SOIL STRUCTURE, WATER AND SOLUTE TRANSPORT

Structure des sols, transfert des eaux et des solutés

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Session 1 Multispecies transport in soils.
Transport et devenir des solutés dans les sols

Session 2 Hydrodynamics of unsaturated soils.
Hydrodynamique des sols non saturés

Molecular modeling of clay-solute interactions

G.Sposito

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Transfert multi-espèces dans les sols : aspects hydrodynamiques et géochimiques

J-P. Gaudet, L. Charlet

La conceptualisation et donc la modélisation des transferts et des interactions de espèces chimiques dans les sols exige une bonne connaissance : de l'état hydrique du sol, des flux d'eau, de la géochimie de l'eau, de la physico-chimie du support solide et de la chimie de l'élément considéré.
Cela implique une modélisation multi-espèces et multi-phases pour décrire le mouvement de l'eau, les concentrations des molécules exogènes et des éléments majeurs, l'évolution du pH, les réactions homogènes (à l'intérieur d'une seule phase) et hétérogènes (entre phases), en incluant les éventuelles cinétiques physiques (diffusion) et chimiques.
Le problème est extrêmement difficile à traiter dans toute sa généralité et on cherche bien souvent à le réduire en identifiant les mécanismes prépondérants pour une situation donnée, notamment pour un polluant métallique dans un sol. On s'attachera à donner ici un aperçu des possibilités de modélisation, de la méthodologie d'identification en laboratoire des mécanismes prépondérants et de modélisation simplifiée « opérationnelle ».

Le milieu poreux et l'écoulement en sol non saturé
La description de l'écoulement de l'eau dans les sols est faite ici à l'échelle macroscopique de l'élément de volume représentatif (EVR), où le milieu poreux polyphasique peut être considéré comme un milieu homogène continu. L'écoulement mono-directionnel vertical (supposé isotherme) de l'eau dans le milieu poreux (considéré comme homogène, isotrope et indéformable) est alors décrit par la relation de conservation de la masse et par une relation phénoménologique (loi de Darcy généralisée). Le système d'équations fait intervenir deux paramètres caractéristiques : la conductivité hydraulique et la pression de l'eau du sol, toutes deux fonction de la teneur en eau.

Le transfert d'espèces chimiques en milieux poreux
On définit les concentrations de l'élément j dans les différentes phases et on écrit la conservation de masse de l'élément j dans l'EVR (échelle macroscopique).
Lorsque toute l'eau du sol participe à l'écoulement, la densité de flux massique de soluté est classiquement décomposée en une partie convective et une partie dispersive.
La consommation par les plantes ou les micro-organismes est un terme du bilan de masse de certaines espèces chimiques.

De cette modélisation ressort l'importance, pour le transport d'un soluté, d'une bonne prédiction (ou évaluation) de la répartition volumique spatio-temporelle de l'eau liquide et de son écoulement.
On montrera, par exemple, l'influence d'un transport où une fraction de l'eau est immobile.

On évite de considérer les écoulements d'eau transitoires, non linéaires et difficiles à traiter, pour identifier les mécanismes chimiques. Il est préférable de se placer dans des conditions particulières visant à instaurer des transferts d'eau permanents et uniformes, notamment en utilisant des colonnes de laboratoire ou des lysimètres sur le terrain.

Les différents mécanismes physiques et chimiques sont alors identifiés pas à pas en essayant de les découpler autant que faire se peut. Cet aspect sera développé et illustré dans le paragraphe consacré à la méthodologie d'identification.

Les réactions et interactions chimiques

Pour une espèce chimique donnée, on distingue les réactions chimiques internes à une phase unique (réactions homogènes) de celles qui mettent en jeu plusieurs phases, notamment liquide et solide (réactions hétérogènes).

Si l'espèce chimique d'intérêt j, est totalement définie par ses concentrations en phase liquide c_j et solide s_j, indépendamment des autres espèces chimiques, il est souvent possible d'établir une relation réversible entre c_j et s_j.

On traite quelques exemples d'adsorption linéaire, instantanée et réversible, d'adsorption linéaire et cinétique du premier ordre, d'adsorption non linéaire.

On aborde également le cas simple correspond à une consommation (ou production) où le taux de consommation de l'élément j , uniquement dû à la biotransformation, est proportionnel à sa concentration. Dans des conditions moins favorables, il faut tenir compte de co-facteurs, tels que l'évolution de la population biotique, ou les inhibitions dues aux fortes concentrations.

Dans le cas le plus général, le transport réactif d'un élément chimique fait intervenir plusieurs réactions homogènes et hétérogènes simultanées, conduisant à des systèmes habituellement non linéaires avec cinétiques.

On écrit alors la stoechiométrie et les systèmes de réactions.

Dans le cas où la réaction est instantanée, l'équilibre est décrit par la loi d'action de masse, appliquée aux activités des éléments.

Le système d'équations obtenu, où interviennent des réactions instantanées et des réactions cinétiques, est résolu selon son niveau de complexité.

Identification des mécanismes en systèmes contrôlés

Plusieurs exemples illustrent l'approche conceptuelle basée sur la dynamique des systèmes, qui permet d'évaluer les mécanismes prépondérants :

l'hydrodynamique est précisée par l'utilisation de traceurs, en analysant les courbes de percée et en calculant les moments temporels,

la fixation d'un soluté sur sol stérile, avec cinétique, non linéarité de l'isotherme, en ne prenant en compte qu'une espèce chimique,

la prise en compte de la présence d'autres espèces (pH, complexants),

des bio-transformations.

Enfin, on discutera d'autres mécanismes, non décrits ici, pouvant contrôler le transport de substances chimiques dans les sols.

Integrated water and soil management in an arid mdeiterranean zone : evolution of secondary salinization in irrigated areas of Morroco

M.Badraoui, M. Lahlou, A. Bellouti

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INTEGRATED SOIL AND WATER MANAGEMENT IN AN ARID MEDITERRANEAN ZONE: EVOLUTION OF SECONDARY SALINIZATION IN IRRIGATED AREAS OF MOROCCO

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ABSTRACT

In arid and semi-arid regions of the world such as Morocco, irrigation is necessary for agricultural production. One million ha are intensively cultivated under irrigation in different agro- cological zones of Morocco. Although Irrigation has increased crop productivity and farmers income in the last 30 years, sustainablility of agricultural production in irrigated areas is questioned. Secondary salinization and alcalization are the most rapid degradation processes of both soil and water qualities. The saline soils area of Morocco is estimated to 300 000 ha. The use of poor quality water for irrigation and the lack of adequate drainage systems caused an important increase of the watertable level, goundwater salinity, and soil salinity/alcalinity.

As a consequence of soil and water salinization, crop yields decreased and farmer s income declined. Examples from Tadla region with a large scale irrigation system, Bahira region under pivot irrigation system in central Morocco, and Ouarzazat oasis system in the south of the High Atlas mountain will be presented to demonstrate the influence of soil and water salinity on crop yield and crop diversity. Because of drought, fermers are using groundwaters having high salinity and alcalinity risks.

Farmers and agricultural development offices have developed strategies to overcome some of the negative effects assopciated with salinization. Soil managements to improve the evacuation of drainage water, crop diversification and irrigation water treatment with sulfur are the most used and documented strategies.

Monitoring of soil and water qualities and crop productivity of intensively croped perimeters under irrigation is necessary to locate areas where sustainability of soil and water resources and thus productivity are affected. Indicators of soil quality changes following management (irrigation) are pertinent tools to measure the sustainability of the irrigated production system. The database collected is being used in simulation medels to predict the evolution of soil and water qualities under irrigation.

Integrated water and soil management in arid and semi arid areas is presently considered as a pre-requisit for the sustainability of intensive agricultural systems in Morocco.

Simulating the composition of the *in situ* soil solution by the model EXPRESO: application to a reclaimed marsh soil of SW Spain irrigated with saline water

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Introduction

The Guadalquivir river marshes in south-west Spain cover an area of 140,000 ha. They were formed by the accumulation of fine material dragged by the river into the large estuary excavated in the Diluvial Era. A series of reclamation projects (installation of drainage systems, irrigation and agricultural practices) were undertaken since the beginning of the last century. The most recent reclamation was initiated in 1970, by irrigating and draining the zone of Lebrija (15,000 ha, Sector B-XII). In this region of low and variable rainfall, irrigation of these soils is necessary for successful crop growth. Drainage is also required to ensure that the highly saline water table does not encroach into the root zone. The scarcity of good quality water during the drought period 1993-1995 imposed on farmers the necessity to irrigate with river water, which at this location is of high salinity due to tidal flow. Knowledge of the chemical composition of solutions extracted from soil *in situ* is of great interest both for understanding salinization of soil and for managing irrigated saline soils. It is difficult to extract solution from fairly dry soil, and so one may instead take soil samples and analyse their extracts in the laboratory. However, it is then necessary to calculate the chemical composition of the *in situ* soil solution, adsorbed complex and precipitated phase. The EXPRESO model enables one to estimate the soil solution and exchange complex composition under field conditions as was shown by Rieu et al. (1998) for the reclaimed soils of the Guadalquivir marshes.

The objective of this work was to determine the composition of the *in situ* soil solution and exchange complex of the reclaimed soil of Lebrija, irrigated with saline water, using the EXPRESO model. This was carried out in order to know the evolution of the chemical composition of the soil solution at the in situ water content.

Material and methods

The soil samples used in this work correspond to experiments carried out during 1997 in a farm plot of 12.5 ha (250 m x 500 m) situated in an area of marshes on the left bank of the Guadalquivir river, near Lebrija (south-west Spain) (Moreno et al., 2001). The plot was provided with a drainage system, consisting of pipes 250 m long, buried at a depth of 1 m and spaced at intervals of 10 m. The soil of the plot is of clayey texture. Two subplots of 0.5 ha (20 m x 250 m) each were selected. In 1997 cotton was growing on both subplots, and irrigation was applied by furrows. Cotton is one of the most important and typical crops in the reclaimed marshes of the Guadalquivir viver. One subplot was irrigated with good quality water (0.9 dS m^{-1}) during the whole season, while in the other subplot one of the irrigations (on 7 July 1997 at flowering stage) was with water of high salinity (22.7 dS m^{-1}). The soil samples (0-30 and 30-60 cm depths) used in this work belong to the subplot irrigated with

saline water. The chemical composition of the saturated paste extracts was determined in the laboratory. Measurements of the soil water content were carried out at the same sampling dates and depths.
The EXPRESO model, described in Rieu et al. (1998), is a model designed to calculate both the chemical speciation of electrolyte solution and the exchange equilibrium with an adsorbed phase during simulated dilution and concentration. The model was validated using soil samples of the same experimental area (Rieu et al., 1998).

Results and discussion

Fig. 1 shows the results of the electrical conductivity (EC_{sp}) and the exchangeable sodium percentage (ESP_{sp}) of the saturated paste extracts of samples taken just before irrigation with saline water and several dates after this irrigation. In the same figure are shown the results simulated by the model for the *in situ* soil water content ($EC_{in\ situ}$ and $ESP_{in\ situ}$). The EC_{sp} increased immediately after irrigation in both soil layers (0-0.3 m and 0.3-0.6 m depths).

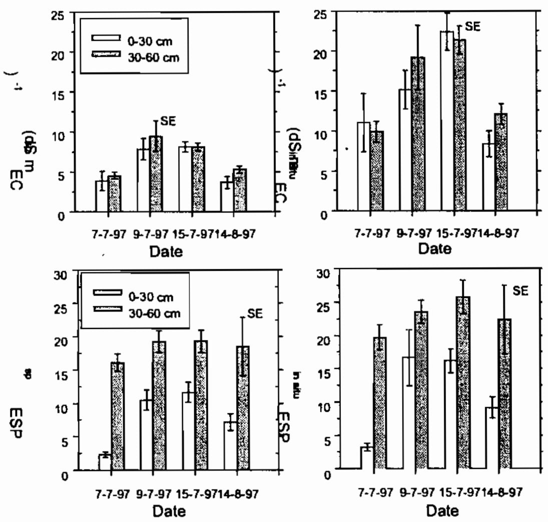

Fig. 1. EC and ESP determined in the saturated paste extract and simulated by the model *in situ*.

In both layers, the EC_{sp} and the $EC_{in\ situ}$ on 14-8-97 decreased due to the irrigations with fresh water applied on 21-7-97, 1-8-97 and 10-8-97. The same occurred with the ESP in the soil layer 0-30 cm. Similar trends were observed for the soluble salts. The exchangeable sodium increased after irrigation with saline water and decreased after irrigations with fresh water. The contrary trend was observed for the exchangeable calcium. The exchangeable magnesium did not practically change. The results simulated by the EXPRESO model, for the *in situ* soil water content, clearly show the differences with the composition of the soil solution and exchange complex determined in the saturated paste extract.

This can imply that the negative impact of irrigation, with water of high salinity, on soil and crop could be more severe than that expected when we use the data given by the analysis of the saturated paste extract.
The EXPRESO model seems to be a very useful tool for understanding salinization processes, and also for practical purpose on agricultural and environmental studies.

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Temporal variations in water quality during stormflow in a rainforest catchment: exchanges with vegetation and soil mineral reactions along water flowpaths

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The chemical composition of stormflow water at the outlet of catchments is frequently used for the separation of flood hydrograph data, certain chemical elements being tracers of various contributing compartments that feed the flows towards the outlet. Reciprocally, when the hydrological functioning of a catchment is known, the chemical composition of water at the outlet provides information on the biogeochemical processes taking place in these reservoirs. These processes relate to exchanges with the vegetation or mineral transformations in the soil. Their study on the scale of the storm event supplements our knowledge of nutrient cycling, which is generally estimated over long scales of time, as knowledge of mineral equilibria that are usually studied outside the context of rainy episodes. In fact, the export of nutrients during storms occurs by overland flow, and the mineral reactions vary according to the conditions of renewal of the soil solution.

The present study was carried out on a small catchment area of 1.6 ha under humid tropical forest in French Guiana (catchment B of ECEREX operation). The pedological cover, developed on schist, is made up of oxisols upslope, while 90% of the remaining area is covered by ultisols, which exhibit features typical of waterlogged conditions downslope. Previous work on the structure of the soil and its hydric behaviour showed the existence of two major structural discontinuities producing lateral flows during storm events: overland flow is established on the soil surface at the beginning of spates and at peak discharge; a perched water table is formed at the top of the zone of weathered schist.

The aim of this communication is to interpret the evolution of water chemistry in this catchment during the course of a storm, in terms of exchange with the vegetation and soil mineral reactions. This is accomplished owing to our preliminary knowledge of the flow paths. The event presented here was investigated by a series of tensiometric measurements that enabled us to locate the subsurface hillslope groundwaters. Samples were taken for water analyses under the canopy, at the outlet and in the groundwater bodies. We have carried out separation of the hydrograph using an end-member mixing model with two tracers, _^{18}O and chloride. The present interpretation is based on the following:

The mobility of chemical elements in the litter and at the surface of the soil is estimated by comparing the throughfall with flows at the outlet identified as surface waters.

The processes that take place in the soil are characterized using the evolution of the groundwater or outlet water concentrations with increasing residence time in the soil. The residence time is parameterized by the chloride concentration, which increases by evapotranspiration in the soil. The differences in mobility between chloride and the other elements provide information about processes other than evapotranspiration, which modify the water chemistry according to its origin and residence time in the soil.

At the outlet, the lower chloride contents at the beginning of stormflow and during each peak discharge reflect the arrival of recent water (event water) corresponding to surface circulation. With each decrease in water level, the chloride content increases, thus marking the arrival of increasingly old water (pre-event water). The groundwater bodies in the soil exhibit highly contrasted ages: they are older upslope than downslope, where the component of old water however also increases towards the end of the rainy episode.

The studied chemical elements all participate to differing degrees in the vegetation cycle. Their variable behaviour during the flood gives some information about the biological compartments from which they are released and on the speed of their uptake by the vegetation. In this way, we find that potassium in particular, as well as chloride and aluminium, are leached in the canopy, whereas sodium, calcium, magnesium and silica are leached in the litter. In the soil, potassium is very quickly taken up again by the vegetation even during the rainy episode; the rate of absorption into roots is a slightly less for calcium and magnesium. Only potassium exhibits a rapid removal from the soil solution. The other elements, even those partially absorbed by the vegetation, show an increase in concentration due to evapotranspiration as a function of increasing residence time in the soil.

At the outlet, the pH is buffered at around 4.6-4.8. In the groundwaters, on the other hand, the pH varies between values lower than 4.5, due to the absorption of nutrient cations, and high values up to 5.7, explained by the release of iron into solution.

The silica and aluminium contents are relatively low in water circulating in the subsurface. By contrast, they increase strongly at the outlet as soon as part of the water enters the zone of subsurface flow where mineral dissolution takes place. In terms of flux, however, the quantities of silica exported during this event are equivalent in surface water and groundwater circulating in the soil. This implies that chemical erosion is just as active at the soil surface as in horizons subject to lateral groundwater flows. Even during the storm, the factors controlling mineral reactions in the soil show strong spatial and temporal variations according to the pH and the conditions of groundwater circulation. Thus, we infer a downslope transition from dissolution to neoformation of kaolinite. Sometimes, we can even observe this trend at the same sampling point during a given storm event.

Our results highlight the importance of linking hydrological and hydrochemical studies at the scale of small catchments, to ascertain the diversity of spatial and temporal processes occurring in an ecosystem. In return, a knowledge of water chemistry dynamics during floods can contribute to the search for relevant chemical tracers in hydrology.

Impact of bacterial structural Fe(III) reduction on the CEC and exchangeable cations of a flooded rice cropped vertisol

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Introduction

The cation exchange capacity (CEC) of soils is widely used to characterize soil sorption properties or to estimate water retention curves. CEC of clays due to ionic substitutions in the crystal units is usually considered to be constant, and only slightly variable with pH due ionization of hydrogen at crystal edges. However, Tessier et al. (1999) showed sharp CEC changes with soil-pH changes. Moreover, significant increase in CEC of iron-containing selected pure clays were found in laboratory reduction experiments. These CEC changes are due to reduction of structural iron (Fe_{Str}) or dissolution of positively charged oxide coatings as reviewed in Stucki, 1997. The same phenomenon was recently observed in the field by Favre *et al.* (in press) who found a twofold increase in CEC upon reduction in a flooded vertisol. Changes in cation fixation upon Fe_{Str} reduction and CEC increase was investigated on pure clay by Khaled and Stucki, 1991. They noted an increase in fixed cations such as K and Zn. Changes in cation selectivity for different $Fe_{Str}{}^{II}/ Fe_{Str}{}^{III}$ ratio and CEC are likely to occur but has not been investigated up to now. This study is difficult to perform, because different methods are required for the exchangeable cation extraction (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, NH_4^{+} and Fe^{2+}), each of them preserving oxidation state. This paper presents the observed changes in exchangeable cations during Fe_{Str} reduction on laboratory incubated samples from vertisols in Senegal.

Material and method

Two samples S1 and S2 coming from the Ap horizon of a rice cropped vertisol were air dried, crunched, sieved and mixed with demineralized water (ratio 1:1) in two incubators under nitrogen atmosphere. The soil characteristics are presented in Favre *et al.* (in press).
During incubation, EH was monitored using a platinum probe. Samples were collected from the reactors at different Eh values. S1 and S2 samples were analyzed for CEC and major exchangeable cations Ca, Mg, Na, K using the Cobaltihexamine (Cohex) method and in addition exchangeable iron and exchangeable ammonium were measured on S2 samples. $Fe_{Str}{}^{II}/ Fe_{Str}{}^{III}$ ratio were measured using Mössbauer spectroscopy for S1 samples and chemical analysis for S2 samples.
Co was analyzed using AAS. Exchangeable Ca, Mg, Na and K were measured using capillary electrophoresis, and exchangeable Fe was measured using a spectrophotometer and NH_4^{+} with colorimetric method.

Results and discussion

CEC of the incubated samples increased markedly with decreasing redox potential (EH). This increase goes with an increase in $Fe_{Str}{}^{II}/ Fe_{Str}{}^{III}$ ratio. Exchangeable cations Ca, Mg, Na and K remained constant upon reduction. S2 experiment showed that the increase in CEC was balanced by exchangeable Fe^{2+} and NH_4^+.

The increase in CEC due to increasing $Fe_{Str}{}^{II}/Fe_{Str}{}^{III}$ ratio is in agreement with the results and interpretations of Favre *et al.* (in press) and previous studies (Stucki 1997). Both measurements on Mössbauer spectroscopy and chemical analyses methods confirmed these observations.

Constant values of exchangeable Ca, Mg, Na and K together with increasing concentration of ferrous iron in the soil solution is not very well documented in the literature. Other authors (e.g., Brinkman (1970) and Ponnamperuma (1972)) worked on soil solution only and they assumed that in temporarily waterlogged soils, the affinity of ferrous iron for clays is so high that the major exchangeable cations are expulsed in the soil solution. An increase in the concentration of major cations in soil solution of paddy soils incubated in the laboratory was interpreted in the same way by Narteh and Sahrawat (1999).

There are several ways to comment these contradictory observations. As far as we know, there is no other reported experiment where increase in CEC, $Fe_{Str}{}^{II}/Fe_{Str}{}^{III}$ ratio and exchangeable cations were simultaneously monitored. The evolution in soil solution results from competition between Fe^{2+} and other cations for exchange sites. Fe^{2+} activity depends on dissolved oxides and other equilibria involving Fe^{2+}. The amount and state of reduction of Fe_{Str} determines soil CEC. The process depends on EH and pH and may have a different extent in soils depending of soil properties. Our experiments on a vertisol containing iron-bearing clays indicate high charges on the clay compared to the amount of ferrous iron in solution. Brinkman (1970) observed soils with kaolinite clays and very low CEC. When the EH drops in kaolinite-rich soils, the CEC remains nearly constant when the amount of dissolved iron gets height. The study of the iron-rich-clay vertisol also demonstrated that the amount of exchangeable major cations is very high compared to soil solution content. Consequently, a low and non significant change in exchangeable cation rates might result in significant changes in the concentrations of major cations in the soil solution.

In this experiment, the charges properties of the clays are sharply modified upon reduction and the consequences of the phenomenon can be measured in the bulk soil. The soil solution content results from an equilibrium highly dependent on iron reduction state. These results lead to new views and many questions about temporarily water logging soils. For example, sorption properties of cations and anions for various reduction states of clays should be determined. It seems necessary to investigate the impact of these phenomenon on the properties of temporarily waterlogged soils. In situ soil monitoring could allow to improve our knowledge of ferrolysis and other processes in water-saturated soils, particularly by comparing soils with iron-bearing clay types with various ratios of free and structural iron.

Modeling of nitrogen transport and transformation in soil with and without straw incorporation

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Introduction

Crop residue incorporation in soil affects strongly carbon and nitrogen dynamics. It induces some basic environmental changes concerning soil carbon storage and groundwater contamination by nitrate. Laboratory experiments have showed that incorporation of residue with high C:N such as wheat straw tends to increase carbon storage and nitrogen immobilization. The goal of our study was to quantify accurately by field experimental data and simulated results the differences of nitrogen dynamics between treatments with and without straw residue incorporations. The one-dimensional mechanistic model PASTIS (Prediction of Agricultural Solute Transformations In Soils) (Garnier et al., 2001) was evaluated under two crop residue treatments. The model simulates water flow, heat flow and solute transport using classic equations. The transformations sub-model CANTIS simulates carbon and nitrogen cycles. A one-year field experiment (September 93 to October 94) was carried out on a bare loamy soil in Northern France to obtain data of water, temperature and transformation of C and N (Néel, 96, Recous et al., 99). Two treatments were applied : a treatment without crop residue and a treatment with weat straw incorporation at the rate of 8 000 kg DM/ha.

Nitrate transport

We compared simulated and measured amounts of nitrate in the soil profile (until 150 cm) without and with straw incorporation. We obtained a good prediction of nitrate content with the model for both treatments. The main difference between the two treatments lied in the amount of nitrate resulting from autumn biological activity that is higher for the treatment without straw incorporation. The amount of nitrate that has reached 150 cm by leaching is also higher for the treatment without straw.

A sensitivity analysis of the model showed that biological factors had very little effect on nitrate leaching. In this context, the model efficiency that is often calculated from data of nitrate content is not a good criteria to evaluate the model properly. Additional information about biological processes like mineralization fluxes is needed to evaluate the model.

Nitrogen transformations

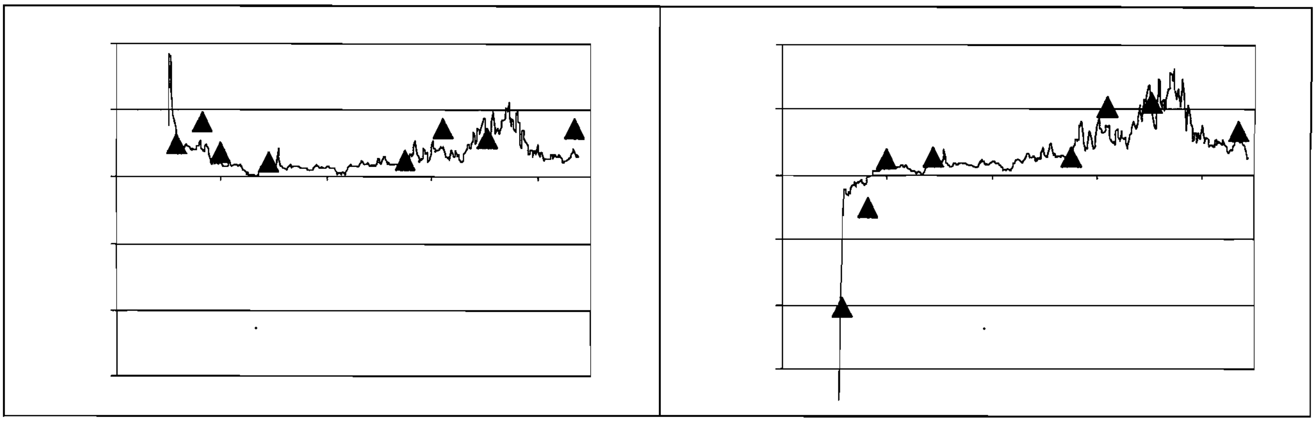
Simulated results were compared to nitrogen mineralization fluxes measured by Recous et al. (1999) for treatments without and with straw. The mineralization fluxes from organic to inorganic compartment are presented below :

$$\boxed{\textbf{Inorganic N}} \xleftarrow{\textit{Gross mineralization}} \boxed{\textbf{Organic N}}$$

Gross immobilisation

Net mineralization =
Gross Mineralization –Gross Immobilisation

For treatment without straw, gross immobilization was always lower than gross mineralization and then net mineralization was always positive. For treatment with straw, gross immobilization was very high just after incorporation which leads to a negative net mineralization for this treatment.



Graphical comparison of measured and simulated net N mineralization with and without straw incorporation

The decrease of net nitrogen mineralization with straw addition was consistence with literature. When decomposing straw with high C:N, the microbial biomass need to use available nitrogen like nitrate and immobilization is high.

Termes of the nitrogen mass balance

Because the model gave a good prediction of both nitrogen transport and transformation, it was used to calculate the nitrogen mass-balance after one year. These data would have been difficult to measure directly in field.

	Gross mineralized	Gross immobilize	Net Mineralize	leached
Without straw	695	473	222	160
With straw	935	757	178	106
Differences	-240	-235	44	54

Table 1 : Simulated nitrogen mass balance (kg N/ha) for the two crop residue treatments after one year (Net mineralisation =Gross Min.-Gros immob.)

Gross mineralization and immobilization was much higher when straw was incorporated but net mineralization was lower of about 20%. This decrease had a direct effect on the amount of leached nitrate that decreased of about 30% when straw was incorporated. Straw decomposition had used soil nitrogen that was less available for leaching.

Sensitivity to straw location

Finally, we analyzed the sensitivity of the model to straw location. We changed the input parameters like the fresh organic matter density in the profile and the hydraulic properties due to the presence of straw. We compared the effect on the model output like nitrate transport and mineralization fluxes.

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Hydrogeochemical modeling of soil salinisation, alkalinisation and sodification. Presentation and calibration of the PASTIS model

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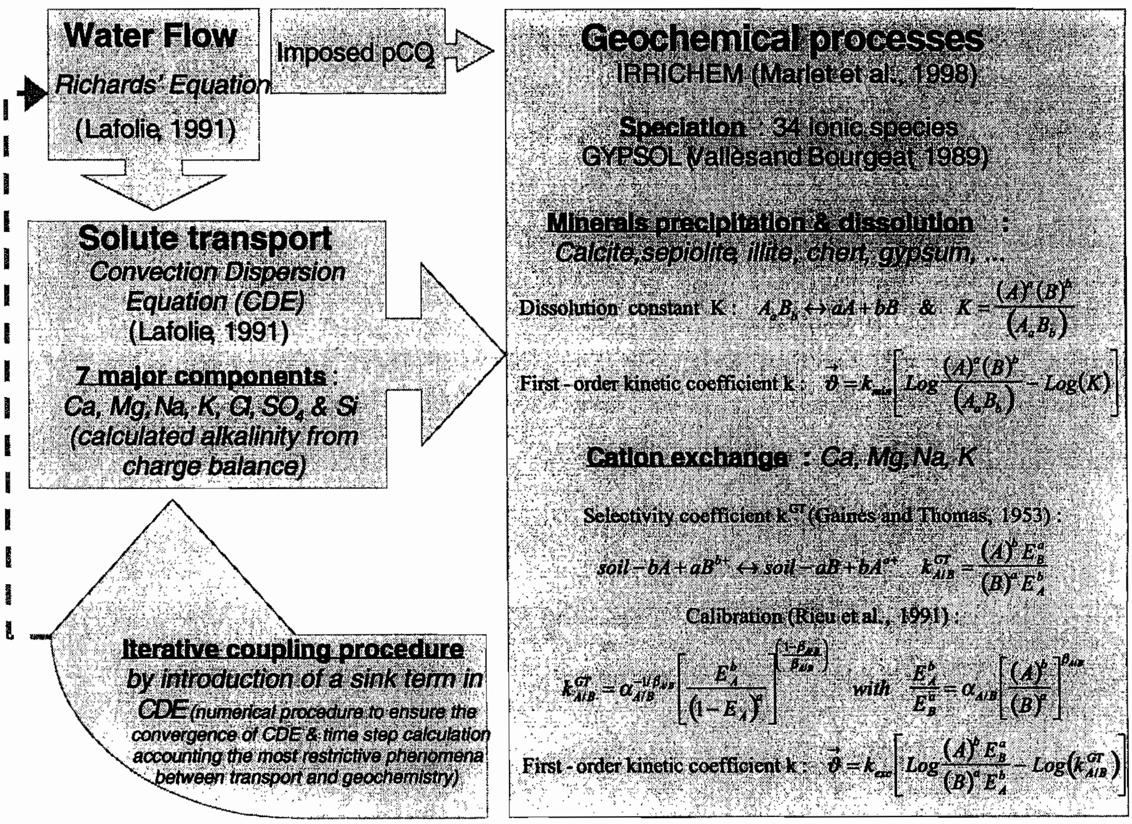
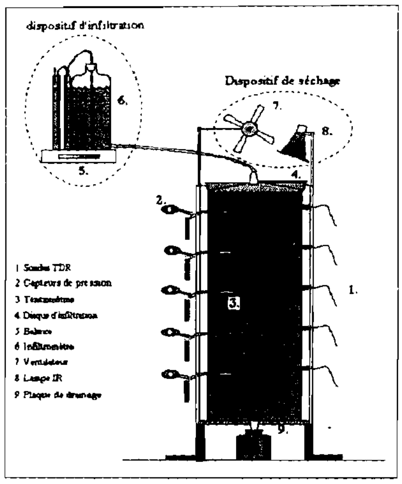
Though the geochemical processes of alkalinisation, salinisation or sodification are well known, the time changes and distribution of alkalinity, salinity, sodicity and various alterations cannot be predicted precisely within the profile if transport phenomena are not considered. On the other hand, if solute transport models allow one to predict displacement of solutes within the profile, the geochemical mechanisms of alkalinisation play an important role whereas the components of the soil solution are adsorbed on the exchange complex or precipitated. Therefore, it appeared necessary to couple transport and geochemistry to take into account of the hydrological causes of concentration and to predict the chemical consequences and the mineralogical modifications induced by these processes. The PASTIS model (Predicting Agricultural Solute Transport In Soil), developed by INRA, is presented and calibrated.



PASTIS presentation

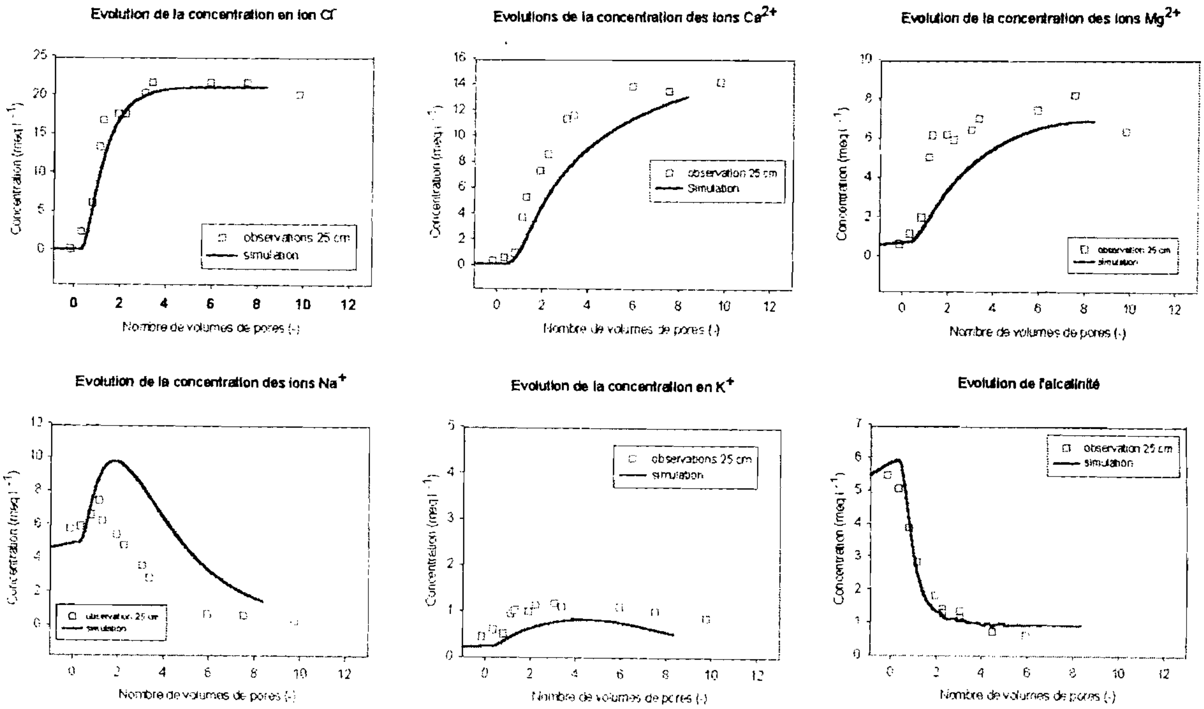
ϑ is the rate of the reaction [mol.l^{-1} s^{-1}], k_{min} [mol.l^{-1}.s^{-1}] and k_{exc} [mol$_c$.l^{-1}.s^{-1}] are kinetic constant for mineral precipitation/dissolution and cation exchange, respectively, R [8.314.10^{-3} kJ. K^{-1}.mol^{-1}] is the gas constant, T is temperature [°K], K is the dissolution constant [-], k^{GT} is the selectivity coefficient in the Gaines and Thomas convention [mol.l$^{(a/b)}$], (A) is the activity of the specie A, $E_A = X_A/(X_A+X_B)$ [-] is the charge (or equivalent) fraction of adsorbed component A in the binary exchange A/B and X_A [mol$_c$.l^{-1}] is the charge amount of adsorbed cation A.

Material and method



The experiment has been achieved in the research center of IRD in Dakar with a soil monolith from Mali of 60 cm high and 23 cm in diameter. Soil texture is loamy sand and CEC equals 0.5mmol$_c$.kg^{-1}. In a first step the soil column has been leached with sodic alkaline solution (EC=0.5 dS.m^{-1}) for a 8 months period and a 16-pore volume has been infiltrated until the stability of the composition at the bottom of the column . The saturated hydraulic conductivity has been assessed simultaneously as 11mm.d^{-1}. In a second step the soil column has been leached with a $CaCl_2$ solution (EC=2.25 dS.m^{1} and $[Ca^{2+}]=[Cl^-]=21$ mmol$_c$.l^{-1}) for a 2 months period and a 4-pore volume have been infiltrated.

Results



In a first step, the non-reactive solute breakthrough curve has been calibrated according to chloride analysis; dispersivity has been assessed as 1 cm. In a second step the reactive solute breakthrough curves have been calibrated according calcium, magnesium, sodium, potassium and alkalinity, simultaneously. Solute breakthrough curves show a typical situation of non equilibrium and kinetically control reactions have to be considered. Coefficients of 8.10^{-5} eq.l

$^{1}.h^{-1}$, $1.2.10^{-5}$ $mol.l^{-1}.h^{-1}$ and $1.2.10^{-6}$ $mol.l^{-1}.h^{-1}$ have been assessed for cation exchange, calcite and silicates (sepiolite and illite) dissolution, respectively.

Conclusion

The results show good agreement between observation and simulation. The model provides an improvement with regard to similar model as LEACHM (Hutson and Wagenet, 1995) or UNSATCHEM (Simunek and Suarez, 1994) due to the use mechanistic geochemical modelling, kinetically control chemical reactions and the introduction of a rigorous iterative procedure for the coupling of geochemical and transport models. The main part of the parameters have been acquired independently and only few parameters for dispersivity and kinetics of chemical reactions have been calibrated.

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Effects of residual NAPL on porous connectivity, aqueous flow, and heavy metal transport in a heterogeneous soil. Implications for cases of mixed soil contamination.

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Mixed soil contamination by petroleum hydrocarbons and heavy metals is a common occurrence in urban and ·industrial localities. This situation poses problems related contaminant interactions and their impact on contaminant mobility, behaviour, and fate, as well as on site remediation and contamination management. To the authors' knowledge, there was no body of evidence, until the present work, on such interactions and the scientific literature on the subject was non existent. The present study is part of a first attempt at identifying and quantifying the mechanisms underlying NAPL[1]-metal interactions in soil. The focus of the study is on the influence residual NAPL have on heavy metal transport in soil. The objectives of the study were to 1) verify the presence of such an influence and 2) characterise the mechanisms by which residual NAPL modify heavy metal transport. Experimental work was conducted at the laboratory scale using laboratory soil columns coupled with a constant head tension infiltrometer (Perroux and White, 1988; Langner et al., 1998). Aqueous flow in NAPL-contaminated and uncontaminated soil columns was modelled by fitting analytical solutions to the mobile-immobile (MIM) system of partial differential equations (Coats and Smith, 1964) using a Mathcad application developed by the Laboratoire d'études des Transferts en Hydrologie et Environnement (LTHE) in Grenoble.

Experimental work was performed in three phases. First, aqueous flow in uncontaminated duplicate soil columns was characterised using tracer injection and mathematical modelling. This phase was conducted to characterise the role of macroporosity in the soil and its influence on preferential flow and transport. Three different conditions were used, i.e. two water-saturated conditions with different hydraulic heads and an unsaturated conditions with a negative hydraulic head selected to drain specifically macropores as defined by the pore classification of Luxmoore (1981). These experiments showed that 17% of the total void volume was occupied by macropores and that this macroporosity conducted significant preferential flow by channelling 87% of the total aqueous flow in saturated conditions. Modelling results and calculations of solute residence times (Sardin et al., 1991) showed that macroporous flow was sensitive to hydraulic head as a decrease in h induced a decrease in bypassing of microporosity by the infiltrating aqueous flux.

A second experimental phase was then conducted using soil columns contaminated with residual NAPL. Residual NAPL was trapped in two different duplicates of soil columns characterised by different water saturation values prior to NAPL injection, namely complete water saturation (_ = n, termed INISAT) and dry (_ ≈ 0, termed INIDRY). These initial conditions ensured specific preferential wettability to soil surfaces, either for water or NAPL.

[1] NAPL = Non-Aqueous Phase Liquids. An acronym commonly employed to describe organic liquids.

The modes of trapping of NAPL were defined by these wettability condition, namely as NAPL ganglia trapped inside pore bodies by capillary cut-off (for INISAT) or NAPL films on pore surfaces and NAPL obstruction of micropores (for INIDRY). Flow modelling also showed that the MIM system of equations was a more adequate representation of the physical system than the classical convective-dispersive equation (CDE). These two modes of residual NAPL trapping had distinct effects on aqueous flow. NAPL ganglia were seen to occupy large mesoporous regions and thereby decreased the connectivity between macroporosity and microporosity. This immobilised a greater proportion of the void network. However, solute residence times showed that water remained longer in mobile regions and, therefore, a greater mass of solute was transferred to immobile regions by diffusion. Conversely, NAPL films and micropore obstruction completely cut off the access of the infiltrating aqueous flux to microporosity. The aqueous flux was therefore confined to macroporosity, a situation which significantly increased preferential flow. Based on the extreme initial water saturation conditions used, it is possible to assumed that the observed effects of residual NAPL on aqueous flow represent limit effects and that intermediate effects are more likely to be observed in the field where mixed conditions of surface wettability are prevalent.

A third experimental phase was finally conducted to determine the effect of residual NAPL on the aqueous transport of four heavy metals (Pb, Cu, Cd, Zn) through soil columns. Duplicates of uncontaminated and NAPL-contaminated soil columns were used. Both types of NAPL contamination were investigated It was observed that residual NAPL had significant effects on heavy metal transport, particularly for heavy metals having a high affinity for the soil surfaces (i.e. Pb and Cu). Effects were less pronounced for Cd and Zn, which stayed longer in solution and were eluted more rapidly than Pb and Cu for all flow conditions. In INISAT columns, the soil showed a greater capacity to attenuate the infiltrating aqueous metallic flux than for uncontaminated soil columns (R+25). This was explained by flow characterisation since, for INISAT, flow velocity was greatly reduced (by 10^2), hence decreasing preferential flow, and a greater mass of aqueous heavy metals diffused to the microporous immobile regions were they were retained due to higher specific surface area. In INIDRY columns, even though flow velocity was reduced by 10^1, the attenuation capacity of the soil was significantly reduced as aqueous heavy metals could not diffuse to surface retention sites and were confined in highly water conductive macropores.

This study has provided a first insight into inorganic-organic contaminant interaction in soils by showing that the individual behaviour of heavy metals can be significantly modified by organic contaminants which are physically and chemically different. It is therefore, necessary to continue studying these interactions because that may have important implications on risk evaluation, contamination management and in-situ soil remediation for cases of mixed contamination.

Nitrate retardation in a Ferralsol from New Caledonia : consequence on nitrate leaching beyond the rootzone using the WAVE model

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Retardation mechanisms can be especially important in highly weathered soils that hold high levels of iron and aluminium oxides with positive variable surface charges. These mechanisms have to be taken into account to predict the fate of anions such as nitrate through the soil. In subtropical and tropical regions, the highly weathered soils are widely distributed. Because of the abundant rainfall and high temperature, this type of soil is considered as one of the most important agricultural soils in the world. The aims of the paper is therefore i) to determine the retardation factor for nitrate in a highly weathered Ferralsol from New Caledonia; ii) to use this factor in the WAVE model to examine its ability to predict the fate of nitrate through the soil and assess the importance of retardation.

On Maré Island in New Caledonia the risk of groundwater pollution by nitrate is expected to be high because of heavy use of nitrogen fertiliser coupled with high rainfall rates and permeable soils. However, Ferralsols from Maré are variably charged and can retard non-specifically adsorbed anion transport such as nitrate. A three year field experiment was carried out to monitor water and nitrate movement through soil under different agricultural practices.

In a previous paper (Duwig *et al.*, 1999), we presented and validated a simple methodology using sectionable columns, called Perroux tubes, to measure the retardation of anions during unsteady flow under unsaturated conditions. Here we used this method to determine the entire nitrate isotherm of the different horizons of the soil profile. These are characterised by different organic matter contents. High retardation values (1.15 to 2.05) were found in deeper horizons with low content of organic matter whereas these values remained low in surface horizon (1.10). In deeper horizons, retardation varies with nitrate concentration of the input solution (5 to 1000 ppm $N\text{-}NO_3^-$).

The field data were used to examine the ability of the WAVE model (Vanclooster *et al.*, 1995) to predict the fate of surface applied nitrogen fertiliser. WAVE is a holistic model which is mechanistic and deterministic, based on full numerical solution. These types of holistic models, while being more complex, still face limitations in terms of parametrisation and validation. Values for about half of the parameters were measured in the field or in the laboratory. Reactive solutes are considered in the model by assuming a linear isotherm, and the distribution coefficient for nitrate was inferred by using results from our Perroux tube experiments. Appropriate values for the remaining parameters were obtained from the literature and some of them (organic matter turn-over parameters, crop water and nutrient uptake) were adjusted using field data from the year with the largest number of data (1996), which was also the wettest one (2173 mm of rainfall). Measurements and simulation of water content, nitrate concentrations at different depths, cumulative drainage and nitrate leaching at the base of the rootzone of a corn plot were compared by means of statistical and graphical criteria to assess the model performance in a deterministic context. The extrapolation capacity of WAVE was then evaluated using data from the same corn crop in 1995, which was a much dryer year (1366 mm). Standard sensitivity analysis was done to determine the relative importance of each parameter.

The nitrate retardation factor was found to be a sensitive parameter towards cumulative nitrate leaching, for both years. Nitrate concentrations and cumulative leaching at the base of the rootzone were simulated, with and without retardation factor (Figure 1). Sorption process not only retards the arrival of the peak and increases the amount of nitrate stored in the soil profile but also decreases the peak height. This has a direct consequence on nitrate leaching because at the peak dates, there were heavy rainfall 490 mm between 23/02 and 15/03/1996, and 180 mm between 30/01 and 3/02/1995). Cumulative nitrate leaching was reduced by 38 % in 1996 and 20 % in 1995 thanks to sorption on soil particles and retardation of nitrate transport.

By assuming a correct calibration of the WAVE model, we could determine the extent to which nitrate retardation obtained through independent measurement could be used to describe observed behaviour in the field. WAVE also allowed us to assess the importance of this process in the loss of nitrate beyond the rootzone. Simulations could be improved by taking into account variations of retardation with input concentrations into the model.

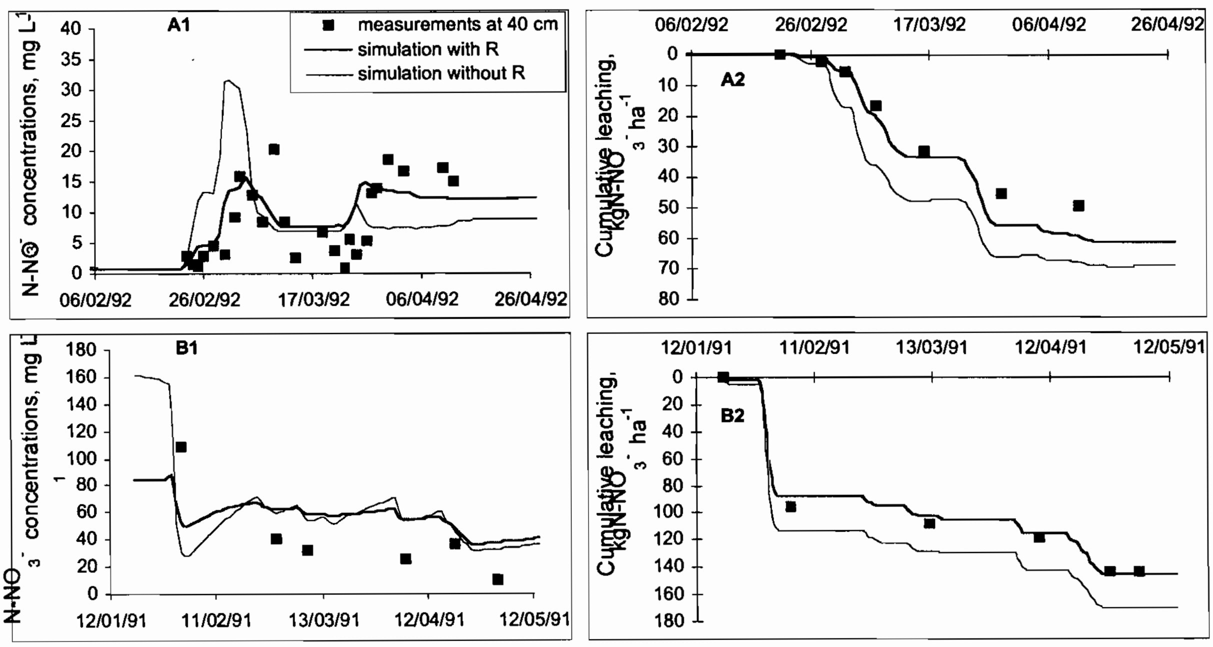

Figure 1 : Measured and simulated nitrate concentration in 1996 (A1) and 1995 (B1) and cumulative leaching at 40 cm deep in 1996 (A2) and 1995 (B2), with and without retardation

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Geochemical effects of a hill reservoir leakage above downstream alluvial aquifer (watershed of El Gouazine, Central Tunisia)

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El Gouazine reservoir (35°55'N, 9°45'E) is one of the five Tunisian experimental sites monitored in the European Union Hydromed program for the development of Mediterranean hill reservoirs (Albergel et Rejeb, 1997).
Analyses of hydrological balance, piezometric fluctuations and isotopic contents (^{18}O et ^{2}H) in downstream wells allow the authors to quantify the leakage of the reservoir to the alluvial aquifer. Underground outflow ranges from 170 m^3j^{-1} to 300 m^3j^{-1}, depending on the water level of the reservoir. In this preliminary phase, the isotopic change of the upstream and downstream groundwaters has been interpreted as being the result of the dilution effect of the groundwater by the reservoir water flow (Grünberger et al, 1999; Montoroi et Grünberger, 1999 ; Montoroi et al, 1998, 2001). The present paper identifies the chemistry of waters and solid phases (rock, soils, sediments...) which can explain the relationships between reservoir water and groundwater.
In May 1998, water sampling (surface water, groundwater and reservoir water) was done within and beyond the 18 km^2 El Gouazine catchment located in Central Tunisia. As well as the chemical water analyses (major and trace elements), the main pedological and geological formations of the watershed, including lacustrine deposits and alluvial materials, were analyzed using X-ray diffraction and chemical analyses (major and trace elements).
On the basis of major ion concentrations, three groundwater types (calcium-bicarbonate, sodium-chloride, calcium sulphate) are distinguished in relation with the bedrock (limestone, marl, gypsiferous marl, gypsiferous argillite, sandstone). Ba, Cr, Mn and Ti are the most reliable trace-elements characterizing the bedrock-groundwater interactions.
The abundant carbonate rock in the basin, and the rapid weathering rate of carbonate minerals suggests that dissolution of carbonate minerals will add significant amounts of Ca and Mg to the reservoir. In argillite and marl, the dissolution of gypsum is the source of sulphate and additional calcium in groundwaters. The composition of the reservoir water suggests a strong influence fromis gypsum weathering. Na is in excess for all the downstream wells, and one potential source of excess Na is weathering of feldspar as found in a sandstone outcrop.
In the dry season, the alluvial aquifer is influenced by other distinct aquifers intersected by the riverbed (Figure 1). The alluvial aquifer is supplied by shallow groundwater stored in limestone aquifers leading to a strong decrease of electrical conductivity. Due to the high porosity of the limestone, these aquifers can accumulate a high water content and rapidly recharge or discharge. The reservoir also tends to decrease the electrical conductivity of the groundwater. In contrast, in alluvial groundwater flowing through less permeable argilleous materials which contain variable amounts of easily soluble minerals such as gypsum, the concentration of dissolved salts is increased.
In the downstream part of the reservoir, the influence of the dam leakage through the reservoir deposits, and the combined effects of the dilution by surface water and the contact with alluvial material is described and discussed.

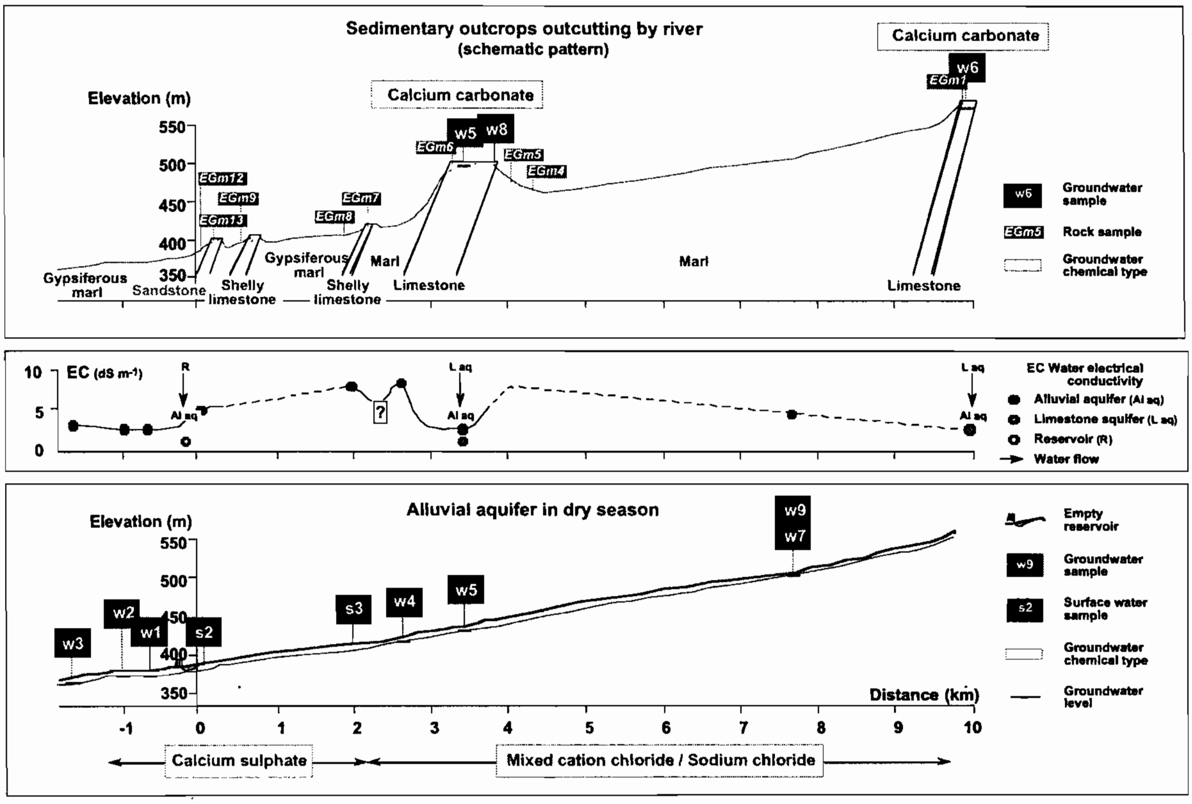

Figure 1. General hydrogeological features of the basin and electrical conductivity variation in relation to watershed geology.

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Generation of percolation clusters for the simulation of solute transport in soils

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Due to the high degree of complexity concerning both the distribution of the solid and the liquid phase the description of water and solute transport in soils is very difficult. Therefore an analytic mathematical solution requires several simplifying assumptions. We chose a different way by simulating and visualizing the transport processes by using a numerical model based on a percolation theory approach.

The goal of the work presented here was to create percolation clusters that show visual similarity to cross sections of soil samples in the lower millimeter range. As a measure for the similarity we use the box counting fractal dimension which has been determined frequently (see Dathe, A.: Contribution to this conference).

The algorithm used for the generation of clusters was structured as follows:

Starting point is the definition of a matrix consisting of single unconnected cells.

Pairs of adjacent cells are chosen randomly and are then connected.

After each step the algorithms checks if a continuous connection from the top to the bottom of the matrix has been established. If a connection has been found the algorithm is termined.

If no continuous connection is found, step ii) is repeated.

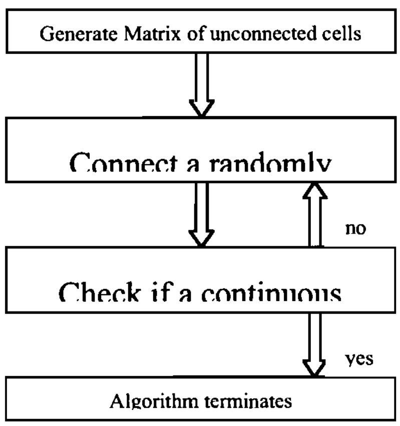

Figure 1: The algorithm

In the next figure some percolation clusters generated with the algorithm described are presented.

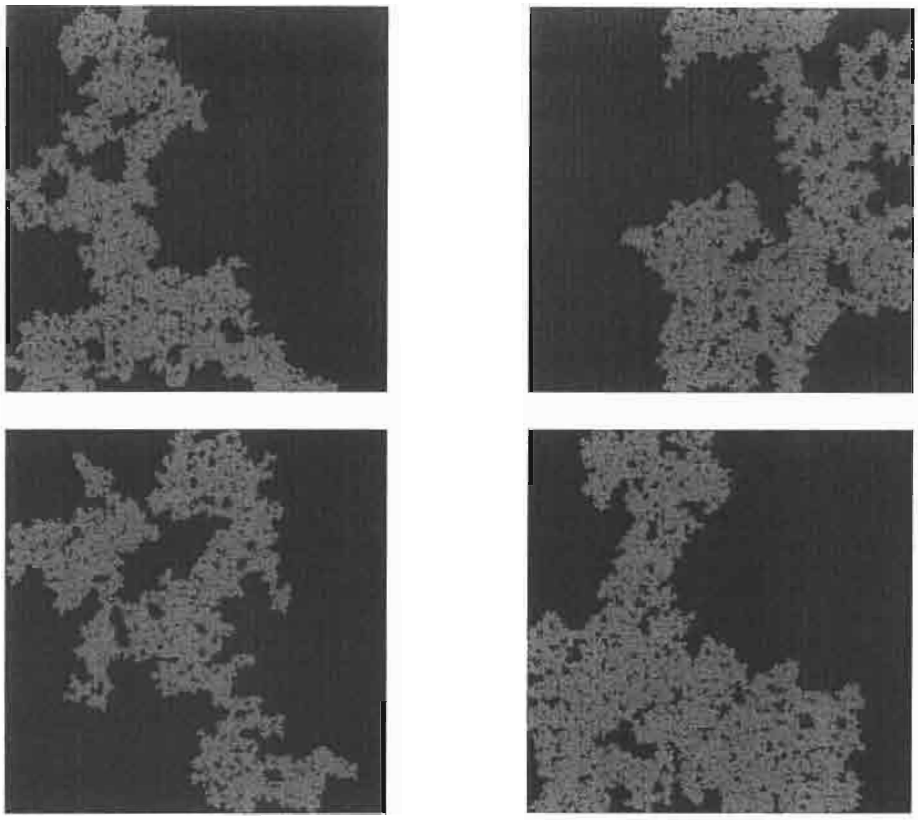

Figure 2: Examples of generated percolation clusters

In order to achive a better representation we removed the „litter“ within the liquid phase of the clusters by defining a minimum size for particles. Furthermore, we added some larger particles (representing „stones“ or „plant roots“) i.e. areas which cannot be affected by the algorithm. The fractal dimension was determined using a box counting algorithm.
This percolation cluster is the basis for the above mentioned simulation of solute transport. The interaction of dissolved molecules with the pore interface will be achieved by defining randomly distributed interaction spots. The intensity of the interaction is simulated by the time a solute is sorbed.

Influence de la mise en culture sur la fertilité des sols en région forestière tropicale humide du sud Cameroun

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Une étude morphostructurale et des analyses physico-chimiques ont été effectuées sur les sols de la région forestière tropicale humide du Sud Cameroun. Le climat de la région est équatorial humide à 4 saisons (pluviométrie moyenne annuelle : 1700 mm d'eau ; température moyenne mensuelle : 24°C). Les sols sont ferrallitiques rouges ou jaunes, acides et fortement désaturés. Ils sont peu fertiles (pauvreté en bases échangeables, acidité, toxicité aluminique). Dans cette région se pratique une agriculture itinérante sur brûlis. C'est donc une agriculture très peu sédentaire, parce que la mise en culture d'une parcelle provoque à terme l'appauvrissement du sol; et l'agriculteur est obligé d'aller à la recherche de nouvelles terres plus fertiles en forêt. Cette pratique a entretenu une déforestation permanente de la région, préparant à un déséquilibre écologique plus généralisé. *La présente étude a permis d'évaluer les effets de la mise en culture (défrichement et labour) sur la fertilité des sols de cet écosystème, dans l'objectif d'une sédentarisation de l'agriculture en zone de forêt tropicale humide en vue d'une protection durable de la biodiversité.*
L'étude a été menée sur 4 sites sélectionnés sur la base du type de culture et du type de traitement apporté au sol. Ce sont : le site de Ngovayang, (*champ de manioc de 3 ans d'âge, labouré à plat, avec engrais chimique (N-P-K + Mg + Na) et urée*) ; le site d'About (*bananeraie de 2 ans d'âge, non labourée, averc engrais chimiique (N-P-K) et urée*) ; le site de Meyo-Elie (*champ de maïs de 3 ans d'âge, labouré à plat, sans amendements*) et le site de Nyabibété *(champ de manioc de 2 ans d'âge, labouré à plat, avec engrais chimique (SO_4K_2) et urée*). Dans chacun de ces sites, 2 parcelles ont été sélectionnées; une sous culture et l'autre sous forêt. La parcelle sous forêt sert de témoins. Chaque parcelle est étudiée sur le double plan morphostructural et analytique. L'étude morphostructurale est basée sur une description fine des sols sur le terrain. Les analyses sont essentiellement physico-chimiques (humidité du sol, densité apparente, granulométrie, N total, CEC, bases échangeables, acidité échangeable, P assimilable et matière organique).
Les principaux résultats obtenus ont permis d'estimer la fertilité physique et chimique de chaque parcelle, puis d'évaluer l'effet du défrichement, du labour et de l'usage de certains amendements sur la fertilité de ces sols. Ainsi, on a noté que la densité apparente (da) est plus élevée en surface pour les sols sous culture *(da de 1.18 à 1.26 sous culture, et de 0.98 à 1.10 sous forêt*). Les sols sous forêt sont donc poreux, et se compacte avec la mise en culture. La compaction est plus significative dans les sols labourés (*da = 1.26 à ngovayang*). La teneur en eau des sols sous culture est élevée en surface (*TEV >35%).* Les sols sous forêt sont argileux et bien structurés en surface (*agrégats grumeleux à nuciformes*). Sous culture, les agrégats La densification sont absents en surface (*structure massive à particulaire*). D'une manière générale, les sols sous forêt ont de bonnes caractéristiques physiques. On note cependant leur densification avec la mise en culture. est attestée par la diminution appréciable de la porosité et une déstructuration des horizons de surface. Ainsi, à la suite du défrichement, la surface du sol est exposée ; et les gouttes d'eau de pluie y tombent directement avec une forte vitesse de chute provoquent l'éclatement des agrégats de sols. Aussi, le remaniement du sol par le labour engendre la destruction des agrégats. Tout ceci explique pourquoi les sols sous culture perdent

rapidement leurs propriétés physiques en surface quelques années seulement après le défrichement. Cette fragilité du sol sou culture s'accentue avec le labour.
Sur le plan chimique, l'équilibre N-pH (diagramme de Dabin, 1966) montre que ces sols s'appauvrissent en N avec la mise en culture *(N total < 0.8‰ sous culture et de 0.5 et 2‰ sous forêt)*. Les facteurs limitant pour la fertilité de ces sols restent leur forte acidité *(pH_{eau} < 5.5)*, la faible quantité (*2 à 10 meq/100g de sol*) et le déséquilibre entre les bases échangeables, la toxicité aluminique élevée (*plus de 35% en forêt*). L'équilibre cationique global Ca-Mg-K signale que les sols sous forêt sont très riches en K *(30 à 57% du total des cations échangeables, et 0.2 à 4% sous culture*). Les sols sous forêt sont donc potassiques. Mais, avec leur mise en culture, ces sols perdent cet élément au profit du Mg (*40 à 65% et 0.2 à 4% sous forêt*). Les sols sous culture sont par conséquent des sols magnésiens. L'indice de Forestier est faible dans l'ensemble [$S^2/(A + Lf) < 0.9$]. Sa légère hausse sous culture peut s'expliquer par la texture plus grossière des sols en surface. Ceci indique pourquoi les sols sous culture sont moins exigeants en bases échangeables. On peut alors dire que l'appauvrissement des sols en argile à la suite de leur mise en culture est chimiquement positif. La toxicité aluminique est très élevée dans les sols sous forêt (*30 à 60%*). Elle diminue considérablement avec la mise en culture (*1 à 18%*). Ceci peut s'expliquer par le taux de minéralisation très élevé sous culture (*C/N < 10*). La minéralisation de la matière organique a, entre autres effets, de diminuer l'acidité du sol et de rendre l'Al^{3+} moins échangeable, c'est-à-dire moins toxique pour les plantes. On signale également un déficit en N et en K dans les sols sous culture (*N de 0.4 à 0.7‰ ; K de 0.01 à 0.1 meq/100g de sol*). Pourtant, ce sont des éléments très importants dans la nutrition des plantes. Leur faible teneur dans les sols sous culture s'expliquerait par leur absorption rapide par les plantes cultivées. Ces deux éléments sont par contre abondants dans les sols sous *forêt (N de 0.5 à 1.7‰ ; K de 0.2 à 1.2 meq/100g de sols*), bien que la somme des bases échangeables y soit faible. C'est ce qui expliquerait les bons rendements agricoles de ces sols en début de leur mise en culture. Dans l'ensemble, les sols sous forêt manquent cruellement de phosphore.
Au total, les sols de la région forestière du Sud Cameroun sont dans l'ensemble peu fertiles. Les limitations à leur fertilité sont l'acidité, la faible quantité et le déséquilibre entre les cations échangeables, la toxicité aluminique, la pauvreté en P assimilable et la structure peu développée. Ainsi, l'apport permanent de fumures phosphorées, de composts et d'engrais chimiques à ces sols est indispensable pour le redressement de leur fertilité. Le compost en parcelles cultivées pourra conserver et entretenir la structure de ces sols qui sont très fragile après le défrichement et/ou le labour. L'apport régulier d'engrais chimiques permet d'entretenir la fertilité chimique de ces sols, soit en relevant l'indice de fertilité de Forestier à 1.5 ; soit en équilibrant la balance cationique dans les proportions de 76% de Ca, 18% de Mg et 6% de K ; soit enfin en neutralisant l'Al^{3+} échangeable et en élevant le pH du sol à 5.5. Les sols sous forêt sont plus exigeants dans le redressement de leur fertilité, parce que moins riches en bases échangeables. Toutefois, sur le plan agronomique, ce sont les meilleurs, car ils sont plus riches en K et en N, et ont une structure bien développée en surface.

Mots clés : Sud Cameroun, forêt dense tropicale humide, sol ferrallitique, biodiversité, mise en culture, fertilité, amendement.

Water transfer in the system reservoir-ebb tide in the semi-arid region in Northeastern Brazil: evidences of preferential flow

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In the semi-arid Brazilian Northeast, river valleys, lowlands and the adjacent flat or slightly undulated areas, have the best potential for agricultural production, due to the best water availability. Water collected in the catchment areas; whether through intermittent rivers or underground flows, converge towards these areas, where traditionally small dams are built in order to retain water, creating small reservoirs. In Northeast Brazil, there are more than 70,000 small reservoirs.

After the rainy season, the small reservoirs become empty because of evaporation, possibly by infiltration and because of multiple domestic uses of water. While the water level in the reservoir decreases, saturated soil areas uncover on them borders, where ebb tide agriculture is performed. Ebb tide agriculture consists of cropping the margins of the reservoir, on slight slopes, while the water level progressively drops.

The problem of water resources is of major concern in the Northeast of Brazil, especially as it is related to agricultural water management in dry land, ebb tide and irrigated cultivation. However, in this area of Brazil, only few studies have been performed on these systems, and little is known on their water balance, and on the characterisation of unsaturated soil hydraulic parameters, and consequently few models describing this local specific condition are available. Many of the existing small reservoir- ebb tide cultivation systems are old and the seasonal behaviour of the system may induce several changes in the soil profile. In clay soils, for example, the wetting and drainage cycles may produce cracks, which form preferential water flow paths and alter the water flow conditions, contributing to more rapid infiltration. In this context, it is essential to be able to quantify preferential flow phenomena, which contribute to rapid water and solute infiltration into soils.

The quantification of this process is of major importance for conservation of water resources quality. This paper is focused on the analysis of preferential flow in a ebb tide cultivated area in the semi-arid region of Northeast Brazil, which has been monitored, in terms of water balance componentes and water dynamics, for a period of time. In the monitoring programme, the water dynamics in two different scales have been pursued: the system reservoir-ebb tide, and the plots individually.

The study has been performed in the ebb tide zone of the basin of Flocos dam, municipality of Tuparetama, PE (7°36'S and 37°18'O). Close to the dam, a meteorological station has been installed, equipped with automatic sensors for recording pluviometry, temperature, relative humidity, wind velocity and direction, as well as a class "A" tank and a "Ville de Paris" rain gauge. The plots have been instrumented with one neutron probe access tube and tensiometers at different soil depths. In the interface reservoir- ebb tide soil saturation extracts have been collected with depth using porous suction cups. Evolution of water level in the reservoir and of piezometric level in the ebb tide zone have been recorded. A transect of six piezometers has been monitored for this purpose. The soils are classified as Fluvents. The soil bulk density increases with depth in the soil profile, and two distinct layers are identified along the profile: a superficial clay textured layer overlying a sandy layer. Unsaturated soil characteristics have been determined, from experimental field and laboratory data. Hydraulic conductivity near saturation has been determined with disk permeameter. The saturated hydraulic conductivity of the sandy layer is 100 times greater than of the superficial clay textured layer. During the monitoring programme, the presence of a network of cracks that remain open even under water was observed in the deepest part of the Flocos dam.

A simplified model has been proposed representing the system small reservoir-ebb tide by a set of different interacting water storage reservoirs. The first one is the small reservoir, which represents the main water storage, accumulated during the rainy season. The second reservoir is the ebb tide zone. This reservoir represents the total amount of water in the soil available for the crop. The link between the two reservoirs, the saturated zone, represents a buffer reservoir for water transfer. The water transfer in the system is described by a set of two balance equations and one flow equation defined in an analogous Darcy equation, with two unknowns: the water level in the small reservoir and a reference level of the water table underneath the ebb tide area, both time dependant. Solution of the set of equations depends on the effective saturated hydraulic conductivity of the medium and on atmospheric conditions, governing the evaporation and the water storage variation.

The recorded water and piezometic levels in the reservoir and in the ebb tide zone clearly shows that the saturated zone is supplied by the lake during the monitored period. The soil saturation extracts data reveals that the salinity decreases with depth in the interface reservoir-ebb tide, showing that no leaching from the surface occurs. The observation of the soil salinity behaviour in the interface during the dry period is an evidence of the preferential flow phenomena through the more permeable deep soil layer.

Simulations allowed the evaluation of the preferential flow contribution throughout the network of cracks in the deepest part of the dam. This contribution has been determined from the difference between the simulated flux considering an effective saturated hydraulic conductivity, calculated from field determined values in different layers, and the flux obtained by the identification of the effective saturated hydraulic conductivity reproducing the measurements of water level in the reservoir and piezometric levels in the ebb tide zone.

This study allowed a better understanding of the water transfer process in the system reservoir-ebb tide. The proposed simplified model was able to evaluate the preferential water flow contribution from the reservoir to the ebb tide throughout the network of cracks located in the deepest part of the dam.

Scaled forms of the infiltration equation: application to the estimation of the unsaturated soil hydraulic properties

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There is a clear need to assess the adequacy of scale matching of soil water dynamics to grid scales relevant for simulation of the vadose zone, aquifers, the land surface and atmospheric interactions. The difficulty of parameterization of soil water movement lies not only in the non-linearity of the saturated/unsaturated flow equations but also in the mismatch between the scale of (point) measurements and the scale of model predictions.
Traditionally, the scaling is performed through normalization analyses of static soil properties such as grain size diameter and/or hydraulic soil characteristics. However, the main importance for vadose zone hydrology is the knowledge of the unsaturated flow behavior of a soil, rather than the knowledge of hydraulic soil characteristics, which are just intermediate relationships used to calculate the flow behavior. For that reason we choose, in this paper, to study the problem of scaling directly through the dynamical analysis of the unsaturated flow equations for both *Dirichlet* concentration type and *Neumann* flux type boundary conditions. Applying inspectional analysis, a rigorous approach is made to scale Richards' equation for one-dimensional, isothermal flow in a homogeneous unsaturated soil resulting in a non-dimensional boundary value problem. The case of one-dimensional constant head infiltration in a semi-infinite uniform soil column using the *Green and Ampt* (1911) and *Talsma and Parlange* (1972) solutions, is applied to illustrate the principles of scaling theory. Full identification of scale factors of the unsaturated flow equation can be illustrated through the generalized constant head infiltration equation developed by *Parlange et al.* (1982) and *Haverkamp et al.* (1990). It had been shown (*Haverkamp et al.*, 1998) that the scale factors introduced for the constant head infiltration come naturally for the flux boundary condition as well.
The results demonstrate that there exists, so far, no unique dynamical similarity in the behavior of soil water movement in general field soils when governed by the *Richards* equation. Instead there is a multitude of dynamical similarity classes depending on the combination of soil type, initial and boundary conditions. In its most general form, the head and/or flux infiltration behavior is defined by three infiltration scaling factors embodying the effect of soil type, initial and boundary conditions. For two particular cases which correspond to the *Green and Ampt* soil and the *Gardner* soil, there is a unique similarity solution for which the physical system is macroscopically similar. These two solutions are the bounds of the envelope of all possible similarity classes; hence they become of great use for water watershed modeling at large scales as they fix the two extreme scenarios on which decision making can be based.
The results demonstrate that the purely soil related flux determined scale factors are identical for infiltration under head (negative or positive) and flux boundary conditions. These scale factors allow for the scaling of the classically used soil hydraulic characteristics in such a way that consistency with the invariant flux equations is maintained. Hence, once the flux defined scale factors have been determined, these factor can be de-convoluted into the classically used

soil hydraulic characteristic parameters. Consequently, the application of this scaling technique to in-situ measured infiltration experiments, is a promising tool to characterize the soil hydraulic soil properties at low costs and with affordable human resources. When performing the identification by means of the *Green and Ampt* and *Talsma and Parlange* infiltration solutions, which determine the invariant upper and lower bounds of the envelope of all possible infiltration classes, good estimations of the extreme soil characteristic parameters can be found which is of great use for watershed studies where stochastic modeling is needed.

In the last stage of this paper, the new method of characterization which was initially launched by *Haverkamp et al.* (1997) as the '*Beerkan*' method, is applied to a practical case of in-situ infiltration performed in the context of the '*Alpilles*' project. A detailed description of the step by step procedure is addressed. An algorithm for the identification procedure of the different soil characteristic parameters is given in an Annex.

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Hydraulic properties and unsaturated flow in structured or macroporous media

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This presentation focuses on the problem of preferential flow in variably-saturated media, a major unresolved issue facing soil scientists and hydrologists in dealing with vadose zone flow and transport processes. Preferential flow is caused by a broad array of processes. In structured or macroporous soils water may move through interaggregate pores, decayed root channels, earthworm burrows, and drying cracks. Similar processes occur in unsaturated fractured rock where water may move preferentially through fractures, thus bypassing much of the rock matrix. Preferential flow may also occur in seemingly homogeneous (especially coarse-textured) soils in the form of unstable flow (or fingering) induced by soil textural layering, water repellency, air entrapment, and/or by funneling of water through high-conductivity soil layers. Often several of the above processes act together and/or reinforce each other.

Process-based descriptions of preferential flow generally invoke dual-porosity or dual-permeability models which assume that the soil consists of two interacting pore regions, one associated with the macropore or fracture network, and one with micropores inside soil aggregates or rock matrix blocks. Different formulations arise depending upon how water and/or solute movement in the micropore region is modeled, and how water and solutes in the micropore and macropore regions are allowed to interact. Early formulations in the petroleum engineering and soil science literature generally assumed the presence of distinct mobile and immobile (non-moving) liquid flow regions, with solute exchange between the two regions being approximated by means of a first-order mass transfer process. Models of this type have been used successfully to describe a large number of laboratory and field-scale solute transport distributions, especially when obtained during steady-state flow.

A simple but still effective approximation of preferential flow results when a single Richards is equations still used in an equivalent continuum approach, but with composite (double-hump type) hydraulic conductivity curves rather than a single smooth curve traditionally used for granular media. More involved dual-porosity type models result when the medium is partitioned into fracture and matrix pore regions, with water and/or solutes allowed to exchange between the two liquid regions. Different formulations of this type are possible. For example, one could permit transient variably-saturated flow in the fractures only, while allowing water to exchange between the fracture and matrix domains. The latter situation leads to both advective and diffusive exchange of solutes between the fractures and the matrix, but still without vertical flow in the matrix.

Dual-permeability models arise when water flow occurs in both the fracture and matrix domains. Models of this type can invoke different formulations for the exchange of water between the fracture and matrix regions. In some models more than two domains are considered, each one having its own hydraulic properties. The modeling approach can be refined further by considering transient flow and/or transport in discrete fractures with or without interactions between the fractures and matrix. The latter approach assumes that the flow and transport equations of the fracture network can be solved in a fully coupled fashion with the corresponding equations for the matrix.

Application of the above dual-porosity or dual-permeability models requires estimates of the hydraulic properties of either the fracture pore network, the matrix region, or some composite of these. Dual-permeability models typically contain two water retention functions, one for the matrix and one for the fracture pore system, and two or three hydraulic conductivities functions: K_f for the fracture network, K_m for the matrix, and K_a for the fracture/matrix interface. Of these functions, K_f is determined primarily by the structure of the fracture pore system (i.e., the size, geometry, continuity and wall roughness of the fractures, and possibly the presence of fracture fillings). Similarly, K_m is determined by the hydraulic properties of single matrix blocks, and the degree of hydraulic contact between adjoining matrix blocks during unsaturated flow. Finally, K_a is the effective hydraulic conductivity function governing the rate at which water exchanges between the two pore systems. Estimates for the K_f and K_m functions may be obtained by assuming that K_f is primarily the conductivity function in the wet range, and K_m the conductivity in the dry range.

Measurements of the composite (fracture plus matrix) hydraulic properties are greatly facilitated by the use of disc infiltrometers. Disc infiltrometry methods involving ponded and tension infiltrometers are now increasingly used for in-situ measurements of the hydraulic conductivity at low soil water tensions. Advantages of these methods are that negative soil water pressures at the soil-infiltrometer interface can be maintained very close to zero, and that they can be decreased in small increments to yield well-defined conductivity functions near saturation. In several studies the hydraulic properties of bimodal or multimodal soils have been modeled using sums of two or more van Genuchten-Mualem type functions. Evidence from field measurements suggests that the fracture conductivity is generally about one order of magnitude larger than the matrix conductivity at saturation. Using neural network analysis of a large unsaturated soil hydraulic database (UNSODA) we found a similar difference between the fracture and matrix saturated hydraulic conductivity. Moreover, the air-entry value of the fracture hydraulic conductivity was found to be at about 3 or 4 cm. This information should help greatly in quantifying the constitutive relationships of dual-permeability models.

Experimental study and numerical modelling of the water transfers in an irrigated plot in Northern Senegal : evidences of air entrapment.

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In arid sahelian areas of West Africa, irrigation has become the only answer to drought and increasing population, for performing sustainable agriculture. On the other hand, under high evaporative demands, irrigation can also result as being a serious hazard for soil conservation, and cropping, as it leads to accumulation of soluble salt in the root area. Salinisation process, responsible for osmotic stress on crops, is usually the major threat in arid areas. Moreover, in the valley of river Senegal, where this study takes place, the quality of the irrigation water shows alkaline composition with a positive sodium carbonate ratio. Although no real evidence of sodic soils has yet been observed, after two decades of irrigation, the intrinsic water quality represents a serious potential threat for soil sodication.

A shallow water table (2m depth), related to the river level, with a neutral saline composition, is present under the irrigation scheme of the studied area. During irrigation periods the water table rises and contributes to salt transfer, but can also be seen as natural drain for water and solutes towards the river.

As soil recuperation or amendment application is economically not possible for the local farmers, adequate water management is the only way to prevent or reduce the potential soil degradation process. Water transfer will play an essential role in the evolution the physico-chemical characteristics of the soil.

To evaluate the risks of salinisation and alkalisation in irrigated paddy fields, apart from a geochemical study it is important to the dynamics of the water and solute transfer.

Therefore a precise monitoring of water budget in an irrigated plot near Podor (N16°40'; W15°) has been performed during a paddy cropping season (100 days). Water inputs have been quantified with the monitoring of the number of calibrated siphons used during each irrigation. Evapotranspiration has been evaluated with lysimeters and the cumulative response of evapotranspiration and vertical infiltration has been quantified by monitoring the daily evolution of the water level in Muntz infiltration rings. At the same time, piezometric level and tensiometric data have been measured in 2 stations in the plot at 5 depths (10, 20, 40, 60 and 80cm).

Global water balances results show that net vertical infiltration of 1.1 mm/d in station 2 and about 0.2mm/d in station 3. In station 2 located in the middle of the plot , evolution of the tensiometric profile follows a typical dynamics with sharp pressure head decrease as infiltration front progresses. In station 3 near the external border, the upper layers (10 an d20cm) follow the same evolution. However at 40 cm the pressure head decreases extremely slowly and progressively during a period of 40 days without reaching complete saturation after the whole period. Underneath the pressure head remains unchanged and unsaturated during the whole cropping period.

Unsaturated hydraulic parameters of van Genuchten (_r, _s, _, n, Ks) have been determined along the profile independently. Consequently, with the tensiometric data, both water contents and water fluxes could be evaluated. Water fluxes calculated with Darcy equation thoroughly

overestimated the values measured with the global water balance method, due to high hydraulic gradients, whereas fluxes estimated from the water stock variation are in agreement.
Water transfer has been modelled with Hydrus-1D and previously determined unsaturated hydraulic parameters. As excepted, the numerical results are in complete disagreement with the experimental data. When used inversely to evaluate the parameters, the best fit of the model gives a saturated conductivity of 0.25mm/d, which does not have a real physical significance as it is 2 orders of magnitude lower than the the saturated hydraulic conductivity determined otherwise. These different results tend to show that infiltration in this area seems to be controlled by a mechanism of air entrapment between the downward wetting front and the shallow water table.
Most of the models simulating transfer in soil consider monophasic flow where air freely escapes, and does not impede water infiltration. However in this case this approximation seems not to be valid.
Basic infiltration models based on Green Ampt concept developed by several authors (Grismer et al 1994, Morel-Seytoux et al 1996, Wang et al. 1997) have been tested to evaluate the hypothesis of air entrapment phenomenon. They have been used with different external conditions : (i) no air escape, (ii) with air counterflow considering that air escapes vertically for a fixed bubbling pressure, (iii) with a maximal air pressure which is the case often observed in experiments (Grismer et al. 1994) and (iv) with a lateral air escape, considering air can escape beyond the irrigated plot. The models have been applied with unsaturated soil hydraulic parameters determined previously, and with the actual water table level evolution.
When no air escape is allowed and the infiltration of water is completely stopped at a depth of around 50 cm and the underneath soil profile remains at its original water saturation. The global solution for infiltration with vertical air counterflow is independent of the water table level,and shows a continuous imbibition dynamics proportional to the square root to time. For both of two other tested cases, infiltration drastically drops at the same depth (around 50-60 cm depth) and where the flux reaches a minimum value around 0.1mm/d, during a period of 100 days, and then accelerate again.
We showed that the dynamics of infiltration measured in field conditions, corresponds to cases where air compression takes place. However the condition with vertical air counterflow does not correspond to the dynamics observed in the field. Moreover no evidence of air bubbles has been observed in the plot during the hole experiment. On the other hand, considering the depth of maximal infiltration reduction and the following water fluxes derived from the models, it seems very likely that air compression occurs in this plot. The particular position of the studied plot, on the border of the irrigation scheme, allows air to escape laterally but due to an important impedance, air pressure builds up and drastically reduces the infiltration rate.
This study showed that in irrigated plots in the area of Podor in the valley of river Senegal, water transfer and consequently solutes, does not follow the classical infiltration models. It has been demonstrated that the presence of a shallow water table and irrigation by immersion for paddy cropping, generates a phenomenon of air entrapment blocking the infiltration of water. The consequence of this mechanisms is that water introduced in the field for irrigation does not leach to the water table and consequently concentrates in the upper part of the soil profile. This unexpected phenomenon, and generally not considered in coupled water and solute transfer models, can chiefly affect the evolution of the soil solution and increase the risk of alkalisation.

Changes in hydrodynamics of a tropical soil cover resulting from intensive cultivation

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Vast areas of central and southern Brazil under tropical-subtropical climates have been cultivated intensively for the past few decades or are expected to undergo such a development. The consequences of this remain unknown, both on the soil fertility and on the environment. Farming practices modify the structure of the soils, either directly or indirectly, via changes in the diversity and activity of the soil fauna. We studied the structure and hydrodynamic behaviour of the soil cover in a cultivated catchment area in the state of Paraná, southern Brazil. In this study, we seek to specify the influence of farming practices on the evolution of soils which, in the long term, may compromise their productive capacity.

The catchment area is located close to the small rural town of Mamborê (24°16'41" S, 52°39'19" W). Agriculture intensified in this area with the growing of soya from 1969 onwards. The landscape consists of hills with gentle slopes that become more marked near the principal thalwegs. Structural analysis of the soil cover allows us to map and characterize a pedological system developed on sandstone. This system is termed "latossolo vermelho escuro - podzólico" according to the Brazilian soil classification, or "ferralsol - acrisol" according to the World Reference Base. It is characterized by the progressive passage downstream from the Bl horizon of the ferralsol, sandy-clayey with microaggregated structure, to the Bt horizon of the acrisol, clayey-sandy with polyhedral structure. A sub-surface horizon E, depleted in clay, appears above horizon Bt. After many years of soya and corn culture, a pasture was established in the catchment area. Two years later, a compact horizon was still clearly perceptible at the base of the tilled horizon.

Samples with unreworked structure were taken in the principal horizons for laboratory analysis of the apparent density (cylinders of 250 cm^3) and the water retention profile between 0 and -160 m matrix potential (cylinders of 100 cm^3). The hydraulic conductivity of these same horizons was measured *in situ* by an infiltrometer with controlled suction, using a 8.5-cm-diameter disc and imposing 4 successive values of matrix potential (-10, -3.5, -1 and sometimes 0 cm). Five tensiometric stations, each one including eight tensiometers at depths of 10, 20, 30, 50, 70, 90, 120 and 150 cm, were set up along a 120 m-long toposequence. The station at the upslope end of the toposequence is located on ferralsol; two stations bracket the limit of appearance of horizon Bt in the acrisol; the fourth station is on acrisol, located at the foot of a slope created to limit erosion; the fifth station is at the bottom of the slope, near the thalweg. The analysis of the spatial and temporal variations of water potential, measured by tensiometers, in particular allows us to specify the expansion and the persistence of the saturated, surface or deep zones as a function of precipitation.

The bulk densities and the hydrodynamic properties show the existence of a structural discontinuity under the tilled horizon, corresponding to the densest and least permeable level in the two soil types. Hydraulic conductivity decreases tenfold between the surface of the ferralsol and the base of the tilled horizon at the four imposed matrix potentials, while the apparent density increases from 1.5 to 1.67. The contrast between the surface and the base of the tilled layer is less marked in the acrisol. The water retention curves also reflect the degradation of the soil structure: the volume per unit mass of water lost when the matrix potential varies from -10 to -100 cm falls from 0.12 $cm^3 g^{-1}$ on the surface ferralsol to 0.07$cm^3 g^{-1}$ at the base of the tilled layer. This difference results from a more compact arrangement of the argillaceous micro-aggregates and sand particles.

Tensiometric measurements during and after a rainstorm of 44 mm (coming at the end of a very rainy period) reveal the existence of two perched water tables. The deeper one appears within horizon E, above horizon Bt of the acrisol. However, the infiltration of water is clearly slowed down between 20 and 30 cm depth, i.e. at the base of the tilled horizon, both in the ferralsol as well as in the acrisol. This shallow perched water table is limited to the tilled horizon and is present over all the hillslope. Being rather transitory, this groundwater body did not persist more than two or three hours after the studied downpour. On the other hand, the deeper body perched above Bt was still present two days after the rainstorm, and even much later at the slope bottom. This groundwater body seems to contribute much less to the flows in the thalweg of the catchment area, as shown by the rapid and important reduction of flow as soon as the cultivated horizon is no longer saturated. Measurements thus confirm the difference in hydrodynamic behaviour between the ferralsol and the acrisol, which thus also involves the role of horizon Bt. However, there is lateral drainage within the tilled horizon of this cultivated catchment area. Consequently, even in the ferralsol, drainage is not strictly vertical in this area, contrary to the situation observed under natural vegetation for this type of soil. A large proportion of the precipitation will therefore join the drainage network rapidly without recharging the soil water storage. In an area where three harvests are carried out each year, this hydrodynamic regime may represent a real constraint .

The *in situ* monitoring of the hydrodynamic functioning of the pedological system has shown the presence of major structural discontinuities. These discontinuities were inherited from soil formation processes or have appeared since the establishment of farming. They limit the vertical hydric transfers and, during rainy episodes, give rise to relatively shallow and sustained lateral flows. These flows determine or accelerate the processes of soil evolution, such as eluviation and erosion, even causing waterlogged conditions in the case of water stagnation. The results obtained stress the importance and the speed (deforestation only dates back a few decades) of the changes in soil water dynamics produced by farming methods. There are at least two important practical consequences : increased risks of erosion and a reduced replenishment of the soil water storage.

Prediction of hydraulic parameters using basic geotechnical properties

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The hydraulic conductivity value is needed for seepage, consolidation and drainage studies under saturated as well as unsaturated conditions. In the latter case, the unsaturated hydraulic conductivity k_u of a soil is usually obtained from the saturated hydraulic conductivity k_s and the measured water retention curve (WRC). The WRC represent the relationship between the volumetric water content θ_w and the suction ψ (only the matrix suction is here considered).

Simple functions to evaluate k_s and WRC using basic material properties, including grain-size distribution, porosity and liquid limit, have been developed by the authors for granular (cohesionless) as well as cohesive (plastic) materials. The k_s-function stems from the Kozeny-Carman equation, while the WRC-function is a modified version of the Kovács (1981) model (MK model). The validity of the estimation methods is confirmed using a relatively large experimental database. These expressions can be used to obtain the k_u-function from the same basic properties.

In the developed functions, the following parameters are used:

ψ: matric suction (cm)
ρ_s :solid grain density (kg/m^3)
μ_w : water dynamic viscosity (μ_w=10^{-3} Pa.s at 20°C)
γ_w : water unit weight (γ_w =9.81 kN/m^3 at 20°C)
θ_w: volumetric water content (-)
C_U: uniformity coefficient (-)
D_{10}: diameter corresponding to 10% passing on the cumulative grain-size distribution curve
e: void ration (-)
G: index standing for granular materials
k_s: saturated hydraulic conductivity (cm/s)
P: index standing for plastic cohesive materials
T_w Surface tension of water (T_w=0.073 N/m at 20°C)
w_L: liquid limit (in %)

1 Prediction of the saturated hydraulic conductivity k_s

<u>For granular materials</u>: $k_{s,G} = f(\mu_w, \gamma_w, D_{10}, C_u, e)$

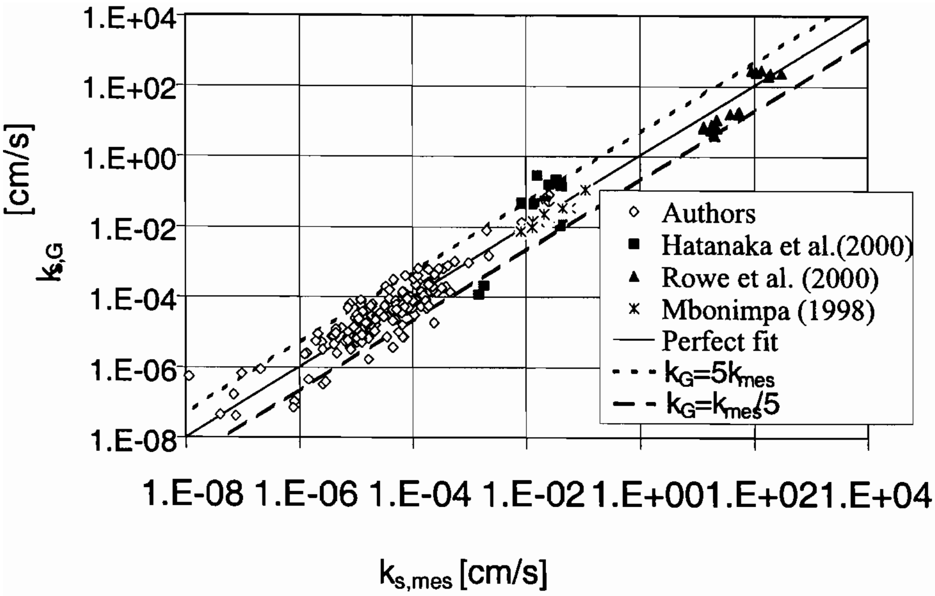

Figure 1 Comparison between measured ($k_{s,mes}$) and estimated ($k_{s,G}$) values of the hydraulic conductivity for data from different sources with $4x10^{-6}$ cm $\leq D_{10} \leq 1.5$ cm.

For cohesive materials : $k_{s,P} = f(\mu_w, \gamma_w, w_L, \rho_s, e)$

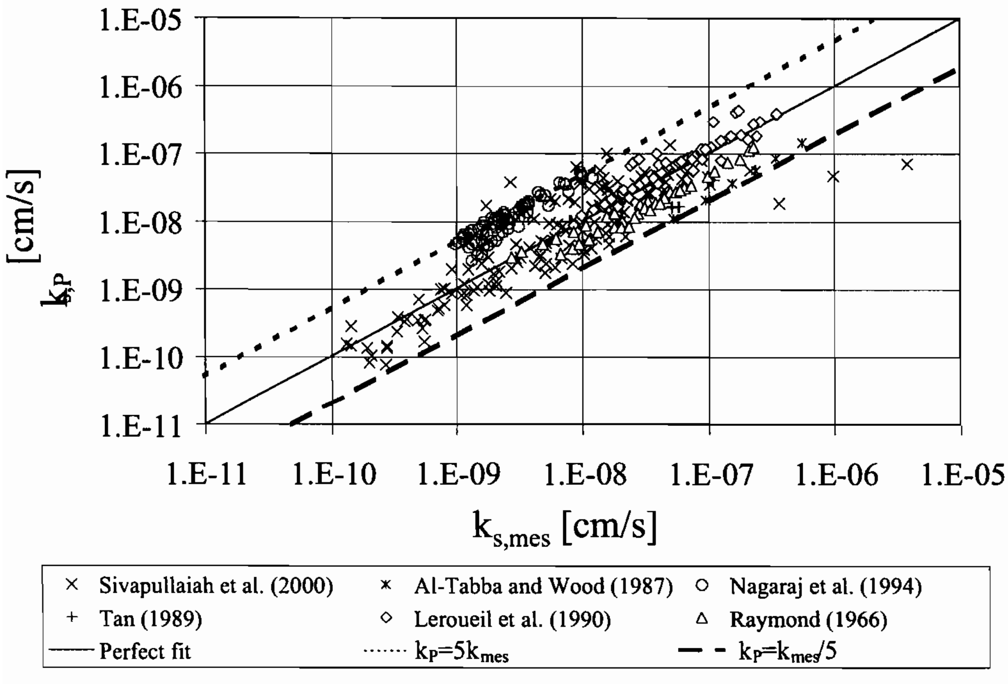

Figure 2 Comparison between measured ($k_{s,mes}$) and estimated ($k_{s,P}$) values of the hydraulic conductivity, for data from different sources with $20\% \leq w_L \leq 495\%$.

2 Prediction of the water retention curve (WRC) (θ_w-ψ relationship)

For granular materials: $\theta_{w,G} = f(T_w, \gamma_w, D_{10}, C_u, e, \psi)$

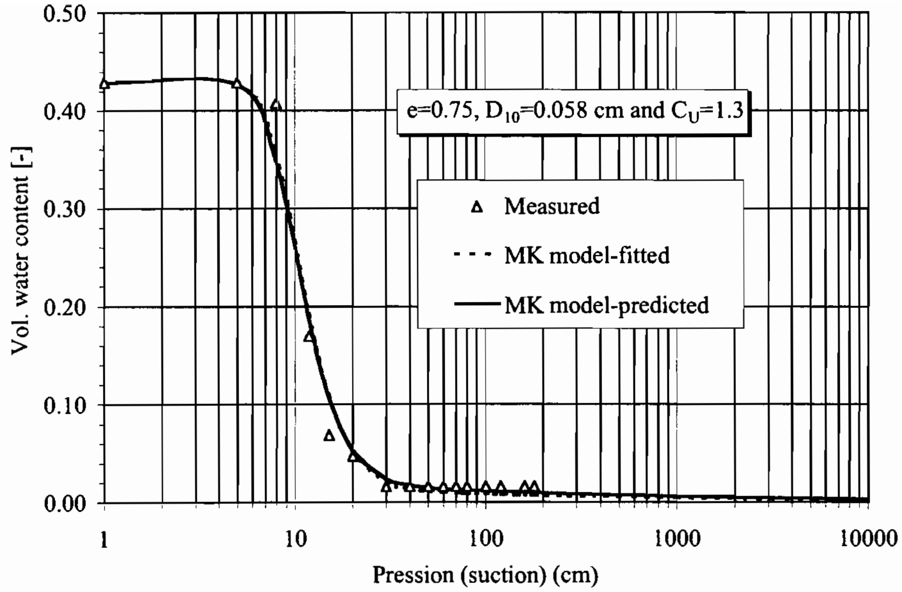

Figure 3 Application of the MK-model to a coarse, uniform and relatively dense sand (data from Sydor, 1992).

<u>For cohesive materials</u> : $\theta_{w,P} = f(T_w, \gamma_w, w_L, G_s, e, \psi)$

Figure 4 Application of the MK-WRC model to Indian Head Till (data from Fredlund, 1999)

Hydraulic properties of recent volcanic ash soils from the high slopes of the Rucu Pichincha volcano (Quito - Ecuador)

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Introduction

The hydrological behaviour of the volcanic catchments is directly related to the specificity of their soils, developed above recent ashes and volcanic tuffs. These soils belonging to the Andisol order are well known for their low bulk density and high water retention capacities. These properties are mainly due to the presence of i) secondary short range order minerals such as allophanes or imogolite and ii) organo-metallic complexes, which are able to promote a soil structural organisation with high porosity. However, we have few knowledge of the hydrodynamic properties of such soils. A conceptual scheme for the infiltration process at the catchment scale in volcanic ash soils is therefore difficult to draw.
A hydro-pedological research program has been carried out at the foot of the Rucu Pichincha volcano in Quito (Ecuador). An experimental network was installed in 1995 on the Rumihurcu catchment, located at the upper periphery of Quito. This 7.5 km^2 catchment, ranging from 4627 m to 3280 m, was chosen because it included most of the physiographic characteristics that can be found on the high slopes of the Pichincha.
Perrin et al. (2001) showed that surface runoff is not likely to occur on the slopes because of the low rainfall intensities of these high altitude zones and the high infiltration capacity of the recent volcanic soils. Conversly, it was found to be generated on continuously saturated areas situated close to the main drain. Saturated area extension which conditions the flood runoff coefficient is directly related to base flow, i.e. infiltrated water storage of the catchment.
Then, the objective of this study is to improve knowledge of punctual infiltration process which appears as a fundamental work subject before to better quantify sub-surface water transfer along the slope and water table recharge at the bottom of it.

Materials and methods

Soil stratification is very homogeneous on the slopes of the catchment and is composed of distinct ash deposits. A reference profile was selected. The topsoil is constituted by two organic-rich horizons (Pic1, 0-20 cm and Pic2, 20-40 cm depth) derived from a 300 years B.P. pyroclastic deposits. A thin organic layer (Pic3, 40-55 cm depth) overlays an un-weathered layer of pumice (Pic 4, 55-80 cm depth) with high proportion (85%) of coarse elements (diameter > 2 mm). Both horizons derived from 980 years B.P. volcanic deposits of the Guagua Pichincha.
Undisturbed soil samples (five replicates) were collected using 250 cm^3 cores in the three topsoil layers: Pic1, Pic2 and Pic3. For each sample, water contents were determined by plate methods using undried and undisturbed cores between 10 and 300 kPa (7 points) and undried but disturbed samples at 1500 kPa. Total porosity was determined using particle and bulk density measurements (3 replicates for each layer). Brooks-Corey's and Van Genuchten's (with a Burdine's or Mualem's capillary models) soil characteristic relations have been fitted to give simple empirical expressions for the *_(h)* relationships and derived *K(_)* expressions.

Rainfall simulations were carried out on two one-square-metre plots. The simulations were performed, using a mini rainfall simulator. The intensity of each simulated rainfall was increased from 20 to 120 mm/h during the 90-minute duration of the event to generate surface runoff. Two rainfall events were conducted on each plot, at an interval of a few hours. This experimental protocol allowed us to characterise infiltration and runoff for a large range of rainfall rates and gave an estimation of saturated surface hydraulic conductivity during steady-state conditions.

Results and discussion

Soil water content is very high, with values ranging from 0.65 cm^3/cm^3 at saturation to 0.40 cm^3/cm^3 at the wilting point. This shows up that in spite of the sandy character of these soils, their micro-porosity is very high. The high amounts of organic matter and particularly Al-humus complexes, which strongly cement the micro-structure explain this apparent contradiction between the youth of the soils and the physical properties close to those of developed ones.

Both Van Genuchten's and Brooks-Corey's _(h) equations with a Burdine's or Mualem's capillary models fitted well experimental data. Fitted curves showed stable retention level from saturation to 10 kPa suction which was one of the main characteristics of these soils.

Conversely, the comparison between Van Genuchten's and Brooks-Corey's K(_) equations showed significant differences. Van Genuchten's K(_) equations is characterised by a large decrease of the relative K values near saturation probably due to inconsistency, for these soils, of fitting parameters of the Van Genuchten's K(_) equations, with the infiltration theory (Fuentes et al., 1992).

Finally, a combination of Van Genuchten's _(h) and Brooks-Corey's K(_) equations with Burdine's capillary model, for which the fitting parameters are physically consistent, have been chosen to describe soil water retention and relative conductivity curves.

These equations and their parameters have been directly used to simulate infiltration and runoff processes in the two one-square-metre rainfall simulation plots. A one-dimensional vertical numerical solution of a two-dimensional model SWMS_2D (Simunek et al., 1994) modified to use the selected _(h) and K(_) equations, has been tested in order to obtain, by calibration, the saturation conductivity of each soil layer (Pic1, Pic2 and Pic3) and to try to validate the _(h) and K(_) equations.

This model applied to the two one-square-metre rainfall simulation plots showed quite good results in term of water balance but also runoff simulation at a 1-minute time step. The calibrated values of the saturated hydraulic conductivity of each soil layer showed little difference from one plot to the other and are consistent with the values of steady-state infiltration capacity obtained during rainfall simulation.

This analysis, which underlines the specificity of volcanic ash soils was a necessary preliminary to runoff modelling in an area where very few experiments have been carried out. Calibrated and partially validated at the rainfall simulation plot scale, the model could be used, at a catchment scale, to better quantify sub-surface water transfer along the slope and water table recharge.

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Effect of soil management on soil porosity and hydraulic properties

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Tillage and traffic modify soil porosity and pore size distribution, leading to changes in the unsaturated hydraulic properties of the tilled layer but these changes are still difficult to characterize. This study aims at investigating the effect of a change in soil bulk density on water retention and conducting properties using field and laboratory evaporation experiments. Freshly tilled soil and soil tilled 6 months earlier and had received 300 mm rainfall, and soil compacted by wheel tracks were created in a loess soil (Typic Hapludalf) and a calcareous soil (Typic Rendoll) to obtain a wide range of soil bulk densities (1.0-1.6 g cm^{-3}). Soil porosity was analyzed by mercury porosimetry and scanning electron microscopy. The laboratory method of Wind (direct evaporation) was compared to an inverse modeling method applied to field measurements of water content and water potential. The Wind soil samples was saturated with water from the top (full saturation) or the bottom (partial saturation) before conducting the laboratory evaporation experiment.

Results showed that the Wind method, for soil samples initially fully saturated with water, overestimated water retention when compared with the water retention deduced from field measurements, except in the compacted soils.. On the contrary, there was good agreement between the Wind method and field data for tilled soils when the samples were only partially saturated from the bottom The Wind and inverse modeling methods gave similar assessments of hydraulic conductivity. In the calcareous soil, the change in bulk density due to traffic did not affect the water retention for water potentials<-20 kPa and increased the hydraulic conductivity-water ratio. In the loess soil, the compacted soil retained more water for water potentials <-20 kPa than did the tilled soil, but the hydraulic conductivity-water ratio was not affected by the change in bulk density. Soil porosity analysis showed that compaction did not affect the matrix porosity (i.e. microporosity). But compaction of the loess soil created relict structural pores (i.e. relict macropores), only accessible through micropores of the matrix. These relict structural pores could be the reason for the hydraulic properties of the loess soil due to soil management.

Finally, our results show how difficult it is to assess soil hydraulic properties and to define the relationships between compaction, porosity and hydraulic properties in situ. They also provide useful references for simulating water transfers in tilled soil as a function of soil management. This is essential for evaluating the complex effects of tillage systems on the soil water regime.

Détermination expérimentale de la conductivité hydraulique à saturation dans les écosystèmes forestiers sud-camerounais.

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Cette note présente les résultats de l'identification hydrodynamique des sols dans les écosystèmes tropicaux forestiers du Sud-Cameroun. L'essai s'intègre dans la thématique "Transferts hydriques au sein des couvertures d'altération. Atelier Zoétélé-Cameroun" inscrite dans le programme international intitulé "Dynamique des sols et environnements tropicaux forestiers" soutenu par l'IRD, le CNRS et auquel sont associés de nombreux partenaires camerounais. L'objectif final est de déterminer, à travers une approche pluridisciplinaire en géosciences, les mécanismes principaux qui ont lieu dans les forêts tropicales humides et d'établir les bilans d'eau et de matières à l'échelle d'un bassin versant représentatif. Notre contribution à la stratégie est l'étude du mouvement de l'eau et de solutés dans les complexes latéritiques de la zone non saturée.
Le bassin versant situé à Nsimi (Zoétélé, Sud-Cameroun) est représentatif des environnements rencontrés dans le plateau sud-camerounais : collines basses (700 m d'altitude moyenne) à versants convexo-concaves qui en font un "modelé en demi-orange" caractéristique, sols latéritiques jaunes rouges très profonds, tandis que l'activité anthropique reste faible. Le climat est de type équatorial à 4 saisons, avec une pluviométrie moyenne annuelle comprise entre 1600 et 1700 mm pour une évapotranspiration potentielle de l'ordre de 1300 mm. Les températures moyennes mensuelles varient peu autour de 23.5 °C.
La méthode mise en œuvre utilise l'infiltromètre à double anneau pour la détermination de la conductivité hydraulique à saturation. Le principe consiste à mesurer l'infiltration (verticale) de l'eau dans le sol. Les données sont exprimées soit sous forme d'infiltration cumulée ou de vitesse d'infiltration en fonction du temps, soit sous forme de profils. La validité des calculs repose sur la vérification de certaines hypothèses, notamment l'uniformité du profil initial d'humidité, l'homogénéité du sol et l'absence de modification du réseau poral par colmatage ou gonflement.
Les courbes d'infiltration cumulée montrent une forte courbure à l'origine, suivie d'une portion rectiligne pour des temps d'essai longs. De ce fait, les vitesses d'infiltration sont décroissantes depuis l'origine et tendent pour des temps longs vers une valeur constante assimilée à la conductivité hydraulique à saturation. Les profils montrent des valeurs très variables suivant la profondeur prospectée, tant au sommet qu'à mi-versant. On remarque en particulier une décroissance des valeurs avec la profondeur. A l'échelle du bassin versant, la variabilité spatiale est également mise en évidence. Ainsi, on passe des valeurs moyennes proches de 50 cm/h dans l'horizon humifère de surface à 6 cm/h dans l'horizon nodulaire. L'une des particularités des profils réside donc dans le contraste élevé de conductivité hydraulique entre les horizons humifères et organo-minéraux de surface et ceux argileux humides plus profonds. La forte conductivité en surface peut être due à la forte porosité biologique et interstitielle à

travers la mise en culture, le développement racinaire et l'activité termitique ; il en résulte une porosité élevée, associée à un fort taux de matière organique. La diminution de la conductivité hydraulique avec la profondeur est due essentiellement à la modification des caractéristiques physiques : baisse de la porosité, diminution de la profondeur d'enracinement et de la matière organique, augmentation du taux d'argiles.
La combinaison des mesures de conductivité hydraulique à saturation, de l'étude des intensités de pluie, du niveau piézométrique, des enregistrements de l'écoulement et du comportement de la zone non saturée permettront d'appréhender la dynamique globale de l'eau à l'échelle du bassin.

Mots clés : infiltration, conductivité hydraulique, vitesse d'infiltration, lame d'eau, porosité, forêt, sol, saturation.

Field evaluation of drainage, actual evapotranspiration and capillary rise using Time Domain Reflectometry (TDR) under growing corn

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For a long time the sandy upland soils of northeast Thailand have been regarded as infertile because of their poor exchange properties and low nutrient content. However, recent studies have proved that soil compaction is also a major problem, as it prevents the roots from extending more than 30 cm in depth. The climate is characterised by a long dry season (October to April) and several dry spells during the rainy season (May to September). Field observations did not reveal any water logging of the soil, even a few hours after heavy downpours. We hypothesised that the compact layer (between 20 and 40 cm depth) was a major constraint for root growth and subsoil water use but not for drainage or capillary rise. In order to test these hypotheses under a growing crop, an experiment was carried out at Korat Experimental Station (15°N, 102°E) where the soil has low nutrient status and a compact layer .

The experiment monitored the variations of the total soil water content and the hydraulic head profiles for four months under growing corn. A Time Domain Reflectometry (TDR) system (TRASE BE, Soilmoisture corp.) equipped with a multiplexer was used to measure the soil water content every 30 minutes. Twelve waveguides were installed vertically in a 9-m^2 plot (at 0-10, 10-20, 20-30, 30-45, 45-60 and 60-90 cm depths). Field calibration used the gravimetric method. Two sets of tensiometers (at 10, 20, 30, 45, 60 and 90 cm depths) were installed in the same plot and monitored twice a day using a pressure transducer (SDEC system) to determine the hydraulic head. A Campbell automatic meteorological station recorded the amount of rain every five minutes and determined the parameters needed to calculate Penman potential evapotranspiration. After harvest, bulk density was measured in the plot using the cylinder method (110 cm^3); the root system of the corn was described using the grid method .

A simple water balance was used: *Total soil water content change = Rain + Capillary rise - Drainage - Actual Evapotranspiration*

The data were split between day (6 a.m. to 6 p.m.) and night values. Using the meteorological data we demonstrated that from 6 p.m. to 6 a.m. the actual evapotranspiration was insignificant due to zero solar radiation, low wind speed (< 0.2 $m.s^{-1}$), and high relative humidity (around 90%). The change in total soil water was calculated for each 12-hour period. Initially, only night data were used.

TDR results and hydraulic head profiles highlighted four periods of water flow with time. A drainage period occurred for a few days after rainfall, when the soil water content decreased during the night. Then, a zero drainage and zero capillary rise period followed for two days when the soil water content remained constant during the night. Then a capillary rise period appeared and lasted, sometimes for several weeks, when the soil water content increased during the night. We used this suite of data to calculate the soil water content changes induced by drainage and capillary rise in the different layers. Capillary rise stopped when the soil volumetric water content decreased to about 0.04 $m^3.m^{-3}$ in the topsoil, probably when the capillary link broke.

During the zero drainage and zero capillary rise period, we considered that the decrease in soil water content in the first 30 cm during the day was the actual evapotranspiration (as the root

system was confined to the first 30 cm). Cultural coefficients were calculated from the daily actual evapotranspiration values and daily Penman potential evapotranspiration values. Then, using Penman potential evapotranspiration values and the cultural coefficients at the different physiological stages of the crop, we estimated the actual evapotranspiration for the whole cycle. To make this estimation, we used the water balance during the day (6 a.m. to 6 p.m.), taking drainage fluxes and capillary rise into account.
The Time Domain Reflectometry system, thanks to a short monitoring period, permitted us to quantify in the field, under a growing plant, drainage, capillary rise and actual evapotranspiration. Drainage values, root description and bulk density determinations confirmed the hypothesis that the compact layer is an obstacle to root penetration but not to infiltration. The unsaturated conductivity of the different layers showed that even the average heaviest yearly downpour (80 mm) was completely drained in less than three days, with most of the infiltration occurring in the first five hours. Capillary rise (between 1 and 3 mm per day) made a large contribution to plant water use, despite the poor rooting depth, until about 0.04 m^3 m^{-3} of volumetric water content; then the plant died. This observation changed our approach to plant available water and root extraction close to compact layers. It is probable that poor plant growth not only resulted from plant water stress but also, to a great extent, from nutrient deficiencies or toxicity.
Keywords : Drainage, Actual evapotranspiration, Capillary rise, TDR, Sandy soil, Corn.

Modelling of saturated hydraulic conductivity from water retention characteristics

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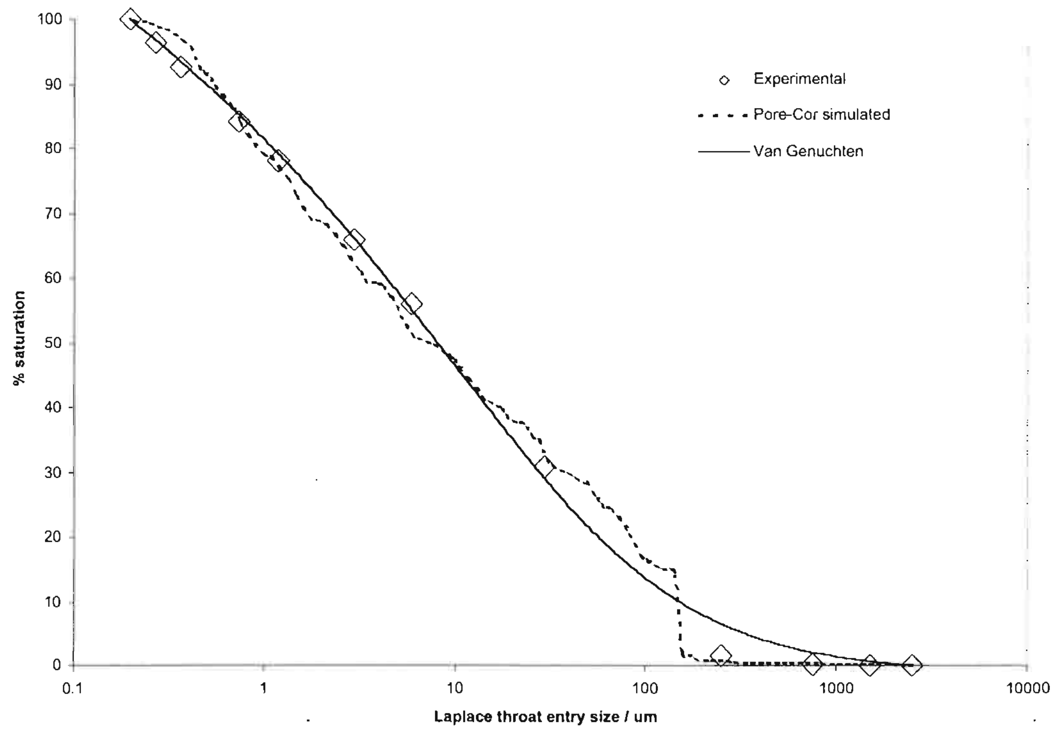
Abstract
In this poster, we will describe preliminary work carried out to provide improved modelling of soil hydraulic properties. Rather than using analytical equations, we generate a three-dimensional void network with the same water retention characteristics as the experimental sample(Peat et al., 2000). The hydraulic conductivity is then calculated by finding the total flow capacity of the individual elements of the network, the fluid flow through each individual element having been calculated by a parameterised Navier-Stokes equation. The approach has four main advantages: (i) it avoids the arbitrary nature of the traditional fitting curves used to smooth experimental water retention curves, (ii) it allows visualisation of the three-dimensional void network, (iii) it allows characterisation of the void structure in terms of useful quantities such as degree of structuring, void size distribution and connectivity, and (iv) once derived, the void network may be manipulated, or filled with more than one different type of fluid or inclusion, to model for example the effect of soil compaction and the effect of oil inclusion on the hydraulic conductivity of a particular soil.

Theory
Traditionally, the relative hydraulic conductivity of soil has been predicted from the soil water retention curve by implicitly assuming a straight capillaric model of void structure – i.e. that the void structure of soil comprises a bundle of tubes, with one end of each accessible to the water entry plane, and the other end of each accessible to the exit plane. The tubes therefore act independently, and there is no 'shielding' or 'shadowing' of large voids by smaller connecting voids, as there is in a random three dimensional network of different sized voids. Van Genuchten (van Genuchten, 1980) proposed that the water retention be expressed by an equation which had the correct asymptotic behaviour but which was otherwise arbitrary, namely:

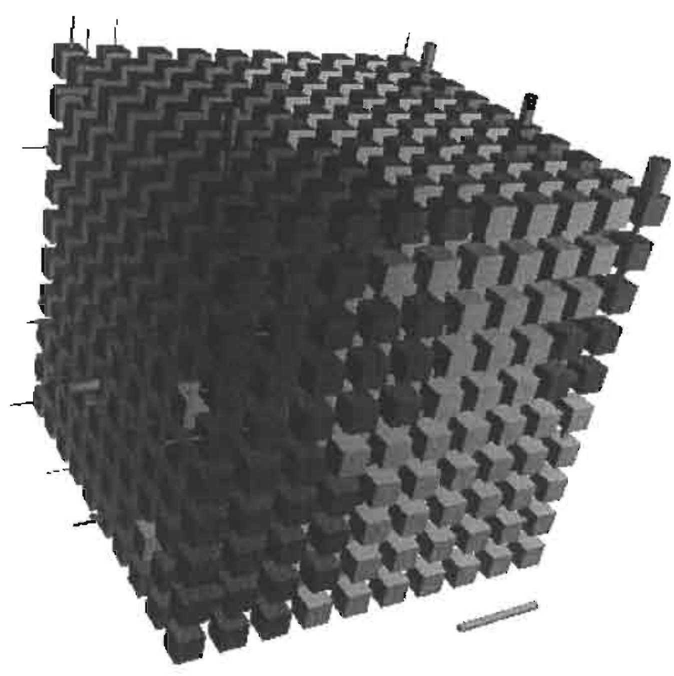
$$\Theta = \left[\frac{1}{1+(\alpha h^n)}\right]^m$$

[3]where a, n and m are fitting parameters. He showed that for the particular case of $k = m - 1 + 1/n$, the equations could be integrated without difficulty. In practice, he used $k = 0$, as $k = 1$ produced an equation much more complicated but only slightly different. He showed good predictions of saturated hydraulic conductivity for four of five soil samples.

Shown below is a comparison of our fitting of a water retention curve for a soil comprising 20% sand, 40% silt and 40% clay. It can be sent hat the Pore-Cor function fits the subtleties of the 'experimental' points at large pore-entry size (low tension) rather better than the Van Genuchten function. The Van Genuchten function is in fact a relatively good fit for pedo-transfer functions curves – for raw experimental data, the improvement in fit is even more marked.



The corresponding Pore-Cor void structure, comprising cubic pores connected by cylindrical throats, is shown below. 50% by volume of the water (shown lighter) has been displaced by air (shown dark), and the scale bar at the bottom is 10 mm.



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Soil structure, water and solute transport: from 3D soil images to particle tracking

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Solute transport is closely linked to hydraulic behaviour. Our research deals first with the determination of soil unsaturated hydraulic properties by collecting information from 3D soil images and by modelling the geometric structure of the pore space, then we investigate computer tools to simulate solute transport in such a context.
Much work has been done in Soil Science to relate hydraulic properties to structural data. From a deterministic and physical point of view, fluid dynamics are fully constrained by the boundary of the void space, but solving the Navier-Stockes within such complex geometry as that of soils is difficult. It needs a lot of power computation and memory. Such attempts have been made in monoscale porous media to predict the saturated hydraulic conductivity by direct solving of Navier-Stockes equations or, using lattice gases simulations in saturated soils (Heijs et all., 1996)Many models have been developed which represent porous media in a simplified approach as a connected set of individualised voids, cylindrical pores or parallepipedal fractures, where simple, integrated forms of the Navier-Stockes equations are available (namely, the Poiseuille Law in cylindrical tubes). In unsaturated conditions, i.e. a soil partially filled with water, the active network is reduced to the smaller, water-filled pores according to the Laplace law and the displacement of air-water boundary with varying capillary pressures. This so-called pore network modelling approach is mainly used in theoretical studies, where a given type of pore network is calibrated by available data, mainly to match a measured pore size distribution (e.g. a given fractal pore size distribution in Perrier et al, 1995). The connectivity of the network has been shown to be crucial, but it is difficult to measure it and different types of modeling assumptions are tested.
We propose a complete framework to actually extract a pore network from nowadays rather easily available 3D soil data. For example computer tomography (CT) provides a new, valuable type of soil structure investigation (Timmerman et al., 1999). A 3D Soil image is first acquired and converted to binary image where the white voxels represent the pore space (a more of less continuous void space) and the black ones represent the solid space. Then a set of computer vision tools (Delerue, 2001) allows to analyse the structure of the pore space. We begin to extract the 3D skeleton of the pore space using a Voronoï based algorithm. This skeleton, gives all local information about local aperture and connectivity. An aperture map is created from this skeleton by mapping balls on the skeleton. This aperture map is a first step in the description of the pore space. Using this map, it is possible to know the local aperture at any point within the pore space.
The next step consists in dividing the pore space in pores. We define a pore as a part of the pore space where all the points belong to the same local aperture class, and which is located between the boundaries of the pore space. A growing area segmentation algorithm is used to actually define these pore objects. Using the skeleton extracted previously, seeds are placed in the pore space. Those seeds consist in maximum balls touching opposite boundaries of the pore space. During the second part of the growing area algorithm, we make those seeds grow in a synchronous way in the pore space until each area reaches boundaries or other pore areas. The result is a partition of the pore space in pores.

For each pore, it is possible to know its aperture, volume, localisation and neighbours. All this information is used to calibrate a pore network model. This model provides hydraulic properties for the whole sample. I.e. it gives the equivalent hydraulic conductivity for the whole soil sample. This pore model also gives local hydraulic properties for each pore, such as local hydraulic conductivity, fluid pressure, flow intensities etc...

All that information, i.e. local hydraulic properties and pore map can then be used to develop a multiagent-oriented approach for solute particle tracking. In this model, two classes of agents are defined: spatial pore agents and moving particle agents. For each pore in the pore map an agent is defined who knows its local hydraulic properties such as local pressure and flow speed as a function of the imposed global pressure gradient. Then particle agents are defined which_know their localisation at any time and physical properties like the amount or type of solute they carry At each time step, each particle moves according to the intensity and direction of the water flow given by the pore where they are located. Up to now this model enables_particle tracking in the pore space using a simple convection model as the pore scale and computing statistics about repartition in the pore space and time needed to go across the whole medium.

However, the agent oriented design is open to lots of extensions : The local direction of particle agent be influenced by local diffusion within the pore or by other simulated physical phenomena. In particular, modelling continuous displacements within the pore space allows to modify particle agent directions when they collide with the interface between solid and void space. Interaction between particle agents could allow particles to split or to merge when two particles collide. Interaction between particle and pore could allow considering probabilities for the particle to be infiltrated in the solid part when particle collide with the void / solid interface. Finally, interaction between pores could allow the model to reorganise itself automatically in case of dynamic modification of the geometry of the pore space. The main originality of the agent-based approach through giving "life" to individualised agents, consists in the straightforward possibility to register individual trajectories and to simulate tracing experiments

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Fractal modeling of unsaturated soil hydraulic properties

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Résumé
La relation entre la conductivité hydraulique d'un sol non saturé et sa teneur volumique en eau est établie sous l'hypothèse que l'écoulement est décrit par la loi de Poiseuille au niveau microscopique et la loi de Darcy généralisée à l'échelle macroscopique. Dans l'émergence de cette dernière loi, une distinction est faite entre les rayons de pore qui définissent une porosité surfacique et une porosité volumique, les relations entre rayons et porosités étant établies à partir du concept de tortuosité et le sol étant considéré comme un objet fractal (Rieu et Sposito, 1991). Cette distinction conduit à proposer un modèle conceptuel de conductivite hydraulique dont on montre qu'il englobe différents formalismes classiquement utilisés dans la littérature.

Abstract
The relation between soil hydraulic conductivity and volumetric water content is established from the hypothesis that water flow at the microscopic and macroscopic levels is described by Poiseuille and Darcy's laws, respectively. In the emergence of the macroscopic law a distinction between pore radii that define areal porosity and volumetric porosity is made. The relation between radii and porosities has been established from tortuosity and connectivity concepts based on the fractal geometry (Rieu and Sposito, 1991). This has led to propose a unifying conceptual model of the soil hydraulic conductivity which allowed to re-examine four simplified models classically encountered in literature . It is shown that these simplifications depend on the soil fractal dimension .

Soil structure and pedotransfer functions

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Soil hydraulic properties have to be estimated to carry out large-scale projects in agronomy, hydrology, and remote sensing. Estimations are made using pedotransfer functions (PTFs), i.e., regression equations to relate hydraulic parameters to basic soil properties available from soil survey. Presently, pedotransfer functions are developed from 5-cm laboratory samples with input data taken from laboratory soil analyses. Soil information from scales other than the laboratory one, i. g., from maps and field soil descriptions, has to be used in large area estimates. As resolution grows coarser, one may encounter changes in (a) values of soil hydraulic parameters measured at different scales, (b) soil hydraulic properties used in models at various scales, (c) soil basic properties suitable to for predicting hydraulic properties, (d) subgrid variability of basic and hydraulic properties. The objective of this work was to present examples of using scaling in soil structural parameters to relate hydraulic and basic soil properties across scales.

The need to correct soil hydraulic properties according the scale is demonstrated with a large UNSODA set of data on water retention of laboratory samples coupled with water retention measured in the same soil in the field. Coarse-textured soils have the average difference between field and laboratory water contents close to zero. Fine-textured soils with sand contents less than 50 % have field water contents substantially smaller than the laboratory water contents in the range of water contents from 0.45 to 0.60. A polynomial regression explains 70% of variability in field water contents as computed from the laboratory data. Fractal scaling of the bulk density proposed by Rieu and Sposito can explain the observed «field – lab» differences in volumetric water contents. PTFs built from the laboratory water retention data can overestimate available water content, and underestimate saturated hydraulic conductivity and sorptivity values.

At coarser scales, the textural class is most often used to estimate soil water retention. We selected 2100 samples the USA soil characterization database to see which field-estimated and available from soil survey structural parameters can augment the textural class to provide better estimates of soil water retention. Regression trees were used to incorporate categorical information about textural and structural parameter classes in the PTFs. A statistically significant improvement was achieved with adding soil grade class (weak, moderate, strong) to the textural class. Soil grade can be quantitatively characterized by scaling exponent of soil aggregates. Model of scaling in soil aggregates suggested by Rieu, Perrier, and Bird has a potential to supply parameters to improve water retention PTFs.

As scales became yet coarser, only the predominant textural class is often available for estimation of soil hydraulic properties. Field determination of texture is error-prone. Structure of soil cover instead of structure of soil pedons becomes a promising additional PTF input. We hypothesized that this structure can be indirectly characterized by topography and including topographic information in water retention estimation may increase the accuracy. To test this hypothesis, we extracted data on soil pedons for soils of moderate and large extent from the NRCS soil characterization database. Textural class was determined in the field correctly only for 50% of those pedons. Textural classes, genetic horizon numbers, slope gradients, slope position classes, and land surface shape classes were the field-defined variables that we used to estimate water retention at -33 and -1500 kPa potentials for each horizon in each pedon. Because our input variables were both categorical and continuous, regression trees were used to subdivide the samples into the smallest number of the most homogeneous groups, that we tentatively called topotextural groups (TTG). Using TTGs leads to a statistically significant but small improvement in the accuracy of the water retention estimates. TTG encompass broader textural groups and have an advantage of lesser demand to the accuracy of soil texture.

Structure of soil cover can be reflected in scaling of soil basic properties used in PTF. To research this scaling, we used the MUUF/MIADS database that provides properties of 60 individual soils found in the Little Washita watershed, Oklahoma where the Southern Great Plain experiments on remote sensing of soil moisture have been carried out. Soil basic properties, that are used in PTFs, demonstrated fractal scaling within the range of resolutions from 0.2 to 7 km. Clay contents scales similarly to cation exchange capacity, and sand content scales similarly to the organic matter content. Multifractal model described this scaling. The presence of scaling allows using

a Markovian cascade model to simulate fractal fields of PTF inputs for purposes of estimating subgrid variability of soil properties, assimilating data obtained at various resolutions, and interpolating/extrapolating in space/scale.

In summary, soil structural properties provide an important information to improve soil hydraulic properties estimates at various scales, to define scale-related corrections for such estimates, and to assimilate soil data obtained at different resolutions for the purpose of estimating soil hydraulic properties.

The pore solid fractal model and soil density scaling

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Variations of soil density and soil porosity with scale have been reported by soil scientists for many years. Modellers have sought to explain these observations in terms of fractal models of soil structure. Two forms of mass fractal have been proposed yielding opposing scaling behaviour. The solid mass fractal describes a porous material with a density which decreases and a porosity which increases with increasing sample size. In particular mass and density scale as powerlaws. This model has found favour as a descriptor of soil aggregates (Young & Crawford; Rieu & Sposito, 1991; Anderson & McBratney, 1995). Conversely, the pore mass fractal describes a porous material with a density which increases and a porosity which decreases with increasing sample size. In this case the porosity scales as a powerlaw. The solid mass fractal exhibits a powerlaw pore-size distribution whereas the pore mass fractal exhibits a powerlaw particle size distribution but neither can represent both solid and void scaling distributions. The two models need to account for a lower cut-off of scale since they are seen to fail immediately if this lower bound is not present, yielding porosities of one and zero respectively.
The Pore Solid Fractal (PSF) model (Perrier, Bird and Rieu, 1999; Bird, Perrier and Rieu, 2000) of soil structure is an extension and generalisation of the fractal approach to modelling soil structure, in which a range of particle sizes and a range of pore sizes are incorporated in a common geometric model. Solid and pore mass fractal models appear as special cases of the PSF. We have already shown that the PSF can be used to model several other scaling properties such as fractal pore-solid interfaces (Perrier et al., 1999) as well as observed distributions of aggregates in a fragmentation process (Perrier and Bird, 2001). The PSF can be developed at arbitrarily small scales without exhibiting unrealistic bulk densities and porosities but, as for the mass fractal models when developed ad infinitum, the latter properties are scale independent. Scale variant bulk densities can be modelled by simple modifications to the PSF. One is to relax self-similarity (Rieu, unpublished work). In this communication we simply consider the existence of a lower cut-off of scale. Any soil system exhibiting scaling of structure must exhibit a lower bound to this scaling. We may take the smallest particle size as an absolute lower bound. By incorporating a lower bound we create a model with either increasing, constant or decreasing bulk density with increasing sample size, depending on the density of structure at scales smaller than that of the PSF regime. This provides a unified approach to modelling density and porosity scaling within the framework of the PSF, and we derive a new expression for density scaling, which reverts to existing forms with selection of parameter values associated with mass fractal models.
In the second part of this communication we consider the link between structural and hydraulic properties. We show that the general expression obtained to describe density scaling is closely related to the general expression for the retention curve already derived for the PSF model (Bird et al., 2000) or for any fractal pore size distribution (Perrier at al., 1996). It involves the same parameters, thus through this link we may infer the water retention function from bulk density scaling and vice versa. In particular we show that the widely adopted Brooks-Corey equation for water retention is associated with a scale invariant density. Conversely, if density varies with scale, the retention curve cannot follow a simple powerlaw,

and one has to account for the porosity of the medium at scales smaller than that of the fractal or PSF regime.
The third part deals with application of our theoretical concepts to data. We show that the general equations easily fit either aggregate bulk density data or retention data; but no data are available both on bulk density and retention over a large range of scale. Density data are available by means of aggregate weighing only at rather large scales. How actually does soil bulk density scale in soils? Further experimental research should be carried out using image analysis, but several conceptual errors may arise.
In conclusion the PSF approach appears now as a general, simple way to represent in the same framework several major structural soil scaling properties and to go beyond conventional fractal models of multiscale soil structure. Further generalizations of the PSF are possible and attractive with a view to developing an operational model. In particular we may relax self-similarity imposed on the system thus allowing bulk density to pass through different scaling regimes and exhibit non-monotonic scaling behaviour.

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A multiscale fractal analysis of silty topsoil structures

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Spatial heterogeneities in soils occurred at different observation scales, from the particle and elementary microaggregate size (nearly 10^{-6} to 10^{-1} mm) and the microstructure size (nearly 10^{-2} to 10^{2} mm) to the slope size (10^{4} to 10^{6} mm). Scale invariants such as fractal dimensions are therefore useful parameters for describing such multiscaled hierarchical heterogeneities but it is difficult to marry different yardstick and observation scales.
In this study the fractal approach was applied to soil structure analysis (e.g. Rieu and Perrier, 1998; Bartoli *et al.*, 1998) of (i) two silty topsoils of a toposequence located 80 km East from Paris, France, and sampled in April, June and August 1993 and (ii) a silty topsoil of the Tarrawarra catchment located in Southern Victoria, Australia, and sampled in August 1997.
For the french topsoils, macrostructure was analysed on photographs, 40 mm square, with a resolution length of nearly 0.1 mm, of vertically oriented soil blocks under ultraviolet light (Uvitex OB dye) whereas its microstructure counterpart was analysed on backscattered scanning electron micrographs (5 millimetre square zone replicates without cracks were selected randomely from each soil thin section within a 1-cm^2 network), 400 _m square, with a resolution length of nearly 0.5 _m, of the thin sections closely associated to the analysed soil block planes. Analysis of the binary images included the square box method and the chord length non-biased method, applied after sequential linear morphological erosion, for computing both matrix and its complement, porosity, as a function of either the observation scale, R, or the yardtick scale, r, respectively (see, e.g., Bartoli *et al.*, 1999).
For the australian wet gradational topsoils, 15 sites were selected within a 140 m thalweg transect characterized by a low slope of 5 %. On each site, 8 cubic undisturbed soil monoliths of increasing size from 14 mm to 140 mm were sampled. Total porosity, drained macroporosity and water-filled microporosity at « field capacicity » were determined. Image analysis of macrostructure was also carried out on the 84 mm size resin-impregnated monoliths (see above), with 2 serial vertically oriented images per monolith, separated by an horizontal distance of 10 mm.
The main results were as follows.

1. The mean total porosities of the french silty topsoils which were calculated from the balance sheet of image data (photographs of soil blocks and SEM micrographs of thin sections) were in the same order of magnitude (less than 10 % of discrepancy) than the mean total porosities computed from bulk density determined on 250 cm^3 cylindrical cores (6 replicates). This allowed us to combine the image data obtained at two combined observation and yardstick scales (e.g., fig. 1).
2. Embedded macro-and micro-structures of each selected french silty topsoil were both characterized by a solid mass (matrix) fractal domain within a short R range (1 and 3 domains of figure 1) followed by a representative porous medium volume (RPMV) domain (2 and 4 domains of figure 1). The fractal behaviour of the matrix was also much more pronounced in the microstructure than in its macrostructure counterpart (fig. 1).

3. Although the micropore size distribution was narrow, a solid D_m (r) value was extracted from each mean chord length analysis and was often in the same order of magnitude than its D_m (R) value counterpart (mean square box method), without significant temporal variation.

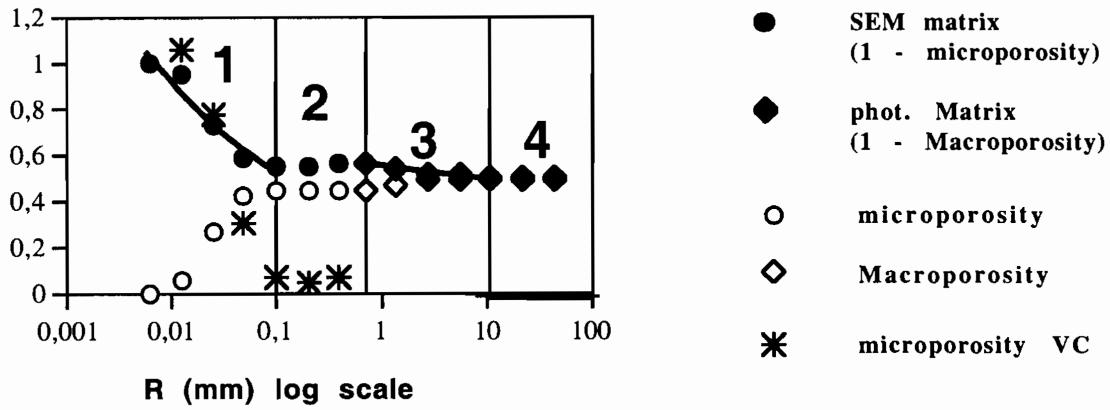

Figure 1 : Plateau silty topsoil sampled in April 1993: soil matrix, micro and macro-porosity and microporosity variation coefficient as a function of observation scale, R. Power law coefficients of the mass fractal 1 and 3 domains : - 0.243 and – 0 .043 ($p < 0.01$) leading to Dm values of 2.76 and 2.96, respectively.

4. Mean total porosities of the australian silty topsoils and their variation coefficient counterparts were nearly constant whatever was the observation scale (porosity of 0.47-0.49 $cm^3.cm^{-3}$ and VC of 3-7 %). Then, 14 mm size cubic monoliths was already a RPMV for this soil type. In contrast, the lower R limit of the RPNV domain was 84 mm for both the drained macroporosity and the water-filled microporosiry et « field capacity ».
5. For the same R range, image and drained macroporosities were in the same order of magnitude. This validated the hypothesis that mobile water was associated with crack networks, observed and quantified on soil block photographs. Mean macroporosity increased from 0.26 to 84 mm R value because its matrix complement followed a fractal law (D_m = 2.99). Conversely, the macroporosty variation coefficient non-linearly decreased from 138 to 16 %. As a complement, mean water-filled microporosity at « field capacity » (low VC of 2 to 6 %) decreased from 14 to 84 mm, following a fractal power law (D_p = 2.95). Although this micropore fractal law should be validated for a wider observation scale it should be only attributed to the observed complementary increase of macropore network porosity (and connectivity) as a function of obervation scale.

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Multifractal measures and microstructure of natural porous media

P. Baveye

Missing abstract

Flow patterns of polymer solutions injected into dispersions of Bentonite

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It is known, that many detergents contain polymers, mostly polyacrylates, in order to prevent the formation of carbonate crusts in washing machines. In sewage plants these polymers are removed from the waste water by adsorption to the sewage sludge. However, as many investigations have shown, these substances are only slightly biodegradable.

In model experiments we investigated, if the penetration behaviour of water into clay dispersions is influenced by these polymers when added to the penetrating water. For comparison purposes natural polymers, mostly polysaccharides, were used as well. The investigations were carried out in a so called Hele-Shaw cell. In this experimental set-up, the clay dispersions are located in a gap between two horizontally arranged glass plates. The width of the gap was roughly 140 μm. The water or the polymer solutions were injected into this gap through a hole located in the center of the upper glass plate.

The developing flow patterns were photographed with a high resolution digital camera. After binarisation these patterns were measured by means of a computer based image analysis system. Several morphometric parameters like the fractal dimension, the roundness, the compactness and the branching number and density were determined. In addition, the developement of these patterns with injection time was measured.

We found, that the penetration behaviour of the polymer solutions was influenced by the chemical structure and the molecular weight of the polymers used. Acidic polyacrylates as well as maleic-acid/arcylic-acid copolymerisates had a destabilizing effect on the dispersions. Cationic polymers has a stabilizing and coagulating effect This we concluded from the changes in the different morphometric parameters of the patterns.

We therefore conclude that in soils the aggregation behaviour of clay particles might be changed by the synthetic polymers and should thus be considered in environmental investigations of these substances. In order to quantify these effects we propose to use Hele-Shaw cells coupled with image analysis.

Fractal dimensions of soil properties as measured by image analysis

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Introduction

Soil structure has been the object of investigation of soil scientists for a long time. Usually, the methods used are destructive (e.g. for obtaining the particle size distribution) or indirect (e.g. concluding pore size distribution from obtaining the retention curve). Image analysis techniques yield a powerful tool for directly investigating the structure of a soil. Once digital images are available, arithmetic, morphologic and boolean operations can be carried out easily. The system used for image analysis (KS400, ZeissVision, Jena, Germany) allows the implementation of user-defined macros. The object of investigation was the pore-solid interface and the pore size distribution, respectively. The fractal dimension D_S of the pore-solid interface expresses the relationship between pore size and particle size distributions (Perrier et al. 1999).

Material and Methods

Undisturbed soil samples from the Bt horizon of a Luvisol were impregnated with resin and thin sections were prepared. From these, field emission scanning electron microscope images (Leo Gemini 1530, Zeiss, Oberkochen, Germany) were obtained for resolutions from 2.50 up to 0.05 µm/pixel. A signal combined of backscattered and secondary electrons clearly yields distinct grey values which allow a sharp segmentation into pores and matrix. The fractal dimension of the pore-solid interface was measured with the box counting and the dilation procedure (Eins, 1998; Dathe et al., 2001). The pore size distribution was measured with the opening procedure. Step sizes for the structuring element increase by two pixels for every measurement step. From the same soil, particle size distribution, bulk and particle densities were measured with classical soil physical methods. Additionally, water retention and conductivity curves and the saturated conductivity were obtained.

Results and Discussion

Results are shown for 82 (Fig. 1) - 97 (Fig. 2) images obtained with five different magnifications from one thin section. The orientations of the thin sections were horizontal and vertical, respectively. The fractal dimension (D) for the lowest magnification is very high with values of about D=1.915. With increasing magnification, D decreases towards values of D=1.563. This unexpected finding is the difference between textural and structural fractality (Orford and Whalley, 1983). To obtain the limit between these two domains, a robust technique (local M-estimates and optimising the absolute derivation) was used to fit two straight lines for the adjusted data from one thin section (Fig. 1) and the crossover points were calculated. The values for the size of the corresponding structuring element reach from 11.13 µm up to 16.60 µm for the series Leo7 and Leo8 (not shown).

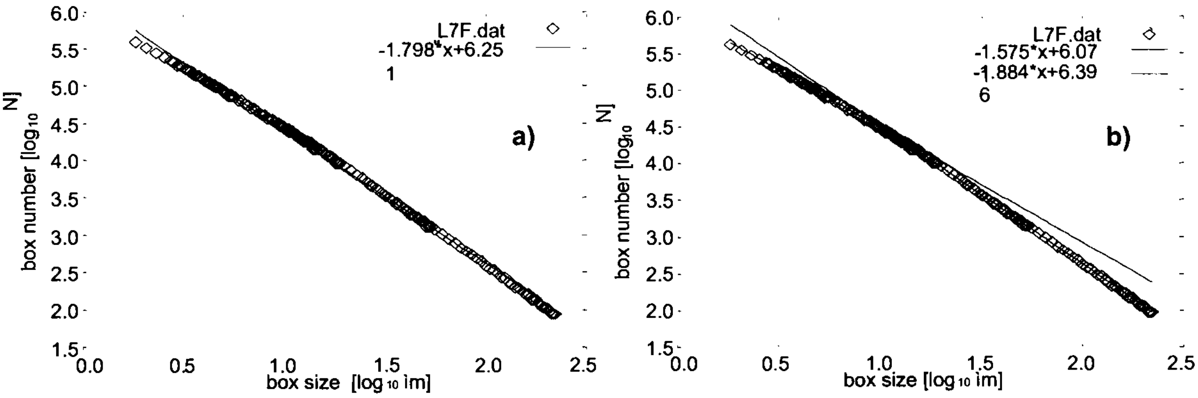

Fig.1: Adjusted combined data pool of the series Leo7 (vertical), measured with the box counting procedure.
(a) One straight line has been fitted using local M-estimates. (b) Two straight lines have been fitted and the crossover point has been calculated by minimising the absolute deviation.

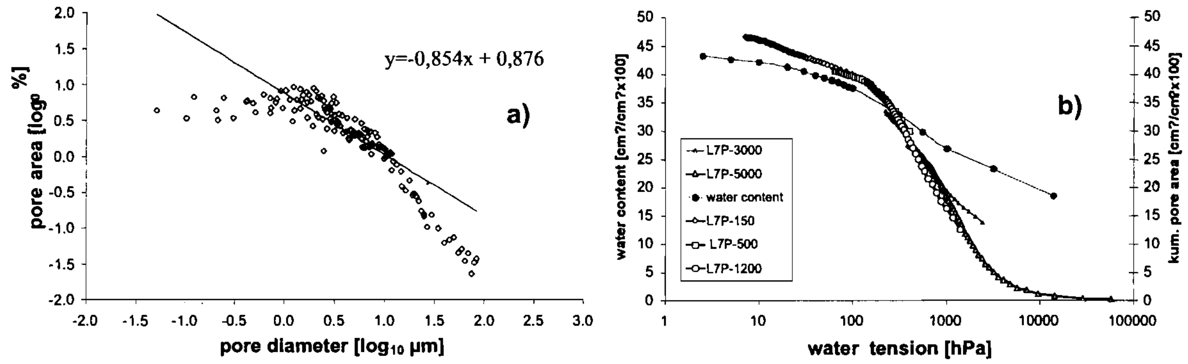

Fig. 2: Pore size distribution for the series Leo7 (vertical), measured with the opening procedure. The values are the means of 19 - 21 images for each resolution. (a) Distribution of pore diameters as log-log plot. (b) Cumulated pore size distribution in comparison with the retention curve which has been obtained at the same soil horizon. To obtain the cumulated distribution, the values have been added where the coefficient of variation of the next higher magnification is smaller than 1 (cv<1).

It is obvious, that (i) the pore size distribution shows a similar behaviour in the sense of higher complexity for an increasing size of the structuring element, and (ii) the cumulated pore area shows a different slope for small pores as could be concluded from the retention curve (Fig. 2). This phenomenon can be explained by the ink-bottle effect, the retention curve additionally grasps the connectivity of the pore network (cf. Bartoli et al., 1999). The change of the fractal dimension of soil properties with the size of the probe used for investigation has been observed by other authors, too (cf. the review of Anderson et al., 1998, chapter III.C). It is difficult to distinguish such a non-linear behaviour in a log-log plot from the influence caused by resolution (Ogawa et al. 1999) and pixel roughness, which can be averaged by choosing a lower cutoff.

Conclusions

The results obtained for the fractal dimension of the pore-solid interface show a higher complexity for images with low magnifications. These images catch the pore network, while images with a high magnification show the surface of single particles. Comparing the retention curve with the pore size distribution shows that the retention curve overestimates the proportion of small pores. The reason is the connectivity, which is included while obtaining the desorption curve in three dimensional space, and is not grasped by measuring the pore size distribution in two dimensional space. The question, how different fractal domains of geometry observed in one soil at different scales can be included in models for estimating water retention and conductivity, requires to be solved.

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A fractal approach to calculate thermal conductivities of soils

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Pore-Solid-Fractals with three generators

Heat conductance of soils depends on the geometrical arrangement of soil minerals, ice, air and water. All soil constituents concduct heat. Therefore, to predict thermal conductivity of porous media, it is not sufficient to characterize the pore space, only. We need a model that describes the pore space *and* the complementary solid matrix.

The Pore-Solid-Fractal approach (PSF) presented by Perrier, Bird and Rieu [1999] models pore- *and* particle-size distributions.

With the PSF-approach it is not possible to describe a wide range of pore- and particle-size distributions. Recently, Bitelly et al [1999] showed that a combination of three different power-law distributions or three different fractal dimensions is needed to characterize any particle-size distribution. Therefore, we extended the PSF-approach by the application of three different generators (3G-PSF). Each generator is applied for a finite number of iterations. With the 3G-PSF approach, we modelled succesfully the porosity and the particle-size distribution of a loamy sand, a silt loam, a clay and a clay loam. The prefractals that charaterize the four soil materials were used to calculate the thermal conductivities for different saturation conditions.

Thermal conductivities of the prefractals

We used the analogy between Ohm's law of electricity and Fourier's law of heat conduction and constructed a network of resistors. The resistance of each soil component was equivalent to the inverse of the thermal conductivity.

For each scale of the prefractals we calculated the effective thermal conductivity and used a renormalization approach to include the effects of smaller scales. For partially air-filled conditions, small pores were filled with water or ice, while larger pores were filled with air. For frozen soils, the volume expansion of liquid water must be included, so pores with an air-filled core and an ice-coating may exist. Under unsaturated conditions, heat exchange is dominated by the limited contact conduction between particles. We included this effect with a reduced heat exchange coefficient for particles under air-dry conditions.

The calculated thermal conductivities of the prefractals were compared with the Johansen' model [1977], a well-proven empirical model to predict thermal conductivities of soils.

The conductivities based on the fractal approach were very similar to the empirical approach. In a next step, we investigated the influence of the geometric arrangement of pores and solids.

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Number and size of anoxic patches in a fractal model of soil

C. Rappoldt, J.W. Crawford

The oxygen concentration is an important factor in a number of biological and chemical soil processes. Mineralization of organic matter, oxidation of organic pollutants and nitrification require oxygen. Denitrification, the reduction of nitrous oxide and methane production take place in anoxic parts of the soil. There is also coupling between aerobic and anaerobic processes by means of diffusion through the transition zones, convective transport and changes in the size of the anoxic spots. A well-known example is the coupling between nitrification and denitrification. A consequence of the induced heterogeneity is that different selection pressures operate on microbial populations at just a few millimeters apart.

Previously (Geoderma 88:329-347) we have studied the distribution of oxygen in a fractal structure. We used a random Cantor set consisting of gas-filled pores and water-saturated soil matrix. The gas-filled porosity can be increased by adding another recursion level to the structure, which creates a new class of small pores. Simulations were carried out for three-dimensional lattices consisting of many random realizations of basically the same fractal structure. Oxygen diffusion (in pores and matrix) in combination with a homogeneous soil respiration (in the matrix) leads to a stationary state in which there is a large-scale concentration gradient associated with the average soil respiration rate and bulk scale diffusion.

The local diffusion-respiration process is characterized by a process length __ whichdepends on the average oxygen concentration in the pores, the oxygen demand and the diffusion coefficient of the water-saturated soil matrix. During the simulation, anoxic patches develop and their distribution appears to be almost completely determined by the presence or absence of pores which are not connected to the surface. Further, the results consistently show that the anoxic volume fraction decreases faster than exponentially with the process length _. This fast decrease implies that large anoxic patches are relatively rare, which is confirmed by the results reported in this poster.

The dominant role of surface-connected pores is the natural consequence of the low oxygen diffusion coefficient in water (10,000 times lower than in air) in combination with the low solubility of oxygen (another factor 30). As a consequence, local differences in oxygen concentration in the surface-connected pores are small compared to the gradients in the disconnected (and potentially anoxic) patches. This implies that methods designed for dual-porosity systems can be applied to the fractal structure. The surface-connected pores act as "macropores", responsible for bulk scale transport, and the small-scale diffusion-respiration process takes place in the water-saturated matrix. We used the method described in Transport in Porous Media (37:1-24). After determining which pores are disconnected from the surface, for each point of the lattice the distance to the nearest connected pore can be determined. This distance distribution indeed leads to a good approximation of the anoxic fraction. Clearly, the difference with a real dual-porosity system is that the structure (and the size of the disconnected patches) drastically changes if the gas-filled fraction of the soil changes.

The distribution of the distance to the nearest connected pore confirms that large disconnected regions are rare. Hence the fast decrease of the anoxic fraction with process length is indeed a purely geometrical effect. For a sufficiently large value of the process length the disconnected patches all become oxic and virtually no anoxic soil is left.

The advantage of the approximate method is that much larger lattices can be handled than in a simulation model. We used the approximate method to study the effect of water content on the anoxic fraction, which requires large lattices with 4 or 5 different pore sizes. For a low water content, the anoxic fraction is obviously close to zero. With increasing water content the anoxic fraction starts to rise slowly, but suddenly, the disconnected patches span the structure and the soil becomes largely anoxic.

The coupling of aerobic and anaerobic processes will be associated with the surface of anoxic patches rather than with their total volume. Therefore, as long as the anoxic patches do not span the structure, their number and their size distribution are also quantified as function of water content. Results are shown on the poster for two different fractal dimensions in order to explore the aeration properties in combination with a "sand-like" and a "clay-like" water retention curve.

Modifications du milieu et conséquences hydrologiques dans la Sierra Madre Occidentale (Mexique). Des résultats expérimentaux et répercutions régionales

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Résumé
Les impacts des changements du milieu modifier le régime des écoulements. Cependant, si les transformations sont progressives dans le temps et diffuses dans l'espace (surpâturage, déforestation, urbanisation, etc.), les répercussions hydrologiques ne sont pas toujours perceptibles de manière très nette.
La Sierra Madre Occidentale a subi une dégradation progressive (surpâturage et déforestation) depuis quelques décennies. Elle présente un climat subtropical avec une longue saison sèche dans l'année (8 à 9 mois), et des sols peu épais (Phaeozems et Lithosols essentiellement). La couverture végétale de cette zone montre un état de dégradation très significatif. Les forêts ont été réduites de plus de 50 % de 1972 à 1992 à cause du déboisement. De même, le surpâturage a laissé des traces dans le paysage : des terrassettes, des versants caillouteux, des zones encroûtées.
Dans le présent travail sont présentés les résultats de plusieurs stations hydrométriques (bassins versants expérimentaux, parcelles, microparcelles et tests d'infiltration) qui nous ont permis d'élaborer des explications sur le fonctionnement hydrodynamique de la zone. Nous nous intéressons également à la recherche de tendances des régimes hydriques des principales rivières du haut bassin du Nazas. Quelques paramètres du comportement hydrodynamique sont proposés comme indicateurs des modifications du régime hydrique au niveau régional.
En général, l'ensemble des caractéristiques physiques et des observations expérimentales expriment un comportement typiquement hortonien. Par ailleurs, les observations expérimentales portent à croire que la surexploitation du milieu dans le haut bassin du Nazas favorise les écoulements de la zone. Par contre, les résultats de tendances des pluies et des écoulements des deux principales rivières de la zone d'étude ne montrent pas de tendances définies à la hausse ou à la baisse. Apparemment, contrairement à ce que l'on observe à l'échelle de la parcelle, la déforestation et le surpâturage de la Sierra Madre Occidentale n'ont pas modifié les coefficients d'écoulement annuels des rivières. Les effets locaux ne sont pas nécessairement observés à l'échelle régionale du fait de la grande variabilité spatiale et temporelle du milieu. Cependant, d'autres indicateurs du comportement hydrodynamique de la zone d'étude présentent certaines tendances :

- la comparaison entre les coefficients d'écoulement de base et de crue montre une diminution de l'écoulement de base. Apparemment, les crues prennent de plus en plus de place dans les hydrogrammes des bassins.
- la diminution des temps de réponse des bassins. Cela signifie que la transformation de la pluie en débit devient de plus en plus rapide.
- le degré de participation de l'humidité préalable du milieu corrobore aussi les observations précédentes. Apparemment, les temps de ressuyage des sols diminuent.

D'après l'ensemble des observations, les transformations physiques de l'espace, dûes à la surexploitation du milieu, sont responsables de la modification du régime hydrique de la Sierra Madre Occidentale. Les différents indicateurs utilisés (comparaison des coefficients d'écoulements de base et de crue, temps de réponse et degré de participation de l'humidité

préalable des sols), peuvent être utilisés dans d'autres régions du globe où se pose le problème de la recherche de tendances de comportement hydrique dues à la transformation du milieu. Ces indicateurs peuvent être plus sensibles que les valeurs totales de pluies et d'écoulements.

Abstract

The impacts of environment changes can modifie the runoff regime. Nevertheless, if the transformations are progressive in time and diffuse in space (overgrazing, deforestation, urbanisation, etc.) the hydrologic repercussions are not always dearly perceptible.

The Western Sierra Madre has suffered a progressive degradation (overgrazing and deforestation) since a few decades. It presents a subtropical climate with a dry long season during the year (8 to 9 months), and not much thick soils (Phaeozems and Lithosol soils mostly). The vegetal cover of this zone shows a very significative state of degradation. Forests have been reduced to more than 50 % from 1972 to 1992 because of deforestation. The same as overgrazing has left marks in the landscape : « terracettes », stony slopes, crusted surfaces.

The results of several hydrometric stations (experimental catchment areas, plots, micro-plots and infiltration tests) have allowed us to elaborate explications of the hydrodynamic functioning of the zone. We are interested in the investigation of the hydric regimes of the principle rivers in the High Nazas Basin. Some of the parameters of this hydrodynamic behaviour are proposed as indicators of the changes in the hydric regime at a regional level.

Generally, the ensemble of the physical characteristics and the experimental observations express a typically hortonian behavior. However, the experimental observations lead one to believe that the overexploitation of the environment in the High Nazas Basin facilitate the runoff of the area. Nevertheless the results of the statistical trends of the rainfall and the runoff of the two principle rivers of the High Nazas Basin do not show changes. Apparently in spite of the experimental results, the deforestation and overgrazing of the Western Sierra Madre have not changed the coefficients of the annual runoff of the rivers. The local effects are not necessarily observed at the regional scale because of the high spatial and temporal variability of the environment. Nevertheless, other indicators of the hydrodynamic behaviour of the study area present certain statistical tendencies :

- the comparison between the base-flow and flood-flow coefficients shows a reduction of the base-flow. It appears that the floods take more and more place in the hydrograms of the watersheds.
- the reduction of the lag time of watersheds. This signifies that the transformation of the rainfall in runoff becomes more and more rapid.
- the degree of participation of previous humidity of the environment also establishes the earlier observations . It would seem that the drying time of the soil decreased.

From the compilation of observations, the physical transformations of the area due to overexploitation of the environment are responsible for the change in the hydric regime of the Western Sierra Madre. The different indicators used, (comparisons of the base-flow and flood-flow coefficients, the lag time and the degree of participation of previous humidity of the soil), can be used in other regions in the world where the problem of the search for tendencies of hydric behaviour due to environmental transformation, exists. These indicators can be more sensitive than the total values of the rainfall and the runoff.

Hydrochemical processes in sahelian microdunes: a study using tracers under simulated rainfall

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Introduction

Soil surface sealing is a common feature of most soils in arid and semiarid regions. It reduces infiltration rate, triggers runoff, and hence increases soils erosion. In the sahelian zone of Burkina Faso, overgrazing and extension of cultivated areas aggravate erosion. Preservation of non-degraded surfaces is crucial in this environment. Aeolian deposits (sandy microdunes) are units where infiltration of water is still significant. They are very important for biomass production. However, these units are subject to livestock overgrazing.
The aim of this study is to improve the understanding of water and solute transport in microdune soils during storm events. Microdunes usually overly haplic solonetzs (FAO classification) and are constituted of more or less permeable microlayers. Several questions arise concerning pathways of water and solutes. Do lateral subsurface fluxes through the microdunes exist? Does rain water (new water) mix with the water already present in the soil (old water)? What are the contributions of surface and sub surface flows in the transport of chemically dissolved compounds? Is solute transfer coupled with chemical reactions?

Materials and methods

The study area is located in the north of Burkina Faso (14°00'20'' N, 0°2'50'' W). It is a degraded watershed, overgrazed by livestock. The climate is of the sahelian type, with a single rain season. Average annual rainfall at the city of Dori is 512 mm. Two non-cultivated soil surfaces are present. The first is the erosion crust, which has formed a smooth surface sealed with finer particles; it has no vegetation cover and shows low infiltration capacity. The second is a sandy aeolian deposit surface, which is more permeable. Measurements were made on the border of a selected microdune composed of two main horizons (Figure 1). The first (about 5 cm deep) corresponds to recent loose sands. The second horizon lies over a silty-sand massive crust.
We used oxygen 18 and chloride as tracers. Simulated rains were used to circumvent the problem of geochemical variability of natural rainfalls. The geochemical signature of the simulated rain is known and does not vary over time. A field sprinkling infiltrometer, produced rainfalls on a 1m^2 experimental plot delimited by a two-level setting. The first level allows surface runoff to be measured and sampled, while the second collects subsurface flow (Figure 1). The simulation were carried out using water with a chemical composition comparable to that of natural precipitation and enriched with chloride and ^{18}O.
Water samples were taken at 5 to 10 minute intervals throughout each simulation for chemical and isotopic analysis. A cumulative sample of rain was collected at the end of rainfalls using a

rain gauge located near the plot. Temperature, electrical conductivity and pH were measured in the field. After microfiltration (0.2 µm), $\delta^{18}O$ and the total concentration of alkalinity, Cl□, SO□, F□, NO_3^-, Ca□, Mg□, Na□, K□ and Si were measured in the laboratory.

These data were used as input in the AQUA ion-pair model for calculating equilibrium pressures of the CO_2 and the saturation index of the solutions with respect to specified minerals (*e.g.* calcite, fluorite, gypsum, silicates). A non reactive mixing model involving two reservoirs and one artificial tracer was then used to estimate the contribution of "new" and "old" water to surface and subsurface flow.

Results and discussion

Surface runoff occurred after approximately 5 minutes of rain. The chloride concentration of surface runoff was greater than that of rainfall. This difference was due to a 5 % contribution of pre-event water. This result shows that surface runoff isn't only composed of Hortonian overland flow. Soil surface roughness is the probable cause for the old water contribution. Subsurface flow and surface runoff began simultaneously. Proportion of the subsurface flow in the total flow ranged from 30 % at the beginning to 5 % at the end of the event. At the beginning of the simulation, subsurface δO^{18} and chloride concentrations were similar to those of pre-event water. As the rainfall continued, chloride concentration increased while δO^{18} decreased rapidly to levels close to new water values. These results prove that subsurface flow is composed of both old and new water. By the end of the rain simulation, a small fraction of old water still remained in the subsurface flow, probably due to the persistence of a small immobile water fraction in the soil.

The concentrations of chemical compounds decreased in surface water as well as in subsurface water, except for fluoride and silica in subsurface water. The equilibrium pressure of the CO_2 decreased to a level lower than the atmospheric one. The difference between measured concentrations and concentrations computed with the mixing model highlighted strong chemical soil/water reactivity. The calcite dissolution which consumes CO_2,, and the cation exchange dominated whereas the dissolution of fluorine, silicate and gypsum appear secondary. Reactive mineral stocks are weak and become exhausted quickly, especially in the surface flow. For some of them, results show a kinetic effect.

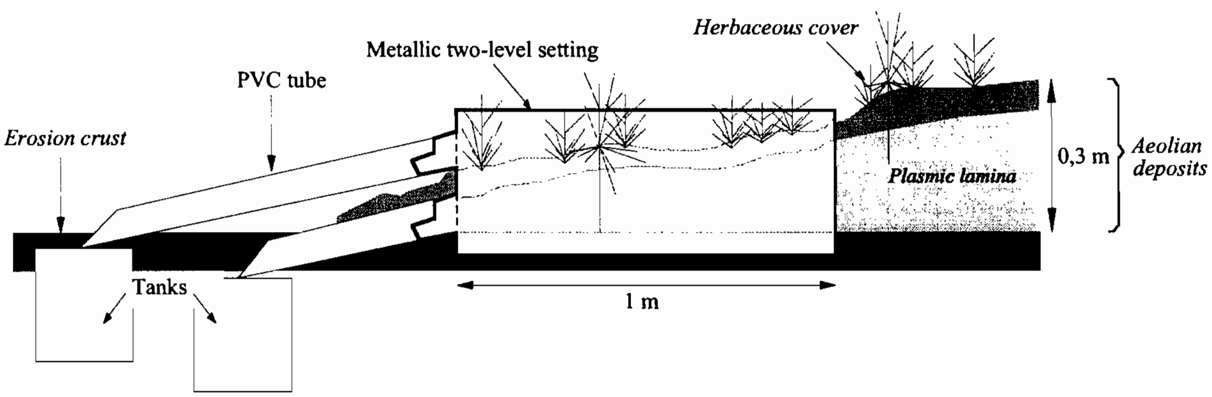

Figure 1 - Soil profile and border setting

Soil crusting and infiltration on steep slopes in northern Thailand

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Introduction

Most recent models to predict soil erosion from small catchments require data on the spatial variability of soil infiltrability. These GIS-based models use infiltration attributes for each main soil units. Such approach may be uncertain when applied to steep slopes because under such conditions a soil map unit is rarely homogenous in terms of soil texture, soil depth and crustability. Likewise, predicting soil infiltrability only from topographic parameters is hazardous because conflicting relations between slope gradient and infiltrability have been reported. Some authors observed no impact of slope gradient upon infiltration (e.g., Mah et al., 1992). Although field observations or experiments more commonly showed a decrease in infiltration with increasing slope angle due to a decrease in overland flow depth and surface storage (e.g. Chaplot and Le Bissonnais, 2000), Fox *et al.* (1997) observed decreasing infiltration rates until a slope threshold and then a steady infiltration rate independent from slope. More surprising are the studies which showed increasing infiltration with slope gradient (e.g., Poesen, 1984; Bradford and Huang, 1992). For interrill conditions, this has been ascribed to lower crusting processes because on steeper slopes, raindrops fall soil with a higher impact angle, and thus a lower kinetic energy

Although agricultural activities are gradually extending into steeplands in many parts of the world, only few field studies on infiltrability have been conducted on steep slopes. This may be due to the inadequacy of classical field methods to assess hydraulic conductivity under these conditions. The objectives of this study were: (i) to investigate the impact of slope gradient on soil infiltrability, (ii) to test various hypotheses regarding the role of surface storage and crusts upon infiltration on steep slopes.

Materials and Methods

Field research was conducted in the Mae Yom experimental catchment located near Phrae, in northern Thailand. The mean annual rainfall, recorded over the last 26 years, is 1 072 mm with most of the rainfall occurring during the Monsoon season during May to September. Convex hills are intensively cropped with soybeans and mungbeans without any period of fallow. The soils developed on shales are mainly sandy loam. Organic matter content ranges from 3.7 to 4.7%. The upper part of the hillslopes is characterized by gentle slopes, the zone immediately below by steep slopes. Fifteen 1-m_ plots were established along such a sequence with slope gradient ranging from 16% to 63%. The surface was hoed to a depth of 0.07-0.10 m and planed with aggregates crushed to less than 4 mm. The plots were subjected to simulated rainfall using the ORSTOM type simulator, with kinetic energy similar to those of the tropical rainfall of similar intensities. Experiments were conducted during the dry season. The first run, on dry soils, lasted one hour at an intensity of 60 mm h^{-1}, the second run, 22 hours later, lasted 30 minutes at an intensity of 120 mm h^{-1} . Soil moisture was monitored on five plots along the hillslope to a depth of 0.95 m, prior to rainfall, and 0.5 hr, 1hr, 2 hrs, 1, 2, 3, 10 and 15 days after the second run. Soil surface features were surveyed using the method of Casenave and Valentin (1992), and surface random roughness was assessed using a laser relief-meter with an accuracy of 1 mm on a 5 cm grid.

Results

Prior to the first rainfall simulation, initial soil moisture conditions (mean 4.6%, st.dev. 1.4%) and bulk density (mean 1.28 g cm^{-3}, st. dev. = 0.07 g cm^{-3}). were similar for the 15 plots. The two rainfalls generated runoff on each plot. Rills did not occur at any stage of the experiment. We corrected the observed volume runoff and infiltration intensity by the cosine of the slope angle to account for the lower rainfall received on steeper slopes (the horizontal length of a 63% slope is 85% of the horizontal length for a flat slope). The steady final infiltration rate measured on each plot (Fnc) tended to increase with slope gradient for the two rain storms (Fig.1). Conversely, the runoff coefficient (runoff-rainfall ratio) calculated for the two runs (Krc) decreased from 76% on gentler slopes to 5% on steeper slopes. The runoff volume from the plots after the stop of the rainfall simulation, which reflects the mean overland flow depth, sharply decreased with increasing slope. Slope gradient had no significant impact on soil depth, total surface gravel percentage and random roughness. By contrast, a clear relation could be established between slope gradient and percentage of embedded gravel (i.e. included in a surface crust, Fig. 2). A significant trend could also be found between slope gradient and percentage of erosion crust. More than 90% of the variance of Fnc and Krc could be thus explained by percentages of embedded gravel and erosion crust.

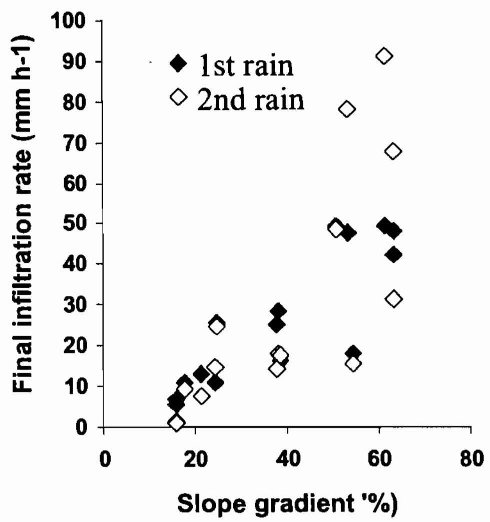

Fig. 1. Final infiltration rate measured during the two rainfalls.

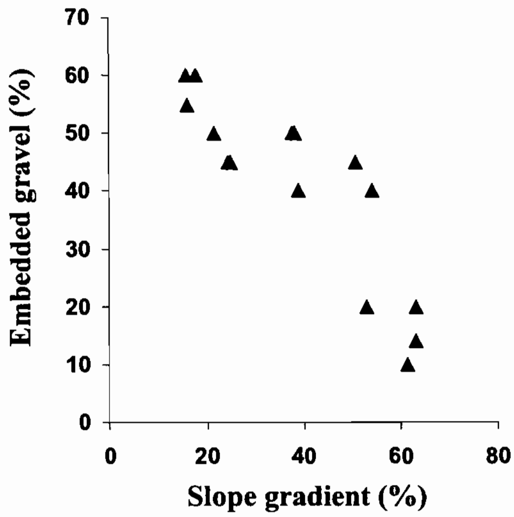

Fig. 2. Percent of embedded gravel as affected by slope gradient.

Discussion

The variations of Fnc between the two rainfalls (Fig.1) indicate that infiltration on gentle slope was less dependent on soil moisture and rainfall intensity than on steep slopes. Similar increasing trend of infiltrability with slope gradient has been also reported in northern Laos under natural rainfall during a rainy season (Huon and Valentin, 2000). This might be achieved by micro-step like profiles due to local mass movement (creeping), or to rilling, but our field observations and surface roughness data did not substantiate these two hypotheses. Rather than the effectiveness of depression storage which could not be confirmed because soil surfaces remained relatively smooth and well inclined.; experimental data supported the hypothesis of decreasing crusting on steeper slopes (Fig.2). These results suggest that for convex landforms, the steep midslope zone can play the role of infiltration trap for runon from upper gentler zone. This may have substantial impacts not only on flow volume generated from small watersheds but also on water quality.

Conclusions

Using similar soil moisture and surface conditions, but different soil depth and slope gradient conditions, rainfall simulation experiments showed that in steep soils prone to crusting, infiltrability decreases with increasing slope gradient whilst crusting intensity greatly decreases.

Keywords

Steep slope, infiltration, surface crust, gravel, Sout-East Asia, Thailand

Acknowledgments

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Which theory for infiltration-excess runoff on rough surfaces ?

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There are several conceptual models that aim at describing runoff processes and the role played by soil characteristics – mostly roughness, retention and permeability. For infiltration-excess overland flow, one of the processes that may occur on hillslopes, runoff is supposed to result from the overflowing of ponds that form due to soil roughness, and the general dynamics is determined by the dependency of the three main fluxes, runoff, infiltration and the time derivative of soil water storage, upon input and structural variables. The simplest model consists in assuming that soil is a reservoir that fills up at a rate equal to the difference between rainfall rate and infiltration and that abruptly overflows when its water content exceed a specific volume. This vision actually extrapolates at a field scale processes that occur at a pond scale. The relevance of this schematic scaling transfer is however questionable since the global dynamics results in a time-dependent spatially-heterogeneous organisation of infilling and overflowing depressions, and of channel flows between ponds or down to the outlet. Determining a theoretical framework for the large-scale dynamics and assessing the control played by soil roughness and infiltration is thus crucial to well pose simplified runoff models.

A key-factor in predicting runoff efficiency is flow connectivity that is obviously strongly related to surface roughness. Significant runoff occurs if, and only if, the length scale of water flow connectivity is of the order of system size. In rough permeable surfaces, connectivity is due either to pond overflowing or to an organised structure of soil topography that define a drainage network. In the former case, connectivity evolves with the amount of water stored in topographic depression. The process is cooperative in the sense that the pond infilling rate can be increased by the overflowing of upstream ponds. In the latter case, connectivity is achieved as the first rain drop hits the surface, and runoff depends only on flow velocity. These two end-member cases exist in nature. Soil aggregates and clods that form depressions can be considered as random with respect to flow, at least at large scale (larger than several decimetres). In contrast, large-scale slopes, rills and even seedbed lines form a drainage network that ensures large-scale correlations to flow. In general, soil erosion tends to increase the “structural” flow connectivity, and thus to decrease the role of pond overflowing.

In this paper, we argue that these two types of connectivity are basically different, and can be related to existing percolation theories. Qualitative arguments were derived from rainfall-simulated experiments on natural soils [*Planchon* et al., 2000; *Darboux et al.*, 2001]. In some laboratory experiments, soils were tilled so that topography can be considered uncorrelated for scales larger than about 10 cm. For the very first rainfalls, runoff shows a classical ‘S-shape’ with a sharp increase around a threshold. This emphasises cooperative pond overflowing as a dominant process, as it is expected in the classical percolation theory. For the last rainfalls, soil topography is significantly eroded with a visible drainage organisation due to rill development. A significant runoff occurs much faster from this drainage network, but the runoff increase with rain is much smaller than in the random case.

To rationalize these qualitative results, we expect theoretical arguments to be derived from percolation theory. Indeed if the average distance between successive depressions is small

enough, the time scale of the problem is given by precipitation in relation to hydrodynamic soil properties, and the runoff dynamics is fully determined by pond connectivity. This process is closely related to percolation problems where the macroscopic behaviour is due to cluster connectivity. For infiltration-excess overland flow, clusters are individual drainage basins defined as the ensemble of points which eventually flow into a pond. The horizontal extension of drainage basins grows when adding water by connection of overflowing ponds.
The analogy to classical percolation problem is intuitively sound but has never been really tested. Natural systems cannot be only considered as running water on top of random impervious surfaces; the consequence of infiltration as well as the existence of long-range correlations are natural conditions that have got to be taken into account. We have analysed this problem by using a "walker" numerical model that simulates runoff on any permeable surface [*Crave and Davy*, 2001; *Darboux et al.*, 2001]. Each walker is supposed to represent a droplet which runs on top of the upper surface (soil or pond) and looses their water content to fill up local holes. Except in holes, walker runs following the steepest slope. It stops when it is empty or it reaches a predefined system boundary.
The simplest case of a random (uncorrelated) impervious surfaces is clearly analogue to percolation problems. Runoff curves have the classical 'S-shape' with a sharp increase of runoff around a threshold rainfall r_c that is about equal to the volume of water potentially storable on the surface. The key process is pond overflowing, a mechanism which is controlled by pond infilling rate equals to rainfall rate multiplied by the ratio between drainage area and pond area (upper surface of water). Overflow occurs when water height reaches the lowest pass in the drainage divide. Because of the potential variations of pond drainage area, this mechanisms of cluster growth is slightly different from classical percolation theory for which it would be assumed a random distribution of the overflow conditions. Also classical percolation theory predicts that percolation clusters are fractal while drainage basins are clearly space filling. Despite these differences, we demonstrate that that the process contains the basic ingredients of the percolation theory with a divergence of the correlation length around threshold characterised by a scaling exponent of about 4/3 that is close to 2D percolation problems. Note that for infinitely large systems, runoff is an all-or-none process as pictured in the overflowing "box" model.
Infiltration does not modify this theoretical scheme, except in two respects:
The percolation threshold is obtained for an amount of water larger than in the impervious case, trivially showing that the infiltration flux do not participate to runoff. But we found that percolation threshold is independent of infiltration rate if the efficient added water (total rainfall – infiltrated water) is considered.

The eventual runoff R decreases with infiltration rate such as $R(t=\infty, I) = 1 - \dfrac{I}{1.7 * p}$ with t the time, I the infiltration rate, and p the precipitation rate. Runoff occurs even when infiltration rate is larger than rainfall rate (up to 1.7 times the rainfall rate) for these flat random topographies. This reflects the fact that the increase of pond height depends on the ratio between drainage basin area and pond area, making possible an increase of the pond height for basins whose drainage area is larger than pond area. If the number of such basins is sufficient, they can eventually form a large connected basin that significantly contribute to runoff.
The case of soil topography with long-range correlations is clearly different from uncorrelated surfaces. We have especially studied the effect of a general slope as an illustrative example of such long-range correlation. A noteworthy result is that the threshold width – that is the amount of water necessary to achieve significant runoff – tends to a non-nil constant value for large sloping systems. This is a strong argument to state that such system does not belong to the same class of universality than percolation theory. It is rather related to directed

percolation problems for which it exists a strong theoretical background. The main difference with percolation theory is that drainage-basin growths are highly anisotropic with a growth-rate parallel to main slope much larger than the perpendicular one. The runoff-rain relationship $R(r)$ is actually controlled by the slowest phenomenon, and we argue that it takes the general expression $R(r) = a\ (r-r_c)^{0.3}$ whatever slope is, with a and r_c two parameters that depends on soil roughness and slope.
These theoretical frameworks, that is percolation theory and directed percolation theory, are helpful to find the general equations that may govern runoff evolution. We aim at generalising the results obtained on rough sloping surfaces to much complex natural soil surfaces.

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Characterization of heterogeneity of water infiltration into crusted soils using dye tracers

C. Bielders, P. Baveye

Missing abstract

Experimental and numerical analysis of the influence of tillage on crust formation and runoff in cultivated sandy soils of Senegal

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Overland flow and soil erosion are the main source of soil and fertility losses during the rainy season in the Sahelian region. The objectives were, primarily to investigate the evolution of soil surface crust formation on the hydraulic conductivity near saturation in relation to the cumulative rainfall and secondarily, to study the effect of the tillage direction in relation to the slope. The analysis was based on 47 in-situ infiltration tests and 18 soil samples which were treated in the laboratory by using the Wind evaporation method to get the soil hydrodynamic properties.

The infiltration tests were carried out in square meter plots distributed on 3 sites : tillage in the direction perpendicular to the slope (site A and site C) and tillage along the slope (site B). Site C is representative of the soil at the end of the rainy season. The plots received between 1 and 5 simulated rainfalls (60 mm/hr during 30 mn). Four infiltration tests were performed on each plot. Analyses concern steady state infiltration flux and the calculation of the hydraulic conductivity near saturation using Darcy's law. The statistical analysis showed a significant evolution of the fluxes for the B plots, but not for the A plots with the applied amount of rain. The type of crusts, mainly runoff type for site B site and structural type for site A could explain this difference.

Immediately after tillage, the surface layers are more permeable than the deeper ones. The hydraulic conductivity values range from 40 mm/hr at surface to 25 mm/hr in depth. After about 150 mm of cumulative rainfall the profile seems to homogenise itself with a hydraulic conductivity close to 5 mm/hr. This weak value confirms the effect of the development of a crust at the soil surface.

The laboratory evaporation tests were performed on samples to determine the parameters of the retention curves (vanGenuchten model). The surface horizon samples show a bubbling air pressure value (h_g) greater than that for the deeper soil layers which were, -39 cm and -19 cm respectively. This can be explained by a more significant structuring of the surface horizon due to soil tillage effects. The parameter of form "n" presents almost identical values for both layers (1.53 and 1.47 respectively) according to their identical particle size distribution. Hydraulic conductivity values calculated using Darcy's law, covered only a small range degree of saturation (from 0.2 to 0.6). The values of hydraulic conductivity close to saturation obtained by laboratory determinations were complemented by the results of the in-situ infiltration tests. All the experimental values were used to estimate by an inverse method the parameters of the van Genuchten-Mualem (VGM) and Brooks and Corey (BC) analytical expressions. The VGM model was found to give better results, especially close to saturation.

The very small thickness of the crust made its direct hydrodynamic characterization difficult. Then the crust hydraulic conductivity close to saturation was estimated by an inverse method using HYDRUS 1D numerical code. It appeared that the saturated hydraulic conductivity of the crust was 2 orders of magnitude smaller than that of the subsurface layer.

The tensiometers data collected during the 1997 rainy season in a groundnut field were used to evaluate the hydrodynamic properties of the crust and to validate the estimated parameters.

It is showed that the simulation of water flow over a 5 day period gave satisfactory results. The calculated pressures were found in better agreement with measured ones for the surface and subsurface layers. For deeper layers the poor results can be explained to some extent by hysteretic effects and local heterogeneity.

Invariance d'échelle dans la structure des champs de pluie sahéliens.

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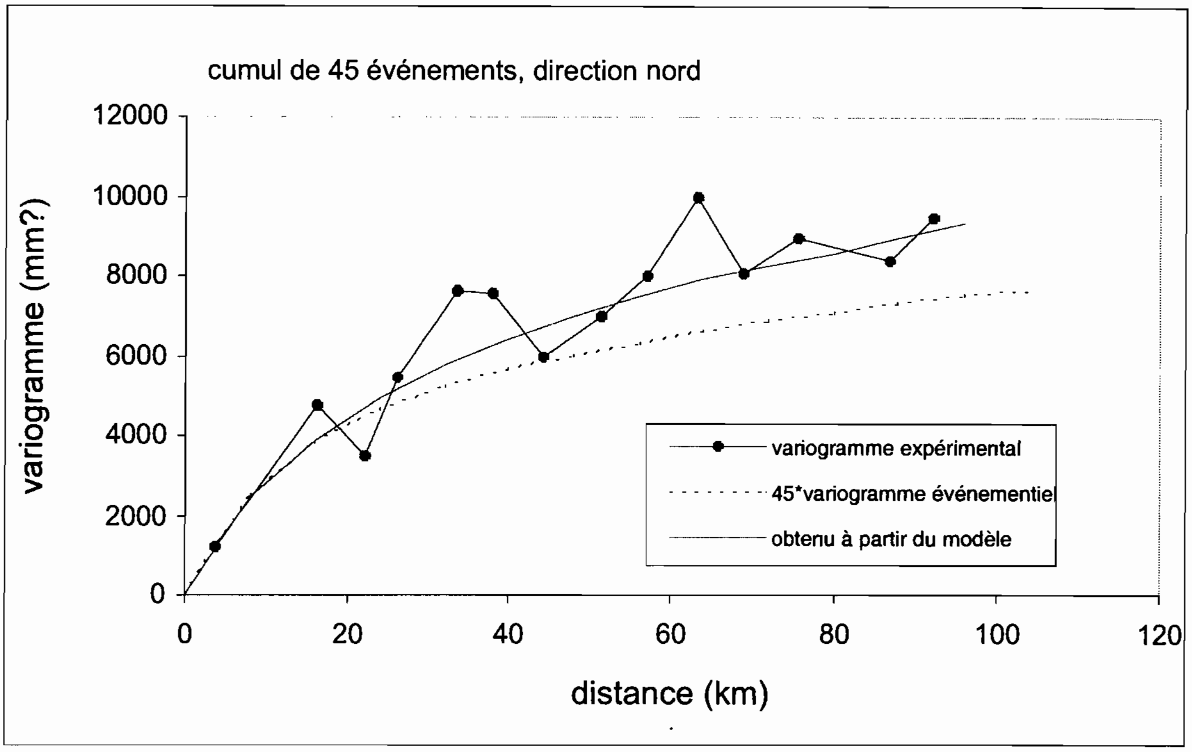
La pluie au Sahel est réputée pour sa grande variabilité sur une large gamme d'échelles temporelles : variabilité décennale associée à la sécheresse 1970-1997 ; variabilité interannuelle incarnée par l'année 1994, seule année humide au sein de la période précédente ; variabilité intrasaisonnière (break de mousson de l'année 2000) et enfin intermittence au sein des événements pluvieux. L'expérience EPSAT-Niger et son prolongement ont permis de démontrer, grâce à un réseau dense de pluviographes et ayant fonctionné depuis 1990, que cette variabilité temporelle est associée à une variabilité spatiale dont l'impact hydrologique est extrêmement important. Sur la base d'un modèle proposé antérieurement par Lebel et Le Barbé (1997), on présente ici une approche intégrée qui rend compte de ces différentes échelles de variabilité dans un contexte cohérent. Ce modèle permet d'identifier la structure spatiale des champs de pluie aux pas de temps plus grands que la journée, à partir de la structure des champs de pluie événementiels. Pour ce faire, on prend explicitement en compte les caractéristiques internes et externes des champs événementiels et on dérive analytiquement l'expression de la structure du cumul de *N* événements. L'étude de ces caractéristiques est basée sur l'identification des trois éléments suivants : i) la structure spatiale des événements que nous modélisons en tenant compte des emboîtements d'échelle et des anisotropies, caractéristiques des systèmes pluvieux de cette région, ii) l'intermittence spatiale, qui est modélisée via le variogramme des indicatrices et iii) le paramètre relatif à la taille des événements, seule inconnue restant du modèle, que l'on obtient alors par résolution numérique. Une fois ces éléments bien identifiés, ils constitueront les invariants du modèle. Les données EPSAT-Niger, du fait de leur haute résolution spatio-temporelle, ont permis dans un premier temps de bien documenter la variabilité spatiale depuis l'échelle convective jusqu'à la méso-échelle, fournissant ainsi une inférence robuste du variogramme moyen événementiel. Dans un deuxième temps, on a mené une étude expérimentale des champs composés par combinaison aléatoire de *N* événements, en montant que la structure de ces champs est bien conforme à celle obtenue pour les champs des cumuls à pas de temps fixe. Le modèle est ensuite mis en œuvre en combinant les éléments invariants identifiés au cours des deux premières étapes. Par ailleurs, la relation analytique qui lie ces éléments invariants permet de quantifier l'importance relative de chacun selon l'échelle d'espace et de temps considérée. Pour certaines échelles on peut négliger un ou plusieurs éléments, car une structure est dominante. Pour d'autres au contraire, il y a une contribution significative de chaque structure et la totalité du modèle doit être prise en compte. Ce travail débouche sur une double conclusion. Tout d'abord, la validation du modèle confirme que la seule connaissance de la structure des champs événementiels et du nombre d'événements *N* donne accès à la structure des champs *N*-événementiels, c'est à dire notamment à la structure des champs de pluie décadaires ou mensuels qui sont utilisés en entrée des modèles de bilan hydrique ou hydrologiques régionaux. La caractérisation des champs de pluie par invariance d'échelle est donc pertinente dans le cas sahélien, pour les échelles considérées ici. Ensuite, on va pouvoir proposer de nouveaux algorithmes pour combiner données sol et satellitaires aux fins d'estimation de pluie par satellite sur la région.

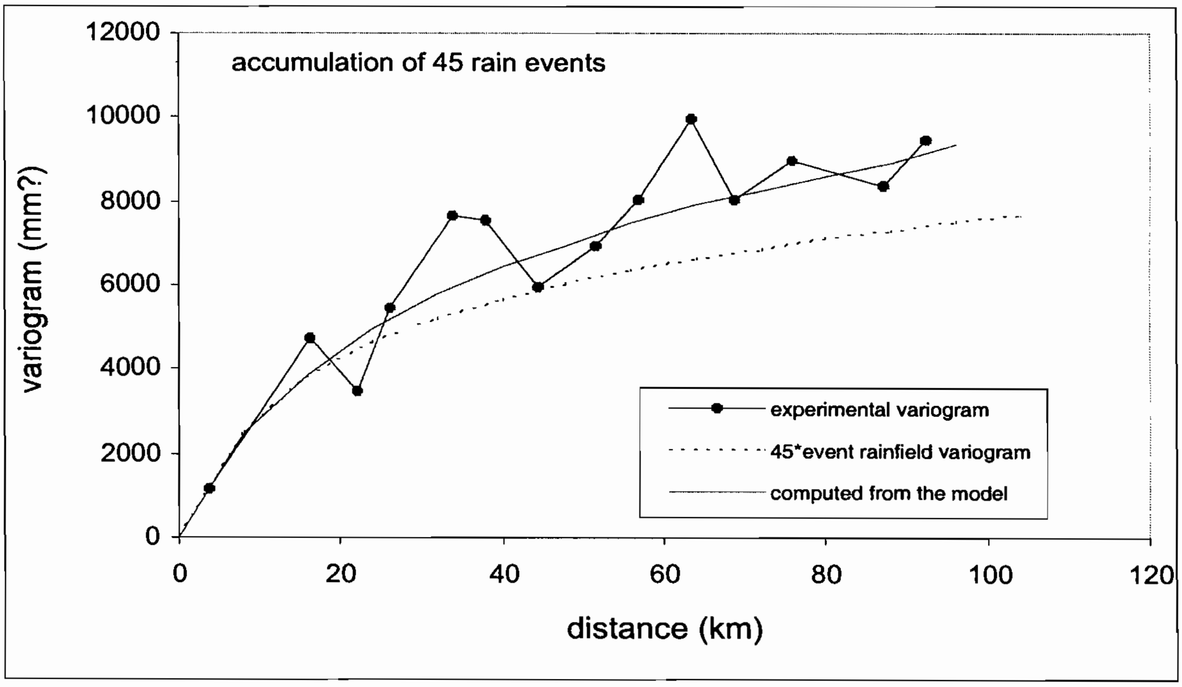


Variogramme expérimental directionnel du cumul de 45 événements pluvieux (correspondant approximativement au cumul saisonnier en année moyenne) et ajustement d'un modèle théorique déduit du variogramme événementiel tracé en pointillés. Les données du variogramme expérimental n'ont pas été utilisés pour le calage du modèle théorique γ_{Ne}, qui est de la forme : $\gamma_{Ne} = \alpha\gamma_e + \varphi(\gamma_N)$, où γ_e est le variogramme événementiel, α est un paramètre relatif à la taille des événements et γ_N est le variogramme du nombre d'événements.

Abstract

Rainfall in the Sahel is notoriously unreliable and characterised by a great variability over a large spectrum of scales: decadal variability associated to the continuous drought that struck the region from 1970 to 1997, interannual variability (for instance the year 1994 was the only markedly wet year during the dry period), intraseasonal variability and internal intermittency of the rainfields at the scale of the convective systems. The EPSAT-Niger experiment, running from 1990 onwards, provided the recording raingauge data required to document the space variability of the Sahelian rainfields. This space variability was shown to be as significant as the time variability from an hydrologic point of view. On the basis of a model proposed by Lebel et Le Barbé (1997), an integrated approach is presented here, accounting for these various scales of variability in a coherent theoretical framework. This model allows the identification of the spatial structure of rainfields at time steps greater than one day, bases on the structure of event rainfields, taking into account that the cumulative rainfall over a period of several days is the accumulation of the rain produced by a number N of events, N being a random variate. In this approach, the internal and external characteristics of the event rainfields are specified and the structure of the N-event rainfields are analytically derived.
These characteristics are associated to three elements: i) a model for the spatial structure of the event rainfields, taking into account the nesting and anisotropy displayed by the rainy systems of this region; ii) the space intermittency, which is modelled via the indicator

variogram; iii) a parameter related to the size of the convective systems, which is a remaining unknown, calculated numerically. Once these elements are identified they constitute the invariants of the model. Thanks to the high space-time resolution of the EPSAT-Niger data, it has been possible to adequately document the space variability from the convective scale up to the mesoscale, thus providing a robust inference of the average event rainfield variogram. In a second step, an experimental study of the rainfields associated to the random combination of *N*-events was carried out. It is shown that the structure of these *N*-event rainfields is indeed similar to the structure of 10-day, monthly or seasonal rainfields, depending on the value considered for *N*. The model is then implemented by combining the invariant elements identified as a result of the two first steps. The analytical relationship between these invariant elements allows the quantification of how important is each element depending on the space and time scales considered. For certain scales, one or two elements may be neglected, since one structure is dominant. For other scales each structure contributes significantly to the overall structure and the model is to be used in its entirety. This work leads to a double conclusion. First, the validation of the model confirms that the sole knowledge of the average event rainfield structure and of the number of events *N* is needed to determine the structure of the *N*-event rainfields. This gives access to the structure of 10-day and monthly rainfields, which are used as inputs to water balance or hydrologic models at the regional scale. The characterisation of the Sahelian rainfields by a scaling approach is thus relevant, at least for the scales considered here. Secondly, new algorithms could be derived, combining ground and satellite data for the purpose of rain monitoring in the region.



Experimental variogram in the North-South direction for the accumulation of 45 rain events (corresponding approximately to the seasonal total of an average year). A theoretical model was computed from the event rainfield variogram drawn as a dashed line. The data of the experimental variogram were not used to fit the theoretical model γ_{Ne}, which is of the following form: $\gamma_{Ne} = \alpha\gamma_e + \varphi(\gamma_N)$, where γ_e is the event rainfield variogram, α is a parameter linked to the size of the events and γ_N is the variogram of the number of events.

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Bilan de l'érosion sur les petits bassins versants des lacs collinaires de la dorsale Tunisienne

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Résumé
Une retenue artificielle de petite dimension est un lieu privilégié pour l'observation des bilans d'érosion sur un petit bassin versant. La majorité des transports solides reste piégée dans le réservoir et la partie déversée, lors des rares débordements par le déversoir, peut être estimée à partir de la connaissance des débits déversés et de leur concentration. Un équipement hydro-pluviométrique du barrage couplé à des mesures annuelles de la bathymétrie du lac permet d'établir des bilans précis en eau et en sédiments du bassin versant drainé. Dans la zone semi-aride de la Tunisie Centrale, un réseau de 24 lacs collinaires a été équipé depuis 1993. Les données qu'il fournit peuvent être généralisées à l'ensemble des petits bassins versants de la dorsale tunisienne.

INTRODUCTION

La majorité des mesures de l'érosion est faite sur des parcelles de taille standard (Wischmeier & al, 1971) et n'intéressent que l'érosion superficielle des sols. A l'exutoire d'un petit bassin versant, le transport de sédiments par la rivière est le résultat de différents processus qui comprennent l'érosion des sols, leur dépôt, l'effondrement des berges, le charriage de fond et la déposition dans le réseau hydrographique. La connaissance du résultat de ces processus à l'exutoire du bassin intéresse, au premier chef, le concepteur d'ouvrages hydrauliques de rétention des eaux de ruissellement. L'expérience mondiale évalue le taux de perte en volume des barrages dans une fourchette de 3 à 10 % (Gazzalo & Bassi, 1969, Karouachov, 1977). Lorsque l'on s'intéresse aux petites infrastructures tunisiennes, on obtient un chiffre annuel voisin de 5% (CES-ORSTOM, 1997).

Les bassins versants expérimentaux sont reconnus, depuis longtemps, comme le dispositif de mesure le plus adéquat pour l'analyse des transports solides globaux (Toebes & Ourivaev, 1970, Dubreuil & al, 1972). Ils sont aussi le lieu privilégié pour la recherche sur les mécanismes du cycle de l'eau (Verel & Houi, 1994) et des interactions entre usage des sols, aménagements hydrauliques et disponibilité ou qualité de l'eau. La difficulté et le coût de gestion des réseaux pluviométriques et hydrométriques sur des bassins versants de petite taille constituent un handicap sérieux à une bonne connaissance des bilans en eau et en sédiments.

Dans le monde méditerranéen, le petit barrage existe depuis l'époque romaine ; mais ce n'est que très récemment que des projets ambitieux de réalisation voient le jour en Tunisie (Talineau, Selmi & Alaya K. ; 1994).

Une retenue alimentée par un seul tributaire, ou pour le moins, par un tributaire principal, est susceptible de fournir une information équivalente à celle que l'on peut obtenir d'une station hydrométrique classique. Pour cela, certaines conditions, souvent moins contraignantes et moins onéreuses que celles nécessaires au bon fonctionnement d'une station hydrométrique, doivent, tout de même, être satisfaites (Nouvelot, 1993).

En Tunisie Centrale, dans la dorsale semi-aride, depuis le Cap Bon jusqu'à la frontière algérienne, 24 retenues artificielles ont été sélectionnées pour constituer un réseau d'observations hydrologiques. Ces retenues ont des impluviums très diversifiés allant d'un milieu semi-forestier plus ou moins anthropisé à un milieu totalement consacré à l'activité agricole. La superficie de leur bassin versant varie de quelques hectares à quelques dizaines km_. Elles sont aussi représentatives du gradient pluviométrique de la zone semi-aride qui est de 250 mm de précipitation inter-annuelle à 500 mm. La mesure de la bathymétrie de façon précise de ces 24 lacs permet une connaissance de plus en plus fine des bilans de l'érosion dans les petits bassins versants de la dorsale tunisienne.

DISPOSITIF EXPERIMENTAL, METHODES ET DONNEES

Installation expérimentale d'un lac collinaire et acquisition des données

Un lac collinaire est équipé d'une échelle limnimétrique, d'un pluviomètre journalier, d'un bac à évaporation et de deux centrales d'acquisition automatique de données ; la première est reliée à un capteur pluviométrique à augets basculeurs (0.5 mm de pluie) et la seconde à une sonde immergée mesurant le niveau de l'eau au cm près et sa température. L'évacuateur de crue est aménagé pour disposer d'un seuil déversant permettant l'estimation des débits.

La bathymétrie de chaque lac est effectuée au moins une fois par année hydrologique. Elle est rapportée au nivellement fin du site et permet d'apprécier le taux d'envasement de la retenue et d'établir les courbes «Hauteur / Volume et Hauteur / surface».

Des prélèvements ponctuels des eaux déversées permettent de connaître la matière solide exportée.

Estimation du transport solide et du volume de sédiment capturé par la retenue

La bathymétrie de la retenue se fait par sondages ponctuels du fond de la retenue suivant des transversales matérialisées par un câble tendu entre les deux rives. Les extrémités de chaque transversale sont nivelées et positionnées sur le plan de recollement de la retenue. Chaque point sondé (environ 500 par lacs) est défini par trois coordonnées cartésiennes (situation et profondeur). Une géostatistique par la méthode du Krigeage (Matheron, 1965), permet d'établir la relation «hauteur / volume» du lac. Le volume de vase est établi par différence des volumes utiles d'une année à l'autre. La figure 1 montre la bathymétrie du lac Fidh Ali (Bassin versant du Merguellil, Tunisie) mesurée en 1997. La retenue se comporte comme un piège à sédiments et lorsqu'elle n'a pas déversé, le volume de vase correspond au transport solide total produit par le bassin. La figure 2 montre sur la coupe AA l'évolution de la sédimentation de la retenue de 1991 à 1997. En cas de déversement, on attribue aux volumes déversés une concentration moyenne de matière en suspension, obtenue par échantillonnage.

Le transport solide est enfin calculé en multipliant le volume de vase par sa densité et en ajoutant la masse exportée.

Figure 1 : Bathymétrie de Fidh Ali 1997

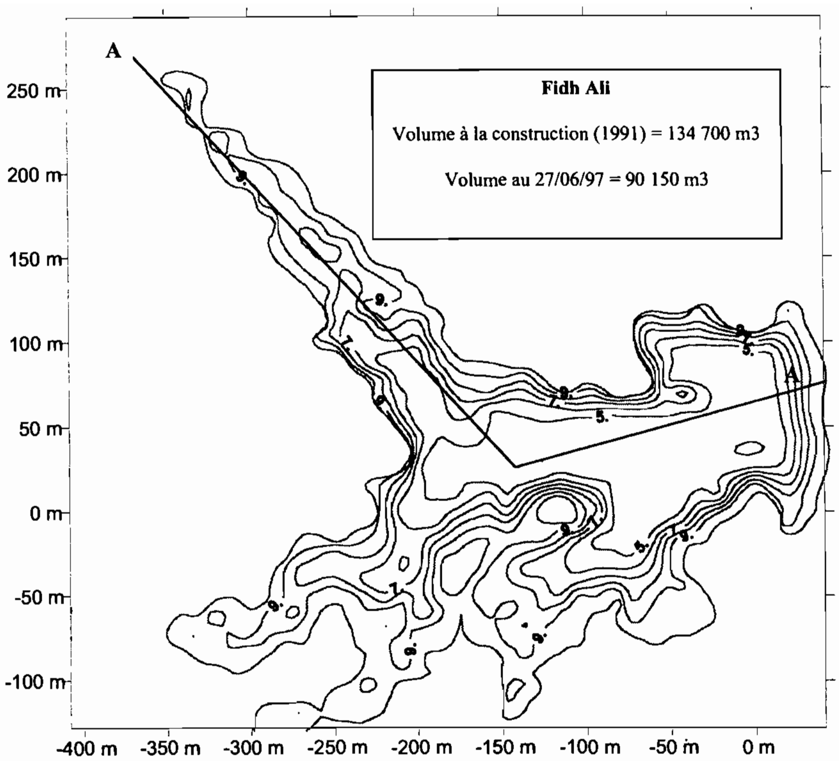
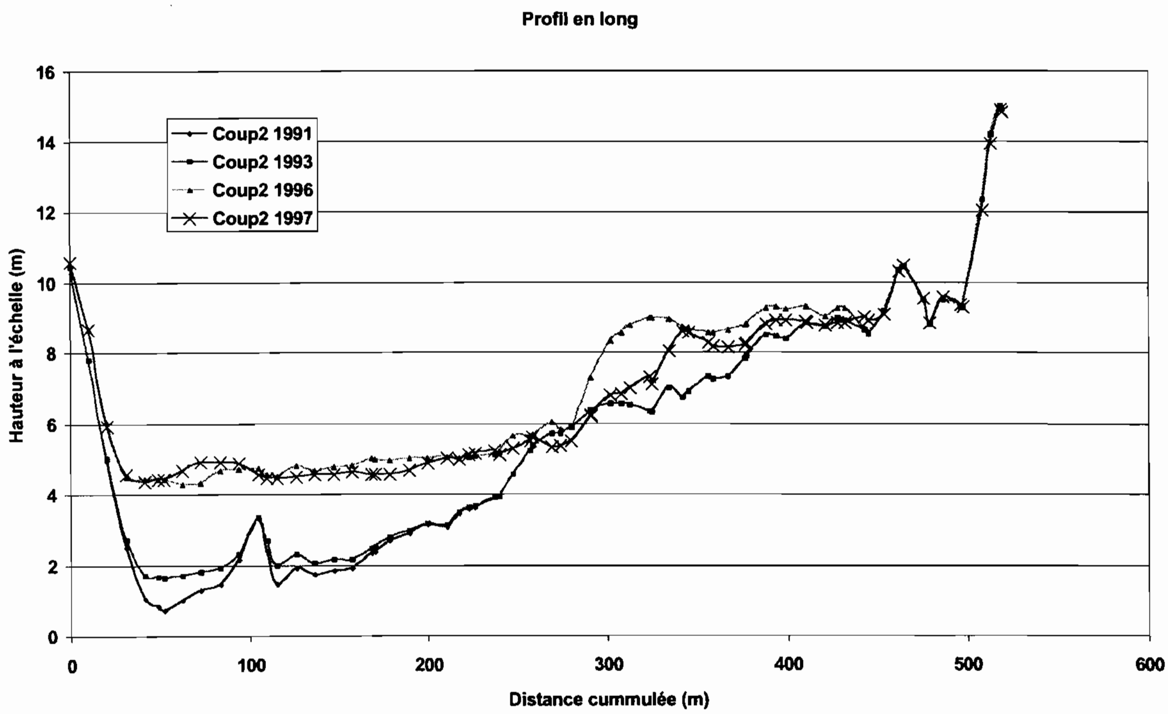


Figure 2 : Evolution de la sédimentation de la retenue



Estimation du transport solide crue par crue

La reconstitution des transports solides, crue par crue, assimilée à l'érosion globale du bassin, utilise une forme de l'équation universelle des pertes en terres développée par Williams (1977) et présentée par Hadley & al en 1985. Cette équation s'écrit :

A = _(Vq_p)_K(LS)CP

Où A représente l'apport en tonne de sédiments ; V, le volume de la crue naturelle entrant dans le réservoir, en m^3 ; q_p, le débit de la pointe de crue, en m^3s^{-1} ; K le facteur d'érodibilité du sol (il se mesure sur parcelle de référence et n'a pas d'unité) ; (LS), le facteur exprimant la longueur et le degré d'inclinaison de la pente ; C, le facteur de couverture végétale ; P, le facteur des pratiques conservatrices effectuées sur les versants ; _ et _ sont des paramètres qui, dans le système unitaire international prennent respectivement les valeurs _ = 11.8 et _ = 0.56.

Le produit _K(LS)CP est caractéristique d'un bassin pour une saison donnée; le facteur C varie en fonction de l'état du tapis herbacé et du stade des cultures. Nous chercherons une valeur moyenne du produit _K(LS)CP à partir des deux premières mesures d'envasement et nous la validerons en l'appliquant aux suivantes. Cette valeur moyenne est calculée par un modèle d'optimisation en comparant la somme des transports solides obtenue entre deux mesures de bathymétrie l'érosion calculée.

$$T_{sobs} = (V_{vobs} \times d) + \sum V_{dev} \times c$$

T_{sobs} est le transport solide observé, V_{vobs} est le volume de vase accumulé dans la retenue entre deux mesures de bathymétrie, d est la densité de la vase, V_{dev} est le volume d'eau déversé pendant une crue et C est la concentration moyenne en matière solide des eaux déversées.

Les crues à l'entrée des barrages sont reconstituées suivant un modèle de bilan hydrologique au pas de temps de 5 minutes (CES – ORSTOM, 1996).

RESULTATS

Envasement / Erosion

Le tableau 1 récapitule les données d'envasement mesuré pour les 24 barrages. Les 24 unités « lacs collinaires », bien suivies par des mesures d'envasement depuis 1993, avaient une capacité initiale totale de stockage de 2 615 000 m^3, elles ont perdu 556 400 m^3 en fin 1998, soit 21% pour une durée d'existence moyenne de 6 années. Soit une perte moyenne de 4.6% de la capacité de stockage par an. Suivant les sites, l'importance de l'envasement est très variable. Pour comparer l'envasement des différentes retenues, on a rapporté sa perte de volume à l'unité de surface de son bassin et à l'année. On remarque une forte variabilité de l'envasement annuel moyen d'un bassin à l'autre, celui ci passe de 1 m3/ha/an pour les bassins faiblement ruisselant comme celui de Seghir qui se trouve essentiellement sur le cordon sableux de Nabeul à environ 18m3/ha/an pour des bassins versants avec marnes gypseuses .

Station	Surface BV ha	année création	mois dernière mesure	volume initial m3	Volume de sédiments stockés m3	Durée de vie de l'ouvrage années	Envas. rapporté à la surface du bassin et par an m3/ha/an
Sadine 1	384	1988	juin-99	35 070	34 610	11	8,2
Sadine 2	653	1990	sep-98	82 400	82 370	8	15,8
Fidh ben Naceur	169	1990	mai-99	47 110	14 720	29	9,7
Fidh Ali	413	1991	sep-98	134 710	46 235	20	16,0
M'Richet el Anse	158	1991	mars-98	42 400	8 665	34	7,8
El Gouazine	1810	1990	mai-98	237 030	16 030	>100	1,1
Hadada	469	1992	mai-96	84 970	14 060	24	7,5
Janet	521	1992	mai-98	94 280	55 910	10	17,9
El Hnach	395	1992	mai-96	77 400	18 770	16	7,9
Abdessadok	307	1990	sep-98	92 820	25 960	29	10,6
Dekikira	307	1991	juin-96	219 100	21 300	51	13,9
Es Senega	363	1991	juin-98	86 420	27 778	22	10,9
Echar	917	1993	juin-96	186 840	5 300	>100	1,9
Abdeladim	642	1992	juil-99	174 870	6 900	>100	1,5
Arara	708	1993	sep-98	91 150	58 940	8	16,6
El Mouidhi	266	1991	sep-98	142 770	26 980	37	14,5
Sbahia 1	324	1993	oct-96	135 570	10 550	39	10,9
Saadine	272	1992	sep-98	35 620	27 610	8	16,9
Es Seghir	431	1992	oct-96	192 460	2 020	>100	1,2
El Melah	85	1991	nov-96	15 395	2 133	36	5,0
Kamech	246	1993	juil-99	142 100	25 765	33	17,5
Brahim Zaher	464	1992	sep-98	86 190	24 920	21	8,9
Baouejer	486	1991	juin-96	66 030	6 510	51	2,7

Tableau 1 : Envasement et érosion

En faisant l'hypothèse que la moyenne de l'envasement sur la période d'observation (1993-1998) est représentative du régime hydrologique (deux années excédentaires, deux années sèches et une année moyenne), nous pouvons estimer une durée de vie moyenne des barrages (comblement jusqu'à la cote du déversoir) : 29 % des lacs auraient une durée de vie inférieure à 20 ans et environ 29% une durée de vie supérieure à 50 ans. La durée de vie moyenne face à l'envasement de l'ensemble des lacs serait de l'ordre de 40 ans.

Reconstitution des transports solides crue par crue : Modèle d'érosion

Le modèle de Williams a été appliqué à cinq retenues parmi les 24 observées et nous estimons qu'il pourra être généralisé à toutes les retenues. Dans le cadre de ce travail les cinq barrages pour lesquels le modèle a été appliqué sont étagés en latitude et leurs bassins versants sont représentatifs de la géologie de la dorsale Tunisienne. Le tableau 2 donne la dimension des bassins versants choisis, les coordonnées géographiques des barrages, les caractéristiques géologiques des bassins versants, la période de calage du modèle et la valeur du paramètre. La figure 3 compare les érosions calculées et observées pour les périodes de calage et pour les périodes de validation du modèle. Au site d'El Gouazine, où un important aménagement en banquettes anti-érosive a été installé en 1996, les valeurs de _K(LS)CP sont très différentes pour les deux périodes de mesures de bathymétries. Nous n'avons pas fait de validation, celle ci sera faite à l'occasion d'une prochaine mesure d'envasement.

Lac collinaire	Coordonnées	Géologie	Période de calage	αK(LS)CP
Kamech 245 ha	36°52'18" N 10°52'08" E	Flanc est de l'anticlinal du Cap Bon sur marne, calcaire et grès.	1995-1996 1996-1998	1.22
Mrichet El Anze 158 ha	36°05'37" N 09°35'41" E	Flanc Nord Ouest du chaînon anticlinal du Bargou, calcaire et marne du crétacé, reliquat d'encroûtement calcaire du villafranchien	1995 -1996	2.29
El Gouazine 1810 ha	35°54'30" N 09°42'13"	Vallée dans des alluvions anciennes encroûtées pléïstocène dominée en rive gauche par la crête calcaire éocène	1993-1996 1996-1997 (aménag. entre les 2)	0.63 0.05
Fidh Ali 238ha	35°42'40" 09°36'13"	Flanc sud ouest d'un anticlinal , BV entièrement situé dans les formations éocène : marnes gipseuses et lumachelles	1993-1996 1994-1996	3.71
Essenega 353 ha	35°29'21" 09°06'18	B.V. dominé par un chaînon du Jbel Semama calcaire du crétacé. Système de faille révélant à l'aval des marnes gipseuses	1995-1996	1.60

Tableau 2 : Modélisation de l'érosion sur cinq bassins

La comparaison des valeurs observées et calculées de l'érosion montrent une dispersion équivalente des points en calage et en validation. Ce modèle est assez grossier et il sera possible de l'affiner par un calcul des paramètre K, LS, C, et P à partir d'une cartographie des états de surface. Il est cependant d'une précision suffisante pour simuler une érosion crue par crue du bassin et c'est ce qui a été réalisé sur le bassin versant de Kamech (figure 4).
Cette simulation a pu être valider à l'occasion de l'épisode pluvieux du 28 au 30 Novembre 99 qui a été encadré par deux mesures de bathymétrie et sur lequel des mesures de concentration des eaux déversées ont été réalisées (moyenne des échantillons = 25g/l) (Tableau 3).
Figure 3 : Comparaison des érosions calculées et observées en calage et en validation

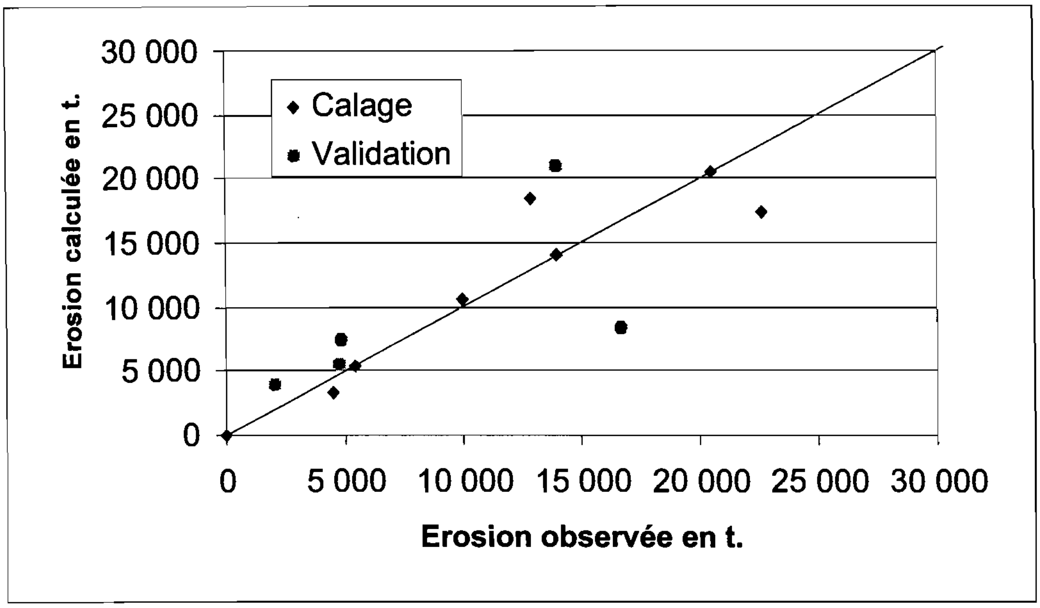
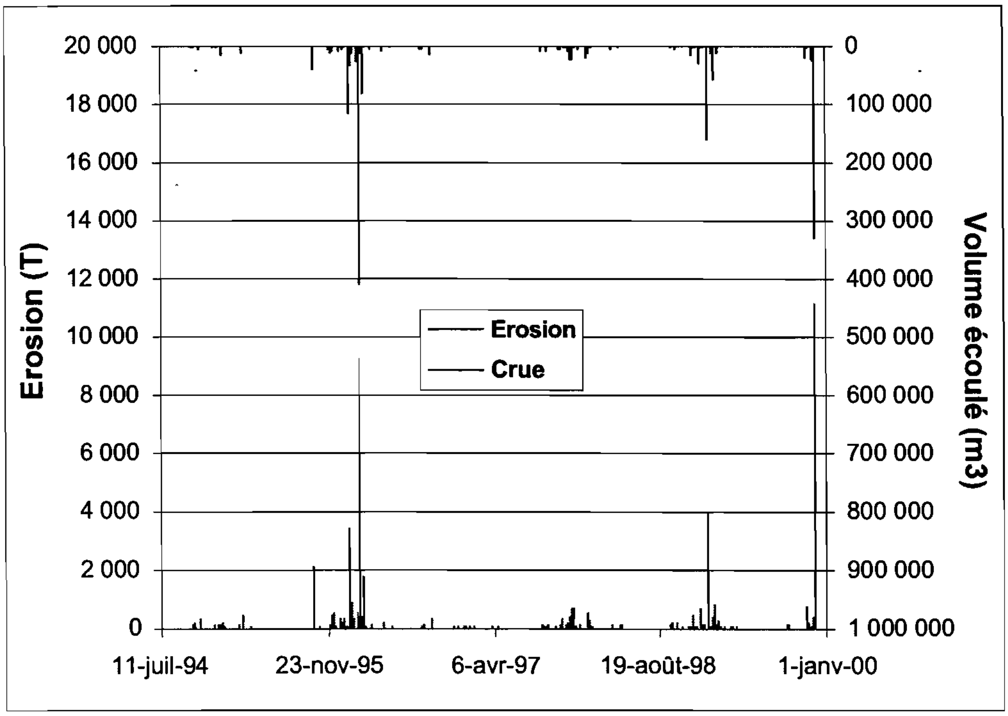


Figure 4 : Simulation des érosions crue par crue*



La figure 4 montre bien que le phénomène d'envasement est lié à des événements paroxysmiques. Dans cette chronique de 6 années, trois crues ont apporté 50 % du transport solide (27 février 1996, 18 janvier 1999 et 29 Novembre 1999). La dernière à contribuée à elle seule pour 23% du transport observé en 6 ans.

Date	Pluie mm	V stocké m3	V déversé m3	V total m3	Qmax m3/s	Erosion calculée T	Sédiment exporté calculé T	Envasement calculé m3
27-28/11/99	51.0	23 100	0	23 100	1.000	340	0	283
29-30/11/99	145.5	35 773	294 892	330 665	35.400	11 120	7 962	2 632
Envasement mesuré (m3)			**2 846**	**Envasement calculé (m3)**			**2 915**	

Tableau 3 : Validation de la simulation du transport solide crue par crue sur l'événement du 27 au 29 Novembre 1999

CONCLUSION

La forte variabilité des érosions observées sur 24 bassins versants, tous situés dans la dorsale tunisienne, montre la difficulté de mettre au point un système d'estimation simple pour prédire l'envasement des barrages. Les mesures effectuées doivent cependant être interprétées en fonction des particularités de chaque bassin pour arriver à dégager des indicateurs pertinents. La géologie, la taille et la forme du bassin et l'occupation des sols semblent être les indicateurs adéquats. Les bassins sur marnes gypseuses et ceux fortement défrichés sont les plus sensibles. Dans les bassins allongés où le réseau hydrographique entaille des formations dures (calcaires), les barrages sont protégés, les produits de l'érosion se déposent aux ruptures de pente.

Le bassin versant d'El Gouazine montre aussi l'efficacité des aménagements anti érosifs en banquettes mécaniques isohypses. Le facteur aKLSCP du modèle passe de 0.6 à 0.05 après l'aménagement, cela correspond à une diminution globale de l'érosion d'un facteur de 10.

Les lacs sont de très bons pièges à sédiments. Ils remplissent un rôle de protection pour des barrages de plus grandes tailles situés en aval. Mais leur colmatage rapide va à l'encontre d'un développement agricole. Implantés dans des environnements fragiles et à faibles activités économiques, ils sont perçus comme une ressource supplémentaire, rare et vitale : l'eau. Pour pérenniser cette ressource, l'aménagement des versants pour protéger ces lacs devient une priorité. La nature et la densité de ces aménagements doivent concilier la réduction du transport solide sans pour autant priver le lac de ces apports en eau par ruissellement.

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Chalk aquifer characterization using Magnetic Resonance Sounding (MRS) at Le Bois de Cize, near Ault (Picardie, France)

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The presence of water within chalk has a consequence on pore pressure whereas the amount of water can influence the rock's mechanical characteristics. Water content thus constitutes one of the major parameters controlling collapse mechanisms.
Within the framework of the ROCC programme, nine MRS measurements (T1 to T9) were carried out along a profile perpendicular to the chalk cliff at the "Le Bois de Cize" site near Ault (Fig. 1). The aim was to test whether MRS is capable of resolving the geometry and characteristics of the chalk aquifer. Other geophysical investigations and a borehole reveal that the subsurface is composed of 5 to 10 m of clay underlain by weathered chalk down to 30 m and fresh chalk beneath.
The decay-time cross section (Fig. 2b) shows that the water level detected by MRS lies at a depth of -30 to -40 m in the southeastern part of the profile and that it appears to drop suddenly to -55 to -60 m about 400 m from the cliff edge. These MRS results are coherent with a) regional knowledge that the water level is about 40 m below surface on the chalk plateau, and b) the borehole drilled 120 m from the cliff edge showing a water level at -73 m.
The sudden drop in the water level could be related to a small valley named "Deuxième Val" on the IGN map (Fig. 1), and which may reflect a preferential drainage structure that could be the cause of water-table depression.
The water-content cross section (Fig. 2a) shows that water content is greater than zero above the water table. By comparison with other experiments (Cyprus, "Région Centre" in France), it appears that fixed water in the unsaturated zone can be detected by MRS in rocks with low magnetic susceptibility (limestone, chalk) and that this may account for 5 to 40% of the water content observed on the cross section.
These preliminary experiments show that the MRS method is capable not only of defining the geometry and characteristics of the chalk aquifer below the water table, but also of characterizing the unsaturated zone. MRS can be used to select the best locations for drilling observation wells and it may provide information that no other method can, i.e. that concerning water in the unsaturated zone.
Since the geometry of the chalk aquifer and the unsaturated zone are assumed to be 3D rather than 2D, complementary MRS measurements are proposed for the "Le Bois de Cize" site. Additional field and laboratory studies are also recommended in order to calibrate the water content derived from the MRS data.

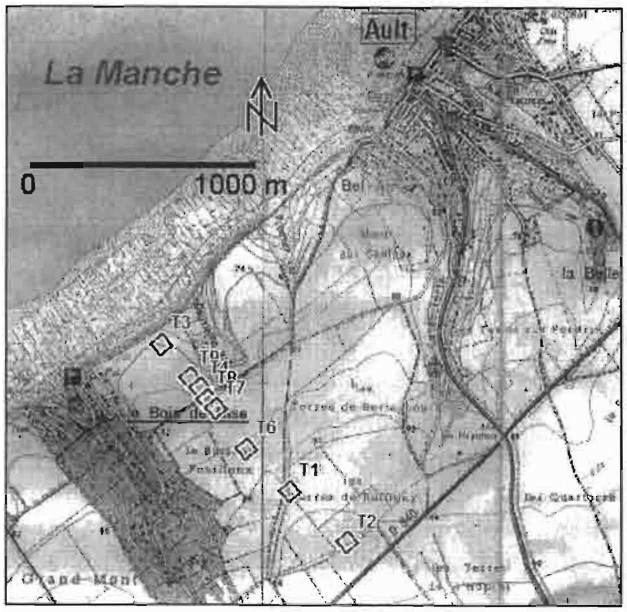

Figure 1: Map of the study area showing the location of the MRS profile (taken from the 1/25000 IGN map n°2007E)

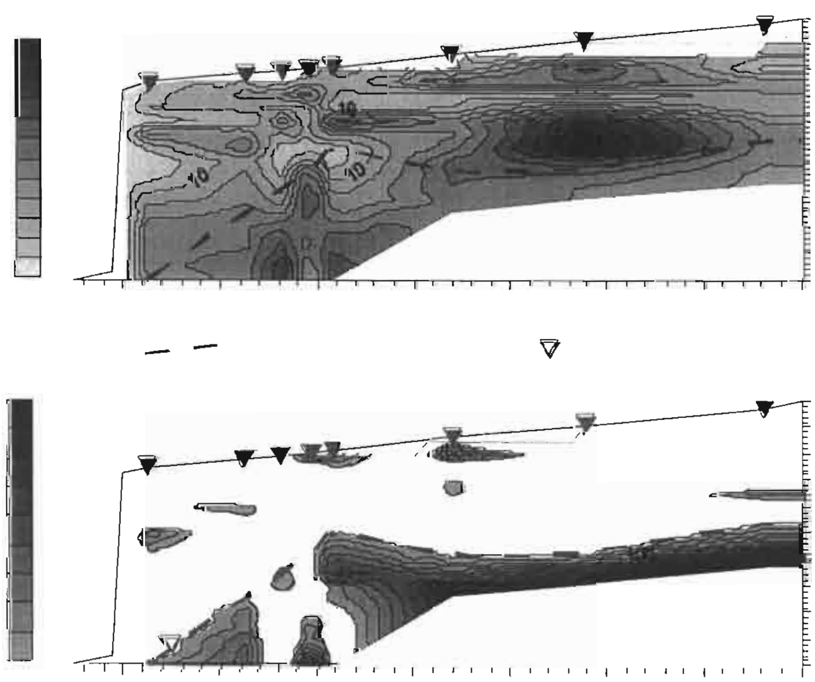

Figure 2: Cross sections of a) water content and b) decay time

Fonctionnement biogéochimique d'une plaine d'inondation en zone sahélienne

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Les paysages sahéliens sont réputés pour être des systèmes pédologiques pauvres en éléments mobilisables utiles à la chaîne trophique. Aussi, de nombreuses études ont pu montrer l'importance de l'organisation des formes du paysage et de son exploitation sur la dynamique spatio-temporelle des flux de nutriments. Or dans le delta intérieur du fleuve Niger au Mali, immense plaine d'inondation de 30 000 km^2 située en pleine zone sahélienne, nous avons montré dans un précédent travail, que l'évolution des concentrations en nitrate, phosphate et ammonium dissous dans les eaux de surface du delta intérieur du Niger décrivent un cycle annuel basé sur le cycle hydrologique, aussi bien dans les eaux du fleuve Niger que dans celles des chenaux et des mares pérennes ou non. Aucune influence des systèmes d'exploitation n'a pu être décelé, tout se passe comme si l'inondation homogénéisait l'ensemble.

Par ailleurs, des études basées sur des bilans de masse entre les apports provenant du versant et les sorties de la zone humide ont montré que les zones inondables pouvaient réduire de façon significative les flux d'azote et de phosphore les traversant, résultat donnant lieu au concept de zone tampon. Qu'en est-il en milieu tropical inondable ?

Cette opération de recherche a été réalisée dans le cadre du projet Gihrex de l'IRD, ayant pour objectif d'aboutir à une modélisation de la productivité du delta intérieur du Niger en fonction de la variabilité hydrologique et des stratégies d'exploitation. Il s'est donc agi entre autres, d'avoir une meilleure connaissance sur les flux de matières qui règlent le fonctionnement du delta intérieur du Niger en relation avec son exploitation. Dans cette zone sahélienne, l'arrivée des eaux fluviales à la faveur des crues annuelles est à l'origine d'un foisonnement de vie donnant lieu à un fort potentiel de production en ressources naturelles renouvelables : poissons, terres fertiles et pâturages. Trois systèmes d'exploitation majeurs (la pêche, l'agriculture et l'élevage) se partagent l'espace et le temps selon le rythme saisonnier imposé par le cycle hydrologique du fleuve Niger. Les premières mesures de qualités chimique, organique et biologique de l'eau montrent que cet écosystème d'une richesse apparente toujours renouvelable est un système oli-mésotrophe, où toute activité trophique est soutendue par l'accès à la ressource primaire. A partir du cumul des informations issues de l'évolution des concentrations et du calcul du bilan de masse entrée-sortie sur une plaine de 750 ha, on met en évidence le fonctionnement biogéochimique d'une plaine d'inondation.

A la fin des basses eaux, l'eau de la mare est une concentration de solutions due à plusieurs mois d'évaporation et à un léger apport par ruissellement des eaux de pluie de juillet sur les bordures de mares. Pendant la montée des eaux, les concentrations fluctuent fortement au rythme des apports de la crue, c'est-à-dire des apports du fleuve. Les concentrations en nutriments ne sont que légèrement inférieures à celles du fleuve, indiquant une légère consommation dans la plaine et non dans le fleuve car celui-ci a une hydraulicité trop forte. A ceci se surimpose les apports ponctuels des eaux de ruissellement des pluies, le tout donnant lieu à de fortes variations de teneurs durant cette période de montée des eaux (variations non enregistrées dans les eaux du fleuve). Puis, à la fin de cette phase de montée des eaux, les concentrations en nitrate et phosphate diminuent par simple effet de dilution (les concentrations du fleuve deviennent inférieures à celles de la mare) alors que les concentrations en ammonium restent au même niveau dans la mare (au centre de la plaine) ou

augmentent brusquement dans les eaux du fleuve et des mares satellites. Cette augmentation est liée à l'inondation des hautes berges qui provoque une mise en solution importante d'ammonium. Or cet ammonium ne peut être consommé que dans les zones à faible turbidité et faible courant. Tout le long de la période des hautes eaux correspondant à l'inondation généralisée, les concentrations en ammonium restent hautes dans les zones à forte hydraulicité malgré une turbidité décroissante. Durant cette période, il y a consommation partout (du fleuve à la mare) des nitrates et phosphates, en même temps qu'une baisse des apports amont. Puis lorsque les eaux rejoignent le lit mineur du fleuve, les concentrations en ammonium, nitrate et phosphate reviennent à leur niveau de base respectif. Le niveau de nitrate et phosphate des eaux du fleuve lors de la décrue devient alors un facteur limitant de la consommation possible en ammonium et donc de la productivité végétale de la plaine, d'autant qu'il s'agit d'une période végétative de croissance pour les plantes de récolte. Enfin, à partir de mars, l'écosystème est à nouveau fermé et les teneurs dissoutes des eaux évoluent uniquement par concentration liée à l'évaporation.
Cette évolution du fonctionnement biogéochimique de la plaine de Débaré met en évidence toute l'importance de l'hydrologie et de la turbidité des eaux sur la consommation en nutriments de cet écosystème et donc finalement sur le bilan stock/consommation en azote et phosphore de la plaine. Ainsi les matières en suspension et la vitesse du courant sont les seuls paramètres explicatifs de l'évolution différentielle des teneurs en nutriments de la plaine par rapport aux apports des eaux du fleuve, la turbidité de l'eau dépendant d'ailleurs notamment de la vitesse de l'eau. On en conclut que $N\text{-}NO_3$ et $P\text{-}PO_4$ sont stockés lorsque les MES sont faibles indifféremment de la vitesse du courant alors que les $N\text{-}NH_4$ le sont uniquement lorsque les MES et les vitesses sont faibles, le tout étant à chaque fois contrôlé par la concentration de l'apport de l'amont. Cela revient à dire que dans les plaines inondées du delta intérieur du Niger l'azote et le phosphore ne peuvent être stockés qu'en périodes de montée des eaux et de début des hautes eaux, alors que $N\text{-}NH_4$ ne peut être stocké qu'en période de début de hautes eaux. Notons que le fleuve ne réunit jamais les conditions favorables à la consommation de $N\text{-}NH_4$.
Finalement, les bilans entrées/sorties de la plaine permettent d'établir que cette plaine consomme 2,3 kg ha^{-1} an^{-1} de NO_3, 0,4 kg ha^{-1} an^{-1} de PO_4 et 0,7 kg ha^{-1} an^{-1} de NH_4, ce qui équivaut à une consommation de 80 % des apports en nitrates et phosphates et seulement 55 % des apports en ammonium. Les plaines d'inondation du delta intérieur sont donc des puits à phosphore, et dans une moindre mesure à azote. En effet, la plaine d'inondation est bien une formidable usine à production de biomasse végétale, à boucle de productivité rapide, limitée cependant par de faibles teneurs en nitrate et phosphate dissous des eaux apportées par la crue du fleuve, d'où une non-consommation de l'azote provenant de l'ammonium.

Can Sph be suitable methods for modeling shallow water flow ?

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The poster presents a smoothed particles hydrodynamics (abbrev. as SPH) system, modeling water flow in a linear canal of constant width. The problem is usually modeled by the Saint Venant equations for the 1-D shallow waters. A short historical survey of the approach, which appeared originally in the context of Astrophysics [Lucy 1977] [Monaghan 1977] is given first. In the context of incompressible fluids [Monaghan 1994][Morris 1996] and especially water flow [Zhu 1997], there have been several contributions, including recent work undertaken by D.Servat as part of a PhD thesis as well as in conferences and publications [Servat &al 1999, 2001]. The intent here is to provide a complement to Servat's work both in the modeling and analysis of SPH systems arising in the case of shallow waters in a canal.
A brief description of the contents is as follows:
First, the basic principles underlying the derivation of an SPH model from an original hydrodynamic or whatever model are summarized, and related to the context of meshfree particles methods [Belytschko & al, 1996, 1998]. Let us just mention that the principle of SPH is to move from a continuum (Eulerian) viewpoint to a discrete (Lagrangian) viewpoint: the water is viewed as a collection (finite or infinite) of particles, each of which consists of a packet of water whose shape changes with time. The end-product is a family of ordinary differential equations, governing the time evolution of the state of each particle.
This is the general scheme, it has been applied here to the PDE 1-D shallow water equations [Chow & al 1988]: a detailed description of the state variables and hypotheses is given, this would be the second part of the poster. The SPH system is stated both in the form obtained from general principles, and then in a form, which comes out from a partial integration,. From the latter form, it appears that the core of the SPH is a system of first order differential equations relating the position and velocity of the particles.
The third part of the presentation reports on the main theoretical results that have been obtained in the study of the SPH system. There are two aspects. The first one is about the way the SPH formulation copes with fundamental properties of the original equations and whether it preserves some invariants. Namely, it has been shown, and is reported here, that the SPH system preserves the mass, momentum and the energy of the system of particles. The other aspect is about the behavioral properties of the SPH system, notably, how it reacts to small perturbations of the uniform flow. A linear stability study is performed and shows the onset of waves of arbitrary spatial frequency, as a response to such perturbations. The main achievements, in our view, are formulas, expressed in terms of the parameters of the system and the wave spatial frequency, for the wave speed. We show in particular that under a scaling assumption, namely that the wave length be large compared to the depth, the wave speed does not depend on the spatial frequency and the formula, in this case, is close to the one derived from the continuous equations [Stoker 1958]
The fourth part of the poster reports on the reciprocal step, that is, to move from the approximation by SPH system to the exact model. Interpolation formulas for the state variables of the continuous model in terms of the state variables of the SPH system are proposed. These are indeed only approximations of the solutions of the full Saint Venant

equations: good agreement with the latter ones is achieved though, which is reflected by the fact, shown in the poster, that the continuity equation is exactly satisfied (by the interpolate solution) and the discrepancies in the momentum equations can be estimated.
Finally, the dynamical behavior of the SPH system is illustrated by numerical simulations, whose results are shown in several figures, and a discussion is made as to the time discretization scheme to be used in the simulator of the SPH system.

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Agent-based vs. PDE modeling of runoff dynamics :simulation experiments

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Modeling the spatio-temporal evolution of the distribution of water depths and velocities is needed to account for the complexity of rainfall-runoff processes : influence of topography, soil roughness, infiltration properties of the soil, presence of natural or human-made obstacles on preferental paths, etc. That is why deterministic models based on partial differential equations (PDE) of water hydrodynamics have been widely used during the past few years [lane98] [zhangcundy89]. Among them, shallow water equations or StVenant equations [vreugdenhil94] are often applied to the study of flow dynamics on a 2D surface covered by a small depth of running water. The use of these models is yet complex when dealing with other processes which interfere with runoff, i.e. resulting in complex boundary conditions [leonard et al99]. Thus, alternatives have been proposed among particle-based simulation techniques which rest upon a discretization of both flow and medium, e.g. lattice-gas simulations [garciasanchez et al96] and random walker moves [cravegascuel-odoux97], [favismortlock et al98] or [murraypaola94]. Yet their formulation either restricts the application domain to processes well beyond the scale of a field, or imposes a simplified vision of the temporality of processes.

In this context, we undertook a methodological and applied research on particle-based models which would provide a suitable balance between physical soundness and scale of application, close to that of shallow water equation PDE schemes [servat et al99]. The need to handle temporal interactions led us to give particles physical, computed velocities defined at the scale where gravitational or other forces induce water depth variations, with the assumption that water depths are represented by local densities of particles, resulting in simple gradient-based principles for the dynamics. The need to handle spatial interactions at different scales led us to favor a strict independence between particle motions and the description of the underlying medium, possibly structured in different layers - soil, topography, vegetation. For this purpose we considered space as meshless, continuous rather than described by a grid of cells : we believe such an unconstrained definition of space shall better enable the use of different representation structures for the description of the environment. The calculations on this meshless, continuous space - motions, velocities, etc. - involve interpolation techniques in the neighborhood of each particle, borrowing from the Smoothed Particles Hydrodynamics (SPH) approach [monaghan92] which was first developed in astrophysics then recently applied to water flows [zhu et al97].

The interest of particle-based approaches lies to a great extent in their ability to provide insights on the destiny of each particle throughout time and give precise knowledge of flow trajectories and transfer times. That is why we favored in our model an extension of the notion of particle towards a broader concept of an abstract, computational entity which is granted some means of coping with its own historical data - positions, velocities, neighboring particles, etc. We called it waterball agent. The simulation of water flows can be seen as the dynamics of a population of waterballs. From this point of view, our simulation approach is inspired by the multi-agent systems theory [gasserhuhns89] in computer science, and served as a challenge application for our own research in this field [servat et al98] [servat00].

Instead of presenting a thorough description of the model - we refer to [servat et al01] for a complete analysis -, the present contribution focuses on simulation experiments involving our model and a PDE model, already validated on a real square-meter topography. These comparison experiments enlighted the potential of our approach which, albeit not conceived as a numerical, particle-based resolution of the shallow water equations, did show a conceptual and numerical proximity with the PDE model. The essential variable in the shallow water equations, the water depth, was assumed to be represented by local densities of waterballs, and beside the difference in methods to compute densities and gradients, due to our use of a meshless, continuous space, both principles of motion appeared to be rather close to one another. As a complementary investigation on this numerical and conceptual proximity we refer to the mathematical analysis provided in our coupled contribution [treuil et al01], which focuses on how to derive and consequently analyze our equations of motion based on SPH formalism from shallow water equations.
This core model is intended to lead to a series of extension that will take into account other hydrological processes, such as infiltration and erosion. The simulator we are developing rests upon interacting computer agents that represent either hydrological (waterballs, water paths, ponds, rain) or natural objects (soil areas, dikes, topograpkhy, vegetation, etc.). This radical distribution feature provides the ability to handle multiple level of representation of runoff dynamics. We are leading an investigation on automatic recognition of emergent water structures in the course of the simulation [servat00phd]. When waterballs agglutinate over local depressions, a pond emerges. In the simulator when such situations occur, the involved interacting waterballs regroup with one another and together create a macroscopical entity representing the whole pond. When waterballs follow the same path, they regroup in a water path. Such layered representation of the dynamics gives a complementary information source in-between a microscopic description of processes and macroscopic indicators which synthesize partial aspects of it (as does a rainfall/runoff rate for instance). In a long term perspective, we believe such constructions will enable new ways of coupling different processes by introducing specific laws of behavior at the scale of these macroscopic entities.

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