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The use of FDEM in hydrogeophysics: A review

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A B S T R A C T

Hydrogeophysics is a rapidly evolving discipline emerging from geophysical methods. Geophysical methods are nowadays able to illustrate not only the fabric and the structure of the underground, but also the subsurface processes that occur within it, as fluids dynamic and biogeochemical reactions. This is a growing wide interdisciplinary field, specifically dedicated to revealing soil properties and monitoring processes of change due to soil/bio/atmosphere interactions. The discipline involves environmental, hydrological, agricultural research and counts application for several engineering purposes. The most frequently used techniques in the hydrogeophysical framework are the electric and electromagnetic methods because they are highly sensitive to soil physical properties such as texture, salinity, mineralogy, porosity and water content. Non-invasive techniques are applied in a number of problems related to characterization of subsurface hydrology and groundwater dynamic processes. Ground based methods, as electrical tomography, proved to obtain considerable resolution but they are difficult to extend to wider exploration purposes due to their logistical limitation. Methods that don't need electrical contact with soil can be, on the contrary, easily applied to broad areas. Among these methods, a rapidly growing role is played by frequency domain electro-magnetic (FDEM) survey. This is due thanks to the improvement of multi-frequency and multi-coils instrumentation, simple time-lapse repeatability, cheap and accurate topographical referencing, and the emerging development of inversion codes. From raw terrain apparent conductivity meter, FDEM survey is becoming a key tool for 3D soil characterization and dynamics observation in near surface hydrological studies. Dozens of papers are here summarized and presented, in order to describe the promising potential of the technique.

Contents

1. Introduction

Geophysical surveys are constantly moving from static imaging of subsoil physical properties to dynamical observation of the state variables changing. Groundwater exchanges in the vadose zone and in aquifers can be efficiently monitored by several geophysical methods (Vereecken et al., 2006). This growing application of exploration geophysics takes from the 1990s the name of 'Hydrogeophysics' (Rubin and Hubbard, 2005; Binley et al., 2015; Hatch et al., 2006). Modern geophysical tools, coupled with the robust inversion process,

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are able in fact to quantify shallow subsurface heterogeneity and the associated dynamics of subsurface fluids (Robinson et al., 2008). In these terms, qualitative images shift to quantitative characterization of new petrophysical relationships, linking hydrologically relevant properties to measurable geophysical parameters (e.g. Gallardo and Meju, 2003). The use of non-invasive indirect characterization of subsurface hydrology finds applications in wide topic areas as contaminant transport, soil-atmosphere interactions, sustainability of ecosystems and biodiversity, plant growth and agriculture (Barrash and Reboulet, 2004). Electric and electro-magnetic methods are the most suitable tools to address the problems related to subsurface groundwater properties and processes, being highly sensitive to soil physical properties as texture, salinity, mineralogy, porosity and water content (Worthington, 1977; Urish, 1981). Electric and EM geophysical methods are in fact widely applied to study subsurface moisture content spatial and temporal variability, and the connecting relations with atmosphere, surface, plants and groundwater reservoirs (Ursino et al., 2014; Cassiani et al., 2012, 2015, Calamita et al., 2015).

Ground based methods such as electrical resistivity tomography (ERT) have high resolution for soil characterization, especially in boreholes configurations (Daily et al., 1992; Boaga et al., 2014; Cassiani et al., 2016). ERT has also the advantage of multi-scale applications, from deep investigations to the smallest domain (Binley et al., 1996, 2001). Despite this, ground based ERT methods are difficult to extend to wider exploration purposes. This is due mainly to their logistical limitation of galvanic contact need with soil, even if some rolling electrodes systems were proposed to overcome these problems (Panissod et al., 1997). Moreover, since dynamical characterization implies time-lapse measurements, acquisition ERT equipment should remain fixed to assure repeatability, with the consequent problems of maintenance. Not ground-tied methods (that can avoid electrical contact with soil) can be on the contrary easily carried, and are therefore recommended for wide area investigations and time-lapse measurements. High frequency electro-magnetic methods, as ground penetrating radar (GPR), have high resolution imaging of dielectric contrasts, but suffer from penetration depth limit in several natural conditions (Grote et al., 2003). Lower frequency electro-magnetic induction methods (EMI) has been adopted to geophysical characterization for decades (McNeill, 1980), in both modalities of time domain (TDEM) and frequency domain (FDEM). TDEM found huge applications in deeper investigation (Jones, 1983; Goldman et al., 1995; Christiansen and Christensen, 2003; Everett, 2012, 2013). Frequency domain electro-magnetic induction method (FDEM) was considered mainly as a quick raw average conductivity estimator. Nowadays, FDEM can be instead efficiently adopted to quantitative 3D characterization of spatial and temporal soil variation. This is due to the improvement of multi-frequency and multi-coils instrumentation (Brosten et al., 2009), quick operational use for simple time-lapse repeatability (Franz et al., 2011), cheap and easy topographical referencing, and the emerging development of inversion codes (Deidda et al., 2014; Schultz and Ruppel, 2005). Multi-depth inverted FDEM data opens new prospectives for time-lapse monitoring of state variables which interest subsoil hydrology. Starting from the illustration of the method and state of the art equipment, hydrogeophysical parameters relationships are discussed. A large set of successful FDEM hydrological applications is then presented, together with the recent progress in data inversion.

2. Method's principles and equipment

2.1. Method's principle

The estimation of soil conductivity properties via low frequency induction methods (EMI) has decades of applications (Keller and Frischknecht, 1966; Wait, 1962). The principles stay in the generation and measurement of electro-magnetic fields trough determined soil portion of convenience. According to the Biot-Savart law, a uniform electrical current produces a magnetic field in the vacuum, whose magnitude, B, depends on the current strength, I, and on the radius-vector r between the current line and the measurement point:

$$B = \frac{\mu_0}{4\pi} I \int \frac{dl \times r}{r^2} \tag{1}$$

where μ_0 is the magnetic permeability of the vacuum ($4\pi\, 10^{-7}\, \mathrm{NA}^{-2}$), and dl is the unit vector along the current line.

Frequency domain electro-magnetic instruments use an alternating current that induces an alternating magnetic field. The alternating magnetic field, in turn, induces the electromotive force e.m.f. according to the Faraday's law:

$$\mathrm{e.m.f.} = -\frac{d\phi}{dt} = -2\pi i f \phi \tag{2}$$

where ϕ is the magnetic flux, f is the frequency, and $i = \sqrt{-1}$ is the imaginary unit, which shows that the e.m.f. is out-of-phase comparing to the magnetic flux. In electrically conductive soils the induced primary field (Hp) e.m.f. produces secondary electrical (Eddy) currents. The secondary currents cause, in turn, a secondary magnetic field (Hs), which is a complicated function of coils configuration and electro-magnetic properties of the ground (Fig. 1). However, working in the so called 'low induction number' conditions (for non-magnetic horizontally layered earth), (Hs) becomes a simple function of these variables. If certain operational constraints are respected, working in the frequency f range of:

$$2\pi f \ll 2/\mu_0 \sigma s^2 \tag{3}$$

being σ the conductivity and s the inter-coil spacing, the fields ratio becomes a direct reading of apparent ground conductivity (σ_a):

$$\sigma_a = \frac{4}{\omega\, \mu\, s^2} \frac{Hs}{Hp} \tag{4}$$

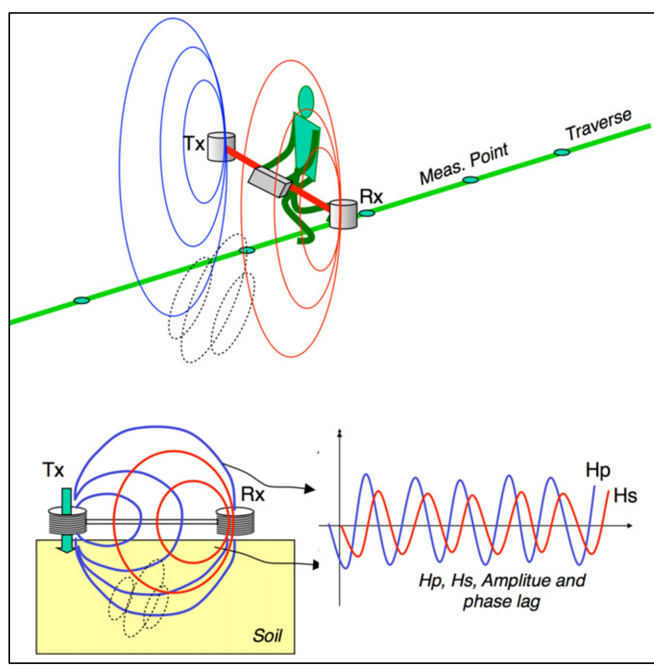

Fig. 1. Schematic representation of FDEM principles. Hp is the primary field generated the transmitter coil Tx; Hs is the secondary field recorded at the receiver coil Rx; dotted lines are Eddy currents. Note that Hp and Hs have amplitude and phase lag. At each measurement point, 2 values are recorded: the real (in-phase) component and the imaginary component (quadrature, or out-of-phase).

where σ_a can be considered as an averaged conductivity between the surface and the depth of the field penetration. The investigated depth depends on the generated electro-magnetic forces. The secondary magnetic field (Hs) is in fact proportional to frequency and electrical properties, so that the field increases with increasing frequency or conductivity. Higher frequencies have short wavelength (increasing resolution) but, on the other hand, reduce the depth of field penetration. Since the low induction number conditions introduced in Eq. (3) should be respected, to increase penetration depth one can use a lower frequency signal or increase the distance between the primary field source and the secondary field points of measurement. However, the magnitude of primary and secondary fields decreases with the increased distance, so that a compromise between the depth of investigation and the strength of the signal should be reached (Spies, 1989). This introduces the concept of exploration 'skin depth' (d), defined as the depth at which the primary field strength is reduced to 1/e times its original value. Skin depth (d) in meter can be calculated as:

$$d = \sqrt{\frac{2}{\omega\mu\sigma}} \tag{5}$$

where μ_0 is again the permeability of the vacuum, ω is the angular frequency and σ the conductivity (Telford et al., 1976). Skin depth (d) depends thus on both the conductivity of the ground and the frequency of the instrument used.

FDEM equipment record both the parts of the field signal, the one in phase with the transmitter (called the 'in-phase' component) and the other orthogonal (90° out of phase, called the 'quadrature'). The former in-phase ratio of the secondary to primary magnetic field, usually expressed in parts per thousand (ppt), is related to the magnetic susceptibility. The latter is related to the ground apparent conductivity and usually expressed in millisiemens per meter (mS/m). This value is an integrated number depending on ancillary of soil properties such as bulk density, salinity, soil structure, moisture content, ionic composition, etc. (Paine, 2003). For the estimation of the true conductivity value at a certain soil depth an inversion process is necessary (see Section 5). Different typologies of FDEM equipment can be used, depending on the target of the survey.

2.2. Equipment

A frequency domain electro-magnetic instrument consists essentially in a couple of coils used to generate and measure the magnetic field components (Fig. 1). Several coils can be oriented along different axes in orthogonal direction, to measure different components of the magnetic field vector. The total field vector measured at the receiver coil is the sum of the primary induced field (Hp) and the secondary magnetic field (Hs). EM method was originally used in a so- called 'passive' way, when the natural earth EM field was measured to investigate relatively deep targets. These approaches take the name of magneto-telluric and audio magneto-telluric methods (Strangway et al., 2008). Here are presented the most suitable equipment for shallower hydrological purposes, the so-called 'active methods'. Active methods consist of one active transmitter coil (Tx) and one receiver coil (Rx). The two coils can be mounted at two ends of an EM probe as a plastic boom, or can be separated (and connected by a cable) to increase their inter-distance. If receiver coil configuration allows recording of all the 3 field components, it takes the name of 'Slingram' method. Electrical conductivity and in-phase magnetic field strength are measured and stored usually along a traverse. If Tx is kept fixed and Rx is moved, the configuration can explore different depths, depending on the coils separation (see CEN, 2011). An example of this equipment is provided by the Geonics EM 34 model (www.geonics.com), which can explore to depths between 1 m and about 60 m. Similar separate coils system for deep FDEM exploring is the CMD-DUO of GF-Instrument (www.gfinstruments.cz), with nominal exploring depth that goes from 7.5 m up to 60 m. Modern 3 in-phase (Slingram) components equipment, with variable dipoles distance, is the PROMIS EM provided by the IRIS instruments (www.iris-instruments.com). It allows wide range of coils offset from 20 m to 400 m, with several investigation depths. For shallower exploration a more convenient setup is adopted: Tx and Rx inter-distance is kept constant and they are moved together along a traverse (e.g. Fig. 1). FDEM equipment with fixed coils distance are non-magnetic boom with different length, usually from 0.5 m to 6 m, considering that the increase of dipoles distance allows deeper exploration target. Furthermore the probes can usually be used both in horizontal and vertical dipole orientation, allowing 2 different exploration depths. Examples of wide diffuses fixed coils instrument are the EM-31 model from Geonics (Abdu et al., 2007), the CMD models from GF-instruments and the multiple options offered by Geophex (www.geophex.com) which built FDEM antennas for every environment: terrain, undersea or airborne uses. Dualem (www.dualem.com) produces single and dual-geometry sensors, covering a wide range of investigation. To explore several nominal underground depths, FDEM equipment can host several coils with different inter-distances, which measure at the same time the electro-magnetic fields. This is the case of the EM-38 Geonics model, or the CMD-explorer setup from GF-Instruments. Other FDEM probes use instead multiple frequencies generators of the primary field. In this way several depths are explored at the same time. An example is the GEM2 instrument from Geophex, that uses up to 10 simultaneous frequencies from 30 Hz to 93 kHz. Multi-frequency FDEM is proposed also by GSSI (www.geophysical.com), with the Profiler model that is able to collect up to 3 frequencies simultaneously. Also EMFAD, a Germany based company, recently proposed 6 frequencies FDEM system (www.emfad.com). All these instruments provide directly apparent resistivity profiles, computed as in Eq. (4). These values are associated with certain nominal depth, but it must be emphasized that the sensitivity of the FDEM instrument is in any case site dependent. The contribution of soil to instrument response depends in fact not only on dipoles orientation and spacing, but also on the soil magnetic properties distribution in depth. The relative contribution to the secondary magnetic field Hs, for all the material below a given depth, can be represented by the cumulative response curve (McNeill, 1980). The cumulative response curve is an important proxy of local sensitivity, being the computation of instrument in-situ response to any hypothetical combination of layers (Callegary et al., 2007, 2012). Some instruments such as the described Geonics, IRIS Promis, Geophex and GSSI Profiler allow the observation of the response cumulative curve directly on the field. This cumulative response gives a quick sensitivity check of the measurements and can be used for preliminary forward modelling (Godio and Naldi, 2009). Comparison of the most common FDEM instruments is summarized in Table 1.

3. Hydrogeophysical relationships

Geophysical measurements are significant only if related to soil derived properties of interest. For FDEM hydrological purposes, this means relating electro-magnetic measurements mainly to soil moisture content and groundwater dynamic. Electric-hydraulic conductivity correlation (usually known as *eh correlation*) was described empirically in a number of laboratory tests, from the milestone work of Archie (1942), to the further works of Waxman and Smits (1968), Bardon and Pied (1969), Rhoades et al. (1976), Topp et al. (1980), Wong et al. (2000), Worthington (1985), and Carroll (1990). Bussian (1982) first proposed the physical basis of Archie equation, going over the parametric empirical use. Other authors such as Herrick and Kennedy (1994) disagree, considering the Archie equation had no physical basis. In the last decades several authors have proposed new theoretical and empirical models connecting electrical response and hydrological properties (e.g. Brovelli et al., 2005; Brovelli and Cassiani, 2011). Purvance and

Table 1
Common FDEM equipment used in hydrogeophysics. Data as provided by the producers.

Producer	Model	Type	Specs	Nominal expl. depth	Positioning
Geonics Limited (Canada)	EM-31/EM-31SH	Fixed distance, single frequency (9.8 kHz) system	Inter-coils spacing = 2 m/4 m	4 m/6 m	External GPS
Geonics Limited (Canada)	EM-38	Double coils system; single frequency (14.5 kHz)	Inter-coils spacing = 0.5 m/1 m	0.375 m to 1.5 m	External GPS
Geonics Limited (Canada)	EM-34	Separated coils, single frequency system: – 10 m (6.4 kHz) – 20 m (1.6 kHz) – 40 m (0.4 kHz)	Inter-coils spacing = 10 m/20 m/40 m	1 m to 60 m	External GPS
IRIS-Instruments (France)	PROMIS	Multi-frequency; multi-spacing; 3 components (vertical Hz and horizontal Hx, Hy)	Ten frequencies: (110 Hz–56 kHz); spacing range: 20 m to 400 m	10 m to 60 m	External GPS
GF-Instruments (Czech Republic)	CMD-DUO	Separated coils, single frequency system	Inter-coils spacing: 10 m/20 m/40 m	7.5 m to 60 m	External GPS
GF-Instruments (Czech Republic)	CMD-Tiny/CMD1/CMD2/CMD4/CMD6	Fixed coils distance, single frequency system	Inter-coils spacing: 0.45 m/0.98 m/1.89 m/3.77 m/5.79 m	0.7 m to 9 m	External GPS
GF-Instruments (Czech Republic)	CMD-explorer/CMD-mini explorer	Multi-coils single probe system	Inter-coils spacing: 0.32 m to 4.49 m	0.5 m to 6.7 m	External GPS
Geophex (USA)	GEM-2	Multi-frequency system: ten frequencies from 300 Hz to 24 kHz.	Single, multiple and stepping frequencies modes	(–)	External GPS
GSSI (USA)	Profiler	Multi-frequency system: 1 up to 3 frequencies (1 kHz to 16 kHz)	Inter-coils spacing: 1.21 m	(–)	Integrated GPS
(Canada)	Dualem 2/4/1s/2s	Fixed distance, single frequency (9 kHz) system and dual-geometry system	Inter-coils spacing: 0.5 m to 6 m	0.5 m to 6 m	External/Internal GPS
EMFAD (Germany)	UG12	Multi-frequency system	Six frequencies: from 19 kHz to 124 kHz	Up to 12 m	(–)

Andricevic (2000) presented an exhaustive discussion about these empirical and theoretical *eh* correlation, showing that electric and hydraulic conductivity relationships are far from being universal, due to the surface conduction mechanism of fine sediments. Electrical conduction through the pore volume is in fact the predominant effect in saline pore water and coarse sediment conditions. This means a positive *eh* correlation, because to the growing of electrical conductivity corresponds an increase of hydraulic conductivity. On the other hand, in common freshwater-clay aquifer, the predominant electrical conduction is along pore surface, causing negative *eh* correlation, i.e. to electrical conductivity increase corresponds a decrease of hydraulic conductivity (Fig. 2).

Considering this, recent research efforts aim to describe model via constitutive equations (Bernabe and Revil, 1995; Revil and Leroy, 2004). In the specific Revil (2012) and Revil and Mahardika (2013) proposed a new set of constitutive equations coupling Darcy and Ohm laws through rigorous physical modeling. The same author studied the effect of conductivity in unsaturated zone, specifically for low frequency electro-magnetic method as FDEM (Revil, 2013, Fig. 3).

Quantification of hydraulic properties from the soil conductivity meter measurements need particular constraints and cannot be assumed to be straightforward. Straightforward relations should be avoided in particular if only apparent resistivity FDEM values are considered. The emerging role of electro-magnetic inverted data (Section 5) will allow further comparisons between true conductivity values and hydraulic parameters, coming from other investigation techniques. This suggests promising progress for future quantitative FDEM hydrogeophysical relationships. However, given the complexity of physico-chemical processes, a universal models search should remain insignificant. This does not invalidate in any case the huge potential of geophysical methods for hydrological models, often based on the greater uncertainties of a few direct sampling points and strong homogeneities assumption. Some successful applications of FDEM for hydrological studies are presented here below.

3.1. Measurements scale

Scale problem should be considered in every geophysical application (Binley et al., 2015). The FDEM method, if compared to others techniques, can assure wide measurements scale, both in term of vertical (depth) and horizontal (spatial) investigation capabilities. As described in the sensors chapter, the modern equipment can provide a wide range of use, varying both frequencies and coils spacing. Obviously larger depth investigation demand corresponds to lower resolution. No soil-contact need is the real advantage of this technique. The horizontal (spatial) investigation scale can be considered in fact as the key point

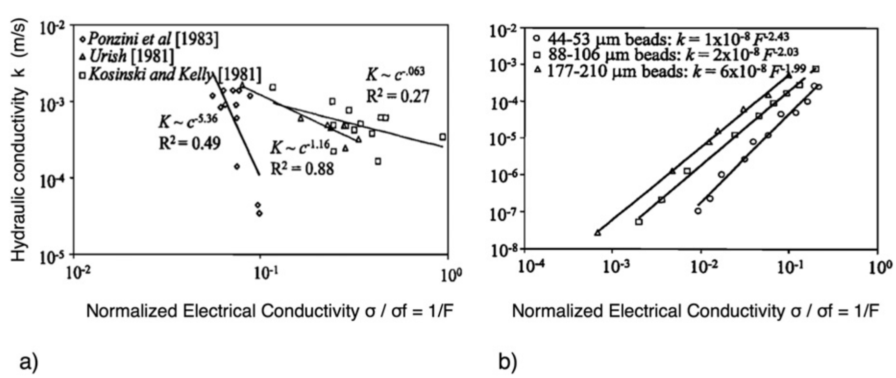

Fig. 2. Negative (a) and positive (b) *eh* correlation as reported in Purvance and Andricevic (2000, mod.). Electrical conductivity is normalized by the formation factor (F) after the experimental evidences of Wong et al. (2000), Ponzini et al. (1983), Urish (1981), Kosinski and Kelly (1981) and Bernabe and Revil (1995).

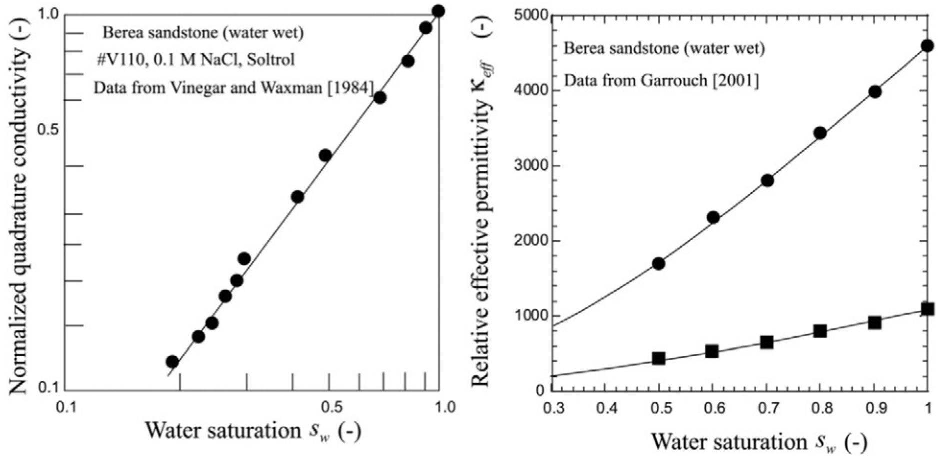

Fig. 3. Examples of the relationship between water saturation Sw - EM conductivity and Sw - Effective permittivity K_{eff} (from Revil, 2013, mod.).

of FDEM method in 3D hydrogeophysics. FDEM equipment mounted on motorized vehicle covers Km of survey in a relatively small time. Fig. 4 shows the range of measurement scale nowadays reachable by modern FDEM equipment, as presented in Section 2.2. In terms of time demanding, we can consider that sensor collect data with sampling frequency usually <1 Hz, thus allowing the records of thousands of measurement points in few hours of field work.

4. Applications in hydrogeophysics

The advantage of the FDEM method is the above-mentioned fact that the ground contact is not necessary. This allows time-lapse big area surveys to be relatively inexpensive, fast, and moreover independent of the nature of the ground (e.g., snow, vegetated areas). For these reasons modern FDEM techniques found huge applications for hydrogeophysical purposes. Binley et al. (2015) gave a comprehensive explanation of hydrogeophysics recent emerging role, including FDEM use. We can divide these hydrogeophysical applications into two main branches: *i*) shallow soil study and agricultural targets (Doolittle et al., 1996, 2001); *ii*) deeper hydrological processes targets (Kravchenko et al., 2002).

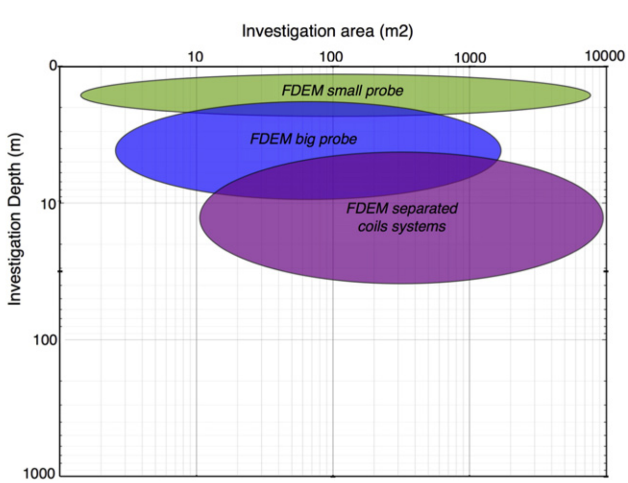

Fig. 4. Common achievable scale of investigation for FDEM methods. Investigation potentials are divided for small fixed inter-distance coils systems (probe lengths = 0.5 m–3 m, green), big fixed inter-distance coils systems (probe lengths = 3 m–6 m, blue), and separated coils systems (purple). Needless to say multi-frequencies and multi-coils systems cover multi scale investigation zones at once.

4.1. Soil studies and agriculture

The use of FDEM as areal distributed estimation of soil conductivity has several successful applications (Corwin, 2008, Anderson-Cook et al., 2002, Lück et al., 2009, Abdu et al., 2008, Farahani et al., 2005). One of the most useful implementations of FDEM in soil studies concerns the study of soil salinity distribution (Corwin, 2008; Lesch, 2005) due to the strong relationship between soluble salts and conductivity properties. In salt-affected soil areas the FDEM survey furnishes in fact a large number of geo-referenced measurements that can be associated with the spatial variability of salinity both at field and landscape scale (Diaz and Herrero, 1992). Pioneering examples of FDEM for soil moisture content mapping in agriculture can be found in Corwin and Rhoades (1982), Williams and Baker (1982) and Kachanoski et al. (1988). Doolittle and Brevick (2014) recently published a complete description of FDEM applications for soil studies, including potential and limitation for agricultural use. The possibility of discriminate wetter and drier zones is in fact the key point for plants activity monitoring (Friedman, 2005). FDEM is widely adopted for this crucial purpose in agricultural studies. Huth and Poulton (2007) extended the FDEM method for soil moisture evaluation in the agroforestry system, as previously experimented by Reedy and Scanlon (2003). Soil patterns can be difficult to retrieve in huge vegetated zones and the non-contact FDEM method was efficiently suggested (Lausch et al., 2013). Similarly, Bréchet et al. (2012) used apparent conductivity maps to observe spatial variation of soil characteristic in teak tropical forests. Data are successfully compared with soil sampling and botanic description, relating forest typology to soil characteristics. Sudduth et al. (2001) presented the use of electro-magnetic method for precision agriculture using real field data, discussing the effects of soil moisture and temperature variation in the conductivity soil measurements.

FDEM surveys for soil studies are often coupled with other geophysical methods such as GPR and ERT. André et al. (2012) showed such application for vineyard high-resolution characterization in France. They retrieved the patterns of apparent conductivity with a single frequency FDEM probe. Results were compared with the map of vegetation index (NDVI), to investigate the influence of soil characteristics and groundwater distribution on vine vigor (Fig. 5). Promising results in studying the spatial relationships between soil and plant distribution can be find also in Comas et al. (2004); while Robinson et al. (2008) give a general overview of geophysical techniques that can help shallow hydrological studies.

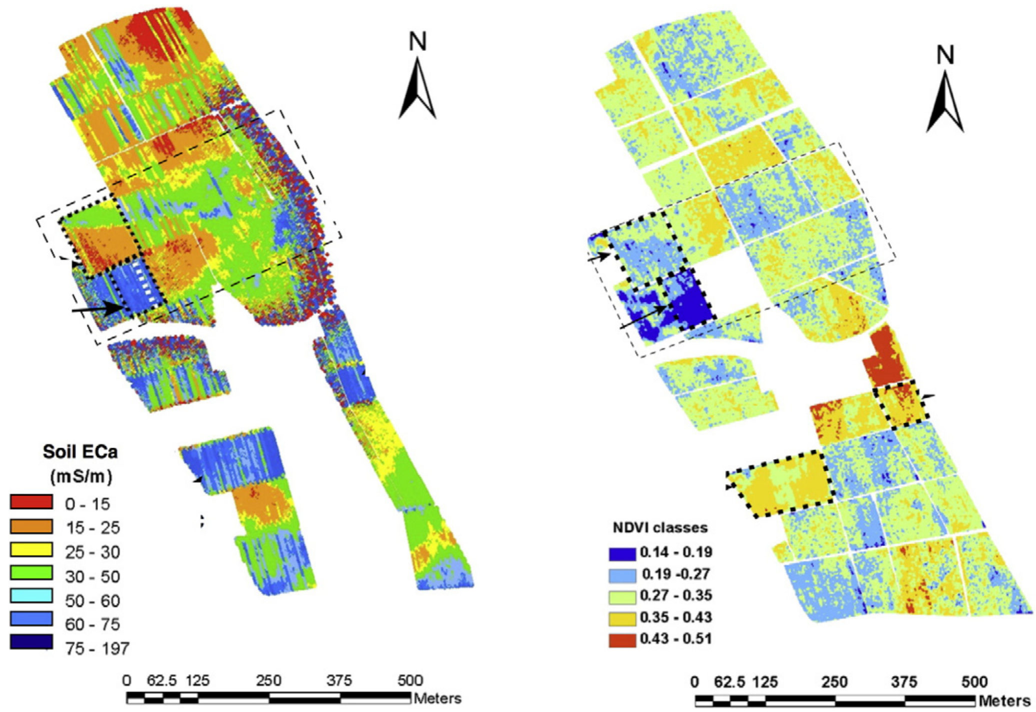

Fig. 5. FDEM apparent conductivity map (left) and NDVI vegetation index derived classes (right) in a France vineyard (from André et al., 2012, mod.).

More recently the FDEM apparent soil conductivity was correlated also to other soil physicochemical properties, such as clay content (Triantafilis et al., 2001; Triantafilis and Lesch, 2005; De Benedetto et al., 2010), chloride concentrations (Binley et al., 2013) or carbon content (Martinez et al., 2009; Bechtold et al., 2013). This has relevant hydrological implications, as in Robinson et al. (2009). They adopted FDEM comparing the irregular wetting soil conditions with the different mineralogical contents.

Frontier use of FDEM soil study is a time-lapse acquisition, shifting static imaging to time dependent characterization able to highlight dynamical processes. In the framework of shallow subsoil, Cassiani et al. (2012) distinguished vegetated soil seasonal behavior thanks to FDEM apparent conductivity maps, coupled with ERT and GPR. They suggest that the method is fast and cheap to monitoring moisture content dynamic, retrieving soil moisture content based on laboratory samples' calibration and considering the effect of temperature on the FDEM response (Fig. 6).

4.2. Subsurface hydrology

The use of FDEM technique to study the spatial variations of soil water content was suggested since the 80s (Kachanoski et al., 1988). From there, a number of works applied electro-magnetic method for subsurface hydrology studies.

Sherlock and McDonnell (2003) presented an application of FDEM data for hillslope hydrology. They estimated spatially distributed groundwater level and soil moisture content in a studied area close to New York (USA). The complexity of landscape often imposes the use of a non-contact technique, such as the electro-magnetic surveys. FDEM fit the purpose and can be used at several scales, from the single field to the entire catchment, filling the gap between punctual sampling and other remote techniques (Doolittle et al., 2012, Fig. 7a). Hydrological characterizations of big areas are usually investigated with time domain airborne electro-magnetic methods. TDEM are however expensive and hard to replicate in time for logistical limitations. Sudduth et al., 2005 demonstrated that quick FDEM data respond efficiently to time variation of soil moisture content, allowing temporal monitoring of soil moisture even at the big catchment scale.

FDEM was applied to hydrological studies also in challenging arid environments. Franz et al. (2011) related the vegetation organization patterns of Kenyan drylands to soil resource heterogeneity thanks to FDEM data analysis. In this case the regulation factors, in terms of catchment hydrology, were to evaluate the portion of penetrating infiltration in respect to extreme run-off effect. They calibrate bulk electrical conductivity and water content in laboratory samples, in order to estimate the soil moisture by the FDEM field data, testing results via numerical models. Previously, Sheets and Hendrickx (1995) compared FDEM with neutron probe to assess the moisture content of the shallow subsoil in an arid area of New Mexico. Dafflon et al. (2013) studied a total different environment, adopting FDEM for permafrost studies in the Alaskan coast (USA). They highlighted the adaptability of the FDEM technique, which is not dependent on the nature of the ground.

Key aspects of subsurface hydrology, such as depth of water table and vadose zone water content, were characterized successfully via FDEM by Shanahana et al. (2014), Robinson et al. (2008, Fig. 7b), Williams et al. (2006), Khakural et al. (1998) and Vignoli et al. (2012). FDEM was in fact widely applied as a water table depth estimator, distinguishing vadose zone thickness. Schumann and Zaman (2003) mapped water table depth in a Florida test site using single frequency FDEM equipment; their results help orienting drainage system design for an existing orchard. Water table oscillations can also be monitored by repeated surveys. Zhu et al. (2010) explored subsurface hydrology dynamics at this scope with time-lapse FDEM measurements. Authors conducted repeated FDEM surveys for more than 10 years of observation period, highlighting the dynamics of soil moisture change and possible subsurface flow paths.

The time-lapse use of FDEM (e.g. Doolittle et al., 2012; Zhu et al., 2013) is probably the most intriguing aspect for subsurface hydrology. Nowadays there is the possibility of monitoring big areas for extended time periods, with the precision of differential GPS positioning and the quick exploration of several depths at once. This opens interesting hydrological applications, but it must be underlined that time lapse measurements need accurate approach to overcome the errors which can occur from calibration issues and signal instability (Delefortrie et al., 2014; Minsley et al., 2012). Repeated FDEM measurements are in fact affected by experimental errors. We can divide these errors in

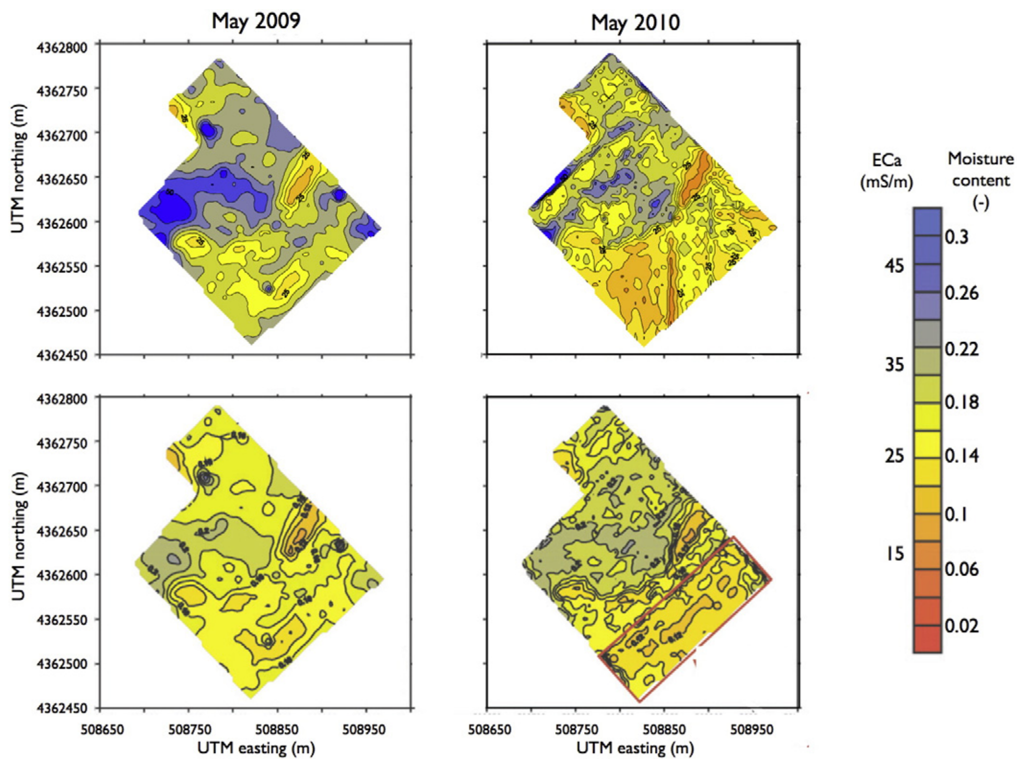

Fig. 6. Time-lapse conductivity maps (a) and derived moisture content (b) of a Sardinia field in Italy (from Cassiani et al., 2012, mod). Conductivity values are corrected with temperature and soil moisture is derived from calibrated Lab tests. The wheat grown is responsible of the observable change in time.

systematic and random, being the former the most relevant for the final results. The most common systematic errors are due to data drift, instrument bias, wrong calibration or improper leveling (see Delefortrie et al., 2014; Deszcz-Pan et al., 1998 for details). Calibration strategies were proposed to correct FDEM data, basing on a predicted forward model response (Lavoue et al., 2010; Minsley et al., 2012). In these cases the electrical properties of soil to be predicted by FDEM can be a priori assessed by other technique, as ERT methods. Calibration parameters can be then derived from the comparison between the measured data and the forward response to the initial resistivity model. Random errors are instead linked to cultural noise or signal instability and can be more easily addressed with appropriate filtering processes (e.g. Minsley et al., 2012).

Additional relevant aspect to consider in repeated FDEM measurement is that the changing in time or space of electrical properties changes the depth to which the FDEM data are sensitive (e.g. changing

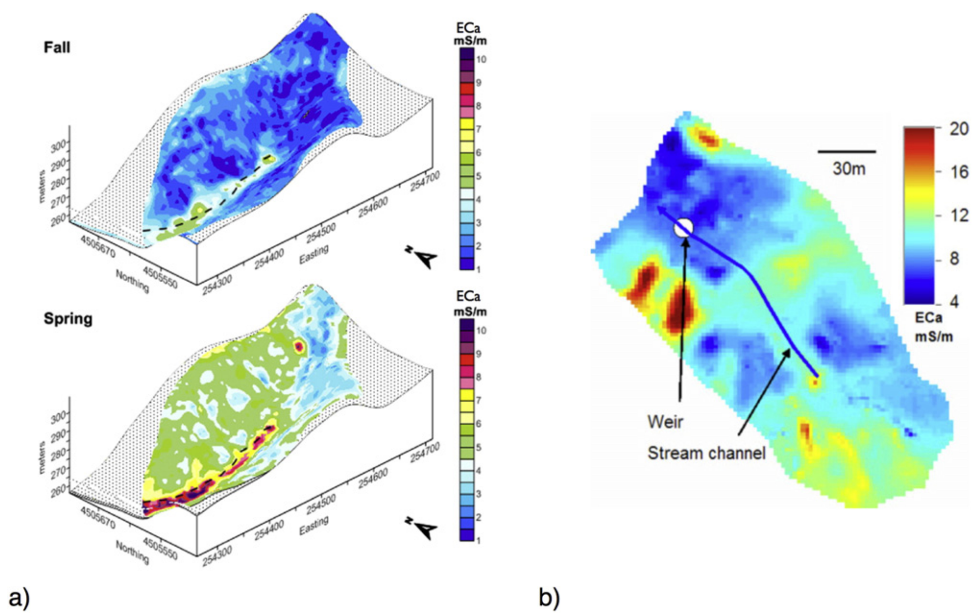

Fig. 7. Examples of FDEM use for subsurface hydrology: a) results of time-lapsed measurements in a Pennsylvania catchment highlighting differences during fall (dry conditions) and spring (wet conditions) as in Doolittle et al., 2012; b) apparent electrical conductivity of a catchment as in Robinson et al., 2008; zones of higher conductivity (in red) indicate locations of greater soil development.

Table 2
Main properties derived by FDEM data, equipment used and some relative references examples.

Main properties derived	FDEM equipment	References
Moisture content	*Fixed distance/multi-coils systems/multi-frequencies systems*	Brosten et al. (2011), Comas et al. (2004), Cassiani et al. (2012), Corwin and Rhoades (1982), Corwin (2008), Doolittle and Brevick (2014), Friedman (2005), Huth and Poulton (2007), Kachanoski et al. (1988), Williams and Baker (1982), Sudduth et al. (2001), Von Hebel et al. (2014)
Soil salinity	*Fixed distance probe*	Paine (2003), Corwin (2008), Diaz and Herrero (1992), Corwin and Lesch (2005), Hatch et al. (2006)
Water table depth	*Fixed distance/multi-coils systems*	Sherlock and McDonnell (2003), Doolittle et al. (2012), Shanahana et al. (2014), Robinson et al. (2008), Williams et al. (2006), Khakural et al. (1998), Schumann and Zaman (2003), Zhu et al. (2010), Kravchenko et al. (2002), Buchanan and Triantafilis (2009)
Soil patterns — preferential paths	*Fixed distance/multi-frequencies systems*	Vignoli et al. (2012), Franz et al. (2011), André et al. (2012), Robinson et al. (2008), Bréchet et al. (2012), Weymer et al. (2015)
Clay content	*Fixed distance probe*	Triantafilis et al. (2001), Triantafilis and Lesch (2005), De Benedetto et al. (2010),
Carbon content	*Fixed distance probe*	Martinez et al. (2009), Bechtold et al. (2013)

in depth of investigation DOI, see Eq. (5). All these types of variables can have great impact on the reconstructed hydro-geophysical model. Therefore final time-lapse FDEM results should careful take in account system calibration errors, random noise and DOI variations, which can seriously affect inversion results (see Section 5). Table 2 summarizes the main subsoil properties derived from FDEM data and some relative references.

5. Data inversion

Despite the fact that FDEM technique applications are increasing, relatively few inversion algorithms have been developed to retrieve subsoil conductivity from raw experimental data. Magneto-telluric and time domain EM posed more attention on data inversion (Parker and Huestis, 1974; Kemna, 2000), but FDEM data inversion was applied only in recent times. As mentioned above, the use of FDEM was in fact widely adopted as simple apparent conductivity-meter. Users considered FDEM technique to be a low-frequency (<200 kHz) technique that yields integrated electrical conductivity measurements of the subsurface. This helped the diffusion of the technique in the field of soil science, agriculture, archeology and geology; on the other hand it limited the quantitative use of FDEM data for hydrological purposes. The quantitative approach needs in fact determine the true physical properties, even if in an indirect way. Sinha and Bhattacharya (1967) presented a first attempt for the estimation of depth-conductivity profiles from FDEM data, with trial-and-error forward modeling. Ill-posedness and non-uniqueness problems imply however more robust geophysical data inversion, that needs the introduction of complex forward model and regularization functions (e.g. Constable et al., 1987; Tarantola, 2005). The inversion can be formulated as an optimization problem where an objective function (or misfit function) is minimized subject to such constraints (e.g. a predefined tolerance level to reproduce the experimental data). For FDEM data objective function can be summarized as:

$$\Delta\mathrm{H}(p) = \frac{1}{M}\sum_{m=1}^{M}\frac{\left|H_m^{meas} - H_m^{mod}(p)\right|}{\left|H_m^{meas}\right|} \tag{6}$$

where ΔH describes the misfit between the measured magnetic field, ($\mathrm{H}^{\mathrm{meas}}$), and the modeled magnetic field ($\mathrm{H}^{\mathrm{mod}}$), being M the number of coil configurations which can includes different coils inter-distance or orientations. This objective function is solved iteratively, considering the misfit between predicted and observed data and a measure of solution complexity based on the chosen regularization function.

The starting point of any inverse model requires the capability to produce the forward model. For FDEM this means the equations that regulate the magnetic field generated by an oscillating magnetic dipole on the surface of a layered earth, as derived from the Maxwell equations (Ward and Hohmann, 1987). For an interesting advanced simulation of 3D electromagnetic diffusion phenomena see Schankee Um et al. (2010). Both non-linear and linear forward models were adopted for the scope (Hendrickx et al., 2002.). Usually the soil is assumed to be a layered structure with n layers, each of thickness $\mathrm{d_k}$, k = 1, …, n; σ_k and μ_k be the electrical conductivity and the magnetic permeability of the kth layer (see Fig. 8). Commonly μ_k can be considered constant if subsoil does not contain ferromagnetic materials. The problem of data inversion consists then of computing the conductivity σ_k of each layer (k = 1, …, n), solving the non-linear (or linear) problem with a technique of convenience, e.g. a least squares approach (Tikhonov and Arsenin, 1977), global or local search (Mester et al., 2011, Elwaseif et al., 2016). Here are presented successful applications of FDEM inversion processes.

Schultz (2002) and Schultz and Ruppel (2005) proposed a regularized 1D (and successively pseudo-2D and 3D) inversion for FDEM multiple frequencies measurements (the FEMIC code). They focused particularly on high-conductivity terrains application, testing both linear and non-linear forward models. Brosten et al. (2011) tested the FEMIC code to retrieve a 3D conductivity map in Colorado, in order to reconstruct the hydraulic conductivity of the area.

Farquharson (2000) developed the EM1DFM code, that is a free FDEM data inversion program designed to reconstruct 1D models. Starting from EM1DFM code, Martinelli and Duplaá (2008) proposed innovative spatial filters to smooth the spurious lateral variations. Brown et al. (2012) proposed a similar inversion codes, initially applied to marine seismically constrained data. These codes are based on the full solution of Maxwell's equations, allowing the calculation of the secondary field (Hs) normalized by the primary field (Hp). Dafflon et al. (2013) tested both these inversion algorithms, with interesting results concerning permafrost study. Smiarowski et al. (2011) applied an interesting joint inversion of horizontal and vertical FDEM dipole configurations to study seasonal variation of water soil content close to Canberra

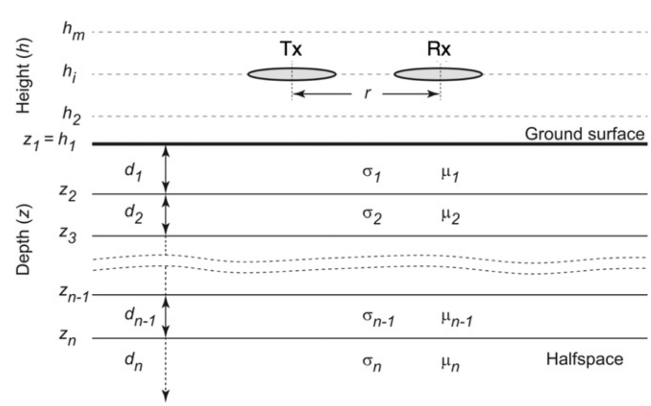

Fig. 8. Schematic representation of the subsoil discretization commonly used in 1D inversion process (from Deidda et al., 2014, mod).

(Australia). Sharma and Kaikkonen (1999) presented joint inversion of DC and EM methods. Moghadas et al. (2011) showed a joint full inversion of different electro-magnetic techniques (GPR and FDEM). They used a non-linear forward model with the global multilevel coordinate search optimization (GMCS), a robust algorithm originally proposed by Huyer and Neumaier (1999).

Deidda et al. (2014) presented efficient solutions for FDEM 1D data inversion. In particular they implemented various methods for the automatic estimation of the regularization parameter. Their algorithm is particularly fast since they proposed the analytical computation of the Jacobian (sensitivity matrix), in contrast with the above mentioned work of Schultz and Ruppel that approximate the Jacobian by finite differences, demonstrating that this makes the inversion more than ten times faster. The results were numerically tested with synthetic data and real field data collected in Sardinia (Italy).

Recently, Von Hebel et al. (2014) provided different states of soil moisture and descriptions of the hydrological patterns of Rhine River, Germany, via inversion of multi-coils FDEM data. They presented an elegant description of EM forward modeling problem, adopting the shuffled complex evolution (SCE) algorithm, a global optimization that guides the search of the minimum with deterministic strategies (Duan et al., 1992).

The examples described show the increasing numbers of FDEM inversion codes nowadays available. This suggests a promising future for soil properties mapping derived from inverted data, which represent relevant contributions to quantitative analyses. Inversion results are obviously not immune from several limitations, that go from the ill-posed non-uniqueness solutions to the previously described systematic and random errors which affect the experimental data.

6. Concluding remarks

The use of FDEM for hydrological purposes is quickly emerging in the framework of non-invasive techniques. FDEM has proved to be a powerful tool in the identification and characterization of spatially varying subsoil properties that have an electro-magnetic signature. This geophysical method facilitates the collection of large volumes of high-resolution data, if compared to ground-based techniques, and provides easy repeatability of measurements over time. FDEM has no need of soil-contact and, coupled with accurate satellites positioning, can be used in a wide range of environmental conditions. It can be adopted especially for time-lapse monitoring of changing state variables, as soil moisture content. The emerging potential of multi-coils and multi-frequencies systems allows, moreover, the collection of multi-depth information at once. Inversion codes for frequency domain electromagnetic method are more and more employed in data processing. These powerful tools support the use of advanced FDEM applications, from raw integrated electrical conductivity subsurface measurements to reliable 3D estimators of physical properties. However it must be emphasized that results are site-specific and can vary depending on the complex interaction among multiple soil properties thus every data processing should carefully address the problem. This suggests that FDEM method cannot replace the detail provided by sampling, field observations and the relevant information coming from other geophysical techniques (Lavoue et al., 2010). In these terms it would be reasonable to consider FDEM modern acquisition as a powerful method to be integrated with other information. FDEM can then be adopted for both the hydrological characterization of the subsurface properties and the dynamical processes which occur within it.

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