ISH Journal of Hydraulic Engineering

ISSN: 0971-5010 (Print) 2164-3040 (Online) Journal homepage: https://www.tandfonline.com/loi/tish20

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ISH JOURNAL OF HYDRAULIC ENGINEERING
https://doi.org/10.1080/09715010.2019.1661802

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Uttam Singh, Pramod Kumar Sharma and C. S. P. Ojha

Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee, India

ABSTRACT

In this paper, an attempt is made to briefly describe different methods for geophysical investigations. Afterward, experiments were carried out in the field to investigate the geophysical strata below the surface of the soil using both ground magnetic resonance (GMR) and resistivity meter. The measured geophysical strata from GMR and resistivity meter are compared with borehole data. It is observed that the results obtained by GMR and resistivity meter of aquifer strata are matching with borehole data. Hence, it is shown that GMR measurements are more economical, time-saving and non-invasive. Finally, the measured hydraulic conductivity can have potential application in the modeling of flow through subsurface soil.

ARTICLE HISTORY
Received 10 December 2018
Accepted 27 August 2019

KEYWORDS
Earth's field; groundwater; hydraulic conductivity; ground magnetic resonance; geophysics and resistivity meter

1. Introduction

The problem of obtaining quality water is generally becoming more important due to increasing population and industrialization (Olorunniwo and Olorunfemi 1987). Hence, geophysical investigations have been carried out in different parts of the world for groundwater investigation. The different methods of geophysical investigation include electrical resistivity, gravity, seismic, magnetic, remote sensing, electromagnetic and nuclear magnetic resonance (Olayinka and Mbachi 1992; Ariyo et al. 2003; Ariyo and Banjo 2008). The application of geophysics for the exploration of groundwater in sedimentary terrain requires a proper understanding of hydro-geological characteristics. Most of the investigators also observed that the geophysical methods are the most reliable and accurate for subsurface investigations (Carruthers 1985; Emenike 2001). Brousse (1963) used electrical resistivity method in the investigation for groundwater in complex granite areas. He used the method to map fractures, gorges gouge and faults which acted as water reservoirs. Ako and Osondu (1986) carried out groundwater investigations at Darazo on the Kerri-Kerri Formation. They observed that Dar-Zarouk parameters are related to borehole characteristics and the highest traverse resistance corresponds to the zone with the highest borehole yield. Ajayi and Adegoke-Anthony (1988) investigated groundwater prospect in the Basement Complex rocks of southwestern Nigeria. They showed that the local geological conditions play an important role in the yield of boreholes located in the basement complex area of southwestern Nigeria. Olorunfemi and Oloruniwo (1987) used the electrical resistivity method for groundwater investigation in different parts of the Basement terrain in Southwest Nigeria and observed that the weathered layer and the fractured Basement constitute the aquifer zones. Olorunfemi and Fasuyi (1993) used the electrical resistivity method in the investigation of geo-electric and hydrogeologic characteristics of areas in Southwest Nigeria. Gnanasunder and Elango (1999) carried out groundwater quality assessment of a coastal aquifer lying south of Chennai City, Madras, India, using geo-electrical techniques. This study was able to delineate a freshwater ridge of good groundwater quality in the central portion of the coastal aquifer, while the eastern and western margins of the aquifer, however, contained groundwater of poor quality.

It is also observed that the use of the geophysics for both groundwater resource mapping and water quality evaluation is increased due to the rapid advances in computer software and numerical modeling (Gev et al. 1996; Yaramanci et al. 1999). The technique of nuclear magnetic resonance (NMR) is used in geophysical applications for determining aquifer properties such as porosity, permeability and water content (Yaramanci et al. 1999; Muller-Petke et al. 2011, 2013). The technique of NMR combines the information content accessible via the NMR measurements with the non-destructive approach to derive the subsurface information from the surface-based measurements (Burger et al. 2006). As such, the NMR is the only geophysical exploration method providing direct and non-destructive information on hydraulic subsurface aquifer properties. The NMR is based on the free induction decay (FID) experiment, emitting an excitation pulse and recording the relaxation signal using large surface coils of tens of meters and detecting signals from depths up to 150 m (Walsh 2008).

NMR logging tools were first introduced for petroleum exploration in the 1960s. The earliest logging tools were used for simple free induction decay (FID) measurement schemes and it was difficult to estimate the useful relaxation times (Brown and Gamson 1960). Modern NMR logging is now considered an invaluable technology in the petroleum industry and has been adopted for hydrologic and environmental investigations (Freedman 2006; Walsh et al. 2013). Surface-based NMR measurements are used in the hydrologic application (Hertrich 2008; Knight et al. 2012), which have the merits of non-invasively determining the aquifer properties. Surface NMR instrument was first developed in the 1980s (Schirov et al. 1991)

CONTACT Pramod Kumar Sharma drpksharma07@gmail.com

and have seen significant improvements during the past decade (Walsh 2008; Walsh et al. 2011). Schirov et al. (1991) used the hydroscopic method and surveyed the groundwater distribution in both plan and in-depth with high efficiency; thus, ensured the most productive areas for water supply bores. In contrast to NMR logging, the NMR measurement schemes have remained relatively simple, relying exclusively on single or double-pulse acquisitions (Legchenko et al. 2010; Grunewald and Knight 2011). Grunewald and Walsh (2013) used a surface nuclear magnetic resonance method to non-invasively characterize aquifers. Walsh et al. (2014) conducted experiments using NMR to detect and characterize water in the unsaturated zone. Their data obtained at pseudo-static vadose zone investigation sites indicated that the surface NMR instrument could detect and image some forms of water held in unconsolidated vadose zone formations at depth up to 30 m. NMR logging tools are used to measure the response of pore water in the geological materials adjacent to a borehole and obtain information about the geometry of the pore space (Dlubac et al. 2013). This information is also used to estimate hydraulic conductivity by employing a relationship originally developed for applications in the oil industry (Knight et al. 2016).

Groundwater is the only source of freshwater and the demand for groundwater is increasing every year due to growing population and urbanization. Hence, it is essential to investigate groundwater and aquifer characteristics. The aim of the present study is to conduct the field experiments using instruments GMR and Resistivity meter and explore their potential using borehole data.

2. Geophysical methods

Geophysical exploration is the scientific measurement of physical properties of the earth's crust by instruments located on the surface for investigation of groundwater. Nowadays, the application of geophysical exploration to groundwater is becoming common. The success of these methods depends on how the best physical parameters deduced are interpreted in terms of aquifer parameters. Geophysical methods detect differences or anomalies of physical properties such as density, magnetism, elasticity and electrical resistivity within the earth crust. The brief description of geophysical methods is described below:

2.1. Electric resistivity method

Surface electrical resistivity method is based on the principle that the distribution of electrical potential in the ground around a current electrode depends on the electrical resistivity and distribution of the surrounding soil and rocks. The electrical resistivity method measures both lateral and vertical variation in ground resistivity from different points on the earth surface. The resistivity of the ground is measured by sending current into the ground at the current electrodes and the corresponding potential difference is measured at the potential electrodes, which is then converted to apparent resistivity value by multiplying with an appropriate geometrical factor (Zohdy et al. 1974; Telford et al. 1990). Geophysical resistivity techniques are based on the response of the earth to the flow of electrical current. In the field, the electric resistivity method consists of measuring the electric potential difference between two electrodes in an electric field as induced by two current electrodes (Telford et al. 1990).

2.2. Seismic method

The seismic method uses both reflected and refracted energy waves to measure how fast and what paths these waves travel through different types of lithological units. This method involves the creation of a small shock at a depth of about 1 m either by the impact of a heavy instrument or by a small explosive charge. The arrival of shock waves at various distances is measured with sound detectors, also called geophones, placed on the ground surface (Francis and Raitt 1967 and Bouwer 1978). This method is suited for shallow geophysical explorations and it works on Snell's principle in which all soil layers are horizontal and each layer is homogeneous and isotropic (Huisman et al. 2003).

2.3. Electromagnetic methods

This method induces a current in the ground with an alternating current-transmitting coil. The magnetic field around the coil induces an electrical field, which is based on the properties of the medium and the moisture content. The terrain conductivity is a form of electromagnetic method where the transmitting coil and receiver coil are mounted a fixed distance (Zohdy et al. 1974; Mishra 2011). The most important application of electromagnetic method is to detect buried features such as waste disposal sites and lost underground storage tanks and pipelines.

2.4. Microwave remote sensing

It is satellite-based active and passive remote sensing and used for soil moisture in large catchments. This method can be used in the day, night and all weather conditions. This technique is mostly depending on a high contrast between the dielectric constant of dry soil (approximate value is 3) and the dielectric constant of water (approximate value is 80). The dielectric constant of soil is mostly depending on four factors, i.e. soil moisture, texture, bulk density, specific surface area and frequency of microwave remote sensing (Dobson et al. 1985; Njoku and Entekhabi 1996).

2.5. Ground-penetrating radar (GPR)

GPR is used to delineate features of the geologic setting, map the distribution of buried objects and predict the configuration of the water table and stratigraphic boundaries. GPR is based on the reflection of radio waves from discontinuities under the earth's surface (Davis and Annan 1989; Fisher et al. 1992). It is also used for the estimation of moisture content and porosity of soil (Greaves et al. 1996; Van Overmeeren et al. 1997; Huisman et al. 2001).

2.6. Ground magnetic resonance (GMR)

The physical property used in near-surface geophysics applications of NMR is the spin of the hydrogen protons in water molecules. The magnetic spin is an intrinsic property of an atom that possesses an angular momentum, without physically rotating, and an associated magnetic moment (Coates et al. 1999; Walsh 2008; Dalgaard et al. 2012). When the magnetic moment of the hydrogen protons is situated within a static magnetic field (B_0), they possess the static magnetic field at the Larmor frequency $f_L = \frac{w_L}{2\pi} = \frac{-\gamma|B_0|}{2\pi}$ where $\gamma = 0.2675 \times 10^9\ s^{-1}T^{-1}$ is the proton gyrometric ratio and w_L represents the Larmor angular frequency. The Larmor frequency depends on the static field strength, which ranges over multiple orders of magnitude for geophysical NMR measurements (Dunes et al. 2002; Levitt 2001). For surface NMR measurements, the static field is Earth's magnetic field (B_E), which ranges from about 25 to 65 μT, corresponding to Larmor frequencies ranging from about 1.06 to 2.8 kH. For borehole NMR, the static field is generated by the instrument and the field strength ranges from 5.75 to 57 mT corresponding to Larmor frequencies ranging from 0.245 to 2 MHz. Geophysical lab-NMR studies use instruments with a large range of magnetic field strengths. Measurements can be collected using Earth's magnetic field or using instruments with field's strengths up to 9.4 T; this corresponds to Larmor frequencies on the order of kHz to 400 MHz (Levitt 2001).

At thermal equilibrium in the static magnetic field, the volume of water in the measured sample acquires a small net magnetic moment. This moment is the sum of all the magnetic moments associated with each of the protons in the volume and points in the same direction as the static magnetic field (Dunn et al. 2002). The net magnetization vector at thermal equilibrium is given by (Curie's law)

$$M_0 = \frac{n\gamma^2 h^2}{4K_B T} B_0. \quad (1)$$

Here, n is the number of protons per unit volume; $\gamma$is the proton gyromagnetic ratio; h is the reduced Plank's constant; T is the absolute temperature; and K_B is the Boltzmann's constant.

The NMR experiment begins when the protons, initially at thermal equilibrium, are perturbed by an energizing pulse tuned to the Larmor frequency. If this pulse is applied and then removed, the protons move away from and then relax back to thermal equilibrium. As the protons relax, they emit a measurable signal. In porous media, NMR relaxation is well described by the phenomenological Bloch-Torrey equations (Bloch 1946; Torrey 1956). The solution to the Bloch-Torrey equations is a multiple exponential (multi-exponential) decay in the transverse direction with respect to the direction of the static magnetic field, i.e. the xy-plane, and multi-exponential growth in the longitudinal direction, i.e. the z-plane (Brownstein and Tarr 1979)

$$E_{xy}(t) = E_0 \sum_i f_{2i} e^{-\frac{t}{T_{2i}}} \quad (2)$$

$$E_z(t) = E_0 \left(1 - \sum_i f_{1i} e^{-\frac{t}{T_{1i}}}\right). \quad (3)$$

Here, $E_{xy}(t)$and $E_Z(t)$are the transverse and longitudinal components of the NMR signal; $E_0$is the initial signal magnitude and is proportional to the number of protons or volume of water in the measured sample. f_{2i} is the proportion of the magnetic field relaxing in the transverse direction with relaxation time T_{2i}, and similarly, $f_{1i}$is the proportion of the magnetic field relaxing in the longitudinal direction with relaxation time T_{1i}. For NMR relaxation in fluid-saturated geologic material, it is often assumed that relaxation occurs in the fast-diffusion, or surface-limited regime.

The GMR directly detects the presence of groundwater using the phenomenon of proton nuclear magnetic resonance. Proton NMR is observed when proton spins associated with hydrogen atoms in groundwater are subjected to a perturbation in the background magnetic field. In this static magnetic field, the proton spins will preferentially align in the same direction as the field and so form a small magnetic moment and the background field is earth's magnetic field (Vouillamoz et al. 2012).

The spin magnetic moments associated with groundwater can be excited from their equilibrium state by transmitting a radio-frequency (RF) pulse at a specifically tuned frequency. This pulse, generated on surface coils, causes a portion of the spin magnetization to rotate perpendicular to the background field and it is known as a transverse plane. In this excited state, the magnetization will then process about the background field and generate an RF signal which has the same frequency as the transmitted pulse. This frequency is known as Larmor frequency, and it is proportional to the magnitude of the background magnetic field. For hydrogen in water, the Larmor frequency can be calculated by$f = 4258(Hz/Gauss) * B_0(Gauss)$, where B_0represents the static magnetic field (Hetrich 2008).

3. Study areas

In this study, two sites are selected for survey and experiment. First site is Solanipuram bridge with latitude 29.8796 and longitude 77.9006. Second site is mango garden near Paniyala with latitude 29.8525 and longitude 77.8460. This study area is within the northern part of Uttarakhand of India. The selected field site near Solanipuram River and Paniyala which is located in Haridwar district of Roorkee tehsil are shown in Figure 1a (Google map). An experimental setup of GMR instrument during the experiment is shown in Figure 1b.

3.1. Experimental procedures

The primary steps involved in setting up a survey are described below:

(a) **Determining survey geometry**

First, we determine the number of coils and coil geometry for ground survey. For noise cancellation, two coils were used as a transmit coil and noise cancellation coil, respectively. The detection coils were located directly over a region of interest and preferably in the area with minimal noise. The shape of the detection coil can be taken as square or circular.

(b) **Lay out surface coils**

To lay out a loop, first one has to select the number of surface coil cable reels or surface coil extension reels that will be required to complete the length of the loop with any

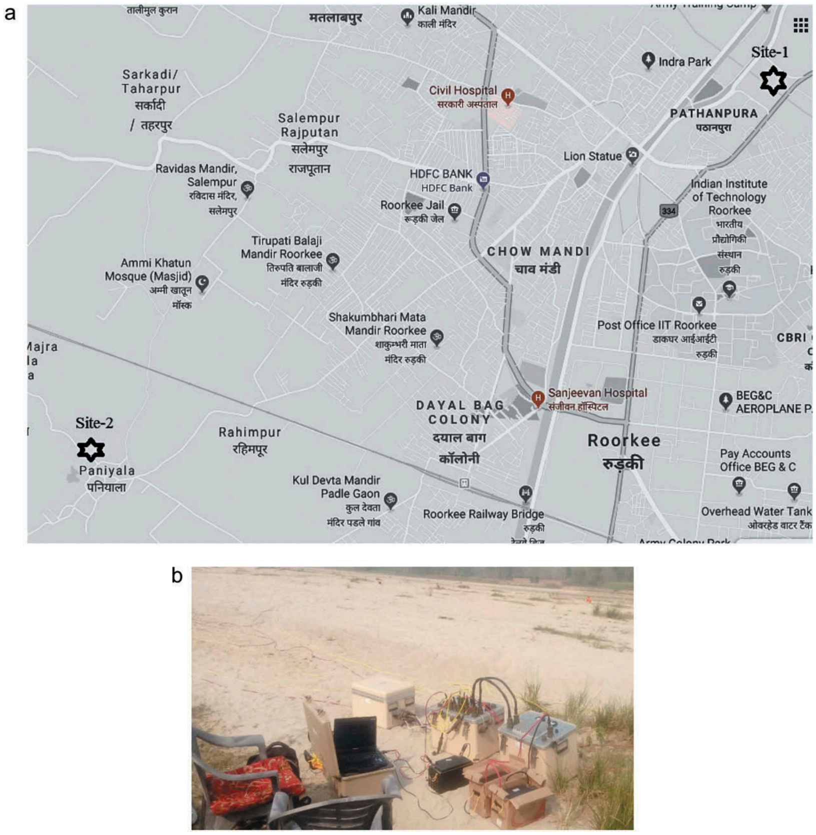

Figure 1. (a) The Google map shows the site 1 and 2 for conducting field experiments. (b) Experimental setup of GMR instrument in the field during the experiment.

necessary extensions. This is followed by laying cable in the desired arrangement as one walks away from the transmitter.

(c) **Setting up the computer**

During setting up the computer, one has to turn on a field laptop computer and connect it to USB cable and the GMR transmitter.

(d) **Tuning the transmit loop**

The GMR autotune software was used to determine the tuning parameters of an arbitrary surface coil, and to calculate the optimal tuning capacitance for resonance at a designated Larmor frequency. For multiple-turn coil, the turning capacitance for an N-turn coil is approximately $(1/N^2)$ times the values given in the manual guide. Start the GMR autotune program on the field laptop computer and enter the value of Earth's local magnetic field intensity (B = 47975.7 nT). The program automatically calculates and displays the local NMR (Larmor) frequency and it was found to be equal to 1976 Hz. The value of initial tuning capacitance equal to 7.5 μF and tuning step size equal to 50 Hz was used. Afterward, one has to process the GMR autotune control screen.

(e) **Data collection**

First of all, the cable was spread in the field having a circular shape of size 30 m. Proper connection was done between cable and GMR equipment. Afterward, GMR equipment started to collect raw data from the field and data were used in the inverse software to get an actual distribution of water below the ground surface.

4. Experimental results

4.1. Fisrt site for conducting experiment

4.1.1. GMR method

First experiment was conducted near Solanipuram river on 24 May 2018 using GMR equipment. The diameter of wire loop equal to 20 m was used and data were collected for 24 stacks. The values of Earth's magnetic field B = 47985 nT, Larmor frequency equal to 1976 Hz was used during the experiment. After processing the data, the sounding curve is shown in Figure 2a. Figure 2b shows the resolution matrix which represents the 2D display of inverted point spread function and sensitivity as a function of depth.

Figure 3a shows the variation of mobile and immobile water with depth. Water content which is pink color indicates mobile and green color shows immobile. Hydraulic conductivity can be calculated by multiplying k relative to 10 to the power minus 8. The depth versus T_2^* graph shows that the different soils are present at different depths of underground surface, i.e. silt and clay up to the depth of 10 m below that sand and gravel up to the depth of 20 m and below 20 m bedrock lime. Figure 3b shows the resolution matrix which represents the variation of water content with depth. This specifies an upper limit value of the largest pulse moment used in the acquisition. Variation of normalized moisture content represents the presence of pore space at deferent depths.

4.1.2. Electrical resistivity tomography (ERT) method

Two-dimensional ERT experiments were conducted at site1. Schlumberger array configuration of electrode was used in the survey. The survey is conducted by '4-point light 10W device' and raw data were recorded by Geo Test software. The survey length of 150 m with electrode spacing 3 m was

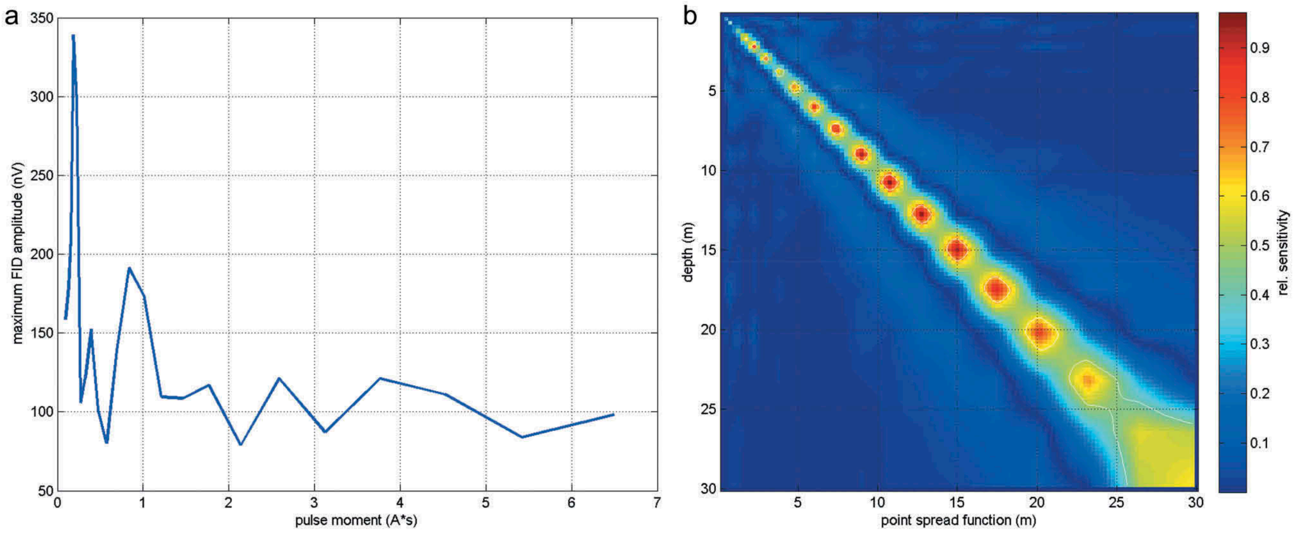

Figure 2. (a) The maximum FID magnitude vs pulse moment (A*s). (b) Resolution matrix.

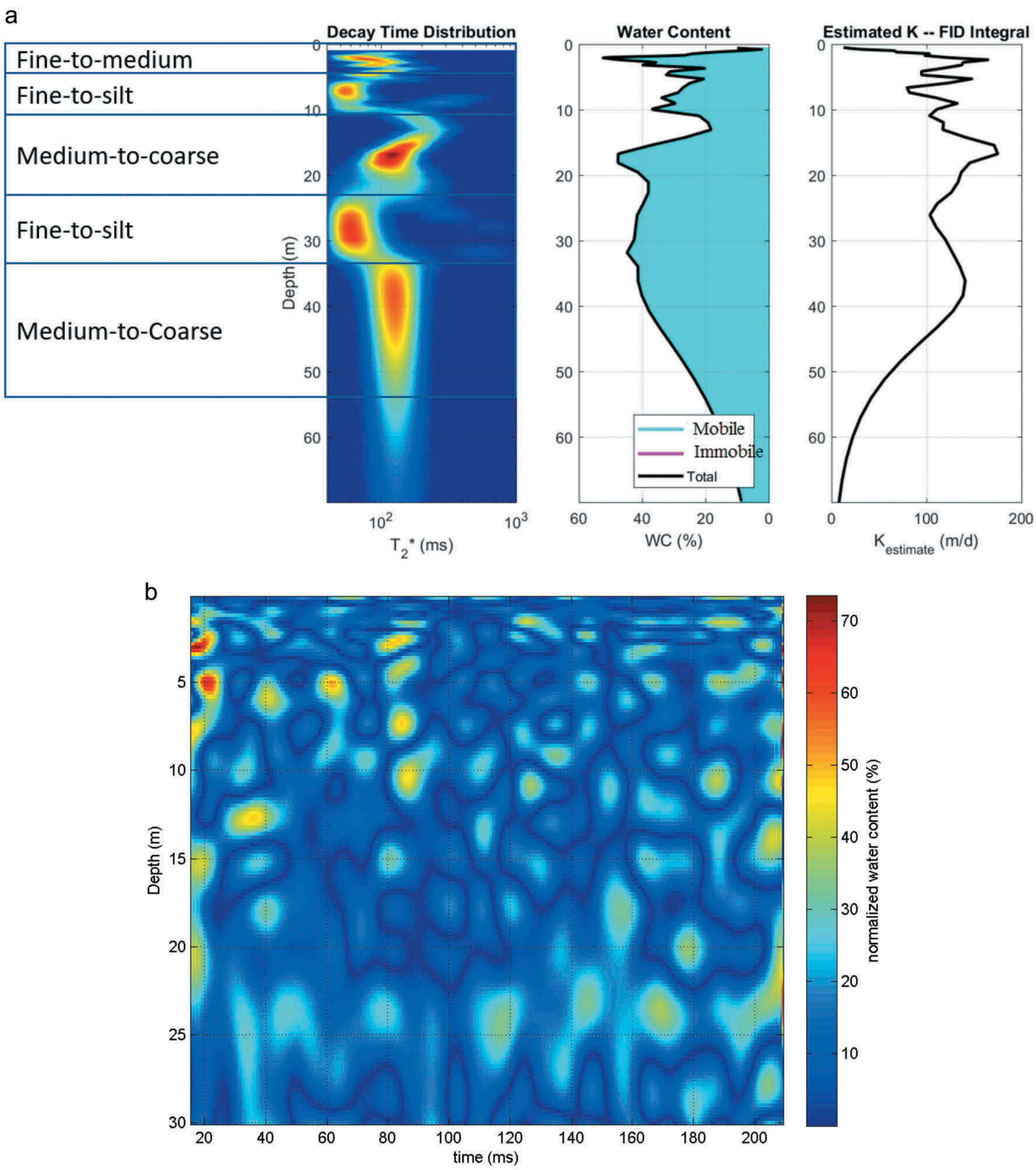

Figure 3. (a) Vertical distribution of water and hydraulic conductivity. (b) The Resolution matrix of 1D inversion.

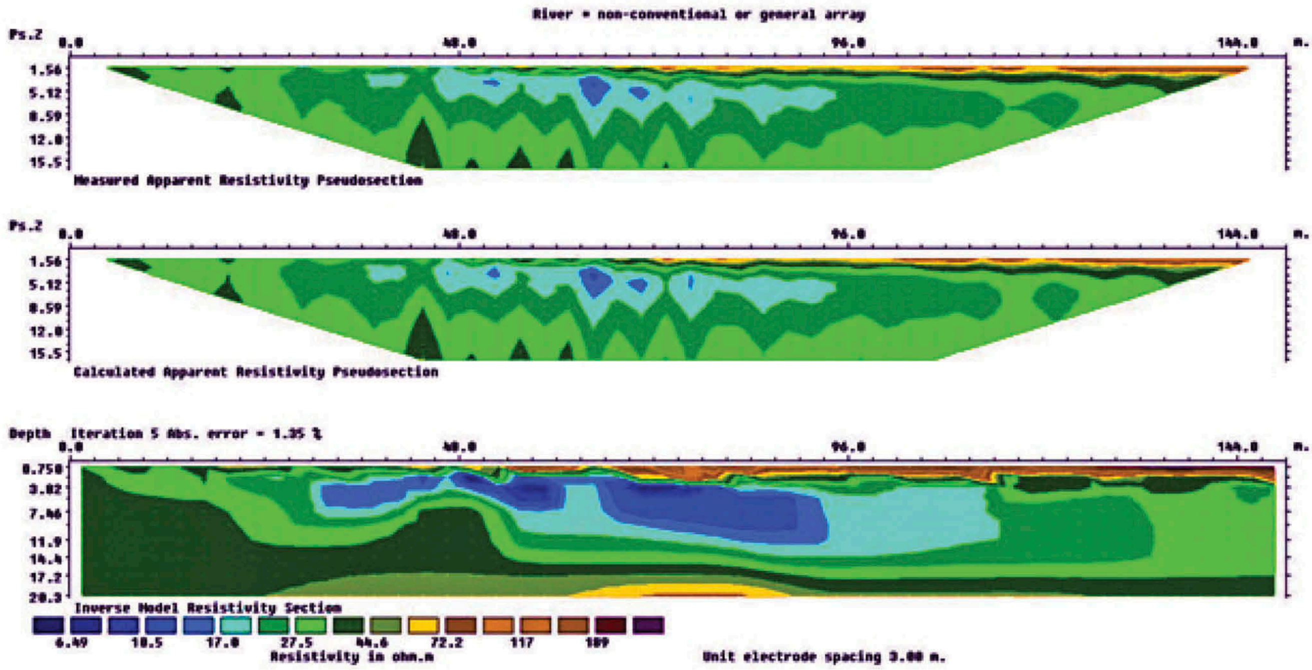

Figure 4. 2D Resistivity pseudo-section inverse models by Schlumberger method Solanipuram Bridge at Roorkee (first site).

considered during conducting experiments. The raw data were processed and interpreted by RES2DINV software in the laptop. The ERT images of the earth subsurface obtained at proposed first site are shown in Figure 4.

The inversion depth up to 20.3 m was obtained. Root-mean-square error (RMS) value of the inverse model is 1.35% and resistivity varies from 6.49 ohm-m to 189 ohm-m. Categorization of the aquifer by the ERT, GMR and borehole data is also available near site 1 (Table 1). The results indicate that the characterization of soil strata is approximately matching among GMR, ERT and borehole measured data.

Generally, the efficiency of the resistivity meter is more than 90%; however, in our study, the efficiency of the inversion result is 98.65% which shows very good relation with the borehole aquifer data (Table 1). The limitation of resistivity meter is the following: (a) the contact of electrodes with soil is not good in the presence of gravel and sand in the top layer of the soil. Thus, efficiency and accuracy of the instrument are reduced in case of gravel and sand present in top layer; (b) underground wiring may also affect the efficiency of the instrument due to increase in electromagnetic noise; and (c) presence of many people, vehicle traffics and animal can also affect the efficiency of the instrument.

4.2. Second site for conducting experiment

Second site is selected near Paniyala of city Roorkee and experiments were conducted on 20May 2018 using GMR. A graph of maximum NMR signal amplitude versus pulse moment is shown in Figure 5a. This is a one-dimensional display of the inverted point spread function and sensitivity as a function of depth (Figure 5b). Resolution matrix shows a 2D display of the inverted point spread function and sensitive as a function of depth. This function can be used to estimate the limits of spatial resolution as a function of

Table 1. Subsoil characterization by borehole, electrical resistivity tomography and ground magnetic resonance methods near Solani river near Roorkee.

Symbols	Depth of Investigation (m)	Borehole test	Electrical resistivity (Ohm-m)	ERT test	GMR test
	0–5	Poorly graded sand, Silty clay	6–189	Sand, Clay, and Fresh water	Sand, Clay and Fresh Water
	5–10	Silty sand and Silty clay	17–44	Clay, Fresh water	Silty sand, Clay and Fresh water
	10–15	Clay, Sand and Gravel	27–44	Clay, Fresh water	Clayey sand and Fresh water
	15–20	Silty gravel with sand	44–117	Clay, Sand, Fresh water	Sand and Fresh water

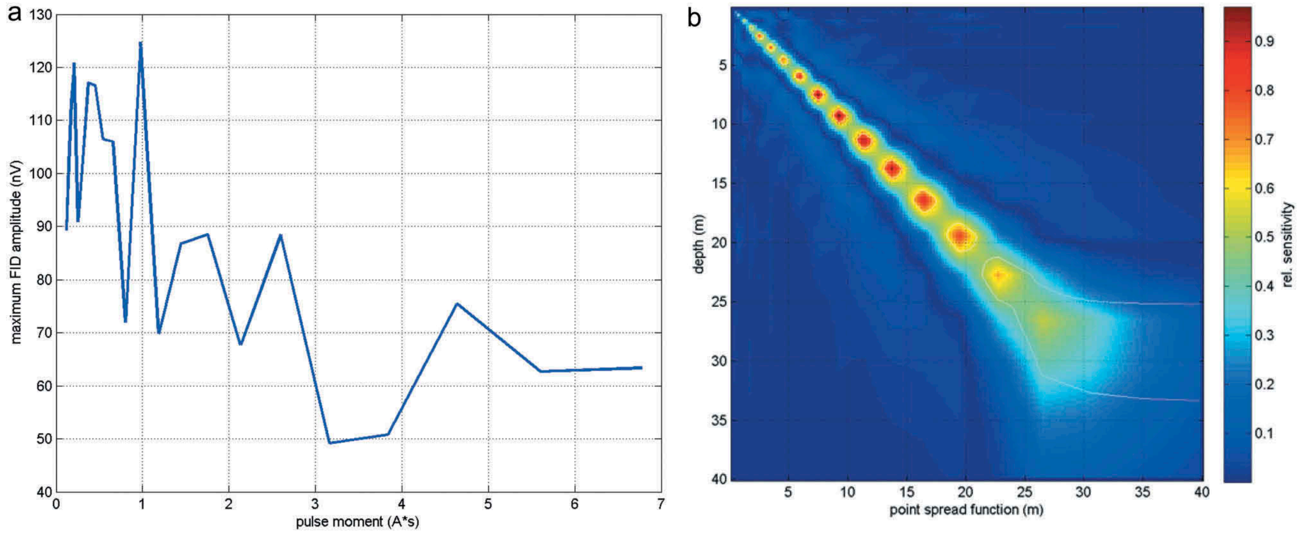

Figure 5. (a) Sounding curve. (b) Resolution matrix.

depth. After the initial inversion, the FID Display will loop through each depth layer, showing the extracted NMR signal from each layer normalized to the water content of 100%. The single magenta-colored line indicates the amplitude of the mono-exponential T_2^* fit for each moment.

This is a 1D display of the inverted point spread function and sensitivity as a function of depth. This function can be used to estimate the limits of resolution. In Figure 6, the first left-hand side graph shows the variation of FID with depth and blue color represents the moisture content variation with depth. This display shows the result of 1D inversion with mono-exponential fitting and estimation of water content and mean T_2^* relaxation rate versus depth. The 1D inversion display also includes a low-SNR permeability indicator, calculated as the square of the time domain integral of the NMR signal from each layer, evaluated at the Larmor frequency. The NMR frequency and phase are also displayed if selected. Variation of FID shows the hydraulic conductivity. From this graph, it is seen that the sandy soil occurs up to 5 m. From a depth of 5 m to 30 m, a mixture of sand, silt and clay occurs.

This is an estimate of the bound water, free (mobile) water, and total NMR-detected water content as a function of depth (Figure 7). Watertable occurs at 6 m below the ground surface. The water content at each depth interval is sorted into a continuous distribution of water content versus T_2^* decay rate. A cutoff of T_2^* = 30 ms is used to

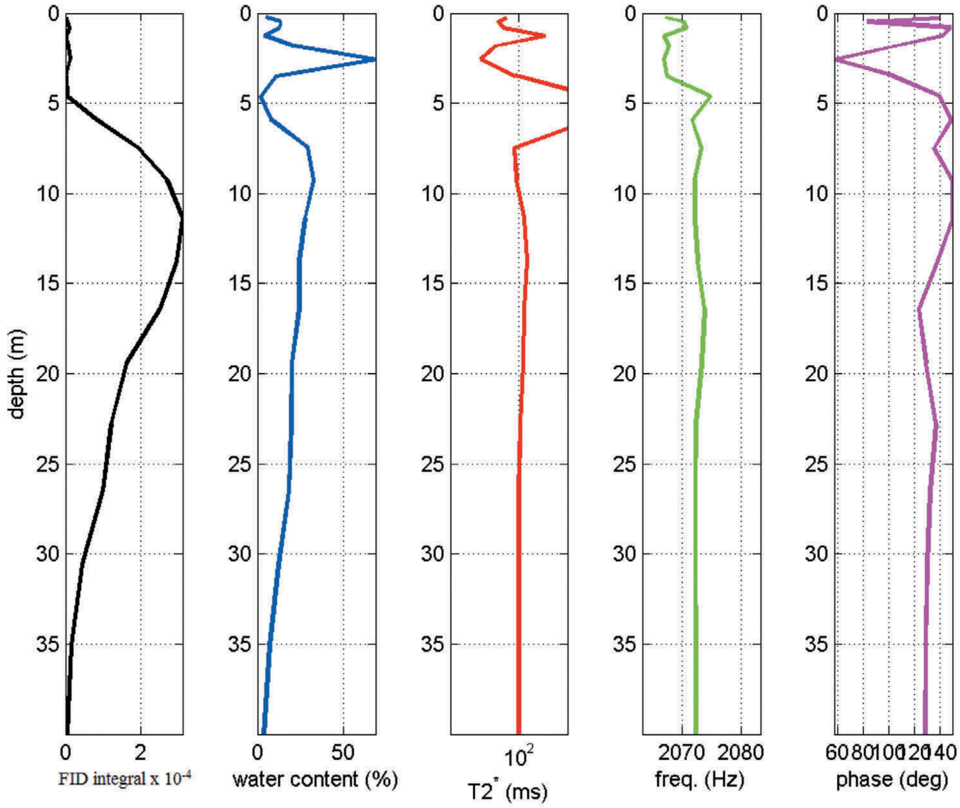

Figure 6. Variation of FID and water content with depth.

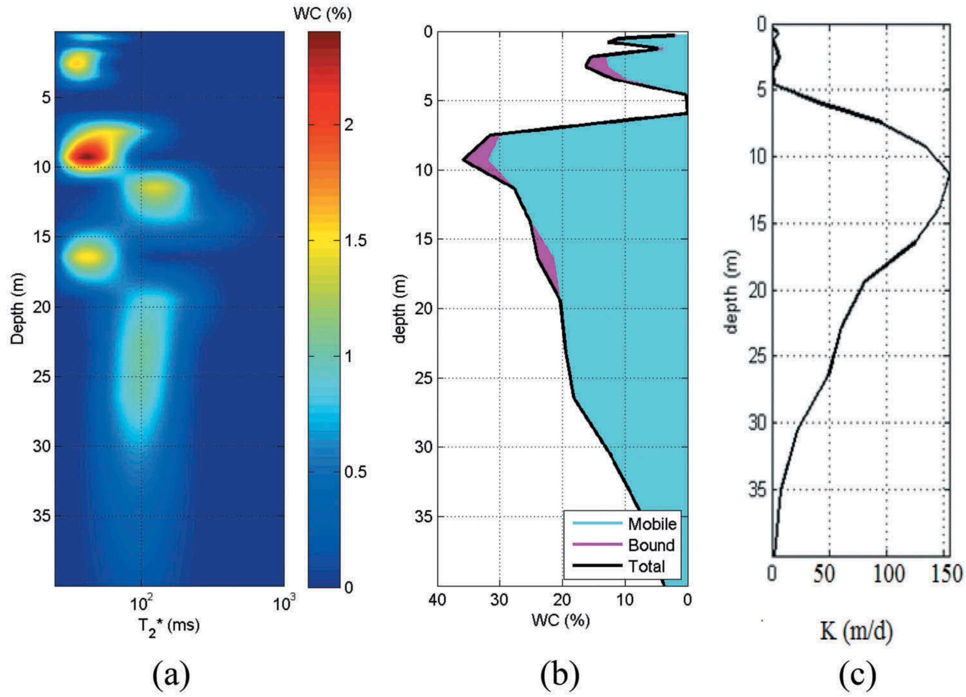

Figure 7. Vertical distribution of water content estimated hydraulic conductivity with depth.

segregate and then bound water content ($T_2^* \leq 30$ ms) from free water content ($T_2^* > 30$ ms).

The second graph shows the water content percentage graph in which T_2^* decay rate which is greater than 33 ms will be called as mobile and the graph which is less than 33 ms called as immobile. For mobile graph, color is light greenish and for immobile graph, color shows pink and black shows the total water content (Figure 7b). The blackline curve in Figure 7c shows the hydraulic conductivity variation continuously. Hydraulic conductivity is used to measure the velocity of water under the subsurface of the earth.

Figure 8 shows a plot of the multi-exponential distribution of water content versus time. The program will compute and display a multi-exponential fit, estimating the distribution of water content versus T_2^* relaxation rate for each depth layer. The multi-exponential fitting procedure fits each extracted NMR signal to a set of exponential functions with variable initial amplitude (water content) and T_2^* decay ranging from 10 ms to 1000 ms. Specifically, the various mixtures of sands, gravels, silts and clay are resolved into various layers.

The precision, accuracy and efficiency measurements of the GMR equipment have been already validated by researchers based on the experiments conducted in the field and lab (Meju e al. 2002; Hertrich 2008). However, the GMR equipment measures the subsurface soil up to 100 m below the surface of the soil accurately. The main limitation of the GMR equipment is that it produces a noisy error in the presence of high voltage electric wire near the study area. The study areas

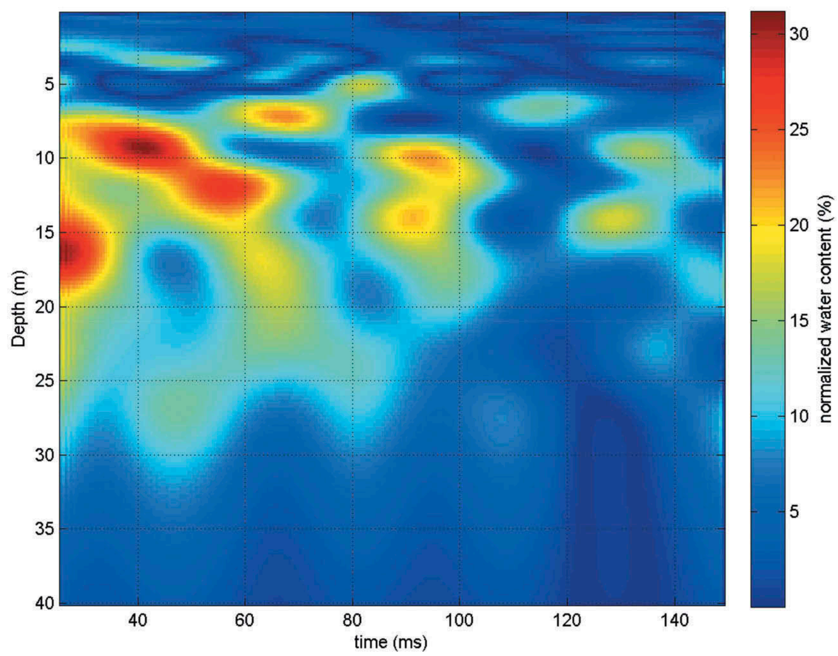

Figure 8. Multi-exponential distribution of water content versus time and depth.

should be flat or having a gentle slope to easily accommodate surface coil loops. The main advantage of the equipment is that it can measure the subsurface water content and hydraulic conductivity of aquifer materials from the surface of the soil without borehole. Hence, the efficiency of the GMR equipment is more than 95% which shows very good relation with the borehole data.

5. Conclusions

In this study, different methods for geophysical investigations are discussed briefly. Afterward, two sites near Roorkee were selected for carrying out experiments using GMR and ERT. The measured subsurface soil strata using GMR and ERT were compared with borehole data for site 1. It was found that the measured subsurface strata using GMR and ERT are in conformity with the borehole data. Thus, it can be summarized that the GMR technique is more accurate, time-saving and non-invasive as compared to the borehole technique. Also, the estimated value of hydraulic conductivity using GMR and resistivity meter can be used for modeling groundwater flow in the subsurface soil which, otherwise, would not have been feasible using disturbed soil samples during borehole tests.

Acknowledgments

This work was financially supported by Pan India Consultants Pvt. Ltd. Gurgaon, Haryana, India. Special thanks to Mr Vivek Bansal, General Manager and his team.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Pan India Consultants Pvt. Ltd. Gurgaon, Haryana-122015, India.

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