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HYDROGEOPHYSICS: AN OVERVIEW OF GENERAL CONCEPTS, APPLICATIONS AND FUTURE PERSPECTIVES.

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Abstract

Hydrogeophysics is an emerging discipline that holds great promise in characterizing hydrogeological parameters and processes. A tight collaboration between hydrogeologists and geophysicists is necessary to achieve the most appropriate use of geophysics in hydrogeology, mainly for planning the geophysical activities in accordance to the hydrogeological target to be investigated and for the interpretation or translation of the geophysical documents into hydrogeological documents. For this collaboration to be meaningful, it is of great importance to share a common language allowing communication feasible: geophysicists have to know the fundamentals of the hydrogeological process, and hydrogeologists have to know the fundamentals of geophysical methods. This is basically the main objective of this paper, where fundamental concepts of both disciplines, their contributions, the methods available, data integration approaches, and future perspectives as well as the hydrogeophysical challenges are presented.

Key words: *hydrogeophysics**,** geophysics, hydrogeology, surface geophysics and hydrogeophysical methods*

Introduction

Hydrogeophysics has emerged over the last decade as one of the more challenging disciplines in near-surface geophysics, aiming to improve the simultaneous use of geophysical and hydrogeological measurements. It can be described as the use of geophysical measurements for mapping subsurface features, estimating properties and monitoring processes that are important to hydrological studies, such as those associated with water resources, seepage throughout the vadose zone, contaminant transport, and ecological/climate investigations (Rubin and Hubbard, 2005)

The field of hydrogeophysics has developed in recent years to investigate the potential of geophysical methods for providing quantitative estimates of hydrogeological parameters needed for shallow subsurface studies. This rapidly expanding cross-disciplinary field involves researchers from geophysics, hydrology, geology, statistics, rock physics, and engineering backgrounds.

Many recently published studies combining both disciplines, hydrology and geophysics, have achieved accurate subsurface characterization and have successfully monitored hydrologic processes with high temporal and spatial resolution over a wide range of spatial scales (Schwinn and Tezkan, 1997; Unsworth *et al*, 2000; Krivochieva and Chouteau, 2003; Meju *et al*, 2003; Goldman and Kafri, 2004; Pederson *et al*, 2005).

Hydrogeophysics provides a meaningful perspective that many water agencies and councils have recently demanded (CUAHSI, 2005).

This essay introduces the hydrogeophysics discipline and its significant contribution to the near-surface environmental applications. It aims to review the actual state of the hydrogeophysics discipline showing the paramount perspectives of the geophysical methods applied to the hydrogeology discipline.

Hydrogeophysics: State of the Discipline

The hydrogeophysics discipline has emerged in recent years to investigate the potential that geophysical methods hold for providing quantitative information about subsurface hydrogeological parameters and processes. Hydrogeophysical investigations strive to move beyond the mapping of geophysical "anomalies" by providing quantitative information that can be used as input into flow and transport models.

Hydrogeophysics as many other geo-scientific disciplines is based on the previous experience associated with the mining and petroleum industries. However, its working scale has to be modified for its applicability to the near surface zone where the pressure, temperature and depth conditions are different, and the contrasts are subtle compared to deeper features. In addition, geological characterization, from a hydrological perspective, concerns the dynamics of the water through the subsurface. Geological structure, transport and storage of water are the key parameters to understand hydrological processes.

There is a pressing need to develop practical solutions to subsurface problems in the face of incomplete basic theory. Many areas within hydrogeophysics are not well understood yet and will require many years of research to develop sufficiently. For example, many of the petrophysical relationships among granulometric, geophysical and hydrological variables used within hydrogeophysical research are either empirical or based on simplifying assumptions that may not be valid. Similarly, geophysical responses in three-dimensional, complex shallow environments that have multiple scales of heterogeneity and that are affected by cultural noise are not yet well understood.

Following this uncertainty scenario, hydrogeophysics is currently trying to strike a balance between an improved understanding of basic principles and implementation of pragmatic solutions to subsurface problems. As such, there is a need within the hydrogeophysics community for researchers that will advance the understanding of the fundamental principles, as well as those who can apply the principles towards subsurface characterization and develop pragmatic approaches when the fundamental principles are subject to uncertainty.

Geophysical Contribution to Hydrogeological Problems

Different hydrogeological problems could benefit from geophysics. Among them are the determination of the aquifer geometry (location of its bottom, top and lateral boundaries), characteristics of fractured rocks (location of faults and fissures, characteristics of fluid circulation), knowledge of hydraulic properties of the aquifer (porosity, clay content, transimissivity, permeability of the porous medium), quality of the water (fresh, salty, heavily mineralized, polluted), and monitoring dynamic processes (seawater wedge dynamics or seepage through the vadose zone) and interpretation pertaining to future effects of exploitation.

Surface Geophysical Methods Available in Hydrogeology

Geophysical methods are based on physical properties of rocks. One possible classification can be done according to the place from where the information is obtained and the nature of the property used:

(a) There is a group of methods that provide an image of the distribution of a property or the surface of the Earth or just from a few centimetres below. These are the methods that make use of the optical properties of rocks and soils (for instance infrared photographs), natural radioactivity (spectrometry), electromagnetic reflectivity (air radar), fluorescence, etc.

(b) The rest of the methods provide an image of the distribution of a property of the rocks in the subsurface, with a great variety of degrees of penetration: from a few metres to thousands of metres. Two families can be distinguished:

b(i) the methods based upon a natural property of rocks: density (Gravity), magnetic susceptibility (Magnetic), natural electric fields (Spontaneous Potential), thermal conductivity (Thermometry), etc. In this group of methods, the instrumentation used is just a passive receiver able to measure some kind of energy related to the property distribution (gravity field, magnetic field, electrical potential, etc).

b(ii) the methods that are based upon some property of the rocks which can only become apparent after excitation: velocity of mechanical waves (Seismic), resistance to the flow of an electrical current (electric, electromagnetic and magnetotelluric methods), dielectric constant (Ground Radar), and chargeability (induced Polarization), etc.. One of the main characteristics of this group is that instrumentation is divided in two parts: one transmitter to excite the rocks, and one receiver to record their answer, giving rise to many possibilities for taking measurements (varying the frequency and power of the transmitted energy, the distance between transmitter and receiver, etc.).

The application of geophysics to hydrogeology comprises a great variety of topics: the most elemental is the search for water in the underground; others are related to the aquifer control; to the contamination of aquifers by sea water intrusion or by industrial activities; to geotechnical activities related with the presence of groundwater; to the use of the underground to stock harmful substances, etc. Any of these topics require the determination of several subsurface parameters: geometry (depth, thickness and extension) of aquifer layers, geometry of aquitards and impermeable basement; others refer to hydraulic properties of aquifers and aquitards (porosity, permeability, storage coefficient, phreatic level, water quality); others to the hydrodynamic parameters (flux velocity and direction).

Combining the possibilities of the geophysical methods with the number of parameters that are demanded by hydrogeology, and with the different geological and geographical scenes possible, it is easy to understand that no single answer can be expected to the question of what method to use for solving one generic problem because of the many exceptions that can be found.

Expectedly, more than a single method must be used. The most important is to make a good definition and identification of the problem to be solved, to translate it correctly to the geophysical world, and to make a good analysis to decide if it is possible to get solution with geophysical techniques. Sometimes, it will be clear that the possibilities of using geophysics are not realistic, and then, the better choice is not to go ahead with the rest of the steps of a geophysical survey. At other circumstances, it can be clear that the problem has a possible geophysical solution, and a selection of the more adequate method(s) can be done. Nevertheless, it is rather usual, especially because of the difficulty of many hydrogeological problems that are actually demanded, that the best solution is to undertake test surveys to better evaluate the most appropriate geophysical methodology.

In deciding about the applicability of one geophysical method, it is very necessary to know its limitations. These limits can arise from the same theoretical basis of the method (for instance, insufficient contrast of physical properties of the rocks), or from the existence of geological or cultural noise (for example, the gravity anomalies produced by the target are of the same order of magnitude or smaller than the ones produced by insufficient changes of density in the overburden), or from the way in which the survey is carried out (for example, inadequate sample rate or distance between measurements, lack of geological control, etc). Other limits are due to the nature of the inversion process, being the most important consequences of the equivalence and resolution limitations. More generally, there is a limitation to the depth at which a certain volume of rock can be detected with surface geophysical methods.

The main hydrogeological objectives to be solved by geophysical methods fall into three main areas: hydrogeological mapping, hydrological parameter estimation and hydrological process monitoring. Geophysical data are used to assist in meeting a wide range of hydrogeological objectives, taking advantage of the fact that the different geophysical techniques are sensitive to different properties and scales. Table 1 below shows the main field of application of the different methods in hydrogeology.

Table 1: Main hydrogeophysical methods classed by investigation scale, its measured properties and the hydrogeological objectives (Modified from Rubin and Hubbard, (2005)

Geophysical Methods		Obtained properties	Hydrogeological Objectives
Airbone Satellite	Remote sensing Aeromagnetic Electromagnetic	Gamma radiation, Thermal radiation, Electromagnetic Reflectivity, gravity, Electrical resistivity	Bedrock mapping, faults, hydrothermalism, aquifer bounding characterization and regional water quality
Surface	Seismic Refraction	P-wave velocity	Bedrock mapping, water table, faults
	Seismic reflection	P-wave reflectivity and velocity	Stratigraphy, bedrock and faults delineation
	Electrical Resistivity DC Electromagnetic (TDEM, FDEM, CSEM, AMT) IP	Electrical Resistivity Electrical Resistivity Complex electrical Resistivity	Aquifer zonation, water table, bedrock, fresh and salt water interfaces and plume boundaries, estimation of hydraulic conductivity, estimation and monitoring of water content and quality Hydraulic conductivity
	GPR	Dielectric constant values and dielectric contrast	Stratigraphy, water table, water content estimation and monitoring
	NMR		Water content, mobile water content, pore structure
Cross hole	Electrical Resistivity DC GPR	Electrical Resistivity Dielectric constant	Aquifer zonation, estimation monitoring of water content and water quality
	Seismic	P-wave velocity	Lithology, estimation and fracture zone detection
Well bore	Geophysical well logs	Many properties such as electrical resistivity, seismic velocity, and gamma ray	Lithology, water content, water quality, fracture imaging
Laboratory	Electrical resistivity seismic, dielectric x-ray	Many properties such as electrical resistivity, seismic velocity, dielectric constant, x-ray attenuation	Development of petrophysical relationships, model validation and instrument sensitivity

The work of Pellerin (2002), Guérin (2005), CUAHSI (2005), Hubbard and Rubin (2005), and Auken *et al* (2006 a) among others, in reviewing the main geophysical applications to hydrogelogical systems is drawn on in the summary highlighted earlier.

Hydrogeological and Geophysical Data Integration Approaches

The approaches used to integrate hydrogeological and geophysical data for improved subsurface characterization fall into two general schools of thought. The choice of methodology typically depended on data density, project objectives, and the interpreter background. The approach that is probably most familiar to geophysicists capitalizes on expert skills and intuition to merge the disparate hydrogeological and geophysical data sets. This methodology allows for incorporation of information that is often very difficult to quantify, such as knowledge associated with geophysical signatures and depositional processes.

Teams of experts who can best interprete subsurface structures, stratigraphy, and hydraulic properties are used extensively within the petroleum industry. However, with this approach, it is often difficult to quantify the uncertainty associated with the components of the problem, such as the conceptual model, the hydrogeological parameter estimate, and the geophysical data inversion procedure.

Another approach is the integration problem using stochastic method. These methods provide a systematic framework for assessing or handling some of the complexities that arise in fusing disparate data sets, such as those associated with spatial variability, measurement error, model discrimination, and conceptual model uncertainty.

Although, a thorough understanding of the geophysical data is required to assess confidence in the hydrogeophysical interpretation, it is different in practice for an investigator to be a master of all geophysical techniques.

Future perspectives/prospects

There is an urgent need to assess the state of the discipline, and to review recent research breakthroughs and obstacles associated with hydrogeophysics.

The shallow subsurface of the earth is an extremely important zone that yields much of our water resources; supports our agriculture; serves as repository for most of our municipal, industrial and wastes/contaminants; and supports our infrastructure. As safe and effective use of the near-surface environment is a major challenge facing our society, there is a great need to improve our understanding of the shallow subsurface. The increased use of chemical pollutants associated with the technological development of countries with evolving market economies, and the increased need to develop sustainable water resources and infrastructure for growing populations all contribute to the urgent need to better understand the shallow subsurface.

Many advances associated with near-surface geophysics have been made in the last decade. For instance, similar to seismic methods a few years ago, Audiomagnetotelluric method (AMT) which is a natural source electromagnetic technique working in the frequency domain that allows the determination of the resistivity distribution of the subsurface based on the simultaneous measurement of the temporal fluctuations of the horizontal electric and magnetic fields on the Earth's surface (Simpson and Bahr, 2005), has gone through an acceptance process by the geo-scientific community. It has been accepted as a good tool for imaging geologic, hydrogeologic, environmental and civil engineering targets. For this reason, geoscientists have to work together to learn how to read all information that could be extracted from AMT data and models. Acquiring sensitivity on accuracy and resolution of the geoelectrical targets may complement the punctual lithological, hydrochemical information and classical seismic structural information to create improved models.

The real world needs to create 3D models that should include structures where dynamic processes can occur. As earlier highlighted, Audiomagnetotellurics is a true 3D geophysical technique. Taking advantage of this multidimensional capability, 3D models are going to increase its usage. The 3D AMT inverse modeling process is still on a testing stage where many improvements still need to be done to ensure good results with faster computing times. Bigger models, that is, finer meshes, and more periods will provide better results.

Also, Petrophysics is one of the paramount perspectives and the ultimate goal that hydrogeophysics has to envisage. Hydrogeophysical quantification of the geophysical models has not been given the needed impetus, perhaps because no clear cut general relationships exist but in general, site-specific relationships can be generated using a big amount of collected geophysical and hydrogeological data or using simple laws assuming standard parameters of ideal environments.

Going by the foregoing, it can be said that advances have been made. These advances, which facilitate the use of geophysical data for hydrogeological characterization, include improvements in understanding geophysical responses in near-surface environments, improved digital technology for acquisition, improvements of many geophysical methods for near-surface imaging, and improved computational speed and capabilities associated with processing, inversion, modeling, and visualization of geophysical data.

Hydrogeophysical Challenges

Although many successful shallow subsurface characterization studies have been performed using geophysical data, several obstacles still hinder the routine use of geophysics for hydrogeological characterization in this zone. Geophysical methods are being applied to assist with a range of hydrogeological investigations such as those shown in Table 1. Some of the techniques and approaches are well developed for particular applications, while for other applications, the techniques have potential but are not yet fully and well developed.

Some of the key obstacles that prohibit routine success include a lack of understanding of the relationship between the geophysical attributes and the hydrogeological parameters, a lack of methods for handling the non-uniqueness often associated with petrophysical relationships, and the current inability to integrate disparate data sets. Integration of geophysical and hydrogeological data sets that sample different parameters over different spatial scales using a systematic approach remains a daunting challenge that is so far only attempted, if at all, on a case-by-case basis.

Hydrogeophysicists are still struggling with obstacles such as how to best capture expert knowledge within these frameworks, and experience within the hydrogeophysical community with stochastic methodologies is still limited as earlier stated. However, in the light of the need to develop pragmatic solutions given an incomplete understanding of underlying mechanisms, the stochastic approach for assessing uncertainty holds great promise.

Again, there is a division in geophysical training between specialization and broad-based skills. Currently, hydrogeophysicists are striving to strike the right balance between having a working knowledge of all geophysical methods, and understanding the nuances of a few methods and the impact of those nuances on the hydrogeophysical interpretation. The importance of thoroughly understanding the geophysical data as a crucial component of the hydrogeophysical investigation cannot be over stated. Potential pitfalls can occur if the interpreter is not intimately involved with the geophysical data acquisition, inversion, and display. Assessing the error associated with geophysical data through repeated or reciprocal acquisition tests is an important goal.

Understanding the effects of data inversion on the geophysical estimate, and how the inversion artifacts translate into both point and spatial correlation estimates of hydrogeological parameters, is a current topic of research. The importance of the influence of visual displays and their influence on the message conveyed should not be glossed over. More studies are needed to assess the utility of using geophysical multi-method and multi-geometric approaches for resolving scale and non-uniqueness issues; to quantify errors associated with data acquisition, inversion, and estimation; to evaluate the relative contribution of stratigraphic information versus detailed hydrogeological parameter estimates to the flow and transport problem; and to modify existing geophysical instrumentation for near-surface use. More research is needed on the theory to support forward modeling and interpretation of three dimensional controlled source electromagnetic induction responses in systems with hierarchical scales of heterogeneity; a better understanding of many geophysical responses in unconsolidated sediments; and more research directed toward emerging methods for hydrogeological applications.

Furthermore, more efforts should be deployed to obtain a better correlation between measured physical parameters and hydrological parameters through laboratory studies and simulation of physical phenomena. Future methodology should include a dense array of electrodes to describe the subsoil system and to map the soil moisture. It should benefit from the development of new sensors in addition to remote controlled measurements with high resolution.

Conclusion

Hydrogeophysics is a novel discipline that combines hydrogeological and geophysical data to improve groundwater system's knowledge. From the hydrological perspective, diverse strategies on using geophysical methods could be performed. The choice of which particular techniques or acquisition approach to use for a particular investigation depend mainly on the objective of the investigation relative to the sensitivity of the geophysical method, the desired resolution, conditions at the site, time, funds and computational resources available for the investigations, and availability of previous data.

Multidisciplinarity, to improve hydrogeological models, is one of the main important goals of hydrogeophysics. Hydrogeological data may be considered as the hard data that controls and calibrates geophysical data, and thus geophysical models have to be in accordance with the hydrogeological data as the best assurance of good, reliable models. Geophysical data can provide more spatial and temporal–continuous information to complete hydrogeological punctual data. Therefore, it is obvious that both disciplines have a meaningful potential to complement each other. But there is a great need to recognize the current limitations, as well as for creating the enthusiasm and collaboration necessary for tackling some of the challenges that exist within hydrogeophysics. There is need for improved understanding of subsurface parameters and that judicious use of geophysical data integrated with hydrogeological data holds great potential for improved subsurface characterisation and monitoring.

Advances within the discipline are expected to be facilitated through increased fundamental studies, increased collaboration; increased publications of hydrogeophysical studies and manuals; increased hydrogeophysical education; and with increased personal experience. Moreso, individual as well as group efforts should be strengthened and sessions should be held in most professional meetings to proliferate the spirit of hydrogeopysical discipline.

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