RECENT ADVANCES IN CHARACTERIZING FLOW AND TRANSPORT IN UNSATURATED SOIL AT THE CORE AND FIELD SCALE

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ABSTRACT. Characterizing the flow and transport mechanisms in unsaturated soil is essential to understand the functioning of soil systems, and it is the basis for many flow and transport models currently used in the different domains of environmental sciences, management and engineering. The experimental characterization of flow and transport is subject to the large space-time variability of soil processes, variables and properties. The traditional experimental techniques, that often have been used to characterize flow and transport, have a small measurement support, which complicates the determination of the space-time dynamics of flow and transport. Hence, there is still a gap between the support scale of experimental characterization techniques and the scale at which flow and transport models are applied. To bridge this gap, new experimental methodologies are needed that increase the accuracy, the resolution and extent of the characterization of flow and transport in soil.

In this keynote paper, some recent advances are illustrated that have been achieved with direct (dye tracing and solution sampling) and indirect techniques (Electrical Resistivity Tomography, Time Domain Reflectometry and Ground Penetrating Radar) for characterizing flow and transport in soil at the scale of the laboratory soil core and the small field scale. Improving direct techniques is still needed, as direct techniques continue to be the reference, and as indirect techniques are often insensitive for many essential soil processes. Indirect techniques, which are based on the physical measurement of proxy's of flow and transport, offer the possibility to increase tremendously the measurement resolution and extent, thereby elucidating the variability of flow and transport at the appropriate scale. We highlight the progress that has been made with these techniques, and identify some strengths, weaknesses and challenges for research in this domain.

1.- Introduction

Soil systems play a key role in terrestrial ecosystem processes. Soil systems provide nutrients, fiber and shelters for all living organism and control the fluxes of matter and energy from the land surface to atmosphere and groundwater systems. Understanding flow and transport through the soil is therefore a key in understanding the functioning of soil systems. It is also at the basis of environmental engineering and management, including water management, agriculture management and waste management, aiming to sustain life and to alleviate soil controlled pressures exerted on terrestrial ecosystems.

Matter and energy fluxes through the unsaturated soil are driven by physical laws and are subjected to the basic thermodynamic principles of mass and energy conservation. These physical laws have been translated in different modelling concepts for describing flow and transport in soils (Feyen and Wiyo, 1999). Unfortunately, the many modelling approaches presented in the recent literature suffer from a set of weaknesses which complicates the application of current models in the many fields of environmental science and engineering. The weaknesses and threats that are associated with the current modelling approaches in this domain were recently reviewed by (Feddes et al., 2004).

Probably, the most challenging issue when dealing with flow and transport in soil is the space and time variability, expressed at different scales, of soil variables, properties and processes (Feyen et al., 1998). The intrinsic variability, at the microscopic scale, of soil particle, aggregate and ped morphology and geometry, at the pedon scale, of soil horizons and profiles, and at the landscape scale, of soil units, will ultimately determine the variability of flow and transport (Fig.1). Unfortunately, experimental techniques are often failing in offering the spatial or temporal support needed to characterize the variability of flow and transport at the larger scale. For instance, earlier studies analysing the variability of flow and transport at the field scale, elucidated the important variability of local flow and transport and demonstrated the need for characterizing this variability in a consistent way (Biggar and Nielsen, 1976; Jury et al., 1987 ; Mallants et al.,1996). Given the non-linear behaviour of flow and transport in unsaturated soil, failing to assess the variability of local properties will introduce significant bias when describing flow and transport at the field scale (Mallants et al. 1996). Similar scaling problems exist when flow and transport is described at the scale of large undisturbed soil columns, using sampling technology with a spatial support that is an order of magnitude smaller than the soil column (Javaux and Vanclooster, 2006).

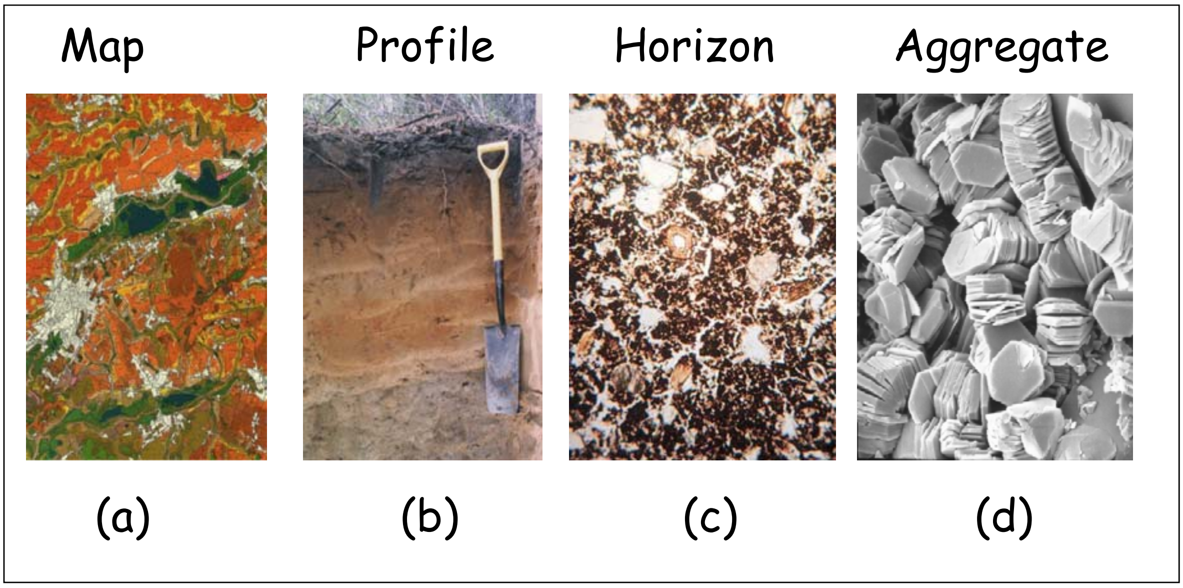

Fig. 1. Illustrations of soil variability at different spatial scales. At the regional scale, variability is expressed by the difference of different soil mapping units within a soil map sheet (a). At the scale of the soil profile, variability is observed by the presence of different diagnostic horizons (b). Within the soil horizons, variability is presented by the heterogeneous appearance of soil aggregates (c). Within aggregates, microscopic variability is observable in the porous structure (d)

The gap between the support scale of characterization techniques and the scale at which models should apply, referred to as the scale paradigm (Fig.2), weakens our ability to model flow and transport in a reliable way (Famiglietti et al., 1999; Vereecken et al., 2007). Whereas in the past, theoretical approaches focussed on the modelling of flow and transport at the local scale (e.g., the laboratory column or the small field plot), there is now a general consensus that this knowledge cannot simply be transferred to the larger scale where the management problems occur (Pachepsky et al., 2003). This scale paradigm challenges hydrologist, soil scientists and environmental engineers to seek for effective approaches to identify flow and transport processes and to improve the validation status of current modelling approaches (Vanclooster, 2006). Fortunately, last decade considerable progress has been made to meet this challenge. The development of new sensor technology and data analysis methods, and in particular the integration of knowledge from different disciplines such as applied geophysics, remote sensing, data mining, increased the space-time resolution and extent of characterization techniques, allowing to proceed in bridging this famous scale gap.

The objective of this keynote paper is to illustrate some recent advances in methods for characterizing flow and transport in soil at the core and the field scale, with most emphasis on indirect techniques, such as Time Domain Reflectometry (TDR), Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR). These latter techniques offer now tremendous opportunities for effective flow and transport characterisation, by increasing the spatial and temporal resolution and extent of measured properties (Vereecken et al., 2003). Adopting indirect techniques allows one to assess the variability of the flow and transport processes at the core and field scale in a convenient way, which may be helpful for effective modelling (Vereecken et al., 2007). Given the rapid evolution in these areas, it is not possible to give an in depth review of all developments. The illustrations below are therefore selective and somewhat targeted to the work in which the authors were involved. For in-depth reviews of some of the techniques, the reader is referred to specialised literature cited later on.

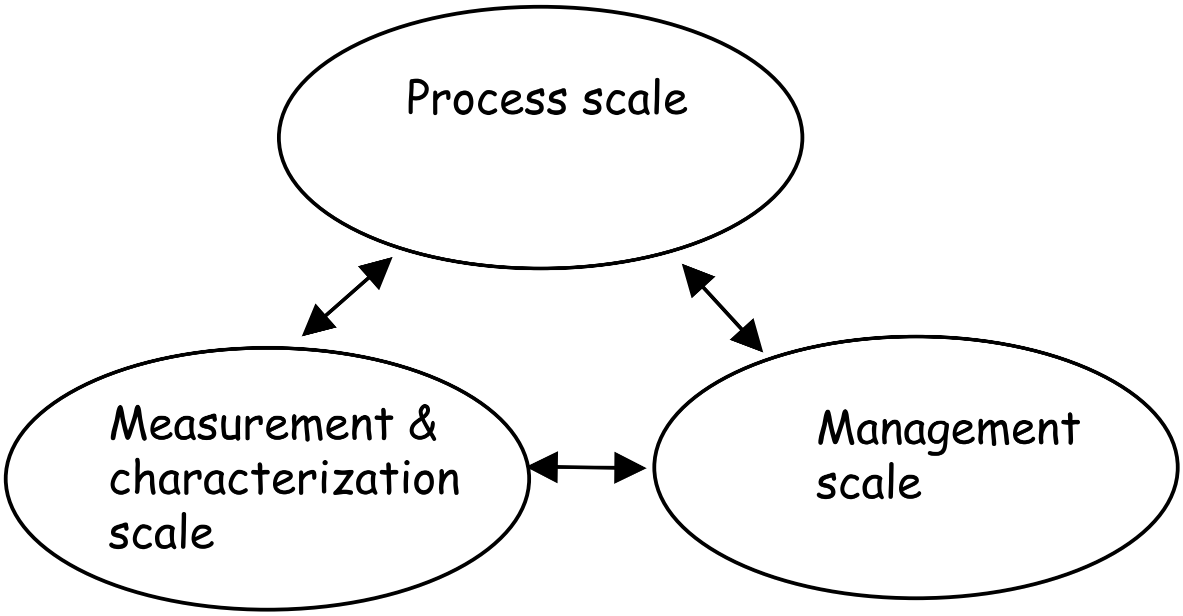

Fig. 2. The scale paradigm. Process occur at different scale as compared to the scale at which measurement techniques are operational. The management scale for which models should be developed differ often from the measurement and process scale

2.- Overview of available characterization techniques

Techniques for characterizing flow and transport properties in soil have been described in detail by (van Genuchten et al. 1999; Dane and Topp, 2002; Alvarez-Benedi and Munoz-Carpena 2005). A distinction can be made between methods typically designed for the characterisation of flow and transport in the laboratory and others that are applicable in-situ. We could also classify characterization techniques in terms of the spatial and temporal resolution of the measurement device, or the spatial and temporal extent. Further, we could consider differences between direct and indirect techniques. The former measures properties that enter directly within the flow and transport model, such as the soil moisture content or the soil suction, while the latter measures a property which is well linked to the former, often called a “proxy” or surrogate measure for the system state variable. Indirect techniques always involve a data interpretation model. In some cases this data interpretation model can be straightforward such as a simple regression equation. For instance, volumetric soil moisture content can be related to the soil dielectric permittivity using the well known Topp’s equation (Topp et al., 1980). In other cases, this data interpretation model becomes much more complicated as for instance with most non-invasive and hydrogeophysical characterization techniques, where non-linear propagation models of electric, electro-magnetic, seismic or acoustic waves in soil are inverted. The inversion of apparent raw ERT data to obtain a 2/3 D resistivity/salinity map is an example of this.

We should note that a clear demarcation in the classification of measurement techniques can not be made. A method such as the instantaneous profile method for characterizing the unsaturated hydraulic conductivity (Vachaud et al. ,1981) can be applied to as well laboratory soil cores as to small field plots. Also, the so-called direct measurement techniques have indirect properties as they use measurement device which are subject to calibration and therefore measurement errors. The determination of volumetric moisture on a disturbed soil sample for instance, passes by a gravimetric loss of mass in the soil sample after a certain time of drying and a conversion of gravimetric to volumetric moisture content. In each of the previous steps, biases and errors can be introduced. Purists may therefore claim that direct measurement techniques do not exist.

Table 1 classifies the characterization techniques which will be further discussed in this paper, using the following classification keys: i) sensor technology; ii) the physical state variable that is measured; iii) the physical flow and transport property that can be inferred; and iv) the space-time resolution and extent of the device.

Table 1: Overview of some characterisation techniques

Sensor technology	Direct /Indirect	Measured variable /property	Flow and transport state variable	Inferred flow and transport property	Spatial support	Spatial extent	Spatial aspect	Temporal support	Temporal aspect
Dye tracing	Direct	Conducting flow path Solute concentration	Mobile water content; Solute concentration	Solute adsorption and degradation paramaters; Effective porosity; Dispersivity length	Picture resolution	Local (~1 m)	Continuous	Time integrated	Instantaneous (disturbed soil)
Suction lysimeter	Direct	Outlet flow rate and water concentration	Water flux; Solute concentration; Solute flux	Hydraulic conductivity; Dispersivity length	Probe scale	Local (~1 m)	Integrated	Time integrated	Continuous
Time domain reflectometry (TDR)	Indirect	Dielectric permittivity; Electric conductivity	Soil moisture content; Solute concentration	Moisture retention curve; Hydraulic conductivity curve; Dispersivity length	Probe scale	Field (~1-10² m)	Discrete	Instantaneous	Continuous
Ground-Penetrating Radar (GPR)	Indirect	Dielectric permittivity; Electric conductivity	Soil moisture content Solute concentration	Moisture retention curve; Hydraulic conductivity curve; Dispersivity length	Probe scale	Horizontal: field Vertical: “reflection depth”	Continuous /discrete	Instantaneous	Continuous
Electric Resistivity Tomography (ERT)	Indirect	Electrical resistivity	Soil moisture content; Solute concentration	Moisture retention curve; Hydraulic conductivity curve; Solute dispersivity	Distance between electrodes	Horizontal: Field Vertical: Probe positions	Continuous	Instantaneous	Continuous

3.- Direct characterization of flow and transport in soil

Direct measurement of flow and transport in soil is often laborious, time consuming and expensive. It is further limited in space-time resolution, support and extent. Yet, direct measurements continue to play an important role, and this because of several reasons. First, as compared to indirect measurements, direct measurements are subject to smaller uncertainty. Direct measurements are therefore often considered as reference measurements and used for calibrating indirect techniques. Second, for many essential soil processes, such as reactive solute transport, indirect techniques do not exist. Indeed, indirect measurement techniques do only yield proxy's for a limited range of soil system state variables such as soil salinity, soil temperature or soil moisture. In the section below, we illustrate two direct measurement techniques: i) dye tracing for characterizing soil flow paths and reactive transport in soil ; and ii) solution tracing using suction samplers for characterizing solute transport in soil.

3.1.-Dye tracing

Dye tracers have for long been used to characterize flow and transport in the vadoze zone (Flury and Wai, 2003). The technique consists in applying a dye on a soil during a controlled transport experiment, and analysing the redistribution of the dye after excavating and disturbing the soil.

Dye tracing allows the assessment of soil transport properties mainly affected by soil structure. It has therefore been a very popular technique for assessing preferential flow in soils (Ritsema, et al. 1993; Mallants et al., 1994; Larsson, et al. 1999; Hangen et al., 2004). However, the quantitative interpretation of dye tracer experiments, and in particular the link between observed dye patterns and flow and transport properties remains complicated (Vervoort et al., 1999). Indeed, dye tracers are reactive chemicals which are subject to sorption and degradation kinetics when vehiculated through the soil (Ketelsen and Meyer-Windel, 1999; Harden et al., 2003). Linking dye tracing experiments to quantitative flow and transport properties therefore implies a robust method to quantify dye concentrations in the soil profile, as well as an appropriate method to model and invert reactive transport in soil.

Forrer and coworkers developed a fast image processing-based method to deduce dye concentrations in excavated soil profiles (Forrer et al., 2000). Unfortunately, to apply this method material specific calibrations of the sorption constants of dye tracers are needed (Vanderborght et al., 2002). The lack of such material constants may therefore add substantial uncertainties on measured profiles, which complicates further the data inversion. Persson and coworkers used these techniques to elucidate scale dependent dispersion in laboratory soil columns (Persson et al., 2005). They analysed dye concentration profiles by means of spatial moment analysis and showed that critical moisture contents could develop in their soil column above which solute transport regime changes from full convective dispersive to stochastic convective. As dye tracers are non-linear reactive products, their concentration profile is therefore affected differently by soil structure than inert solutes, which makes dyes bad tracers for flow heterogeneity (Kasteel et al. , 2002). However. dye tracer are good proxies for investigating the fate of reactive products through soil. In a recent study, Javaux and co-workers estimated brilliant blue transport through an unsaturated and undisturbed soil monolith (Fig. 3) (Javaux et al., 2006). They showed that a two-site kinetic solute transport with effective water content and sorption constant was needed to reconstruct the observed brilliant blue profiles and to infer quantitatively flow and transport properties of the soil

3.2.- Suction samplers

Suction sampling by means of porous cups, suction candles, or porous plates has for long been a popular technique for characterizing transport of chemicals in soil. Suction devices allow extracting the soil solution and dosing the solution for its relevant composition. In contrast to the disturbed technique such as dye tracing, suction sampling allows time integrated measurements and is therefore more appropriate for time continuous monitoring of the soil quality. Suction candles, however, may introduce significant instrumental biases, since they may adsorb sample components (McGuire et al., 1992). In addition, the surface is often too small, while their sampling extent is not well known (Weihermüller et al., 2005). In order to improve the sampling extent, suction plates can be used, while artefacts on sampled volume may be minimised through a specific design of the sampling device, e.g. (Gee et al. 2003). Thereby different options can be used to control the tension of the suction plate, and hence the sampling support. The simplest option is probably obtained when using the zero tension suction plate. In this case, however, only gravity water will be sampled, and samples may not be representative of the overall quality of the soil solution (Jemison and Fox, 1992). With passive wick samplers (Holder et al., 1991; Gee et al., 2003) or equilibrium tension plates (Brye et al. 1999) a controlled suction is applied. The former technique is much less expensive and easier to install, and can also be applied to measure outflow at the bottom of soil columns.

Different studies compared the performance of different suction sampling devices. For a volcanic soil for instance, Van der Velde and coworkers compared the performance of passive suction wick samplers with zero tension wick samplers (Van der Velde et al., 2005). They observed significant differences between the performance of both sampling devices, with larger amounts of intercepted water with the passive wick sampler as compared to the zero tension wick sampler (Fig. 4). Sampler performance was also numerically analysed for different designs by means of two-dimensional (2D) and 3D modelling codes of flow and transport in unsaturated soil (Mertens et al., 2005;

Weihermüller et al., 2005; Mertens et al., 2007). The numerical studies confirmed the complexity of the analysis of suction sampler data and the significant impact of design parameters, soil parameters and boundary conditions on sampler performance. They also showed that considerable bias may be introduced in the estimation of the relevant transport properties from suction measured data, when device and soil parameters are not appropriately accounted for in the analysis (Weihermüller et al., 2006). Hence, the selection and control of an appropriate suction device for a given study remains far from evident (Gee, 2005).

4.- Indirect characterization of flow and transport in soil

In contrast to direct measurement techniques, indirect techniques physically measure soil proxies of functional flow and transport variables. Indirect measurements are generally characterized by higher space-time resolution and can therefore be applied to a larger extent. They are therefore excellent tools to elucidate the space-time dynamics of flow and transport.

4.1.- Time domain reflectometry (TDR) as a support for flow and transport characterization in soil

Detailed reviews on the use of TDR in soil science are found in (Wraith and Das, 1998; Noborio, 2001; and Robinson et al., 2003). With this technology, reflected electromagnetic waves are recorded in the time domain for wave propagation along waveguides inserted into the soil. The shape of the reflected waveform is determined by the soil electromagnetic properties, including their spatial distribution. An analysis of the TDR waveform permits simultaneous estimation of both soil dielectric permittivity and electric conductivity, which can be subsequently correlated to key hydrological state variables using so-called petro-physical relationships. Usually, dielectric permittivity is inferred from the wave propagation velocity in the waveguide and electric conductivity is derived from wave attenuation. Since the pioneering work of Topp and coworkers (Topp et al., 1980; Topp et al., 2003), experience with TDR in soil sciences evolved considerably such that it now can be considered as a robust and cost effective technique for monitoring flow and transport in soil. As such, TDR has been used in hydrological studies (Lambot et al., 2004a; Starks et al., 2006), ecological studies (Li et al., 2007), root water uptake studies (Green et al., 2006; Gong et al., 2006), water management studies (Ould et al., 2007; Dehghanisanij et al., 2006; Starr, 2005), precision agriculture studies (Noborio et al., 1994) and waste management studies (Imhoff et al., 2007). The technique is

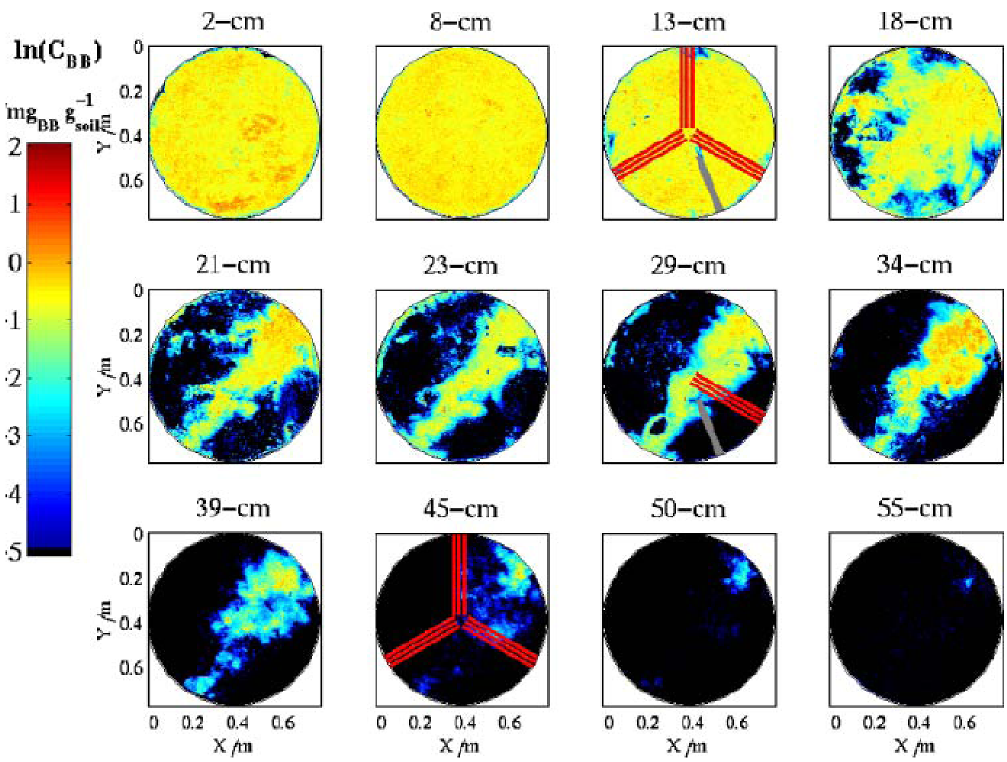

Fig. 3. Observed preferential flow in an undisturbed sandy lysimeter. Results of a brilliant blue tracer experiment is shown. A discontinuous clay layer is situated at a depth of 20 – 30 cm causing the brilliant blue to funnel in a preferential flow path. (Source: Javaux et al., 2006)

also widely used as a supporting technique for ground truthing in remote sensing (Zhang and Wegehengel, 2006).

In a recent ecological study for instance, (Cubera and Moreno, 2007) used 928 TDR sensors to assess the water balance of different dehesas ecosystems, i.e. open wood lands with scattered oak trees, in Central-Western Spain. They showed that TDR measurements were able to detect the impact of different land uses below the oak trees (shrubs, grassland, cultivate land) on the soil water balance, as well as the competition for soil water between the undercrop and oak crop. The robustness of the technique also allows implementing TDR studies in extreme hot, as well as cold conditions. For instance (Boike et al., 2007) used TDR in arctic conditions to monitor water and solute dynamics in a mud boil in Spitsbergen. They illustrated how strong vertical transport gradients below the mud boils were established, which were controlled by the seasonal climatic regime of freezing and thawing.

The interesting feature of electromagnetic measurement technology, such as TDR, is that the dielectric permittivity of the soil is highly correlated to soil water content, due to the overwhelming dielectric properties of water compared to the other soil components (Topp et al., 1980). In contrast, soil electric conductivity is multivariate and simultaneously depends on several factors, including essentially soil water content, salinity, clay content, and temperature. Yet, since the bulk electrical conductivity of the soil is largely determined by the electrical conductivity of the soil solution, which on its turn is determined by the ionic composition, solute transport can be determined by TDR. Hence, in addition to soil moisture monitoring, TDR has widely been used to monitor soil salinity (Corwin and Lesch, 2005) and solute transport processes (Vogeler et al., 2005). For instance (Vanclooster et al., 1995; Vogeler et al., 1996; Vogeler et al., 1998; Ritter et al. 2003; Javaux and Vanclooster, 2003) used TDR for monitoring transport of inert ionic tracers in soil (Fig.5). (Wraith and Das, 1998; Das et al. 1999) illustrated the use of TDR for monitoring nitrate transport in soil, while (Abassi et al., 2004), illustrated the potential for tracing sulphate transport in soil.

Since TDR allows easy monitoring of soil moisture and bulk electrical conductivity, time series of TDR waveforms can be combined with inverse modelling to assess the elementary flow and transport properties. In early work at the laboratory scale, (Vanclooster, et al., 1993) used steady state TDR measured breakthrough curves with analytical solutions of the governing transport equation to identify the transport parameters of undisturbed sandy soil samples. They were able to elucidate non-equilibrium flow and to assess the corresponding transport parameters of the soil. In their analysis, however, TDR probes were calibrated using suction cup samples which introduced uncertainty in the interpretation of the results (Vanderborght et al., 1997). Similar laboratory scale studies were performed by Mallants et al. (1994), Comegna et al. (1999), and Lee (2004).

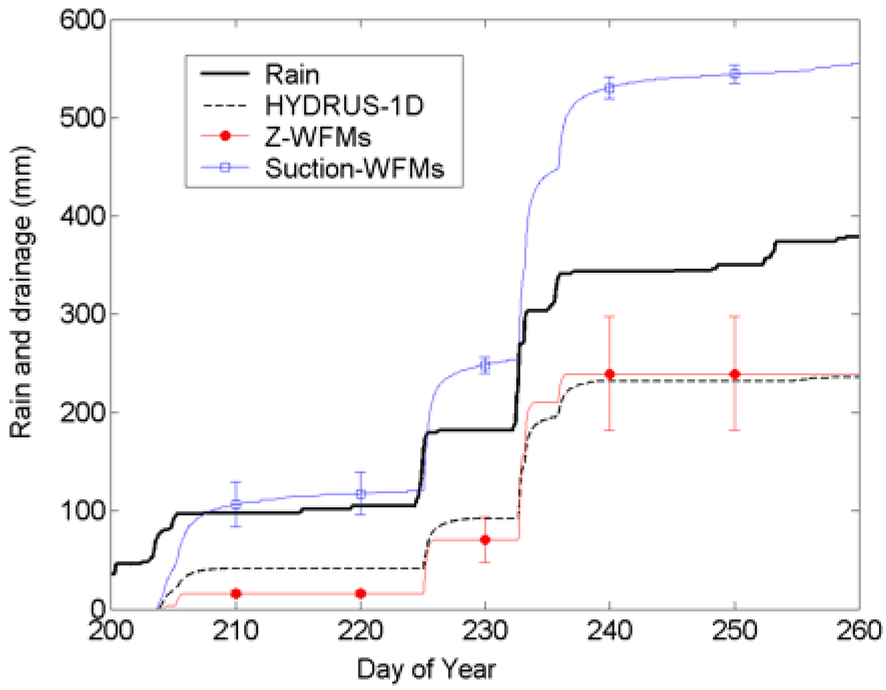

Fig. 4. Comparison of the performance of 2 suction plate devices with the results of a numerical model (HYDRUS 1-D) for a volcanic soil during a cropping season. Rain, is the cumulative amount of rain (mm); HYDRUS-1D is the simulated cumulative drainage at the level of the installed suction plates (mm); Z-WFM, measured drainage by means of a zero suction plate sampler (mm); Suction-WFMs, measured drainage by means of a suction wick sampler (mm). (Source, Van der Velde et al.,2006).

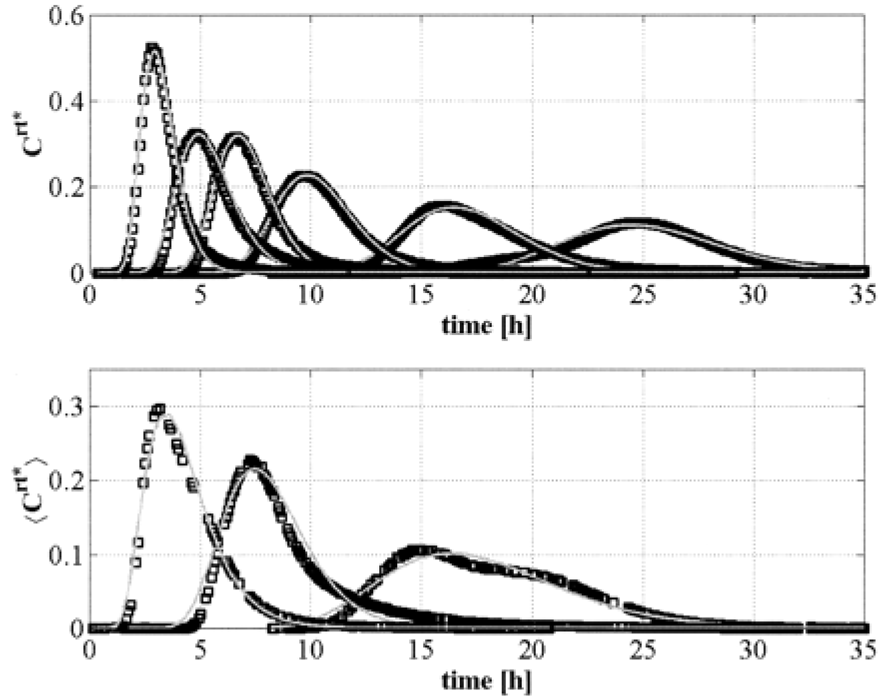

Fig. 5. Local scale (top) and meso-scale (bottom) breakthrough of an inert solute tracer in an undisturbed soil monolith. The six local scale breakthrough curves were measured by horizontally installed TDR probes positioned at different depths in the monolith. The meso scale curves were obtained by averaging estimated solute concentrations. Gray lines show the fitted breakthrough curve by means of an analytical solution of the governing transport equation. (Source: Javaux and Vanclooster, 2003).

The approach was also adopted to estimate solute transport properties at the scale of large undisturbed soil cores and soil lysimeters (Vanclooster et al., 1995; Javaux and Vanclooster 2003; Ritter et al., 2005) or in-situ in small field plots (Kachanoski et al., 1992). For instance, the governing transport model for solute transport in a set of Belgian soil types was tested, by analysing the scale and rate dependency of solute dispersivity as estimated from TDR measured breakthrough curves (Vanderborght et al., 2001) (Fig.6). Similar scaling relationships were analysed for subsoil samples (Javaux and Vanclooster, 2003). Al-Jabri and coworkers for instance, combined steady state flow experiments with transport from an inert tracer below dripper lines and identified the spatial variability of surface flow and transport properties (Al-Jabri et al., 2006).

The major problem with the use of TDR in solute transport studies is the correct interpretation of the signal in terms of functional soil properties such as tracer concentration, or nutrient concentration. This problem is not specific for TDR, but pertinent for all measurement techniques that measure the bulk electrical conductivity of a porous system. Indeed, the relation between soil bulk electrical conductivity and composition of the soil solution is, in addition to the mineralogical properties of soil, largely determined by soil structural properties, the moisture saturation degree and the distribution of electric charges in the heterogeneous porous medium. In petrophysics, this problem is usually modelled with Archie's law. Yet, its application to unsaturated soil is problematic due to the poor definition of saturation exponent in this law. For instance (Munoz-Carpena et al., 2005) showed that the estimation of soil solution electrical conductivity in a volcanic soil needed site specific calibration. For solute transport studies, field specific calibration can partially be avoided by adopting either an indirect calibration approach (Vanclooster et al., 1994) or by considering additional hypothesis on flow regime and mass recovery of solute pulses (Mallants et al. ,1996; Vanderborght et al., 1996 ; Javaux and Vanclooster, 2003).

The significant progress that has been made with TDR in flow and transport studies has been facilitated by new technological developments for TDR devices and probes, and by a better understanding of the TDR waveform. Multiplexing and automated logging technology is now commercially available, allowing for quasi time continuous TDR measurements at multiple locations (Heimovaara and Bouten, 1990). Probe design has also been optimised. The behaviour of double and triple rod probes was already analysed and optimised in earlier studies (Zegelin et al., 1989; Heimovaara, 1993), while more recently single rod probes have been designed to improve the robustness during field installation (Oswald et al., 2004). In addition new devices were designed to allow TDR measurements to be taken along boreholes and for profiling soil moisture measurements. For instance West and Truss (2006) investigated the hydraulic behaviour of the vadose zone above a layered sandstone aquifer using two borehole TDR monitoring devices, allowing to elucidate the appearance of perched systems in the formation. They also showed that other geophysiscal techniques such as ERT or borehole GPR did not have the appropriate resolution to identify key flow processes in this formation. Also, significant improvements have been made to measure flow and transport in saline soils by isolating and coating the probes (Persson et al., 2004).

In terms of data analysis progress has been made in modelling TDR signature, and hence the extraction of the relevant properties through inverse modelling. For instance, Heimovaara and coworkers used a frequency analysis of TDR to model wave propagation in soil (Heimovaara, 1994; Heimovaara et al., 1994), while Oswald and co-workers developed a wave propagation model in the time domain (Oswald et al., 2003). A particular application is the profiling of soil moisture by combining the wave propagation model with an inverse algorithm. Heimovaara and coworkers combined their frequency domain scattering model with a Bayesian inversion algorithm to obtain moisture distribution along the TDR probe (Heimovaara et al., 2004). Also more empirical approaches have been proposed. Moret and coworkers for instance used a graphical technique to decompose the TDR waveform, allowing the calculation of the local dielectric constant of a section of the TDR probe, thereby considering the dependency of the attenuation function on the dielectric constant. The method allowed considerable profiling of soil moisture during a wetting and drainage infiltration experiment in a wet soil column.

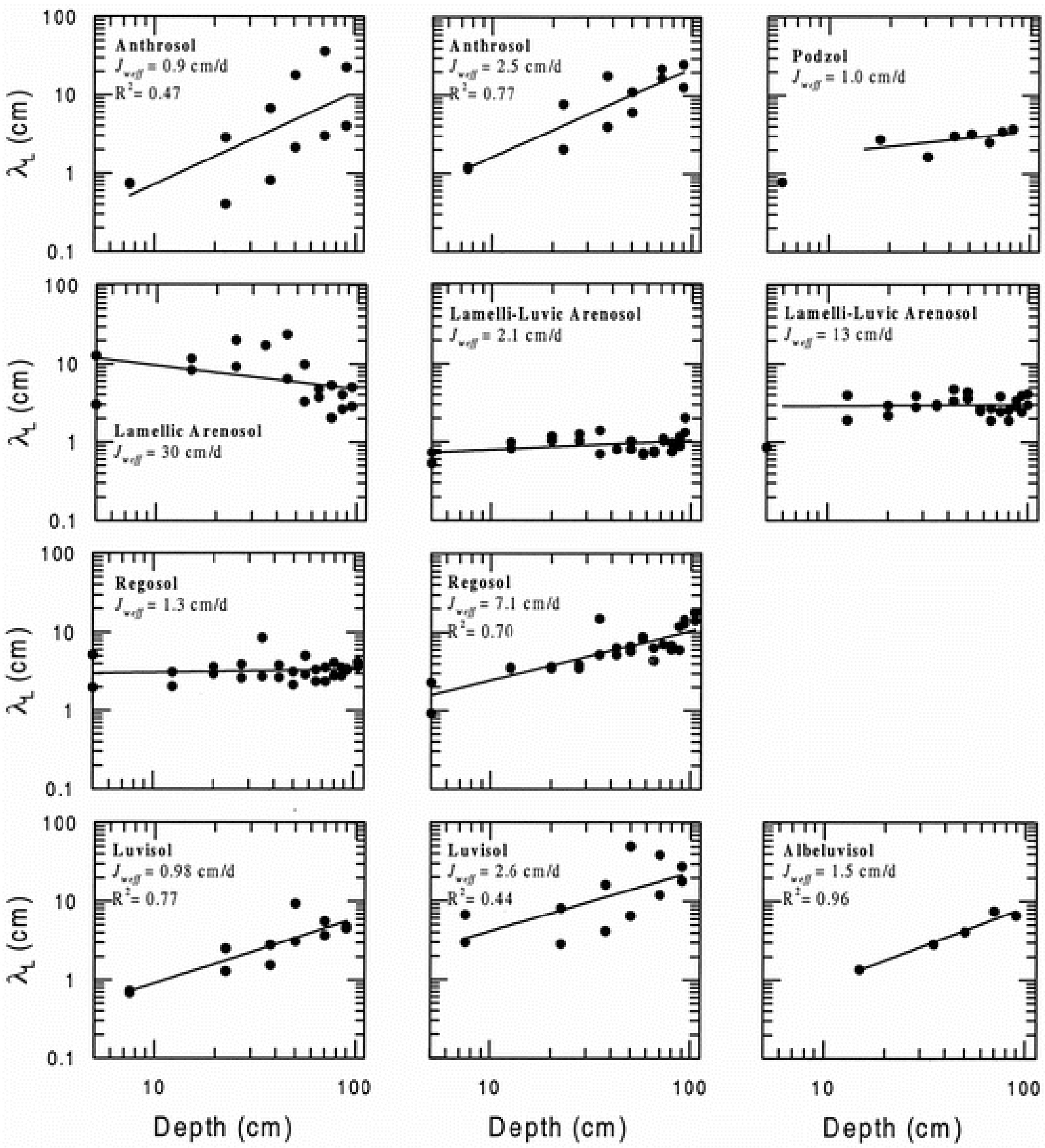

Fig. 6. Scale and rate dependent local dispersivities measured in a set of Belgian soils (Source: Vanderborght et al., 2001).

Lastly, TDR has also inspired researchers to develop new measurement technologies but based on similar physical principles. For instance, Time Domain Transmission technology (TDT) has recently be introduced (Blonquist et al., 2005; Gorriti et al., 2005). With this latter technique, EM waves are propagated along transmission lines which are back connected to the input device. In contrast to TDR, TDT allows an easier interpretation of the TDR signal. However, the probe geometry does not allow an easy installation in all soils. However, the design of TDT and electronic implementation makes this technology a cheaper alternative to the rather expensive TDR technology.

4.2.- Ground Penetrating Radar (GPR) as a support for flow and transport characterization in soil

A principle disadvantage of TDR is that waveguides need to be installed in the soil and that the spatial extent of the soil moisture measurement remains very low. Due to the inherent variability of the soil properties and the inaccessibility of the subsurface, an option consists in developing non-invasive monitoring techniques (Vereecken et al., 2003). GPR is such a non-invasive technique, which consists in analysing the reflection of a ground directed electromagnetic wave. GPR has already been applied to identify soil stratification (Davis and Annan, 1989), to locate the water table in soil systems (Nakashima et al., 2001), to monitor wetting front movement (Vellidis et al., 1990), to measure soil water content (Chanzy et al., 1996; Huisman et al., 2003; Serbin and Or, 2003), to assist in subsurface hydraulic parameter identification (Hubbard et al., 1997), to assess soil electric conductivity and salinity (Yoder et al., 2001), and also to support the monitoring of contaminants. The application of GPR in civil engineering, agronomical engineering, environmental engineering, archaeology and other earth sciences related disciplines is therefore ever increasing. Further in this paper, we focus on GPR measurements for soil moisture determination. Excellent reviews on this application of GPR have already been given by (Davis and Annan, 2002) and (Huisman et al., 2003).

Soil water content can be obtained from GPR measurements in different ways, usually based on the determination of the wave propagation velocity using ray-propagation approximation. Fig. 7 illustrates the different propagation paths that are usually considered. This includes the direct wave between the antennas and propagating through air, the direct wave propagating through the soil surface, and the reflected and refracted waves at different interfaces. Usually, GPR antennas are electrically coupled with the soil to increase penetration depth, requiring physical contact. Antennas can be configured in a single offset mode, i.e., with a constant emitter and receiver separation, or in multiple offset mode. With the single offset method, also called common reflection method, a subsurface electromagnetic contrast that yields a clear reflection is needed and the depth of this reflector needs to be known in order to be able to estimate the average propagation velocity above the reflector. With multiple offset methods, such as with the common midpoint method (CMP) or the wide angle reflection and refraction method (WARR), the depth of the interfaces should not be known a priori and stacking velocity fields can be derived using Pythagorean theorem or tomographic reconstruction methods solving simultaneously for several unknowns. As compared to single offset measurements, multiple offset measurements are more laborious to implement. In addition, the interpretation of the reflected waves in terms of soil moisture is subject to large uncertainties if well defined electromagnetic reflectors are not available. As an alternative, the ground wave which directly propagates from the emitter to the receiver can be used (see Fig. 7) to identify surface soil moisture, which is more convenient for soil moisture mapping (Hubbard et al., 2002). An other commonly used GPR mode of operation is borehole GPR, where the antennas are lowered in boreholes and transmission tomography techniques are used to reconstruct 1,2 or 3D images of the subsurface (e.g., Binley et al., 2001).

Ground-coupled GPR devices are not easy to handle, in particular when soils are cultivated or when they are characterized by an important roughness. As an alternative and as in remote sensing, off-ground or proximal GPR can be implemented (Chanzy et al., 1996; Lambot et al., 2003; Serbin et al., 2004). In this case, the basic analysis consists in determining the surface reflection coefficient that can be related to the dielectric properties of the soil surface. Alternatively, full-wave propagation in the antenna-air-subsoil system can be modelled and inverted as illustrated by Lambot et al. (2006). Given the complex nature of the GPR measuring technique, particular attention should be given to the accuracy of GPR-derived soil moisture. For instance, Huisman et al. (2001) compared moisture measurements estimated from 24 multiple offset measurements collected using 225 MHz antennas with independent gravimetric samples and found a reasonable accuracy of measured soil moisture of 0.024 m^3 m^{-3}. Similar good results were found by Grote et al. (2003). Weihermüller and coworkers recently compared two GPR techniques, a ground-coupled GPR and an off-ground GPR, with TDR, capacitance probes and reference gravimetric soil moisture measurements to map the spatial soil water content in the upper layer of a silt-loam textured soil (Weihermüller et al., 2007). They obtained poor agreement between the different characterization techniques. The surface ground-wave method suffered from strong attenuation of the surface wave, due to high electric conductivity, making difficult to pick up wave arrival time, and hence, to accurately estimate the wave propagation velocity and soil water content. The 1700 MHz centre frequency of the used off-ground system provided water content estimates of the top 1-2 centimetres only, which appeared to be significantly different from the deeper water contents as provided by the other characterization techniques (> 5 cm). The different characterization scales appeared to be a major concern in that study, due to the particularly high microvariability in that agricultural field.

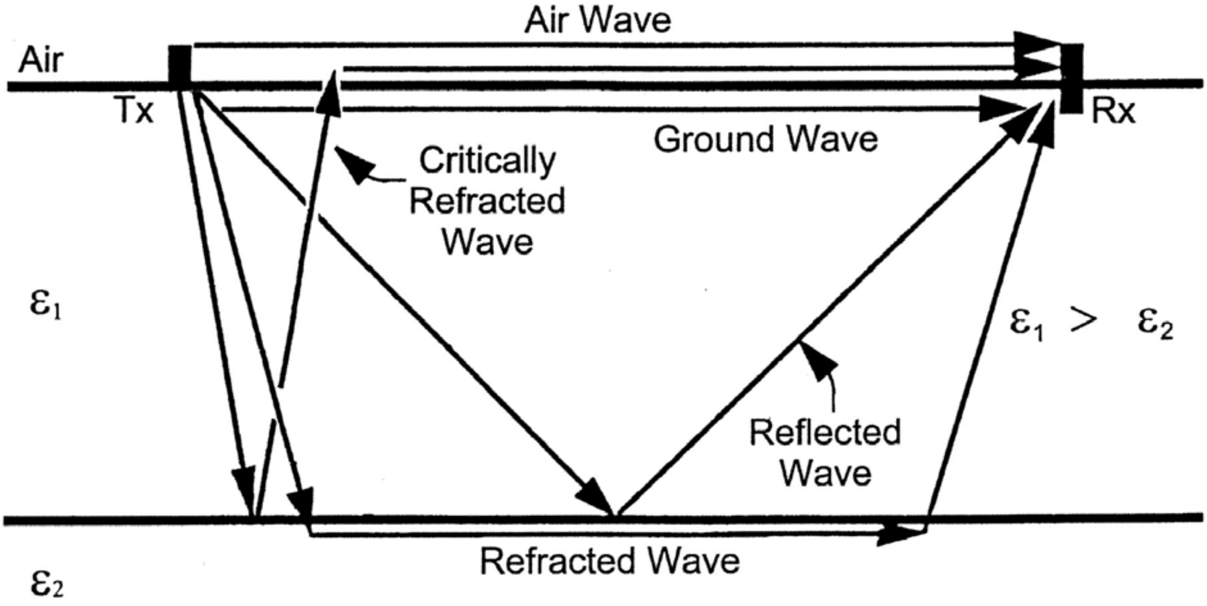

Fig. 7: Principles of measurements of wave propagation in bi-static GPR systems (Source: Huisman et al., 2003)

Gerber and coworkers used GPR for monitoring Pleistocene periglacial slope deposits at shallow tests in a test facility in Germany and used TDR as a reference for comparing moisture of the different materials in the test facility (Gerber et al., 2007). They focussed on the mapping of loess rich formation above stone layers. They showed that GPR with antennas of 400 MHz were appropriate for detecting the different materials in the test facility, but that the soil moisture was decisive for the performance.

The principle limitation with GPR is probably the more complex analysis of the propagation of the electromagnetic signal in the radar-air-soil system. In his recent review paper, Sander Huisman stated "*Although the number of TDR applications has increased immensely in the past 20 yr, the number of GPR applications for measuring soil water content has only recently increased. Probably, the most important reason behind this delay is the more complicated behavior of the unguided waves used in GPR as compared with waves guided by a TDR sensor.*" Indeed, the lack of accuracy of the classical GPR methods is mainly due to the poor modelling of the GPR signal and the strongly simplifying assumptions with respect to the electromagnetic wave propagation phenomena in the radar-antenna-subsurface system. In addition, the GPR devices that have been used in soil science sofar, have not been designed to take into consideration the specificity of the soil unsaturated zone. As a result, the information contained in the GPR signal is only partially used and the estimated parameters inherently suffer from accuracy problems as compared to other measurement techniques. Resorting to a more rigorous modelling of GPR wave propagation is therefore needed to improve the estimation of soil functional properties, including the soil moisture content and electric conductivity. This has become a rational choice due to the ever increasing power of computers.

In order to improve the accuracy and analysis of GPR for soil moisture and salinity mapping,

Lambot et al., (2003) recently designed an ultra wideband off-ground stepped-frequency continuous-wave (SFCW) GPR combined with a transverse electric and magnetic (TEM) horn antenna, playing simultaneously the role of emitter and receiver (monostatic mode of operation). The technique is based of international standard vector network analyzer technology, for which, in contrast to traditional commercial GPR systems, the physical quantity measured is fully known. They further modelled wave propagation in the antenna-air-subsurface system using linear transfer function theory in the frequency domain and specific 3D solutions of Maxwell's equations for wave propagating in multilayered media. This model has shown high accuracy and permits to relate the raw radar data to the soil electromagnetic properties (Lambot et al., 2004c). The full wave inversion of this model permits theoretically to maximize in terms of quantity and quality the information that can be retrieved from the GPR data and allows to estimate soil moisture and salinity in various conditions (Lambot et al., 2004bcd). The technique have been shown to be robust with respect to surface roughness, which offers practical possibilities for applying the technique in-situ (Lambot et al., 2006a). When focussing the signal analysis on a time window encompassing the surface reflection, the full wave inversion have been shown to be superior and more practical to the common surface reflection method for estimating the soil surface water content (Lambot et al., 2006b). However, this latter analysis also elucidated that accurate measurements with the common reflection method and the full wave inversion can only be obtained when the soil electrical conductivity is sufficiently low (typically lower than 0.1 dS/m) or when no strong dielectric contrasts in the surface soil layer are expected. Yet, these particular conditions can anyway be accounted for in the full wave inversion method.

Given the potential of GPR to monitor soil moisture and salinity, it has also been applied to identify flow and transport properties. Lambot et al. (2004e) measured the soil water profile within an artificial tank in equilibrium with a water table. The measured soil profile corresponded to the soil moisture retention curve and could reasonably be well estimated with this technique (Fig. 8). It was also shown, with a synthetic experiment, that the radar signature contains sufficient information to estimate the continuous dielectric profile. However, the experiment demonstrated that the inverse solution may not be stable when the operating frequency range is too high. A major difficulty with continuous profiles, as often encountered in the vadose zone, is that they preclude strong wave reflections, as e.g. emphasized also by Bano (2006). In a recent numerical study Lambot and coworkers coupled the GPR wave propagation model with a hydrodynamic model and demonstrated that the proximal GPR time lapse measurements contains sufficient information to estimate the soil hydraulic properties from a transient infiltration experiment (Lambot et al., 2006) (Fig. 9).

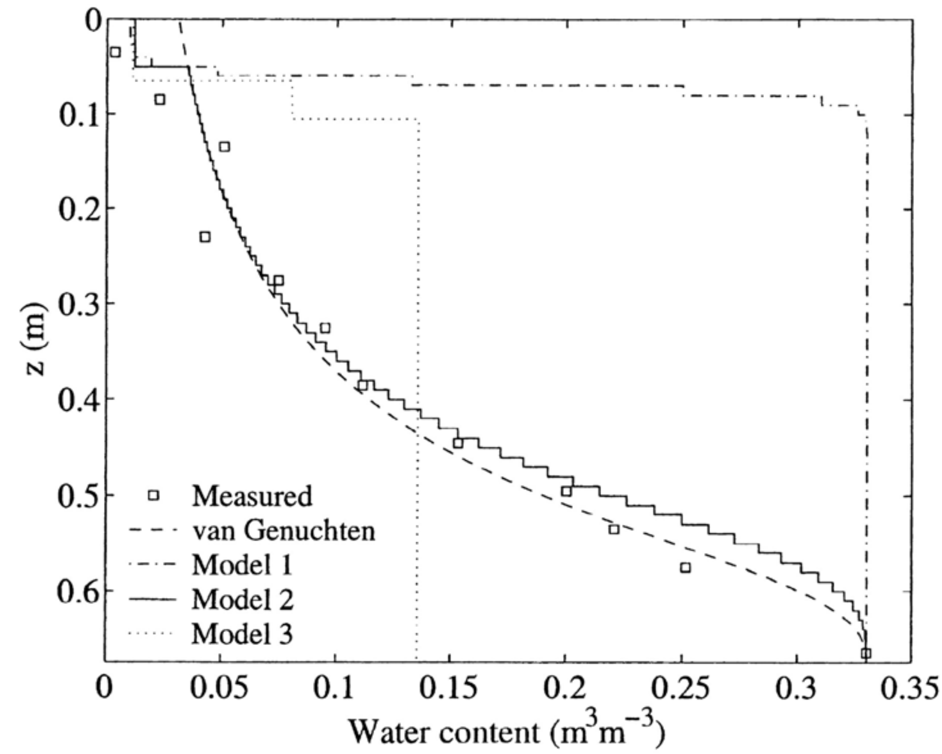

Fig. 8. Measured and fitted retention curve for the sand box and estimated curves with three different GPR inversion models (Source: Lambot et al., 2004)

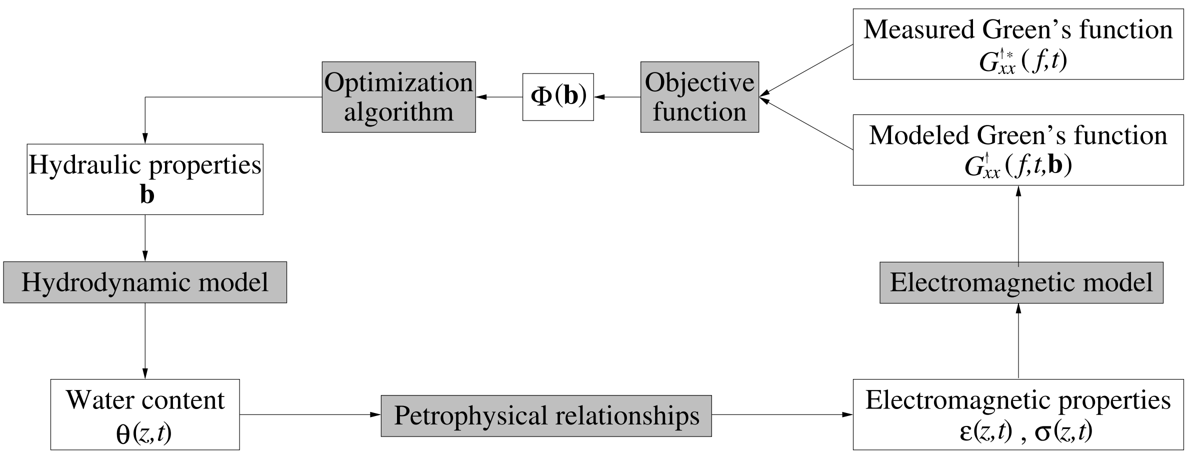

Fig. 9: Closed-loop inversion of GPR (Source: Lambot et al., 2006).

4.3.- Electrical Resistivity Tomography (ERT) as a support for flow and transport characterization in soil.

Electrical resistivity tomography (ERT) is a classical geophysical technique that has been developed already in 1900, but that became more widely used since 1970, due primarily to the availability of computers to process and analyse the data (Reynolds, 1997). The electrical resistivity of soil is influenced by the temperature, the soil structural properties, the water saturation degree, the surface electrical conductivity of the soil solid phase and the electrical conductivity of the soil solution. Properties related to soil structure, soil moisture and soil salinity can therefore be mapped by means of ERT. Though existing since long in the domain of applied geophysics, ERT was only recently introduced in soil science. A review of the use of ERT in this domain is given by (Samouëlian et al., 2005).

ERT has first been used to map soil structural features. At the field scale, Tabbagh et al. (2000) successfully used ERT to identify the structure of a hard-pan in a sandy soil in an arid area, and clayey horizons in a Miocene deltaic formation. Similarly, Besson et al. (2004) showed how soil structural change by tillage practices in a cultivated loamy soil could be assessed by means of ERT. However, they warranted that 2D surveys may be insufficient to get an appropriate view of the relevant soil structural changes and recommended to increase the spatial resolution to elucidate relevant structural changes at the smaller scale. At the smaller scale, and using specific electrodes to ensure good contact between the soil and the reduced space electrode array Samouëlian et al. (2003) identified soil structural properties with a high spatial resolution. In particular, they were able to assess cracks in soils at the centimetric scale. This ability of ERT is extremely relevant for identifying preferential flow mechanisms. Above mentioned studies showed that ERT may be an excellent technique to assess flow related structural properties at the field as well as at the meso-scale.

ERT has early been used for characterising soil moisture (Bouyoucos et al., 1939; Zhou et al., 2001) and solute transport (Binley et al., 1996) in unsaturated soils. Time lapse ERT coupled to appropriate hydrodynamic model inversion may allow estimating flow and transport properties. For flow in saturated media for instance, Kemna et al. (2002) illustrated that effective solute dispersion could be estimated from a solute tracer experiment as monitored by means of time lapse ERT. Numerical experiments performed by Vanderborght et al. (2005) further showed that the ERT had a sufficiently high spatial resolution to infer the hydraulic conductivity spatial correlation. In unsaturated undisturbed soil columns, Binley et al. (1996) measured solute transport of an inert tracer by time lapse ERT. They were able to trace preferential flow and to estimate the solute dispersivity from fitting the solution of the governing transport equation to the observed breakthrough curve. In a heterogeneous unsaturated sandy coarse formation, French et al. (2002) used time lapse ERT to monitor tracer transport after snow melt. They used spatial moment analysis to identify the regions of this unsaturated zone characterised by high infiltration patterns. Recently, Köstel et al. (2007) showed that a quantitative mapping of the water concentration distribution was feasible, which renders possible the tracking of 3-D solute pulses.

As compared to TDR and GPR, ERT is probably easier to implement. The technology is also less expensive. However, data inversion and modelling for extracting the relevant flow and transport features in unsaturated soils is still a challenge, as illustrated by Furman et al. (2003) and Liu and Yeh (2004).

5.- Conclusions

In this keynote paper, some recent advances for characterizing flow and transport in soil has been described. The existing gap that exists between the support scale of classical characterisation techniques and the scale for which flow and transport need to be described in operation soil and water management, forces environmental scientists to develop new characterization strategies. We illustrated some recent progress with direct (dye tracing and suction sampling) and indirect (TDR, GPR and ERT) techniques. Though direct techniques do not help very much in solving the scale issue, further research attention is still needed for improving these techniques. Indeed, direct techniques will always be needed for the “ground truthing” of the many recently developed indirect techniques. In addition, indirect techniques are often insensitive for many relevant soil processes such as reactive solute transport for instance.

Each characterisation technique described above has its strengths and weaknesses and each technique offers some opportunities for improving the characterisation of flow and transport in soil, and no single optimal technique will, and never will, exist. It is therefore our believe that effective and efficient strategies for characterizing flow and transport will likely encompass the combination of several techniques, each providing a part of the required information. Gomez-Ortiz et al. (2007) for instance illustrated how GPR and ERT can jointly be applied to image volcanic material and structures in Tenerife. Binley et al. (2002) used cross borehole ERT, with transmission GPR to monitor a tracer test through an unsaturated sandstone, to estimate the effective unsaturated conductivity of the soil. The combination of the different techniques in these studies definitely added considerable value to the characterization of flow and transport, yet, the way how this combination should best be performed will remain a matter of active research. In particular, the design of new integrated hydrogeophysical inversion techniques is needed as deterministic data fusion approach to improve subsurface characterization and help in understanding the various processes occurring in the subsurface.

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