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PREDICTING WATER MOVEMENT IN A MEDITERRANEAN SOIL-CROP SYSTEM WITH TWO SIMULATION MODELS

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A b s t r a c t. We evaluated the WAVE 2.1 and the EURO-ACCESS-II models for the dynamics of volumetric soil water content in a cropped soil under Mediterranean conditions. A detailed data set was constructed for a furrow-irrigated experimental plot on a homogeneous sandy soil, cropped with maize during the seasons 1992 and 1993. The calibration and the validation results of the models were evaluated by using both simulation graphics and two specific modelling evaluation statistics: the root mean square error and the modelling efficiency. Results showed that both models were able to predict the fate of water in this coarse textured irrigated soil subjected to semi-arid Mediterranean environmental and agronomical conditions. Reasonably good predictions of soil moisture were obtained by the models when considering total soil moisture storage in the root zone of plants. The deviations between the predicted and observed moisture values increased when considering each soil layer separately. Sensitivity analysis showed that the input values of the crop coefficient have a significant influence on predictions made by the WAVE 2.1 model. The input value of leaf area had a significant influence on the predictions of both models. Calibration for the specific environmental conditions of the field sites is required before using any of the two models. Special attention must be given to the input values of those variables which are most affected by spatio-temporal variability within the field.

K e y w o r d s: water movement, simulation models.

INTRODUCTION

The management of water resources in arid and semi-arid areas causes frequent conflicts between different sectors of the population. Most of the pressure goes to the agricultural sector, responsible for the consumption of about 80% of the water resources in many of those areas. As a consequence there is an increasing demand for information oriented to a better water management in agriculture. In the last two decades several models for the simulation of water fluxes in the soil-crop system have been developed. Some of these models are nowadays considered as useful tools in the task of optimising the use of water resources at different levels, from individual farms to whole regions. Two of these models, WAVE 2.1 [15], from now on referred to as WAVE, and EURO-ACCESS-II [2], from now on ACCESS, are comprehensive models with different modules or submodels for simulating the fate of water, heat and solutes in the soil-crop-atmosphere system. Thus, WAVE has been used for simulating from drainage fluxes [10] to transpiration under different conditions of water in the soil, besides its recent use in simulating pesticide leaching [13,14]. The originally one dimensional ACCESS model, after being implemented with a horizontal flow sub-model [12,18], is able to take into account bypass flow through cracks and macropores. Uncertainties arise, however, when the models are used for conditions different from those to which have been previously tested.

In this work we evaluate the capability both of the WAVE and the ACCESS model to predict the temporal evolution of the volumetric soil water content in a furrow irrigated plot cropped with maize located in a semi-arid region in Southwest Spain. Both models were calibrated and validated with two different field data sets. We followed the recommendations given by Sławiński *et al.* [13] for the models evaluation. Sensitivity analysis was carried out to identify the crucial input parameters of both models.

MATERIALS

The models

The mechanistic-deterministic WAVE model [15], considers different soil layers within the soil profile explored by the roots, each subdivided in space intervals called the soil compartments, which thickness is specified by the user. The model inputs are specified on a daily basis and the model yields daily outputs to a maximum simulation period of one year. The water transport module of the model solves the Richards equation for a set of variable boundary conditions. The soil moisture retention characteristic and the hydraulic conductivity values must be specified for each soil layer, and can be described by means of different parametric models. The crop growth module calculates the time course of the leaf area, the accumulation of the dry matter of the different plant organs and the root length and root density extension rates. Further, crop coefficients (K_C) are needed to convert the reference evapotranspiration (ET_r) to the potential crop evapotranspiration (ET_C). The soil water component of the ACCESS model [2,8] solves the one-dimensional Richards' equation for a vertical soil profile [2,8]. The soil water balance submodel was modified by involving an option for preferential water flow through soil macropores [12,18]. As in WAVE, ACCESS works on multiple soil layers and the results are given as daily values.

The data sets

The experiments were carried out in the experimental farm La Hampa, of the Instituto de Recursos Naturales y Agrobiología (37^0 17' N, 6^0 3' W, 30 m a.s.l.). The area is typically Mediterranean, with an average ET_r (grass reference) of 1397 mm and an average rainfall of 494 mm (period 1971-1999). Details on the experiments are given by Moreno *et al.* [11] and Fernández *et al.* [5]. Basically, maize (*Zea mays*, Prisma) was grown from 1991 to 1996 under Mediterranean management practices in the Guadalquivir River Valley. Rain falls mainly from October to May, being dry and hot for the rest of the year. About 625 mm of water were supplied by furrow irrigation during each crop season (end of March middle of August) to cover the crop water needs. The soil showed to be highly uniform with depth and was classified as a sandy loam Xerochrept. Physical properties of the soil are summarised in Table 1. Measurements of soil water content (θ, m^3 m^{-3}; neutron probe and gravimetry), soil matric potential (h, MPa; mercury tensiometers) and hydraulic conductivity (K, mm h^{-1}; the internal drainage method) were taken at three representative locations within the plot. Crop height (h_C, m) was measured five times during the crop period of 1992, and every week in 1993.

Table 1. Mean physical soil characteristics of the experimental plot. The values shown are the mean of 25 replicates for textural values, and between three and nine replicates for physical values (O.M.= organic matter; D_b = bulk density; θ_R = residual water content; θ_S= soil water content at saturation; K_{sat} = soil hydraulic conductivity near saturation)

Depth (m)	C. sand (%)	F. sand (%)	Silt (%)	Clay (%)	O.M. (%)	Depth (m)	D_b (Mg m^{-3})	θ_R (m^3 m^{-3})	θ_S (m^3 m^{-3})	K_{sat} (mm h^{-1})
0.0-0.5	62.1	15.8	8.6	13.5	0.88	0.0-0.2	1.45	0.07	0.21	110
0.5-1.0	57.9	17.6	8.5	16.0	0.55	0.2-0.4	1.55	0.07	0.23	40
						0.4-0.6	1.55	0.08	0.23	20
						0.6-0.8	1.65	0.08	0.25	9
						0.8-1.0	1.65	0.08	0.25	4

These measurement were done on one plant of each 5x5 m grid (n = 25). Leaf area index (LAI) was determined for the fully mature crop in 1992, and every 7-10 days in 1993, on three plants of a representative size. Root depth (z_r, m) and crop yield (Y, kg ha^{-1}) were determined at the end of both crop periods. The crop evapotranspiration was determined from the water balance equation applied at the plot level by Fernández *et al.* [5]. The values of ET_r needed for determining K_c were calculated from the data recorded at the automatic weather station of the farm, some 120 m from the experimental plot.

The models testing

The measurements carried out in the experimental field during the 1993 crop period were used for calibrating the models, since this was the most detailed data set. For the validation phase, we used data of the 1992 crop period, and no adjustments of the models parameters was thereby done. The models were tested following the protocol described by Vanclooster *et al.* [13]. Measurements carried out by Angulo *et al.* [1] showed marked temporal variations of the hydraulic conductivity in the range near saturation (K_{sat}). Since this is among the parameters considered in the models as being static, a mean value for the whole calibration period was considered as initial parameter set. The model parameters were calibrated by the trial and error method, minimising thereby the difference between the simulated and measured data. The final value of the parameters was always kept within the range of physical possible values.

In the WAVE model we used the power function formalism of the van Genuchten model [17] to describe the soil moisture retention characteristic, and Mualems model [12] for the soil hydraulic conductivity relationship. The time courses of LAI and z_r were considered as model inputs. Daily data of LAI were interpolated from the measurements made in the field. Three K_c values were input in the model, 0.8 for the crop stage of fast growth, 1.4 for maturity and 0.7 for senescence. These K_c values were obtained by Fernández *et al.* [5]. For the evaluation of both the WAVE and the ACCESS model, simulations were done up to a depth of 1 m, which includes the major part of the root system [5]. Five 0.2 m depth soil layers were considered, each divided into two 0.1 m numerical compartments. The water content of each compartment was measured at the beginning of the simulation period, and was specified as model input ($\theta_{initial}$). For the numerical solution of the Richards' equation the soil profile was divided into homogeneous genetic horizons, and each one of them was characterised by a set of hydro-physical parameters, including the soil water retention and hydraulic conductivity curves. For characterising the soil hydraulic properties we input the m, n and α parameters of the van Genuchten function, plus the values of θ_r, θ_s and K_{sat} determined in the field (Table 1). In the ACCESS model, these parameters are converted to those required by the Clapp and Hornberger relationships [4] used by the model for describing the soil water retention and hydraulic conductivity curves. In the ACCESS model the daily *LAI* values are calculated based on the so called accumulated heat unit, *HU*, and the heat unit for maturity, *MHU*. The value of *HU* is the sum of degree-days from the beginning of plant growth, and *MHU* is 1950 degree-days for maize. The root length (L_v, $cm_{root}\ cm^{-3}{}_{soil}$) as a function of time is calculated using the curvilinear function proposed by Borg and Grimes [3]. The maximum values both of *LAI* and L_v are input into the model, as well as ET_r. The ACCESS model does not use the K_c coefficient.

For the evaluation of the predicted results, both simulation graphics and modelling statistics were used. The graphical evaluation concerned the seasonal time courses of θ in the five considered soil layers. Two statistical model indicators were used, the root mean square error (*RMSE*, the percentage of overestimation or underestimation of the predicted value as compared to the mean observed value) and the modelling efficiency (*EF*, the degree to which the predictions give a better estimate of observations compared to the mean of the observations) [7].

RESULTS

Calibration

Figure 1 shows the measured and simulated values of θ at five different depths for the 1993 cropping season. These graphical calibration results are completed with the statistical model indicators calculated for the same period (Table 2). Lower values of *RMSE* were obtained with WAVE than with ACCESS, except for the 0.2-0.4 m and 0.4-0.6 m soil layers. The *RMSE* suggests that WAVE was slightly better in simulating θ than ACCESS. The same conclusion can be drawn when analysing the values of *EF* for each soil layer. When considering the total soil depth explored by the roots both models yielded similar *EF* values. The results of the sensitivity analysis (Table 3) shows that the simulation prediction of the crop water consumption by both models depended very much on the input values of *LAI*, as well as on K_c for WAVE. The values of K_{sat} resulted to be less crucial than those of *LAI* and K_c, and those of $\theta_{initial}$ were relatively crucial for WAVE, but not for ACCESS.

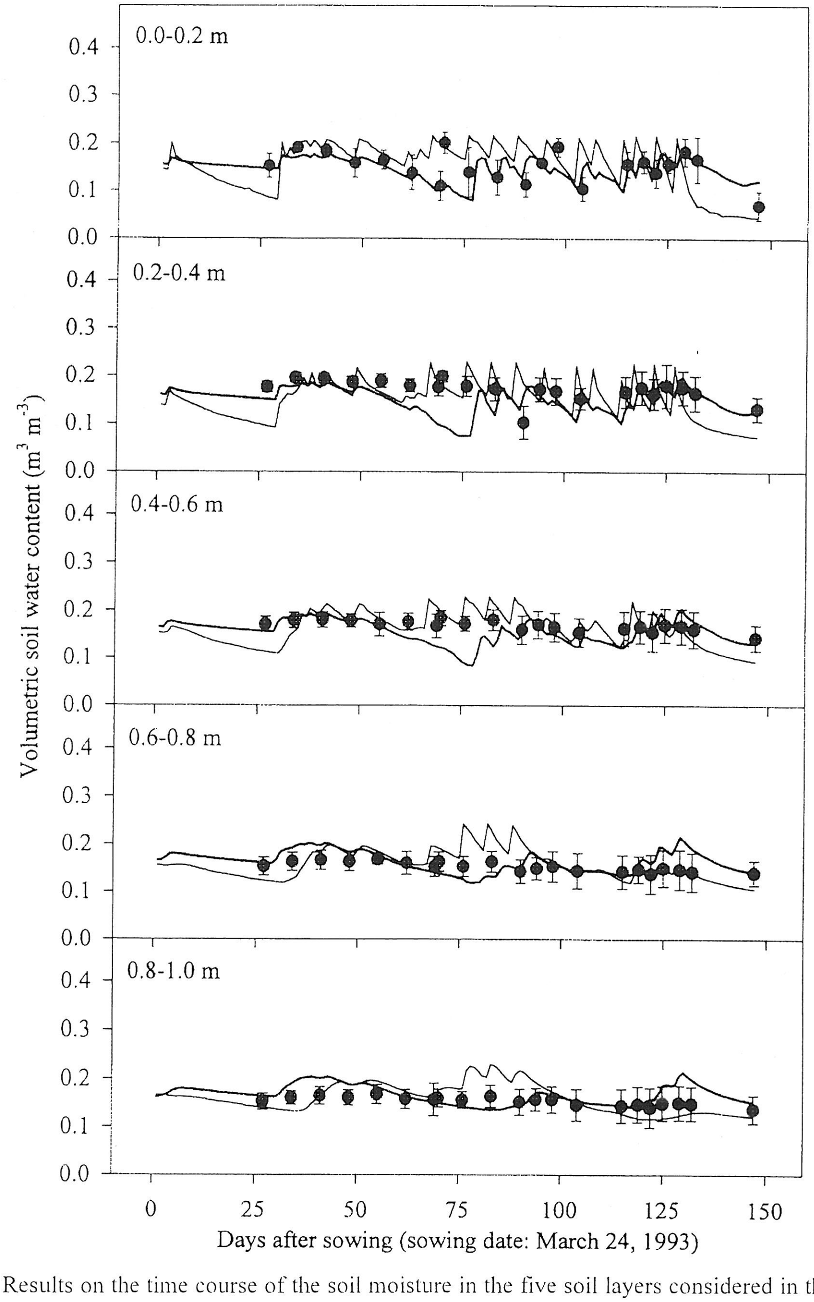

Fig. 1. Results on the time course of the soil moisture in the five soil layers considered in the evaluation of the WAVE and ACCESS models during the calibration phase in 1993. Thick line: WAVE; Thin line: ACCESS; Points: average of three measured values; Vertical bars: 95% confidence inter-

Table 2. Statistical performance criteria for the simulated volumetric water content in the different soil layers and complete soil profile during the model calibration (1993 crop period) and the model validation (1992 crop period) phase. n = number of observations or predictions; RMSE = Root mean square error; EF = model efficiency. Details on the statistical indicators are given in the text

Depth (m)	n	Calibration: 1993 crop period				Validation: 1992 crop period			
		WAVE		ACCESS		WAVE		ACCESS	
		RMSE	*EF*	*RMSE*	*EF*	*RMSE*	*EF*	*RMSE*	*EF*
0.0-0.2	21	21.96	-0.08	35.97	-1.89	18.21	-4.69	19.18	-0.25
0.2-0.4	21	26.16	-1.34	24.08	-2.77	16.38	-0.57	24.41	-3.93
0.4-0.6	21	19.56	-1.91	18.72	-8.97	20.33	-0.27	21.66	-7.06
0.6-0.8	21	17.99	-7.61	22.63	-12.71	26.37	-0.18	19.41	-6.17
0.8-1.0	21	15.90	-7.42	18.94	-11.95	31.20	-0.88	18.90	-6.80
0.0-1.0	105	15.58	0.96	20.49	0.96	15.62	0.96	16.09	0.96

Table 3. Sensitivity analysis for the WAVE and ACCESS models in which the influence of five key input parameters (K_{sat} = hydraulic conductivity in the range near saturation; m = fitting parameter of the van Genuchten and Nielsen equation; $\theta_{initial}$ = volumetric soil water content at the beginning of the simulation period; LAI = leaf area index; K_c = crop coefficient) on the volumetric soil water content (θ) has been determined. The analysis shown here was made with the results of the 1993 crop period

Parameter	Sensitivity coefficient for θ	
	WAVE	ACCESS
K_{sat}	-0.017	-0.06
$\theta_{initial}$	0.026	0.034
LAI	-0.026	0.115
K_c	-0.13	

Validation

Reasonably good results were obtained in the values predicted for the five considered soil layers (Fig. 2). The graphical simulation shown in Fig. 2 is completed with the statistical evaluation of the results shown in Table 2. Both analysis of the deviations between the predicted and observed results show a performance for both models as good as during the calibration phase, in some cases even better.

DISCUSSION

Results show that, in general, any of the two models can be used with confidence for simulating soil moisture in the whole soil profile, but caution should be

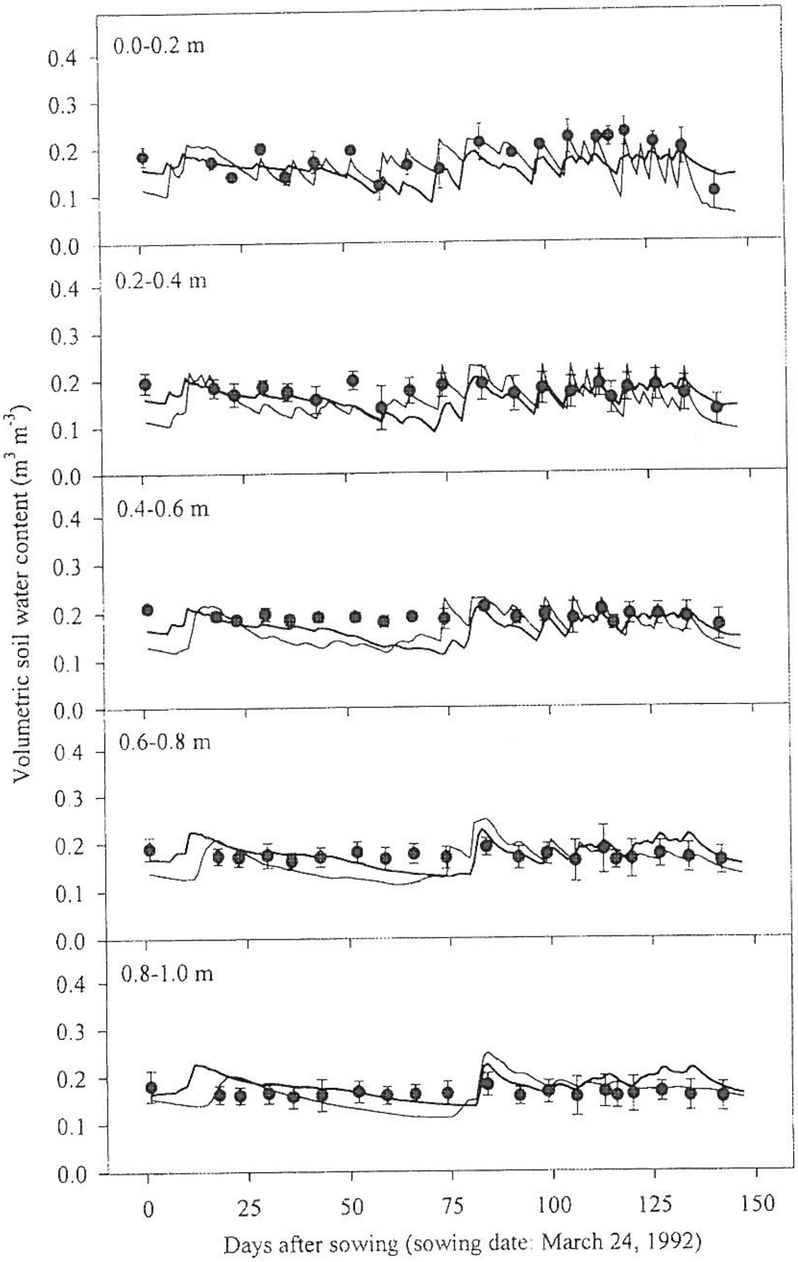

Fig. 2. Results on the time course of the soil moisture in the five soil layers considered in the evaluation of the WAVE and ACCESS models during the validation phase in 1992. Thick line: WAVE; Thin line: ACCESS; Points: average of three measured values; Vertical bars: 95% confidence inter-

taken when simulating moisture contents at different soil layers. The inability of the WAVE model to reconstitute the soil moisture correctly at the 0.2-0.6 m soil depth during the calibration phase (Fig. 1) is a well known problem in the 2.1 version which is attributed to a poor performing root uptake mechanism in the subsoil, which will be updated in future releases of the model. A substantial part of the modelling error is due to scale problems in the data collection and parameter identification phase. Actually, parameters governing *in situ* water flow are well known to be subjected to important spatio-temporal variations. Any spatial or temporal variation in the soil texture or soil compaction, for instance, will have a significant impact on the lack of agreement between the predicted and the measured results, if it is not well reflected in the modelling structure.

The user of any of these models should pay special attention to the accuracy of the input *LAI* values, and take into account the quick variations of this variable in certain periods of the crop development. In the WAVE model just a reduced number of K_c values can be input for the whole crop period, which can be the reason for part of the disagreement between the observed and the predicted results. In this work we have input three K_c values for each of the studied crop periods, obtained by Fernández *et al.* [5] in the experimental plot on both experimental years. We can assume, therefore, that these seasonal time courses of K_c were close to reality. Even so, errors in the WAVE predictions still arise from the fact that just three K_c average values were input for each experimental period, which it does not reflect the marked K_c variations reported by Fernández *et al.* [5]. The model user should also be aware of possible errors coming from spatial variations of $\theta_{initial}$ and K_{sat}. In addition, the temporal variation of K_{sat}, due mainly to soil compaction throughout the crop period, is not taken into account by the models, since just a single average K_{sat} value can be input for each considered soil layer.

The models must be calibrated for the conditions in which they are going to be used as predicting tools. The results presented by other authors, seem to show that the processes related to the water movement and storage in the soil, as well as to the crop water consumption, are well described in both models. In an experiment carried out in a Manawatu fine sandy loam soil in New Zealand, the WAVE model was able to predict reasonably well the temporal change in water content in the root zone of a mature apple tree for a period of time in which several irrigation events occurred [6]. Van Uffelen *et al.* [18], in the Netherlands, validated the WAVE model comparing the predicted values with those measured in fine-loamy soils cropped with potato. They simulated the dynamics of water in the soil-crop system, using SUCROS for the crop growth. The predictions of the soil water content at different depths agreed reasonably well with the field measurements (r^2 = 0.65). During a validation exercise of the ACCESS model in a clay soil in England, Armstrong *et al.* [2] found that the predicted values followed the pattern of observed data moderately well. The authors mentioned the reasonable good results obtained by Loveland *et al.* [9] when calibrating ACCESS for the prediction of the crop growth. The ACCESS capability of predicting soil moisture was further evaluated by Walczak *et al.* [19] in two kinds of soils in Poland, a loam sandy soil and a silty soil. Previously, Slawinsky *et al.* [13] had included a module for preferential flow. This increased the agreement between predicted and observed values. In addition to all that work already done with the models, it can be assumed from the results obtained in this work that both the WAVE and the ACCESS models are reliable engineering tools for predicting water dynamics in the soil-plant system of an irrigated cropped plot of sandy loam soil under semi-arid Mediterranean conditions.

CONCLUSIONS

Both the WAVE and the ACCESS model are reliable tools for predicting the soil water storage in an irrigated cropped plot of coarse soil under semi-arid Mediterranean conditions. Both models were able to predict reasonably well the total soil moisture storage in the root zone. The within profile variability of soil moisture was less accurately predicted. The two models require different inputs, so the user can choose the most appropriate model according to the available data set. It is suggested to calibrate the models prior to any use as a predicting tool. Special care must thereby be taken to the input variables which are most affected by the within field spatio-temporal variability. The predictions of the WAVE model were most sensitive to the input values of K_c and LAI, where in the case of ACCESS the LAI and K_{sat} values were those influencing most the predicted results.

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MODELOWANIE RUCHU WODY W SYSTEMIE GLEBA-ROŚLINA W WARUNKACH KLIMATU ŚRÓDZIEMNOMORSKIEGO

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S t r e s z c z e n i e. W pracy przedstawiono ocenę możliwości zastosowania dwóch modeli przewidywania plonów WAVE 2.1 i EURO-ACCESS II do szacowania dynamiki wilgotności w profilu glebowym w warunkach klimatycznych południowej Hiszpanii. Otrzymane wyniki symulacji dynamiki wilgotności w profilu glebowym dla poszczególnych modeli zostały porównane statystycznie ze zmierzonymi w latach 1992-1993 wartościami wilgotności na nawadnianym zalewowo poletku doświadczalnym z kukurydzą. Otrzymane wyniki pokazują, że oba modele mogą służyć do przewidywania dynamiki wilgotności na nawadnianych, uprawianych rolniczo polach w ekstremalnych warunkach klimatu śródziemnomorskiego, co stwarza możliwości lepszego wykorzystania zasobów wodnych tego regionu.

S ł o w a k l u c z o w e: modelowanie, wilgotność gleby, przepływ wody.