Use of simulation modeling and pedotransfer functions to evaluate different irrigation scheduling scenarios in a heterogeneous field

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Abstract

Increasing water use efficiency in agriculture is a multi-faceted optimization problem which could benefit from the use of a pro-active planning process. Simulation models are tools that can facilitate such planning, but their parameterization may be a difficult and costly task. Pedotransfer functions (PTFs), however, can provide important soil physical data at relatively low cost. Few studies, however, explore what contributions PTFs can make to land-use planning, in terms of being applied to evaluate the expected outcome of changes in management. We use an exploratory research approach using simulation modeling to evaluate benefits and risks posed while using different irrigation scenarios to a heterogeneous field. We also evaluate the applicability of pedotransfer functions to parameterize the simulation model for this task. Using this research approach we provide quantitative answers to several "what if" type questions, allowing the distinction of trends and potential problems. The approach may help increase water use efficiency while evaluating potential associated risks.

Key Words

Irrigation scheduling, heterogeneity, pedotransfer function, simulation model, SWAP, Hungary

Introduction

Large areas in the world face either a shortage of (irrigation) water or a decline in available water resources; while the demand for water by agricultural, industrial and municipal users keeps increasing. To keep up with the demand, it is necessary to find ways to increase water use efficiency in agriculture. Natural, technical or financial limitations of using different irrigation systems combined with the potential shortage or high cost of irrigation water poses a complex problem for practitioners in quest of maximizing yield and profit without posing avoidable risks the environment.

Field experimentation with different management scenarios is time consuming, costly and sometimes can even be risky. Changing land management, irrigation or fertilization practices can carry undesired and hazardous risks. However, given that a suitable model is available, exploratory ('what if?') simulation modeling offers an alternative that is quicker and easier to execute, and may give at least indicative answers about trends that are expected to occur without risk to the environment.

Plant-soil-atmosphere models need input on soil hydraulic properties, regardless of their complexity. However, measurement of these properties is relatively time-consuming and costly, especially when data are needed for large areas of land. Extensive research exists on pedotransfer functions (PTFs) that can estimate such properties from easily or routinely measured soil properties (e.g. Pachepsky and Rawls, 2004 and other papers therein), but few studies go further to evaluate the functionality of PTFs in field applications (e.g. Wösten *et al.*, 1995; Soet and Stricker, 2003). Well tested PTFs can assist such modeling by providing low-cost and low-risk input data.

In this study we explore the use of a simulation model and estimated soil hydraulic properties to evaluate different irrigation scheduling scenarios in a heterogeneous field. The specific objectives of this study are (1) to examine the effect of different irrigation scheduling scenarios on selected soil water balance components and the soil's ability to supply the vegetation with water; (2) to examine the effect of apparent soil heterogeneity on those water balance components at the selected site; and (3) to evaluate the functionality and effectiveness of using a cost saving soil hydraulic pedotransfer function to parameterize the applied simulation model.

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Materials and Methods

Three soil profiles were sampled in central Hungary within 50 meters from each other in a field that has a history of heterogeneity in crop yield (Czinege, 2000). The profiles had 2 to 4 distinct horizons. Textural and other differences among the top 120 centimeters of the three profiles can be seen in Figure 1.

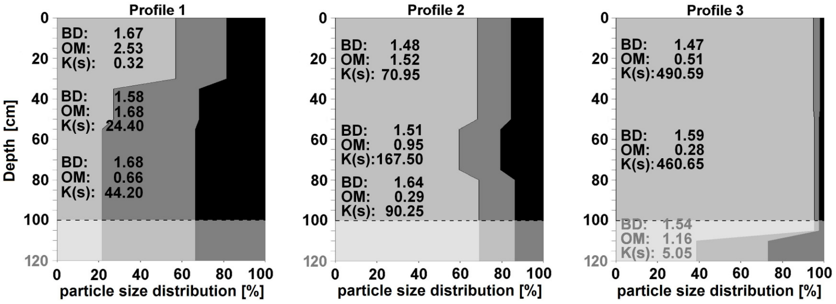

Figure 1. Physical properties of the top 120 cm of the soil profiles. The depth of 1 meter was considered as the bottom of the simulated profile. Light grey: sand (0.05-2mm); dark grey: silt (0.002-0.05mm); black: clay (<0.002mm) content. BD: bulk density [g/cm^3]; OM: organic matter content [%]; K_s: saturated hydraulic conductivity [cm/day].

Simulations of one-dimensional flow were carried out on a daily basis, using the SWAP model (van Dam *et al.*, 1997). This model has previously been tested under Hungarian climatic and soil conditions (e.g. Farkas and Rajkai, 2002; Nemes *et al.*, 2003). Groundwater levels were recorded at variable time intervals and were used as lower boundary condition for the simulations. Simulated weather data were used as upper boundary condition. The stochastic weather generator of Semenov and Barrow (1997) was used to generate one-year-long data sets of daily average temperature, solar hours and amount of precipitation. These were used to calculate daily values of potential evapotranspiration (ET_{pot}) using an empirical equation developed for the Hungarian Great Plain area (N. Fodor, pers. comm., 2002). Three drier and warmer than average years were simulated. The average annual precipitation was 416.5 (SD=29.2) mm, annual average temperature was 11.47 (SD=0.25) °C, and the calculated sum of annual ET_{pot} was 1280.6 (SD=71.5) mm; yielding considerably long periods of dry soil conditions. The simple crop growth routine of SWAP was used with grass as cover crop. Factors to characterise plant growth were derived by adjusting general factors suggested by van Dam *et al.* (1997), and FOCUS (2000) to local conditions. Soil hydraulic properties were described using the four parameter van Genuchten water retention model - with $m=1-1/n$ - combined with Mualem's solution to describe unsaturated hydraulic conductivity, $K(h)$ (van Genuchten, 1980). The M9 neural network PTF of Nemes *et al.* (2003), developed from Hungarian data, was used to predict the van Genuchten model parameters for all soil horizons. Soil texture, BD and OM content were used as input to a neural network model to predict saturated hydraulic conductivity (K_s) (A. Nemes, pers. comm., 2004). Predicted K_s, coupled with an assumed $L=0.5$ was used to describe $K(h)$. Laboratory measured water retention and K_s data were used in alternative simulation runs to validate the PTF driven results.

Three different irrigation scheduling scenarios were evaluated for each of the three profiles. A "simple" (empirical) irrigation scheduling scenario was based on simple decision criteria that relied on daily weather observations as follows: (1) From May to September, 20 mm of irrigation water was applied on a particular day if the average daily temperature of the preceding five days was >20 °C, and the sum of the precipitation for the same period was <1 mm; (2) The same amount of irrigation was applied when daily average temperature was 17-20 °C for the preceding 8 days, with <1 mm of precipitation. Hence, irrigated days were at least 6 days apart to account for the need to rotate the irrigation equipment between fields. The alternative ("advanced") irrigation scheduling technique used decision criteria based on a preceding run of the simulation model. Using the available weather data, the model calculated when the vegetation started to suffer from water stress. When daily actual plant transpiration fell below 85% of the potential transpiration, we applied 20 mm of irrigation water, considering the same rule to rotate irrigation equipment as above. As the three profiles are physically close enough to each other to fall within the same irrigation unit in reality, we calibrated the latter scheduling technique to the profile with the intermediate texture (Profile 2) and applied the resulting irrigation schedule to all three soil profiles. As a control, we also ran simulations for each profile without any irrigation.

Results and Discussion

An average of 293 (SD=23.1) mm irrigation water was applied during the irrigated period annually following the "simple" irrigation scheduling system; while a total of 353 (SD=23.1) mm irrigation water was applied to the field following the "advanced" irrigation scheme. This gives a possible indication that the "simple" system does not supply enough water or proper timing to cover the needs of the vegetation.

Table 1. Water deficit for the vegetation (a); number of days with soil water pressure below –80 kPa in the top 50 cm of the soil (b); and flux balance of the soil profiles (c) in the period May 15 – October 15 under different irrigation schemes. Different letters indicate significant differences at 95% confidence level. First letters compare soil profiles within each irrigation scheme; second letters compare irrigation schemes within each profile; third letters compare results between pedotransfer function (PTF) and measured water retention (WRC) within the same profile and irrigation scheme.

	Pedotransfer function			Measured water retention and hydraulic conductivity		
irrigation	Profile 1	Profile 2	Profile 3	Profile 1	Profile 2	Profile 3
scenario	MEAN (STD)	MEAN (STD)	MEAN (STD)	MEAN (STD)	MEAN (STD)	MEAN (STD)
	a) Water deficit [mm] for the vegetation					
no	544.7 (52.6) ^{a,a,a}	413.7 (49.2) ^{b,a,a}	172.6 (76.6) ^{c,a,a}	569.7 (54.4) ^{a,a,a}	436.7 (56.0) ^{b,a,a}	221.8 (83.6) ^{c,a,a}
simple	317.3 (23.6) ^{a,b,a}	144.4 (20.5) ^{b,b,a}	14.2 (20.1) ^{c,b,a}	343.3 (32.1) ^{a,b,a}	166.1 (25.3) ^{b,b,a}	37.8 (38.2) ^{c,b,a}
advanced	296.2 (16.7) ^{a,b,a}	100.9 (10.5) ^{b,c,a}	2.3 (0.2) ^{c,b,a}	323.5 (25.8) ^{a,b,a}	121.1 (17.6) ^{b,b,a}	4.6 (2.5) ^{c,b,a}
	b) Number of days with soil water pressure below -80kPa in the top 50cm					
no	153.0 (0.0) ^{a,a,a}	129.3 (13.0) ^{b,a,a}	51.3 (13.1) ^{c,a,a}	152.7 (0.6) ^{a,a,a}	128.0 (12.0) ^{b,a,a}	61.3 (12.7) ^{c,a,a}
simple	135.7 (6.4) ^{a,b,a}	71.7 (13.0) ^{b,b,a}	7.0 (12.1) ^{c,b,a}	140.3 (8.5) ^{a,a,a}	69.0 (13.5) ^{b,b,a}	18.3 (19.1) ^{c,b,a}
advanced	100.3 (13.3) ^{a,c,a}	31.3 (7.2) ^{b,c,a}	0.0 (0.0) ^{c,b,a}	101.7 (16.7) ^{a,b,a}	26.7 (5.1) ^{b,c,a}	1.7 (2.1) ^{c,b,a}
	c) Flux balance of the soil profiles [mm, negative downwards]					
no	-0.4 (0.5) ^{a,a,a}	76.2 (3.3) ^{b,a,a}	235.7 (21.6) ^{c,a,a}	-5.0 (0.3) ^{a,a,b}	36.1 (1.8) ^{b,a,b}	184.3 (25.7) ^{c,a,a}
simple	-0.5 (0.5) ^{a,a,a}	73.4 (3.9) ^{b,a,a}	133.2 (23.6) ^{c,b,a}	-5.1 (0.2) ^{a,a,b}	33.9 (3.6) ^{b,a,b}	100.6 (24.1) ^{c,b,a}
advanced	-0.5 (0.5) ^{a,a,a}	75.4 (3.2) ^{b,a,a}	88.7 (18.1) ^{b,b,a}	-5.1 (0.3) ^{a,a,b}	36.0 (1.8) ^{b,a,b}	75.7 (14.6) ^{c,b,a}

We used eight different output measures to evaluate the result of different irrigation schemes, of which we show and discuss three measures. Water deficit to the vegetation, as the difference between potential and actual transpiration (expressed in mm), was added up for the period from 15th May to 15th October. Flux balance – defined as the sum of daily bottom fluxes - at the depth of 1 meter in the profiles was summarized for the same period; and days were counted, when the average matric potential in the top 50 cm of soil – representing the root zone – was below the suggested starting point of water stress for grass (–80 kPa, FOCUS, 2000).

Table 1a shows that for each soil, irrigation significantly decreased water stress for the vegetation, calculated using the PTF estimates. For the heaviest textured Profile 1, using the simple irrigation scheduling scenario reduces plant water deficit by a predicted ~40% compared to using no irrigation. For Profile 2 such improvement is by ~65%, and for Profile 3 it nearly removes all water deficit. Using the advanced irrigation scheme resulted in further significant improvement for Profile 2. For Profiles 1 and 3 any such improvement was not significant. Differences between respective values for the three profiles are significant in all cases. Differences between respective values obtained using PTFs or measured soil hydraulic data are not significant in any of the cases.

The number of days with the average pressure in the top 50 cm below -80 kPa, were significantly different for the three profiles and were significantly reduced by both irrigation schemes (Table 1b). For Profile 3, the simple scheme reduced the presence of such stress condition to the plant to only 7 days a year. Additional improvement by the advanced irrigation scheme proved insignificant. Despite the coarse texture and thus low water holding capacity in the top 100 cm, Profile 3 had the least amount of water deficit. The overlying horizons greatly benefited from the favorable hydraulic properties of loamy material beneath 105 cm. That layer retains a considerable amount of water that later may partially be available by upward flux during water redistribution. Differences between results obtained using measured or estimated soil hydraulic data were not significant.

Table 1c summarizes the flux balance of each profile at the depth of 1 meter. Some of the water/soluble that flow below this depth may still reach shallower horizons by capillary rise during water redistribution, but most will end up in the subsoil and/or ground water. Only Profile 3 with its very coarse texture in the top 1 meter showed to be sensitive for the irrigation treatments. Differences between simulated results using PTF estimates and measured soil hydraulic properties were small in absolute values, but significant for two of the three profiles. None of the applied irrigation schemes had any influence on the leaching pattern of Profiles 1 and 2, but the amount of water leached into the subsoil increased significantly for Profile 3 (not shown). This signals an increased risk of subsoil/groundwater pollution introduced locally at the coarse part of the field by the application of extra water. Such leached pollutants will redistribute in the subsoil and groundwater due to the three-dimensional nature of water flow in field soils.

Conclusions

We used predicted soil hydraulic properties in exploratory simulation modeling to quantify the benefits and risks of using different irrigation scheduling scenarios. Studies of these kinds can be used to extend expert knowledge by giving a quantitative dimension to the outcome of planned or implemented changes. A simulation-assisted "advanced" irrigation system is more complicated, but for some soils, it brings further improvement in terms of plant water supply as compared to a simple "empirical" irrigation system. However, we also showed some dilemmas soil heterogeneity may cause: one action optimal for part of a management unit may be far from optimal for other parts, and the extent of the differences may be large. We quantified a major reason for the observed heterogeneity in crop yield, and showed that while one part of the field is sensitive for leaching; other parts are sensitive for drought. For most water balance components, and for at least two of the three soils, simulation results using PTF estimates and measured soil hydraulic properties did not differ significantly. Using well tested PTFs to provide soil hydraulic data appears to be a reasonable, reliable and cheap alternative to sampling and laboratory measurements; especially since laboratory measurements themselves are not error-free. PTFs appear to be useful in planning sustainable, productive and environmentally sound management systems.

Results of this demonstration are based on a limited number of simulation years. The presented approach can be further broadened and improved by running simulations using a larger number of years of different weather scenarios or by involving e.g. simultaneous yield estimation, estimation of cost-effectiveness, or assessment of uncertainty in the inputs. Besides quantifying different risk factors, such studies can also support the delineation of new management units that better balance contradictory demands within fields.

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