Hydrogeophysics: opportunities and challenges

A. Binley[1], G. Cassiani[2] and R. Deiana[2]

[1] Lancaster Environment Centre, Lancaster, United Kingdom
[2] Dipartimento di Geoscienze, Padova, Italy

(Received: February 09, 2010; accepted: May 04, 2010)

ABSTRACT The field "hydrogeophysics" emerged in the 1990s as a multi-disciplinary subject that focuses on the use of geophysical methods for characterising subsurface features, determining hydrogeological properties and monitoring processes relevant to soil and groundwater processes. Hydrogeophysical methods can allow large scale aquifer characterization, previously unobtainable through conventional hydrogeological techniques. In addition, time-lapse deployment of appropriate methods can give useful insight into complex subsurface processes, aiding hydrological model development and the assessment of groundwater restoration strategies. Here, we review hydrogeophysical approaches and highlight potential new (or emerging) application areas, such as hyporheic zone characterization and monitoring soil-water-plant interactions. We discuss new approaches for analysis of hydrogeophysical data, including the fusion of multi-modality data and hydrological models. We emphasise the need for appropriate constitutive relationships, which are fundamental to most hydrogeophysical investigations. Finally, we list a number of key challenges, namely resolution and scale of method, computational demands on multi-dimensional modelling and the need for quantification of the information content in the various hydrogeophysical data sources.

1. Introduction

Hydrology has traditionally relied upon the availability of point measurements: precipitation at rain gauges, groundwater potentiometric surface at boreholes and, more recently, soil moisture content as measured, for example, by time-domain reflectometry (TDR: Topp *et al.*, 1982). This body of information is necessary, but often far from being complete. In particular, it has been largely demonstrated (e.g., Beven and Binley, 1992) that, given the point information above, there will always be a number of different models that reproduce equally well the observed hydrological data (such as river discharge). This equifinal nature of different models is limited to their capability of matching the observed limited and local data, and may not be reflected in their prediction capability, i.e., the model forecasts may differ substantially should the forcing conditions (e.g., precipitation) be changed beyond the observed values. This critical model limitation is essentially driven by the fact that the actual structure of the subsurface is poorly known in terms of geometry, geology and hydraulic properties; this limitation often forces the models to be black boxes, either explicitly or implicitly due to the poor knowledge of the actual system characteristics.

Overcoming these serious limitations of hydrological modelling is not related to the nature of the models, but rather requires extra information. This is one of the fundamental needs addressed by hydrogeophysical measurements.

Hydrology research has developed a number of sophisticated tools to try and account for model uncertainty, particularly with respect to the limited knowledge of the subsurface in terms of its hydraulic property distribution. In particular, stochastic techniques have had a tremendous development in both surface (e.g., Bras and Rodriguez-Iturbe, 1993) and subsurface hydrology (e.g., Rubin, 2003). However, stochastic models require even more data than traditional deterministic models, as an estimate of the underlying spatial statistical structure of the governing parameters is needed. Heavy reliance was initially put on densely monitored sites with hundreds of boreholes drilled over a few hectares (e.g., LeBlanc *et al.*, 1991), but this approach could not be realised except at a few advanced research sites. As a consequence, during the 1990s there was a rapid growth in the use of geophysics to try and provide spatially dense, quantitative information about hydrological properties and processes. This need, in addition to the growing availability of fast field acquisition instruments and powerful computational tools, has led to much of the current developments in hydrogeophysics.

In addition to the above, important new requirements have been posed lately upon hydrological characterization and modelling, for example, by the new European Union regulations (in particular the Water Framework Directive 2000/60/EC, and the Groundwater Directive 2006/118/EC). In particular, the growing issue of water quality requires that the presence and location of contaminants be assessed, and their migration in the hydrological system be monitored. The limitations of hydrological modelling and point measurements are even more severe in the case of water quality than in water quantity assessment. Here too geophysical methods have a potential role.

In summary, hydrogeophysics is asked to provide data for the following purposes:

a) structural characterization,
b) fluid-dynamics,
c) presence and motion of contaminants.

Geophysics has long been used to support hydrogeological studies, but mainly for lithological boundary delineation (e.g., Giustiniani *et al.*, 2008), i.e., to support structural (geometrical) characterization of aquifers. This use of geophysics does not fully exploit the geophysical measurements, but rather seeks to highlight contrasts in whatever physical property can distinguish one geological formation from its neighbours. This classical approach is also common to other major applications of geophysics, such as in the petroleum industry. However, geophysics has long been used also to exploit the physical nature of measurements, and translating these measurements into quantitative estimates of the soil/rock properties of interest. This has been particularly used for downhole measurements, i.e., for borehole logs (Schlumberger, 1989). This translation requires that suitable constitutive laws link physical and structural properties of soil/rock, and the relevant discipline is petrophysics (e.g., Mavko *et al.*, 2009). The use of borehole logs for hydrogeological studies has a long history too (e.g., Kobr *et al.*, 2005) even though it has never reached the popularity enjoyed in petroleum applications.

In view of the needs above, the current developments in hydrogeophysics are aimed at providing quantitative information on the hydrological and hydraulic characteristics of the soil and subsoil, as well as quantitative data on the presence and motion of fluids and solutes in and

Table 1 - Use and effectiveness of geophysical methods for hydrological studies

	Structure	**Fluid dynamics**	**Contamination**
Gravimetry	+	++	
Magnetics	+		
Seismics	+ +	+	
DC resistivity	+ +	+ +	+
Electromagnetics	+	+ +	+
Induced Polarization		+ +	+ +
Self Potential	+	+	+
GPR	+	+ +	+
NMR	+	+ +	

out of the subsurface. Hydrogeophysics is therefore becoming a key instrument towards an effective characterization of hydrological systems.

Among the available geophysical methods, not all of them are equally suitable for hydrogeophysical applications. Each geophysical technique measures at least one physical quantity:

- seismics: elastic moduli and density,
- gravimetry: density,
- magnetics: susceptability and permanent magnetization,
- geoelectrics [DC resistivity, e.g., electrical resistivity tomography (ERT)]: electrical conductivity,
- geoelectrics [induced polarization (IP)]: complex electrical conductivity,
- electromagnetic (EM) methods: electrical conductivity,
- self potential (SP): electrical conductivity and potential sources,
- ground penetrating radar (GPR): dielectric constant, electrical conductivity,
- nuclear magnetic resonance (NMR): number or protons, free pathway in pores, electrical conductivity.

In view of the hydrological aspects described above, potentially all geophysical methods can have some useful hydrogeophysical application, particularly in terms of structure characterization. However, some techniques have a more specific link to hydrological properties and to the presence/motion of water: these are listed above. In particular, the physical quantities more specifically affected by water presence or motion are, among the ones most commonly measured, electrical conductivity via ERT (Binley and Kemna, 2005) and dielectric constant via GPR (Annan, 2005). Other more specialized measurements (IP, SP and NMR) have strong connection to the pore-medium structure and presence/motion of water, solutes and free-phase contaminants, but are still of less common use as the relevant signal can be either below ambient noise or of uncertain attribution to hydrological causes.

Table 1 lists in a qualitative (somehow subjective) manner the relative suitability of different methods for the different hydrological aspects.

In this paper, we wish to highlight:

1) the main approaches taken in hydrogeophysical research over the past two decades, and how these approaches address the fundamental hydrologic needs discussed above;
2) the most promising opportunities in view to extend and improve the role of hydrogeophysics;
3) the relevant challenges to be faced.

2. Hydrological problems and hydrogeophysical approaches

Effective hydrological studies require a quantitative assessment of water presence and motion in the environmental compartments of interest. Depending on the specific aims of the study at hand, one or more of the following compartments shall be considered: saturated zone, vadose (unsaturated) zone, shallow soil. The three compartments differ not only in terms of their hydrological role and mechanisms, but also in terms of the hydrogeophysical measurements that can be conducted profitably on them. In the following, we try and give a short outline of the subsurface hydrology compartments with some of the recent, key papers relevant to each compartment.

2.1. The saturated zone

Aquifer studies are a traditional area of interest of subsurface hydrology. Their focus has been progressively shifting from water quantity to water quality problems. Transport of dissolved substances in groundwater is the most important mechanism controlling the migration of pollutants in the subsurface and is strongly controlled by geological heterogeneity at a variety of scales. In particular, hydraulic conductivity can vary by up to thirteen orders of magnitude. This fact has as a consequence a strong spatio-temporal variability of solute concentrations, that makes conventional monitoring techniques, based on a few boreholes and limited water sampling in space and time, often incapable of capturing the variability of transport properties, as well as the complexity of transport processes. Hydrogeophysics can provide spatially and temporally dense information on the evolution of solute plumes, particularly during tracer tests (Kemna *et al.*, 2002, 2006; Cassiani *et al.*, 2006; Monego *et al.*, 2010). Electrical and electromagnetic techniques have been predominantly used for these purposes, as they are sensitive to changes in aqueous phase electrical conductivity caused by saline tracers. Tomographic techniques offer the possibility to construct “images” of the subsurface, in 2D or 3D, that are well suited to picture the evolution of solute plumes. ERT, in particular, has been the key methodology applied for saline tracer imaging (e.g., Binley *et al.*, 1996), but some notable examples using GPR attenuation for the same purpose have also been made possible, due to the increased electrical conductivity of the tracer (Day-Lewis *et al.*, 2003; Johnson *et al.*, 2007). In all cases, and in contrast to structural hydrogeological characterization, where “static” properties of the subsurface are explored, transport characterization involves the monitoring of “dynamic” processes associated with spatio-temporal variations of subsurface state variables. The mapping and monitoring of transport processes therefore requires application of time-lapse geophysical methodologies that allow the user to distinguish between static and dynamic effects. Early applications (e.g., Bevc and Morrison, 1991; Daily *et al.*, 1992, 1995; Binley *et al.*, 1996; Slater *et al.*, 1997a, 2000) were limited to imaging solute transport as accurately as possible, but did not provide estimates of hydraulic parameters and their spatial variability. In order to quantify the hydraulic parameters of the subsurface, it is essential to make use of hydrological models. The geophysical time-lapse data are used as equivalent concentration data to infer the timing and location of tracer breakthrough. In conjunction with transport models, such data can be directly interpreted in terms of transport parameters, such as flow velocity and dispersivity. The recent literature on time-lapse ERT applied to saline tracer tests follows this conceptual pathway to different extents (Kemna *et al.*, 2002; Slater *et al.*, 2002; Singha and Gorelick, 2005; Vanderborght *et al.*, 2005). Tracer mass balance issues linked to ERT resolution issues prompted a series of possible approaches to tackle the limited resolution of ERT (Singha and Gorelick, 2006a, 2006b; Singha and Moysey, 2006) and the research is ongoing (Day-Lewis and Singha, 2008; Pollock and Cirpka, 2008; Singha *et al.*, 2008).

2.2. The vadose zone

The vadose zone, i.e., the part of subsurface above the water table, is home to a number of key processes that control the mass and energy exchanges between the subsurface and soil surface. Vadose zone hydrology provides information about exchanges with the soil compartment, and from there with the atmosphere, and subsurface water migration, with strong implications in water resources management: aquifer recharge is controlled by movement through the vadose zone. Contaminants released from the surface invade the vadose zone and, before reaching the aquifer system underneath, can be altered, retarded or wholly removed by biological, chemical and physical processes in the vadose zone. Unsaturated processes control also the availability of water for agriculture, and are the driving mechanisms in slope stability, floods and other major engineering geology problems. However, in practice, the hydrology of the vadose zone is poorly known, mainly because of technical limitations in sampling and access just at one or two metres below ground. The most useful measurements of unsaturated zone conditions (moisture content via TDR and suction via tensiometers) are limited in depth to no more than a couple of metres depth and extensive monitoring over large areas is labour intensive and time consuming and are essentially local scale measurements. Other techniques are, therefore, needed. The vadose zone deeper than a couple of metres below ground surface can be mapped from the surface, at the expense of severe resolution losses, and more efficiently using borehole geophysical methods: single-borehole, borehole-to-borehole and borehole-to-surface geophysical measurements achieve a resolution sufficient for quantitative hydrologic interpretation [Hubbard *et al*. (1997); Slater *et al.* (1997b); Binley *et al.* (2001, 2002a, 2002b); Alumbaugh *et al.* (2002); French *et al.* (2002); Binley and Beven (2003); Cassiani *et al.* (2004, 2008, 2009b); Schmalholz *et al.* (2004); Cassiani and Binley (2005); Chang *et al.* (2006); Deiana *et al.* (2007, 2008); Koestel *et al.* (2008); Looms *et al.* (2008a, 2008b); among others; for reviews see Huisman *et al.* (2003); Cassiani *et al.* (2006)]. In most cases, the ultimate goal is the identification of hydraulic properties and parameters of the vadose zone. The dependence of the geophysical response on changes in soil moisture content, e.g., via changes in electrical resistivity or dielectric properties, is the key mechanism that permits the use of non-invasive techniques to monitor the vadose zone in time-lapse mode, i.e., via repeated measurements over time. The use of these techniques in different configurations in the shallow and deep vadose zones can provide high-resolution images of hydrogeological structures and, in some cases, a detailed assessment of dynamic processes in the subsurface environment. Both natural infiltration processes and specifically designed tracer tests can be monitored over periods of time that can last from a few hours to several years. The data from non-invasive techniques can subsequently be used to calibrate physical-mathematical models of water flow in the unsaturated zone.

2.3. Soil

Soil is a non-renewable resource, subjected to serious threats such as soil erosion, decline in organic matter, local and diffuse contamination, sealing, compaction, decline in biodiversity, salinization, floods and landslides. Soil protection and restoration require high-resolution information about soil properties. Conventional, sample-based soil property mapping is very time-consuming, cost-intensive, and the data collected are available only for discrete points in a landscape. Various soil parameters can be mapped using rapid, nearly non-destructive methods (geophysics, spectroscopy), for quasi-continuous 2D as well as 3D mapping of soil physical and hydrological properties (Allred *et al.*, 2008): electromagnetic induction (EMI); GPR; magnetics, seismics, gamma ray spectrometry.

Soil is also the shallowest portion of the vadose zone. One of the key aspects of hydrological characterization of soil relies on our capability of mapping soil moisture content in its space-time variations. A leap forward was made by the introduction of time domain reflectometry (TDR) in the early 1980s, that provided a means for quick and inexpensive time-lapse monitoring of moisture content in the first couple of metres. TDR paved the way towards the general acceptance of indirect measurements of soil moisture content. Consequently, the estimation of water content space and time variations in shallow soil layers using in-situ non invasive techniques has been the focus of intensive research over the past three decades, with particular attention to techniques that measure the dielectric constant of the porous media (e.g., Topp and Davis, 1985; Roth *et al.*, 1990; Robinson and Friedman, 2003), that is strongly affected by the presence of water in the soil pores. Among other techniques, two methods have gained popularity for the in-situ estimation of soil moisture content: surface-to-surface GPR and ERT. GPR used in surface-to-surface configuration has increasingly been proposed as a means to obtain fast and inexpensive images of soil moisture content over large areas at shallow depth (e.g., van Overmeeren *et al.,* 1997; Parkin *et al.*, 2000; Huisman *et al.*, 2001; Grote *et al.*, 2003) In surface-to-surface GPR measurements, the velocity of direct ground waves that travel from the transmitting antenna to the receiving antenna just below the soil surface can be used to estimate the soil water content at shallow depths over relatively large areas, at a scale of interest for hydrological models. Generally, three different survey types [i.e., Wide Angle Reflection and Refraction (WARR); Common Mid Point (CMP); Single Offset (SO) methods] can be used to estimate the direct ground wave velocity and infer the water content. The success of the method relies on the assumption that identifying such direct arrival is straightforward and cannot be confused with other events. This condition is not always met, e.g., in the presence of critically refracted radar waves (Bohidar and Hermance, 2002) or guided waves (Arcone *et al.*, 1984, 2003; van der Kruk *et al.*, 2006; Strobbia and Cassiani, 2007).

Geophysical methods have also shown some success in characterization of structural properties of the shallow soil (e.g., Besson *et al.*, 2004; Samouélian *et al.*, 2004). Such properties have direct links to hydrological responses but also impact on the ecological function of the soil (see later).

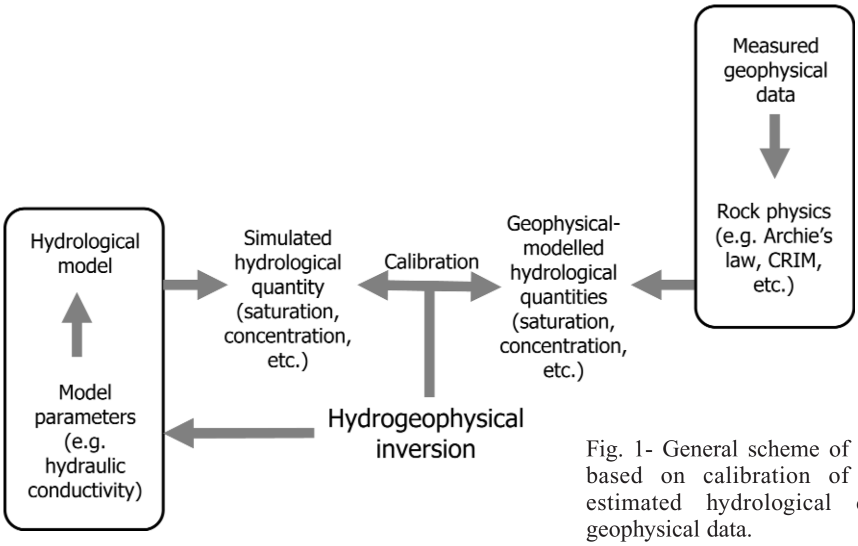

Fig. 1- General scheme of hydrogeophysical inversion based on calibration of hydrological models on estimated hydrological quantities derived from geophysical data.

2.4. General hydrogeophysics approach

Of the three key aspects of the hydrological problem, it goes beyond doubt that the most important and general aspect is the understanding of fluid-dynamics (Vereecken *et al.*, 2002, 2004, 2006; Rubin and Hubbard, 2005; Pellerin *et al.*, 2009). This aspect effectively is key to all hydrologically-controlled environmental problems. Irrespective of the hydrological compartment of interest, two general frameworks have been adopted to address the understanding of subsurface fluid-dynamics, i.e.,:

1) a direct link has been sought between geophysical (e.g., electrical resistivity) and hydrological parameters (e.g., hydraulic conductivity);
2) a link has been exploited between geophysical quantities and hydrological state variables (e.g., moisture content or water salinity), and identification of hydrological parameters via model calibration.

The first approach dates back to the earliest attempts to relate geophysics to hydrological parameters (e.g., Kelly, 1977; Mazác *et al.*, 1985) and in its original formulations sought essentially a link between electrical resistivity and hydraulic conductivity. This approach has had limited success, as the uncertainty associated to such link is far too wide and site-specific to be of any practical use. Some more sophisticated recent findings may lead to future developments using other geophysical techniques (see section 3).

The second approach, mentioned above, is based on the more reliable links that can be established between geophysical quantities and hydrological variables such as water content and solute concentration, generally in the form of empirical or semiempirical relationships (constitutive relationships). Consider e.g., the classical relationships proposed by Archie (1942) for electrical conductivity and by Topp *et al.* (1980) and Roth *et al.* (1990) for the dielectric constant. Using such relationships, it is possible, albeit not always straightforward, to obtain quantitative estimates of hydrologic data to be used for the calibration of hydrologic models, thus identifying the parameters of interest (Fig. 1). Intuitively, the calibration of a hydrological model requires that the system is adequately stressed so that different states of the variables are explored. This condition is not guaranteed to be met under natural conditions. Consequently, it is faster and more informative to conduct controlled experiments that can be monitored in a time span of hours, days, or weeks depending on the dynamics of the system. Key to the possibility of using this approach is the capability of measuring geophysical quantities repeatedly, over time. It is interesting to note that although numerous synthetic model studies have been utilised to demonstrate quantification of hydraulic properties from time-lapse geophysical studies, very few (e.g., Binley *et al.*, 2002a) have illustrated the approach in field-based studies.

Today many shallow geophysical techniques have the potential to highlight two concurring aspects of the subsurface:

a) its static aspects, i.e., the characteristics that do not change over time, principally the geology;
b) its dynamic aspects, i.e., the characteristics that do change over time, and that are inherently linked to the motion of fluids, water above all.

In this respect, the development of shallow geophysical methods is very similar to that of classical deep applications, such as reflection seismics, as utilized in the petroleum industry. More and more often, petroleum geophysics is seen as a means for understanding the nature of a site and its evolution in terms of fluid-dynamics, such as changes in fluid saturation (e.g.,, water versus oil or gas), and is being used as a key supporting technique for a site's management during petroleum production (time-lapse surveying). Similarly, the future of environmental geophysics stays in its capacity to describe a site in its current state and evolution, and in the integration of this information into the calibration of hydrological, hydrogeological and geomechanical predictive models. If time-lapse measurements are made, changes in geophysical response at the same spatial location are generally linked to hydrological changes, e.g., in the vadose zone to changes in water saturation. Features that are not changing over time can be reasonably attributed to geological control: e.g., water saturation may be consistently different at different spatial locations as a consequence of lithological differences. This use of geophysical data requires:

1. that the collected geophysical data have a clear, identifiable and possibly quantitative meaning in terms of environmental variables of interest, e.g., water saturation: petrophysical constitutive models are needed for this conversion; the experience of borehole geophysical logs and TDR provide the starting point for these;
2. that the resolution and sensitivity of geophysical methods in space and time is fully understood, in order to assess the actual information content in the data, and prevent, e.g.,, the erroneous interpretation of artefacts;
3. that hydrologic modelling be devised to be able to incorporate the non-invasive data in the most profitable and effective way, accounting for resolution, sensitivity and scale effects.

The three points above are, as of today, only partly achieved. The efforts aimed at fulfilling these requirements constitute the body of a fascinating and diversified area of research.

3. Opportunities in hydrogeophysics

The rapid development of hydrogeophysical techniques over the past two decades has led to tremendous progress in a number of areas of practical and scientific interest. However, a number of opportunities and challenges remain unexplored.

3.1. Areas of new developments

Hydrogeophysical techniques have been focused for the most part on the areas of applications described above (saturated, unsaturated zones and soil). These areas comprise a large portion of interests in hydrological sciences, but are far from completing the range of problems where data, extensive both in space and time, are needed.

One of the key limitations of the most commonly used hydrogeophysical techniques is their scale of application (metres to hundreds of metres): the type of time-lapse measurements described above cannot easily exceed this limited scale. However, the majority of hydrological problems requires, in principle, monitoring and parameter assessment over the much larger catchment scale (km to thousand of km). Key hydrological questions, including the vulnerability of hydrological systems to climate changes, can only be answered in this larger setting (Robinson *et al.*, 2007).

Many important hydrological environments, such as shallow fresh and brackish waters, have not received so far sufficient attention in terms of hydrogeophysical characterization. One such environment is hill and mountain slopes. The understanding of hillslope processes is key to an appropriate modelling of catchment response. However, only very few examples of hydrogeophysical hillslope studies are available to date (Suzuki and Higashi, 2001; Uhlenbrook *et al.*, 2008; Miller *et al.*, 2008, Cassiani *et al.*, 2009a).

Hydrological science has also been developing towards the understanding of more complex systems, particularly at critical interfaces in the hydrosphere. In many areas, understanding the interaction between surface and subsurface water bodies is key to successful management of water resources. In particular, the hydrological and bioeochemical mechanisms related to nutrient transformation in the hyporheic zone is poorly understood and there is a need for new field-based methods to provide improved characterization. Very little efforts have been devoted so far to the use of hydrogeophysical techniques in this area (e.g., Crook *et al.*, 2008; Singha *et al.*, 2008; Nyquist *et al.*, 2009), but this is an area of necessary development.

Improved characterization of hydrological-ecological interactions is also emerging as an area of potential development in hydrogeophysics. Robinson *et al.* (2008) and Kettridge *et al.* (2008), for example, demonstrate the value of geophysical methods for understanding spatial patterns in plant ecology, while Petersen and Al Hagrey (2009) investigate the potential of electrical methods for mapping root zone distribution. As food security, optimised management of agriculture and the preservation of ecologically vulnerable areas grow in importance, there is a clear future need for growth in hydrogeophysical developments in this area.

Another field where non-invasive characterization techniques have been used, but maybe not to their full potential, is the study of contaminated sites. All aspects of soil, unsaturated zone and saturated zone characterization are to be considered at these sites, but the presence and motion of contaminants are a further key aspect. In addition, monitoring of in-situ remediation techniques is a very promising area of time-lapse hydrogeophysical research (e.g., LaBrecque *et al.*, 1996; Slater and Binley, 2006).

The integration of geophysical data into digital soil mapping is an area of active research (Allred *et al.*, 2008). However, the current techniques are deficient in terms of the understanding of relationships between mapped soil parameters and relevant soil functions, the scaling up for investigating large areas (e.g., catchments and landscapes) and the evaluation of soil degradation at such scales. In this context new strategies must be developed to derive from multi-parameter geophysical measurements the necessary information to derive unique estimates of specific soil parameters (van Egmond *et al.*, 2009).

3.2. New/other techniques

The core of hydrogeophysical research has been long based on few well established techniques, particularly ERT and GPR. However, novel techniques have attracted a growing interest in recent years. Spectral Induced Polarization (SIP) is an extension of the classical induced polarization (Sumner, 1976) that uses multi-frequency measurements, typcially in the 0.01 Hz to 1 kHz range. From a hydrological perspective, SIP (and IP) offer useful information as the measured signals are influenced by interactions along the grain boundary, rather than entirely in the pore space (as in bulk resistivity, for example). Recent evidence exists that SIP response of porous media can be linked to their structure and hydraulic properties (e.g., Binley *et al.*, 2005), the presence of free-phase contaminants (e.g., Cassiani *et al.*, 2008) and micro-biological activity (e.g., Ntarlagiannis *et al.*, 2006). Successful SIP field applications have been reported (e.g., Kemna *et al.*, 2004) but substantial technological and scientific developments are strongly needed.

Spontaneous Potential (SP) is based on the measurement of electrical potential differences present in the ground. The origin of SP has two main components: (1) the electrokinetic contribution associated with groundwater flow through the permeable soil and (2) oxido-reduction phenomena. Both can have very interesting applications in the study of water flow (e.g., Revil *et al.*, 2003) and contamination (e.g., Naudet *et al.*, 2003). However, some major progress is needed to be able to identify, case by case, the relative contribution of different SP sources to the observed field SP data.

Like SP, the measurement of gravity acceleration is not a new technique. However, the sensitivity of modern micro-gravity meters allows for accurate time-lapse measurements of gravity changes due to changes of water storage underground (Biegert *et al.*, 2008). The impact on large-scale hydrological monitoring can be tremendous, as microgravimetry allows for extensive and precise monitoring of mass storage in the system, and can be potentially used to calibrate full scale catchment hydrology models.

EM methods have been long utilized in the frequency and time domain, but their hydrogeophysical applications have been limited. This is mainly due to the apparent difficulty at identifying the precise support volume of the measurements and the often invoked 1D nature of EM inversion. However, EM methods have also the advantage of providing data on subsoil electrical conductivity with no need for galvanic contact. This advantage leads to the possibility of collecting data from airborne platforms over large areas in very short time. Airborne Time-Domain EM methods are strong candidates for large scale hydrogeophysical monitoring (Christiansen *et al.*, 2006).

Surface proton magnetic resonance sounding (MRS), or nuclear magnetic resonance (NMR), measurements can be used to indirectly estimate the water content of saturated and unsaturated zones in the Earth's subsurface. MRS can be used to estimate aquifer properties, including quantity of water contained in the aquifer, porosity, and hydraulic permeability, thus being one of the most promising areas of active hydrogeophysical research (e.g., Braun *et al.*, 2009). Up to now, the main limitations of MRS stand in their low signal-to-noise ratio, that make them suitable only to regions with limited anthropogenic presence.

3.3. Rock physics

The availability of reliable constitutive models linking geophysical and hydrological quantities is key to the overall success of hydrogeophysics. A number of models exist, e.g., for electrical properties (Lesmes and Friedman, 2005), even though many of them require site-specific parameters that need calibration, and some such parameters are not necessarily independently identified (e.g., Brovelli and Cassiani, 2008). The need exists for advanced models, accounting also for multiple links between geophysical quantities (e.g., electrical conductivity and dielectric constant) with hydrological quantities (e.g., moisture content, water salinity) having parameters with defined meaning in terms of soil/rock characteristics. These multi-parameter models, still in their infancy, are essential in order to devise quantitative means for joint hydrogeophysical data inversion (Linde *et al.*, 2006; Brovelli and Cassiani, 2010). Among the tools applicable to investigate these relationships are pore-scale models (e.g., Dalla *et al.*, 2004; Brovelli *et al.*, 2005).

3.4. Data fusion and joint inversion.

The availability of multiple geophysical data on the same subsurface structure calls for effective data integration. This can be done in many ways. One of the most promising approaches is the “Stochastic Engine” approach developed at the Lawrence Livermore Laboratory (Ramirez *et al.*, 2005). This approach explores multiple realisations of subsurface geophysical structures (conditioned on a priori soft and hard information) as models that are consistent with the observed data. The technique, which follows a Markov chain Monte Carlo (McMC) approach, uses geophysical forward models to test for consistency between proposed models and measured response. Although potentially computationally prohibitive for routine applications at present, the method has significant advantages over conventional deterministic approaches: (i) a wide range of data types may be integrated; (ii) the final result does not suffer from artefacts of regularisation in an inversion algorithm; (iii) estimates of model uncertainty naturally result from the model search. Within such an approach, one may also adopt a hydrological model as a means of proposing potential geophysical models. This was tested (albeit with a much simpler search algorithm) on ERT/GPR data applied to a vadose zone study by Looms *et al.* (2008a). More sophisticated search approaches have been developed recently (e.g., Huisman *et al.*, 2010) and we anticipate greater development and application of such approaches in the future.

In Fig. 2, we outline a basic workflow for hydrogeophysical inversion. The key elements worthy of highlight are: (1) the hydrological conceptual model is key to geophysical survey design; (2) the rock physics (constitutive relationships) are likely to be uncertain and this must be recognised in model proposals; (3) there is likely to be a range of possible hydrological

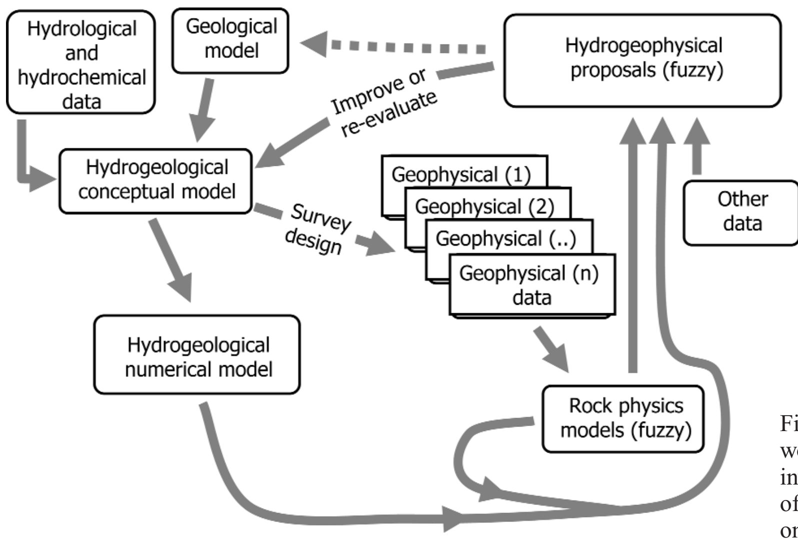

Fig. 2 - Proposed basic workflow of hydrogeophysical inversion based on calibration of hydrological models directly on geophysical data.

models that are consistent with the observed data; (4) multiple data sources should be used to help propose models and test outcomes.

4. Challenges and limitations

The tremendous potential of hydrogeophysics faces also a number of limitations; challenges for the future are to overcome or at least circumvent some of these limitations. The most notable ones are:

a) geophysical data are limited in terms of resolution. This is true even in cross-hole configuration (Cassiani *et al.*, 1998; Day-Lewis and Lane, 2004; Day-Lewis *et al.*, 2005). The key consequence of this is that not the entire geophysical "image" has the same degree of accuracy and practically all inversion methods require some sort of a-priori information (e.g., smoothness) to ensure convergence. Interpreting (also, quantitatively) these hydrogeophysical images with no account for resolution limitations can lead to serious problems. The most notable one is the mass balance errors very often present in tracer tests monitored e.g., via ERT both in the saturated and the unsaturated zones (Binley *et al.*, 2002a; Singha and Gorelick, 2005; Deiana *et al.*, 2007, 2008);
b) scale issues: most hydrogeophysical work has been conducted to date at the small scale. But hydrology needs large scale evaluation. For this reason some techniques that hold the promise to develop into large scale time-lapse monitoring tools should be considered as top priority research areas;
c) inversion and joint inversion is still computationally very expensive, especially in 3D and time-lapse. This, together with the acquisition time in the field, still limits our capability of fully exploiting the conceptual potential of hydrogeophysics;
d) there is a need to demonstrate the information content obtained from geophysical methods in hydrogeophysical studies. Much of the literature, to date, has focussed on developing

and testing methods and approaches. For some problems, geophysics may not be an appropriate tool and there is a danger of overestimation (or assumed knowledge) of the information available from geophysics in some cases. Objective approaches are, therefore, needed in order to test the value of geophysics in hydrological investigations.

In summary, a number of key issues shall be considered when approaching hydrogeophysics as a hydrological tool:

- the hydrologic behaviour of the shallow subsurface can be pictured via non invasive methods;
- the information is maximized by time-lapse measurements and strong changes;
- constitutive laws linking hydrology and geophysics are essential;
- the acquisition and inversion characteristics of the adopted hydro-geophysical methods have critical impact (e.g., scale effect);
- the importance of auxiliary information concerning lithology and geology cannot be over-stressed.

Acknowledgement. This review was made possible by partial funding from the EU FP7 collaborative project ModelPROBE `Model Driven Soil Probing, Site Assessment and Evaluation'.

REFERENCES

Allred B.J., Daniels J.J. and Ehsani M.R.; 2008: *Handbook of Agricultural Geophysics*. CRC Press, Taylor and Francis Group, New York.

Alumbaugh D., Chang P.Y., Paprock L.I., Brainard I.R., Glass R.J. and Rautman C.A.; 2002: *Estimating moisture contents in the vadose zone using cross-borehole ground penetrating radar: A study of accuracy and repeatability*. Water Resources Research, **38**, 1309, doi:10.1029/2001WR000754.

Annan A.P.; 2005: *GPR methods for hydrogeological studies.* In: Rubin Y. and Hubbard S.S. (eds), Hydrogeophysics, Ser. 50, Springer, Dordrecht, pp. 185-214.

Archie G.E.; 1942: *The electrical resistivity log as an aid in determining some reservoir characteristics: Trans.* AIME, **146**, 54-62.

Arcone S.A; 1984: *Field observations of electromagnetic pulse propagation in dielectric slabs.* Geophysics, **49**, 1763-1773.

Arcone S.A., Peapples P.R. and Liu L.; 2003: *Propagation of a ground-penetrating radar (GPR) pulse in a thin surface waveguide.* Geophysics, **68**, 1922-1933.

Besson A., Cousin I., Samouélian A., Boizard H. and Richard G.; 2004: *Structural heterogeneity of the soil tilled layer as characterized by 2D electrical resistivity surveying*. Soil & Tillage Research, **79**, 239-249.

Bevc D. and Morrison H.F.; 1991: *Borehole-to-surface electrical resistivity monitoring of a salt water injection experiment*. Geophysics, **56**, 769-777.

Beven K.J. and Binley A.M.; 1992: *The future of distributed models: model calibration and uncertainty prediction*. Hydrological Processes, **6**, 279-298.

Biegert E., Ferguson J. and Li X.; 2008: *4D gravity monitoring - Introduction*. Geophysics, **73**, Special Section - 4D gravitiy monitoring, WA1 (2008), doi:10.1190/1.3010377.

Binley A. and Beven K.; 2003: *Vadose zone flow model uncertainty as conditioned on geophysical data.* Ground Water, **41**, 119-127.

Binley A.M. and Kemna A.; 2005: *DC resistivity and induced polarization methods.* In: Rubin Y. and Hubbard S.S. (eds), Hydrogeophysics. Water Sci. Technol. Library, Ser. 50, Springer, New York, pp. 129-156.

Binley A.M., Cassiani G., Middleton R. and Winship P.; 2002a: *Vadose zone flow model parameterisation using cross-borehole radar and resistivity imaging*. Journal of Hydrology, **267**, 147-159.

Binley A., Henry-Poulter S. and Shaw B.; 1996: *Examination of solute transport in an undisturbed soil column using electrical resistance tomography*. Water Resources Research, **32**, 763-769.

Binley A.M., Slater L.D., Fukes M. and Cassiani G.; 2005: *The relationship between frequency dependent electrical resistivity and hydraulic properties of saturated and unsaturated sandstone*. Water Resources Research, **41**, W12417, doi:10.1029/2005WR004202.

Binley A.M., Winship P., Middleton R., Pokar M. and West J.; 2001: *High resolution characterization of vadose zone dynamics using cross-borehole radar*. Water Resources Research, **37**, 2639-2652.

Binley A., Winship P., West L.J., Pokar M. and Middleton R.; 2002b: *Seasonal variation of moisture content in unsaturated sandstone inferred from borehole radar and resistivity profiles.* Journal of Hydrology, **267**, 160-172.

Bohidar R.N. and Hermance J.F.; 2002: *The GPR refraction method*. Geophysics, **67**, 1474-1485.

Bras R.L. and Rodriguez-Iturbe I.; 1993: *Random functions and hydrology*. Dover publications, New York.

Braun M, Kamm J. and Yaramanci U.; 2009: *Simultaneous inversion of magnetic resonance sounding in terms of water content, resistivity and decay times*. Near Surface Geophysics, **7**, 589-598.

Brovelli A. and Cassiani G.; 2008: *Effective permittivity of porous media: a critical analysis of the Complex Refractive Index Model (CRIM)*. Geophysical Prospecting, **56**, 715-727, doi:10.1111/j.1365-2478.2008.00724.x.

Brovelli A. and Cassiani G.; 2010: *A combination of the Hashin-Shtrikman bounds aimed at modelling electrical conductivity and permittivity of variably saturated porous media*. Geophysical Journal International, **180**, 225-237, doi:10.1111/j.1365-246X.2009.04415.x.

Brovelli A., Cassiani G., Dalla E., Bergamini F., Pitea D. and Binley A.M.; 2005: *Electrical properties of partially saturated sandstones: a novel computational approach with hydro-geophysical applications*. Water Resources Research, **41**, W08411, doi:10.1029/2004WR003628.

Cassiani G. and Binley A.M.; 2005: *Modeling unsaturated rlow in a layered formation under quasi-steady state conditions using geophysical data constraints*. Advances in Water Resources, **28**, 467-477.

Cassiani G., Boehm G., Vesnaver A. and Nicolich R.; 1998: *A geostatistical framework for incorporating seismic tomography auxiliary data into hydraulic conductivity estimation*. Journal of Hydrology, **206**, 58-74.

Cassiani G., Binley A.M. and Ferré T.P.A.; 2006: *Unsaturated zone processes*. In: Vereecken H, Binley A., Cassiani G., Kharkhordin I., Revil A. and Titov K. (eds), Applied Hydrogeophysics, NATO Sci, Ser. 51, Springer-Verlag, Berlin, pp. 75-116.

Cassiani G., Ferraris S., Giustiniani M., Deiana R. and Strobbia C.; 2009b: *Time-lapse surface-to-surface GPR measurements to monitor a controlled infiltration experiment*. Boll. Geof. Teor. App., **50**, 209-226.

Cassiani G., Fusi N., Susanni D. and Deiana R.; 2008: *Vertical radar profiles for the assessment of landfill capping effectiveness*. Near Surface Geophysics, **6**, 133-142.

Cassiani G., Godio A., Stocco S., Villa A., Deiana R., Frattini P. and Rossi M.; 2009a: *Monitoring the hydrologic behaviour of steep slopes via time-lapse electrical resistivity tomography*. Near Surface Geophysics, special issue on Hydrogeophysics, 475-486.

Cassiani G., Strobbia C. and Gallotti L.; 2004: *Vertical radar profiles for the characterization of the deep vadose zone*. Vadose Zone Journal, **3**, 1093-1115.

Chang P., Alumbaugh D., Brainard J. and Hall L.; 2006: *Cross-borehole ground-penetrating radar for monitoring and imaging solute transport within the vadose zone*. Water Resources Research, **42**, W10413, doi:10.1029/2004WR003871.

Christiansen A.V., Auken E. and Sørensen K.; 2006: *The transient electromagnetic method.* In: Kirsch R. (ed) Groundwater Geophysics: A Tool for Hydrogeology, Springer-Verlag, Berlin, pp. 179-224.

Crook N., Binley A., Knight R., Robinson D.A., Zarnetske J. and Haggerty R.; 2008: *Electrical resistivity imaging of the architecture of sub-stream sediments*. Water Resources Research, **44**, W00D13, doi:10.1029/2008WR006968.

Daily W.D., Ramirez A.L., LaBrecque D.J. and Barber W.; 1995: *Electrical resistance tomography experiments at the Oregon Graduate Institute*. Journal of Applied Geophysics, **33**, 227-237.

Daily W., Ramirez A., LaBrecque D. and Nitao J.; 1992: *Electrical resistivity tomography of vadose water movement*. Water Resouces Research, **28**, 1429-1442.

Dalla E., Cassiani G., Brovelli A. and Pitea D.; 2004: *Electrical conductivity of unsaturated porous media: pore-scale models and comparison with laboratory data*. Geophysical Research Letters, **31**, L05609, doi:10.1029/2003GL019170.

Day-Lewis F.D. and Lane Jr. J.W..; 2004: *Assessing the resolution dependent utility of tomograms for geostatistics*. Geophysical Research Letters, **31**, L07503, doi:10.1029/2004GL019617.

Day-Lewis F.D. and Singha K.; 2008: *Geoelectrical inference of mass transfer parameters using temporal moments*. Water Resources Research, **44**, W05201, doi:10.1029/2007WR006750.

Day-Lewis F.D., Lane J.W., Harris Jr. J.M. and Gorelick S.M.; 2003: *Time-lapse imaging of saline-tracer transport in fractured rock using difference-attenuation radar tomography*. Water Resources Research, **39**, 1290-1303, doi:10.1029/2002WR001722.

Day-Lewis F.D., Singha K. and Binley A.M.; 2005: *Applying petrophysical models to radar travel time and electrical resistivity tomograms: resolution-dependent limitations*. Journal of Geophysical Research-Solid Earth, **110**, B08206.

Deiana R., Cassiani G., Kemna A., Villa A., Bruno V. and Bagliani A.; 2007: *An experiment of non invasive characterization of the vadose zone via water injection and cross-hole time-lapse geophysical monitoring*. Near Surface Geophysics, **5**, 183-194.

Deiana R., Cassiani G., Villa A., Bagliani A. and Bruno V.; 2008: *Model calibration of a water injection test in the vadose zone of the Po River plain using GPR cross-hole data*. Vadose Zone Journal, **7**, 215-226, doi:10.2136/vzj2006.0137.

French H.K., Hardbattle C., Binley A., Winship P. and Jakobsen L.; 2002: *Monitoring snowmelt induced unsaturated flow and transport using electrical resistivity tomography*. Journal of Hydrology **267**, 273-284.

Giustiniani M., Accaino F., Picotti S. and Tinivella U.; 2008: *Characterization of the shallow aquifers by high-resolution seismic data*. Geophysical Prospecting, **56**, 655-666.

Grote K., Hubbard S. and Rubin Y.; 2003: *Field-scale estimation of volumetric water content using ground-penetrating-radar wave techniques*. Water Resources Research, **39**, 1321, doi:10.1029/2003WR002045.

Hubbard S.S., Peterson J.E., Majer Jr. E.L., Zawislanski P.T., Williams K.H., Roberts J. and Wobber F.; 1997: *Estimation of permeable pathways and water content using tomographic radar data*. Leading Edge, **16**, 1623-1628.

Huisman J.A., Hubbard S.S., Redman J.D. and Annan A.P.; 2003: *Measuring soil water content with ground penetrating radar: a review*. Vadose Zone Journal, **2**, 477-491.

Huisman J.A., Rings J., Vrugt J.A., Sorg J. and Vereecken H.; 2010: *Hydraulic properties of a model dike from coupled Bayesian and multi-criteria hydrogeophysical inversion*. Journal of Hydrology, **380**, 62-73.

Huisman J.A., Sperl C., Bouten W. and Verstraten J.M.; 2001: *Soil water content measurements at different scales: Accuracy of time domain reflectometry and ground-penetrating radar*. Journal of Hydrology, **245**, 48-58.

Johnson T.C. , Routh P.S., Barrash W. and Knoll M.D.; 2007: *A field comparison of Fresnel zone and ray-based GPR attenuatin-difference tomography for time-lapse imaging of electrically anomalous tracer or contaminant plumes*. Geophysics, **72**, 21-29, doi:10.1190/1.2431638.

Kelly W.E.; 1977: *Geoelectrical sounding for estimating hydraulic conductivity.* Ground Water, **15**, 420-425.

Kemna A., Binley A. and Slater L.; 2004: *Cross-borehole IP imaging for engineering and environmental applications*. Geophysics, **69**, 97-105.

Kemna A., Binley A., Day-Lewis F., Englert A., Tezkan B., Vanderborght J., Vereecken H. and Winship P.; 2006: *Solute transport processes*. In: Vereecken H. *(*ed), Applied Hydrogeophsics, Springer-Verlag, Berlin, pp. 117-159.

Kemna A., Vanderborght J., Kulessa B. and Vereecken H.; 2002: *Imaging and characterisation of subsurface solute transport using electrical resistivity tomography (ERT) and equivalent transport models*. Journal of Hydrology, **267**, 125-146.

Kettridge N., Comas X., Baird A., Slater L., Strack M., Thompson D., Jol H. and Binley A.; 2008: *Ecohydrologically important subsurface structures in peatlands revealed by ground-penetrating radar and complex conductivity surveys*. Journal of Geophysical Research, **113**, G04030, doi:10.1029/2008JG000787.

Kobr M., Mare S. and Paillet F.; 2005: *Geophysical well logging. Borehole geophysics for hydrogeological studies: principles and applications*. In: Rubin Y. and Hubbard S.S. (eds), Hydrogeophysics, Water Sci. Technol. Library Ser. 50, Springer, New York, pp. 291-331.

Koestel J., Kemna A., Javaux M., Binley A. and Vereecken H.; 2008: *Quantitative imaging of solute transport in an unsaturated and undisturbed soil monolith with 3D ERT and TDR*. Water Resources Research, **44**, W12411, doi:10.1029/2007WR006755.

LaBrecque D.J., Ramirez A.L., Daily W.D., Binley A.M. and Schima S.A.; 1996: *ERT monitoring of environmental remediation processes*. Measurement Science and Technology, **7**, 375-383.

LeBlanc D.R., Garabedian S.P., Hess K.H., Gelhar L.W., Quadri R.D., Stollenwerk K.G. and Wood W.W.; 1991: *Large-scale natural gradient tracer test in sand and gravel, Cape Cod, Massachusetts, 1, Experimental design and observed tracer movement*. Water Resources Research, **27**, 895-910.

Lesmes G. and Friedman S.; 2005: *Relationships between the electrical and hydrogeological properties of rocks and soils*. In: Rubin Y. and Hubbard S.S., (eds), Hydrogeophysics, Springer, Dordrecht, The Netherlands, pp. 87-128.

Linde N., Binley A., Tryggvason A., Pedersen L. and Revil A.; 2006: *Improved hydrogeophysical characterization using joint inversion of crosshole electrical resistance and ground penetrating radar traveltime data*. Water Resources Research, **42**, W04410, doi:10.1029/2004WR003806.

Looms M.C., Binley A., Jensen K.H., Nielsen L. and Hansen T.M.; 2008a: *Identifying unsaturated hydraulic parameters using an integrated data fusion approach on cross-borehole geophysical data*. Vadose Zone Journal, **7**, 238-248.

Looms M.C., Jensen K.H., Binley A. and Nielsen L.; 2008b: *Monitoring unsaturated flow and transport using geophysical methods*. Vadose Zone Journal, **7**, 227-237.

Mavko G., Mukerji T. and Dvorkin J.; 2009: *The rock physics handbook, 2nd edition*. Cambridge University Press.

Mazác O., Kelly W.E. and Landa I.; 1985: *A hydrogeophysical model for relations between electrical and hydraulic properties of aquifers*. Journal of Hydrology, **79**, 1-19.

Miller C.R., Routh P.S., Brosten T.R. and McNamara J.P.; 2008: *Application of timelapse ERT imaging to watershed characterization*. Geophysics, **73**, 7-17.

Monego M., Cassiani G., Deiana R., Putti M., Passadore G. and Altissimo L.; 2010: *Tracer test in a shallow heterogeneous aquifer monitored via time-lapse surface ERT*. Geophysics, in press.

Naudet V., Revil A., Bottero J.V. and Bégassat P.; 2003: *Relationship between self-potential (SP) signals and redox conditions in contaminated groundwater*. Geophysical Research Letters, **30**, 2091, doi:10.1029/2003GL018096.

Ntarlagiannis D., Williams K.H., Slater L. and Hubbard S.; 2006: *Low-frequency electrical response to microbial induced sulfide precipitation*. Journal of Geophysical Research, **110**, G02009, doi:10.1029/2005JG000024.

Nyquist J.E., Heaney M.J. and Toran L.; 2009: *Characterizing lakebed seepage and geologic heterogeneity using resistivity imaging and temperature measurements*. Near Surface Geophysics, **7**, 487-498.

Parkin G., Redman D., von Bertoldi P. and Zhang Z.; 2000: *Measurement of soil water content below a wastewater trench using ground-penetrating radar*. Water Resources Research, **36**, 2147-2154.

Pellerin L., Holliger K., Slater L. and Yaramanci U.; 2009: *Methods and processes, foreword*. Near Surface Geophysics, Special Issue on Hydrogeophysics, **7**, 303-305, doi:10.3997/1873-0604.2009045.

Petersen T. and Al Hagrey S.A.; 2009: *Mapping root zones of small plants using surface and borehole resistivity tomography*. Leading Edge, **10**, 1220-1224.

Pollock D. and Cirpka O.A.; 2008: *Temporal moments in geoelectrical monitoring of salt tracer experiments.*Water Resources Research, **44**, W12416.

Ramirez A., Nitao J., Hanley W., Aines R., Glaser R., Sengupta S., Dyer K., Hickling T. and Daily W.; 2005: *Stochastic inversion of electrical resistivity changes using a Markov chain, Monte Carlo approach*. Journal of Geophysical Research, **110**, B02101.

Revil A., Naudet V., Nouzaret J. and Pessel M.; 2003: *Principles of electrography applied to self-potential electrokinetic sources and hydrogeological applications*. Water Resources Research, **39**, 1114, doi:10.1029/2001WR000916.

Robinson D.A. and Friedman S.P.; 2003: *A method for measuring the solid particle permittivity or electrical conductivity of rocks, sediments, and granular materials*. Journal of Geophysical Research, **108**, B02076.

Robinson D.A., Abdu H., Jones S.B., Seyfried M., Lebron I. and Knight R.; 2008: *Eco-geophysical imaging of watershed-scale soil patterns links with plant community spatial patterns*. Vadose Zone Journal, **7**, 1132-1138.

Robinson D.A., Binley A., Crook N., Day-Lewis F., Ferré P.T., Grauch V.J.S., Knight R., Knoll M., Lakshmi V., Miller R., Nyquist J., Pellerin L., Singha K. and Slater L.; 2007: *Advancing process-based watershed hydrological research using near-surface geophysics: A vision for, and review of, electrical and magnetic geophysical methods*.

Hydrological Processes, **22**, 3604-3635.

Roth K., Schulin R., Fluhler H. and Hattinger W.; 1990: *Calibration of time domain reflectometry for water content measurements using a composite dielectric approach*. Water Resources Research, **26**, 2267-2273.

Rubin Y.; 2003: *Applied stochastic hydrogeology*. Oxford University Press, New York, 391 pp.

Rubin Y. and Hubbard S.S. (eds); 2005: *Hydrogeophysics*. Springer, Dordrecht, 523 pp.

Samouélian A., Richard G., Cousin I., Guerin R., Bruand A. and Tabbagh A.; 2004: *Three dimensional crack monitoring by electrical resistivity measurement*. European Journal of Soil Science, 55, 751-762, doi:10.1111/j.1365-2389.2004.00632.x.

Schlumberger; 1989: *Log interpretation, principles/Applications*. Houston.

Schmalholz J., Stoffregen H., Kemna A. and Yaramanci U.; 2004: *Imaging of water content distributions inside a lysimeter using GPR tomography*. Vadose Zone Journal, **3**,1106-1115.

Singha K. and Gorelick S.M.; 2005: *Saline tracer visualized with three-dimensional electrical resistivity tomography: field-scale spatial moment analysis*. Water Resources Research, **41**, W05023.

Singha K. and Gorelick S.M.; 2006a: *Hydrogeophysical tracking of three-dimensional tracer migration: the concept and application of apparent petrophysical relations*. Water Resources Research, **42**, W06422.

Singha K. and Gorelick S.M.; 2006b: *Effects of spatially variable resolution on field-scale estimates of tracer concentration from electrical inversions using Archie's law*. Geophysics, **71**, 83-91.

Singha K. and Moysey S.; 2006: *Accounting for spatially variable resolution in electrical resistivity tomography through field-scale rock-physics relations*. Geophysics, **71**, 25-28.

Singha K., Pidlisecky A., Day-Lewis F.D. and Gooseff M.N.; 2008: *Electrical characterization of non-Fickian transport in groundwater and hyporheic systems*. Water Resources Research, **44**, W00D07.

Slater L.D.; 2007: *Near surface electrical characterization of hydraulic conductivity: From petrophysical properties to aquifer geometries - A review*. Surveys in Geophysics, **28**, 169-197.

Slater L. and Binley A.; 2006: *Synthetic and field based electrical imaging of a zerovalent iron barrier: Implications for monitoring long-term barrier performance*. Geophysics, **71**, 129-137.

Slater L., Binley A. and Brown D.; 1997a: *Electrical imaging of fractures using ground-water salinity change*. Groundwater, **35**, 436-442.

Slater L., Binley A.M., Daily W. and Johnson R.; 2000: *Cross-hole electrical imaging of a controlled saline tracer injection*. Journal of Applied Geophysics, **44**, 85-102.

Slater L., Versteeg R., Binley A., Cassiani G., Birken R. and Sandberg S.; 2002: *A 3D ERT Study of Solute Transport in a Large Experimental Tank*. Journal of Applied Geophysics, **49**, 211-229.

Slater L., Zaidman M.D., Binley A.M. and West L.J.; 1997b: *Electrical imaging of saline tracer migration for the investigation of unsaturated zone transport mechanisms*. Hydrology Earth System Sciences, **1**, 291-302.

Strobbia C. and Cassiani G.; 2007: *Multi layer GPR guided waves in shallow soil layers for the estimation of soil water content*. Geophysics, **72**, 17-29, doi:10.1190/1.2716374.

Sumner J.S.; 1976: *Principles of induced polarisation for geophysical exploration*. Elsevier, Amsterdam.

Suzuki K. and Higashi S.; 2001: *Groundwater flow after heavy rain in landslide-slope area from 2-D inversion of resistivity monitoring data*. Geophysics, **66**, 733-743.

Topp G.C. and Davis J.L.; 1985: *Measurement of soil water content using Time Domain Reflectometry.* Soil Sci. Soc. Am. J., **49**, 19-24.

Topp G.C., Davis J.L. and Annan A.P.; 1980: *Electromagnetic determina¬tion of soil water content: measurements in coaxial transmission lines*. Water Resources Research, **16**, 574-582.

Topp G.C, Davis J.L. and Annan A.P.; 1982: *Electromagnetic determination of soil water content using TDR, 2: evaluation of installation and configuration of parallel transmission lines*. Soil Sci. Soc. Am. J., **46**, 678-684.

Uhlenbrook S., Wenninger J., Didszun J. and Tilch N.; 2005: *Use of electrical resistivity tomography (ERT) and tracers to explore flow pathways and residence times at the hillslope scale*. Geophysical Research Abstracts, **7**, 2nd GA, EGU-A- 04948.

Vanderborght J., Kemna A., Hardelauf H. and Vereecken H.; 2005: *Potential of electrical resistivity tomography to infer aquifer transport characteristics from tracer studies: A synthetic case study*. Water Resources Research, **41**, W06013, doi:10.1029/2004WR003774.

van der Kruk J., Streich R. and Green A.G.; 2006: *Properties of surface waveguides derived from separate and joint inversion of dispersive TE and TM GPR data*. Geophysics, **71**, 19-29, doi:10.1190/1.268011.

van Egmond F.M., Dietrich P., Werban U. and Sauer U.; 2009: *iSOIL: exploring the soil as the basis for quality crop production and food security*. Quality Assurance and Safety of Crops & Foods, **1**, 117-120, doi:10.1111/j.1757-837X.2009.00019.x .

van Overmeeren R.A., Sariowan S.V. and Gehrels J.C.; 1997 : *Ground penetrating radar for determining volumetric soil water content: results of comparative measurements at two test sites*. Journal of Hydrology, **197**, 316-338.

Vereecken H., Binley A., Cassiani G., Kharkhordin I., Revil A. and Titov K. (eds); 2006: *Applied hydrogeophysics*. Springer-Verlag, Berlin, 372 pp.

Vereecken H., Hubbard S., Binley A. and Ferre T.; 2004: *Hydrogeophysics: an introduction from the guest editors*. Vadose Zone Journal, **3**, 1060-1062.

Vereecken H., Yaramanci U. and Kemna A.; 2002: *Non-invasive methods in hydrology*. Journal of Hydrology: Special Issue, **267**, 175 pp.

Corresponding author: Andrew Binley
Lancaster Environment Centre, Lancaster University
Lancaster, LA1 4YQ, United Kingdom
phone: +44 01524593927; fax: +44 01524593985; e-mail:a.binley@lancaster.ac.uk