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SNMR Imaging for Groundwater

1.1. Brief history of SNMR development

Surface Nuclear Magnetic Resonance (SNMR) imaging is a non-invasive geophysical technique developed for groundwater investigation. This method was initially used for investigating a homogeneous subsurface. In a one-dimensional (1-D) implementation, the subsurface is assumed to be horizontally stratified and the method is known as the Magnetic Resonance Sounding (MRS) method or Surface Nuclear Magnetic Resonance (SNMR). In France, the name RMP (*sondage par la Résonance Magnétique Protonique*) is used.

The MRS method was developed in Russia in the early 1980s by a team of Russian scientists under the guidance of A.G. Semenov. Their research program started from the Varian patent [VAR 62] where using the Nuclear Magnetic Resonance phenomenon (NMR) was proposed for non-invasive detection of proton-containing liquids (hydrocarbons or water) in the subsurface. The very first MRS instrument, named HYDROSCOPE, was built in 1981 [SEM 89]. The method was used in Russia and has been tested in other countries: [SCH 91], [GOL 94], [LIE 94], [LEG 95] and [GEV 96]. In 1996, IRIS Instruments (France), in cooperation with the Bureau de Recherches Géologiques et Minières (BRGM (The French Geological Survey), France) and the Institute of Chemical Kinetics and Combustion (ICKC, Russia), released the first commercial MRS instrument (NUMIS), thus rendering MRS commercially available and easily accessible for the international scientific community. Since then, MRS has been intensively tested by different teams and in different countries. A two-dimensional (2-D) implementation named the Surface Magnetic Resonance Tomography or 2D-SNMR was developed around 2005 [HER 07], which was further extended to the three-dimensional (3-D) applications named 3D-SNMR [LEG 11]. MRS equipment was also improved and MRS instruments of the new generation were developed in France, USA, Germany and China.

Today, SNMR imaging for groundwater is an emerging geophysical method which is routinely used for groundwater investigations but it is still a subject of research and development for an international community composed of geophysicists and hydrogeologists.

1.2. The basic principles

The phenomenon of nuclear magnetic resonance (NMR) consists of selective absorption and transmission by atomic nuclei of electromagnetic energy of a specific frequency, particular to different nuclei. This phenomenon was discovered in 1946. The Nobel Prize in Physics, 1952, was jointly awarded to Felix Bloch and Edward Mills Purcell for their development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith: [BLO 46] and [PUR 46]. The NMR phenomenon can be observed in nuclei possessing both magnetic moments and angular momentum. The SNMR method is based on the observation of the NMR phenomenon in hydrogen or protons (H^1) contained in water and oil [ABR 61]. In the first 200 m of the subsurface, the probability of finding oil reservoirs is negligibly small and hence SNMR is principally targeted at groundwater. The resonance behavior of proton magnetic moments in the geomagnetic field ensures that the method is selective and sensitive only to groundwater. Thus, a non-invasive detection of subsurface water is the competitive advantage of SNMR compared with other geophysical tools used for hydrogeological investigation. SNMR is a large-scale method, and the investigated volume can be approximated by a cube of $1.5 \times a$, where $10 \le a \le 150$ m is the side of a square loop.

In the classical model, nuclei are represented as macroscopic magnetic moments $\mathbf{M}$. A typical scheme of magnetic resonance measurement consists of three phases (Figure 1.1). In the natural, non-perturbed state (equilibrium position), all magnetic moments $\mathbf{M}$ are oriented along the static magnetic field $\mathbf{B}_0$ and do not produce any measurable signal. Nuclei are able to absorb electromagnetic energy at the Larmor frequency $f_0 = \gamma B_0 / 2\pi$. The gyromagnetic ratio γ has a specific value for each type of nucleus, and hence the Larmor frequency is a physical property of the nuclei. Thus, when an external electromagnetic field is applied to a sample, the nuclei absorb the energy and magnetic moments precess from their equilibrium. After the external field is cut off, they return to their initial position and generate a magnetic field, which is also oscillating at the Larmor frequency. This field can be measured, and then analyzed. For data acquisition, a pulse of current, oscillating at the Larmor frequency is generated in the transmitting coil. The magnetic resonance response is recorded at the same frequency after the pulse is terminated. A typical scheme of the data acquisition is presented in Figure 1.1.

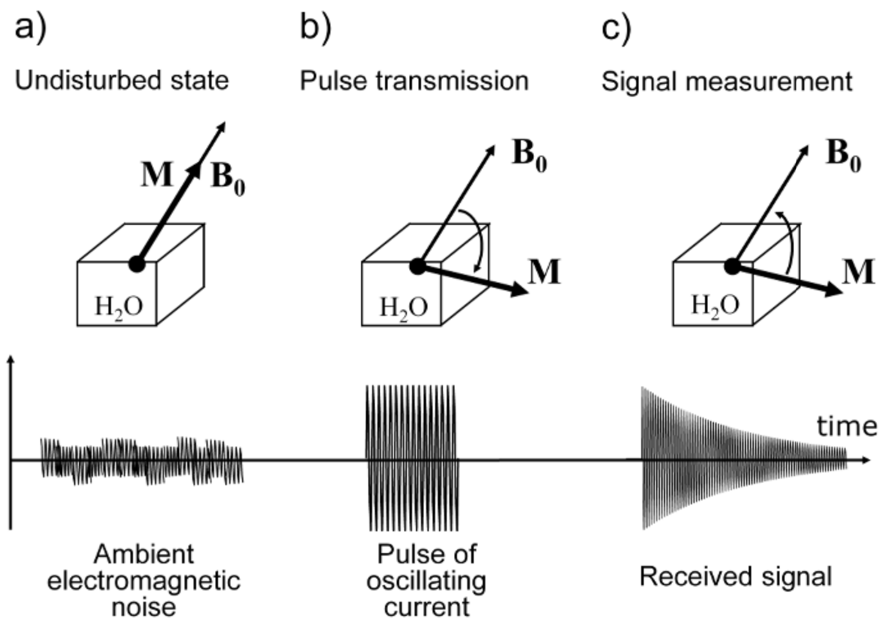

Figure 1.1. *Typical phases of a magnetic resonance experiment (top) and corresponding magnetic resonance measurements (bottom)*

Electromagnetic noise is recorded during a few hundreds of milliseconds before the outgoing pulse. After an instrument delay, called the "dead time", the magnetic resonance signal is then measured. Comparison of records before and after the pulse determines whether a magnetic resonance response is detected or not. As noise is independent of the transmitted pulse, a stacking procedure is used to improve the signal-to-noise ratio. The amplitude, the relaxation times and the phase of the magnetic resonance signal are measured.

A similarity between the well-known proton magnetometer and the SNMR is shown in Figure 1.2. The magnetometer is used for measuring the magnitude of the Earth's magnetic field using the linear relationship between the Larmor frequency and the magnetic field: $f_0=\gamma B_0/2\pi$. A container with kerosene or some other hydrogen-rich liquid (or just water) is put inside the acquisition coil of the magnetometer, and we are looking only for the frequency of the magnetic resonance signal. For performing SNMR measurements, the coil is enlarged and becomes a wire loop that is spread out on the surface and groundwater acts as a hydrogen-containing liquid. The Larmor frequency may be known from the magnitude of the Earth's magnetic field when measured with a magnetometer. Thus, when tuning the SNMR system at the Larmor frequency we are looking for the magnetic resonance response that allows us to either detect groundwater, or may confirm the absence of water in the investigated volume of the subsurface.

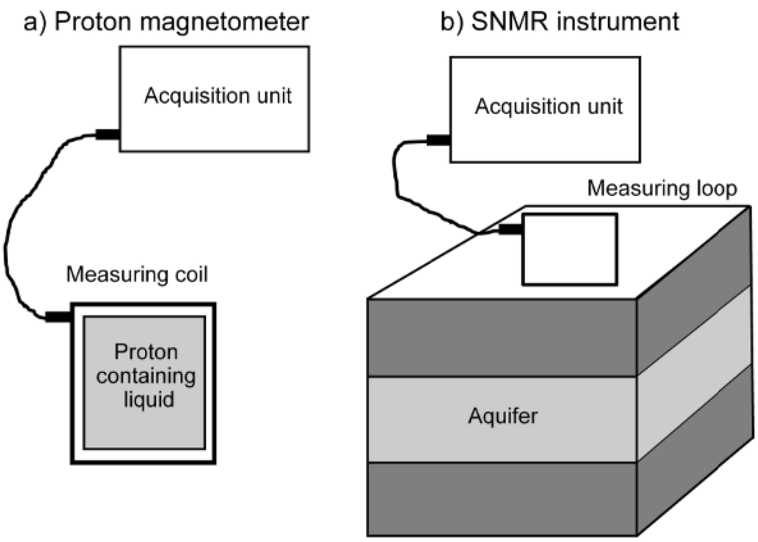

Figure 1.2. *Similarity between SNMR tool and proton magnetometer*

Since only protons of groundwater can generate the magnetic resonance signal at this frequency, SNMR is really a direct method for groundwater detection from the surface.

It will be shown later that the amplitude of the magnetic resonance response is proportional to the volume of the investigated sample and to the square of the static magnetic field $E_0 \sim B_0^2 V$. Thus, to increase the signal-to-noise ratio, the static magnetic field and/or the volume of the sample should be increased. Consequently, NMR instruments can be classified according to the volume of the investigated sample (Figure 1.3).

Investigated volume		
$V \sim mm^3$	$V \sim cm^3$	$V \sim m^3$
Artificial static magnetic field	Artificial static magnetic field	Geomagnetic field
Lab. NMR	NMR logging	SNMR

Figure 1.3. *Classification of NMR applications by investigated volume*

In the majority of applications, the static magnetic field is artificially created in a relatively small volume. Chemical NMR spectrometers and Magnetic Resonance Imaging (MRI) instruments used in medicine, which offer a very high spatial resolution and are commonly used in laboratories, operate in a broad artificial static magnetic field and a small sample volume (a few mm^3). Much larger sample volumes (a few cm^3) and smaller artificial static magnetic fields are used in borehole geophysics, whereas only a limited number of applications use the Earth's magnetic field [PAC 54; CAL 82; STE 90; CAL 98; TAI 02; APP 06; MIC 10]. SNMR equipment operates in the geomagnetic field and uses sample volumes of a few thousand m^3.

1.3. Magnetic Resonance Sounding

For demonstrating SNMR experiments let us use the classical model [ABR 61].

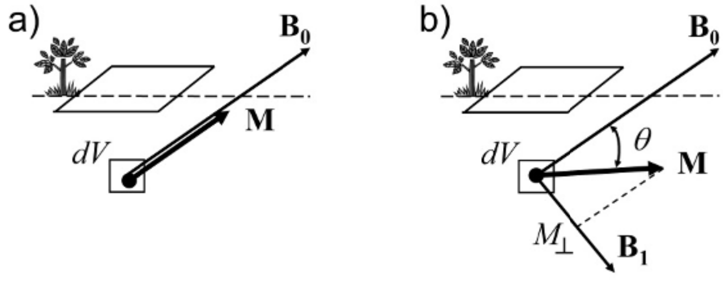

Figure 1.4. *Macroscopic magnetic moment* **M** *of the volume dV below SNMR loop: a) equilibrium position along with the static magnetic field* $\mathbf{B_0}$*; b) position after the excitation pulse* $\mathbf{B_1}$ *and the projection of* **M** *on the plan transversal to* $\mathbf{B_0}$

The macroscopic magnetic moment $\mathbf{M}$ of the volume *dV* which is located below a surface loop is oriented along the static magnetic field $\mathbf{B}_0$ as shown in Figure 1.4. The Earth's magnetic field acts as the static field $\mathbf{B}_0$. A pulse of alternating current generated in the loop produces an electromagnetic field within the volume *dV*. The frequency of the current is set as equal to the resonance frequency for protons in the geomagnetic field (Larmor frequency). The component of the loop's magnetic field $\mathbf{B}_1$ transversal to the Earth's magnetic field $\mathbf{B}_0$ makes rotating the magnetic moment $\mathbf{M}$ in the plane perpendicular to the plane ($\mathbf{B}_0$,$\mathbf{B}_1$) at the angle $\theta = \gamma B_1 \tau$ (flip angle), where τ is the pulse duration and γ is the gyromagnetic ratio. Magnetic resonance signal induced in the loop is proportional to the projection of $\mathbf{M}$ on $\mathbf{B}_1$: $E_0 \sim M_\perp$. As $M_\perp = M\sin(\theta)$, the signal also depends on θ and hence $E_0 \sim \sin(\theta)$. For the same loop the flip angle θ depends on two parameters: current in the loop I_0 and distance between the loop and the sample *dV*. I_0 is known and hence, by measuring θ, we obtain information on the depth of water saturated formations. A magnetic resonance signal is generated by water molecules and simple observation of the NMR response using an SNMR field setup is sufficient for reliably detecting groundwater. The maximum sensitivity of the method with regard to groundwater will be achieved when the flip angle $\theta = 90°$ (Figure 1.4).

However, SNMR can also be used in a sounding mode. In this case depth to water saturated formations can be derived from SNMR measurements. Implementation of a Magnetic Resonance Sounding (MRS) is schematically presented in Figure 1.5. Two distinct cases are presented: a shallow aquifer and a deep one. If the pulse duration is fixed, then for the same current in the loops the flip angle θ of the macroscopic magnetic moment **M** will be larger for a shallow water saturation formation than for a deeper one. One sounding consists of measuring the amplitude of the SNMR signal E_0 for different values of the current I_0 in the loop. The amplitude is then plotted versus the current, as shown in Figure 1.5. The shape of the sounding curve $E_0(I_0)$ allows us to resolve the depth to the aquifer.

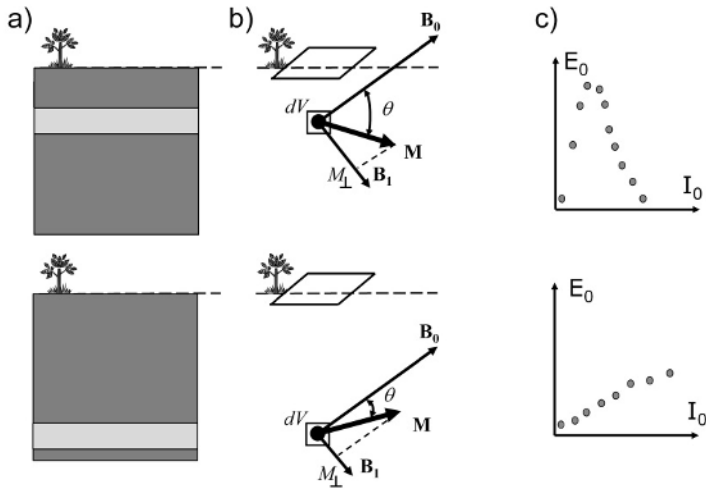

Figure 1.5. *Schematic presentation of SNMR sounding (MRS): a) aquifer location (top – shallow aquifer, bottom – deep aquifer); b) position of the macroscopic magnetic moment* **M** *after the excitation pulse with the current I_0 considering shallow (top) and deep (bottom) aquifers; c) amplitude of SNMR signal versus current in the loop for shallow (top) and deep (bottom) aquifers*

For performing SNMR sounding, a wire loop is laid out on the ground, normally in a circle or a square with a size of between 10 and 200 m (diameter or side respectively). The depth of investigation is proportional to the loop size (Figure 1.6).

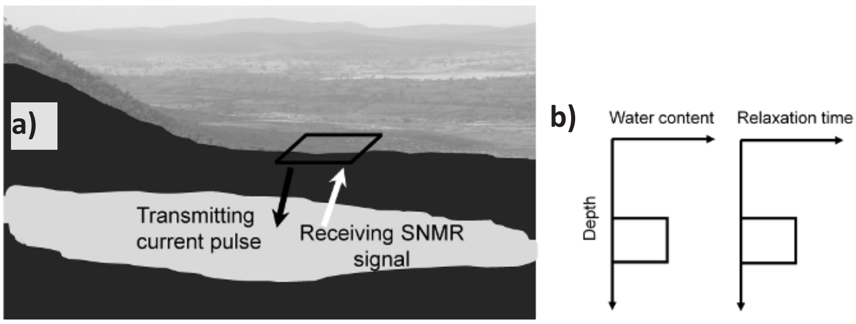

Figure 1.6. *SNMR system: a) field setup; b) measuring scheme; c) results*

The loop is then energized by a pulse of alternating current $i(t) = I_0 \cos(\omega_0 t)$. The frequency of the current is equal to the Larmor frequency of the protons in the geomagnetic field. The Larmor frequency is obtained from measurements of the geomagnetic field (B_0) on the surface using a proton magnetometer. Depending on the global geographical location of the investigated area, the geomagnetic field varies between approximately 20,000 and 60,000 nT, and the Larmor frequency correspondingly varies between 800 and 2,800 Hz. The pulse causes precession of spin magnetization of the protons in groundwater around the geomagnetic field, which creates an alternating magnetic field that can be measured after the pulse is terminated (the free induction decay method). SNMR can be used in the coincident transmitting/receiving (Tx/Rx) loop mode when the same loop is used as a transmitter and receiver or in a separated Tx and Rx mode when one loop is a transmitter and another a receiver. Oscillating with the Larmor frequency, the MRS signal has an exponential envelope and depends on the pulse moment $q = I_0\tau$ with I_0 and τ being respectively the amplitude and duration of the pulse. Measurements of the magnetic resonance signal are performed, varying the pulse moment and then inversion of the data reveals the distribution of the water content and of the relaxation time in the subsurface. The depth interval in the sounding log with increased values of the water content and relaxation time correspond to an aquifer.

1.4. Measuring setup

SNMR field setup is composed of one or more surface loops. One loop is the transmitting loop (Tx) and one or more loops are the receiving loops. The coincident loop configuration allows us to use the same loop for both transmitting and receiving (Tx/Rx loop). The commonly used loops are shown in Figure 1.7.

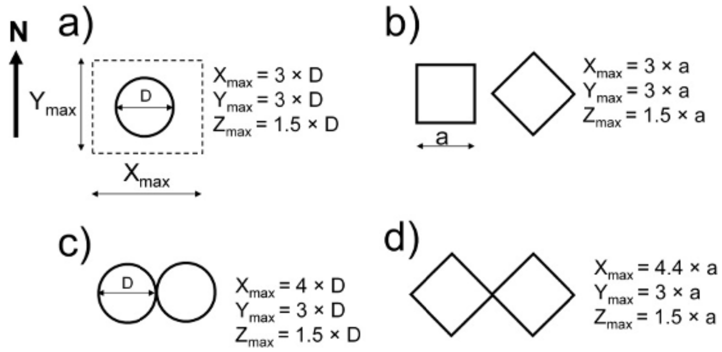

Figure 1.7. *SNMR field setup: a) circular loop; b) square loop; c) figure-eight circular loop; d) figure-eight square loop*

The loop sizes may vary between a=20 m and a=150 m. Loops larger than 80 m usually have one turn and small loops may have 2 to 5 turns of wire. Each transmitting loop is made of electrical cable with a cross-section of more than 6 mm^2. Such a thick wire allows generating large current pulses (up to 600 A). Special attention should be paid to the electrical insulation of the wire because of a high-pulse voltage (up to 4 kV). The volume affected by each Tx loop depends on the loop size and shape. Approximate volume affected by different loops is shown in Figure 1.7.

For a wire of fixed length, circular and square loops allow getting the maximum amplitude of SNMR signal and the maximum depth of investigation. Often, the figure-eight loop can be used for improving the signal-to-noise ratio (S/N). The figure-eight-shaped loop consists of two equal squares or circles connected as shown in Figure 1.8.

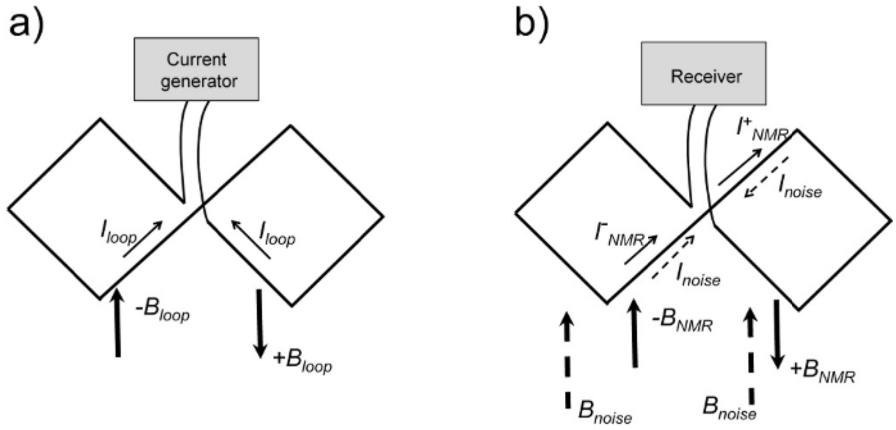

Figure 1.8. *Principle of the noise cancellation with the figure-eight loop: a) transmitting current pulse; b) receiving SNMR signal and noise*

Indeed, the magnetic fields generated by the squares of the figure-eight loop (B_{loop}) are oriented in the opposite directions (Figure 1.8a). Consequently, SNMR signals induced in each square (I^-_{NMR} and I^+_{NMR}) also have inverse polarity (Figure 1.8b). Note that noise induced in each square has the same polarity. The squares of the loop are connected so that the currents induced in each square are subtracted and the signal is doubled, but the noise is canceled. Using the figure-eight loop one may get up to a tenfold improvement in S/N [TRU 95].

For canceling noise with the figure-eight loop, the principal axis of the loop has to be set parallel to the noise source (Figure 1.9a). Otherwise, the noise induced in the squares of the loop will be not equal and the noise cancellation may be not efficient (Figure 1.9b).

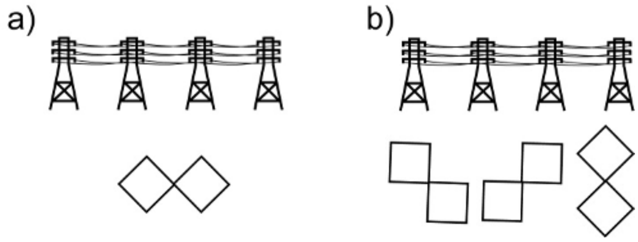

Figure 1.9. *The orientation of the figure-eight loop relative to a power line for canceling a magnetic field generated by the power line: a) correct orientation; b) incorrect orientations*

The figure-eight loop is efficient when it can be oriented so that the squares are symmetric relative the noise source. It is relatively easy to obtain when only one power line is located in the investigated area. However, the power line may change direction, or two or more power lines may cross the area (Figure 1.10). In this case the figure-eight loop may be inefficient, but the signal-to-noise ratio may be improved by using one measuring loop and one or more additional reference loops. The reference loops should be located far enough from the transmitting loop to measure only noise. In this configuration, voltages induced in each loop are recorded separately and special processing algorithms allow subtracting noise from signal records [WAL 08].

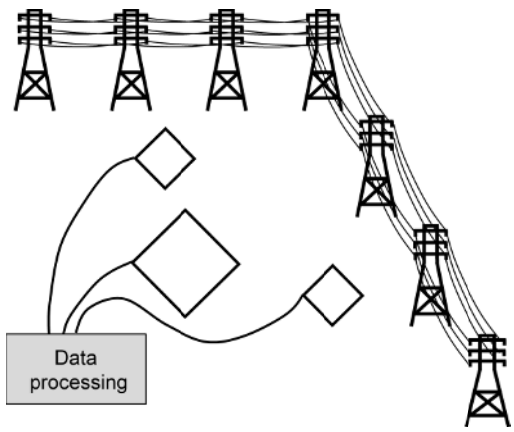

Figure 1.10. *Measuring setup consisting of one Tx/Rx loop (large square) and two noise measuring loops (small squares)*

If SNMR loops are separated at the distance of more than *a* (Figure 1.7) then measurements within each loop are independent and these measurements should be considered as a 1-D survey (Figure 1.11a). When loops are set side by side (Figure 1.11b) measurements can be interpreted as a 2-D profile. The resolution of a 2-D survey may be improved by using half-overlapped loops (Figure 1.11c). Note that setting loops closer than the half-overlapped loops will increase the labor proportionally to the number of the loops without proportional improvement in resolution.

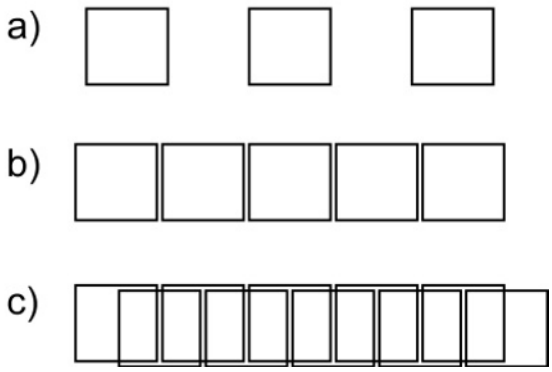

Figure 1.11. *SNMR field setup: a) 1-D; b) 2-D minimal coverage; c) 2-D optimal coverage*

3-D field setups are shown in Figure 1.12. In order to be well resolved, an investigable anomaly should be located within the area occupied by SNMR loops. The half overlapped loop setup seems to be a good compromise between the resolution, and the time and labor consumption.

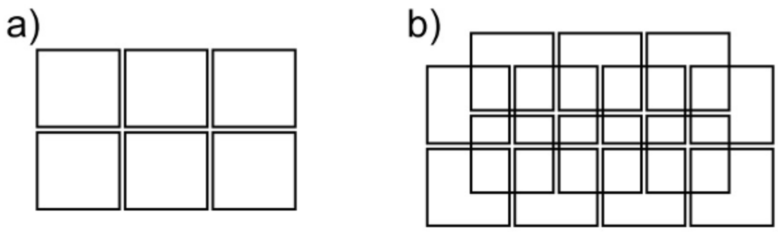

Figure 1.12. *SNMR field setup: a) 3-D minimal coverage; b) 3-D optimal coverage*

1.5. Geophysical tool for hydrogeologists

SNMR imaging is a non-invasive geophysical method that can be used independently or in conjunction with other geophysical and hydrogeological tools for groundwater investigation [ROY 03; LUB 04]. SNMR has a selective sensitivity to groundwater and could provide complementary hydrogeological information about aquifers. The following features of the method render it particularly efficient for hydrogeological surveying: the reliable detection of groundwater, information on the aquifer geometry and the estimation of aquifers' hydrodynamic properties.

Detection of groundwater in the area investigated with SNMR loop is the most reliable parameter provided by SNMR. Correct use of the measuring procedure and experimental setup allows unambiguous identification of the magnetic resonance signal and thus of groundwater. There is no other source that could produce a signal that could mislead interpretation of SNMR results. If the magnetic resonance signal is not observed and external electromagnetic noises are low, then SNMR points to the absence of aquifer formation. The threshold of water detection in the rocks with hydraulic permeability of more than 10^{-5} m/s depends on the measuring conditions, but typically the water content should be more than 0.5%. Water in rocks with hydraulic conductivity of less than 10^{-6} m/s (clay, for example) is undetectable with SNMR. In the SNMR log, low permeable rocks are presented as dry intervals.

Aquifers' geometry can be derived from distribution of the water content in the subsurface provided by SNMR inversion. Depending on the survey design, SNMR results can be presented as a 1-D, 2-D or 3-D distribution of the water content and relaxation times. Figure 1.11 shows discretization of the subsurface for these three cases.

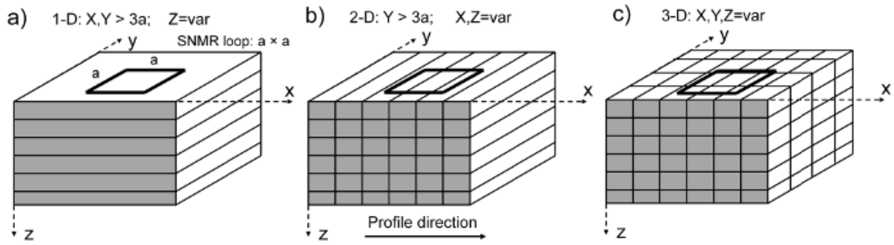

Figure 1.13. *Visualization of SNMR results: a) 1-D survey: the water content and relaxation times are represented as infinite horizontal layers; b) 2-D survey: the water content and relaxation times are represented as parallelepipeds, infinite in the transversal to the profile direction; c) 3-D survey: the water content and relaxation times are represented as cells smaller than the loop size*

Resolution of the inversion is limited by the properties of the linear equation used for inversion, but also depends on the survey design and the signal-to-noise ratio. In general, SNMR is a low-resolution method, and water-saturated structures can be resolved with the uncertainty of a few meters to a few tens of meters. This will be discussed in more detail in Chapter 4.

Aquifer hydrodynamic properties. Porosity and hydraulic conductivity are the basic parameters that characterize the productivity of an aquifer formation [LAC 05]. Actually, existing SNMR instruments allow the investigation of only hydraulically permeable rocks. For example, clay may contain a lot of water but, being a low permeable material, is seen with SNMR as a dry rock. The water content w derived from SNMR inversion allows the estimation of the effective porosity $n_e \approx w$ and an empirical relationship $k = C_p w T_1^2$ allows the prediction of the hydraulic conductivity k. C_p is an empirical constant that needs to be calibrated. w and T_1 are the water content and the relaxation time derived from SNMR inversion. In some rocks, T_1 can be replaced by T_2 or T_2^*. The transmissivity $T = k\Delta z$ is a product of the hydraulic conductivity k and the aquifer thickness Δz both estimated with SNMR. T is a more robust parameter than k and Δz separately.

Finally, for positioning SNMR in the geophysical toolbox let us compare SNMR with other popular surface geophysical methods.

Method	***Measured parameter***	***Rock property***	***Information about subsurface***
Electric and/or electromagnetic	Electrical resistivity	Electrical properties of rocks	Subsurface formations of different electrical resistivity
Seismic	Velocity of propagation of seismic waves	Elastic properties of rocks	Structural geological information
SNMR	Magnetic resonance response of groundwater	Water saturation	Rock hydraulic properties

Table 1.1. *Comparison of SNMR with electric/electromagnetic and seismic methods*

For example, Table 1.1 shows that electric and EM methods provide distribution of the electrical resistivity in the subsurface, and seismic methods provide elastic properties of rocks. These physical parameters of the rock have indirect and often non-unique information about groundwater and hydrodynamic properties of water-saturated formations. On the contrary, the SNMR signal is directly linked with groundwater which allows more reliable interpretation of SNMR results in terms of groundwater.