SHORT NOTE ON
THE PRINCIPLES OF GEOPHYSICAL METHODS
FOR GROUNDWATER INVESTIGATIONS

DEFINITION OF MAIN HYDROGEOLOGICAL PARAMETERS

ELECTRICAL METHODS FOR GROUNDWATER

MAGNETIC RESONANCE METHOD FOR GROUNDWATER

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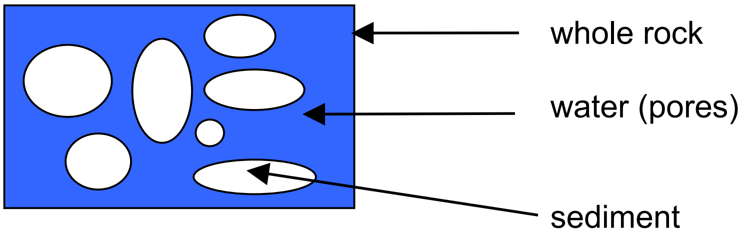
J. BERNARD, June 2003

DEFINITION OF POROSITY AND PERMEABILITY

POROSITY:

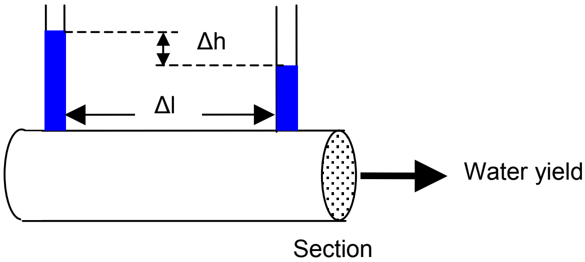
$$\text{Porosity} = \frac{\text{volume of pores}}{\text{volume of rock}}$$



PERMEABILITY:

$$\text{Permeability} = \frac{\text{water yield}}{\text{sample section}} \,/\, \text{hydraulic gradient}$$

with hydraulic gradient = Δh / Δl



POROSITY AND PERMEABILITY OF ROCKS

DEFINITIONS

- **POROSITY**: (unit: %) — *quantity of water*, existing in rocks = volume of water / volume of rocks
- **PERMEABILITY**: (unit : m/s) — *speed of the water*, when pushed by pressure = yield per unit of hydraulic pressure gradient

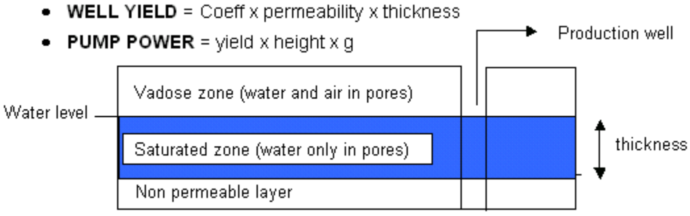
NUMERIC VALUES FOR VARIOUS TYPES OF ROCKS

TYPE OF ROCKS		POROSITY (%)	PERMEABILITY (m/s)
UNCONSOLIDATED (Soft sediments)	gravel	30	10^{-2}
	sand	25	10^{-4}
	clay	50	10^{-12}
CONSOLIDATED sandstone limestone granite, basalt	massive	1	10^{-10}
	fissured / fractured	5	10^{-8}
	weathered	15	10^{-6}

NB: These values are only indicative and largely depend on local conditions

GROUNDWATER PUMPING

- **WELL YIELD** = Coeff x permeability x thickness
- **PUMP POWER** = yield x height x g



CONDUCTIVITY AND SALINITY OF WATERS

- **CONDUCTIVITY** (Siemens) = 1 / resistivity (ohm.m)
- **USUAL UNIT** of conductivity = microS / cm

Conductivity (microS / cm) = 10^4 / resistivity (ohm.m)

- **SALINITY** (mineralization): Total Dissolved Salt (TDS)

TDS (mg / l) = 0.7 x conductivity (microS / cm)

- **NUMERIC VALUES FOR VARIOUS TYPES OF WATER:**

Type of water	*Resistivity ohm.m*	*Conductivity microS / cm*	*Salinity mg / l*
very fresh	200	50	35
fresh	20	500	350
salted	10	1 000	700
very salted (sea water)	0.3	30 000	21 000

Usual rule for drinkable water: resistivity > 10 ohm.m ⟺ conductivity < 0.7 g/l

DEFINITION OF MAIN HYDROGEOLOGICAL PARAMETERS

Groundwater is characterized by a certain number of parameters which geophysical methods are trying to determine from surface measurements, mostly indirectly, but sometimes directly. The most usual parameters are the porosity, the permeability, the transmissivity and the conductivity.

THE POROSITY

The porosity is the ratio between the volumes of the pores and that of the rock. When dealing with saturated layers (under the water level, that is to say under the vadose zone where the pores are filled with air and with water), the water content is equal to the porosity.

Porosity = (volume of pores) / (volume of the rock)

Being a ratio, the porosity is expressed in %. The total porosity also includes the water located in clay, even if clay is impermeable. For the exploitation of water, it is important to determine the porosity of free water (water which can move), and hydrogeologists speak of the **effective porosity** which is the ratio of the volume of the pores which are interconnected to the volume of the rock. As an order of magnitude, the effective porosity can be for instance 80% of the free water porosity. The porosity of a fissured rock can be a few percents, that of a gravel or a sand of the order of 30 percents.

THE PERMEABILITY

The permeability (which, as defined in the usual hydrogeological language, is actually the hydraulic conductivity) is the ability of a material to let a water current flow through it when an hydraulic pressure is applied, can be defined on a sample of rock by the Darcy law:

Permeability = (Yield / Section) / Pressure gradient

The yield being expressed in m^3/s, the sample section in m^2, and the pressure gradient (difference of water pressure / sample length) in m/m, the unit of permeability is m/s.

If the porosity is almost zero the permeability is necessarily also very weak. But the porosity can be high, such as in the case of a clay layer, and the permeability very weak. The porosity and the permeability are not two parameters independent from each other: the permeability already includes the information of the porosity for determining the volume of water which can be extracted from the ground. **The permeability is linked not only to the volume of the available water, but also to the size of the pores:** for a given value of the porosity, large size pores lead to a higher permeability than small size pores, as the water flows more easily in the first case than in the second one.

The permeability of a clay layer can be as low as 10^{-10}m/s, of a weakly permeable layer 10^{-6}m/s, of a highly permeable layer 10^{-2}m/s

THE TRANSMISSIVITY AND THE PRODUCTION YIELD

The transmissivity of an aquifer layer is the product of the permeability by its thickness:

Transmissivity = Permeability x Thickness

The transmissivity is expressed in m^2/s. The interest of this parameter is that it is proportional to the production yield obtained by pumping:

Production yield = param. x Transmissivity x Drawdown

The drawdown is the difference of level of the water in the pumping well and far away from it. The ratio yield / drawdown is called the specific capacity of the well. In the field, the transmissivity of a formation is usually determined by hydrogeologists by a pumping test.

THE ELECTRICAL CONDUCTIVITY

The electrical conductivity of the water is usually expressed in microSiemens / cm:

Conductivity (microS/cm) = 10^4 / Resistivity (ohm.m)

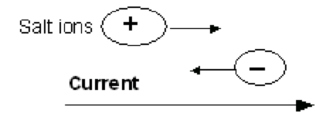
The electrical conductivity is the ability of a material to let an electric current flow through it when an electical voltage is applied . It is linked to the quantity of salts dissolved in the water:

Conductivity (microS/cm) = 1.4 x Total Dissolved Salts (mg/l)

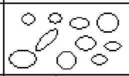
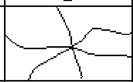
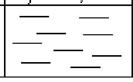
A usual rule for drinkable water is 10 ohm.m, or 1000 microS/cm, or 0.7 g/l

ELECTRICAL PROPERTIES OF ROCKS

➡ **THE ELECTRIC CURRENT** FLOWS INTO THE GROUND THANKS TO THE IONS OF SALTS DISSOLVED IN THE WATER



+ ions: Na, Ca, K, ...
- ions: Cl, SO_4, NO_3, ...

TYPE OF POROSITY	TYPE OF WATER	TYPE OF ROCK	
matrix	free		sand, gravel
fracture	free		limestone, sandstone
adherence	bound		clay

➡ **THE RESISTIVITY OF ROCKS DEPENDS ON:**

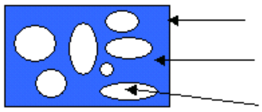
- THE WATER CONTENT (Porosity)
- THE RESISTIVITY OF THE WATER
- THE CLAY CONTENT
- THE CONTENT IN METALLIC MINERALS

➡ **VALUES OF RESISTIVITY OF ROCKS:**

0.1	ohm.m	SALTED WATER
1	ohm.m	MASSIVE SULPHIDE
10	ohm.m	CLAY
100	ohm.m	SAND, MARL
1 000	ohm.m	DRY SAND, LIMESTONE
10 000	ohm.m	HARD GRANITE, BASALT

RESISTIVITY AND POROSITY OF ROCKS

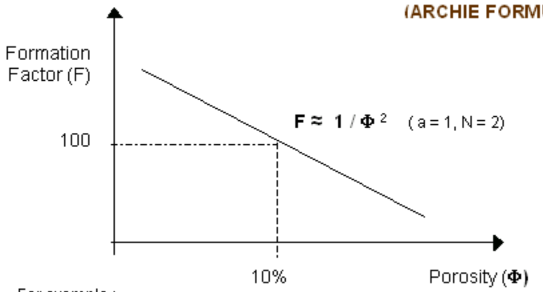
Relation between the resistivity of and the porosity for non clayey rocks



ROCK RESISTIVITY = F x WATER RESISTIVITY

F = Formation Factor = a / (porosity)^{N}

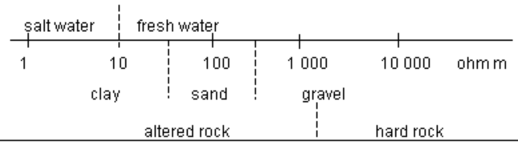
(ARCHIE FORMULA)



For example :

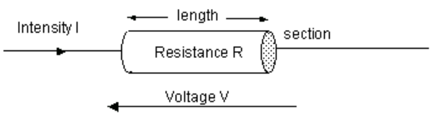
Water resistivity	= 10 ohm.m	Rock resistivity = 250 ohm.m
Porosity	= 20%	
Formation factor	= 25	

RESISTIVITY SCALE FOR WATERS AND ROCKS



MEASUREMENT OF RESISTIVITY

➡ **MEASUREMENT OF RESISTIVITY OF A LINEAR CONDUCTOR**



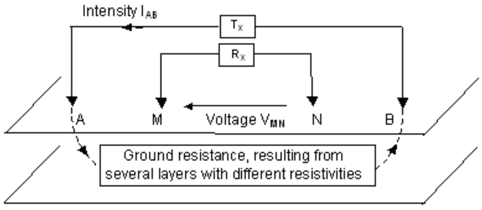
RESISTANCE (ohm) = Voltage (V) / Intensity (A) (OHM law: V = R x I)

RESISTANCE (ohm) = Resistivity (ohm.m) x length (m) / section (m²)

RESITIVITY = (section / length) x voltage / intensity

Rho = K x V / I

➡ **MEASUREMENT OF RESISTIVITY OF A 3-DIMENSION CONDUCTOR**



APPARENT RESISTIVITY = (coefficient) x voltage / intensity

Rho = K x V_{MN} / I_{AB}

K = 2 x Pi / (1/AM – 1/AN – 1/BM + 1/BN)

Units: Rho (*ohm.m*), K (*m*), V_{MN} (*mV*), I_{AB} (*mA*)

HOW TO DETECT AN AQUIFER FROM THE VALUE OF THE RESISTIVITY ?

FROM THE ABSOLUTE VALUE OF THE RESISTIVITY

Resistivity (rock) ≈ Resistivity (water) / porosity²

Fresh water resistivity	*Porosity*	*Aquifer resistivity*
10 to 200 ohm.m	1 to 30%	50 to 2000 ohm.m

FROM THE RELATIVE VALUE OF THE RESISTIVITY

Geological background	*Aquifer resistivity*
Hard rock (resistant)	Lower than background
Clayey or salty (conductive)	Higher than background

ELECTRICAL METHODS FOR GROUNDWATER

BASIC PRINCIPLE

Groundwater, through the various dissolved salts it contains, is ionically conductive and enables electric currents to flow into the ground. Consequently, measuring the **ground resistivity** gives the possibility to identify the presence of water, taking in consideration the following properties:

- **a hard rock** without pores or fracture and a **dry sand** without water or clay are very resistive: several tens thousands ohm.m
- **a porous or fractured rock** bearing free water has a resistivity which depends on the resistivity of the water and on the porosity of the rock (see below): several tens to several thousands ohm.m
- **an impermeable clay layer**, which has bound water, has a low resistivity: several units to several tens ohm.m
- **mineral orebodies** (iron, sulphides, …) have very low resistivities due to their electronic conduction: usually lower or much lower than 1 ohm.m

ARCHIE LAW

The resistivity of a porous non-clayey material can be estimated by the following Archie law formula: **rock resistivity = a x (water resistivity) / (porosity)^n**, where “a” and “n” are constants which depend on the nature of the rock. In a very rough approximation, “a” can be taken equal to 1 and “n” to 2. For example, a 10 ohm.m water and a 20% porosity give a rock resistivity of the order of 250 ohm.m.

This formula means that a low value of a non-clayey rock resistivity means either a high porosity or a low water resistivity, hence an uncertainty in the interpretation of resistivity anomalies. As mentioned previously, clay formations also give low resistivity values.

VERTICAL AND LATERAL INVESTIGATIONS

For measuring the ground resistivity, **a current** has to be transmitted with two electrodes, while **the potential** created on the surface by the circulation of this current into the ground is measured with two other electrodes. Increasing progressively the distance between the transmitting and the receiving electrodes permits to increase the depth of investigation (**sounding array** for aquifer depth and thickness determination); translating the four electrodes together permits to detect lateral change of resistivity (**profiling array**, for fault or fracture localization).

GROUNDWATER DETECTION

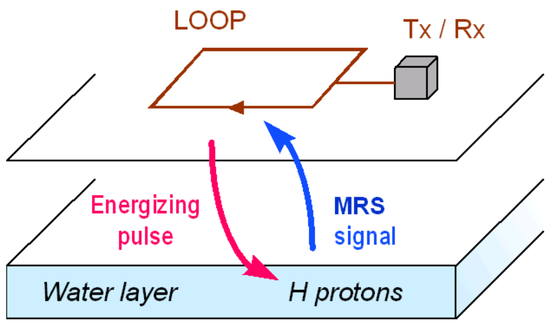
To identify the presence of groundwater from **resistivity measurements**, one can look to the **absolute value** of the ground resistivity, through the Archie law: for a practical range of fresh water resistivity of 10 to 100 ohm.m, a usual target for aquifer resistivity can be between 50 and 2000 ohm.m.

Most of the time it is the **relative value** of the ground resistivity which is considered for detecting groundwater: in a hard rock (resistant) environment, a **low resistivity** anomaly will be the target, while in a clayey or salty (conductive) environment, it is a **high resistivity** anomaly which will most probably correspond to (fresh) water.

In sedimentary layers, the product of the aquifer resistivity by its thickness can be considered as representative of the interest of the aquifer. However, electrical methods cannot give an estimation of the permeability but only of the porosity.

The contrast of resistivity between **a fresh water** and **a salted water** (coming from a sea intrusion for instance) is high and the depth of the water wedge is usually well determined with electrical methods

MRS METHOD : FIELD SET UP

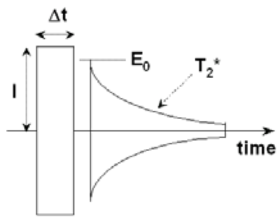


MRS METHOD : MEANING OF PARAMETERS

E_0 : Initial amplitude (nV)
Proportional to the **water content** (%)

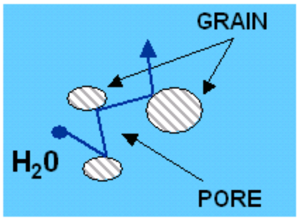
T_2^* : Decay time constant (ms)
Related to the **mean pore size**

I.Δt : Pulse moment (A.ms)
Related to the **investigation depth**



RELATION BETWEEN THE TIME CONSTANT AND THE PERMEABILITY

small pores : low permeability → many shocks of H_2O against grains → quick decrease of energy → short time constant

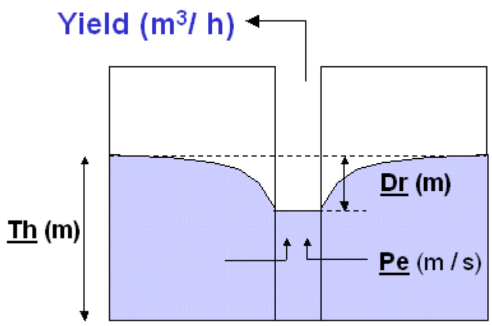


EXPRESSION OF THE YIELD IN HYDROGEOLOGY

in Hydrogeology :

Yield = factor x Transmissivity x Drawdown
(m^3 / s) (1) (m^2 / s) (m)

Transmissivity = Permeability x Thickness
(m^2 / s) (m / s) (m)



in Magnetic Resonance Sounding :

Permeability = coeff. x Porosity x $(T1)^2$

Transmissivity = coeff. x Porosity x Thickness x $(T1)^2$

= coeff. x (Equivalent Water Thickness) x $(T1)^2$

PERMEABILITY scale
10^{-9} m/s: clay
10^{-6} m/s: low
10^{-3} m/s: high
10^{0} m/s: extreme

MAGNETIC RESONANCE METHOD FOR GROUNDWATER

BASIC PRINCIPLE

The Magnetic Resonance Method permits a **direct detection of water** from surface measurements: it consists in exciting the H protons of the water molecules with a magnetic field produced by a loop of current at a specific frequency. The amplitude of the magnetic field produced in return by these protons in the same loop is proportional to the **water content**, while the time constant of the decay is linked to the **mean pore size** of the formation, thus to the permeability.

The clay layers which have bound water produce responses with very short time constants, filtered by the equipment. The only response measured is coming from free water.

DETERMINATION OF THE POROSITY

The measurement of the initial amplitude of the response of the protons determines **the porosity** of the formation at a depth which is function of the intensity of the current which is transmitted into the loop. For a given wire loop position, **the sounding** consists in repeating the measurements for various values of the intensity of the current which correspond to various depths of investigation.

As in other electrical methods, **there are cases of equivalence** which give the same response for a thick layer (10m) with little water (5%) and for a thinner layer (5m) with more water (10%). However, the product of the water content by the layer thickness is constant (10mx5% = 5mx10% = 0.5m), which mean that the **total quantity of water** available is well determined (0.5m).

ESTIMATION OF THE PERMEABILITY AND TRANSMISSIVITY

After the excitation field is turned off, the protons loose their magnetic energy progressively, at a rhythm which depends on their mean free displacements. This is the reason why when the pores have a small size, the time constant of the decay is short, while when the pores have large dimensions this time is longer. The time constant of the decay is thus linked to the permeability of the rocks. The complete empirical formula for the permeability from Magnetic Resonance data is:

$$\textbf{Estimated permeability = coeff. x porosity x (Time constant)}^2$$

In the same way, the transmissivity can be estimated by:

$$\textbf{Estimated transmissivity = coeff. x porosity x thickness x (Time constant)}^2$$

The product of the porosity by the thickness represents the total quantity of water available, which, as seen previously, is well determined. The proportionality coefficient can be determined after a calibration with results of pumping tests in the area.

CONDITIONS OF APPLICATION OF THE METHOD

The Magnetic Resonance method can hardly be used in **magnetic rocks** such as volcanics, because the amplitude of the Earth magnetic field which determines the frequency of excitation of the water molecules has to be stable in the area of investigation.

Besides, the method is very sensitive to natural and cultural **electromagnetic noises** such as power lines, pipes, fences, etc.

Finally, in the present stage of the technology, the **maximum depth** of investigation which can be reached with this method to detect an aquifer layer is 150m.

Being a property of H protons, the Magnetic Resonance method do not see the difference between **fresh and salted** water.

The main advantage of the Magnetic Resonance method is that it permits **to directly detect** the presence of water at depth. In particular, this method can find water when resistivity method do not make the difference between a formation with and without water due to the low contrast of resistivity of both cases. It is also the only geophysical method capable of **estimating the permeability** and of predicting a yield, after calibration.


SYSCAL Junior resistivity meter

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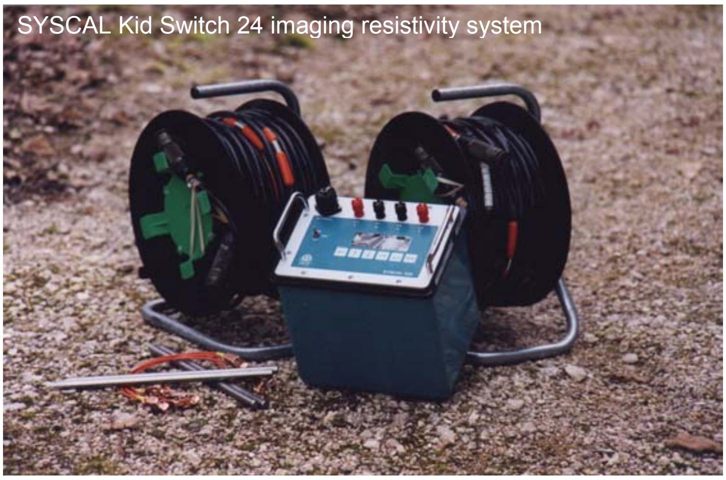
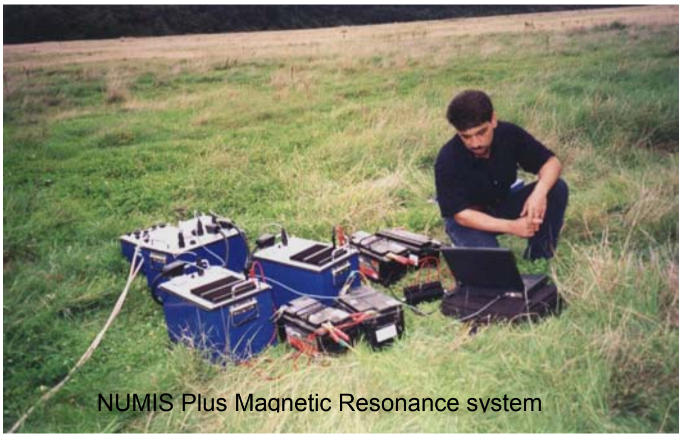
GEOPHYSICAL INSTRUMENTS FOR GROUNDWATER INVESTIGATIONS


SYSCAL Pro Switch 48 imaging resistivity system


SYSCAL Kid Switch 24 imaging resistivity system


VIP 4000 and ELREC 6 electrical system


NUMIS Plus Magnetic Resonance system


NUMIS Plus Magnetic Resonance system