Workshop Proceedings

'SCALE AND VARIABILITY ISSUES IN THE SOIL- HYDROLOGICAL SYSTEM'

The 25-27th of August 1999 at Wiks Castle, Sweden

Editor: Annemieke Gärdenäs

Organised by:
Swedish University of Agricultural Sciences, SLU,
Royal Institute of Technology, KTH, Sweden &
Technical University of Denmark, DTU

Institutionen för markvetenskap
Avdelningen för lantbrukets hydroteknik

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PREFACE

This report comprises the abstracts of the papers and posters to be presented at the international workshop **'SCALE AND VARIABILITY ISSUES IN THE SOIL-HYDROLOGICAL SYSTEM'**, at Wiks Castle, Sweden the 25-27th of August 1999.

The main objective of the workshop is to discuss the state of the art in scaling and variability issues within environmental physics and chemistry and to clarify the most interesting future developments. For example, consequences for estimation of leaching of pollutants of upscaling from hydrological characteristics estimated in the laboratory to field scale are discussed. Another issue is how to deal with spatial and temporal variability within different scales. The workshop includes three sessions of oral presentations, **'From pore to pedon'**, **'From pedon to field'**, and **'From pedon to catchment'** and a poster session. Altogether, 28 papers are presented by 44 participants from 15 different countries.

The workshop is organised by the Swedish University of Agricultural Sciences, SLU (Per-Erik Jansson, Nicholas Jarvis, Annemieke Gärdenäs) in co-operation with the Royal Institute of Technology, KTH, Sweden (Georgia Destouni) and the Technical University of Denmark, DTU, (Karsten H. Jensen). International Association of Hydrological Sciences sponsored the workshop with announcements in their journal Hydrological Sciences Journal.

On behalf of the organising committee, I would like to welcome you to interesting presentations and discussions. We appreciate the contributions of the participants very much!

Annemieke Gärdenäs

Uppsala, August 1999

CONTENTS

SESSION I: FROM PORE TO PEDON

SESSION II: FROM PEDON TO FIELD

CONTENTS CONTINUED

SESSION III: FROM PEDON TO CATCHMENT

POSTER SESSION

CONTENTS CONTINUED

SESSION I,

"FROM PORE TO PEDON"

SOIL PHYSICAL PROCESSES FROM THE PORE TO THE PEDON

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The past several decades has seen tremendous progress in the conceptual understanding and mathematical description of vadose zone flow and transport processes. A large number of analytical and numerical models of varying degrees of complexity and dimensionality are now available to predict water flow and solute transport in variably-saturated porous media. The purpose of this presentation is to highlight recent progress in flow/transport research at especially the local (pedon) scale. Improved process-based understanding of underlying processes, continued advances in numerical methods development, and the presence of increasingly powerful computers, are now making it possible to couple the most important flow/transport processes and soil/rock properties relevant to a particular problem. Examples involve multicomponent major ion chemical transport, simulations of the soil-plant-atmosphere continuum, and multiphase flow. Special attention is focused on the problem of preferential flow in variably-saturated structured (fractured or macroporous) media, and the need for more user-friendly software to enable a more effective application of models to a variety of flow/transport problems in research and management. Also discussed is a recently developed hierarchical neural-network approach for improved estimation of the unsaturated soil hydraulic properties, and their uncertainty, from more readily available or more easily measured data.

FROM LOCAL HYDRAULIC PROPERTIES TO EFFECTIVE TRANSPORT

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Soils are heterogeneous porous media and this implies that the hydraulic properties vary in space. Therefore, knowledge of the spatial structure of hydraulic properties, i.e. of the corresponding parameter field, is a prerequisite to predict the flow and transport behavior in heterogeneous systems. In the past years, much emphasis is given on the parameterization of hydraulic properties. The spatial structure of hydraulic parameters, however, is rarely addressed, because direct measurements of continuous parameter fields are very difficult. In our contribution, we present an approach where the effective solute transport behavior at the scale of a soil column (100 mm) is predicted by taking into account the spatial structure of the hydraulic properties at the local scale (1 mm).

An undisturbed soil column, 10 cm high and 16 cm in diameter, was taken from the upper A-horizon of a silty agricultural soil (Orthic Luvisol). The breakthrough curve of bromide was measured during a constant irrigation experiment and was characterized by the mobile-immobile solute transport model. Then, the soil column was saturated with water and scanned in 1 mm sections using a medical x-ray tomograph to get a 3-dimensional image of densities within the entire soil column. The greylevels of the images obtained by the CT-scanner are related to the local x-ray absorption coefficients which themselves are linearely related to the local bulk density within the water saturated soil column. By postulating that bulk density is a proxy for hydraulic properties, i.e. regions with the same density have the same hydraulic properties, the x-ray images can be interpreted as a representation of the three-dimensional spatial parameter structure of hydraulic properties within the entire soil column. As a first approximation, the x-ray image was partitioned into two different density classes separating the dense aggregates and the less dense matrix.

The local hydraulic properties for the less dense matrix were deduced using a network model which was based on the directly measured pore geometry including pore size distribution and pore connectivity. Considering the dense aggregates, no measurements of the hydraulic properties were available.
Morphological investigations showed that there are only very few pores > 0.04 mm within the dense aggregates. Consequently, we choose the air entry value so that water is not allowed to desaturated under the experimental conditions regarded here.

The effective hydraulic conductivity of the soil column was measured during the constant irrigation experiment and was split up between the dense aggregates and the less dense matrix.

A STATISTICAL DISTRIBUTION FOR MEASURING SOLUTE- AND WATER-FLUX HETEROGENEITY IN VADOSE ZONE EXPERIMENTS

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Multiple sampling is widely used in vadose zone percolation experiments to investigate the extent in which soil structure heterogeneities influence the spatial and temporal distributions of water and solutes. In this paper, a simple, robust, statistical model, based on the beta-statistical distribution, is proposed as a method of quantifying the magnitude of heterogeneity in such experiments. The model relies on fitting only two parameters to the cumulative elution curves generated in multiple-sample percolation experiments. These parameters are incorporated into a single measure of heterogeneity, called the Heterogeneity Index (HI). The model does not require knowledge of the soil structure. A homogeneous or uniform distribution of a solute and/or soil-water is indicated when HI = 1 and heterogeneity is indicated by HI > 1. A large value for this index may indicate preferential flow. The heterogeneity index relies only on knowledge of the elution curves generated from multiple sample percolation experiments and is, therefore, easily calculated. The index may also be used to describe and compare the differences in solute and soil-water percolation from different experiments. The use of this index is discussed for several different leaching experiments.

Keywords
Soil heterogeneity, soil-water, heterogeneity index, solute, contaminants, nutrients, preferential flow, nitrate, chloride, phosphate, beta distribution.

IN-SITU METHOD FOR DETERMINING SUBSURFACE UNSATURATED HYDRAULIC CONDUCTIVITY

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The characterization of the hydraulic properties of the deep zone of variably saturated and porous material is critical to predictions and modeling of transport processes between the soil surface and the groundwater. The complexity and the high costs associated with sampling in the deep vadose zone create a need for cost-effective, simple and physically sound methods for estimation of subsurface hydraulic properties. A method for the determination of unsaturated hydraulic conductivity in-situ was developed and field-tested. The new method is based on (i) steady flow from a small subsurface cavity; (ii) the transient behavior of the initial stages of the same infiltration event as in (i) from the same subsurface cavity. Measurements of water pressure within the cavity and the associated discharge are used to infer the soil's saturated hydraulic conductivity (Ks) and capillary length (α). A probe for conducting the measurements was designed and field-tested, and a measurement-protocol was established. Comparisons were made with existing surface and subsurface-based methods. The results show that the method provided estimates of the soil parameters that are in a close agreement with those obtained using the other surface or subsurface in-situ methods.

DETERMINING SOIL WATER RETENTION CURVES IN FIELD SCALES

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The soil water retention curve is an important part of physical based hydrological models, especially for small scale investigations. There exist a lot of models - with and without hystereses - for its parametrization, which show at frequently occurring soil moisture values, near field capacity, a nearly similar behaviour. The main problem is not to fit a model, but to get representative experimental data for field scales.
In principle there are three main methods for determining the water retention curve. The use of the grain size distribution and transfer-functions from literature give first values, but some soil properties are disregarded, for example skelet. Laboratory measurements at soil samples is only useful in homogeneous soils and needs undisturbed representative samples. In heterogeneous soils the representative unit volume can be greater than 1 m^3, than a laboratory measurement is not possible. The simultaneous measurement of soil suction and moisture in situ is dependent of an appropriate soil moisture measurement and has often a lack of data under dry conditions. The different problems show the necessity of a stand specific method for parametrization.

This paper tries to show a method for parametrization for a heterogeneous, skeletal soil. In 2 different research stations, one with a homogeneous soil, the other with a heterogeneous, skeletal soil, we used different methods for determining the water retention curves. Even in the homogeneous soil we found a great difference between the methods and various soil samples. Therefore the attempt to determine an average water retention curve for a heterogeneous soil needs an optimized strategy, which takes the representative unit volume in consideration.

A depth dependent water retention curve cannot be determined in such a soil. For the root zone in a continuous drying period the soil suction between different layers will be in balance. Measuring the soil suction and the soil moisture in different depth in the root zone provides averages for the whole water available for plants. In a period of artificial drying, the soil moisture decreases continuously up to wilting point. The use of TDR-probes and Tensiometers allows continuos measurements for the drying period up to soil suctions of 90 kPa. Equitensiometers provide further information of the soil suction up to values of 1 MPa.
Together with an accurate calibration of the TDR measurements it was possible to fit a water retention curve for this heterogeneous soil. The comparison of this result with normally used methods demonstrate the necessity of such an strategy, which averages over large volumes.

RESIDENCE AND MOVEMENT OF SORBED AND COLLOIDAL CONTAMINANTS IN SOIL PORES

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In studies of water-borne pollutants through and out of soil, attention has recently been moving towards sorbed or colloidal transported contaminants where processes are more complex than for solutes such as nitrate. Such contaminants include phosphorus, some pesticides, and biological micro-organisms. There are restrictions on movement of such substances due to sedimentation, straining and filtration of colloids, and due to sorption of contaminants by soil minerals, leading to long residence times in the soil profile. There is also competition between static sorption sites and sites on otherwise harmless colloidal material. Restrictions on movement of colloids are very dependent on the size and geometry of water-filled soil pores.

In this paper, the size distribution of water filled soil pores (both matrix pores and macropores) is first estimated theoretically from hydraulic properties using a combination of the capillary equation and Poiseuille's law. Assumptions have been made about the variability of pore sizes and geometry along flow paths which can cause restrictions on movement of particles. Such restrictions can be described in terms of the processes of sedimentation, filtering and straining in relation to pore sizes as discussed in the extensive literature on deep bed filtration.

Information has been collected on typical sizes of colloidal particles (mainly clay particles and organic matter derived from manure), which have large numbers of sites for contaminant sorption. Similarly, size ranges are defined for micro-organism types, the smallest (viruses) being extensively sorbed like chemical contaminants, the largest (protozoa) being themselves colloidal particles, while bacteria are in the intermediate size range and exhibit some of the behaviour of both viruses and protozoa.

A set of equations has been defined representing a model of colloid movement and contaminant sorption in laboratory column experiments. Using this model, filtration coefficients and parameters of sorption isotherm equations for different soil types and contaminants are estimated from column experiments (some previously reported in the literature). These equations will later be linked to a field scale hydrological model (such as SOIL or MACRO), and (in simplified form) to a catchment scale hydrological model.

COLLOID TRANSPORT IN LARGE, VARIABLY SATURATED SAND COLUMNS

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Facilitated transport by mobile colloids is a potentially important transport mechanism of strongly adsorbing contaminants in soils. Colloids are mobile in some subsurface environments, and the mobility is controlled both by chemical interactions between colloids and immobile matrix surfaces and by hydrological factors that control flow rates and flow paths of the water. Research so far has focused on colloid and colloid-facilitated transport in saturated soils. Very few studies address the question of colloid transport in unsaturated soils although colloids are found in higher concentrations in soil water than in groundwater. The fact that the majority of potential contamination sources are located at the soil surface or within the unsaturated zone, requiring transport through the unsaturated zone before the groundwater is reached, highlights the need for improved understanding of the processes controlling transport of dissolved and suspended substances in the unsaturated zone. The work presented here focuses on colloid transport in variably saturated soils. The macroscopic effect of pore-scale colloid processes controlling the transport is investigated in the laboratory, using large homogeneous sand columns.

Replicate experiments were conducted in 35 cm long columns with a diameter of 14 cm. The columns were packed with well described washed sand; two different sand types were used. Different water fluxes corresponding to different water contents were applied from the top at a constant rate. By introducing suction at the bottom a uniform distribution of water was obtained throughout the column. Measurements of water content were made by TDR-probes and water tension was measured using tensiometers. Saturated colloid transport experiments with similar pore water velocities as in the unsaturated experiments were made for comparison. A pulse of several pore volumes colloid suspension was applied at the same rate as the colloid-free suspension. Fluorescent latex microspheres with a diameter of 477 nm were used as model colloids whereas chloride was used as the non-reactive tracer.
Results show that the transport of colloids is highly dependent on the water saturation. The initial breakthrough of colloids occur simultaneously or slightly prior to the chloride breakthrough. As the water content decreases an increasing amount of colloids is retained in the column. This observation infers that the colloids are retained not only due to straining and sorption to the grains. Sorption to the air-water interface is an additional mechanism which increases the colloid retention and control the mobility in unsaturated homogeneous soils.
A recently developed conceptual and numerical model for simulation of colloid transport in unsaturated homogeneous columns is used for analyzing the experimental results. The model is among the first to include the retarding effects of the air phase, conceptualized as a second sorption mechanism, which depends on the degree of air saturation. Preliminary results have shown that the model satisfactorily can reproduce the experimental breakthrough curves when the sorption parameters are fitted, whereas the model fails to simulate the observed data, when parameters are estimated independently.

DEVELOPMENT OF PREFERENTIAL FLOW IN POROUS MEDIA DUE TO BIOLOGICAL CLOGGING

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The influence of a growing biomass on the hydraulic properties of porous media was investigated in a laboratory column inoculated with bacteria. The feed solution contained only acetate and nitrate, the flux of water was constant, and concentrations were measured at six sampling ports and in the outlet. Pressure measurements were made in order to quantify indirectly the reduction in hydraulic conductivity (K) along the column.

Significant growth was observed by measuring the initial and starting biomass concentrations over the column. This correlated well with the calculated reduction in K (up to four orders of magnitude in the first section of the column). Pulse tracer experiments with a non-reactive tracer (Cl) were carried out prior to and during the experiment. Prior to and early in the experiment, breakthrough curves reveal uniform flow indicating porous single-porosity flow.

At later times, during the time with significant growth and biomass build-up, breakthrough curves indicate a change to what looks like preferential flow. Fitting an advection-dispersion model (CXTFIT) to the pulse experiments, show that the longitudinal dispersivity increases several orders of magnitude, from the mm to m scale. The late time pulse experiments could only be fitted with a very low pore water velocity and a meter scale dispersivity. Allowing for dual-porosity and linear diffusion between the two porosity domain could, however, also explain the observed breakthrough and maintain mm scale dispersivities. The distribution of porosities (mobile and immobile) were in agreement with numerical predictions by a reactive transport and biomass clogging model and suggests that preferential flow developed during the course of the experiment.

Presently, 2D flow experiments are carried out to further investigate the effects of biological clogging on flow.

SESSION II,

"FROM PEDON TO FIELD"

SOIL CHEMISTRY IN RELATION WITH THE SCALE PROBLEM

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Chemical reactions in soil (and groundwater) are typically quantified by equilibrating a designated quantity of soil with an electrolyte which is followed by a controlled perturbation of this equilibrium (in batch, by titration, or by column flow experiments). In view of the microscopic heterogeneity of soil, the chemical reactions and their kinetics must be regarded as an overall process that averages 'individual' reactions. The inferred process descriptions are therefore apparent or operational process descriptions only. This has severe drawbacks on mono-solute chemical descriptions that are based only on variation of the main component under consideration and which are only relevant as limiting situations in reality. Such descriptions are illustrated to be inadequate in general by an example of reaction kinetics. On the other hand, descriptions that take every possible interaction into account lack focus and are not practical. As is the case for other earth sciences, the challenge is to consider the dominant chemical interactions with due consideration of the accuracy of the final result.

Mechanistic studies of chemical interactions may provide basic information on the behavious of dirty real world systems like soil. An impression of the methodology and its results is presented, where the translation from reasonably purified sorbing substances to a soil column, a field soil, and natural lake chemistry is shown. In other words, the chemistry of pure substances can be upscaled to real world systems. Such an upscaling procedure is necessarily associated with a loss of generality, as upscaling is not only scale dependent but also dependent of the dominating mechanisms. The latter may differ from one system to another. However, the loss of generality must not be viewed as a shortcoming of the approach as it implies advanced understanding of 'what is going on' in one system or in another. As will be shown, the upscaling to larger soil volumes leads to at least two problems: (i) the properties vary spatially and (ii) pure substances chemistry is replaced by competitive substances chemistry. Both problems can be easily demonstrated with the available literature and this will be done with examples arising from soil physics/chemistry and for the effect of contamination on biota. Whereas these complications are involved in upscaling perse, it may be recognized that the upscaling is commonly done to approach the reality of actual soil or ground water systems. In such systems, state variables that are assumed to be constant in the original approaches may appear to vary, e.g. as a function of time. In that case, upscaling involves also the consideration of quite different dependencies than were accounted for in the "pure substances approach". For all three approaches, considerations involved in approaching the real world will be illustrated and commented upon.

SOLUTE TRANSPORT THROUGH PREFERENTIAL FLOW PATHS IN MUNICIPAL SOLID WASTE: SCALE EFFECTS.

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Solid waste deposits constitute integral parts of the soil hydrological system and pose a serious threat of polluting both groundwater and downstream surface water. There is therefore a need to understand and quantify the solute transport process in solid waste under different conditions. This includes investigating and quantifying the possible scale-dependence of the transport process and associated model parameters that may be expected due to the generally high and irregular spatial variability evident in solid waste deposits. If unresolved, such scale-dependence may seriously limit our ability to generalise and extrapolate laboratory and small-scale experimental results, such that they can be appropriately used for quantifying the field-scale transport process in environmental applications.

In this paper, we present experimental results from tracer tests performed in two different experimental set-ups: a large, undisturbed solid waste sample, and a pilot-scale experimental landfill. The undisturbed waste sample had a depth of 1.2 m and a volume of 3.5 m^3. It was taken up from a landfill containing 22 years old, degraded municipal solid waste with a dry density of 590 kgm^{-3}. Five tracer tests, using lithium as a conservative tracer, were performed under ponding and sprinkling conditions, at different flow rates. The pilot-scale landfill, constructed at Filborna landfill site, Helsingborg, Sweden, had a depth of 4.2 m and an experimental volume of 410 m^3. It contained the fresh municipal solid waste that arrives to the landfill site on a daily basis. The dry density of the landfill was estimated to 390 Kgm^{-3}. Also in the experimental landfill, a tracer test was performed using lithium as a conservative tracer.

All experimental breakthrough curves (BTCs), from both the tracer tests in the undisturbed waste sample and the test in the pilot-scale landfill, were highly and positively skewed, exhibiting early peaks and prolonged tails. A probabilistic Lagrangian representation of the transport process was used for model interpretation of all the experimental BTCs, which allowed for ready incorporation and investigation of three different transport models within the same modeling framework. The three different models were: a) an advection-dispersion model (the ADE model), b) a mobile-immobile water zone model (the MIM-model), and c) a bimodal solute advection model (the BIM model). The MIM-model assumes that the transport domain contains both mobile and immobile water zones and that a diffusional exchange of solute mass takes place between these zones. The BIM model assumes mobile water and solute advection in two different flow domains, one domain with fast, preferential flow, and one domain with slow flow.

The model interpretation suggests occurrence of fast, preferential flow in both the undisturbed waste sample and the experimental landfill. Although both the ADE and the MIM model can be fitted to the experimental BTCs, the obtained model parameters are not physically meaningful, yielding unacceptably high local dispersivity values. The BIM model can successfully interpret all the BTCs and cumulative mass recoveries, with apparently meaningful parameter values.

In the undisturbed solid waste sample, the BIM model suggests that all water is mobile, however with 55-70% of the infiltrating water flowing fast through preferential flow paths, which contain only between 5% and 16% of the total water volume in the sample. Also in the pilot-scale landfill, the BIM model suggests all water to be mobile, with 90% of the infiltrating water flowing through preferential flow paths. In this case, the preferential flow paths are quantified to contain about 47% of the total water volume in the landfill.

The solute transport process through the solid waste thus appears to be essentially the same in both experimental set-ups and scales, such that the same conceptual transport model can successfully represent it. However, the fraction of infiltrated water that moves through preferential flow paths appears to be considerably larger in the pilot-scale landfill than in the undisturbed waste sample. Physically, it seems reasonable that the coarser, fresh waste in the pilot-scale landfill is structured such that it leads to more channelling of water flow and solute transport through preferential flow paths than the old, degraded and more compact waste material in the undisturbed sample.

SOLUTE TRANSPORT THROUGH AN INTEGRATED SOIL-GROUNDWATER SYSTEM: THE ROLE OF DIFFERENT HYDROLOGICAL-PHYSICAL SPREADING MECHANISMS

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Transport of solute from areally distributed sources at the soil surface, through the integrated soil-groundwater system is influenced by many different factors. These include: (i) the longitudinal source distribution that causes spreading because solute that is deposited at different upsteam distances from a given control plane has to travel different lengths to reach that control plane, (ii) flow non-uniformity in the mean horizontal flow velocity that is caused by the infiltrating water through the soil surface, all the way along the different solute pathways to the control plane, (iii) flow heterogeneity that leads to high hydrodynamic dispersion, (iv) possible flow and transport through preferential flow paths and the associated diffusional mass transfer between mobile and immobile water zones, and (v) biogeochemical processes that may act on the solute as it is transported through the domain. We use a stochastic modeling approach to sorptive solute transport through an integrated soil-groundwater system that incorporates all these factors, to investigate the relative importance of the different hydrological-physical factors affecting solute spreading. Specifically, we evaluate the relative importance of random flow heterogeneity (as expressed by an advective solute travel time probability density function and the associated geostatistical parameters: log transmissivity variance and log transmissivity integral scale) on the spreading of the expected field-scale breakthrough curve (BTC) as compared to the spreading effect of the longitudinal source extent. Moreover, we also investigate the relative spreading effect of preferential flow and transport and the associated diffusional mass transfer between mobile and immobile water zones.

We show that, for both nonreactive and degrading solute, the dispersive effect of random flow heterogeneity decreases as the longitudinal source extent increases. Specifically, for a source that covers the whole soil surface of a considered transport domain, the temporal spreading of the expected field-scale solute BTC around the mean arrival time is dominated by the source geometry, rather than by flow heterogeneity. This does, for instance, imply that field tracer studies of stable isotopes, used to experimentally determine water residence time distributions in catchments, may not provide a sufficiently fine tool for identifying various flow heterogeneity effects that are important for the subsurface transport of solute originating from smaller sources within the catchment. Another implication is that the transport problem for solute sources of large extent relative to their distance to the control plane becomes essentially deterministic, since the source geometry is known deterministically, and the random flow heterogeneity effects are not so important. For transport further away from a distributed source, however, the dispersive effects of both random flow heterogeneity and preferential flow become increasingly more significant and need to be identified and quantified for understanding and predicting the field-scale solute transport behavior. The results and modelling approach presented in this study may, for instance, be of interest for identifying and quantifying dominant transport mechanisms in evaluations of nutrient leakage from agricultural fields and their subsurface transport to various sensitive environments, such as coastal zones.

FIELD-SCALE SOLUTE TRANSPORT – INTEGRATIVE VERS. POINT-SCALE MEASUREMENTS

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The experimental characterization of solute transport through the vadoze soil zone at field-scale may be achieved either by multiple point- or local-scale measurements or by monitoring an integrative signal such as concentration distributions in ditch or tile-drain discharge. The combination of both methods allows to assess qualitatively the error resulting from up-scaling local-scale measurements. Large-scale bromide transport was quantified at a 0.5 ha tile-drained field site by (i) averaging 35 individual breakthrough curves derived from classical displacement tests on small-sized soil columns that were taken at spatially distributed locations and (ii) by field tracer experiments with quantitative registration of drain discharge and bromide concentrations over three discharge periods. The bromide breakthrough curves (BTCs) from drain outflow measurements were also averaged to obtain one 'true' response signal of the entire experimental site.

The large-scale BTC derived from the column test exhibited double peak behaviour, reflecting the contribution of at least two flow domains on solute transport. The BTC from the tile-drain approach was dominated by early (preferential) bromide breakthrough; no significant second concentration rise was observed. Only the field test had large solute loss rates during the preferential peak. From the columns the predominant bromide fraction was leached during later stages of the test, when matrix-flow conditions governed solute movement.

Both experimental approaches had different boundary conditions and are therefore not directly comparable. However, a first model evaluation of the data revealed that local-scale methods might be suitable to identify processes relevant for the field-scale. Further efforts are needed to exactly determine the change of the quantitative contribution of the individual processes on overall transport during up-scaling.

STOCHASTIC ANALYSIS OF FIELD SCALE SOLUTE TRANSPORT IN HETEROGENEOUS VARIABLY SATURATED SOILS UNDER TRANSIENT FLOW REGIMES

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The purpose of this research is to quantify flow and transport prediction uncertainty in heterogeneous unsaturated soils subject to transient water flow regimes. A stochastic unsaturated flow model is developed based on Richards equation. This model predicts approximate means and autocovariances of the soil-water content, Darcy's flux and pore-water velocity as a function of the means and covariances of temporally random rainfall, spatially random saturated hydraulic conductivity, and spatially variable, temporally random water uptake. The pore water velocity statistics obtained from the flow model are incorporated into a stochastic advective-dispersive solute transport model that is derived in a Lagrangian framework. The transport model predicts approximate closed-form expressions for the mean and variance of the solute flux. Both inert solutes as well as reactive solutes affected by retardation resulting from a spatially random, linear equilibrium adsorption process are considered. Flow and transport model predictions are tested against extensive synthetic data generated from Monte-Carlo simulations for two soil types and two weather patterns.

Both the numerical Monte-Carlo experiments and the stochastic model demonstrate the dominance of the rainfall variability over that of the soil variability in determining overall prediction uncertainty in the near surface vadose zone. The flow model predictions compare favorably to the Monte Carlo statistics, particularly when the coefficient of variation of the boundary flux is on the order of 1, and the soil has a fine texture. The solute transport model yields good estimates of the mean solute flux breakthrough curves (BTC's) in all cases, but tends to underestimate the standard deviation of the BTC's at the mean center of mass. Incorporating water uptake in the flow equation reduces the mean and the variance, but increases the temporal correlation scale, of the pore water velocity. Therefore, incorporation of water uptake results in reduced and delayed peak solute arrival at a given control plane, and enhanced spreading of the mean and standard deviation of the solute flux BTC's. Compared to an inert solute, consideration of a spatially random adsorption coefficient leads to a smaller mean, but larger variance, of the apparent solute velocity. This results in reduced and delayed peak solute arrival, and enhanced spreading of the mean and standard deviation of the solute flux BTC's.

QUANTIFYING MACROPORE FLOW EFFECTS ON FIELD-SCALE LEACHING USING A DUAL-POROSITY MODEL

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In this study, a dual-porosity/dual permeability model (MACRO) is used to identify and quantify macropore flow effects on leaching of agricultural chemicals from a structured clay soil in south-west Sweden. Measured data obtained in 0.4 ha size tile-drained field plots were compared to model simulations run both with and without accounting for macropore flow. The two-domain simulations were able to satisfactorily match all components of the measured mass balances for bromide, one weakly-sorbed herbicide (bentazone) and nitrogen, implying that the local-scale model could succesfully reproduce the field observations using effective soil parameters. Simulations ignoring pore-scale macropore flow failed to match the observed behaviour at the field scale. Comparative simulations suggested that macropore flow reduced leaching of bentazone by c. 20% and nitrate by c. 28%, because these solutes were largely stored in micropore water moving at a reduced convective transport velocity, and 'protected' against bypass flow in macropores.

A MODIFIED INVERSE METHOD FOR DERIVING EFFECTIVE SOIL HYDRAULIC PROPERTIES IN THE FIELD.

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Recent Australian water reforms place limitations on the volume of water which can be removed from a water source. The impact of the water reforms on individual farmers is to encourage efficient irrigation water use. Drip (or trickle) irrigation has long been regarded as a potentially efficient method for the irrigation of many field crops. However, poor design and management of drip irrigation systems can result in similar volumes of water being used by drip irrigation systems as would be applied with more traditional irrigation systems. To assist in the design and better management of drip irrigation systems, we began to use the soil-water flow model SWMS_2D.

To use SWMS_2D (or any other soil-water flow model), soil hydraulic properties must be defined. However, obtaining soil hydraulic properties for use in soil-water flow models is complicated by heterogeneity that typically exists in the field. One method commonly used to overcome heterogeneity in field soils is use the average of many soil samples as input to the soil-water flow model. Also, soil hydraulic properties obtained from existing literature values (based on the soil texture) are often used. Both of these methods were used to obtain input soil hydraulic properties for the prediction of soil-water flow beneath drip emitters on a loamy sand soil at Camden, N.S.W. Unfortunately, poor agreement was found between the model-predicted wetting front position and the wetting front position observed using the time domain reflectometer (TDR). It was hypothesised that error in the values of the soil hydraulic properties was responsible for poor model predictions.

In an attempt to define the soil hydraulic properties more accurately, a numerical inverse procedure was used. This procedure was similar to those already used in the literature and involved making alterations to the input soil hydraulic properties until the value of the objective function was minimised. The objective function was defined as the weighted sum of the squared differences between the TDR-observed and the predicted soil moisture contents. Using these soil hydraulic properties as input to SWMS_2D, poor agreement was again found between the observed and predicted soil-water flow patterns. As before, it was assumed that error in the soil hydraulic properties was responsible for the poor model predictions. Based on this assumption, it follows that a problem had occurred in the numerical inverse method. Close examination revealed that the values of the soil hydraulic properties derived using the inverse method were highly sensitive to minor changes in the value of the objective function. It was also found that the value of the objective function was dependent on the value of the initial soil moisture content used in SWMS_2D.

To overcome these problems an alternative to the objective function approach was used. The alternative approach used was to make alterations to the input soil hydraulic properties so as to minimise the difference between the observed and the predicted wetting front position. It was found that two separate irrigation treatments were required to allow precise definition of the soil hydraulic properties. When these derived soil hydraulic properties were used in SWMS_2D to predict soil-water flow from a further two irrigation treatments (using very different types of emitters), good agreement was found. These results not only provide encouragement from a soil-water modelling viewpoint, but also "loosen" the requirements placed on the information that is needed to perform a numerical inverse method.

SEASONAL VARIATIONS IN FLOW AND TRANSPORT CHARACTERISTICS OF A FRACTURED GLACIAL TILL

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The flow and transport characteristics of a surficial glacial till vary seasonally due to stratification of the bulk permeability and fluctuations in saturation, according to a conceptual model developed to explain field tests at a site in Flakkebjerg, Denmark. The site has been studied in detail by continuously monitoring heads in multilevel wells, conducting hydraulic and tracer tests, and by mapping exposures in excavations. The bulk permeability of the 10-meter-thick till decreases with depth over 4 orders of magnitude from 10^{-5} to 10^{-6} m/s in a shallow (< 2.5 m) zone, to 10^{-7} to 10^{-8} m/s in an intermediate (3.0 to 4.5 m) zone and 10^{-9} m/s in the deep (4.5 to 10 m) zone. Fracture mapping in excavations to 6 meters depth revealed that the till is intensely fracture at shallow depths and the fracture intensity decreases with depth. Hydraulic and tracer tests have confirmed that the till is fractured throughout its entire thickness.

In the winter and spring piezometric heads are the highest and the water table is within the shallow till zone. During this period horizontal flow is at an annual maximum. Tracer tests revealed that horizontal flow occurs predominately within the shallow till zone and is dominant of vertical flow. Vertical flow through the till to the underlying aquifer is also at an annual maximum as the high permeability upper till readily supplies water to the connected vertical fractures. The transport of tracers to depths of up to 7 meters was observed to occur within 1 day.

The shallow till dewaters during the summer, while the intermediate and deep till zones remain saturated. During this period, horizontal flow goes to zero in the shallow till and decreases in the intermediate till. Vertical flow through fractures to the underlying aquifer is also markedly reduced and is controlled by the dewatering of matrix blocks in the intermediate till. During this period tracer concentrations remained relatively constant in the upper and intermediate till and decreased in the lower till.

Heads decrease further during autumn, dewatering major fractures in the intermediate till zone. This results in the formation of saturated matrix blocks bounded by partially saturated fractures. During this period horizontal flow in the intermediate till approaches zero, as the partially saturated fractures become flow barriers. Vertical flow through the intermediate till occurs only through the matrix and discontinuous fractures. Vertical flow through major fractures to the underlying aquifer reaches an annual minimum and is controlled by the matrix permeability of the lower till.

SESSION III,

"FROM PEDON TO CATCHMENT"

HYDROLOGICAL TRANSPORT PROCESSES FROM THE PEDON TO THE CATCHMENT

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Hydrologic modeling can, and often does, ignore the small-scale processes which control the transport water and solutes through a catchment. Traditional unit hydrograph models typify this spatially aggregated or "lumped" approach to catchment hydrology. By contrast, "distributed" hydrologic modeling describes catchment response by deriving the cumulative effect of processes which act at space scales as small as individual soil pores. Although the distributed approach is much more demanding than the lumped alternative, the hope is that it can more accurately portray the fundamental processes which control catchment hydrology.
This approach can only succeed if the effects of processes acting at scales smaller than the spatial resolution of the distributed model can be properly accounted for in the model equations. The resulting model is often said to be "upscaled". The most common way of doing this is through the use of "effective" model parameters which play a role similar to small-scale physical properties.

The distributed approach to hydrologic modeling raises a number of conceptual questions which are worth considering in this workshop. Is there evidence that distributed models produce better catchment-scale predictions than lumped models? How can we derive upscaled models from applicable physical principles and realistic descriptions of natural variability? When can these models be expressed in terms of effective parameters? What is the effect of nonlinearity on upscaling and on the distribution of variability over scale? These are open research questions which cannot yet be definitively answered. However, we can elaborate on these and other questions by examining some particular examples of interest to hydrologists and soil scientists. These examples can help to structure discussions about the role of scale and natural variability in hydrologic modeling.

UPSCALING, PREDICTIVE MODELS AND CATCHMENT WATER QUALITY- THE CAMSCALE PROJECT

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Most detailed research models are developed from an examination of environmental processes at points or very small areas, often at very short time intervals. Moving from this purely research position to an applied or policy-driven approach involving large areas of land and time-scales of weeks, months or years means changing the scale of operation of the models. This, in turn, almost invariably means that the amount of information available to run the model is very much less than the ideal.

The principal objective of the CAMSCALE project (funded by the Commission of the European Communities under the Framework IV Programme, Climate and Environment-DGXII) is to improve the understanding of the effect of changes of spatial and temporal scale within input data to process-based models. This will be reflected in comparisons between modelled output and concentrations of reference substances (nitrate-nitrogen and pesticides) in surface waters at the catchment scale.

Within this framework, the following are to be targeted:
- comparison of the performance of more complex process-based models (ANSWERS and MACRO) with that of simpler empirical models (SWANCATCH);
- quantification of the effects of upscaling on model predictive ability;
- derivation of functions to calculate 'missing data' at the Regional and European scales;
- application of the upscaling approach at the Regional and European scales.

The models listed above are to be used within at least one representative catchment in each of the UK, France and Sweden, in order to obtain the necessary pan-European dimension for the project. The data on the soils, climate, cropping and agrochemical (fertilizer and pesticide) usage of the catchments, as required for the modelling exercises, will cover a range of resolutions from:

- detailed catchment-level data measured within the catchment and mostly provided by the Group;
- regional-level data provided by the Group or available from national Governments and others organizations;
- European-level data available from departments of the European Commission, national Governments and others. These will include the: 1:1,000,000 scale digital Soil Map of the European Communities and associated databases; REGIO agricultural and land use statistics from EUROSTAT;

Modelling results from SWANCATCH will be presented for the UK catchment using detailed, regional and European-level data. Emphasis will be given to the effect of upscaling of soil information on river flow and water quality predictions.

SOLUTE MASS TRANSFER BETWEEN MOBILE AND IMMOBILE WATER IN SOILS: COMPARATIVE ANALYSIS OF RATE OBSERVATIONS ON DIFFERENT SCALES

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Solute transport through the soil hydrological system may be greatly influenced by flow through preferential flow paths. Preferential flow is here used as a term for describing the process through which much of the water and chemical movement through a porous formation follows favored flow paths, bypassing other parts of the medium. As a consequence of the hydrological balance, water must flow considerably slower (or not at all) in the bypassed parts than in the preferential flow paths of the formation. This concept does neither exclude nor imply advective transport in the regions of less mobile water; it only implies that advective travel times in the relatively immobile water zones are significantly greater than in the preferential flow paths, and approach infinity if the water is truly immobile.

Preferential flow leads to an apparent non-equilibrium situation with respect to pore water pressure, or solute movement, or both, which may severely limit our ability to predict flow and transport processes in undisturbed field soils. The degree to which the resulting effects can be predicted depends upon our ability to characterize these non-equilibrium phenomena on the scale of interest. For environmental applications, such characterization will commonly require relevant extrapolation of laboratory results to other scales and conditions. With regard to predictive modeling of the effects of preferential flow on solute transport, extrapolation of laboratory results to field conditions is particularly required for the rates of diffusive exchange of solute mass between mobile and relatively immobile water zones. Previously reported results have indicated an experimental range with regard to such rate parameter values that is many orders of magnitude wide, while their quantitative dependence on specific experimental conditions has remained unresolved.

In this paper, we analyze reported tracer test results from a range of different scales and soils. The observation scales include undisturbed soil monoliths in the laboratory, a field plot, and a small catchment. The soils include loamy sands and sandy-silty till. All the considered experiments have been interpreted with the same probabilistic Lagrangian approach to modelling sorptive solute transport, whereby model results are directly comparable. This compatibility is used for identifying and resolving soil and scale dependences in the rates of solute mass transfer between mobile and immobile water zones. The comparative analysis indicates a relatively consistent rate coefficient over the investigated range of experimental soils and scales. Moreover, it indicates a consistent ratio between the mobilisation and immobilisation rate coefficients, which determines the overall retardation of solute transport due to the kinetics of the diffusional mass transfer process. By use of the same modelling approach as for the experiment interpretation, we discuss and illustrate the implications of these experimental observations for our ability to extrapolate laboratory, or small-scale experimental results to predict large-scale solute transport in field soils.

PEDOTRANSFER UNCERTAINTY AND SPATIAL VARIABILITY IN DERIVING SOIL HYDROLOGICAL PARAMETERS FOR MODELING APPLICATIONS AT REGIONAL SCALE

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In an area of the Pianura Padano-Veneta (Northern Italy) defined at high environmental risk, the coupled simulation models MACRO and SOIL-N are used to quantify soil nitrogen potential leaching, given a set of locally representative management practises for selected crops such as winter wheat, sugar beeet and maize.

Soil data collected on benchmark soils from experimental sites were used to characterise soil hydrological properties at local scale and to quantify the uncertainty of the pedotransfer functions (PTFs) used to derive soil hydrological parameters, necessary as models inputs. Basic soil data, such as textural fractions, organic carbon content and bulk density, contained in available local soil databases were regionalised using a geostatistical methodology capable to take into account the exhaustive secondary information available for each soil series from local soil catalogue (*simple kriging with varying local means*). Estimated values were then interpolated at the nodes of a regular grid to predict soil hydraulic properties using the validated PTFs in a 1:50.000 cartographic sheet of the local soil map. The PTF estimated retention curves were compare with the experimental ones, and for most soil series, they were entirely within the uncertainty interval of PTF estimation as derived by the validation procedures. Results among and within soil mapping units were then analysed in terms of both spatial and pedotransfer uncertainty using a variance component analysis.

SPATIALLY DISTRIBUTED REPRESENTATION OF SOIL HYDROLOGY AT THE CATCHMENT SCALE

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At the catchment scale (100-10,000 km2) representations of hydrological processes must be significantly simplified for modelling purposes. Yet for many applications, such as integrated catchment management, it is desirable to retain an understanding of spatial variability in processes across the catchment, and how the variability is controlled by the physical attributes of the area. Heterogeneity in soils is one important aspect, but the parameters of catchment scale models cannot be directly identified from measurable soil physical properties. Model calibrations have demonstrated that a wide range of acceptable values can be identified for these parameters to give an equally good prediction of hydrological behaviour at the catchment scale (Dunn, in press). Therefore, it is difficult to relate variability in the soil-hydrological system to catchment scale hydrological response. An approach to overcoming this problem is investigated in this paper using the HOST classification (Boorman et al, 1995) as a spatial carrier, in conjunction with a model parameterisation based on relative values. The parameterisation recognises the problem of non-uniqueness by identifying the ranges of parameters that give an acceptable prediction of stream flow at the catchment scale. The ranges are then disaggregated into several sets according to the areas of different HOST classes in the catchment, and relative values of the parameters for each HOST class. The result is a set of parameter ranges that can be applied to each HOST class.

The modelling is performed using the distributed model DIY (Dunn et al, 1998), that accounts for spatial variation in physical properties at a fine resolution by categorising 50x50m blocks of the catchment according to their attributes. Different sets of model parameter ranges can be applied to different categories, as appropriate, to describe heterogeneity. For this application, one component of the categorisation is based on the HOST classification.

The approach is tested on two Scottish catchments, contrasting in their soils and hydrology. The results are analysed to determine the sensitivity of predictions to the soil parameterisation and qualitatively assess the behaviour of different soils at the catchment scale.

Boorman, D.B., Hollis, J.M. & Lilly, A., 1995, Hydrology of soil types; a hydrologically based classification of the soils of the United Kingdom, Institute of Hydrology Report No. 126.

Dunn, S.M., McAlister, E. and Ferrier, R.C., 1998, Development and application of a distributed catchment-scale hydrological model for the River Ythan, NE Scotland, Hydrol. Process., 12, 401-416.

Dunn, S.M., in press, Imposing constraints on parameter values of a conceptual hydrological model using baseflow response, Hydrol. Eart Sys. Sci. 3 (2).

IDENTIFICATION OF RUNOFF PROCESSES AT THREE SPATIAL SCALES BY HYDROCHEMISTRY AND TIME SERIES ANALYSIS.

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In this contribution we discuss runoff generation and solute transport in sub-alpine catchments at three different scales. We combine transfer function models estimated from rainfall and runoff data with hydrochemical evidence about the origin of the runoff water. We measured the runoff and its chemical composition (major anions and cations, DOC) at three spatial scales:

(1) One headwater catchment of about 0.7 km2, consisting of 40 % forest and 60 % grassland.

(2) Three experimentally delineated sub-catchments (1500m2), two of them are located in the forest, one in the grassland.

(3) Two soil plots (13 m2) representing the major soil environments of the sub-catchments: well-drained mounds covered with a mor humus layer and temporarily waterlogged depressions covered with a muck humus, both on top of a gleyic subsoil. We measured the outflow of the soil plots in three depths (0-5 cm, 5-30 cm, 30-60 cm), which correspond to the main soil horizons.

We modelled the runoff dynamics by means of a time series analysis approach. For this purpose we first linearized the rainfall-runoff data by using information on the soil moisture content. From the linearized data we then estimated discrete transfer functions. This allowed us to compare the runoff dynamics at all scales during natural rainfall events and irrigation experiments.

To get information about the origin of the runoff an end-member mixing analysis (EMMA) was performed during rainstorms. The EMMA bases on water chemistry measurements and allows to describe the runoff as a mixture of observed sources (so called end-members).

At all scales the runoff responded rapidly within minutes to rainfall events. The runoff measurements on the soil plots showed that the water moved through the subsoil via a continuous network of macro pores. In the sub-catchments, the waterlogged areas in the muck humus depressions caused a direct contribution of the rainfall to the runoff. Despite the different distribution and abundance of the muck and the mor humus areas, the runoff dynamics of all sub-catchments were almost identical. Furthermore, by means of the EMMA we could show that water flowing from the mounds, which cover 68 % of one of the forest sub-catchments, contributed on the average only 15 % to the total runoff. In the headwater catchment, the runoff dynamics were only slightly slower compared to the sub-catchments. This is likely due to a network of drainage trenches connected to permanent brooks, which covers the headwater catchment. Runoff generated in the wet grassland areas and in the muck humus depressions flows into the drainage trenches towards the permanent brooks and to the catchment outlet.

Our results strongly suggest that the connectivity of structural units, as macro pores on the plot scale, depressions on the catchment scale and trenches and brooks on the headwater scale, determines the runoff generation, rather than the relative abundance of muck and more humus or forest and grassland areas.

SESSION IV,

"POSTER SESSION"

ESTIMATION OF HYDRAULIC PARAMETERS OF NEW ZEALAND VOLCANIC SOILS

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Models are commonly used to simulate water fluxes for soils, generally using a pedon approach. Volcanic soils however are under-represented in such studies. Determining soil hydraulic parameters for volcanic soils is necessary for accurate simulation of water movement. The aim of this paper was to obtain hydraulic parameters for sandy volcanic soils (Vitric Orthic Allophanic under the New Zealand system) that are irrigated with wastewater from Rotorua, New Zealand. We measured drainage characteristics, soil water retention- and saturated conductivity at three covered flood plots and used a simulation model, SOIL. The drainage process was simulated for 20 days and model output was compared with measured water contents and drainage graphically and statistically. The model output agreed excellently for one of the three profiles (less than 1% error in the prediction of the drainage) whereas the agreement was poor for the other profiles (35 and 138% over-estimation of the drainage) when water retention curves determined from soil cores were used. We repeatedly ran the model using new values of the Brooks & Corey coefficients, until the best agreement between simulated and measured data was achieved. Estimated residual water content was large (about 25%) which might be related to the large content of allophane clay in these soils (about 8%). Finally, we constructed a three layered soil profile with common soil hydraulic parameters. The uppermost 1 m layer of local volcanic soils can be adequately simulated as a profile with three layers for prediction of water fluxes and drainage.

RETRACTOMETRY

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To achieve efficient water use for irrigation requires a good knowledge not only of the plant and its water needs, but also of the properties of the soil, particularly those related to soil structure : available water reserve, aeration, aggregation, stable and favourable support for root development, etc.

The measurement instruments commonly used in soil physics to characterise the structural properties of soils are few in number and are conceptually dispersed. They give only an empirical and subjective idea of the soil's structural properties. This is true, for example, for water and air reserves which are usually estimated using standardised tests unrelated to soil structure functioning.

We propose a new methodology for measuring the structural properties of the soil, the *retractometry*. It makes it possible, in a single experiment and on a single soil sample, to make quantitative and significant measurements of a set of structural properties of the soil, including moisture reserves. The method is based on three main elements :

1- A recently-developed laboratory instrument, AMPHYSOL® (Appareil de Mesure des Propriétés Hydrostructural du Sol) which provides the shrinkage curve of a soil sample (figure).

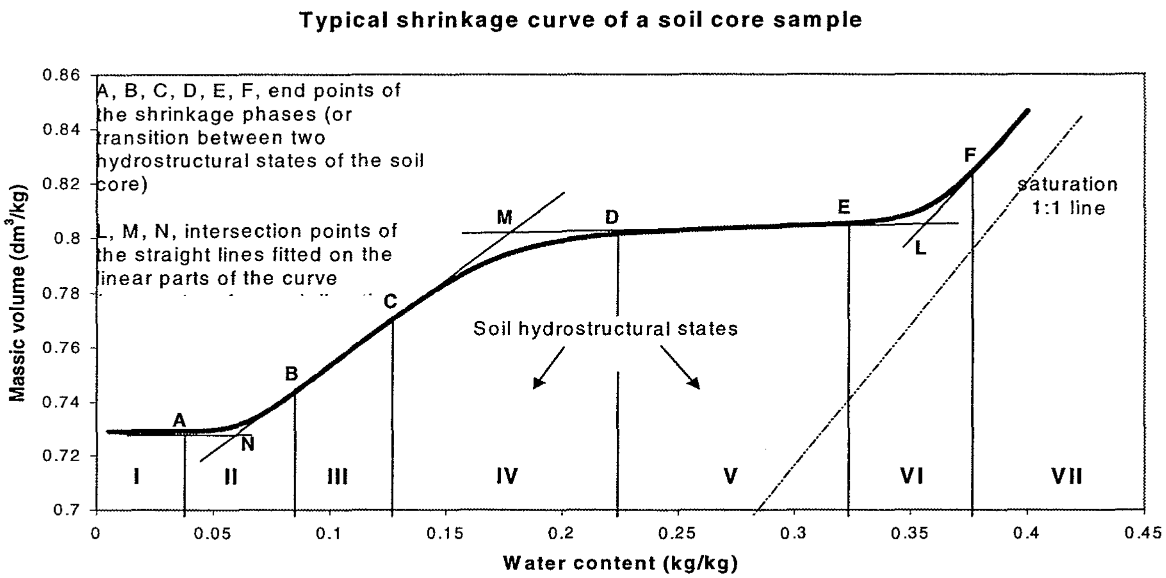

Figure 1. The points of transition between the different shrinkage zones are considered as characteristics of the shrinkage process. They are used as parameters to model the experimental shrinkage curves by linear shrinkage zones separated by curvilinear transition ones. Thus, a parametric adjustment to the experimental data permits to determine the best position of the characteristic transition points of the shrinkage phases.

2- A functional model of the pedostructure, e.g. soil structure at the horizon level. This model is composed of i) a morphological description of three levels of organisation, (matrix, primary peds, horizon peds) and ii) a limited number of hypotheses concerning the hydro-structural functioning of these organisations, in relation from one level to the other. This functional model defines the different variables of state of the three levels, and gives a signification to each shrinkage phase as a particular *hydro-structural state* of the pedostructure.

3- A parametric modelling of the shrinkage curve. By optimising the adjustment of the parametric equations to the measured shrinkage curve, this makes it possible to determine the characteristic transition points (coordinates) between two shrinkage phases, and so the quantitative delimitation of these shrinkage phases.

The association of these three points permit to provide a series of characteristic and significant data on soil structure and structural properties that can be used to calculate water reserves, micro- and macroscopic porosity, specific hydro-structural states (wilting point, retention capacity, etc.).

This makes retractometry a valuable tool : for making a cartographic soil physical properties inventory or for monitoring soil structure and properties under different factors of evolution: cultivation practices, irrigation, fallow land, etc. It is also a research tool, in the sense that the functional model of soil structure established here should be examined more thoroughly by studying its underlying hypotheses. A new emerging possibility is that this functional model, established to correspond as closely as possible to the functional morphology of the soil fabric, could be a reference for modelling process within the soil. This concerns disciplines such as agronomy, geotechnics or hydrophysics, where the soil is a porous material considered as a black box.

FOREST EDGE ZONES IN THE LANDSCAPE

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Forest edge zones in the landscape occupy increasingly larger part of the total forested area due to generally growing fragmentation of vegetation. In the edge-zone, the microclimate and the vegetation structure differ from that of the interior forest. This affects fluxes of carbon and water in forest edge zones, which herewith represent "hidden" enhancements to these fluxes. This should be considered when calculating fluxes at larger scales using models that were parameterized for homogeneous (interior) vegetation cover.

To calculate water and carbon flows from forest edge-zones on a regional scale, areal estimations and classifications of the edge-zones (vegetation type, exposition and orientation) are required. This can conveniently be achieved using GIS and satellite imagery in combination with other tools such as panchromatic aerial photography and a vector-length-calculating program. By creating different themes (maps) on vegetation, exposition and orientation and combining them with a forest-edge-zone theme, new themes can easily be made. Selecting different variables in the themes allows filtering of only selected features. The resulting themes provide a graphical representation that can also be numerically evaluated.

VERTICAL VARIABILITY OF WATER TENSION: FIELD MEASUREMENTS USE FOR DOWNWARD WATER FLUXES MONITORING AND FORECASTING AT THE PEDON SCALE.

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A strong vertical variability of soil properties is very often encountered at the pedon scale. A stationary random field describing these properties along the vertical direction is the exception rather than the generality. This variability can dramatically influence the downward flux of water and solutes to the aquifers. On the other hand, most existing soil surveys are based on the description of single profiles and therefore detailed information at this scale is available. In order to obtain indicators of the behaviour of the whole soil units to which these profiles are associated, it can be practically important to model the influence of the vertical spatial variability at the single profile scale.

The objective of this work is to test the information contained in field water tension profile data in different soil units, to use them for estimating the field saturated hydraulic conductivity and to compare the results with drainage tests performed in the same sites.
Time series of field water tension were considered because of their higher accuracy compared to water content ones. They were measured in experimental sites prone to assessing nitrate leaching from agricultural fields. The soils are fluvial and eolian coarse ones in the Italian North-West plains.

From the modelling point of view, the problem of numerically averaging the darcian conductivities at the interfaces between different layers has long been, and still it is, an open problem: therefore particular care is devoted in the integration of the one dimensional Richards' equation. The soil water properties are estimated by an inverse procedure which utilises the tension profiles especially for evaluating the field saturated conductivity. The other soil parameters are derived comes from bulk densities and steady-state laboratory retention curves. The influence of roots, when they are active, is also taken into account by a simple literature approach.

A sensitivity analysis with the Richards'code shows the validity of the information contained in both the steady-state field water tension profiles and in their time series.The results of the inversion are compared with the parameters obtained by drainage tests, showing the noise induced by the gravimetric water content measurements performed in those tests.

FIELD SCALE VARIABILITY OF WATER POTENTIALS IN A FINNISH FOREST SOIL.

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The spatial variability of water potential is significant in heterogeneous unsaturated media. Aim of this study is to determine the variability of water potentials in small field scale. Rectangular of 6*8m of fertile OMT (Cajander 1949) forest site type was selected for water balance measurements. In a Norway spruce stand there were installed 15 tensiometers in four pits (altogether 60 tensiometers). In six layers there were taken undisturbed cylinder samples with a volume of 150 cm^3 for water retention characteristics determinations (altogether 24 samples). Measurements were carried out in 1991-1998. Second purpose of the work is to use Andersson's (1990) arcus tangent functions in predicting water retention characteristics from particle size distributions. In third part of this work water balance simulations for the experiment plot are performed. The water potential variability is very large under dry conditions, although the soil is relatively homogeneous.

SOME INITIAL RESULTS FROM FIELD MEASUREMENTS OF GROUNDWATER POLLUTION DUE TO INTENSIVE AGRICULTURAL SOIL USE

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The aim of the investigation is to be studied the process of anthropogenic pollution of groundwater system in regions with intensive agriculture. Some initial results from test field observations collected at an experimental area of 2 ha placed at about 20 km in NE direction from Bulgarian capital Sofia are presented. The investigations are performed to a depth from 2 to 10 m where the hydrogeological structure consists of Upper Neogen and Quaternary deposits. The constructed observation points provide the possibility to determine the hydraulic parameters of existing groundwater flow in the considered layers near to the ground surface. Also a meteorological cell has been equipped in the proximity of the test field. The collected data include information for soil parameters, applied fertilisers and chemical composition of first extracted water samples. The presented type of soil in the test field is leached cinnamon forest one. The specific density, granular composition, dry density and pore volume of the soil is found by the laboratory testing of core soil samples. For defining the mass balance it is specified the exact amount of nitrogen and phosphate fertilisers applied to the existing crops of maize, wheat, sunflower and barley. The first performed chemical analysis of the collected water samples include pH, specific electric conductivity and also the concentrations of ammonia, nitrates, phosphates, sulphates and some of the other basic anions and cations specific for the presented groundwater.

MASS TRANSPORT AND SCALE-DEPENDENT HYDRAULIC TESTS IN A HETEROGENEOUS GLACIAL TILL - SANDY AQUIFER SYSTEM

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Many clayey till mantles are deformed and fractured due to glacial tectonics and weathering processes. The hydraulic connectivity of these fracture systems in relation to embedded sand lenses and underlying regional aquifers is poorly understood. A series of slug tests, free flow tests, large-scale infiltration tests, and tracer experiments were conducted in such a typical till - sand lens - sandy aquifer system in Funen, Denmark to assess the spatial variability of hydraulic characteristics together with mass transport estimates and travel times for a conservative tracer applied to the ground surface. The K values derived from the hydraulic tests varied with the size of substrate volume that the individual tests represent. The large-scale infiltration tests and the free flow tests yielded substantially higher K values than the slug tests, where the slug tests represented a restricted sampling volume and only a localized fracture network. Both the free flow tests and large-scale infiltration tests captured the decrease in bulk K from the uppermost bioturbated till to the underlying fracture dominated till. Previous investigations at this site indicated that the upper 2 m of till exhibited transport characteristics of both an equivalent porous media and a discrete fractured media, while the underlying till behaved strictly as a fractured media. Values of K derived from the four test methods range from 1.5×10^{-6} to 1.2×10^{-4} m s^{-1} in both the bioturbated and fracture dominated till. These values are considerably higher than K values reported for tills in North America. Rapid transport of water and chloride was observed throughout the coupled till - sandy aquifer system. This rapid transport was especially evident between the sand lens (at 5.5 m depth embedded in the till) and the sandy aquifer (20.5 m depth). Model estimates of mass recovery indicated that nearly all the applied chloride tracer could be accounted for in the sand lens and that about 31% of the chloride mass reached the sandy aquifer below the eastern portion of the infiltration basin. This mass recovery at a sampling point in the aquifer corresponds almost exactly with estimates of the percentage of the total recharge emanating from the eastern portion of the coupled system. The remaining chloride could be attributed to the heterogeneity in recharge rates and the westward flow within the regional aquifer. The rapid recharge into the aquifer implies that preferential flow is also significant in the lower till. Results are useful to characterize the susceptibility of fractured till mantles to past or present contaminant spills, to evaluate the vulnerability of aquifers, and to establish guidelines for remediation of contaminated sites.

EVALUATION OF CHLORIDE TRACER MOVEMENT AND SPREADING AT MOREPPEN-3 SITE, GARDERMOEN OSLO AIRPORT NORWAY

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Background

Contaminants can enter the groundwater zone from the regional sources such as Gardermoen Oslo airport on which de-icing chemicals are applied during the winter months to remove ice from aeroplanes and airport runways. The underlying unconfined sandy aquifer run the risk of diffuse pollution, not only because of sandy aquifers are the most vulnerable to pollution, but also because the excess de-icing chemical's load in the region. The solute plume originating at the soil surface may eventually migrate through the soil and likely to join the groundwater system. A relative success of attempts to protect the groundwater resource from the potential pollution is a measure of how well the processes transporting the de-icing chemicals are understood. Estimation of dispersion among the other processes at this particular geologic setting is essential to predict the contaminant transport in this aquifer.

A small-scale field experiment over a distance of 12 m, under forced gradient conditions (3 L/min) was carried out at a research site adjacent to the western runway of the Oslo airport. The purposes of establishing the site were; 1) to provide a specific groundwater setting similar to those parts of the aquifer which are being recharged and perhaps polluted from the airport areas, 2) to access the upper few meters of groundwater table considered vital to study the governing processes involved in transport and degradation of the de-icing chemicals.

The experiment was started with the injection of solution as a pulse (80 L/min) into the groundwater, comprising sodium-chloride (Cl^- 455 mg/L) and de-icing chemical, potassium acetate (452 mg/L). Time-dependent concentration distribution data was accumulated corresponding to the depth-specific multi-level samplers (MLs) erected in the upper 3 m saturated portion of the aquifer. The experiment was run for a period of 60 days. In particular, the chloride tracer test formed a basis for the simulation of the transport and degradation of the de-icing chemicals with the 3-D numerical models.

In this study, an overview of the non-reactive (chloride) plume movement and dispersion is described. Spatial moments, zero-th, first and second of the concentration distribution were applied to obtain qualitative description and quantitative assessment of plume movement. These moments defined the location of the centres of mass and variance of the plume's central mass as a function of longitudinal displacement and elapsed time. Finally, the dispersivities (longitudinal, transverse and vertical) were estimated.

Methodology

Following are the prominent steps followed to obtain detailed information on the distribution of chloride plume:
The mean position and the variances were calculated for 5 synoptic snapshots using spatial moments. Depth averaged chloride concentration values were plotted as contours in x-y plane, to examine the overall horizontal distribution and temporal movement of the plume.
The co-ordinates of the centre of mass of chloride plume were estimated with first spatial moment and the variance of the centre of mass was calculated with the second spatial moment. The vertical co-ordinate z was truncated into two equal parts, to examine the relative displacement of the plume's upper and lower parts. The solute velocity was estimated from the mean slope of the horizontal displacement versus time plots. The longitudinal and transverse dispersivities were calculated from the men variances of the solute plume.

Results and Discussion

In this paper, the average behaviour of the chloride plume is evaluated. The natural heterogeneity and horizontal distinct bedding structures played an important role in determining the shape and internal structure of the plume. The plume was truncating at the later stage of transport. The different travel times of the chloride tracer breakthrough curves demonstrated the directional effects. The upper part of the plume moved at an average 1.25 times faster than the lower part. The longitudinal mixing was the dominant dispersion process and displacement of the chloride centre of mass followed a nearly constant velocity of 0.084 m/d. The centre of mass made a strong vertical displacement during the 31^{st} and 43^{rd} days because of the flow induced by aquifer recharge. In the beginning the plume was under the influence of the pumping well. However, after 31^{st} day, a change in the chloride longitudinal variance with travel distance and time of the centre of mass followed a linear trend, indicating that the velocity has reached a constant value. The corresponding longitudinal dispersivities, in the earlier mode it was 0.16 and in the later mode 0.32 m. With the least squares regression, the estimated mean longitudinal dispersivity value was 0.242 m, after 60 days travel of the centre of mass. The dispersion transverse to the flow was much more limited. The calculated transverse horizontal dispersivity was 0.022 m and transverse vertical dispersivity was 0.059 m.

The results suggest that, there is a scale dependency of longitudinal dispersivity. Deterministic three-dimensional numerical models are needed to adequately predict the migration of contaminants in the aquifer. The Oslo airport civil aviation authority is regularly monitoring the groundwater. The long-term monitoring data, for example 5-7 years, can be included into a regional-scale model in order to establish the nature of the scale dependence. Detailed information on the aquifer geometry and hydraulic conductivity distribution will be required, wherein the up-scaled results of this experiment can be included.

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AREAL DISTRIBUTION OF GROUNDWATER RECHARGE IN A GLACIAL TILL CATCHMENT

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Eastern Denmark is primarily covered by clay till. The transformation of the excess rainfall into laterally diverted groundwater flow, drain flow, stream flow, and recharge to the underlying aquifer is governed by complicated interrelated processes. Distributed hydrological models provide a framework for assessing the individual flow components and for establishing the overall water balance. Traditionally such models are calibrated against measurements of stream flow, head in the aquifer and perhaps drainage flow. The head in the near surface clay till deposits have generally not been measured and therefore not considered in the calibration procedure.

In a 16 km^2 rural catchment, 15 shallow wells were installed in the upstream end for continuous measurements of the fluctuations in hydraulic head. In addition data were obtained from two wells penetrating to the deeper artesian aquifer, one located near the shallow wells and one in the valley adjacent to the stream. Precipitation and stream flow gauging along with potential evaporation estimates from a nearby weather station provide the basic data for the overall water balance assessment.

The geological composition was determined from geoelectrical surveys along three transects, supported by geophysical logs in deep wells, lowflow records at the outlet of the catchment and three tributaries, and soil maps. Slug tests were carried to obtain data for hydraulic conductivity.

The time series of hydraulic head depth in the shallow wells were analyzed using linear transfer noise functions on driving input time series and kriging techniques in order to identify correlation structures in time and space among the wells.

The distributed and physically based hydrological model code MIKE SHE was applied to the catchment. The model considers one-dimensional flow in the unsaturated zone and three-dimensional below. Drainage flow is empirically modelled as a linear reservoir using a time constant related to drain pipe capacity, spacing and soil hydraulic conductivity. Key parameters are calibrated against records of precipitation, potential evaporation and stream flow. Simulation based on historical records prior to the installation of subsurface drainage in 1/3 of the catchment was carried out in order to investigate the impact of drainage on streamflow and access the use of the linear reservoir assumption. Subsequently, data from the shallow wells were considered in order to analyse the value of such data in the calibration procedure and particularly in estimating the areal variation in recharge.

SOIL PHOSPHORUS LOSSES MEASURED AT DIFFERENT SCALES:
FROM LYSIMETER TO CATCHMENT SCALE

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Measurements of phosphorus (P) losses by hydrological processes in the soil can be done at various scales, which all have their advantages or disadvantages. Generally, the results from measurements at small scales are useful for establishing causal relationships between soil conditions and transport, and hence are useful for development of transport models. Field-scale drainage water measurements may provide a more overall view and show the combined effect of all P processes in the soil and the flow conditions. However, techniques need to be designed to take account of the temporal variation. A catchment scale is very popular for monitoring and for environmental work, but source separation of phosphorus is difficult and processes in the watercourse may provide additional phosphorus.

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