Screening and understanding the importance of soil hydrology related factors in a SVAT scheme.

Part 1: Screening factors to establish the relative importance

Part 2: A study of numerical discretization, rooting depth, and bottom boundary condition

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climate changes spatial planning

Main results

In this report a simulation experiment using a hydrological water balance model is executed. Results show that the choice of the lower boundary condition, the maximum root depth, and whether or not leaf area index is a function of time, have a strong effect on yearly and monthly evapotranspiration.

The second part focuses on the importance of the lower boundary condition and maximum rooting depth as conditioned by discretization. Results show that sensitivity to the lower boundary condition and maximum rooting depth decreases with a decreasing number of soil layers. Using a coarse discretization may therefore underestimate their importance. In the presence of a groundwater table, assumptions regarding root water uptake under very wet conditions become important.

Part 1 Screening factors to establish the relative importance

Abstract

In this report a simulation experiment using a hydrological water balance model is executed. Using a little simulation runs as possible, the experiment is set up to estimate the main effect of an individual variable on different water balance terms given simultaneous variation in all other factors. The ranking of the variables in terms of their relative effect suggests a priority in the processes to be incorporated in new versions of a SVAT scheme. The experiment was set up to analyze the effects of 13 variables. Variables varied are leaf area index and its time course, root depth and its time course; profile discretization, description of the soil hydraulic characteristics (Hornberger-Clapp vs. van Genuchten), stoniness, the reduction of vegetation transpiration as a function of moisture content or as a function of soil matric head, the point at which reduction of transpiration occurs, and the lower boundary condition of the soil (lateral drainage at 1 m and an impermeable layer at the bottom of the soil profile or free drainage at the bottom of the profile). Results show that the choice of the lower boundary condition, the maximum root depth, and whether or not leaf area index is a function of time, have a strong effect on yearly and monthly evapotranspiration.

Introduction

According to the IPCC 2001 assessment (IPCC, 2001): “accurate prediction of soil moisture is crucial for simulation of the hydrological cycle, of soil and vegetation biochemistry, including the cycling of carbon and nutrients, and of ecosystem structure and distribution as well as climate.” The basis for this statement is that through the soil water balance, soil moisture is linked to groundwater recharge, and to runoff. As soil moisture is one of the controls of evapotranspiration, it furthermore is a controlling factor in the surface energy balance. It links indirectly to the surface energy balance and to the carbon and nutrient balances by regulating canopy cover and plant growth. The IPCC model evaluation chapter concludes with the statement

“Overall, at regional scales, and if land-surface quantities are considered (soil moisture, evaporation, runoff, etc.), uncertainties in our understanding and simulation of land-surface processes limit the reliability of predicted changes in surface quantities.”

Given this incentive for SVAT-model improvement, what are the options? In literature two approaches to develop and improve models are encountered:

1. Model elimination - formulate different models or submodels, test them predictively, and continue with the best predictor (e.g. de Wit et al, 1970; Sinclair and de Wit, 1976). In model elimination one needs to establish that prediction errors between models are indeed different.
2. Model evolution - is, for a given model, to analyze its prediction errors, and, based on an analysis of the causes, reformulate the model (e.g. Beck, 1985). In model evolution one needs to establish that (part of) the prediction error is indeed systematic.

At present there is very little formal guidance for an individual modeller as to the formulation of a set of competing models, or as to the reformulation of an individual model.

The case in which a group of models is compared in terms of predictive quality, and the predictive quality of this group as a whole has to be improved, has not been studied theoretically at all. Yet this is the situation SVAT modellers are in. As the different model intercomparison experiments (PILPS, 2006) have shown, establishing common causes for the predictive error for different models of similar complexity is far from trivial. It would seem that procedures to establish common causes for prediction errors are weakly developed and that -at least at present- the conclusions from expert discussions set the improvement agenda. Nevertheless, the conclusion from 30 years of SVAT modelling is that progress has been made (IPCC, 2001).

If we return to the case of a single SVAT model, an intermediate step in the elimination approach may be to prioritize different processes in a model in terms of the sensitivity of the model output to their variation. Determining relative importance of processes may offer some guidance in model simplification, but also in increasing model complexity. When simplifying a model one would remove or simplify processes which have a low sensitivity. When increasing complexity one may decide to test different descriptions of the process to which the relevant output is most sensitive. Alternatively, one may develop increasingly complex versions of the model sequentially including additional processes ranked in terms of decreasing sensitivity.

In this paper we will consider the case of two models (TESSEL, and SWAP) which differ in number and detail of processes included. Sensitivity analysis of the SWAP model is used to prioritize processes to include in TESSEL.

The two SVAT models considered

TESSEL

TESSEL is a version of the ECMWF SVAT-scheme (ECMWF, 2006), used at KNMI in its regional forecasting model RACMO. It solves the Darcy-Richards equation numerically, based on an implicit numerical solution.
In its operational settings for Europe, this SVAT scheme has a constant leaf area index (LAI) and a constant rooting depth (up to the total profile depth) with a fixed root density profile for each vegetation type. It uses a single deep homogeneous soil type, i.c. loam, is numerically discretized in four layers, and uses a transpiration reduction function which is a linear function of soil moisture content. In addition it has a free drainage bottom boundary condition. Partitioning between soil evaporation (E) and transpiration (T) is based on area averaged fluxes. The algorithm is used with an input time step with meteorological forcing variables as inputs. Soil moisture retention $h(\theta)$ and hydraulic conductivity $k(h)$ are described by the Hornberger-Clapp functions.

SWAP

SWAP (SWAP, 2006) is a SVAT scheme developed for use in agrohydrological studies at field scale, and for detailed studies of processes, such as infiltration, and soil evaporation. It solves the Darcy-Richards equation numerically, based on an implicit solution scheme. In contrast to TESSEL it has few standard operational settings. It may be used with a variable leaf area index, a variable rooting depth, with layered heterogeneous soils, and hysteretic soil physical characteristics. It is flexible in its numerical discretization, partitions evapotranspiration in evaporation and transpiration on the basis of the *LAI*, and uses a transpiration reduction function which is a linear function of soil pressure head h. In addition it allows for different bottom boundary conditions. The algorithm has been developed for a daily time step with daily meteorological forcing variables. Soil physical characteristics are described by the Mualem-van Genuchten functions.

Differences between TESSEL and SWAP

Differences between the two SVAT-schemes are in their discretization, their temporal resolution, the boundary conditions possible, in their parameterization of the soil physical properties, in the degree of within-profile soil heterogeneity, and in the argument and parameterization of the transpiration reduction function. Partitioning of potential evapotranspiration *ETp* in transpiration *T* and evaporation *E* is an additional aspect in which the models differ.

Application domain: Europe

The selection of the processes to include in the sensitivity analysis is a central issue. To resolve this issue the application domain of the models is considered. Taking the spatial variability of the domain into account, we select specific processes with a high degree of variability included in one but not in the other model.

Spatial aspects

In SVAT-schemes discrete classes are generally chosen to represent variation. This approach is retained here. The application domain of interest is Europe. In terms of vegetation patterns the main land cover in Europe is agricultural areas and forests and semi-natural areas. Land cover with a seasonality in leaf area index is between 70 and 75% (the total of agricultural and forests without pastures, coniferous trees, and part of the mixed forests). The estimate of the relative area with changing rooting depths would be 30%. The area percentages are presented in Table 1 in more detail.

Soil texture (although predominantly loamy) varies across Europe; more importantly however, other factors, such as soil depth, stoniness, salinity and drainage vary as well. Only half of the area is considered to be well-drained. Table 2 offers an overview of the variation in terms of relative area (Fraters, 1996).

It is clear that based on the above aggregation and in its present operational settings it would seem that TESSEL excludes a large amount of the spatial and temporal variability present in Europe. As in any predictive application, the justification of this reduction is in the predictive quality of the model, not in the close correspondence of its parameterization to existing maps. Nevertheless, an analysis of the sensitivity of a SVAT scheme to inclusion of additional variability may be helpful in improving predictive quality.

A different spatial aspect is that presented by climatology. To include effects of climate in the study the experiment was executed for two sites with different climates. Climate classification was based on an analysis by Metzger (2005).

Table 1 Land cover percentage different classes derived from the Corine land cover statistics per country, Version 06-1999 ©EEA Copenhagen. (EEA, 2005).

Land cover code	Name	Name		Relative area %	Relative area %
2	Agricultural areas			57.0	
2.1		Arable land			30.9
2.2		Permanent crops			3.1
2.3		Pastures			8.0
2.4		Heterogeneous agricultural areas			15.1
3	Forests and semi-natural areas			37.2	
3.1		Forests	Broad-leaved forests		10.2
			Coniferous forest		9.4
			Mixed forest		5.1
3.2			Scrub and/or herbaceous vegetation associations		10.5
3.3			Open spaces with little or no vegetation		1.9
	Other			5.8	
1	Artificial surfaces				3.8
4	Wetlands				0.9
5	Water bodies				1.1

Table 2 Area (% of total) of aggregated soil units based on the FAO soil map (Fraters, 1996).

	Sand	Loam	Clay	Organic	Total
Well-drained	10	32	2		44.
Shallow and stony	8.5	21	2		31.5
Imperfectly drained	0.5	8.5	4.5	3	16.5
Arid and saline	-	6.5	1.5		8.0
Total	19	68	10	3	

Temporal aspects

Studies regarding different aspects of soil water balance modelling and their effects of water balance terms should address two scales: spatial and temporal. The processes to be introduced should be based on the variation present at both scales. As the application domain for the SVAT-scheme is Europe, the present paper focuses on variability present at the European scale and analyzes output at two time scales: yearly and monthly. To ensure that the conclusions are robust with respect to weather variability the effects are analyzed over a period of 44 years for two locations in Europe.

Screening: Experimental design, factors, levels, settings, and analysis

Based on this brief description of variability of soil and land cover over Europe, and on the discussion of the differences between TESSEL and SWAP, we would like to estimate the relative effect of each individual variable on state variables of interest. Establishing which differences and which variables have an important effect on relevant model output may suggest possible options for model reformulation.

Variables selected

Table 3 presents an overview of variables. The argument for inclusion was their variability on the scale of interest, an existing difference between SWAP and TESSEL, or the possibility to use different values in the model itself. Most of the parameters selected are based on an existing difference between SWAP and TESSEL (Factor numbers 1, 2, 3, 4, 5, 6). Variables which vary within SWAP are the parameter defining the partitioning of ET_P over E and T (7) and the parameter defining the matric head h at which transpiration is reduced from a potential level to lower levels (8). A variable which has been varied in TESSEL is the soil depth (A). Climate (B), soil texture (9) and soil phase (10), and lower boundary condition (11) are factors which vary within Europe. Additionally we have included contrasting settings of maximum leaf area index (11) and root density profiles (12).

Table 3 shows that in total 15 variables (Factors A and B, and factors 1-13) need to be considered. If we were to analyze all possible combinations, this would require 2^{15}(=32768) simulations. As the effects need to be assessed over a number of years (≥30) and at a number of climatologically different locations (in this case 2), given the need for the conclusion to be robust with respect to weather variability, the methodology used to establish the sensitivity needs to be very efficient in terms of the number of simulations required. The number of variables to be considered requires a severe simplification of the analysis. We will therefore only allow a limited number of values for each variable. The set of cases of a variable is then known as a factor, the numbers of the cases contained in the factor are the levels, and the parameter values associated with each level within a factor are the settings.

Screening and experimental design

In this context establishing the relative importance of a large number of different factors as efficiently as possible is known as screening. In regression analysis screening is used to select a regression model with the highest descriptive performance. Several techniques (Welch et al. 1992; Kleijnen, 1987) are available. In this paper we have used a design with two factor levels (Plackett & Burman, 1946, also quoted in Genstat, 2003) which allows estimating main effects only, and has no residual degrees of freedom. We used a setup with 13 factors which we executed 4 times: twice to analyze the results for different climates, twice to include the effect of different total soil depth. Additional degrees of freedom to allow for missing runs were introduced by generating the design for 15 factors.

Factors, levels, and settings

The design prescribes the number of levels (2), which requires that we have to choose if variability suggests more than two levels. E.g. only two levels of soil texture (clay, sand, loam and organic soils) can be selected. In the third column we indicate choices made in the present study. The settings are presented in Appendix 1. The settings for variables describing differences between TESSEL and SWAP are relatively straightforward, as they can be based on the default settings for both models. Soil physical characteristics were based on Wösten et al., 1994. Settings for the factor *Root density(depth)* was based on data for natural temperate grassland. The settings for *Max(LAI), LAI(time),* and the profile with groundwater influence *(Lower boundary condition)* were based on expert knowledge. We have executed this experiment at two climatologically different locations (Atlantic climate in England and Pannonian climate in Hungary, based on the climatic analysis by Metzger, 2005) and for two different profile depths (3 and 5 meter) as used by Lenderink et al, 2003.

Analysis

Values of the response variables and the associated levels are input to an analysis of variance. Analysis of variance (ANOVA) partitions the total variation in the response variable in variation related to the different factors. The model underlying analysis of variance is linear, and given the design of the experiment (2 levels for each factor) it can not be otherwise. The mean sum of squares (MSE) is the sum of squares attributed to the factor divided by the degrees of freedom for that factor. In real-world experiments the mean sum of squares of a factor (signal) is then compared to the mean sum of squares of the residuals (RMSE). The residual mean square is the variability which could not be attributed to any factor, and may be regarded as “noise”. This signal-to-noise ratio (MSE/RMSE) is a measure of the relative importance of the factor. As in simulation studies the importance of different factors does not depend on unknown and uncontrolled factors, the noise term is irrelevant (although it does reflect the quality of the linear model assumed). What is interesting, however, is the effect of a factor relative to the effect of weather (i.e. $MSE_{factor}/MSE_{weather}$). A ratio larger than 1 indicates that changing from one factor level to another has an effect larger than the effect attributed to weather. This would mean that when comparing two sites differing in a specific factor their response variable (averaged over a number of weather periods) would be different, the more so, the larger the ratio $MSE_{factor}/MSE_{weather}$. For each climate, and for each soil depth, the results were analyzed in terms of this ratio. Ranking the factors in terms of this ratio reflects the relative importance when changing to one setting to the other.

Simulation

We used the SWAP model in the simulation experiment. To allow for the comparison of concepts which differ between SWAP and TESSEL two additional options were included in SWAP:

1. Reduction root water extraction with critical water content instead of critical matric head
2. Soil physical functions Clapp and Hornberger instead of van Genuchten

Table 3 Variables included in the simulation study.

Variable	Selected settings	Alternative, contrasting settings	Setting selected where choice is possible.	Factor number	Factor name
Profile depth	Deep	Shallow	Two depths, (3 and 5 m)	A	Soil depth
Climate	Hungary (Pannonian)	England (Atlantic)		B	Climate
Numerical discretization	Coarse	Fine		1	Discretization
Soil physical characteristics	Clapp and Hornberger	van Genuchten		2	Soil physical functions
Leaf area index	Constant	Function of time		3	LAI(time)
Rooting depth	Constant	Function of time		4	Root depth (time)
Rooting depth	Deep	Shallow		5	Max(root depth)
Sink term	Soil moisture	Soil matric presssure head		6	Sink term (argument)
Partitioning ETp	Extinction coefficient high	Extinction coefficient low		7	Partitioning ETp
Sink term	Point at which reduction starts			8	Sink term (critical)
Soil texture	Loam	Sand, clay, organic	Sand	9	Texture
Soil phase	Homogeneous	Stones/salt	Stones	10	Stones
Lower boundary condition	Free drainage	Groundwater/ bedrock	Groundwater	11	Lower boundary condition
Leaf area index	High	Low		12	Max(LAI)
Root density	Constant	Function of depth		13	Root density (depth)
Soil profile	Single horizon	Multiple horizons	Single horizon	-	
Hysteresis	No	Yes	No	-	

Results

The analysis of the simulation experiment provides a ranking of the factors in terms of their relative effect on the response variable. Presented are the results for yearly and monthly evapotranspiration.

Ranking should be interpreted as the importance of a variable. This importance is expressed as the effect of its variation on evapotranspiration relative to the simultaneous variation of all other factors. The measure is relative to the effect of meteorological variation, i.e. a value of 100 means that the effect is 100 time stronger than the effect attributed to the meteorological variability.

Yearly evapotranspiration

Figure 1a and b show the ranking of the factors in terms of their variance ratio for cumulative yearly evapotranspiration for different soil depth. Most important factors are lower boundary condition, max(rooting depth) and the temporal variation in leaf area index LAI(time). These main conclusions do not seem to be sensitive to soil depth, and to climate.

Monthly evapotranspiration

The above analysis also allows establishing sensitivity patterns on shorter timescales. Figure 2a presents the variance ratio for the three most important factors in the Atlantic climate (England) as a function of time. Figure 2b does so for the Pannonian climate (Hungary); both results are based on the simulations for the soil depth of 3 m.

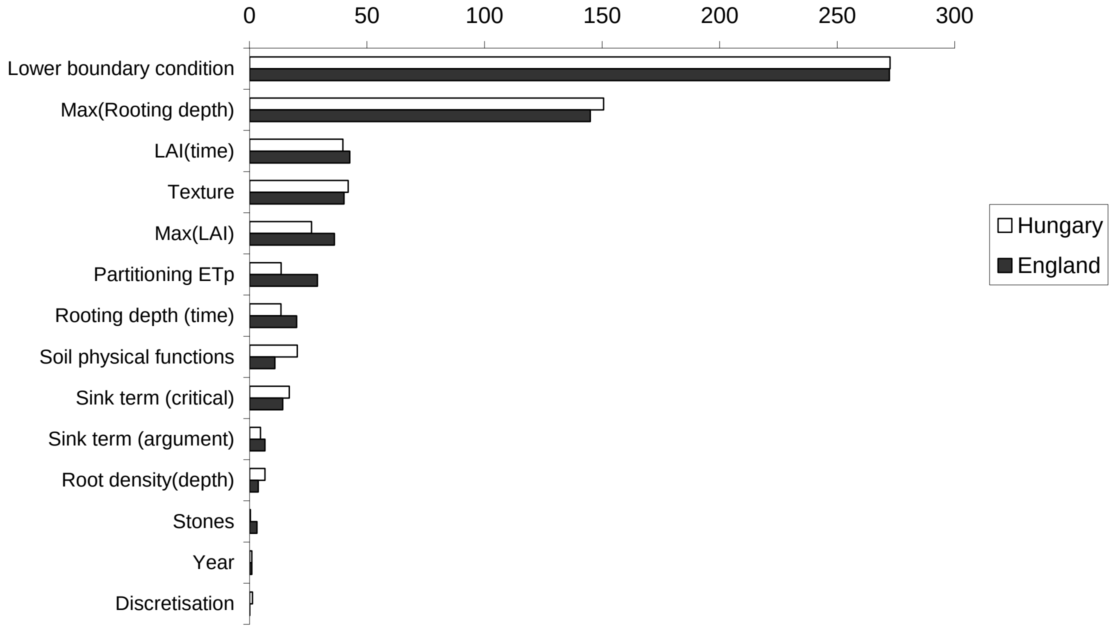

Figure 1a: Soil depth of 3 meter and effects of the different factors on yearly cumulative evapotranspiration for two climates (Pannonian in Hungary and Atlantic in England). Effects are presented as a variance ratio, i.e. expressed relative to the mean variance of the meteorological variability (year-to-year variation)

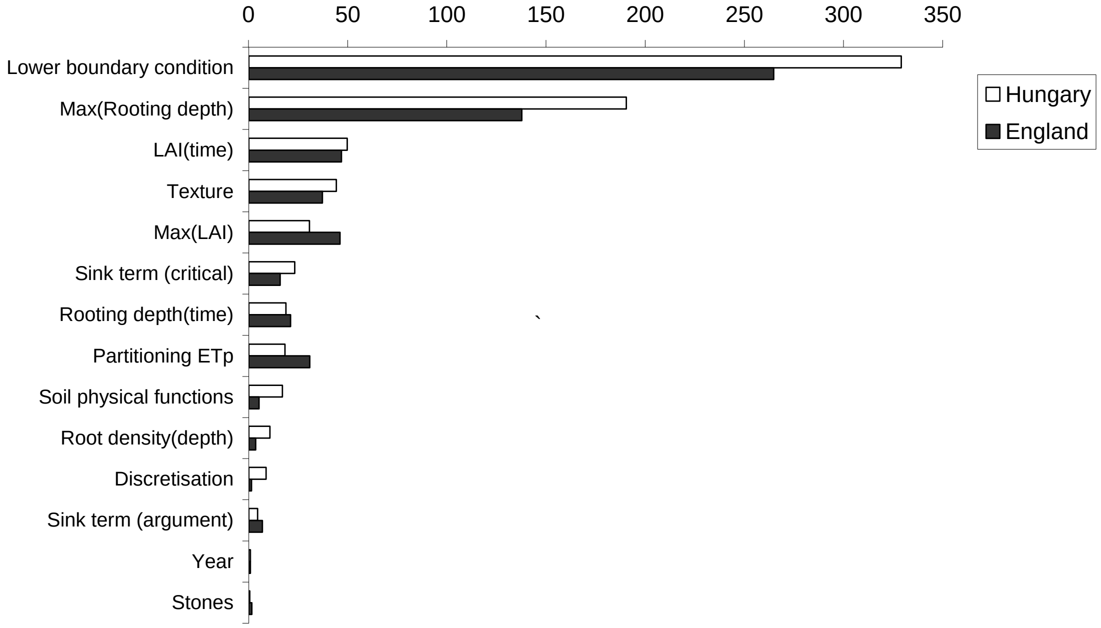

Figure 1b: Soil depth of 5 meter and effects of the different factors on yearly cumulative evapotranspiration for two climates (Pannonian in Hungary and Atlantic in England). Effects are presented as a variance ratio, i.e. expressed relative to the mean variance of the meteorological variability (year-to-year variation)

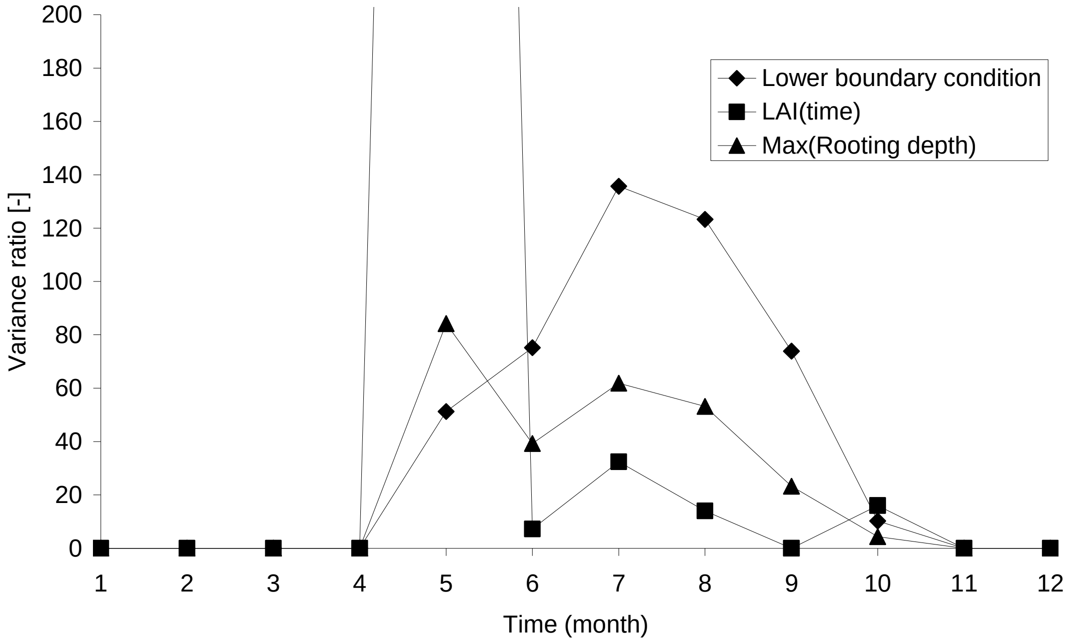

Figure 2a Variance ratio for lower boundary condition, for time course of leaf area index, and for maximum root depth as a function of time for the Atlantic climate (England) and 3 m soil depth. Note that the peaks (leaf area index is off the scale in May) suggests that late summer differences in evapotranspiration for the same crop and the same soil could reflect differences in lower boundary condition.

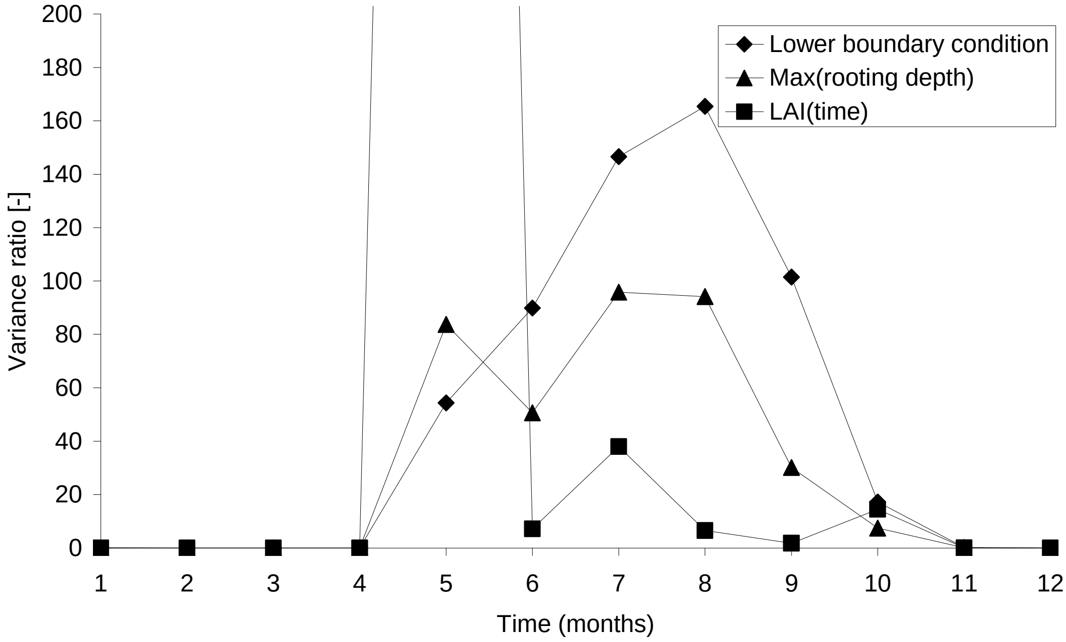

Figure 2b As Figure 2a, in this case for the Hungarian climate.

Discussion and conclusions

Importance of factors
Overall the effect of factors does not vary with climate and soil depth: the ranking of the most important factors does not seem overly sensitive to both climate and soil depth. For the current settings the lower boundary condition, the maximum rooting depth, and the presence or absence of a temporal variation in LAI have the highest score. This suggests that analyzing the effect of these parameters on predictive quality might be interesting.

Temporal sensitivity
The result presented in Figures 2a and b suggests that in specific months (notably after leaf area index has stabilized) analysis of remote sensing images in terms of evapotranspiration may indicate differences in patterns of lower boundary conditions - absence or presence of a ground water level. Interestingly enough, differences in rooting depth may also have a similar effect on evapotranspiration.

Choice of factor settings and intercomparability of factor effects.
It should be quite clear that the choice of factor settings will influence the results. In an earlier study (Metselaar and Feddes, 2006) in which the contrast in drainage conditions was not so strong, rooting depth relatively shallow, and a deep soil (5 m), discretization was the dominating factor. At present a factor missing form the analysis is the depth of the soil, i.e. shallow, stony soils, from mountainous regions. This remains to be done.
It should also be clear that given the nature of the factors considered, intercomparability of effects will always be problematical. Numerical discretization and maximum LAI are completely different types of variables, - LAI can be measured over Europe; discretization is a model property. Even if the mathematical interpretation of the value would be the same, e.g. the same probability of exceedance, the population from which the value stems (the population of experiments versus a population of models) would be incomparable.
The intracomparability of factors (comparison of factors of the same type - e.g. a comparison of the effects of default model settings -) is less problematical, as these values already have (roughly) the same meaning.

Understanding of the effect of individual factors
The results of the experiment executed here do not allow understanding why maximum rooting depth and lower boundary condition have such a huge impact. Causal relations can only be studied in one-at a time experiments. Why e.g. rooting depth has such a huge impact is studied in the second part of this report.

Methodology
Whereas the approach itself is relatively straightforward, both the execution and the analysis of the results are not. Additional software for input file generation and output file analysis was written.
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Appendix 1: Settings for SWAP

Inputfile	Factoren	Instelling 1	Instelling 2
swp	Onderrand	Q-h	vrij
swp	3 instellingen	qbot =0	
		drains op 1 meter, weerstand =100 dagen	
	initieel	GWI = -100 cm	h = -300 cm
	Profieldiepte	296	296
swp	Discretisatie	4	56
swp		1x8+1x24+1x72+1x192	(8x1)+(8x1+8x2)+(8x4+8x5)+(16x12)
swp	Mobiliteit	1	0.6
crp	worteldiepte	296	74
crp	worteldiepte	constant	tijdsafhankelijk
crp	worteldichtheid	BASED ON AVERAGE NON-TROPICAL GRASSLAND	constant
crp	laimax	3	6
crp	lai	constant	tijdsafhankelijk
swp	bodems	coarse	medium
swp	vanGres	0.025	0.01
swp	sat	0.403	0.439
swp	alfa	0.0383	0.0314
swp	npar	1.3774	1.1804
swp	ksat	60	12.061
swp	lexp	1.25	-2.3421
swp	alfaw	0.0766	0.0628
swp	soil physics	clapp (asymptotically approaching v Genuchten)	
swp	clapptsat	0.403	0.439
swp	claphsat	26.110	31.847
swp	clappcoefb	2.650	5.543
swp	clappksat	60	12.061
crp	sinkterm	h	theta
crp	hlim1	-15	
crp	hlim2u	-30	
crp	hlim2l	-30	
crp	h3h	-600	
crp	h3l	-500	-500
crp	h4	-16000	-16000
swp	klimaat	Hongarije	Engeland
	groeiseizoen	1 mei - 15 october (168 dagen)	
crp	kdif	0.4	1.1
crp	h3l	-150	-8000
	warmtebalans		
swp	isoillay	1	1
swp	psand	0.83	0.58
swp	psilt	0.09	0.16
swp	pclay	0.09	0.27
swp	orgmat	0.05	0.05
swp	Zone	22.00	48
swp	ALT	50.3	354.2
swp	lat	52.139	44.29
swp	long	0.00	21.094

Part 2: A study of numerical discretization, rooting depth, and bottom boundary condition

Abstract

In Part 1, we concluded that lower boundary condition and maximum rooting depth are important factors in SVAT schemes. This analysis therefore focuses on the lower boundary condition and maximum rooting depth. We include discretization as a potentially important factor. Results show that sensitivity to the lower boundary condition and maximum rooting depth decreases with a decreasing number of soil layers. Using a coarse discretization may therefore underestimate their importance. In the presence of a groundwater table, assumptions regarding root water uptake under very wet conditions become important.

Introduction

In part 1 of this report, transpiration was found to be the most sensitive to the lower boundary condition and maximum rooting depth. At the same time, given the strong nonlinearity of the transport of water in the soil, the discretization of the soil profile chosen in the SVAT scheme influences this sensitivity. This sensitivity is also influenced by the numerical solution scheme used. The argumentation for the discretization selected in a specific SVAT (ECMWF, 2006) is summarized as follows:

“The depths of the soil layers are chosen in an approximate geometric relation (see Table 7.5), as suggested in Deardorff (1978). Warrilow et al. (1986) have shown that four layers are enough for representing correctly all timescales from one day to one year. Using the numerical values of the heat capacity and soil depths defined in Table 7.5, the amplitude and phase response of the numerical solution of Eq. (7.45) were analysed by Viterbo and Beljaars (1995) for typical values of soil moisture in Eq. (7.48), and for harmonic forcings at the surface with periods ranging from half a day to two years. The analysis points to an error in the numerical solution of less than 20% in amplitude and 5% in phase for forcing periods between one day and one year.”

Objective of this research is to assess the influence of the maximum rooting depth and discretization of the soil profile on the local water and - energy balances. Two boundary conditions are applied: free drainage, i.e. gravity determines the flux at the lower boundary, and laterally drained soils, a condition, which is often found in riverine plains. Lateral drainage is implemented using a linear flux-head relationship for a given depth of the drains.

Experimental setup

The profile was assumed to be 5 meter deep with a constant evaporative demand and no rainfall. The soil chosen was fine sand (B 2, Wösten et al, 1994). The experimental setup was defined by two contrasting hydrological conditions: Free drainage, and a lateral drainage system at -100 cm. These conditions are presented in Figure 1. The initial condition for free drainage was a pressure head of -200 cm. The drained soil was assumed to be in equilibrium with groundwater at -100 cm, with a zero-flux condition at the bottom of the profile. In the experiment two factors were varied: discretization of the soil profile, and maximum rooting depth. Starting point for the discretization was a profile with layer thicknesses of 8, 32, 128 and 336 cm, corresponding closely to the soil profile discretization as defined by Lenderink et al. (2003). In the 6 subsequent simulations with finer discretization, the layer thickness was halved, up to a thickness of 1 cm. Rooting depth was varied between 50 cm, and (almost) full profile depth (500 cm).

Figure 1: The setup of the two contrasting hydrological conditions: on the left the situation with lateral drainage on an impermeable layer, with *r* the transport resistance to the drain (left); a situation with free drainage - i.e. drainage driven by gravity in a deep and permeable profile, with *k* the hydraulic conductivity at the matric head of the lowest compartment.

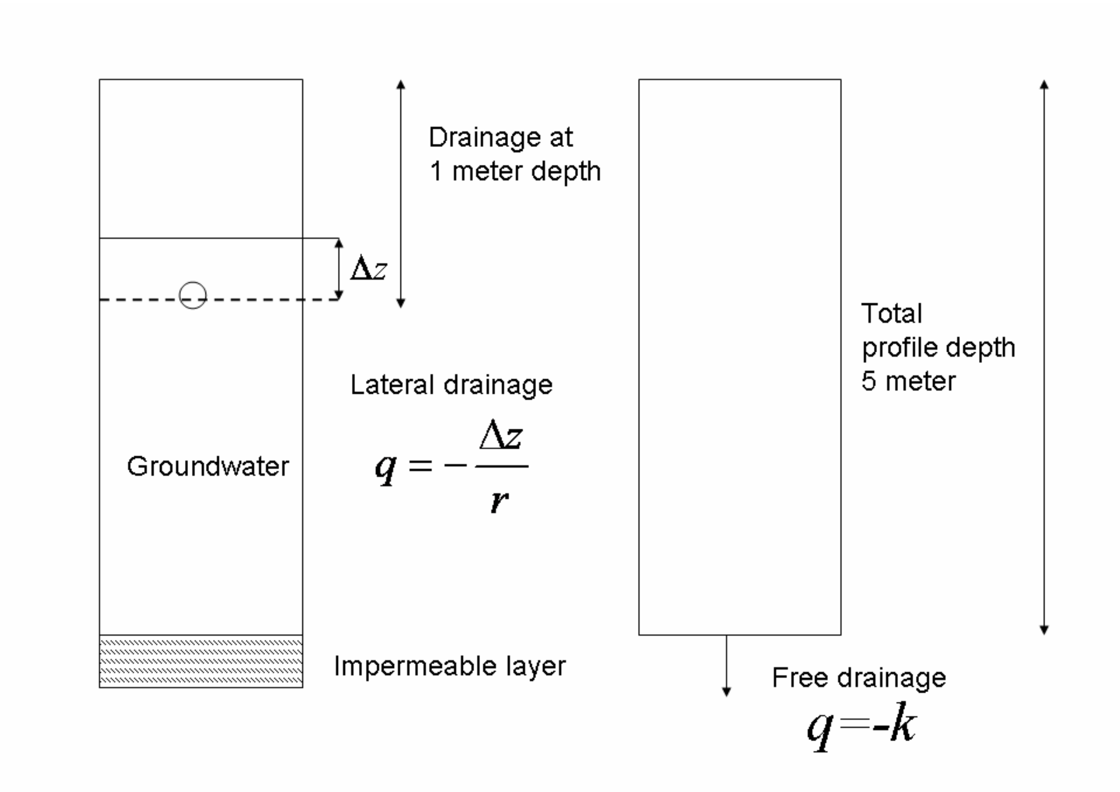


Table 1: Values for maximum rooting depth (cm), and the discretization of the profile as defined by the total number of layers, thickness per layer, and number of layers with a given thickness.

Rooting depth (cm)	Total number of layers	Thickness per layer; layer 1		Thickness per layer; layer 2		Thickness per layer; layer 3		Thickness per layer; layer 4	
50	4	8	1	32	1	128	1	336	1
75	8	4	2	16	2	64	2	168	2
100	16	2	4	8	4	32	4	84	4
150	32	1	8	4	8	16	8	42	8
300	56	1	8	2	16	8	16	21	16
500	104	1	8	1	32	4	32	10/11	27/6
	168	1	8	1	32	2	64	5/6	60/6

Results and Discussion

Results were evaluated in terms of cumulative yearly transpiration. The results for a soil with free drainage are presented in the Figs 1-4. Results for simulations for a soil with lateral drainage are presented in the Figs. 5-7

A soil with free drainage

As Figure 1 shows for large rooting depths cumulative transpiration increases as a function of the number of layers; for small rooting depths cumulative transpiration decreases, with intermediate behaviour for intermediate rooting depths.
At present the decreasing branch is not well understood.
In the increasing branch of Figure 1, one needs to consider the difference in matric head profiles between fine and coarse discretization. In the case of evapotranspiration the matric head profile will be convex upward. Depending on the degree of convexity pressure heads in a coarse discretization will be more negative - the soil will be drier, and given the definition of the transpiration reduction function, transpiration will be lower. Increasing the number of layers will decrease the error between the convex "true" function and its approximation. The soil will become relatively humid, and transpiration will increase. The explanation for the decreasing branch and the effect of improving function approximation are opposite in sign - this explains the occurrence of both decreasing and increasing transpiration in intermediate situations.

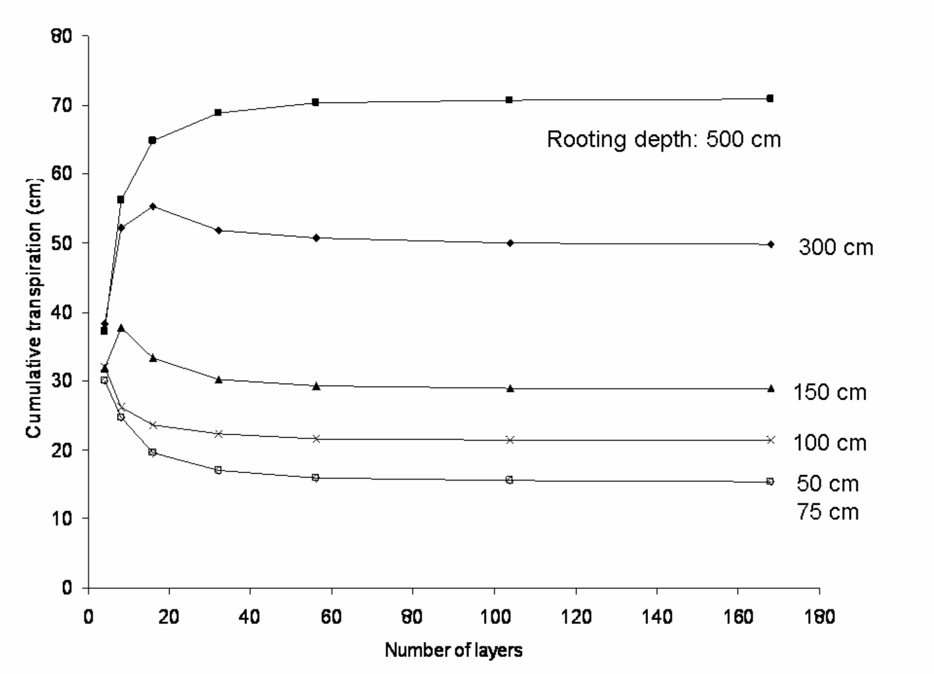


Figure 1: Cumulative transpiration as a function of the discretization for the case of free drainage. All cases show that the solution converges for increasingly finer discretization. For 4 layers the difference between vegetation with 50 cm rooting depth and one with 500 cm vegetation depth is too small. On the basis of available moisture in the root zone one would expect a value in the order of 0.1, but the actual value is in the order of 1.

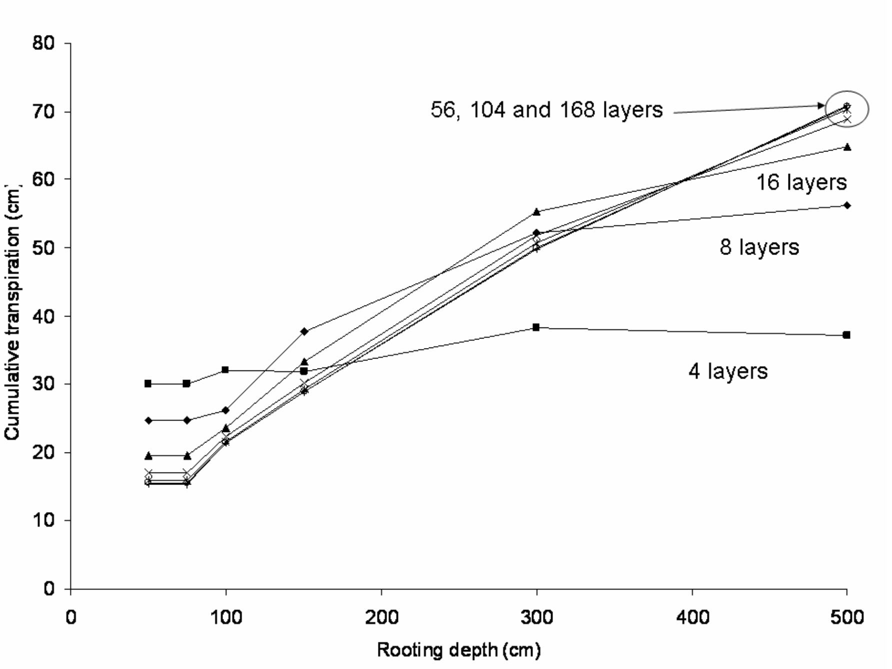


Figure 2: Sensitivity of cumulative transpiration to maximum rooting depth for different discretization for free drainage. Results show that sensitivity to rooting depth decreases with decreasing number of layers.

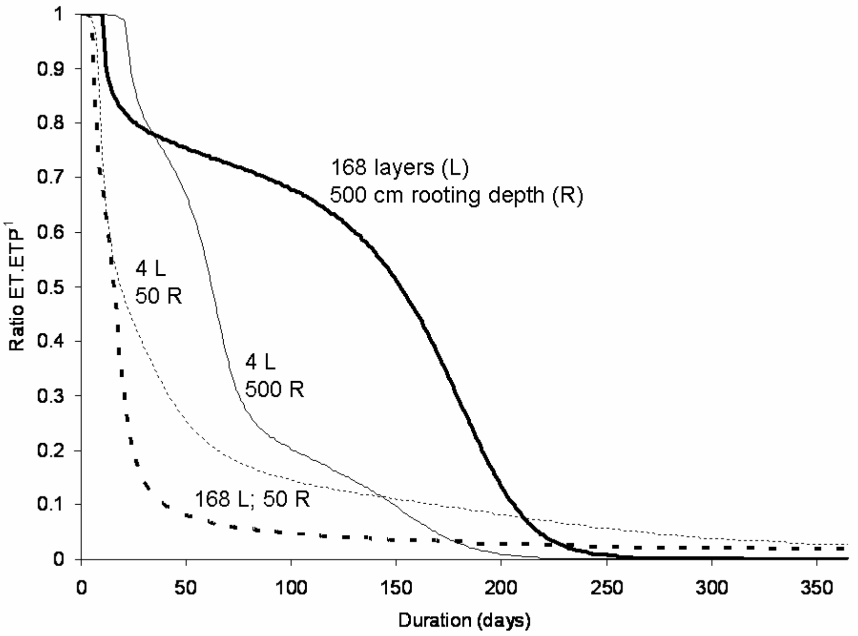


Figure 3: Decrease in relative evapotranspiration for free drainage as a function of time for extreme values of maximum rooting depth (50 and 500 cm) and numerical discretization (4 and 168 layers). The most extreme buffering occurs in the profile with very detailed discretization.

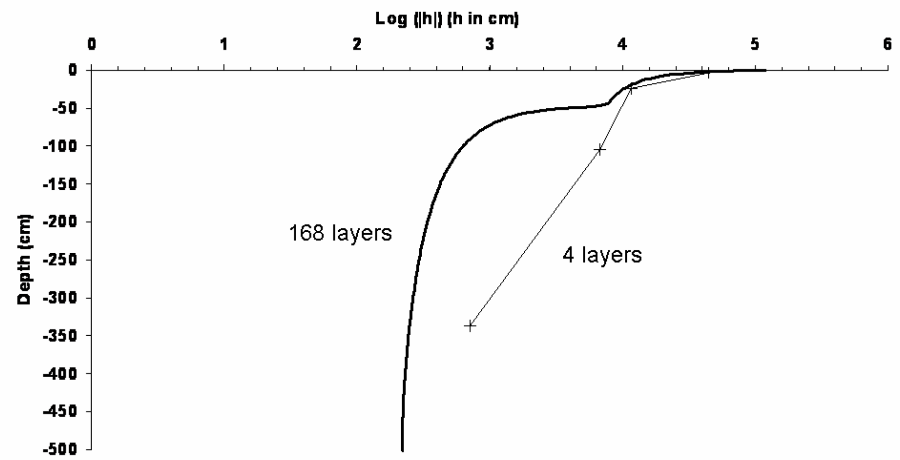
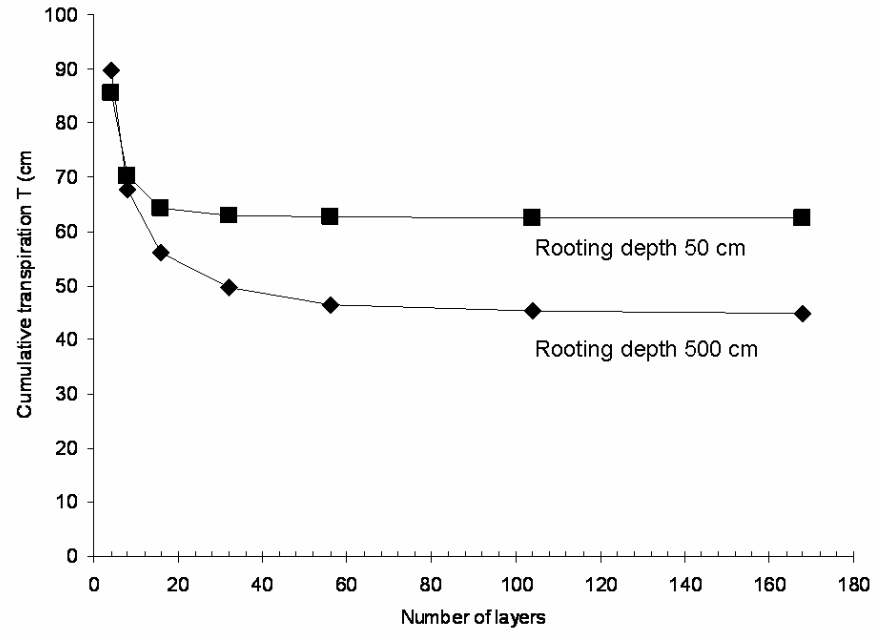


Figure 4: Final result at the end of the simulation period: The log of the absolute soil matric head |h| as a function of depth for the 500 cm deep rooting profile and for the two extremes of the discretization in conditions of free drainage. The result shows that the approximation of a convex function by a very limited number of nodal points leads to a profile which becomes much too dry, notably in the deeper layers.



A soil with lateral drainage

Figure 5 shows that in the case of a soil under groundwater influence, transpiration decreases as a function of discretization. For vegetation with deep roots to have transpiration decreasing with discretization, the profile has to become drier with increasing number of layers. Alternatively, as the model used also simulates a reduction in root water uptake at pressure heads lower than -30 cm, and no uptake above -15 cm, the profile may also become comparatively wetter with an increasing number of layers. This last explanation (reduction due to a wetter profile) describes what happens, as shown in Figure 6: the profile with the fine discretization is still too wet to allow uptake to occur in the deep layers. In the coarsely discretisized profile, the depth of the groundwater table is already below the profile boundary. For the shallow rooting depth the effect is not yet well understood.

Figure 7 shows this completely different behaviour: in terms of relative transpiration a soil with a small number of layers and a groundwater level within the profile behaves almost like a soil with free drainage, whereas the soil with a large number of layers has a very low relative transpiration level which increases slowly.

Figure 5 Effect of discretization and maximum rooting depth in the profile with lateral drainage (groundwater level initially at -100 cm).

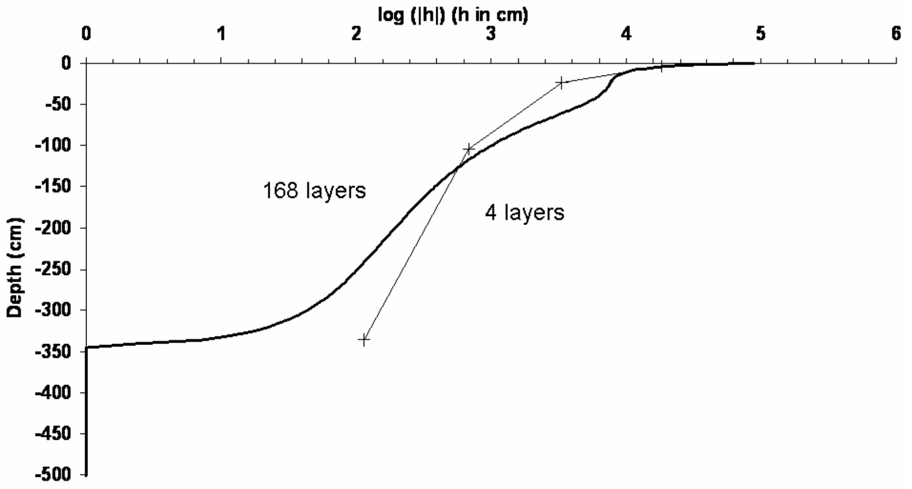


Figure 6 Final result at the end of the simulation period: The log of the absolute soil matric head |h| as a function of depth for the 500 cm deep rooting profile and for the two extremes of the discretization in the profile with lateral drainage. The result shows that the approximation of this function by a very limited number of nodal points leads to a profile which is too dry in the lower nodes.

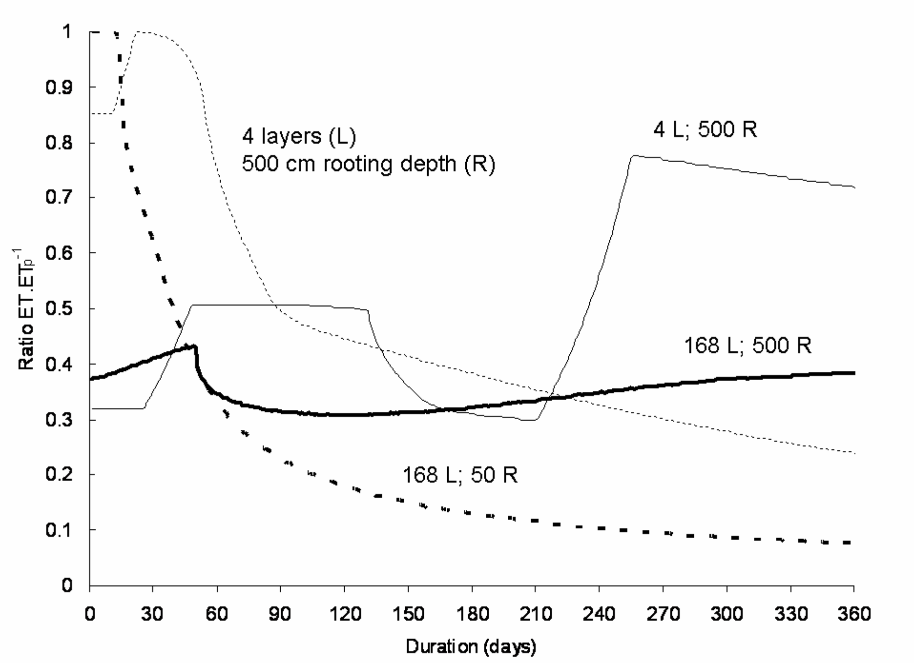


Figure 7 Decrease in relative evapotranspiration (*ET.ET*$_p^{-1}$) on a sandy soil as a function of time for extreme values of maximum rooting depth (50 and 500 cm) and numerical discretization (4 and 168 layers).

Conclusions

Overall, a coarse discretization decreases the sensitivity of the transpiration to rooting depth and to groundwater level. Buffering in ET increases with maximum rooting depth and discretization. Simulation in presence of a groundwater level is sensitive to the assumption regarding root water uptake in very wet conditions.

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