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New technologies in groundwater exploration. Surface Nuclear Magnetic Resonance

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ABSTRACT

As groundwater becomes increasingly important for living and environment, techniques are asked for an improved exploration. The demand is not only to detect new groundwater resources but also to protect them. Geophysical techniques are the key to find groundwater. Combination of geophysical measurements with boreholes and borehole measurements help to describe groundwater systems and their dynamics. There are a number of geophysical techniques based on the principles of geoelectrics, electromagnetics, seismics, gravity and magnetics, which are used in exploration of geological structures in particular for the purpose of discovering georesources. The special geological setting of groundwater systems, i.e. structure and material, makes it necessary to adopt and modify existing geophysical techniques. A new discipline called hydrogeophysics has been formed and is growing fast. Efforts for direct detection of groundwater led recently to a new technique: Surface Nuclear Magnetic Resonance (SNMR). The principle of nuclear magnetic resonance, well known in physics, physical chemistry as well as in medicine, has successfully been adapted to assess the existence of groundwater and the aquifer parameters. This technique allows for the first time detecting and assessing water directly by only surface measurements allowing quantitative information about mobile water content as well as pore structure parameters leading to hydraulic conductivities. Function, results, interpretation, advantages and drawbacks of SNMR are reviewed in this paper showing the current state of art and developments. A comprehensive example of SNMR is presented with measurements conducted at the site of Nauen near Berlin. The site has Quaternary aquifers with differing layering of sand and till. The results are very satisfying as aquifers down to 50 m depth can be identified quite reliably. The water content is estimated with a high degree of accuracy and relaxation times allowed to derive hydraulic conductivities. Supplementary measurements with geoelectrics and radar made possible to complement and confirm the information achieved with SNMR as well as to apply a joint multimethod approach to aquifer assessment.

KEYWORDS **Ground water exploration. Surface Nuclear Magnetic Resonance. Water content. Pore size.**

INTRODUCTION

Hydrogeological systems and hydrological processes are quite complex. There are still some phenomena which are not well understood yet and not even properly described or observed. As for the study of any complex system there is a great need and demand of improving the technology for the investigations. Very often the improvements are on measuring and processing of currently used methods. This includes collection of more data in a more accurate, faster and cheaper way. Along with the improvements of computers in speed and storage also processing of data gets faster and in particular new algorithms can be applied. These kinds of improvements are result of continuous efforts on developing technology in hardware and software. Besides these improvements there is a need on a better access to some properties of hydrosystems, which allow an improved understanding, description and prediction of the behaviour of these systems.

In comparison to the almost continuous improvements of existing technology, very rarely in geophysics a completely new technology or approach will emerge which is different from the ones already existing. In the following one such new technology will be presented which just passed the experimental stage to become a promising and valuable complementary tool for investigating hydrosystems. Surface Nuclear Magnetic Resonance (SNMR) allows for the first time detecting and assessing water directly by only surface measurements allowing quantitative information of mobile water content and pore structure parameters leading to hydraulic conductivities. The technique is occasionally called also Magnetic Resonance Sounding (MRS) or Proton Magnetic Resonance (PMR).

The SNMR method is a fairly new technique in geophysics to investigate directly the existence, amount and producability of groundwater by measurements at the surface. The first high-precision observations of nuclear magnetic resonance (NMR) signals from hydrogen nuclei were made in the forties. This technique has found wide application in chemistry, physics, tomographic imaging in medicine, as well as in geophysics. It is also a standard investigation technology on rock cores and in boreholes (Kenyon, 1992). The first ideas for making use of NMR in groundwater exploration from the ground surface were developed as early as the 1960s, but only in the 1980s was effective equipment designed and put to operation for surface geophysical exploration (Semenov et al., 1988; Legchenko et al., 1990). Extensive surveys and testing have been conducted in different geological conditions particularly in sandy aquifers but also in clayey formations as well as in fractured limestone and at special test sites (Schirov et al., 1991; Lieblich et al., 1994; Goldman et al., 1994; Legchenko et al., 1995; Beauce et al., 1996; Yaramanci et al., 1999; Meju et al., 2002; Plata and Rubio, 2002; Supper et al., 2002; Vouillamoz et al., 2002; Yaramanci et al., 2002) revealing the power of the method as well as the shortcomings which need to be improved.

BASIC PRICIPLES OF SNMR

The protons of the hydrogen atoms in water molecules have a magnetic moment μ. They can be described in terms of a spinning charged particle. Generally μ is aligned with the local magnetic field B_0 of the Earth. When another magnetic field B_1 is applied, the axes of the spinning protons are deflected, owing to the torque applied (Fig. 1). Hereby only the component of B_1 perpendicular to the static field B_0 acts as the torque force. When B_1 is removed, the protons generate a relaxation magnetic field as they become realigned along B_0 while precessing around B_0 with the Larmor frequency

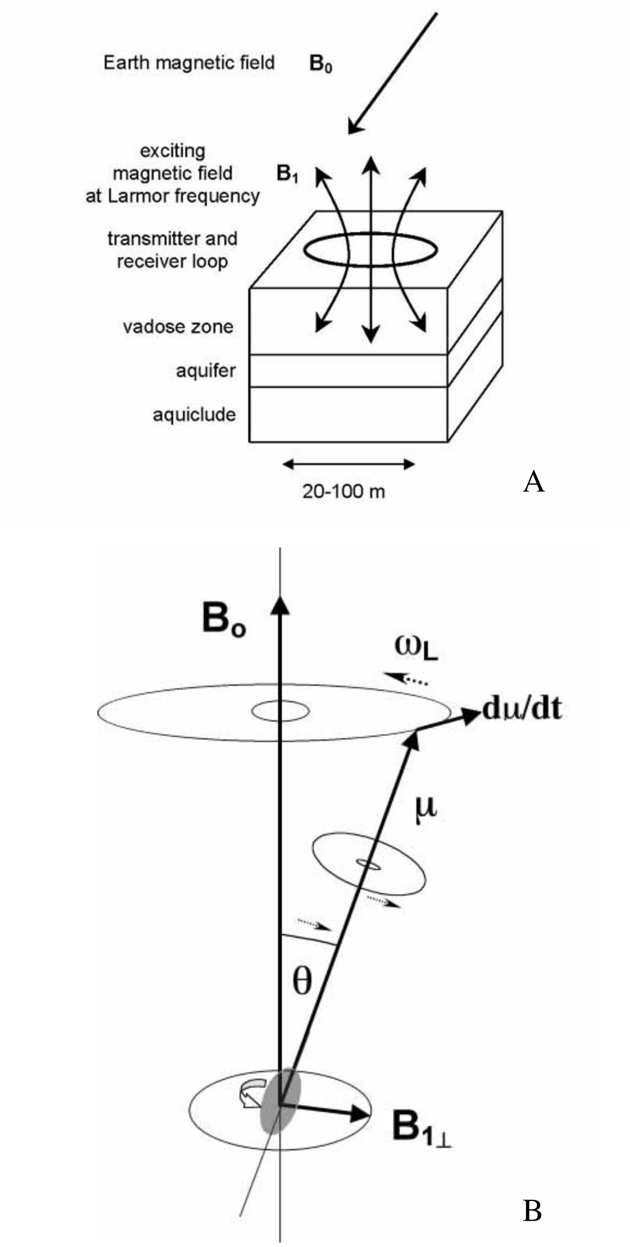

FIGURE 1 **(A) Elements of SNMR measurements and (B) behavior of relaxing protons.**

$$f_L = \omega_L / 2\pi \quad \text{with} \quad \omega_L = \gamma B_0 \text{ and}$$
$$\gamma = 0.267518 \quad \text{Hz/nT} \qquad (1)$$

where γ is the gyromagnetic ratio of hydrogen protons. The measurements are conducted using a loop usually with a circular or rectangular lay out. An alternating current,

$$i(t) = i_0 \cos(\omega_L t), \qquad (2)$$

with the Larmor frequency ω_L and strength i_0 is passed through the loop for a limited time τ so that an excitation intensity (pulse moment) of $q = i_0 \tau$ is achieved. After the current in the loop is switched off, a voltage e(t) with the frequency ω_L and decaying amplitude is induced in the loop by the relaxation of the protons:

$$e(t) = \omega_L M_0 \int f(r)\, e^{-t/T(r)} \cos(\omega_L t + \varphi(r)) B_\perp(r) \sin(0.5\, \gamma\, B_\perp(r)\, q)\, dV. \qquad (3)$$

Here is $M_0 = 3.29 \times 10^{-3}\, B_0$ J/(T m^3), the nuclear magnetisation for water at a temperature of 293 K. In a unit volume dV at the location r(x,y,z) the volume fraction of water is given by f(r) and the decay time of protons by T(r). $B_\perp(r)$ is the component of the exciting field (normalised to 1 A) perpendicular to the static magnetic field B_0 of the Earth. In a conductive medium $B_\perp(r)$ is composed of the primary field of the loop and the induced field. The induced field causes a phase shift $\varphi(r)$ in respect to the exciting field. The argument of the sine function, $\Theta = 0.5\, \gamma\, B_\perp(r)\, q$, is the angle of deflection of the magnetic moment of the protons from the magnetic field of the Earth. The signal e(t) is usually approximated by (Fig. 2)

$$e(t) = E_0\, e^{-t/T} \cos(\omega_L t + \varphi). \qquad (4)$$

The envelope of this voltage is directly related to the water content and to the decay time of every volume element in the underground contributing to the signal: For non conductive media, i.e. negligible phases, the initial amplitude E_0 at t=0 is related only to the water content:

$$E_0 = \omega_0 M_0 \int f(r)\, B_\perp(r) \sin(0.5\, \gamma\, B_\perp(r)\, q)\, dV. \qquad (5)$$

Using this equation the initial amplitudes for various excitations intensities and for water layers at different depths and thicknesses can be calculated. It happens that for deeper water layers the maximum of E_0 occurs at higher q values and the strength of E_0 is directly related to the thickness of the layer and the amount of the water.

The recorded decay time T is the relaxation-time constant (spin-spin or transversal relaxation time) denoted usually with T_2^* in the usual NMR terminology. It is related to the mean pore size and, therefore, grain size as well as hydraulic conductivity of the material. Clay, including sandy clays, usually has a decay time of less than 30 ms, whereas sand has one of 60 - 300 ms, gravel 300 - 600 ms, and pure water 600 - 1000 ms (Schirov et al., 1991).

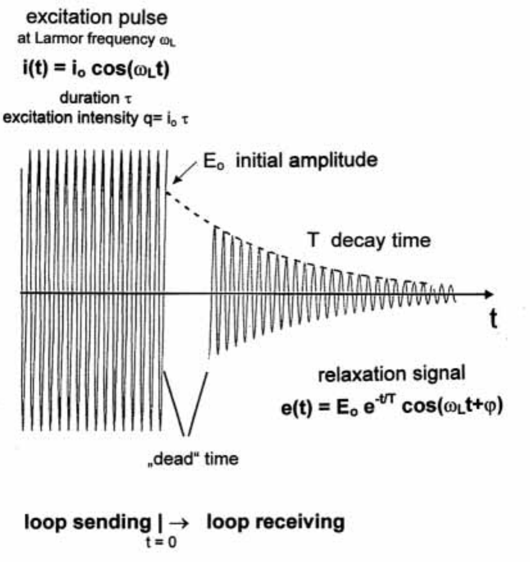

FIGURE 2 | **Input and output signal in the SNMR measurements.**

The measurements are conducted for different excitation intensities q and the main parameters recorded for every q are the initial amplitude E_0 and the decay time T. This set of data in form of $E_0(q)$ and T(q) are inverted to find the distribution of water content with depth f(z) and of decay time with depth T(z). Thereby equation (3) is the basis of the inversion which is used in the form modified for models having horizontal layering. Two or three dimensional inversion and suitable measurement approaches for this are not available yet but are currently being investigated. The usual inversion scheme used in SNMR is based on a least square solution with a regularisation (Legchenko and Shushakov, 1998). Lately new inversion schemes are developed which use model optimisation with Simulated Annealing and allow more flexibility in designing the layer thicknesses imposed on inversion even with free layer thicknesses to be optimised (Mohnke and Yaramanci, 1999, 2002).

INVESTIGATIONS AT THE SITE NAUEN

To demonstrate the field work, advantages and drawbacks of SNMR a case history from the test site in Nauen is very suitable and will be briefly presented here extracted from a previous detailed work (Yaramanci et al., 2002). The geology of the Nauen site is quite typical for large areas in Northern Germany. It is build up of Quaternary sediments emerged in the last glacial period (Weichsel) and overlying Tertiary clays. In the actual area of investigation these sediments mainly consist of fluvial sands bordered by glacial till. The topography is characterised by flat hills underlain by till and plains comprising glacial fluvial sands and gravels. In the test area there is an unconfined shallow aquifer consisting of fine to medium sands underlain by an aquiclude of marly and clayey glacial till. North of the site the glacial till approaches the surface in a nearly E-W strike. For this reason all the main profiles were chosen N-S.

SNMR measurements

The SNMR soundings were measured at 5 locations, 25 m apart from each other on the main profile using eight shaped loop antennas with 50 m in diameter. The antenna main axis was directed E-W, parallel to the strike. The simple circular or square loop, as used for an earlier single sounding, could not be used because of the high noise, generated by an electrical railway some 5 km away. The eight shaped loop allowed to increase the signal to noise ratio very effectively, almost ten times compared with simple loops. Therefore, moderate stacking rates of 32 were quite sufficient; 16 to 24 different excitation intensities (q) levels were used. The frequencies have been around 2082 Hz, corresponding to the total intensity of local Earth magnetic field about 48900 nT, very stable within ± 0.5 Hz for all excitation intensities. Measurements were conducted with the NUMIS system (NUMIS, 1996). The processing and inversion of the data were made with the standard inversion software provided with this system (Legchenko and Shushakov, 1998).

In Fig. 3 an example of a raw data set is shown for the location B8. These data document the good quality of the measurements and is representative for the other soundings as well. The decaying is well recognisable because the amplitudes of stacked noise are about 25–50 nV, which is quite low compared to the amplitude of the SNMR signal, in particular to the initial amplitude.

In Fig. 4B the actual measurements of amplitudes, decay times, phases and stacked noise for different excitation intensities are shown. The amplitudes, showing a prominent maximum of about 550–750 nT for q $\cong$ 400 A ms, qualitatively suggest that a significant aquifer is present at a very shallow depth. Decay times are around 100–200 ms, suggesting sandy material. All phases start at 0^o, increasing up to about 60^o with increasing excitation intensity. This usually points to an increasing conductivity with depth.

In Fig. 4A the results of inversion are shown. The inversion scheme used is a least squares type of algorithm using a regularisation parameter, affecting the smoothness of water content distribution with depth (Legchenko and Shushakov, 1998). The range of smoothness might be very high leading to different interpretation of the water content distributions (Yaramanci et al., 1998). In particular by smooth inversion it is not possible to see sharp boundaries or changes of water content with depth as it would be expected for aquifers in medium to coarse sands with small capillary fringes or in the presence of a distinct aquiclude as it is the case here. Therefore a moderate regularisation was used which does not smooth the structures very drastically. A low regularisation would smooth less but may cause unrealistic variations for small depth ranges which are not conform with the resolution ability of the method.

The water contents are about 20% near surface, increasing up to 30% at depths of 10 m followed by a strong decrease down to 5% in a depth range of around 25 m. In deeper areas the water contents get unusually high; even up to 40%. The upper part of the picture, showing clearly an aquifer, is in quite good agreement with the expected and partly known geology. The low water content range must correspond to the glacial till because of the very low amount of mobile water in that type of geological material. The increase of water content below the till suggests a second aquifer which is confirmed with a recent borehole.

The inverted decay times are in the range between 100 - 300 ms. The common feature of all decay time distributions is the maximum of roughly 200 ms at about 20 m and an average value of 150 ms at a depth of about 10 m, thus corresponding to the maximum water content. Otherwise there is no general similarity i.e. decay times increase or decrease to greater and shallower depths. The range in general shows fine to medium sands, even coarse sands. The higher decay times at the depth of low water content is difficult to explain for the geological conditions at this site. This would be only possible for low porosity material but with relative high degree of mobile water content i.e. compact sediments with little cementation or fractured hard rock, but not for glacial till. It is not clear yet, whether this problem is due to the use of the special eight shaped loop antenna and/or the corresponding inversion as the signal is small from this depth. In an earlier measurement with square loop the inverted decay times show the expected behaviour (Yaramanci et al., 1998) whereas the water contents are the same as those with eight shaped loop.

Radar measurements

An extensive GPR survey has been carried out at the test site. For the measurements 200 MHz antennas were used to achieve an optimum in penetration and resolution. The profiles were orientated in N-S and E-W directions

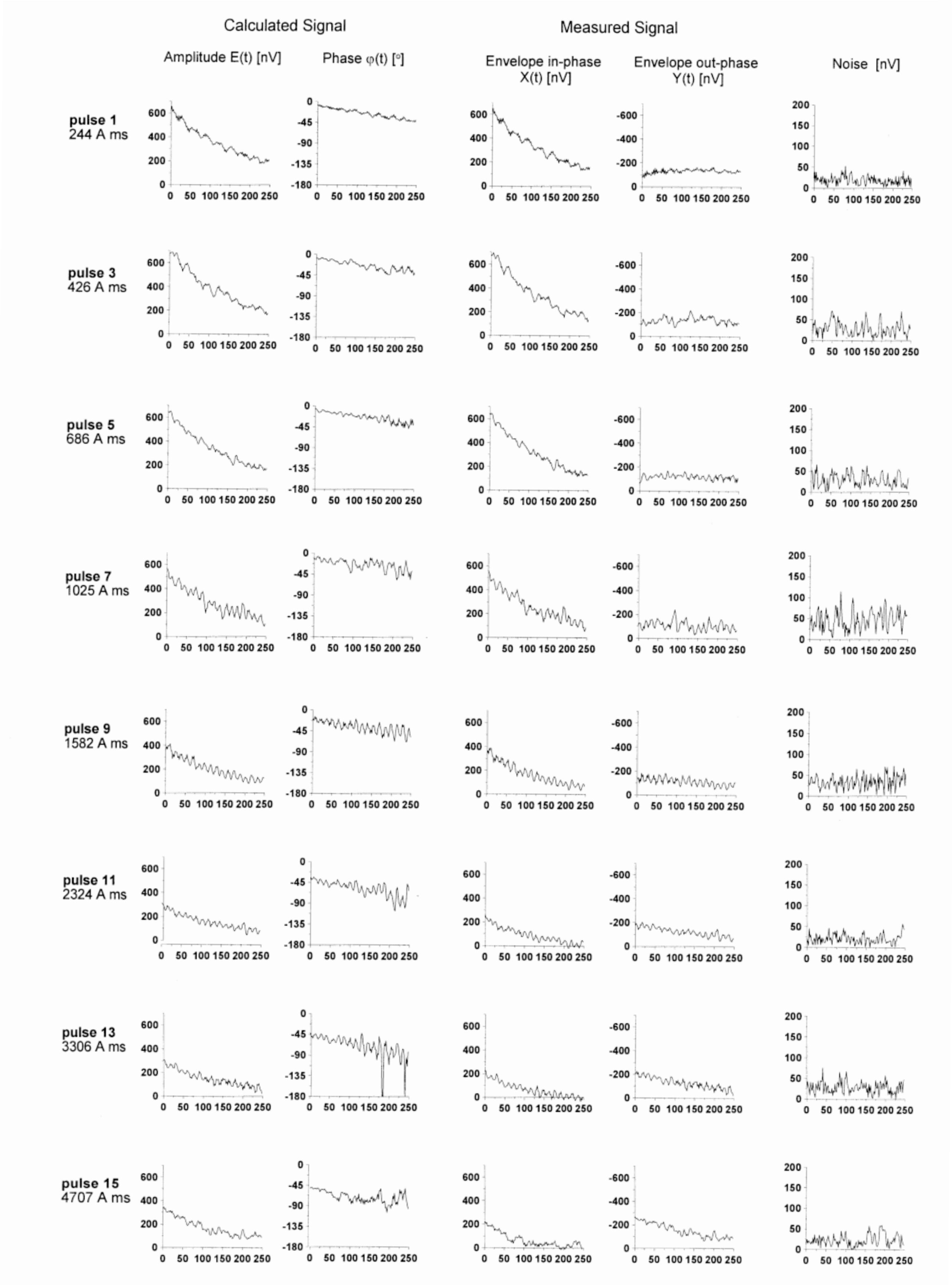

FIGURE 3 **Example of a SNMR data set in the location B8 at the test site Nauen. Time axes are in ms. Envelopes of in-phase and out-phase components, X(t) and Y(t), are measured to yield the amplitude $E(t) = (X(t)^2+Y(t)^2)^{1/2}$ and phase $\varphi(t) = \arctan(Y(t)/X(t))$. The parameters used for the inversion are $E_0 = E(t=0)$ and the decay time T, determined by an exponential fitting of $e^{-t/T}$ to E(t). The actual phase of the signal is $\varphi_0 = \varphi(t=0)$.**

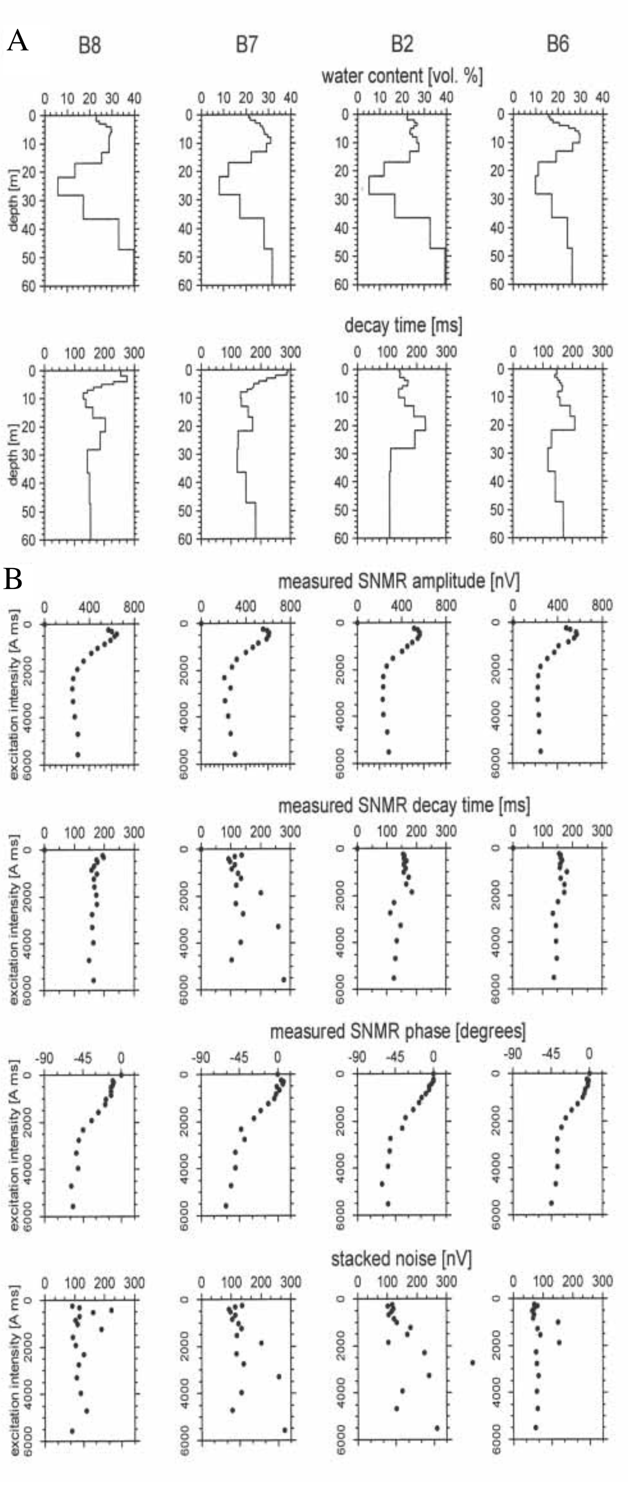

FIGURE 4 **SNMR measurements and results at the test site Nauen.**

consisting of 4 sections each 25 m apart. An example of a N-S sections, perpendicular to geological strike, is shown in Fig. 5. Also shown is the CMP (Common-mid-point) measurement at this profile in order to derive proper velocities for time to depth conversions and rock physical considerations.

GPR can be used to map water table by radar reflection if there is a sharp discontinuity and not a large transition zone due to the capillary fringe. Usually the aquifer will not be penetrated properly to give reflections from its bottom due to the high absorption, i.e. energy loss in the aquifer. In Nauen both favourable situations are met, that there is a sharp water table due to the high hydraulic conductivity of the sand, and therefore a good reflection and there is low electrical conductivity of water and therefore good bottom reflections, i.e. reflections from the top of glacial till.

According to GPR measurements the water table is at about 2–3 m depth depending on the slowly varying topography. The bottom of the aquifer, i.e. the top of glacial till, is about 15 m at the south and gradually comes up on the surface in northern direction. North of this, below the top of till, there is no radar signal due to high absorption.

Geoelectric measurements

The clear indication of a 2-dimensional structure in GPR measurements was the reason for performing 2D-geoelectric measurement in order to get more detailed information about the resistivity structures.

Different geoelectric sections were measured with various lengths and electrode spacings. The result of the measurement at the same profile as for radar measurements, where a Wenner array with an electrode spacing of 2 m was used, is shown in Fig. 5. The result of a standard smooth inversion (Loke and Barker, 1996) shows well recognisable structures of high resistivities at shallow ranges in the south, corresponding to the vadose zone, and medium resistivities below, corresponding to the aquifer and glacial till. To the north this low resistivity layers come up to the surface and the values of resistivity get even lower.

The meanwhile classical inversion of geoelectric pseudosections, imposing a smoothness on the resistivities, has some drawbacks in case of well defined structures with sharp resistivity contrasts (Olayinka and Yaramanci, 2000). Not only the boundaries of the structures are blurred, but also the resistivities are far from true values. In cases like Nauen, where sharp boundaries occur, block inversion may be used (Fig. 5). By this kind of inversion distinct resistivities are found for individual blocks i.e. formations. The resistivities found are: 3000 Ωm for the vadose zone, 280 Ωm for the aquifer and 90 Ωm for the glacial till. These values are in very good agreement with those known from other geoelectrical surveys at Quaternary aquifers in the Berlin region. The unusually low resistivity of 34 Ωm for shallow ranges within the glacial till in the northern part of the

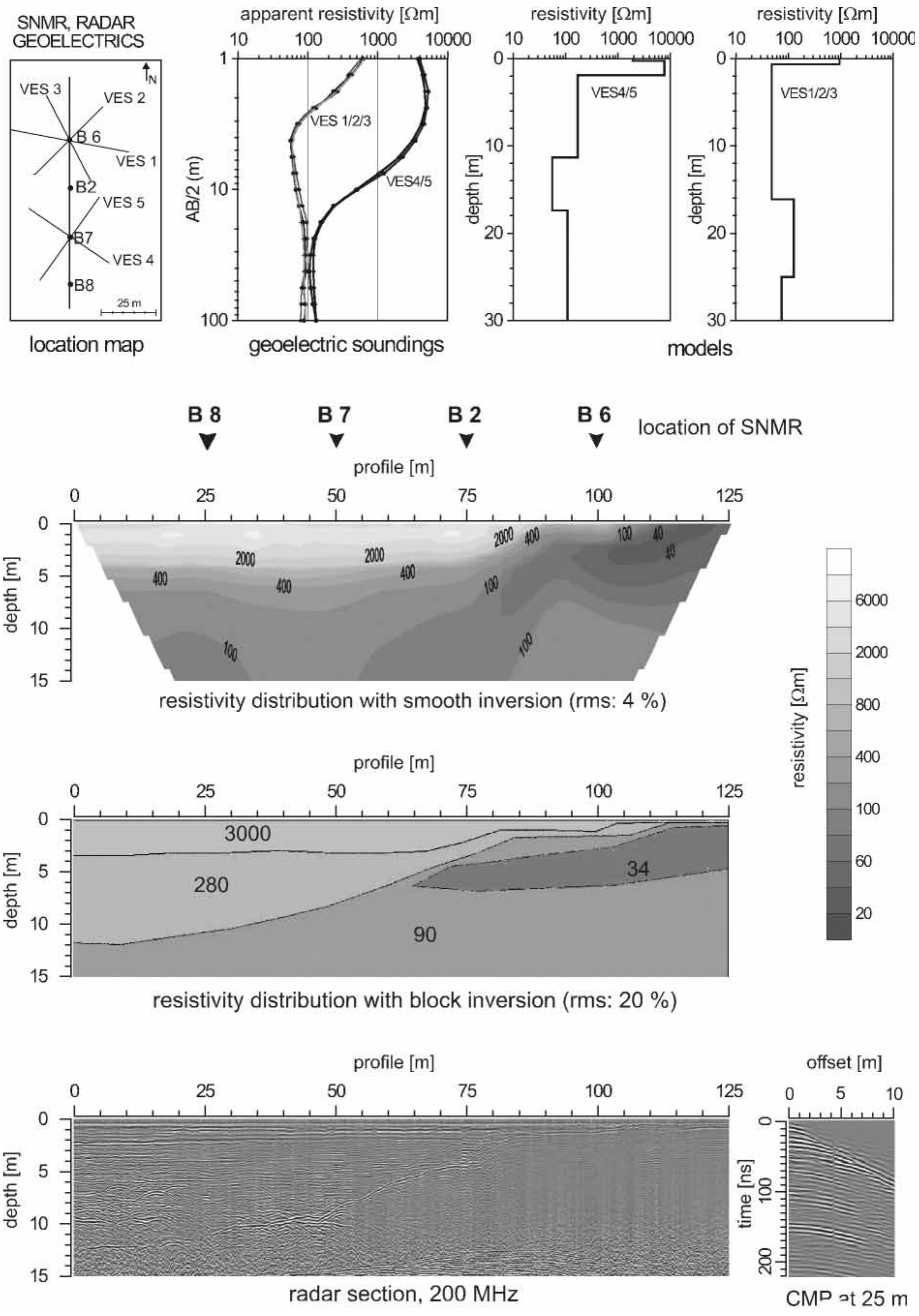

FIGURE 5 | **Geoelectric and radar measurements at the test site Nauen at the same profile as for SNMR measurements.**

profile shows an internal structure, probably reflecting higher clay content.

ESTIMATION OF WATER CONTENT

The water content for the aquifer indicated by SNMR is about 25–30% (Fig. 4). That corresponds to the mobile (free) water in the pores. This is an average value for at least 3 locations to the south, B8, B7 and B2. Although the sharp boundary of water table is not well determined by the SNMR inversion used, the vadose zone with a mean water content of 10–20 % is distinguishable to some degree here. This water corresponds to the seeping water which needs some time to reach the aquifer. Below the aquifer a material with some 5–10 % water content is shown, which should be the glacial till. This, in fact, is in agreement with free water contents which can still be accommodated in glacial till. The higher water contents found for deeper regions, suggesting a second aquifer, are confirmed with a recent borehole.

Estimation of water content from radar measurements

The estimation of water content with GPR is quite straightforward and widely used (Greaves et al., 1996; Hubbard et al., 1997; Dannowski and Yaramanci, 1999). The dielectric permittivity of the rock can be determined by the velocity of electromagnetic waves measured with radar using

$$\epsilon = (c/v)^2 \qquad (6)$$

with c the velocity of electromagnetic waves in air. To estimate water content from radar data the usual CRIM relation (Mavko et al., 1998) has been used. According to this formula the dielectric permittivity of the rock is related to the properties of the rock components by

$$\sqrt{\epsilon} = (1-\phi)\sqrt{\epsilon_m} + S\phi\sqrt{\epsilon_w} + (1-S)\phi\sqrt{\epsilon_a} \qquad (7)$$

with ϵ dielectric permittivity of rock, ϕ porosity, S degree of saturation, ϵ_w dielectric permittivity of water = 80, ϵ_m dielectric permittivity of matrix ≈ 4.5, ϵ_a dielectric permittivity of air = 1. The porosity is defined as $\phi = V_p/V$ and the degree of saturation as $S = V_W/V_p$, with V, V_p and V_W being the volumes of the rock, pores and water respectively. The water content $G = V_W/V$ is then given by

$$G = S\,\phi \qquad (8)$$

In case of (full) saturation i.e. S = 1 the relation (7) turns to be (9)

$$\sqrt{\epsilon} = (1-\phi)\sqrt{\epsilon_m} + \phi\sqrt{\epsilon_w} \qquad (9)$$

and water content is equal to porosity, $G = \phi$. The porosity determined using (9) is then used in (7), to estimate the water content in the vadose zone with the dielectric permittivity of the vadose zone.

Estimation of water content from geoelectric measurements

In order to interpret the resistivity and its local variations, the physical cause of resistivity and the influencing factors must be well understood. The general model of rock conductivity σ is described by two conductivities in a parallel circuit and therefore in addition (Gueguen and Palciauskas, 1994; Mavko et al., 1998)

$$\sigma = \sigma_V + \sigma_q \qquad (10)$$

σ_V is the volume conductivity caused by the ionic conductivity of the free electrolyte in the pores and σ_q the capacitive interlayer conductivity due to adsorbed water at the internal surface of the pores. The conductivity σ_q is, in contrast to σ_V, strongly frequency dependent - being very small for zero frequency and becoming large with increasing frequency. For rocks with a large internal surface, for example containing a great portion of clay, σ_q might be very high and it is therefore called the "clay term". For aquifers in more sandy formations and at low frequencies σ_V is much larger than σ_q, so that $\sigma \cong \sigma_V$. Going back to the more familiar expression in terms of resistivity, with $\rho = 1/\sigma$, the ohmic resistivity of rock is

$$\rho = \rho_W\,\phi^{-m}\,S^{-n} = \rho_W\ F\,I \qquad (11)$$

where ρ_W is the resistivity of water, ϕ the porosity, m the Archie exponent (or cementation factor), S the degree of saturation, n saturation exponent. The actual dependence of the resistivity on the pores is expressed with the formation factor $F = \phi^{-m}$ and saturation index $I = S^{-n}$. For a saturated rock (i.e. S=1) the resistivity in (11) becomes

$$\rho_O = \rho_W\,\phi^{-m} \qquad (12)$$

where the index o stands for (fully) saturated rock. This is the well known Archie equation (1942), which is widely used, particularly in interpretation of resistivity well logs.

Equation (12) is used first to estimate the water content in the aquifer and the porosity determined hereby is then used for the estimation of porosity in the vadose zone. Very often it can be assumed that $m - n \cong 0$ and consequently $S^{m-n} \cong 1$. Even though the effect of S is not that high, it should not be neglected a priori, particularly in such cases, when values for m and n are available. The

TABLE 1 **Estimation of water contents (in Vol. %) with different methods at the test site Nauen/Berlin(1)**

	RADAR	**GEOELECTRICS**		**SNMR**
		sounding	2D-section	
Vadose zone 0 – 2 m	**5%**	**4%**	**5%**	**15-20%**
	using: $v = 0.130$ m/ns $\varepsilon = 5.3$ $\phi = 20\%$ $\varepsilon_w = 80$ $\varepsilon_m = 4.5$ $\varepsilon_a = 1$	using: $\rho_0 = 8x10^3\ \Omega m$ $\phi = 28\%$ $\rho_w = 33\ \Omega m$ $m = 1.3$	using: $\rho_0 = 3x10^3\ \Omega m$ $\phi = 20\%$ $\rho_w = 33\ \Omega m$ $m = 1.3$	
Aquifer 2 – 13 m	**20%**	**28%**	**20%**	**25-30%**
	using: $v = 0.86$ m/ns $\varepsilon = 12.2$ $\varepsilon_w = 80$ $\varepsilon_m = 4.5$	using: $\rho_0 = 170\ \Omega m$ $\rho_w = 33\ \Omega m$ $m = 1.3$	using: $\rho_0 = 280\ \Omega m$ $\rho_w = 33\ \Omega m$ $m = 1.3$	

(1) The estimations are first conducted for the aquifer. Derived water contents in the aquifer equal to the porosities which are then used for the estimations in the vadose zone. Take note of that the SNMR estimations relate to free water and estimations from GPR and Geoelectrics relate to total water.

parameters used for the estimation of porosity and water content at the test site Nauen and the corresponding results are shown in Table 1.

ESTIMATION OF HYDRAULIC CONDUCTIVITIES FROM SNMR

In order to obtain hydraulic conductivities from SNMR measurements, the empirical relationship between decay time and average grain size observed in many SNMR surveys (Schirov et al., 1991) can be used. Combining this with the relationship between grain size and hydraulic conductivity often used in hydrogeology (Hölting, 1992) leads to a simple estimation of hydraulic conductivity as proposed by Yaramanci et al. (1999):

$$k_f \approx T^4 \qquad (13)$$

with k_f the hydraulic conductivity in m/s and T the decay times in s. An average decay time of 150 ms yields a hydraulic conductivity of $5x10^{-4}$ m/s which fits quite well with the hydraulic conductivities determined on core material.

DISCUSSION

In the SNMR measurements at Nauen site an aquifer can easily be identified at a shallow depth range, followed by a low water content layer. The boundaries are not very well defined, as the used standard NUMIS inversion scheme favours and even imposes a smooth distribution of water content with depth. Thus, the small vadose zone is not well resolved, but still detected. In contrast GPR allowed a very good determination of the structure with clear reflections from the water table and the top of glacial till. This situation is, however, not usual that way with GPR elsewhere. The resistivity distribution derived from 2D-geolelectrical measurements shows a general trend, indicating the vadose zone and the aquifer and even the glacial till below. But the obtained results are too smooth to allow the determination of exact depths of layers. The block inversion here yields more reliable true resistivities of the layers but needs some a priori information about the geometry.

The estimation of water content with SNMR worked very well showing 30% mobile water in the aquifer which is in extraordinary good agreement with the independent measurements in the laboratory. The water content shown by SNMR for the vadose zone is somewhat higher as its true value can be, but this is caused by the problems to resolve the thin vadose zone. Even under very favourable conditions for interpreting 2D-geoelectrics - the structure is known from GPR and used in geoelectric inversion, thus producing more reliable resistivities - the estimated water contents are far from reality. The seemingly good result from geoelectric sounding is not real as there should be a large influence by side effects.

CONCLUSIONS AND DEVELOPMENTS

The method of SNMR has just passed the experimental stage to become a powerful tool for groundwater exploration and aquifer characterisation. Some further improvements are still necessary and just in work. The largest concern currently is the effect of resistivities and their inclusion into the analysis and inversion as the exciting field will be modified and polarised considerably by the presence of conductive structures. Earlier considerations of this (Shushakov and Legchenko, 1992; Shushakov, 1996) have led to appropriate theoretical description and numerical handling of this problem (Valla and Legchenko, 2002; Weichmann et al., 2002). In fact the incorporation of resistivities allows modelling of the phases in a reliable way (Braun et al., 2002) which is not only useful for understanding the phases measured but also the basis for a successful inversion of phases to yield the resistivity information directly from SNMR measurements.

In the analysis of SNMR the relaxation is generally assumed to be monoexponential. Even if individual layers were monoexponential in decaying, the integration results in a multiexponential decay in the measured signal. The most comprehensive way taking account for this is to consider decay time spectra in the data as well as in the inversion (Mohnke et al., 2001). This leads to the pore size distribution which is a new information and allows improved estimation of hydraulic conductivities. The estimation of water content also will be improved significantly as the initial amplitudes are much better determined using decay spectra approach.

Currently SNMR is carried out with a 1-D working scheme. However, the errors might be very large by neglecting the 2-D or even 3-D geometry of the structures (Warsa et al., 2002) which have to be considered in the analysis and inversion in the future. Measurement lay outs are to be modified to meet the multi-D conditions, which is easier to accomplish for nonconductive structures. In multi-D structures the actual difficulty is the numerical incorporation of the electromagnetic modelling for the exciting field.

As in any geophysical measurement, also with SNMR the inversion plays a key role by interpreting the data. The limits of inversion and also the imposed conditions in terms of geometrical boundary conditions as well as differences in the basic physical model used may lead to considerable differences. The inversion of SNMR data may be ambiguous, since not only different regularisations in the inversion impose a certain degree of smoothness upon the distribution of water content (Legchenko and Shushakov, 1998; Yaramanci et al., 1998; Mohnke and Yaramanci, 1999) but also the number of layers and the size of layers forced in the inversion may considerably effect the results. The rms-error is not necessarily a sufficient measure for assessing the quality of the fit of a model to the observed data. The most recent research suggests that a layer modelling with free boundaries avoids the problems associated with regularisation and takes into account the blocky character of the structure where appropriate (Mohnke and Yaramanci, 2002).

Further improvement in the inversion can be achieved if geoelectrical measurements are available and they can be incorporated into a joint inversion with SNMR. Examples of joint inversion of SNMR with Vertical Electrical Sounding show considerable improvement in the detectability and geometry of the aquifers and allows also, by utilising of appropriate petrophysical models, the separation of mobile and adhesive water (Hertrich and Yaramanci, 2002).

At sites where no information is available in advance, SNMR should always be carried out along with geoelectrical methods, i.e. direct current geoelectric, electromagnetics and even GPR. This will help to decrease ambiguity in the results and also allow hydrogeological parameters to be estimated (Yaramanci et al., 2002). But despite all the difficulties, the quality of geophysical exploration for groundwater and aquifer properties will have an increased degree of reliability by using SNMR as a direct indicator of water and soil properties.

The importance of the SNMR method lies in its ability to detect water directly and allowing reliable estimation of mobile water content and hydraulic conductivity. In this respect it is unique, since all other geophysical methods yield estimates, if ever, indirectly via resistivity, induced polarisation, dielectric permittivity or seismic velocity. Using SNMR in combination with other geophysical methods not only allows direct assessment but is complementary to the information yielded by other geophysical methods.

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