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Sensitivity of computed values of water balance and nitrate leaching to within soil class variability of transport parameters

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Abstract

Variability with respect to model input data is recognised as a potential source of uncertainty in model predictions. The aim of this study is to estimate the sensitivity of computed values of water balance terms, in particular drainage below the root zone of crops, and that of nitrate leaching, to variability of soil transport parameters within a soil class, and to quantify the domains of sensitivity as a function of soil type. The methodological framework is based on the concept of Areal Non-Point Source Watershed Environmental Response Simulation, coupled with a Latin Hypercube Sampler, to obtain a stochastic model. Two applications are considered. First, a case study is made of the experimental catchment of LaCote St André, predominantly a loam soil, where intensive experimentation has been carried out from 1991 to 1995. Second, a generalisation to different types of soil is carried out.

It is shown that for this model within-class variability has no effect in long-term simulations for soils with saturated hydraulic conductivity K_s higher than 100 mm/day. For these soils, the concept of representative elementary area is fully acceptable and convenient. Corresponding soil classes can each be described by a single set of parameters (the barycentre (centroïd) of the class) with a very small loss of information compared to a very important gain in terms of input data requirements and simulation time. This has important consequences for large-scale distributed models, since it reduces considerably the number of measurements necessary to describe the soil; in particular there may be no need, in this range, to account for spatial variability of textural parameters within a class.

In contrast, within-class variability of transport parameters becomes an important source of uncertainty for soil classes below this threshold value of saturated hydraulic conductivity. An estimation of errors resulting from aggregation of transport parameters values to those corresponding to the centroïd of the soil class is given. These errors are obviously dependent on K_s values and rainfall intensity.

Keywords: Water balance; Nitrate leaching; Uncertainty; Latin hypercube sampling; Stochastic model; Pedotransfer function

1. Introduction

The impetus of this paper is to bridge the immense gap between the amount of experimental effort made, since the 1970s to characterise the variability of soil physical properties (Nielsen et al., 1973; Wilding, 1985; Jury, 1989) and to conceptualise the regionalised variable analysis (Vauclin et al., 1983; Webster, 1985; Gutjahr, 1985) and the degree of simplification made in recent years to characterise soil properties in more or less complex hydrological distributed models

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at a catchment scale. An illustration is given in the basic paper of Refsgaard (1997) in which only four unsaturated hydraulic conductivity relationships, one for each of the four soil types characterising the catchment, were used to simulate the hydrologic behaviour of a 440 km^2 area. Similarly, in the paper of Merz and Plate (1997), the assumption of spatially constant soil hydraulic properties within a 6 km^2 hilly watershed was one of the options for simulation of runoff, the resulting simulated hydrograph being quite close to that obtained with a random distribution. This point was already thoroughly investigated in the well known papers of Wood et al. (1988) proving the concept of Representative Elementary Area (REA) in the context of hydrologic responses: "a critical area in which implicit continuum assumptions can be used without knowledge of the patterns of parameter values", and Grayson et al. (1992) dealing, in particular, with the fact that the scale of measurements of hydraulic parameters is generally non-compatible with their use in hydrologic models.

It is quite evident, given the simple problems of cost and of amount of data required, that a distributed hydrologic model cannot account for small-scale variability (soils, vegetation, relief). A catchment is generally subdivided into subcatchments on the basis of soil maps, landscape maps and DTM. The variability is usually described by soil attributes (for example, soil class) and by landscape attributes (for example, type of crop). With the more frequent use of GIS, the catchment is discretised in spatially discrete computational units, defined as blocks: a unique combination of soil, vegetation and slope. The model is parameterised at the size of the blocks; very often the hydraulic parameters are not measured, but directly related to soil attributes with the use of surrogates, such as pedotransfer functions (Rawls et al., 1982).

Apart from the crucial aspect of model verification (Grayson et al., 1992; Freer et al., 1996; Refsgaard, 1997), an important problem is the estimation of the sensitivity of model output to uncertainties concerning the variability of input parameters within the REA.

The aim of this study is to estimate the sensitivity of computed values of water balance terms, in particular drainage below the root zone of crops, and that of nitrate leaching, to variability of soil transport parameters within a soil class, and to quantify the domains of sensitivity as a function of the soil type. The methodological framework is based on the concept of Areal Non-Point Source Watershed Environmental Response Simulation (ANSWERS, Beasley et al., 1980; Bouraoui et al., 1997a,b), coupled with a Latin Hypercube Sampler (LHS) to obtain a stochastic model. Two applications will be considered: first, a case study on the experimental catchment of LaCote St André, predominantly a loam soil, where intensive experimentation has been carried out from 1991 to 1995; second, a generalisation to different types of soil.

2. The model

The ANSWERS is originally a watershed scale, event-oriented, distributed parameter, non-point source pollution surface model for long-term simulation. The first version (Huggins and Monke, 1966) included only surface water hydrology. It was expanded by Beasley et al. (1980) to include erosion and sediment transport. The sediment transport routine was later updated to simulate sediment detachment and transport of mixed particle sizes (Dillaha and Beasley, 1983).

An important step was made by Bouraoui (1994) with the transformation from an event-based model to a continuous model in order to simulate runoff, erosion, transport of dissolved and sediment-bound nutrients, and transformation of nitrogen and phosphorus pools. Holtan's infiltration equation was replaced by the widely used and physically based Green and Ampt equation. Soil water redistribution and percolation were determined on the assumption of gravity flow, and with the use of a storage routine technique (Williams et al., 1985). Soil evaporation and plant transpiration were modelled separately using Ritchie's equation (Ritchie, 1972). Nutrient transformation and nutrient transport subroutines (Knisel, 1993) were also added to the model. Finally, further changes were made recently by Bouraoui et al. (1997a,b) to account for aquifer recharge and leaching of nitrate below the root zone of crops.

The core of the system is a one-dimensional vertical model applied to square blocks of soil for which topographic, soil and crop characteristics are uniform. A vertical discretisation (usually three layers: upper soil horizon (0–0.3 m), root zone, and unsaturated layer to the ground water) is considered to account for water movement through the soil profile. In its complete version, it requires a large number of input parameters in order to simulate properly the water cycle (infiltration, runoff, evapotranspiration, drainage), the nutrient cycle (in the soil, but also in the sediments), and the crop uptake on the basis of a daily time step. Details are given in Bouraoui (1994). Since it is not in practice possible to characterise the spatial variability of all the input parameters through the watershed with the use of time consuming, difficult and costly measurements, an alternative was selected very early: to use Model Parameter Estimation Routines (MPER) related to easily obtainable properties, and/or to parameterise the processes with easily obtainable properties or large data bases.

In this study, erosion and transport of sediment-bound nutrients will not be considered. The important processes of concern are the transport of water in the unsaturated zone of the soil–plant–atmosphere continuum, and the nutrient cycle (nitrogen). Basically, the following processes are being solved at an hourly time step, with output on a daily basis:

terms of the water balance: infiltration, actual evapotranspiration, runoff, change of water storage in the root zone and loss of water (drainage) below the root zone; runoff is defined as the excess of water not infiltrating within the soil at the end of the time step. In the simplest case, this excess water is routed directly to a river;

terms of the nitrogen cycle: mineralisation in the root zone, plant root uptake and leaching of nitrate below the root zone. Leaching is defined as the product of nitrate concentration in the root zone with the drainage of water from the root zone.

To simulate these processes, the most important MPER are the following:

the parameters describing the hydraulic properties of the soil; obtained with the use of statistical correlations (pedotransfer functions) from a data-base of 2000 types of soils (Rawls and Brakensiek, 1989). Among others: K_s, the saturated hydraulic conductivity (cm/h); ψ_f, the wetting front capillary pressure head (cm); n, the available porosity (cm^3/cm^3) (Green and Ampt, 1911); λ, the conductivity shape parameter (Brooks and Corey, 1964), and θ_s, the water content at natural saturation (cm^3/cm^3) are determined from the knowledge of soil texture, Organic Matter (OM) content and Cation Exchange Capacity (CEC);

the parameters describing the plant behaviour in terms of water uptake and actual evapotranspiration and nutrient uptake; obtained from a data base concerning 78 different types of crop, and giving, at different phenological stages (from sowing to harvest) time course values of the Leaf Area Index and root depth (Knisel, 1980);

the parameters describing the nitrogen cycle. The procedure is that described in GLEAMS (Knisel, 1993).

When used in a spatially distributed system, this model simulates sequentially the transport processes in a series of unconnected vertical blocks. It can then be linked to a Geographic Information System to allow automation of the input file creation (soil and plant parameters); easy modification and manipulation of the cell sizes and of the georeferenced data; and visualisation of input and output data. A basic assumption is, however, that at the grid scale (few hectares to few square kilometres) soil parameters and vegetation can be represented by single effective values, an assumption known to be contrary to the observations reported in the literature dealing with natural field variability. The main objective of this paper is to address this key issue by making use of a stochastic generator (LHS) to generate a representative set of soil samples within different soil classes and to estimate the dependence between the sensitivity of the model output to this variability and the class of soil. The vegetation will be considered as being uniform within the grid. The method rests on the following steps:

1. validation of the model at a point scale to assess its capacity to simulate long-term observations and its predictive uncertainties.
2. development of a LHS; comparison between estimation of drainage losses and nitrate leaching (yearly scale) obtained under irrigated maize either for a large number of realisations (200) or for a

Table 1
Validation of model. Agronomic characteristics for the experimental plot with irrigated maize (doy = day of the year)

	Sowing (doy)	First application fertiliser (kg N/ha) and (doy)	Second application fertiliser (kg N/ha) and (doy)	Harvest (doy)	Annual rainfall (mm)	Irrigation (mm, total of year)
1991	112	260 (112)	–	297	767	268
1992	114	50 (114)	110 (169)	312	1010	120
1993	110	22 (110)	160 (160)	293	1115	108

unique aggregated set of parameters for a representative class of soil (Loam).
3. sensitivity of the results to different soil classes.

3. Local validation

In accordance with the recommendations of Heuvelink (1998), application of a distributed physically based type model at a *point scale* is the basic step to test directly in the field the accuracy of model process descriptions and its practical applicability in view of field parameter estimation. This was done on the experimental site of LaCote St André.

3.1. Site description

The site selected for this application is the agricultural catchment of 'La Côte St André', 60 km north East of Grenoble (South East of France), with a total area of about 200 km^2. The choice of this site was related to important threats concerning the degradation of groundwater resource with the development of intensive agricultural practices. The major part of the catchment (about 80%) is a flat plain with very permeable, fertile, unconsolidated soil mostly within the loam classes. The land use is partitioned between irrigated crops (mostly maize), dry farming crops (rainfed maize, wheat and sunflower), and pasture. The root zone layer is shallow (average 0.8 m) and rich in OM; it consists mostly of sandy loam, with stone content becoming progressively coarser with increasing depth. There is almost no surface water system (river, ponds, etc.) due to the high infiltrability of this layer. Below, there is a very coarse glacial deposit extending to a water table aquifer at about 20–30 m depth.

Meteorological data are available from the Grenoble Airport, in the middle of the catchment. A set of 16 continuous years of daily values (rainfall, wind, air and soil temperature, PET) is available. The average annual rainfall is around 1000 mm, with two characteristics: a very high interannual variability (± 300 mm) and an annual pattern with the most important rain events in September–October and another rainy season, weaker and more uncertain, in April–May. Mean potential evapotranspiration computed by the Penman Monteith approach for grass is around 850 mm/year.

An intensive interdisciplinary study was initiated in 1991 aimed at optimising agricultural practices, and developing sustainable management schemes. Special attention was given to the characterisation of the relationships between fertilisation, irrigation and crop production, in particular to the water and nutrient balance in the soil–plant–atmosphere continuum, through a set of local scale field experiments. They were carried out at measurement sites during three continuous years (1991–1993) for three types of soil cover: maize, grass and bare soil with different levels of fertilisation. Eight sites were instrumented with neutron probe access tubes, tensiometers, soil solution suction cups and soil temperature probes, and some basic micrometeorological observations (rainfall, temperature). Detailed results are reported in Kengni et al. (1994) and Normand et al. (1997).

3.2. Validation: bare soil and maize

Measurements were made at each measurement site at a daily time step during the crop growth period. Daily values of actual evapotranspiration, and fluxes below the root zone (drainage of water and leaching of nitrate) were estimated during the 3-year period by the use of Darcy's law and the assumption of convective transport of nitrate. This was based on time course

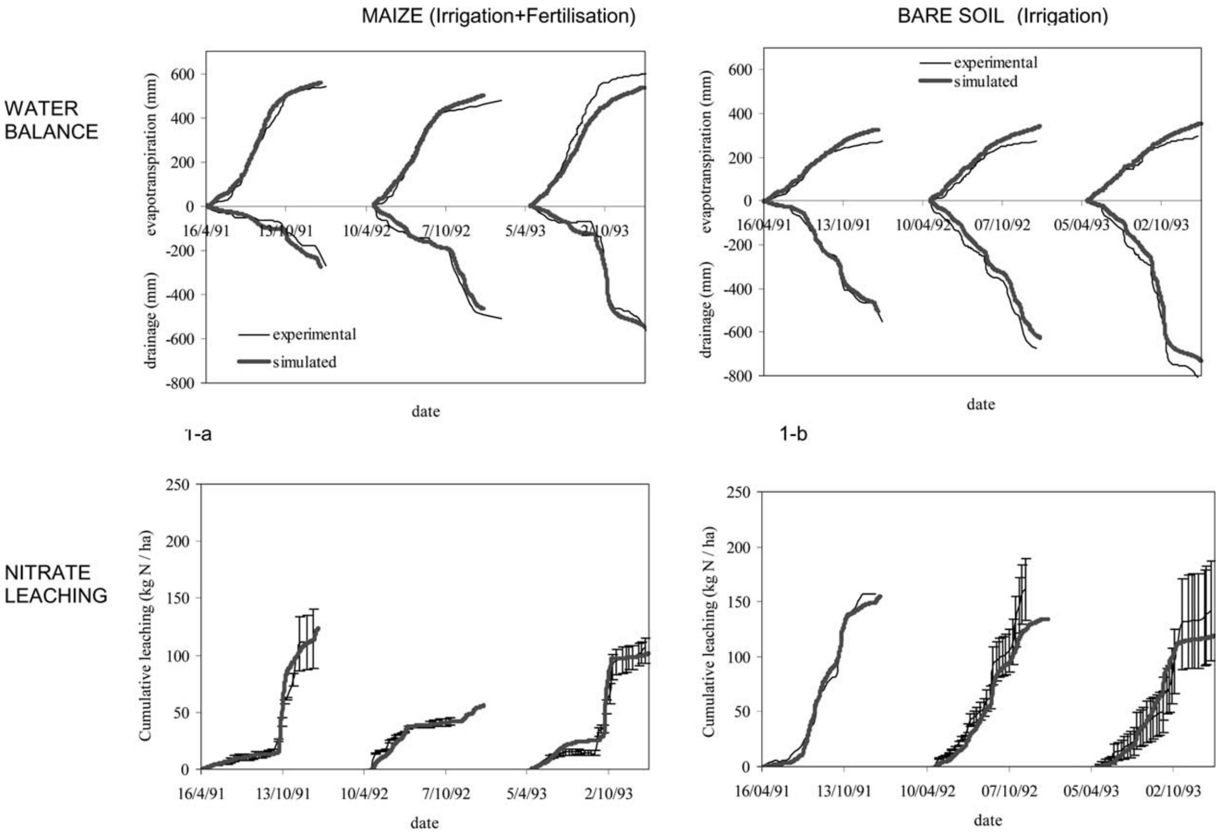


Fig. 1. Comparison between simulated and measured cumulative values of actual evapotranspiration, drainage and nitrate leaching during three continuous years; (a) maize (irrigation + fertilisation); (b) a plot on bare soil (+irrigation).

measurements of changes of soil water content, soil water pressure, concentration of *N*-nitrate in the soil solution and direct estimation in the field of the $K(\theta)$ relationship.

The model was run for each measurement site. The meteorological data were those measured during the simulation period. The input data characterising the cultivation techniques (date of sowing, date of harvest, fertilisation (dates and amount), irrigation (dates and amount)) and the soil characteristics (texture, OM, CEC) were site specific. Results presented here to validate the model were obtained for two extreme situations: irrigated maize with fertilisation (input data in Table 1), and irrigated bare soil (with the same amount of irrigation, but without fertiliser application). It must be noted that quantities of nitrogen applied annually as mineral fertiliser on maize were determined for experimental purposes (response of crop to fertilisation). They are not really representative of regional practices.

The comparison between simulation and measurement was carried out on the basis of accumulated values during the measurement period, basically April to November every year (Fig. 1). Measurements concerning leaching of nitrate are given with errors bars corresponding to nitrate concentrations obtained in replicate suction cups installed at 0.8 m (Kengni et al., 1994).

Water balance simulations were made without calibration. Fig. 1 shows that evaporation from bare soil is slightly overestimated, while the prediction of water balance for maize is satisfactory (an indication that the plant component is appropriate, in spite of being simple). In both cases, predictions in terms of annual cumulative drainage are within 10% of the measured data. This goodness of fit can probably be explained by the fact that the Green and Ampt

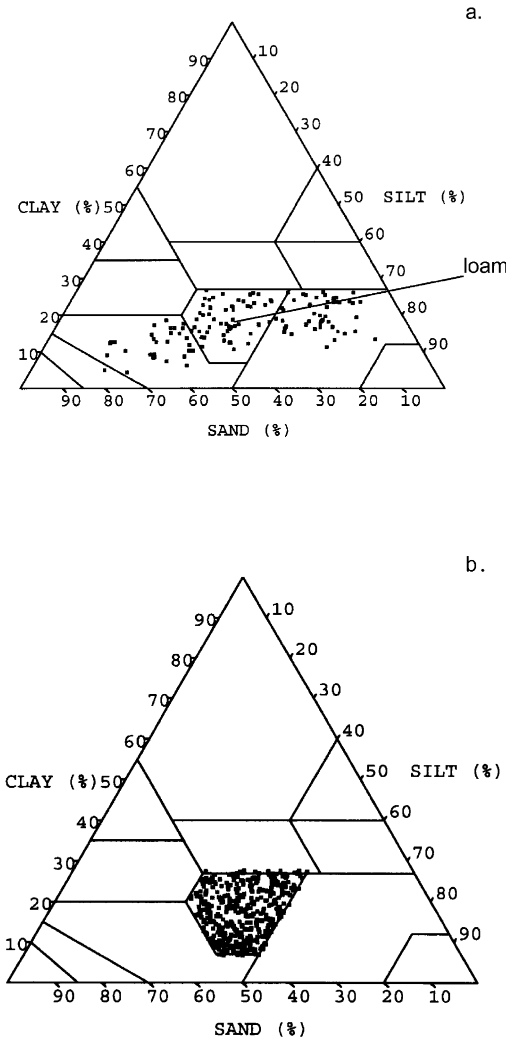


Fig. 2. (a) Soil texture measurements obtained from 138 sampling pits within the catchment and the surrounding region; (b) values of soil texture corresponding to a set of 200 samples generated with LHS for the Loam class.

equation is well adapted to the simulation of infiltration in this type of soil.

In terms of nitrate, there was a need for calibration to adjust the transfer time of nitrate to the bottom of the profile. This results from the fact that the discretisation of the root zone in two layers cannot account properly for mixing and convective–dispersive transport of nitrate. The calibration was run on measurements done on maize during the first year; the corresponding retardation factor was then applied for all treatments, and all years. Leaching obtained on bare soil is essentially a result of OM mineralisation, which is more important here than is usual for bare soil conditions, due to irrigation. Mineralisation determined by modelling seems to be underestimated with respect to the measured values. On the other hand, results obtained with maize seem to show that the plant uptake and the transport and transformation of mineral fertiliser are simulated satisfactorily (see Fig. 1).

4. Effect of within-class variability, Loam

Before upscaling the model to a larger area, it is essential to examine its sensitivity to the description of the soil, the basic objective being to minimise the amount of data collection required for the simulation with the smallest possible degradation of output. A stochastic modeller has been associated with ANSWERS to generate a large number of samples within soil classes, to examine systematically the response of the model to the variability of soil characteristics within a soil class (within-class variability) and to define uncertainties resulting from the simplest possible aggregation: the representation of a soil class by a single set of parameters corresponding to the barycentre of the class defined as its centroïd value.

Within the catchment and the surrounding region, the soil parameters (i.e. sand, clay and silt content, OM content, and CEC of clay) used as input to the model were obtained from measurements made on 138 sampling pits. The corresponding values, in term of texture, are reported in Fig. 2(a) within the textural triangle. Quite clearly these values cover three classes of soils, the most important being ‘Loam’. This soil class will be used to illustrate a methodology based on three steps:

1. from the sampling set within the soil class, generate a larger set of samples (200 samples covering the whole class) then a set of transport parameters;
2. from the set of transport parameters, generate stochastic simulations (200 realisations) with one crop (irrigated maize);
3. compare the results obtained with 200 realisations

Table 2
Soil parameter values concerning measurements (57 samples) within the Loam class (first layer: 0–0.3 m; second layer: 0.3–0.8 m)

	Sand content (%)	Silt content (%)	Clay content (%)	Org. Matter (%)	CEC (Meq, %)
First layer	41.6 ± 6.3	39.6 ± 4.9	18.9 ± 3.8	4.0 ± 1.8	11.2 ± 3.3
Second layer	40.8 ± 6.6	38.9 ± 5.6	20.3 ± 5	1.4 ± 1.1	9.2 ± 3.3

with those resulting from a single realisation corresponding to the centroïd value of the soil class or to those obtained on the experimental site.

4.1. Stochastic generation of transport parameters by LHS

Fifty-seven sample pits are localised on Loam. The basic parameters describing the soil samples are normally distributed, with mean and standard deviation values given in Table 2.

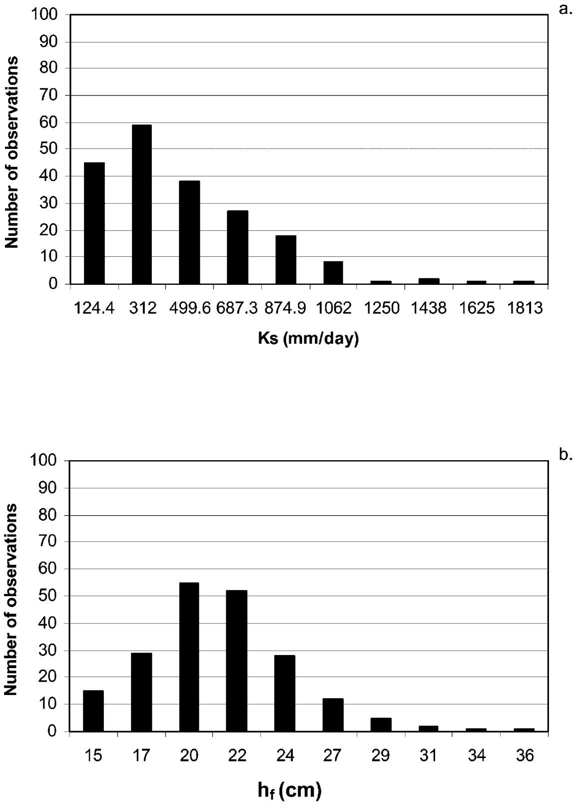


Fig. 3. Histograms of saturated hydraulic conductivity, K_s and wetting front capillary pressure, h_f obtained from the set of 200 samples generated with LHS for the Loam class.

In order to generate sets of stochastic values derived from different variables, a LHS scheme algorithm was developed. LHS is a stratified random sampling technique (Mc Kay et al., 1979) in which a sample of size N from multiple variables is drawn in such a way that for each individual variable the sample is maximally stratified and a random permutation applied to get a target-oriented matrix between ranks. The method is very clearly explained and illustrated by Pebesma and Heuvelink (1999). The aim of the algorithm is to draw a sampling of size N for K independent variables. Following Pebesma and Heuvelink, the ith sample element for variable j is obtained as

$$Z_{ij} = F^{-1}{}_j((p_{ij} - \xi_{ij})/N),$$

in which F_j is the cumulative distribution function of variable j, where $j = 1,\dots,K$; p_{ij} $(i = 1,\dots,N)$ is a random permutation of $1,\dots,N$; ξ_{ij} is $U[0,1]$, a uniform distributed random number between 0 and 1; and the K permutations and the NK uniform variables ξ_{ij} are mutually independent. If compared to a classical Monte Carlo technique, the main interest of LHS is the strong reduction of samples to obtain the same results.

In our case, 200 samples were generated with this algorithm for every one of the five variables in order to create a population covering entirely the Loam class; about 1000 samples would have been necessary to achieve the same goal with a Monte Carlo sampling. In spite of the fact that the sand content, silt content and clay content values are highly correlated, random sampling had to be drawn separately for the three variables, and the sum normalised to 100%, in order to constrain the corresponding points to be within the polygon characterising the soil class domain in the textural triangle. It is quite clear from Fig. 2(b) that in terms of texture this objective was met successfully. The corresponding population is very similar (in terms of

Table 3
Comparison between transport parameters computed with pdf function resulting from the sampling set generated with the LHS algorithm and values published by McCuen et al., for the Loam class. λ, h_b and h_f are, respectively, the conductivity shape parameter of hydraulic conductivity relationship and the bubbling pressure of the Brooks and Corey functionals and the wetting front pressure of Green and Ampt

	Our simulation		McCuen et al.[a]	
	Mean	$\pm\sigma$	Mean	$\pm\sigma$
Ln K_s (mm/s)	−5.90	0.54	−6.40	0.28
K_s (mm/day)	237.28		143.85	
λ	0.57	0.02	0.50	0.01
Ln h_b	3.05	0.27	3.14	0.14
Ln h_f	2.83	0.24	2.91	0.14

[a] See McCuen et al. (1981).

statistical properties) to that obtained from the measurements, since it is forced by the stratified method of sampling to obey the same PDF function. We can thus assume the method to be unbiased.

Transport parameters were then generated from the simulated soil characteristics with the use of pedotransfer functions. Histograms concerning the distribution of the saturated hydraulic conductivity, K_s and that of the wetting front capillary pressure head h_f for the upper layer of the loam are given in Fig. 3. The corresponding populations are log-normally distributed.

The results can be validated by comparison with those published by McCuen et al. (1981) (Table 3). A Fisher–Snedecor test applied to the two sets of data (respectively, 200 and 83 samples), with the values reported on Table 3 (ln K_s, ln h_f, ln h_b, and λ) shows clearly that the null hypothesis is accepted at the 0.05% level. Consequently, the two populations can be considered as being identical.

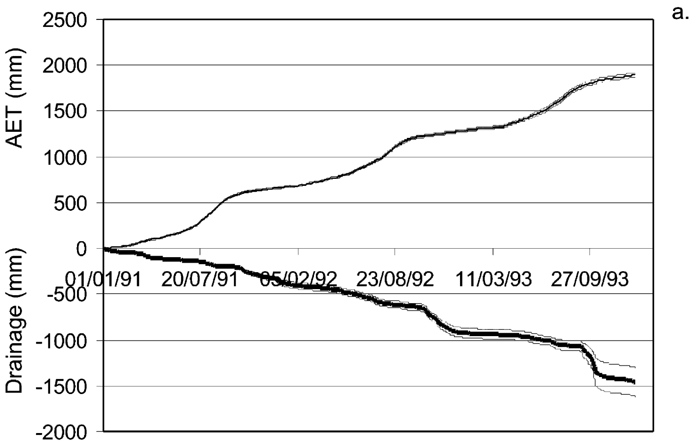
An important point of discussion could concern the assumption that the original samples obtained from 57 pits can be considered as a set of independent variables, and that the 200 realisations obtained from this set do not yield to a biased representation of the catchment. It has not been possible to make any spatial correlation test on the original set of data, since they were not georeferenced, but it was shown earlier by Kengni et al. (1994) that at the scale of the 2 ha plot used for the intensive series of experiments, it was not possible to detect any autocorrelation between samples taken on a regular grid of $17 \times 17\ \mathrm{m}^2$ size. It was thus assumed that the hypothesis of independent measurements, and thus independent realisations, was justified at a larger scale, and that it was unnecessary to use a method for drawing LHS for dependent variables (Stein, 1987)

4.2. Stochastic simulation of water and nitrogen transport within the Loam unit

The set of 200 independent simulations was then run with the use of ANSWERS to simulate water balance and nitrate leaching for irrigated maize on Loam. This was done for the period of 3 years corresponding to the validation of field experimentation, using the same inputs in term of fertilisation and irrigation (Table 1).

Fig. 4 shows the simulated cumulative values of actual evapotranspiration, drainage and nitrate leaching from January 1, 1991 to December 31, 1993. For every variable, the mean value together with the domain of uncertainty corresponding to 2σ (95% of probability) on 200 realisations are given. It is quite striking that in terms of water flow components (drainage and AET, Fig. 4(a)) the sensitivity of results to the variability within the soil class is very small: the standard deviation, σ, for drainage is of the order of $\pm 5\%$; it is negligible for AET. There are two possible explanations: first, the saturated conductivity of this soil is so high (mean value of ln K_s (expressed in mm/day): 5.48 with limits of confidence at $\pm\sigma$: 4.92 and 6.00 respectively) that all rain infiltrates; second, actual evapotranspiration is not controlled by the soil under irrigated conditions. Variability in drainage is associated with variability in soil water storage. Some large differences between instantaneous values of drainage can, however, be found shortly after important rain events, but they are generally smoothed in the long term. An illustration is given by the results obtained at the end of 1993, which was marked by very important rainfall events during the fall (510 mm from mid-September to mid-October): during this period the standard deviation for drainage increased significantly (see Fig. 4(a)).

Nitrate leaching is slightly more sensitive to the variability within the soil class. The standard deviation is now, on the same basis, about $\pm 7\%$. Two factors can explain this difference in behaviour:



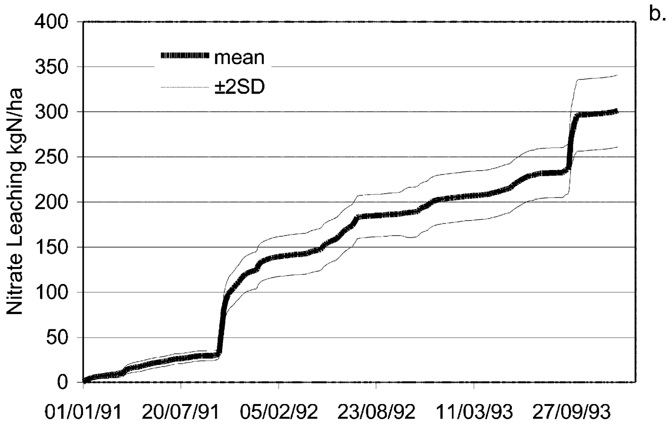


Fig. 4. (a) Cumulative values of actual evapotranspiration and drainage below the root zone during three continuous year of simulation for irrigated maize with fertilisation. Results were obtained from 200 realisations corresponding to samples generated by LHS within the loam series. For each variable the mean and the domain of uncertainty corresponding to $\pm 2\sigma$; are given (b) idem, concerning the leaching of nitrate.

first the variability of OM within the soil class, second differences in soil water storage at short time scales. Tests of sensitivity analysis done on the nitrogen transformation subroutine of ANSWERS have indeed clearly shown that these two factors are the most important to explain noticeable changes in mineralisation during rain periods.

4.3. Impact of aggregation of soil parameters

Since for this type of soil, the sensitivity of outputs of the model to variability of inputs (in terms of soil parameters) is small, a further simplification was tested: each of the five parameters used to define the pedotransfer functions (Table 3) was represented by a single value: the barycentre of the class attribute within the textural triangle, or the mean value for OM content and CEC. This is the simplest possible case of aggregation. The corresponding data and the most important resulting transport properties are given in Table 4.

Annual values of drainage and nitrate leaching for the 3 year simulation corresponding to this assumption are given in Table 5 and compared to those

Table 4
Aggregated parameters to describe the loam and associated transport properties

	Loam, layer 1	Loam, layer 2
Aggregated soil parameters		
Sand (%)	41	41
Silt (%)	39	39
Clay (%)	20	20
OM (%)	4.02	1.42
CEC	0.59	0.59
Transport properties		
K_s (mm/day)	227	165
h_f, wetting front pressure (cm)	16.7	18.6
λ (Brooks and Corey, 1964)	0.320	0.321
h_b (Brooks and Corey, 1964)	20.1	23.8
Field capacity (cm^3/cm^3)	0.23	0.23
Residual water content (cm^3/cm^3)	0.06	0.06
Porosity (%)	0.41	0.47

obtained by stochastic simulations (in one case, 1 realisation; in the other, 200 realisations) and also to outputs of the model corresponding to the simulation on the measurement site with maize.

It can be concluded that for this class of soil the loss of information resulting from aggregation is extremely small compared to a very important gain in terms of input data and time of simulation. An important consequence is that variability of soil characteristics within this soil class can be neglected, at least for long-term simulations. It is worth noting that among the five parameters used to define the class, the first three can be simply deduced a priori (the barycentre of the polygon describing the class in the textural triangle), whereas some measurements are necessary to obtain the other two (OM and CEC).

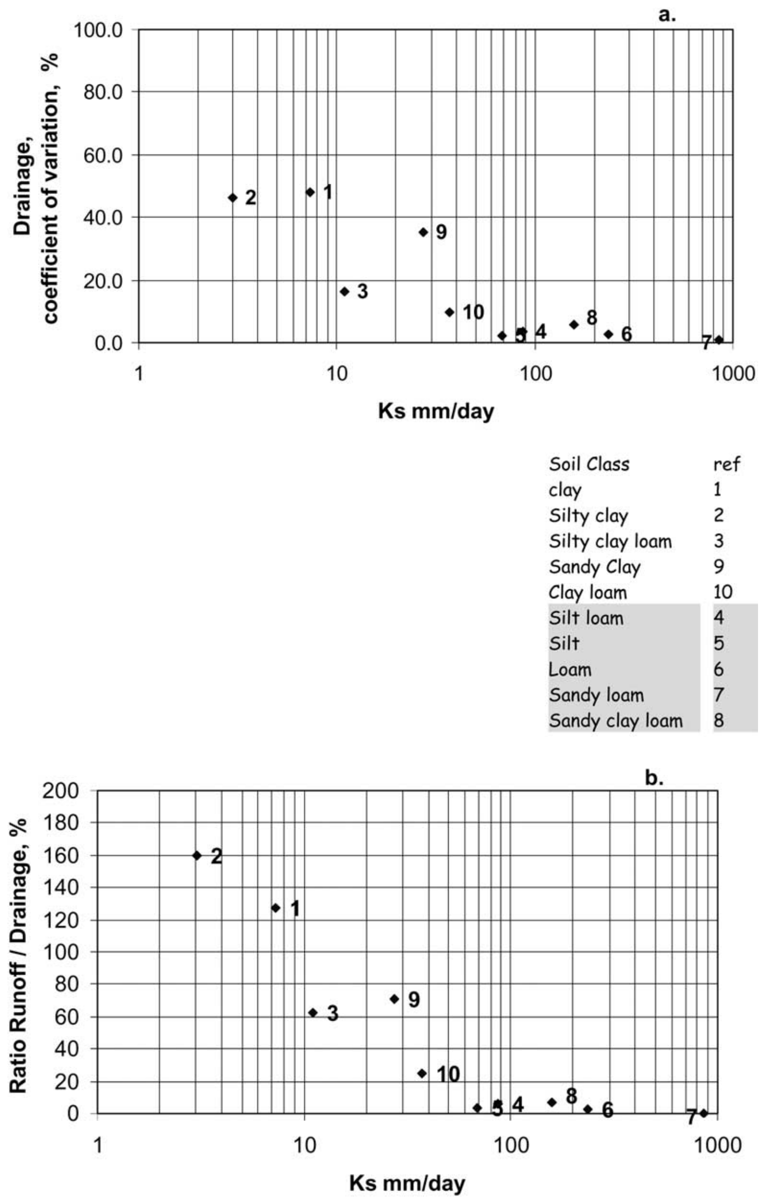
5. Discussion, generalisation to different conditions of soil

An essential point is to determine at which level

Table 5
Comparison over the 3-year period between cumulative values of drainage and nitrate leaching resulting from deterministic simulation on measurement site, from stochastic simulation or from use of aggregated soil parameters. Crop: IRRIGATED MAIZE (with fertilisation); class of soil: LOAM

		Model on measurement site	Stochastic modelling		Aggregated parameters
			Mean	$\pm\sigma$	
Drainage (mm)	1991	369.7	366.0	15.7	377.0
	1992	549.2	545.9	10.4	547.9
	1993	571.1	547.9	55.4	570.9
	1991–1993		1459.9[a]	78.3	
Nitrate leaching (kg N/ha)	1991	138.4	133.2	10.7	130.8
	1992	68.5	69.5	4.0	68.0
	1993	107.0	98.4	7.7	98.2
	1991–1993		301.1[a]	20.0	

[a] Three-year cumulative values.



Soil Class	ref
clay	1
Silty clay	2
Silty clay loam	3
Sandy Clay	9
Clay loam	10
Silt loam	4
Silt	5
Loam	6
Sandy loam	7
Sandy clay loam	8

Fig. 5. (a) Relative error on the 3-year cumulative drainage resulting from within-class variability of soil characteristics; climate data base: Grenoble. For each soil class, defined by a number (see Table), the abscissa is the mean value of the saturated hydraulic conductivity obtained from a set of 200 samples, and the ordinate the coefficient of variation on drainage, ratio between the standard deviation on 200 realisations divided by the mean drainage for the class. (b) Relative importance of total runoff; same conditions as for (b); the abscissa is the ratio between mean cumulative runoff and mean cumulative drainage at the end of the 3-year period on the set of 200 simulations.

the results obtained in this example can be extended to other classes of soils. The same method was thus applied to different soil classes within the textural triangle. Some limitations were imposed by the fact that there exist limits of applicability of pedotransfer functions: the % content of clay should be between 5 and 60%; that of sand between 5 and 70% (Rawls and Brakensiek, 1989). Ten classes within the textural triangle satisfy these constraints. Within each class (and for clay within these limits), the same methodology was used. In order to increase the sensitivity to drainage, simulations were run with the assumption of bare soil with 200 realisations for every class in order to exacerbate the importance of soil variability within a class. The climatic conditions, and the simulation period, correspond to those used in the previous example.

The results characterising the effects of within-class variability on cumulative drainage (below a depth of 0.8 m) at the end of the simulation period can be expressed schematically in two different ways (Fig. 5).

First, in Fig. 5(a), each class of soil is represented by one point, with an attribute ranging from 1 to 10 to describe the class. The abscissa of each point is the mean value of saturated hydraulic conductivity, K_s, mm/day, corresponding to a log normal population resulting from 200 samples within this class (an example of such a population is given in Fig. 3(a)). The ordinate of each point is the coefficient of variation on cumulative drainage induced by within-class variability, defined as the ratio between the standard deviation on 200 realisations divided by the mean drainage for the class. Some care should be taken with the results regarding the clay (class 1), since the limitations imposed by the applicability of pedotransfer functions produce a strong truncation of the class area. Basically, the smaller is K_s, the higher is the relative error on drainage. This is mostly a result of one of the basic hypotheses of our model: all rainfall infiltrates as long as K_s is larger than rain intensity.

In Fig. 5(b), with the same identification of soil classes, and the same reference for abscissa, the ordinate is modified to account for infiltration excess. With the above assumption, all excess becomes instantaneous runoff; runoff values are cumulated over the 3-year period and the ordinate of Fig. 5(b) corresponds to the ratio between 3-year cumulative runoff and 3-year cumulative drainage. The corresponding numbers are certainly overevaluated, since in many cases runoff occurring on a given day may infiltrate during the following day.

It is important to emphasise the general trend of the results reported in the figures. It is quite clear from both figures that within-class variability has no effect on the long-term simulations for soils corresponding to K_s higher than 100 mm/day. For this range, there is no runoff, and no control of the soil on the water balance; soil classes can be described by a single set of parameters: the centroïd value of the class. The concept of REA is then fully appropriate and convenient (at least with the use of this model). For classes of soil with smaller K_s values, the increase of uncertainty in drainage due to within-class variability is clearly related to the occurrence of runoff; the soil then becomes the limiting factor for infiltration.

The relationship reported in Fig. 5 is of course strongly dependent on climatic conditions, in fact rainfall intensity. For our case study, with rainfall intensity exceeding 100 mm/day two or three times per year, the within-class relative spatial error on drainage estimation at the end of the 3 year simulation would be about 30% for 'sandy clay' and for 'silty clay loam', and the total runoff approximately equivalent to 2/3 of drainage.

6. Conclusion

The results show that for long-term modelling, and depending upon the conditions of the soil, there exists a domain in the textural triangle for which classes of soil can be defined by a single set of textural parameters (sand, silt and clay contents obtained, for example, at the barycentre of the class). This domain, corresponding to classes of soil darkened in the table given in Fig. 5, can be described as an 'insensitive' area. This has an important consequence, when this condition applies, for large-scale distributed models, since it reduces considerably the number of measurements necessary to describe the soil; in particular, there is no need, in this range, to account for spatial variability of textural parameters within a class. On the contrary, for the classes of soil corresponding to the domain of 'very sensitive' area (from clay loam to clay), great care should be taken to account for the variability of soil transport parameters within every soil class to obtain a feasible estimation of water balance and nitrate leaching. This conclusion depends of course on the particular model being used, and it would certainly be worthwhile in the future to test the same approach with different models in order to reach a general assessment on the matter.

Another study which relates to results obtained with the same model with the use of either distributed inputs accounting for the spatial distribution of soils and land use or with stochastic inputs based only on statistical distribution of soil and the land use management at different spatial scales (regional or European) will be published in a second paper.

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