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Analysis of DRAINMOD performances with different detail of soil input data in the Veneto region of Italy

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Abstract

The deterministic field scale model DRAINMOD was tested in an experiment on subsurface pipe drainage in the Veneto region, in an environment of NE Italy characterised by the presence of a shallow water table in a flat area. The objective was to determine whether a minimal set of field data would suffice to use DRAINMOD for predictive purposes. The measured water table depth and drain outflow from a 5-year field experiment were compared to those determined by DRAINMOD using three levels of detail in input data. The results indicated that even very limited input data (texture and porosity of the top 30 cm of soil) gave good predictions. More elaborate data improved the estimates. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: DRAINMOD testing; Pipe drainage; Soil hydraulic properties; Veneto region

1. Introduction

Within the general framework of the water resources integration in agriculture, problems of drainage and irrigation have to be examined together, particularly in the humid areas where there is a succession of humid and dry seasons with opposing drainage

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and irrigation needs. The problem becomes even more complex if water quality is taken into consideration.

Given the complexity of the problem, simulation models are useful tools to understand the processes better, to compare different strategies, to suggest solutions, and to predict consequences in the medium to long term.

For a long time, models have been used by experts (often the author of the model), and in conditions where it is possible to carry out accurate calibration and validation. However, it is desirable that irrigation and drainage models find wide application for practical purposes, from water management planning at basin level to operation scheduling at field level.

Within this framework, the final user has to be aware of the risks connected with the wrong use of the models. It is important to not only know how to run a model, but also how to apply it. That is, the assumptions and accuracy of the models, the space and time scale, and the boundary conditions have to be known.

The selection of models for practical purposes involves some preliminary considerations. Many of them are simple empirical models, requiring few input data, and unsuitable for environments differing greatly from those where the models were developed. Other models are complex physical based models and should be more generally applicable. However, requiring more parameters than the simple models, they are often difficult to calibrate and do not always guarantee better predictions.

Among the numerous irrigation and drainage models available in the literature, DRAINMOD (Skaggs, 1980), developed for the design and evaluation of different combinations of surface and subsurface water management systems, is one of the most applied in the world.

The poor availability of data on soil water relationship (p*F* curve, hydraulic conductivity, etc.) can be a serious constraint in the application of DRAINMOD in Italy and in other regions abroad where analyses are carried out commonly for only some essential chemical–physical characteristics (texture and organic matter) that are easier to be determined.

In the authors' opinion, the application of DRAINMOD for practical purposes in Italy will rely on the possibility of achieving reliable simulations even if the model is applied with indirectly estimated data for the hydrologic properties of the soil.

Different indirect methods have been proposed to represent the water retention characteristics and hydraulic conductivity (Arya and Paris, 1981; Lehmann and Ackerer, 1997). One of the approaches is to apply some form of power curves (e.g. Brooks and Corey, 1964) with constants that must be evaluated empirically.

The objectives of this study were

1. to test DRAINMOD in an experiment on subsurface pipe drainage in the Veneto region, an environment of NE Italy characterized by the presence of a shallow water table in a flat area,
2. to verify the feasibility of running DRAINMOD with different levels of input data by both measuring and estimating the main soil hydraulic properties and
3. to determine the suitability of applying DRAINMOD for practical purposes in the Veneto region when faced with the problem of lack of sufficient input data.

2. Materials and methods

2.1. Test site and drainage design

DRAINMOD (version 5.0) was applied to a long-term experiment on subsurface pipe drainage carried out during the period 1982–1996 on the University of Padova Agricultural Experimental Station's farm near Padova, in NE Italy (45°21′ N, 11°58′ E, 6 m above sea level).

According to De Martonne (1962), the climate of the site may be defined as subhumid, with an annual rainfall of about 850 mm rather uniformly distributed throughout the year. The long-term rainfall record indicates greatest variability in September, October and November. In those months, there is a 5% probability of exceeding 220, 195 and 185 mm, respectively. Temperature increases from January (average of minimum values: −1.5°C) to July (average of maximum values: 27.2°C).

The soil, according to FAO–UNESCO classification, is fulvi-calcaric Cambisol, with loamy texture in the upper 80 cm. The percentage of silt increases gradually with the depth, reaching values of 68–75% at 2–2.4 m of depth. Soil infiltration rates, evaluated with the double cylinder infiltrometer (Oosterbaan and Njiland, 1994), vary from 0.1 cm h^{-1} if the soil is compacted with crust or silty deposits on the surface, to 10 cm h^{-1}. Average lateral hydraulic conductivity measured with the auger hole method (Van Beers, 1958) is 4.2 cm h^{-1}. In Fig. 1, also shown are the water retention curves at various soil depths, determined on 5 cm diameter undisturbed soil samples with the Stakman apparatus (Stakman et al., 1969) for low-range potentials and with a pressure plate apparatus (Klute, 1986) for mid and high-range potentials.

The monthly average water table depth, in the absence of drainage control, ranges between 1 m at the end of winter and 1.9 m in summer, but daily values of 0.5–0.6 m are not rare in winter.

The drainage system was installed in autumn 1981 with a trenching machine. Corrugated 65 mm diameter PVC drains were used. Drains were installed with spacing of 8 m, slope of 0.2% and average depth of 0.85 m, and the surface was sloped with a grade of about 0.3%. Drains discharged into an open ditch, as is usual in Italian conditions.

Parallel to the drains, a ditch bordered the drained land along the longer sides. At the upper part of the system, another ditch was used as water feeder for subirrigation, that was managed as reported in Giardini and Borin (1995).

2.2. The model

DRAINMOD is a deterministic field scale model developed by R.W. Skaggs at North Carolina State University. It has been developed and tested for use in humid regions characterized by the presence of a shallow water table (Skaggs et al., 1981; Rogers, 1985; Fouss et al., 1987; Sabbagh et al., 1993).

The model predicts the effects of different combinations of surface and subsurface water management on the water table and soil water conditions.

The basis for the model is a water balance on a thin section of soil located midway between drains and extended from the impermeable layer to the soil surface.

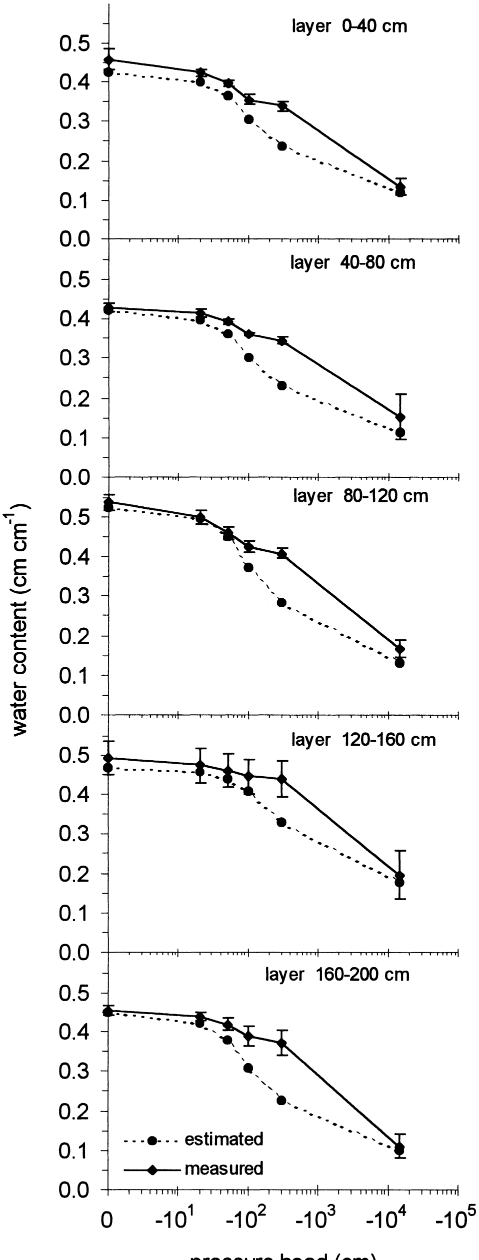

Fig. 1. Measured and estimated water retention curves in the different soil layers (±standard deviation is indicated for measured points).

The water balance equation is as follows:

$$\Delta V_a = D + ET + DS - F \quad (1)$$

where ΔV_a is the change in air void volume (cm), D the drainage (cm), ET the evapotranspiration (cm), DS the deep seepage (cm) and F the infiltration (cm). The basic time increment is 1 h.

Approximate methods were used to simulate the water movement processes to avoid prohibitive amounts of computer time for long-term simulations due to the application of numerical solutions to nonlinear differential equations.

Under most conditions, drainage rates are calculated with the Hooghoudt equation (Van Schilfgaarde, 1974), which is based on the Dupuit–Forchheimer assumptions with a correction for the convergence near the drains. When the water table rises to the surface and the surface is ponded, the drainage rate is calculated with an equation by Kirkham (1957). Deep seepage is simulated by a straightforward application of Darcy's law. *ET* is calculated on the basis of daily potential evapotranspiration, which may be estimated by any method for which meteorological data are available and read into the model, or it may be calculated within DRAINMOD by the equation of Thornthwaite (1948). When the soil water availability in the root zone and upward flux from the water table are not limiting, *ET* is set equal to potential *ET*, otherwise it is set equal to the upward flux. Infiltration is simulated applying the Green–Ampt equation.

The key point in DRAINMOD is the representation of the soil water distribution, on the basis of which evapotranspiration and drainage are calculated. It is assumed that the soil water is distributed in two zones: a wet zone and a dry zone. In the wet zone, the water content distribution is assumed to be that of a profile drained to equilibrium.

The model inputs are mainly of four groups: climate parameters (rain, temperature, *PET*, etc.), drainage design parameters (drain spacing, depth, etc.), soil hydraulic properties (water retention curve, saturated hydraulic conductivity, drainable porosity, etc.) and crop parameters.

In addition to the standard outputs (drainage volumes, runoff, *ET*, etc.), objective functions, including crop yields on a relative basis, are given in the model to help the users to interpret the model results.

2.3. Test simulations

Simulations were conducted in the years 1991–1995. The crop rotation was soybean–barley–soybean (second crop)–maize–wheat–maize. Conventional tillage practices, consisting of a sequence of moldboard plow, harrow and rotary hoe, were adopted in the plot. During the summer of 1993, three subirrigations were carried out on maize. Climatic data were measured at a weather station within the drainage field.

Water table depth was monitored daily from January 1992 to December 1995. The drain discharge was measured in all 5 years of the study. Measurements were done in the morning of working days, when drainage occurred, by determining the time required to fill a $1000\ cm^3$ (1 l) container. This value was then integrated over the whole day to obtain the daily discharge. This procedure is quite approximate, but was the only feasible one because automatic measurement devices were not available.

To evaluate the feasibility of applying DRAINMOD for practical purposes using indirect estimated soil hydraulic data, it was proposed that the model be run with three different sets of soil hydraulic properties input, corresponding to the following hypotheses:

1. Hypothesis 1 (H1): It was assumed that the soil texture and soil porosity, both measured for the first soil layer (0–30 cm), were the only data available. This is a common situation in the farms of the Veneto region. The water retention curve was estimated from the application of the power curve proposed by Brooks and Corey (1964) with constants derived by a set of multiple regressions based on soil texture and porosity (Rawls and Brakensiek, 1982). The vertical saturated hydraulic conductivity was estimated from tabular data based on soil texture (Rawls et al., 1993). The lateral saturated conductivity was set at twice the vertical saturated conductivity, as suggested by Skaggs (1980). The drainage volume, upward flux and Green–Ampt parameters were calculated by an internal DRAINMOD subroutine, based on the estimated water retention characteristics.
2. Hypothesis 2 (H2): It was similar to the first one, with no soil hydraulic data assumed to be available and which were estimated in the same way as described for H1. Texture data and porosity data were, however, assumed to be accessible for the entire profile (five layers: 0–40, 40–80, 80–120, 120–160 and 160–200 cm). In this way, the variability of the hydraulic properties down the profile due to the characteristics of the different layers was considered.
3. Hypothesis 3 (H3): The measured saturated hydraulic conductivity and water retention curves of the soil profile determined for the same layers as in the case of H2 were used. For practical purposes, this situation is very unusual in the Veneto region and is feasible, actually, only if specific research is carried out on the site. The drainage volume was calculated, as suggested by Skaggs (1980), according to the drainable porosity of two different layers (0–80 and 80–160 cm). The latter was derived from the relationship between water table elevation and rainfall depth, as proposed by Kabat (1988). The procedure is valid when the water table is rising under the influence of rainfall, according to which, the drainable porosity (μ) over a certain period of time is given as
$$\mu = \frac{P}{\Delta H} \tag{2}$$
where P is the amount of percolation (mm) and ΔH the change in the water table (mm). To apply this procedure, data for water table depth and P recorded daily at the meteorological station during the period 1982–1996 were used. This procedure was applied to only the winter data, assuming that, in this period, the water is retained at high potential, evapotranspiration is negligible and almost all the rain percolates through the profile to reach the water table.

2.4. Model testing

To assume practical applications of the model, no attempt to calibrate input data or coefficients was carried out. Outputs provided by the model were compared to water table depths and drainage volumes measured during the experiment.

In order to test the model results, two indices were added to the traditional least squared method: the standard deviation (s.d.) (Sabbagh et al., 1993) and the model efficiency index (e.i.) (Loague and Green, 1991). The s.d. is defined as

$$\text{s.d.} = \sqrt{\frac{\sum (P_i - O_i)^2}{n}} \tag{3}$$

where P_i is the predicted value, O_i the measured value and n the number of pairs of values. If s.d. is equal to zero, the model produces exact predictions. Loague and Green (1991) defined e.i. as

$$\text{e.i.} = \frac{\sum_{i=1}^{n} (O_i - \bar{O})^2 - \sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \tag{4}$$

where P_i is the predicted value, O_i the measured value and $\bar{O}$ the mean of measured values. The values of e.i. can range from e.i. = 1 downward. If e.i. = 1, the model produces exact predictions.

3. Results and discussion

3.1. Measured and estimated soil hydraulic properties: water retention curve and drainage volume–water table relationship

Observed (H3) and estimated water retention curves (H1 and H2) are reported in Fig. 1. They were linearly interpolated, starting from the soil water content at the tensions of 0, 20, 50, 100, 300 and 15 000 cm. As the Brooks and Corey equation describes only the portion of the curve for tensions greater than the pressure at which the air will enter the soil (bubbling pressure, around 20 cm in our soils), the water content for tensions less than that value were interpolated by DRAINMOD.

In the entire profile, the disagreement between measured and estimated data is greatest for tensions between 100 and 1000 cm, with a maximum for 300 cm. In the portion of the curve at less than 100 cm of tension, differences are not remarkable, and consequently, during the drainage season with shallow water table, this agreement should allow a reliable description of the soil water profile. Especially in the layers mostly characterized by water table oscillations (80–120 and 120–160 cm), the estimated values are very close to the observed ones. The estimated wilting points in all the layers, with the exception of 80–120 cm, are within the standard deviations too.

From a qualitative point of view, the layers 80–160 cm present a greater water retention capacity (about 5% more than in the other layers at the same tension), and this is adequately described by the Brooks and Corey equation (Fig. 1).

The relationship, drainage–water table depth, is used in the model to determine how far the water table falls or rises when a given amount of water is removed or added.

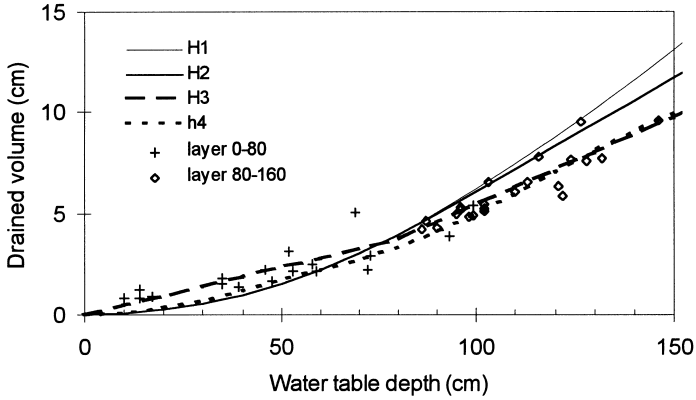

Fig. 2. Drainage volume–water table level relationship in the soil profile.

Fig. 2 shows the three relationships used in H1, H2 and H3. The last is a composite curve obtained by merging two single straight lines built up using the drainable porosity, as calculated with Eq. (2). In fact, the drainable porosity represents the slope of a plot of drainage volume versus water table depths. The relationships used in H1 and H2 are calculated by DRAINMOD's subroutine inputting the estimated water retention curves. In addition, in the same figure, a fourth curve (h4) calculated with the same subroutine, on the basis of the measured water retention values, is also shown. This curve is reported only to verify the reliability of DRAINMOD's subroutine and it was not used in the simulations.

Estimated drainage volume–water table depth curves are very close to each other in the initial 90 cm. Particularly for the first 70 cm, the relationships calculated by the DRAINMOD subroutine are essentially identical. This coherence can be related to the good agreement in the low portion (<100 cm) of the water retention curves. In fact, in calculating the water yield from the retention curve, DRAINMOD assumes that the vertical hydraulic gradient above the water table is zero and the unsaturated zone is essentially drained to equilibrium. In this way, the soil water profile above a shallow water table (<100 cm), and the derived drainable volumes can be described accurately with the indirect estimated water retention curves.

In the case of a shallow water table (<50 cm), the drainable volumes of H3 are slightly larger than those estimated for H1 and H2. Probably, this is caused by the adoption of a unique drainable porosity value for the first layer. Actually, the drainable porosity is not a constant value but it changes, increasing with the water table depth, even if below 100–150 cm depth it can be considered constant.

At depth greater than 100 cm, there is a good agreement between H3 and the relationship estimated from the measured water retention curve, while for H1 and H2, the relationships diverge somewhat. The differences between H1 and H2 are not really strong, even if the last one is closest to H3. The larger drainable volumes estimated in H1 and H2 are a consequence of the differences in the portion of the water retention curves below a tension of 100 cm.

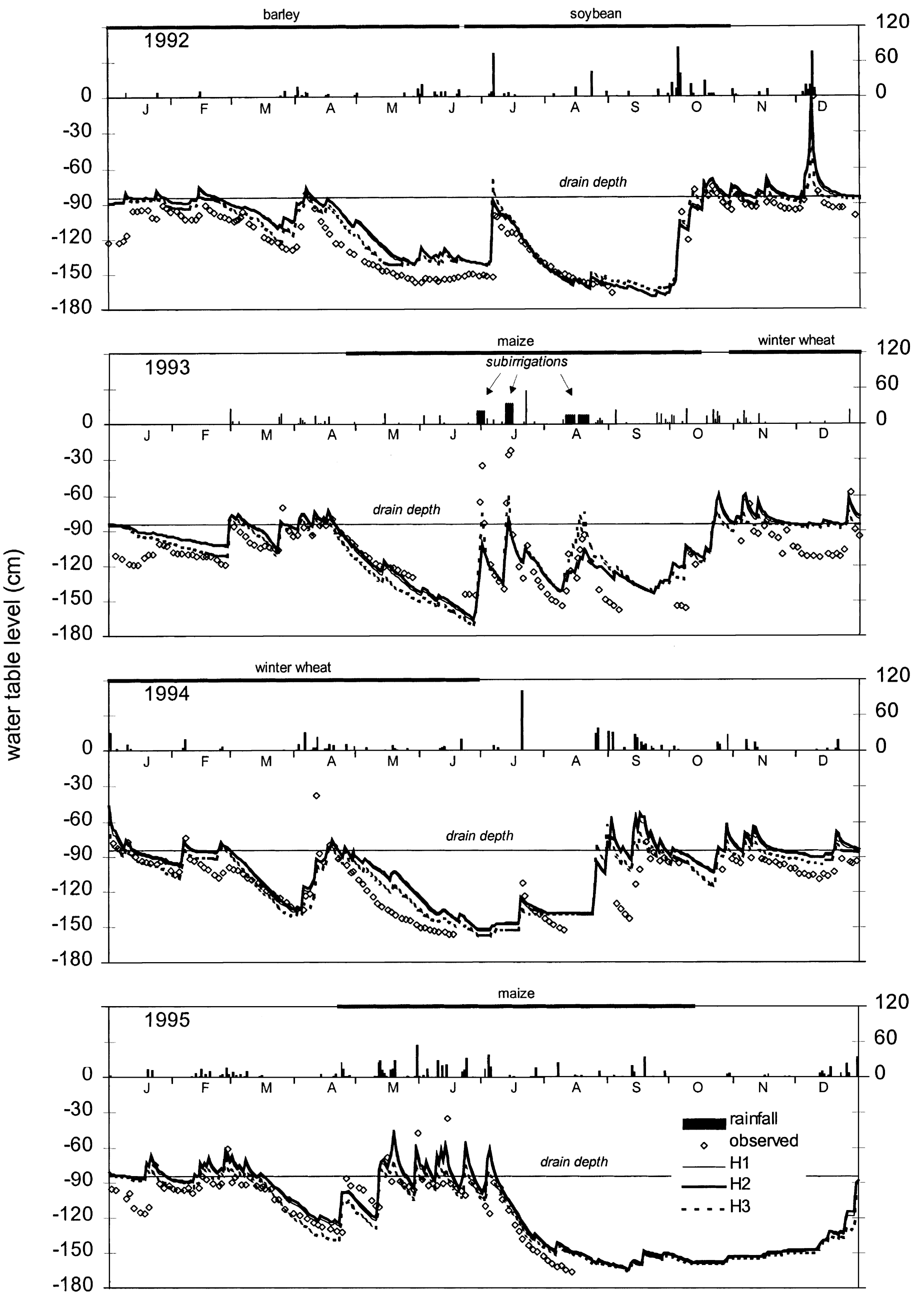

Fig. 3. Water table level observed and simulated in the years 1992–1995.

3.2. Water table level

With all three hypotheses, the time pattern of the simulated water table depth fits the observed data quite satisfactorily (Fig. 3), particularly during the growth of the summer crops: soybean in 1992 and maize in 1993 and 1995. The water table rises caused by subirrigation during summer 1993 were quite well described in H3, while they were underpredicted by the other two simulations. In the spring of 1992 and 1994, when barley and wheat were grown, in September 1994, at the beginning and end of 1993, and in winter in the years 1994–1995, the model underpredicted the water table depth. Probably, the deeper water table during winter was caused by lateral seepage under the pipe drains induced by the open ditches surrounding the plot. Disagreement observed during spring may be related to the underestimation of the actual evapotranspiration. DRAINMOD sets the maximum rate of evapotranspiration equal to the potential evapotranspiration, usually estimated with the equation of Thornthwaite (1948). It is known, however, that when the soil is fully covered by the small grain crops, the actual evapotranspiration can be larger (Doorenbos and Pruitt, 1975).

On the average, the simulations gave reliable predictions of the water table level. The average values were -102 cm in H1, -101 cm in H2 and -107 cm in H3, with coefficients of variation of 22.5%, 24.5% and 20.9%, respectively. The values were very close to the observed value of -111 cm with a coefficient of variation of 23.0%.

The daily observed and simulated water table depths were fitted to a linear regression model. The three regressions are all significant ($p < 0.01$) with an R^2 of around 0.7 (Table 1) and are not significantly different ($p < 0.01$) from each other for the intercept, but the slopes of H1 and H2 are both significantly different ($p < 0.01$) from the slope of H3. The slopes and intercepts are all significantly different ($p < 0.01$) from 1 and 0, respectively.

More detailed information on the response of DRAINMOD to the different input quality is obtained by analyzing the s.d. index and e.i. On an annual basis, they confirm the goodness of fit of the simulations (Table 1). They are slightly different in H1 and H2, while there is an improvement in H3. The annual s.d. values were similar to the results obtained in an implementation of DRAINMOD carried out by Sabbagh et al. (1993) in LA, USA.

The monthly s.d. and e.i. values were based on daily data taken for 1 month at the time.

Table 1
Regression parameters (simulated vs. observed) and annual indexes (e.i. and s.d. index) for the three simulations

	Water table depth			Drainage volume		
	H1	H2	H3	H1	H2	H3
a	0.75	0.76	0.73	0.56	0.56	0.58
b	17.90	15.32	24.39	3.62	3.50	4.38
R^2	0.68	0.69	0.68	0.43	0.46	0.32
s.d.	16.30	17.10	14.80	14.80	14.40	17.90
e.i.	0.55	0.51	0.64	0.39	0.42	0.10

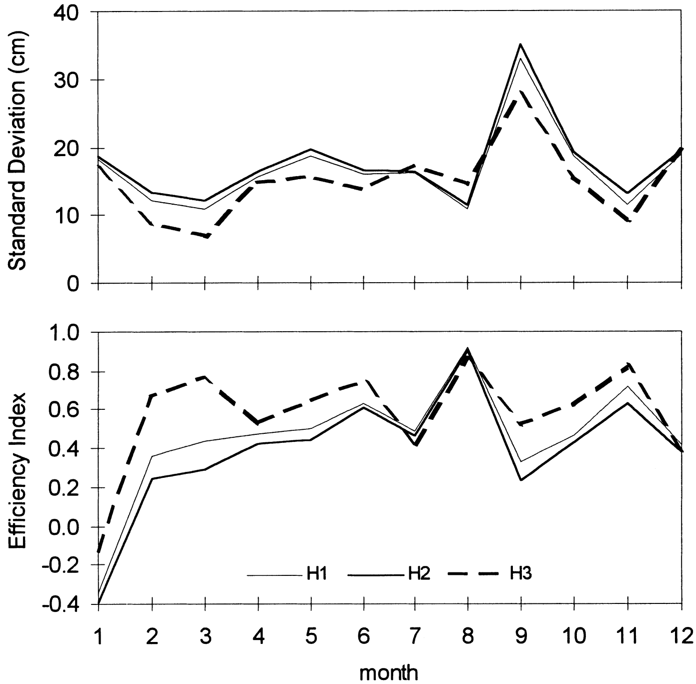

Fig. 4. e.i. and s.d. index calculated on monthly data of the water table level, based on daily values taken for 1 month at the time.

The monthly s.d. (Fig. 4) ranges between 6.5 and 36 cm, but it is usually lower than 20 cm. The high value obtained in September is probably due to the few data measured in this month.

The monthly values of e.i. (Fig. 4) confirmed the trend shown in Fig. 3. In January, e.i. is negative in all hypotheses and greatly improves in the other months. In H3, the index is always greater than 0.4, and exceeds 0.6 in 6 months.

Both s.d. and e.i. show more reliable predictions in H3, particularly during the winter–spring period, which is the season when drainage is the most important.

3.3. Drainage volume

Due to the procedure of drain discharge measurement, the measured data set was not complete and the data of daily discharge were affected by approximation. For these reasons, the comparison between simulated and observed data was carried out considering only the days in which the experimental observations were available. Moreover, to avoid comparing different daily patterns in the simulated events with an average measured value, the comparisons were carried out with the monthly cumulative volumes. As a consequence, the comparisons, simulated/observed, are more interesting when considering the time trends than the absolute values.

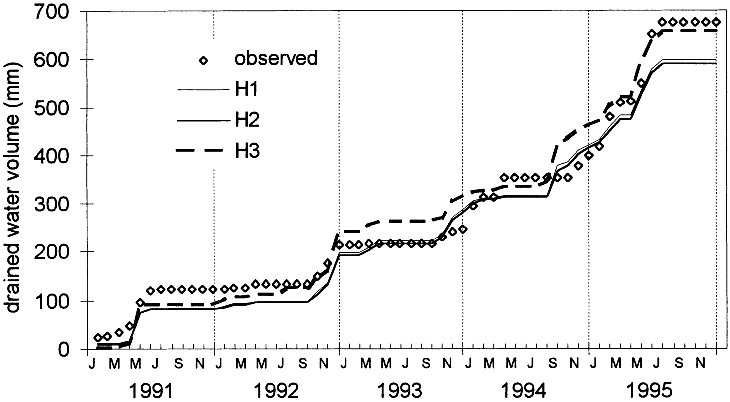

Fig. 5. Cumulated drained water volume.

Drainage occurred with a discontinuous time pattern: mainly, during the autumn–winter season of 1992, 1993 and 1994, the spring of 1991 and 1994, and the late spring–early summer season of 1995.

The pattern of the simulated cumulative monthly data confirms the general goodness of predictions (Fig. 5). In only a few cases did model prediction anticipate drainage with respect to the period in which it was measured (winter 1993–1994 and September 1994). The simulated annual average drainage volumes were 119, 118 and 132 mm, respectively, in H1, H2 and H3, versus an observed value of 135 mm.

The linear regressions between monthly measured and simulated values, although significant ($p < 0.01$) for all three simulations, showed a weak R^2, explaining only 32–46% of the observed variability in monthly values (Table 1). The three regressions are not significantly different among themselves ($p < 0.01$), their slopes are significantly different ($p < 0.01$) from 1 and intercepts do not differ significantly from 0.

The values of s.d. and e.i. are far from the optimum, especially in H3, and confirm the results of the regression analysis (Table 1).

4. Conclusions

DRAINMOD was able to describe the water table depth and drain discharge in a proper way, even when soil hydraulic properties input were derived from a few easy to measure soil characteristics.

On a yearly basis, simulations were carried out with soil hydraulic parameters estimated from the texture and bulk density of the first 30 cm layer and were similar to those obtained with the parameters measured in all the different soil layers down to a depth of 2 m. It should be pointed out, however, that the soil profile was quite homogeneous in the first layers and that the average water table depth was 111 cm. In this case, the good agreement in the low portion (<100 cm tension) of the estimated and measured water retention curves allowed a relatively accurate description of the relationships between drainage volumes and water table depth.

These first preliminary results suggest that a quick and easy survey of the main physical properties of the top soil could be sufficient for mapping a territory in relation to its suitability to drainage, using the DRAINMOD model, at least in soils where the profile is homogeneous.

Some improvements of water table depth simulations were obtained by increasing the accuracy of soil hydraulic properties inputs, especially with respect to time pattern behavior. This was also confirmed by the statistical indexes calculated on a monthly scale, in particular, during the late winter–spring period, the most interesting being for drainage in the region.

As a consequence, the authors believe that, if the model has to be used for soils with heterogeneous profile, a better description, as in H2, could be suggested. Finally, for more precise applications (i.e. designing a pilot system), or for research purposes, a thorough investigation of the input parameters is justified. This requires use of more resources, but allows a better representation of the phenomena.

Nevertheless, in this work, even the increased accuracy of the input data did not allow a perfect fit of the experimental data. Calibration of the model by integrating information coming from measurements made on different scales and the influence of assumptions on field boundaries, geological structure and boundary conditions can further improve its performance.

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