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General concepts in Hydrogeology and Geophysics related to MRS

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ABSTRACT

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 fruitful 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 the main objective of this paper, where definitions of basic concepts of both disciplines related to Magnetic Resonance Sounding (MRS) are reminded. All surface geophysical methods are actually used in groundwater studies. MRS deserves special attention because of its singularity and novelty: it is the only method able to detect directly the presence of water in the underground. As research is going ahead, MRS reveals also its ability for the evaluation of hydraulic parameters, being nowadays a real alternative to the use of boreholes tests in some circumstances. The other standard surface geophysical methods are valid to determine the geometrical parameters of aquifers, and just in a few cases they allow the evaluation of hydraulic properties. The MRS method is at present limited to the investigation of the first 150 m of depth. Most groundwater catchments areas, at any geological environment, fall within the category of shallow confined or unconfined aquifers; otherwise hydrogeological research in the first 150 m is basic not only from the standpoint of groundwater supply but also for geotechnical and environmental groundwater related studies. The use of MRS can be adapted to any scale of the hydrogeological study. In regional research the main goal is the evaluation of water resources and the acquisition of parameters to make a mathematical model to the aquifer control. To achieve such a model the area in which the aquifer is situated, as well as its recharge and discharge zones, are divided into cells where the flux variables or parameters that characterise the aquifer have to be evaluated. MRS can be used to get part of these parameters adapting the sampling or distance between MRS measurements to the desired scale: cells size of kilometres or hundreds of meters. Local hydrogeological surveys are mainly focused at water extraction for human supply or for agricultural and/or industrial use, requiring a higher resolution in the methodology applied, for which MRS can play again an important role for the best location of sites for well drilling. Evaluation of hydrodynamic parameters from MRS data needs an initial calibration with known reference data, being necessary to fully understand the relation between hydrogeological and MRS parameters, for what a description of the former ones as well as a summary of the hydrological tests for its evaluation, in special of pumping tests, is presented.

Key words: aquifer model, Geophysics, hydrogeological parameters, Magnetic Resonance Sounding, pumping test

Conceptos generales sobre Hidrogeología y Geofísica en relación con el método SRM

RESUMEN

Para un adecuado uso de las técnicas Geofísicas en Hidrogeología es necesaria una gran colaboración entre hidrogeólogos y geofísicos, fundamentalmente en la planificación de las actividades geofísicas a llevar a cabo de acuerdo con el objetivo de la investigación hidrogeológica, y en la fase de interpretación o traducción de los documentos geofísicos a documentos hidrogeológicos. Para una colaboración fructífera es de gran importancia compartir un lenguaje común, de tal forma que la comunicación sea posible: el geofísico tiene que conocer los fundamentos de los procesos hidrogeológicos, y el hidrogeólogo tiene que conocer las bases de los métodos geofísicos. Este es el principal objetivo de este trabajo, en el que se repasan los conceptos fundamentales de ambas disciplinas que tienen relación con los Sondeos de Resonancia Magnética (SRM). En realidad, todos los métodos geofísicos se utilizan en los estudios del agua subterránea. Los SRM requieren una atención especial por su singularidad y novedad: es el único método capaz de detectar directamente la presencia de agua en el subsuelo. Además, según las actuales investigaciones, se revela como un método con capacidad para la evaluación de parámetros hidrogeológicos, pudiendo considerarse actualmente como una alternativa a la utilización de ensayos en sondeos mecánicos, en determinadas condiciones. El resto de los métodos geofísicos de superficie encuentran su aplicación en la determinación de los parámetros geométricos de los acuíferos, y sólo en muy pocos casos permiten su utilización para evaluar las propiedades hidráulicas. El método SRM está actualmente limitado a la investigación de los primeros 150 m de profundidad. La mayor parte de los recursos de agua subterránea, en topo tipo de ambientes geológicos, están dentro de la consideración de acuíferos superficiales, tanto libres como confinados; por otra parte, las investigaciones hidrogeológicas en los primeros 150 m de profundidad son fundamentales, no sólo desde el punto de vista de la extracción de agua subterránea, sino en estudios geotécnicos y medioambientales relacionados con la presencia de agua. La *utilización de los SRM puede adaptarse a cualquier escala de trabajo. En los estudios regionales, el objetivo final es la evaluación de recursos de agua subterránea y la adquisición de parámetros para la utilización de modelos matemáticos en el control de los acuíferos. Para formar los modelos, el área del acuífero, así como sus zonas de carga y descarga, se dividen en celdas en las que se precisa conocer las variables de flujo o parámetros que caracterizan el funcionamiento del acuífero. El método SRM puede utilizarse para la obtención de parte de dichos parámetros, adaptando la distancia entre mediciones a la escala deseada: celdas de kilómetros o de centenares de metros. Los estudios hidrogeológicos locales tienen normalmente como objetivo la captación de agua subterránea para uso humano, agrícola o industrial, requiriendo un mayor grado de detalle en las metodologías utilizadas, y los SRM pueden jugar nuevamente un papel importante para la localización del mejor emplazamiento de pozos. La evaluación de parámetros hidrodinámicos a partir de datos de SRM precisa una calibración inicial con valores de referencia conocidos, siendo necesario comprender perfectamente la relación existente entre parámetros de SRM y parámetros hidrogeológicos. Por ello, en este trabajo se efectúa una breve descripción de dichos parámetros, así como de los aspectos básicos de los ensayos hidrogeológicos utilizados para su evaluación, en especial de los ensayos de bombeo.*

Palabras clave: ensayo de bombeo, Geofísica, modelo de acuífero, parámetros hidrogeológicos, Sondeo de Resonancia Magnética

Introduction

Ground water exploration has always been one of the main fields of Applied Geophysics. These two Earth's Sciences disciplines are so much tight together that even a special name has started to be used: Hydrogeophysics. Magnetic Resonance Sounding (MRS) is the new tool that geophysicists try to put in the hands of hydrogeologists. Although MRS is still in its infancy, it has already demonstrated its very special characteristics of the only scientific methodology being able to detect the presence and quantity of groundwater, as well as its present and promising capabilities to evaluate some hydraulic parameters. To avoid a wrong use of the method, it is more necessary than ever to share with the hydrogeologists a common language and a good understanding of the terminology used. This is one of the objectives of this MRS Tutorial, and this first paper is mainly devoted to remind basic definitions of fundamental concepts in Hydrogeology and in Geophysics. The topics discussed here are already well known by the specialists of the respective discipline; the explanations given are addressed to the non specialists. The background of this reminder is to show that MRS, although it has nowadays a limited depth of exploration, can be used at any kind of aquifer (confined or unconfined) and at any scale of groundwater study (regional or local). For the evaluation of hydraulic parameters, MRS data have to be initially calibrated with pumping test

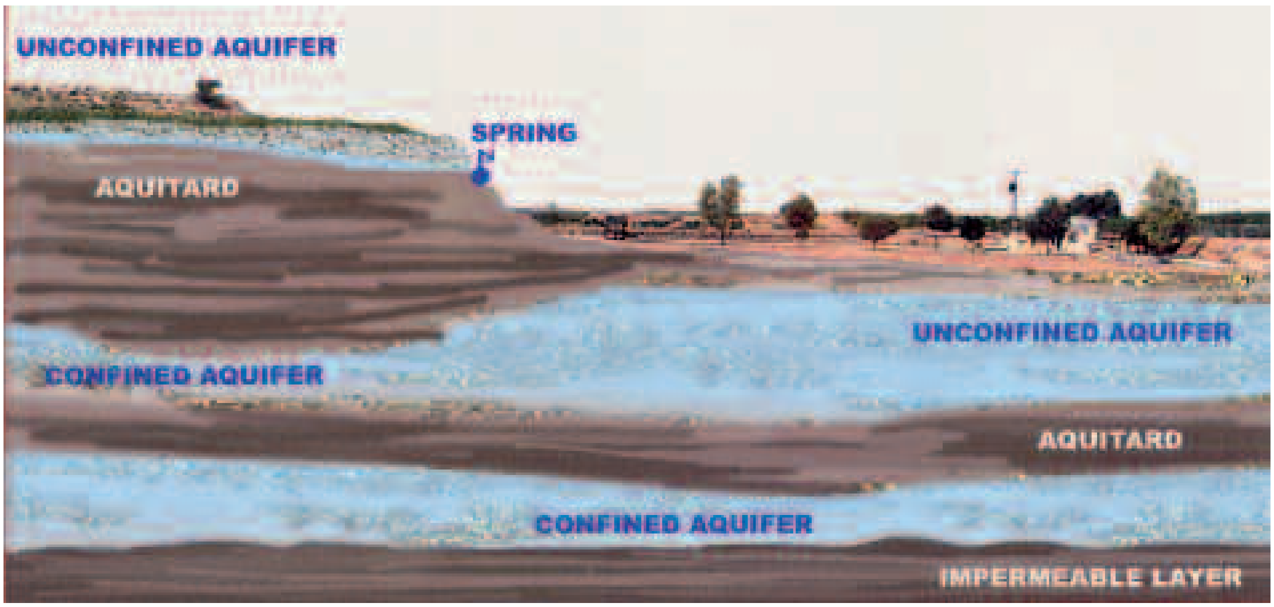

Fig. 1. Types of aquifers according to the hydrostatic pressure of the water they contain (López-Geta *et. al.*, 2006).
Fig. 1. Tipos de acuífero según la presión hidrostática del agua que contienen (López-Geta et. al., *2006).*

results; for this reason a rather basic definition of the parameters involved is also included, as well as a summary of the pumping tests technique. Finally, the general characteristics of a geophysical survey are reminded, to underline the place occupied by MRS.

Aquifers and hydrogeological studies

One of the principal applications of Hydrogeology concerns the study and understanding of the geological formations of the aquifers, in order to identify and characterize the water resources available. This area of knowledge is certainly of a multidisciplinary nature, requiring the implementation of diverse techniques in order to acquire precise knowledge of the subsurface geological medium.

An aquifer can be defined as a geological formation in which water accumulates and may circulate, via its pores and fissures, thus enabling humans to make use of it in economically viable quantities (Custodio and Llamas, 1996).

Depending on the hydrostatic pressure of the groundwater they contain, aquifers may be classified as unconfined, confined or semi-confined (Figure 1).

- Free, unconfined or phreatic aquifer: defined as an aquifer in which the top of the water mass forms a real surface, water table or phreatic level, that is in contact with the air of the unsaturated zone and, therefore, is at atmospheric pressure. When a well is drilled down from the land surface, water appears in it when the water table is reached and remains at this depth.

- Confined aquifer: at the upper limit or top of this aquifer, the water pressure is higher than that of the atmosphere. This is typical when permeable materials are covered by a confining layer that is much less permeable (aquitard), e.g. a sandy layer lying beneath a layer of clay, or completely impermeable (aquiclude or aquifuge). If a well is drilled into an aquifer of this type, when its top is reached the water level quickly rises inside the well until it stabilizes at a certain level (piezometric or potentiometer level). The ideal or virtual surface of the piezometric level at all the points of the aquifer is named piezometric surface.

For both kinds of aquifers the static water level (SWL) is defined as the water level in a well crossing the aquifer when pumping is not running. SWL is then used indistinctly as the phreatic or the piezometric level.

- Semi-confined aquifer: may be considered a special case of confined aquifer, in which the bottom, the top, or both, are not totally impermeable, but allow the vertical movement of water. This vertical passage of water can occur towards or away from the aquitard, and may even vary in time, depending on the relative values of the piezometric levels.

In lithological terms, aquifers may be formed of unconsolidated sedimentary rocks, consolidated sedimentary rocks, volcanic, igneous or metamorphic rocks.

- Unconsolidated deposits of loose materials: these geological formations are formed by the accumulation of particles that are transported by gravity, water, wind or ice, in riverbeds, lakeside or marine settings. They are usually comprised of sands and gravels of varying geological origin: fluvial deposits are made up of the alluvial materials of rivers and their terraces; deltaic deposits accumulate at river mouths. In general, such deposits are recent, in geological time. The main hydrogeological targets in the study of this kind of aquifers are the determination of the depth, thickness and extension of the permeable deposits and confining layers. Its porosity is due to the voids or space between the rock particles, or single porosity.

- Consolidated sedimentary rocks: are made of sediments that have become consolidated by compaction or diagenesis processes, which reduce the space occupied by the voids. They are classified, according to their origin as detritic (conglomerates, sandstones, clays), chemical (limestone, dolomites, chalk, marls) and organic (carbons and natural hydrocarbons). On the basis of their porosity they can be classified as double porosity aquifers (as is the case of sandstones with primary or interstitial porosity and secondary porosity due mainly to fracturing), and karstic aquifers (as limestone and dolomites, in which the secondary porosity is due to fracturing and chemical dilution processes). The most important are the carbonate rocks: chalk, limestone and dolomites. They vary considerably in density, porosity and permeability, depending on the sedimentation environment surrounding their formation and the subsequent development of permeable zones caused by the solution of carbonate materials, especially in the case of limestone rocks; if these rocks are not karstified, they are relatively impermeable. To localize the fractured and voided areas is one the main targets in the study of these kinds of aquifers.

- Igneous, metamorphic and volcanic rocks: igneous rocks are formed by the cooling and consolidation of magma. They can be extrusive (volcanic) or intrusive (plutonic), depending on whether they consolidate on the surface or within the Earth's crust, respectively (e.g. granites, gneiss, gabbros, basalt, etc). Metamorphic rocks are those that have undergone intensive physical and chemical transformations, giving rise to changes in the structure of the rock itself, thus adjusting to new pressure and temperature conditions and possible chemical inputs (e.g. slates, schist, etc). The possibilities of an aquifer forming among such rocks are limited to the altered shallow weathered zone or to areas fractured by faults and diaclases, which enable an appreciable degree of water circulation. Volcanic rocks may or may not constitute aquifers, and they have a hydrogeological behaviour between that of porous consolidated and fractured rocks. The levels of scoria, pyroclasts and retraction fissures play a significant role. The main factors influencing the flow of groundwater are the composition, the age and mainly the degree of alteration. The determination of the thickness of the weathered zone and fractures in hard rocks is a normal objective in the study of these aquifers.

A distinction can be made between shallow and deep aquifers. Simplifying somewhat, deep aquifers are defined as those located at depths exceeding some 300 m. In a more precise way, they are considered to be unconfined aquifers in which the phreatic level is at the depth of 300 m or more, or confined aquifers with its roof at this depth or deeper. In general, deep aquifers require very deep drilling to take advantage of the water they contain, and specific techniques to determine their hydrogeological structure and characteristics (Mejías *et al.,* 2006).

Most subsurface water catchments fall within the category of shallow aquifers, and so hydrogeological research in the first 300 m is a basic objective in many studies, not only from the standpoint of groundwater drilling projects but also taking into account environmental studies such as aquifer protection from surface or underground waste disposal, the protection of the unsaturated zone from farming and industrial activities, and the development of infrastructures and public works. In this context, it is of particular interest the availability of surface geophysical techniques such as Magnetic Resonance Sounding, able to fulfil data directly related with the nature of the targets down to a depth of about 150 m.

Scale and objectives of groundwater studies. Mathematical models

Hydrogeological research can be carried out at a regional or at local scale. Regional studies are aimed at achieving a general evaluation of water resources and to the control of aquifers by means of models of their functioning. Work that should be carried out in this respect includes performing a geological survey to characterise the geometry (bounds, extension), lithology and structure of the aquifer units or water bodies, in which Geophysics plays an important role.

In addition, hydrogeological mapping is necessary, with sufficient coverage to define recharge and take out areas, as well as the relations between them. A hydroclimatic study is needed to evaluate the water input; this study is the start point in establishing the water balance for the zone and in determining the areas of recharge and discharge. Recharge can be estimated on the basis of this hydroclimatic study and by the application of numerical methods used within a geographic information system (Andreo *et al.,* 2004).

A mathematical model of a groundwater system can be defined as a description of an aquifer system based on mathematical equations that represent the physical medium and the water flow. To achieve such a model, the area in which the aquifer is situated, as well as its recharge and discharge zones, are divided into cells to discretize the value of the variables or parameters that characterise the aquifer regime. The simplifications made in the mathematical model, joined to the uncertainties associated with the required data, give rise to a model that should be seen as an approximation and not as an exact replica of the system's conditions. Nevertheless, mathematical models of groundwater systems are very sophisticated tools used in Hydrogeology both to investigate the behaviour of an aquifer and to predict possible future scenarios.

Mathematical models of groundwater describe flow and transport processes on the basis of a combination of physical-chemical laws applied to the particular conditions of the system, and on a series of simplifications of the medium with respect to the geometry of the system, the boundary conditions and the parameters that control water flow: hydraulic conductivity and storage coefficient, as well as the transport of solutes in the aquifers: porosity, dispersivity (it measures the separation of the solutes from the flow lines of the groundwater), etc. The cell size for a mathematical model must be capable of representing abrupt changes in the physical-chemical properties of the system. The higher the number of cells, the better the model will represent the variations in the hydrogeological properties, although it is necessary to take into account the working scale, the availability of computing resources and the numerical stability. In general, considering the above observations, for regional-type models (of the size of a river basin or regional aquifers), kilometre size are normally used, while for small aquifers or more localised studies cells of a few tens to several hundreds of metres are normally used.

Another essential activity in regional studies is the design and inventory of groundwater observation networks, with a density depending on the characteristics of the aquifer formations, the type of aquifer, the variability of hydraulic properties and the importance and necessity of existing water resources. In designing such networks, it must be taken into account that, as well as identifying the piezometric levels that are the basis for the plotting of isolines, they must enable obtaining information on questions related to hydrochemical characteristics, evaluation of the recharge, contamination processes and possible marine intrusion. Geophysics, and MRS in special, can be used at this step for optimizing the positioning of the observation wells and, in a lesser degree, to measure the phreatic level.

Hydrochemical and isotopic techniques are used to identify the age, the water types and the relations between them, the model of groundwater flow circulation, the evolution of the water within the aquifer and the influence of human activity. Analysis of environmental tritium, for example, enables to identify the presence of water that has entered the aquifer after the thermonuclear tests carried out during the 1950s and 1960s.

The tasks to be performed in a hydrogeological study at a local scale are focused, as an immediate objective, on activities aimed at obtaining water for human supply or for agricultural and/or industrial use. The activities developed, in principle, are analogous to those required for a regional study, with the basic difference being the scale of implementation and the end goals; in the case of urban water supply, these refer to estimating demand, and defining the water-use system and supply points. The degree of detail necessary for studies at this scale is, logically, higher than that required in regional studies, and thus investigation techniques with a higher resolution capacity must be applied.

At both regional and local scales of studies near surface Geophysics techniques as MRS can play a key role in helping to define the groundwater availability, the geometrical aspects of the aquifer layers, hydrogeological bounds and hydraulic connections, positioning of suitable points for the observation and control network, and in the evaluation of the hydraulic parameters.

Parameters needed to characterize an aquifer

In daily geophysical practice, and in most of the published papers dealing with applications of surface geophysics to hydrogeology, only two single hydrogeological parameters are used: porosity (effective porosity is mentioned in very few cases), and permeability or hydraulic conductivity (using these terms indistinctly). The potential opened by MRS demands a more complete and concise definition of the hydraulic parameters. In this paragraph, a brief presentation is made mainly addressed to geophysicists.

To define the main hydrogeological parameters required to determine the hydraulic characteristics of an aquifer formation, and in relation with MRS, criteria from several authors are going to be followed, mainly from Custodio and Llamas (1996), Kruseman and de Ridder (1970) and Lubczynski and Roy (2003 and 2005) among others. In particular, the following description of storage parameters is based on the storage concept presented in Figure 1 of Lubczynski and Roy (2007, this Issue).

Three conditions are necessary for the existence and use of an aquifer: the rock must be able to store the water (aquifer storage property), the water has to be able to circulate through the rock (aquifer flow property) and there must be water replenishment (aquifer recharge). Moreover, water has to be removed out from the aquifer.

The rocks are formed by grains and voids (pores, fractures and cavities). From the view point of the ability to store water it is obvious that only the voids can be occupied by a fluid. The proportion of voids in relation to the total volume of rock considered is evaluated by the total porosity n. But some voids may be not connected with other voids, and the fluid inside them is trapped; its volume proportion is named trapped porosity n_t. The total porosity is not then appropriate to define the water content that can circulate through the rock, and the term effective porosity or kinematics porosity n_e is used instead, referring to the portion of the interconnected voids volume that allows the circulation or flow and advective transport of the water. In principle, this volume may be not equal to the difference between n and n_t, because not all the space of the connected voids may allow water flow.

These single concepts are then not enough to characterize an aquifer, because not all the water filling the connected pores can be extracted from the aquifer, and instead of talking about porosity or classes of voids, it is preferable to talk about the different forms in which the water can be installed inside a rock, or water contents.

A small part of the water can be attached by molecular forces to the walls of the grains (water within 0.0002 mm of the surface of a soil particle), and its proportion to the total volume of rock is called bound water θ_b; the rest of the water is called free water, θ_f.

If the rock is water saturated (the only fluid inside pores is water), part of the free water is mobile (can flow through the rock) and its proportion is represented by θ_m. The free water retained inside the not connected pores or fractures is called trapped water θ_t. So, the total free water is the sum of the mobile water and the trapped water and is the one responsible of the MRS detected signal:

$$\theta_{MRS} \approx \theta_f = \theta_m + \theta_t$$

The volume occupied by the mobile water θ_m is the same volume as the one of the effective porosity:

$$n_e = \theta_m$$

The total porosity (n) can then be seen as the sum of the mobile water (θ_m), plus the trapped water (θ_t), plus the bounded water (θ_b). If θ is the total amount of water inside the saturated rock

$$n = \theta = \theta_b + \theta_m + \theta_t = \theta_b + \theta_f \approx \theta_b + \theta_{MRS}$$

If θ_b can be neglected, then the total porosity is equal to the free water, and this is why it is said that MRS gives a measure of the total porosity. In as much as the trapped water is also negligible, MRS provides the mobile water, or effective porosity.

If the rock is not water saturated the voids are filled with air and water. Part of this water is bound water (hygroscopic water) and can only be removed from the soil through heating or by centrifuges. There can be also free trapped water, and free mobile water can be gravitational water θ_g and/or capillary water θ_c, the later one held by capillary forces as a layer around grains and in spaces between them that cannot be removed by gravity forces. Free water of soils will also produce a MRS signal, but in this case it is not a measure of porosity.

Neither the total porosity n nor the free water θ_f concepts are enough to provide a value of how much water can be extracted from the aquifer, because an important part of the water can be bounded and/or trapped. Effective porosity n_e and mobile water θ_m are closer to this value, but are theoretical concepts. The practice is then to consider another type of parameters to measure the capacity of water extraction from an aquifer: the storativity or storage coefficient family. A difference is made depending what force is applied to the water to leave the aquifer: the gravitational force or the hydraulic gradient (difference in the hydraulic head, or energy due to the water gauge pressure and to elevation, between parts of the aquifer). From this approach, the water content in the rock that can not be removed by gravity forces is defined by the specific retention, S_r or field capacity, that is the ratio of the maximum volume of water a rock can retain against gravity drainage, to the volume of that rock.

For gravitational forces, the storage coefficient is known as specific yield, defined as the volume of water V_w that an aquifer releases from storage under the forces of gravity per unit surface area ΔA of aquifer per unit decline of the water table ΔWT (in unconfined aquifers), and is designated as S_y. As it is the ratio between volume of drained water V_w and desaturated volume of aquifer given by $V_a = \Delta A x \Delta WT$, it is dimensionless and expressed in percentage. S_y provides an estimation of the quantity of extractable water. Table 1 shows typical values of specific yield for different materials.

For the hydraulic gradient in saturated confined aquifers, the storage coefficient or volume of water V_w drained by a change in one unit of the hydraulic head ΔH ($V_w/\Delta H$), depends on the compressibility of the rock grains and fluid, and has two formulations:

Material	minimum	average	maximum
Peat	30	44	50
Gravel, fine	20	25	35
Gravel, medium	15	24	25
Gravel, coarse	10	23	25
Sand, fine	10	23	28
Sand, medium	15	28	32
Sand, coarse or gravelly	20	27	35
Sand, dune	30	38	40
Loess	15	18	35
Silt	1	8	30
Glacial till, silty	5	6	20
Glacial till, sandy or gravelly	5	16	20
Clay	0,1	2	5 (20)
Clay, sandy	3	7	12 (20)
Sandstone	10	25	40
Limestone and Dolomite	1	14	25
Schist		26	
Volcanic tuff	2	21	35
Siltstones	1	12	35
Igneous, weathered	20		30

Table 1. Typical values of specific yield in percent for different materials (Renard, 2005a)

Tabla 1. Valores típicos del rendimiento específico para varios materiales (Renard, 2005a)

- if expressed as the water volume released from storage by unit volume of aquifer [$V_w/\Delta H\ V_a$] it is known as specific storage S_s, and has the dimensions of m^{-1}. It is given by

$$S_s = \rho g(\alpha + n\beta)$$

where ρ is the water density, g the acceleration due to gravity, α the compressibility of the rock, n aquifer porosity and β the compressibility of the water under a given stress.
- if expressed as the water volume released from storage per unit surface area of the aquifer [$V_w/\Delta H\Delta A$] it is the elastic storativity S_e, with

$$S_e = S_s \Delta z$$

Δz is the thickness of the aquifer layer ($V_a = \Delta A\Delta z$) ; it is dimensionless, and ranges between 0 and the effective porosity, corresponding to the water that can be removed from the rock due to the water expansion and aquifer compaction attributed to aquifer pressure changes.

The sum of S_r, S_y and S_e is again the volume represented by the total porosity.

In unconfined aquifers, S_y defines the storage coefficient or storativity, while S_e is very small; in confined aquifers S_e is relevant as well as the specific drainage S_d, although the latter only in cases where confined conditions change to unconfined (see Figure 3 in Lubczynski and Roy (2007, this Issue)). Specific drainage S_d is the gravitational component of storativity in confined aquifers, defined by the ratio of the volume of water that could potentially be released from the confined aquifer by gravity forces if the piezometric surface falls below the top of the aquifer layer, thus creating unconfined conditions, to the total confined aquifer volume (Lubczynski and Roy, 2004).

In coarse rocks the values of specific yield and effective porosity are similar, because the specific retention is small; but in rocks where the specific retention is high (i. e. fine-grained rocks) S_y differs from n_e.

The storage conditions of an aquifer depend on the type of rocks from the point of view of its internal configuration, mainly related to the granulometry, lithology and geological history. Porosity (n) and water content (θ) are linked to a model of the space distribution inside de rock. The concept of porosity (n) obeys to a classification of the physical voids in a rock, indistinctly with the kind of fluids filling the voids and with the possibility of removing them out from the rock. Water content (θ) is a conceptual approach to this extraction chance, classifying the ways water can be found inside the rocks. Storativity parameters (S) reflects the experimental reality of the water extractability, and after its definition this kind of parameters is not directly related to MRS measurements, and indirect methods have to be used for its evaluation from the MRS data.

Effective porosity and specific yield is many times used indistinctly for unconfined aquifers. Specific retention (S_r) can be considered as the difference between the total porosity and specific yield. In the hydrogeological literature some different definitions from the ones given here can be found. It is also possible to find some differences and simplifications in the use of the terminology among different languages and countries. The word storativity or storage coefficient is also used normally instead of elastic storativity or specific yield.

There are still two more concepts used to express the ease of the water to move through the aquifer or flow parameters: the hydraulic conductivity and the transmissivity, with definitions much more universal than the previous ones. The hydraulic conductivity gives the idea of the ease by which a solid is crossed by a fluid; the transmissivity introduces the idea that with the same hydraulic conductivity, the flow will depend on the thickness of the aquifer.

Hydraulic conductivity (K) is defined as the amount of water which will flow through a unit cross-section area of the aquifer (confined or unconfined) under a unit gradient of hydraulic head at a determined temperature. It is dependent of the aquifer's properties (type of pores) and of the fluid's properties (viscosity and specific weight). The dimensions are [L/T]. Table 2 shows typical values of hydraulic conductivity for different materials. Its value is given by

$$K = k\gamma/\mu$$

being k the intrinsic permeability, a parameter affected only by the properties of the medium, and not by the properties of the fluid, with the dimensions of $[L]^2$; γ is the specific weight of the fluid and μ the viscosity of the fluid. In practice, for shallow groundwater where temperature gradients are not important, the names permeability and hydraulic conductivity are used indistinctly.

Transmissivity (T) is the product of the average hydraulic conductivity K and the saturated thickness of the aquifer Δz. It represents the rate of flow under a unit hydraulic gradient through a cross-section of unit width over the whole saturated thickness of the

Material	K (m/s)
Coarse gravels	$10^{-1} - 10^{-2}$
Gravel	$10^{-2} - 10^{-4}$
Sand and gravels	$10^{-3} - 10^{-4}$
Clean sand	$10^{-2} - 10^{-5}$
Sand dune	$10^{-4} - 10^{-5}$
Silty sand	$10^{-3} - 10^{-7}$
Fine sand, Silt, Loess	$10^{-5} - 10^{-10}$
Clay, Shale, Glacial till	$10^{-6} - 10^{-13}$
Sandstone	$10^{-5} - 10^{-8}$
Shale	$10^{-7} - 10^{-11}$
Quartzite	$10^{-8} - 10^{-9}$
Weathered chalk	$10^{-3} - 10^{-5}$
Unweathered chalk	$10^{-8} - 10^{-9}$
Karstified limestone	$10^{-2} - 10^{-6}$
Dolomitic limestone	$10^{-3} - 10^{-5}$
Limestone and dolomite	$10^{-5} - 10^{-9}$
Permeable basalt	$10^{-2} - 10^{-6}$
Rhyolite	$10^{-5} - 10^{-7}$
Schist	$10^{-6} - 10^{-9}$
Coal	$10^{-4} - 10^{-7}$
Fractured igneous and metamorphic rocks	$10^{-4} - 10^{-8}$
Unfractured igneous and metamorphic rocks	$10^{-9} - 10^{-13}$

Table 2. Typical values of hydraulic conductivity for different materials (Renard, 2005a)
Tabla 2. Valores típicos de la conductividad hidráulica para varios materiales (Renard, 2005a)

aquifer. It is the parameter that best describes aquifer flow potential, and the dimensions are $[L]^2\ [T]^{-1}$

$$T = K\Delta z$$

Table 3 shows the qualitative classification of transmissivity with respect to its value and the estimated variations in specific pumping rate (rate/drawdown) for different ranges of transmissivity.

Another parameter also used is diffusivity: it is the ratio between the transmissivity and the storativity

T ($m^2\ d^{-1}$)	Classification	Specific rate (l/s/m)
T < 10	Very low	< 0,1
10 < T < 100	Low	0,1 - 1
100 < T < 500	Medium	1-5
500 < T < 1000	High	5-10
T > 1000	Very high	> 10

Table 3. Transmissivity values and qualitative classification (Villanueva and Iglesias, 1984)
Tabla 3. Clasificación cualitativa de valores de transmisividad (Villanueva and Iglesias, 1984)

(T/S_e) in a saturated aquifer (Kruseman and de Ridder, 1970). It governs the propagation of changes in hydraulic head in the aquifer. When the diffusivity is high, the propagation of the perturbation is faster.

All these concepts, and the way they are evaluated with MRS data, will be seen in more detail in Lubczynski and Roy (2007,this Issue), and Vouillamoz *et al.* (2007, this Issue).

Evaluation of the hydrodynamic parameters. Pumping tests

To calculate the hydrodynamic parameters from the MRS measurements, a calibration with the values determined from hydrogeological techniques is needed, as will be explained in Lubczynski and Roy (2007, this Issue). The hydraulic parameters of a geological formation can be determined by laboratory methods and by field surveys. Laboratory methods always involve some alteration to the sample of the geological formation in which the test is to be carried out, as a result of the process of obtaining the sample, and its manipulation and transport. Therefore the values obtained always present a certain degree of uncertainty. Field surveys provide more realistic data; although it should be taken into account that their result is representative of the zone in close proximity to the point at which the data are obtained, the "size of the sample" is much closer to the one measured in MRS than at laboratory determinations, improving the scale effect in aquifer characterization.

The basic hydraulic parameters required to evaluate the characteristics of an aquifer are the effective porosity, the storage coefficient and the hydraulic conductivity. Laboratory assay methods enable obtaining values for total porosity and effective porosity, while field survey methods only determine the latter. Pumping tests with observation boreholes enable to calculate the value of the storage coefficient; in unconfined aquifers, the specific yield is close to the effective porosity in coarse grained rocks, provided the pumping time is of a sufficient duration, although the proximity of aquifer barriers and limits, as well as heterogeneities, may contribute to obtain erroneous values if these uncertainties are not taken into account. When correctly interpreted, they provide averaged values in heterogeneous media. The hydraulic conductivity can be obtained using laboratory testing methods and also by field survey methods. In general, the determination of this parameter is more complicated than the porosity (Custodio and Llamas, 1996), as the margin of variability of the hydraulic conductivity is much greater, being affected by small variations in granulometry and composition; it may also vary with the direction. Hydraulic conductivity is a very heterogeneous parameter, with a high degree of dependence of the measurement scale (it is more variable in laboratory determinations than using pumping tests) and a high range of variability, mainly in the case of fractured formations. Nevertheless hydraulic conductivity is better defined than storativity in heterogeneous medium.

The laboratory test that is most frequently used is based on the application of Darcy's law, using a cylinder of the material to be tested placed within a permeameter. The hydraulic conductivity value thus obtained is only an approximation to what may be achieved from field surveys, as a column extracted from the geological formation has undergone a certain degree of manipulation thus is unlikely to exactly represent the typical characteristics of an aquifer.

Field-based measurements are carried out using hydraulic tests in boreholes. They are analytical methods used to determine the hydraulic properties, the boundary conditions and the relations with the physical medium of a given geological formation. Values for an isolated range of depths of such a formation can also be determined by means of packers. This analysis is based on mathematical expressions

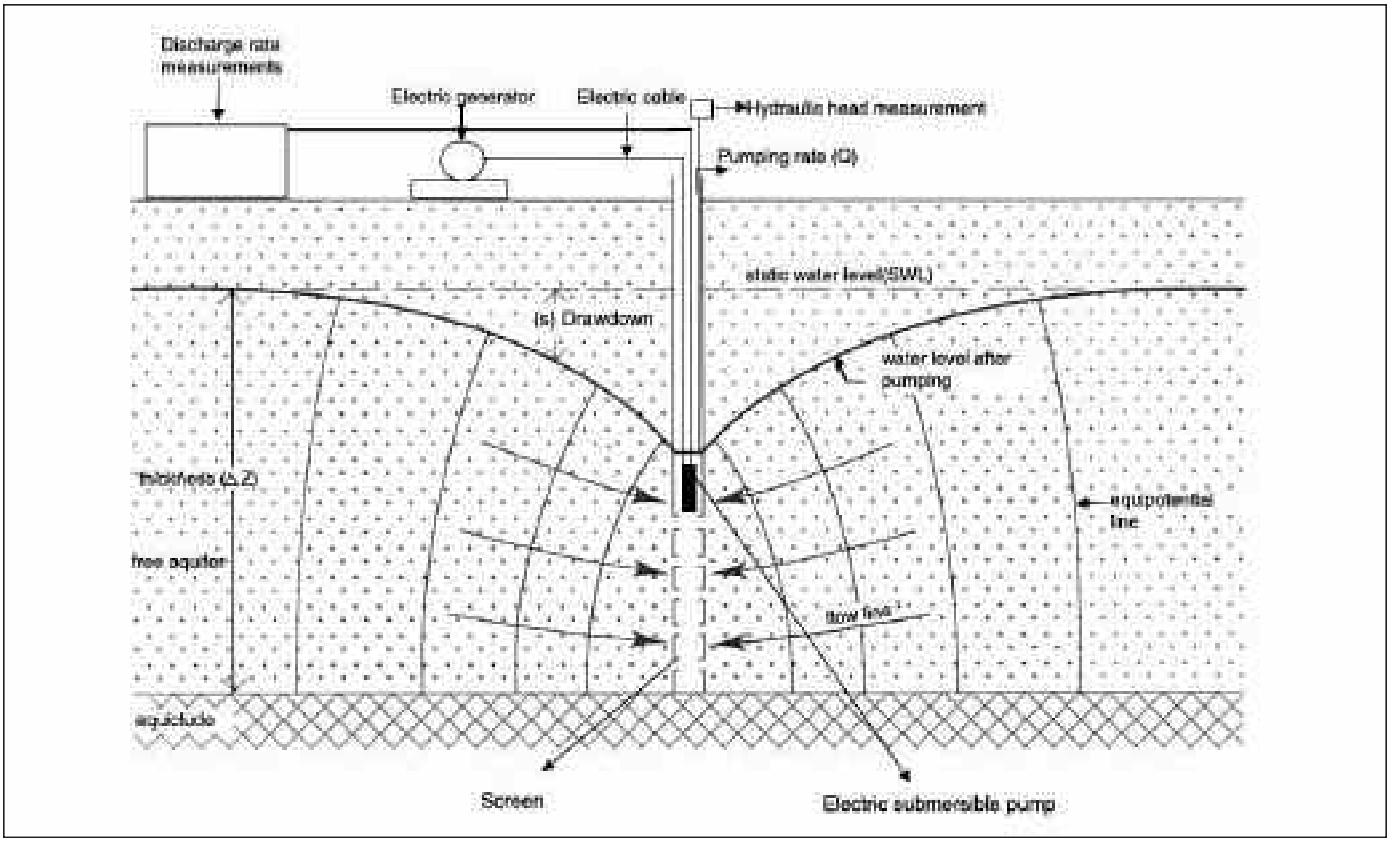

Fig.2. Cross-section of an unconfined aquifer during water pumping (modified from Kruseman and de Ridder, 1970)
Fig. 2. Sección de un acuífero libre durante el bombeo (modificado de Kruseman and de Ridder, 1970)

involving certain assumptions and generalizations. For a correct interpretation, it is necessary to pay special attention to the conditions and limitations implicit in the use of each of the possible methods of analysis.

The hydraulic test that is most frequently used in Hydrogeology is the pumping test (Figure 2). It involves using wells which extract groundwater. With respect to the aquifer, it provides the values of the hydraulic parameters, the connectivity between the aquifer and the well, and identifies anomalies and exceptional situations (external recharge, impermeable margins, storage within the borehole, etc.).

In outline, pumping tests may be carried out in accordance with the following procedures (Villanueva and Iglesias, 1984):

Steady-state flow: in steady-state flow pumping tests, the water level remains practically invariable (stabilisation) after a certain period of pumping. The aquifer acts as a transmitter of the charge and water is not extracted from the stored volume. From the data obtained the transmissivity values, the radius of influence, and head losses (if piezometers are available) can be calculated. In no case can the storage coefficient be evaluated.

Unsteady-state flow: in unsteady-state (transient) flow pumping tests no interpretation is made of the final drawdown (as occurs in the steady-state flow), but instead the variations in the drawdown during the implementation of the pumping test is identified. The water extracted is taken partially or entirely from the stored volume. The test may be carried out at a constant discharge rate, in which case the control variable is the water level, or at a constant head in which case the variable to be controlled is the discharge rate. Under an unsteady-state flow, it is possible to determine the transmissivity, the storage coefficient and information on various characteristics of the aquifer (boundaries, anisotropy, external recharge, etc.).

The pumping rate and drawdown values obtained from a pumping test are subsequently interpreted to obtain the hydraulic parameters previously mentioned. Various methods may be employed for this interpretation, which are selected according to the characteristics of each pumping test and tested aquifer, applying in each case a series of mathematical simplifications and conditions that must be fulfilled for the results obtained to be coherent with the characteristics of the physical medium being analysed.

On occasion, when a pumping test is performed, anomalies or special situations may occur, in which the conditions established for each type of analysis are not met, and then the interpretation may be complicated and even become unreliable. In such cases, the analyst must attempt to eliminate the effects of the anomalies and simplify the analysis as far as possible so that at least an estimative value of the parameters in question may be achieved.

Another question to take into account in planning and interpreting a pumping test is to determinate precisely the aquifer layer that is to be examined, in the case of multilayer aquifers; the superposition of two or more aquifer layers drilled by the borehole means that the results obtained from the test are influenced by the values of the most transmissive levels of the aquifers; therefore, it is sometimes desirable to identify the characteristics of a particular level, on an individual basis. In such cases, it is necessary to use packers to isolate the test sections and to obtain the hydraulic parameters of a formation or of a specific sector. The use of packers involves some complexity in the instrumentation to be employed for the pumping test. Thus, the in-depth equipment must provide the possibility of isolating the test section from the rest of the borehole, and must be fitted with pressure transmitters to record the pressure values, both in the section that is isolated and in those immediately above and below, to ensure that in carrying out the test, the section to be tested is correctly isolated from the over and underlying ones (Mejías, 2005). The use of packers also requires the utilisation of a system for inflating them; this can be done using nitrogen or, in certain cases, pressurized water (i.e. for extended sealing times in the case of long-duration pumping). Also recommended is the use of a test valve so that water can be injected into or removed from the assay section. This will also involve the utilisation of a cable to transmit the electrical signals bearing the pressure data to the data acquisition system. The available instrumentation used for this type of measurements makes it possible to obtain hydraulic conductivity and storage coefficient in single sections of whatever length may be required, from a few centimetres to several tens of metres, and thus characterise the physical medium with a high degree of accuracy.

Interpretation of the hydraulic tests

After the publication of Darcy's Law in 1856, Dupuit published the first analytical solutions for pumping tests in unconfined and in confined aquifers in 1863. These solutions, however, were not utilised for interpreting hydraulic tests until 40 years later (Thiem, 1906). Theis (1935) managed to obtain the analytical solution for the unsteady-state flow, a solution that is currently the basis for most techniques used in interpreting hydraulic tests. It can be applied to confined, infinite, homogeneous and isotropic aquifers, with a fully penetrating borehole and with a negligible radius. Theis' unsteady-state equation was derived from the analogy between the flow of groundwater and the conduction of heat, and is written as (Kruseman and de Ridder, 1970):

$$s = \frac{Q}{4\Pi T}\int_u^{\infty}\frac{e^{-u}}{u}du = \frac{Q}{4\Pi T}W(u)$$

where: s is the drawdown in m measured in a piezometer at a distance r (m) from the well; Q is the constant well discharge in m^3/day; T is the transmissivity of the aquifer in m^2/day, and

$$u = \frac{r^2 S}{4Tt}$$

or

$$S = \frac{4Ttu}{r^2}$$

where S is the dimensionless storage coefficient, and t is the time in days since pumping started.

The exponential integral is written symbolically as W(u), which in this usage is generally read "well function of u" or "Theis well function".

Theis' solution was the starting point for the scientific community to develop pumping well theories, with more complex aquifer and borehole conditions. Advances were made, particularly, in the analysis of the influence of many perturbing factors such as boundaries (Theis, 1941), nonlinear head losses in the pumping borehole (Jacob, 1947), the introduction of the skin effect (Van Everdingen, 1953), the effect of the unsaturated zone in unconfined aquifers (Boulton, 1954), the influence of adjacent aquifers (Hantush and Jacob, 1955), partial penetration boreholes (Hantush, 1961), large diameter boreholes (Papadopulos and Cooper, 1967), a fracture network continuum within a porous matrix, introducing the concept of double porosity (Gringarten *et al.,* 1974), flow dimension (Barker, 1988), etc.

In parallel with the development of the analytical solutions for the different aquifer types, work began on developing a series of techniques for interpreting data from pumping tests by fitting of the results obtained. These analyses were based on asymptotic solutions that were valid for data derived at the end of the tests. The solution most commonly used, in this respect, is the asymptotic technique of Theis' solution, as applied to extended time periods (Cooper and Jacob, 1946).

Over the last 25 years, a series of techniques have been presented for interpreting tests in the context of hydrocarbon prospecting; these techniques have subsequently been extended to hydrogeological characterisation (Horne, 1995; Bourdet, 2002). They are based on graphs that represent the logarithmic derivative of the drawdown over time (Renard, 2005b). This parameter is more sensitive to small variations in levels than pure drawdown graphs (Bourdet *et al.,* 1983), and is constant for long time periods in the case of Theis' model, its expression being proportional to the inverse of the transmissivity value.

From the equations obtained in the different types of tests, drawdown as a function of time can be represented in semi logarithmic or logarithmic plots. Depending on the type of test and interpretation model selected, these representations can be extrapolated to a straight line, the slope of which is used to calculate the hydraulic conductivity. Once the fit has been obtained from the drawdown (s) and the initial time (t_0), the hydraulic parameters (hydraulic conductivity, transmissivity and storage coefficient) are calculated (Figure 3).

When using hydraulic parameters obtained by pumping test for calibration of MRS data a great attention should be paid to the conditions the hydraulic tests have been performed, as well as of its interpretation and range of error. It is evident that the volume of the aquifer involved in MRS measurements must be equivalent to the one involved in the hydraulic test, mainly in heterogeneous aquifers, and in the case of overlaying aquifer layers it is still more important that both determinations corresponds to

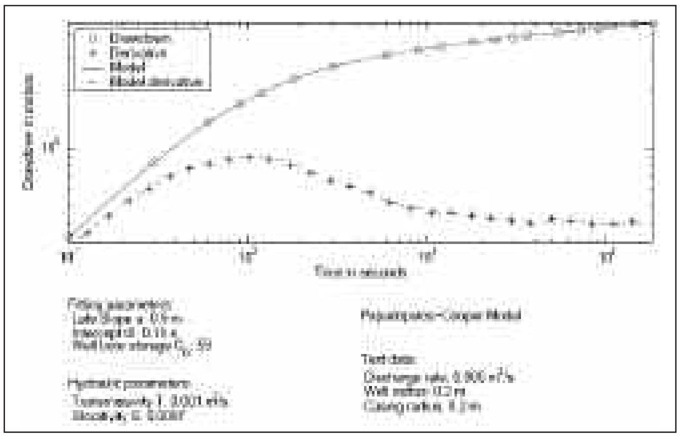

Fig. 3. Interpretation of a pumping test with Hytool (Renard, 2003)
Fig. 3. Interpretación de un ensayo de bombeo mediante Hytool (Renard, 2003)

the same layer or group of layers, what unfortunately is not always true.

Carrying out a hydraulic test always involves the need to make at least two suitable drillings (one well for pumping and other one for observation) and the availability of the specific instrumentation required for this purpose; such tests, therefore, are relatively time consuming and expensive. In consequence, the possibility of obtaining porosity data via Magnetic Resonance Sounding, together with an indicative value of the hydraulic conductivity and storativity, may constitute an important qualitative advance in hydrogeological exploration methodology. Specially, storativity determination through MRS measurements is a promising tool in hydrogeological studies, because it is a very sensitive parameter to heterogeneities and to asses its value with pumping test is not an easy task. Once the MRS data are calibrated in one area, hydrodynamic parameters can be obtained at other sites of the aquifer where no hydraulic tests are available in a much faster and cheaper way than with pumping tests.

General characteristics of the geophysical surveys

The geophysical prospecting can be defined as a technology that allows establishing a diagnosis of the subsurface rocks constitution through the interpretation of documents that are the result of some measurements and calculations.

A geophysical survey has, or should have, the following steps:

1/ The definition of the hydrogeological problem to be investigated.

2/ The translation of the problem to geophysical terms: possible geometries and petrophysical properties involved. This allows selecting the geophysical method/s to be used and the setting of its measurements parameters.

3/ Field measurements.

4/ In general the field measurements have to undergo a processing step, ending by the elaboration of a document where the spatial distribution of some property of the rocks is drawn. The algorithms used at this step are normally the result of some simplifications of the real physics involved in the studied phenomenon.

5/ Interpretation or translation of the former geophysical document into a geological document, giving an answer to the problem posed. This step has always some degree of subjectivity, and is better suited to confirm or to refuse the possibility of previous hypothesis, than to guarantee the solution found.

At least at the initial and final steps, a tight collaboration between hydrogeologists and geophysicists is necessary, being of a great importance that they have a common language to make communication feasible: geophysicists have to know the fundamentals of hydrogeological process, and hydrogeologists have to know the fundamentals of geophysical methods.

It is of special significance the adequate knowledge and understanding of the "philosophy" of the whole process of geophysical interpretation: a real phenomenon (for example, the existence of a magnetic field on the surface of the Earth) is explained by proposing a model in the world of the Physics (the magnetic field is proposed as a vector, and its existence due to something denominated magnetic poles); this physical model is converted into letters and symbols, forming some equations, or mathematical model, that can reproduce, in mathematical language, the physical model, but not the real phenomenon. In general, some assumptions and simplifications have to be introduced in the physical model (for instance, in the geometry of the subsurface rocks), and in the world of equations (for instance, the conditions of the studied phenomenon and in the treatment of the equations). The mathematical model is used to make some modifications or conversions to the measured data, to deduce the theoretical measurements that should be taken giving a model of the subsurface (direct problem), and finally to compare the answer of theoretical models with the real measurements, for deducing the distribution of rock properties in the subsurface (inversion process). This scheme will work properly as much as the assumptions and simplifications can be assumed by the real physical and geological world. Geology is not always the best scenario to make too many assumptions and simplifications, mainly when a high degree of resolution is required. In consequence, it has to be understood that Geophysics is not an Exact Discipline; it has four key words: measurements, calculations, diagnosis, and interpretation. Data processing and inversion of Magnetic Resonance Sounding data will be explained in detail in Yaramanci and Hertrich (2007, this Issue), and Legchenko (2007, this Issue).

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 group of methods that provide an image of the distribution of a property on 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 meters to thousands of meters. Two families can be distinguished:
   b1) 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.).
   b2) 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), chargeability (Induced Polarization), etc. One of the main characteristics of this group is that the 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 presence of water in the rocks modifies several properties: density, velocity of mechanical waves, dielectric constant, etc., but the most significant one is electric resistivity. Its value may change several orders of magnitude depending on porosity, water content, and salinity of the water; for instance: the resistivity of clay is normally more than one hundred times lower than that of gravels, but the water content can give to gravels the same resistivity as clay. No value of a petrophysical property can be directly associated to just one lithology, nor can the water content be straight forward deduced from the value of the petrophysical parameter.

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); other to the hydrodynamic parameters (flux velocity and direction).

It would be very nice if it could be established a unique correspondence between each hydrogeological problem and the geophysical method to solve it. But, combining the possibilities of the geophysical methods with the number of parameters that are demanded by the Hydrogeology, and with the different geological and geographical scenes possible, it is easy to understand that no a 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.

Normally, more than one 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 its 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.

To decide about the applicability of one geophysical method it is very important 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 instance, the gravity anomalies produced by the target are of the same order of magnitude or smaller than the ones produces by insignificant changes of density in the overburden), or from the way in which the survey is carried out (for instance, 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 the equivalence and resolution limitations. The equivalence means that several different combinations of rocks geometry and physical properties can produce the same theoretical solution, and then fit the measured values; geological control and the use of more than one geophysical method are the main tools to discriminate between different equivalent geological models as a solution to the geophysical measurements. Resolution is a consequence of the relation between the amplitude of the anomaly or geophysical signal produced by a volume of rock and its distance to the observation point; as the signal is normally inversely proportional to some power of the distance, the volume of rock necessary to produce a measurable signal increases with increasing depth, and in the models for the inversion process it is not realistic to introduce the same size of rock bodies all over the depth range of the model. In other words, there is a limitation to the depth at which a certain volume of rock can be detected with surface geophysical methods.

The main field of application of the different methods in Hydrogeology and its quantitative distribution is shown in Figure 4. The parameters that are normally looked for can be group in three categories: 1/ the determination of geological structures (basin morphology, location of faults, etc.) not affected by the presence of water, in which all the methods can be used, depending its selection on the particular case. 2/ the determination of geometric parameters in structures affected by the presence of water (depth, thickness, extension of aquifers and aquitards), for which the geological situation makes some methods better suited than others; and 3/ the evaluation of hydraulic and hydrodynamic parameters of aquifers (porosity, permeability, velocity and direction of water flux, phreatic level, water quality, etc.), for which the use of surface geophysical methods is very limited, being necessary the use of boreholes and geophysical logging as the most appropriate technique. From the geophysical point of view, the geo-

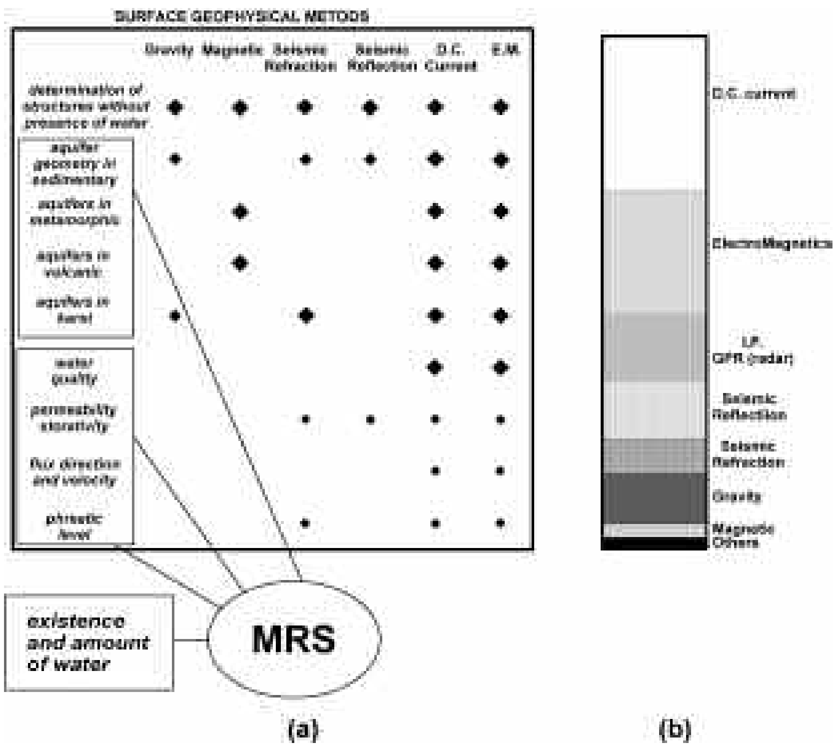

Fig. 4 a) Main field of applicability of the surface geophysical methods in Hydrogeology. The size of the diamond symbol indicates the relative importance of the method to the application. b) Statistical distribution of its utilization in real cases (Plata, 1999)

Fig. 4. a) Principal campo de aplicación en hidrogeología de los métodos geofísicos de superficie. El tamaño del símbolo indica la importancia relativa del método dentro de cada aplicación. b) Distribución estadística de la utilización en casos reales (Plata, 1999)

logical environment is often mandatory in the selection of the method to be used, as indicated in Figure 4.

All the geophysical methods can then be used in Hydrogeology. Plata (1999) shows that in nearly the 65% of the geophysical surveys in Hydrogeology (Figure 4b), electrical methods are used, being more frequent the methods of direct current (like Vertical Electrical Soundings), than the electromagnetic ones. Induced Polarization, Ground Radar and Mangnetotellurics, are used about in 10 % of the surveys. Seismic occupies the 20% of the applications, with some more frequent use of reflection than refraction. Potential fields (Gravity and Magnetic) have a shear of the 10% and the rest of the methods the remaining 5% (Spontaneous Potential, Thermometry, Enanometry, satellite images, electrokinetic, Magnetic Resonance Sounding (MRS)). This last group is especially important, because its use is normally due to the need to solve very specific problems. Every year it is more frequent the use of several methods simultaneously, what is not only to add information but to power it and to prevent for the interpretation errors.

The appraisal of the Magnetic Resonance Sounding method

Magnetic Resonance Sounding method is changing the scene. MRS deserves special attention because of its singularity and novelty: it is the only method able to detect directly the presence of water in the underground, and as research is going ahead, it reveals its capacity to evaluate hydraulic parameters, being nowadays a real alternative to the use of boreholes tests in some circumstances. The rest of the geophysical surface methods are valid to determine the geometric parameters of aquifers, and just in a few circumstances they allow the evaluation of hydraulic properties. MRS can be used nowadays normally for investigations down to 100 m of depth, reaching 150 m in favourable conditions, as will be described together with the basic concepts of MRS in Plata and Rubio (2007, this Issue).

The use of MRS for hydrogeological studies started in Russia about 1978 with the HYDROSCOPE instrument (details about MRS instrumentation can be found in Bernard (2007, this Issue)). The number of surveys undertaken with this instrument is high, mainly in the former Soviet Union countries, but in the Anglo-Saxon scientific literature only a dozen of these works, made after 1990, are reported (with surveys not only in Russia, but also in Australia, Israel, Guinea, Saudi Arabia, Spain and USA).

Since de availability of the NUMIS instrumentation (make by Iris instruments, France) in the year 1997 until 2006, the method has expanded all over the world. At least sixty surveys made with this tool, with more than one thousand MRS measurements, have been reported in the geophysical literature. Half of them have been carried out in Europe (France, Germany, Spain, The Netherlands, Austria, Portugal, United Kingdom and Denmark). More than ten surveys have been conducted in African countries (Morocco, Botswana, South Africa, Namibia, Niger, Burkina Faso and Mozambique), and about the same number in Asia (China, India, Israel, Saudi Arabia, Cambodia, Myanmar, Thailand and Cyprus), and only three in North America. The real number of the total experiments made may be not far from these figures, except in China, where probably there are quite a high number of unpublished works. References of most of these publications are given throughout this Tutorial.

More than forty scientific institutions are involved in these surveys, most of the times conducted by the BRGM (Bureau de Recherches Géologiques et Minières) and IRD (Institut de Recherche pour le Développement) of France, the TUB (Technical University of Berlin) and BGR (Bundesanstalt für Geowissenschaften und Rohstoffe) of Germany, the ITC (International Institute for Geo-Information Science and Earth Observation) from Holland, and the IGME (Instituto Geológico y Minero de España) from Spain.

The objectives of these field works have been mainly experimental, as corresponds to a new geophysical method. The interest has been put in the evaluation of the capabilities of MRS, to verify, improve and tune the method and instrumentation, to test the inversion process, and to develop the evaluation of hydraulic parameters from MRS data. Nevertheless, at least the thirty per cent of the surveys are involved with water exploration projects, and their results have been directly used in drilling programs or groundwater related studies.

All these experiments cover a wide range of geological environments: about the 40 % has been done over non consolidated sediments, 40 % on fractured carbonates and karsts (10 %), and 20 % on weathered or fractured hard rocks. Some of the most valuable experiments conducted in these geological conditions are presented in Vouillamoz et al. (2007, this Issue).

As a general rule, at all sites where MRS have been measured, boreholes with hydrogeological information were available, as well as other geophysical data (geoelectrical methods mainly) previously taken or made especially for the verification and complement of the MRS tests. The experience gained through these years has also been used to improve the instrumentation and the inversion software.

Geophysical and hydrogeological symbols used

In the published papers about MRS different symbols are often used for the same variable. Throughout this Tutorial the same names for the parameters and variables and the same corresponding symbols are going to be used. For the hydraulic variables and parameters the symbols are gathered in Table 4. For MRS Table 5 resumes the symbols proposed.

For the linking between hydrogeological and geophysical parameters, letter C will be used for the calibration coefficient, with the subscript T (C_T) for transmissivity, K (C_K) for hydraulic conductivity, e (C_e) for elastic storativity and y (C_y) for specific yield. For instance, the transmissivity value deduced from MRS data will be written:

$$T_{MRS}=C_T x \text{ (transmissivity MRS estimator)}$$

The MRS estimator is the corresponding combination of data deduced from the MRS measurements.

At the beginning of the Magnetic Resonance Sounding method in Western Europe, a great variety of initials or abbreviations were used: SNMR (Surface Nuclear Magnetic Resonance), PMR (Proton Magnetic Resonance), SPMR (Surface Proton Magnetic Resonance), SGW-NMR (Surface Ground Water Nuclear Magnetic Resonance), among others, with the purpose of making a distinction of the use of the NMR physical principle from the surface of the earth, from its use in geophysical well logging or laboratory determinations. In 1999, at Berlin Workshop, the name MRS was proposed and since then it has been generally accepted; this name resumes the use of the physical principle, avoiding the word "nuclear", not always welcomed and understood, and gives the idea of a depth-wise technology. Therefore, and to avoid the confusion produced by different initials, it is recommended to adopt the name MRS for this geophysical method when applied in 1D mode. The name MRT (Magnetic Resonance Tomography) is also proposed when applying this method in 2D.

symbol	Parameters and variables
n	Total porosity
n_e	Effective porosity
n_t	Trapped porosity
θ_m	Mobile water
θ_t	Trapped water
θ_b	Bound water
θ_f	Free water
θ_G	Gravitational water
θ_c	Capillary water
S_u	Unconfined storativity
S_c	Confined storativity
S_r	Specific retention (field capacity)
S_y	Specific yield (storativity, storage coefficient in unconfined aquifers)
S_s	Specific storage (specific coefficient)
S_e	Elastic storativity (storativity, storage coefficient in confined aquifers)
S_d	Specific drainage
K	Hydraulic conductivity
k	Permeability
T	Transmissivity
z	Depth
Δz	Thickness

Table 4. Symbols for the hydrogeological parameters and variables used in this Tutorial. Subscript $_{MRS}$ will be used for values obtained by MRS, and subscript $_{pt}$ for values from pumping tests
Tabla 4. Símbolos utilizados para los parámetros y variables hidrogeológicas empleadas en este Tutorial. Se utilizará el subíndice $_{MRS}$ para los valores deducidos de SRM, y el subíndice $_{pt}$ para los deducidos de ensayos de bombeo

symbol	variable
f_L	Larmor frequency
ω_L	Larmor angular frequency
f	Pulse frequency
ω	Pulse angular frequency
γ	Giromagnetic ratio of protons
r	Modulus of the coordinates vector
$M_0(r)$	Macroscopic magnetic moments of hydrogen protons
B_0	Amplitude of geomagnetic field
Tx	Transmitter coil or loop (antenna)
Rx	Receiver coil or loop (antenna)
$i(t)$	Current in the transmitter coil
I_0	Maximum excitation current intensity or current-amplitude
τ	Duration of the excitation pulse
q	Excitation moment or amplitude of the excitation pulse
$e(t)$	f.e.m. in receiver coil (water signal)
E_0	Maximum initial value of e(t)
B_T	Primary generated field at the transmitter coil
B_R	Secondary field at the receiver
$B_{T\perp}$ $B_{R\perp}$	Primary or secondary magnetic field orthogonal to B_0
$\theta(r)$	Tilt angle of M_0 in respect to B_0 produced by $B_{T\perp}$
T_2	Time decay constant of e(t) [either T_1 or T_2]
T_1, T_2	Theoretical longitudinal and transversal time decay constants
T_1^* T_2^*	Measured time decay constants
φ	Phase shift
$w(r)$	Water content distribution in the model
θ_{MRS}	Water content from MRS data inversion

Table 5. Symbols for the MRS variables used in this Tutorial
Tabla 5. Símbolos utilizados para las variables de SRM empleadas en este Tutorial

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