. در این مطالعه از مدل LEACHW به منظور تخمین رطوبت خاک در طول دو دوره تر (۱تا ۶ ژولای) و خشک (۲۰ تا ۲۹ اوت) در طول فصل زراعی سال ۱۹۹۵ استفاده گردید. به منظور بررسی حساسیت پارامتر های هیدرولیکی در تعیین مقدار رطوبت حجمی خاک از مقادیر مختلف این پارامترها استفاده گردید. بنابراین مقدار پارامتر b (ضریب توزیع خلل و فرج در رابطه کمپل ۱۹۷٤) در محدوده ۲ تا ۲٤ تغییر نمود. همچنین مقدار $k(\theta)/k_s$ نیز با چهار نسبت مختلف ۰/۱، ۱، ۱۰ و ۱۰۰ و در کل ۳۲ تیمار برای هر دوره مورد بررسی قرار گرفت. نتایج نشان داد که با وجود مقادیر متفاوتی از پارامترهای هیدرولیکی، در تمامی تخمین های رطوبت حجمی خاک روندی مشابه وجود دارد. مقایسه تحلیل آماری مقادیر اندازه گیری شده و تخمین زده شده رطوبت حاکی از وجود خطای سیستماتیک بوده که این خطا می تواند با استفاده از اندازه گیری چندین نقطه اصلاح گردد. به عنوان مثال نتایج تخمین زده شده با مقادیر b=۲٤ و $k(\theta)/k_s =$ ۰/۱ کالیبره گردید. نتایج این مطالعه نشان داد که توسط یک روش کالیبراسیون ساده میتوان رطوبت حجمی خاک را بدون نیاز به داشتن اطلاعات وسیعی با دقت قابل قبولی تخمین زد.

واژه های کلیدی: آنالیز حساسیت، رطوبت خاک، شبیه سازی، عوامل هیدرولیکی خاک و LEACHW

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