Electrical structure of an unsaturated zone related to hard rock aquifer

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The flow characteristics of moisture through the unsaturated zone remains an enigma for scientific understanding and groundwater studies. Prediction and modelling of moisture movement through unsaturated medium forms an important aspect in hydrology as it helps estimating the recharge to groundwater system. Electrical resistivity measurements through time lapse electrical resistivity tomography provide a means to study the variability of moisture content as a function of time. In the present study, the influence of natural recharge on the correlation structure of resistivity data has been studied over a typical hard rock aquifer. This study shows the non-uniform distribution of moisture in the vertical profile following the rainfall.

Keywords: Hard rock, time lapse electrical resistivity tomography, unsaturated zone, variography.

ELECTRICAL resistivity is a function of the textural and structural characteristics and is particularly sensitive to the water content[1] of the geological formation. Soils are a porous medium, made up of nonconductive solid particles and contain electrolyte solutions that conduct electric current by the movement of free ions in the bulk solution and ions adsorbed at the matrix surface. Water infiltration and aquifer recharge can be determined by studies of variations in electrical sounding curves[2,3] as change in moisture content affects the resistivity in a nonlinear way. Groundwater flow direction and velocity were determined through observation of the electrical resistivity decrease in alluvial deposits following salt water tracer injections[4]. The surface multielectrode method, known as electrical resistivity tomography (ERT), offers some interesting perspectives. This method is particularly well suited for the 2D description of geological structures perpendicular to the measurement electrode line[5–8]. ERT presents advantages for monitoring and is used in hydrological and environmental studies to monitor solutes and fluid flow in porous media.

Monitoring of vadose zone water flow such as water infiltration, root water uptake, movement of moisture front effects has been reported[9–13]. Three-dimensional monitoring of small fresh water plume movements through the vadose zone has become possible[14]. Zhou *et al.*[15] also proposed a non-invasive method to monitor soil water content changes over time by means of 3D electrical tomography. The cited works revealed the capability of ERT data in monitoring water infiltration in unsaturated soil or through the vadose zone, as is the present case. Our study, unlike the previous ones, investigates recharge flow dynamics with respect to changes in electrical resistivities.

The primary geophysical method for monitoring the time and spatial pattern of recharge in the unsaturated zone is ERT using small electrode spacings on the surface. ERT is particularly appealing because it is non-invasive and allows for long-term quasi-continuous and spatially extensive data for monitoring in the saturated and unsaturated zones. Earlier workers[16] attempted to track the changes in resistivity through time and their work has been found to be useful for detecting the temporal changes in the moisture content of the unsaturated zone. Arora *et al.*[17] have used the time lapse ERT (TLERT) to monitor variations in resistivity tomograms for short duration recharge. Barker *et al.*[18] have used the high-resolution electrical imaging to map the 3D movement of fluid in the unsaturated zone of the sandstone at a test site. Dutta *et al.*[19] have used the resistivity imaging data of the hard rock terrain and also processed it to obtain a 3D variation of resistivity in the granitic terrain and identified the potential water-bearing zones by correlating the results. Long-term monitoring of recharge at a fixed location under different meteorological conditions will enable an improved understanding of groundwater recharge mechanisms, a critical component of the watershed system.

The variability of moisture content is determined by the variability of electrical resistivity measurements through ERT. In the present study, the influence of natural recharge on the correlation structure of resistivity data has been documented by analysing the variogram of the electrical resistivity imaging data. This analysis provides the condition or the extent of saturation of moisture in the unsaturated zone.

Resistivity measurements were carried out with the resistivity meter Syscal R1 Junior (IRIS Instruments, Orléans, France) equipped with 48 electrodes at the National Geophysical Research Institute (NGRI) campus (Figure 1). The intensity and voltage accuracy is 0.3%, which is consistent with the measurements carried out under constant hydrogeologic conditions for about 10 h were persistent within a tenth of an ohm-metre, i.e. 1000th of the measured resistivity could reach several ohm-metres between two sets of measurements 1 h apart. The electrodes remained on the soil surface during all the experiment time to avoid any electrode polarization changes and to ensure best measurements quality.

ERT has evolved as a potential geophysical technology to monitor the natural changes in resistivity as it is not dependent on hydraulic, chemical and thermal conditions in the subsurface. This knowledge of resistivity

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Figure 1. Study area with two sites S1 and S2.

can be used to obtain information about subsurface flow and moisture movement taking place in the unsaturated zone. TLERT is a new prototype that has been planned for the long-term monitoring of recharge movement in the hard rock terrain of earth's subsurface. Electrical resistivity imaging has been used extensively in the past for 2D imaging of the subsurface. But for monitoring the flow of water through the unsaturated zone, the change of subsurface resistivity is checked with the change in time. In the present study, the change in resistivity distribution has been observed in the unsaturated zone as an aid to examine the movement of natural recharge, i.e. rainfall.

The additional work has been to introduce a simple, single step kriging routine that improves on existing methods used with 2D electrical resistivity data and the soil moisture data. A statistical analysis was subsequently made to explore the effects of spatial variability of the electrical resistivity–moisture relation on the interpretation of the change in water content in the vadose zone, using the change in electrical resistivity.

The experimental field set-up was laid along a profile of 94 m with the electrode spacing of 2 m at site S1 at NGRI campus (Figure 1). The Wenner–Schlumberger array was used to survey the profile. A total of 529 data points were measured at 23 data levels, which lead to the plotting of a pseudosection.

The acquired TLERT data (Figure 2) and soil moisture data were collected from the field site S1 to study the spatial variability of the electrical resistivity–moisture relation. The variography and block kriging approach was employed to improve the level of interpretation possible from the measured TLERT data.

A total of 35 tomograms were obtained, but only a few relevant ones are being shown here. The numerals along the numbering denote the date of data acquisition. The subsequent models show the difference in the resistivity of the models obtained from the inversion of the initial and the time-lapse datasets.

On the basis of the profile at site S1, the first layer is extremely resistive as seen in the tomograms. The layers below the first layer, at a depth of 2 m, are much less resistive. They can be identified as the dry red soil sediments above the saturated levels, with the intermediate unconsolidated sapprolite.

The altitude on the northern side of the profile is slightly higher and most of the measurement devices (like neutron probe for soil moisture, borewell for water level measurement, raingauge for measuring rainfall) are situated on the southern side of the profile. The resistivities of the underlying layers are less resistive in the profile 'g' to 'm' (Figure 2), which indicate that recharge is more downwards along the profile. Overall change observed in the layers show that water flux moves both

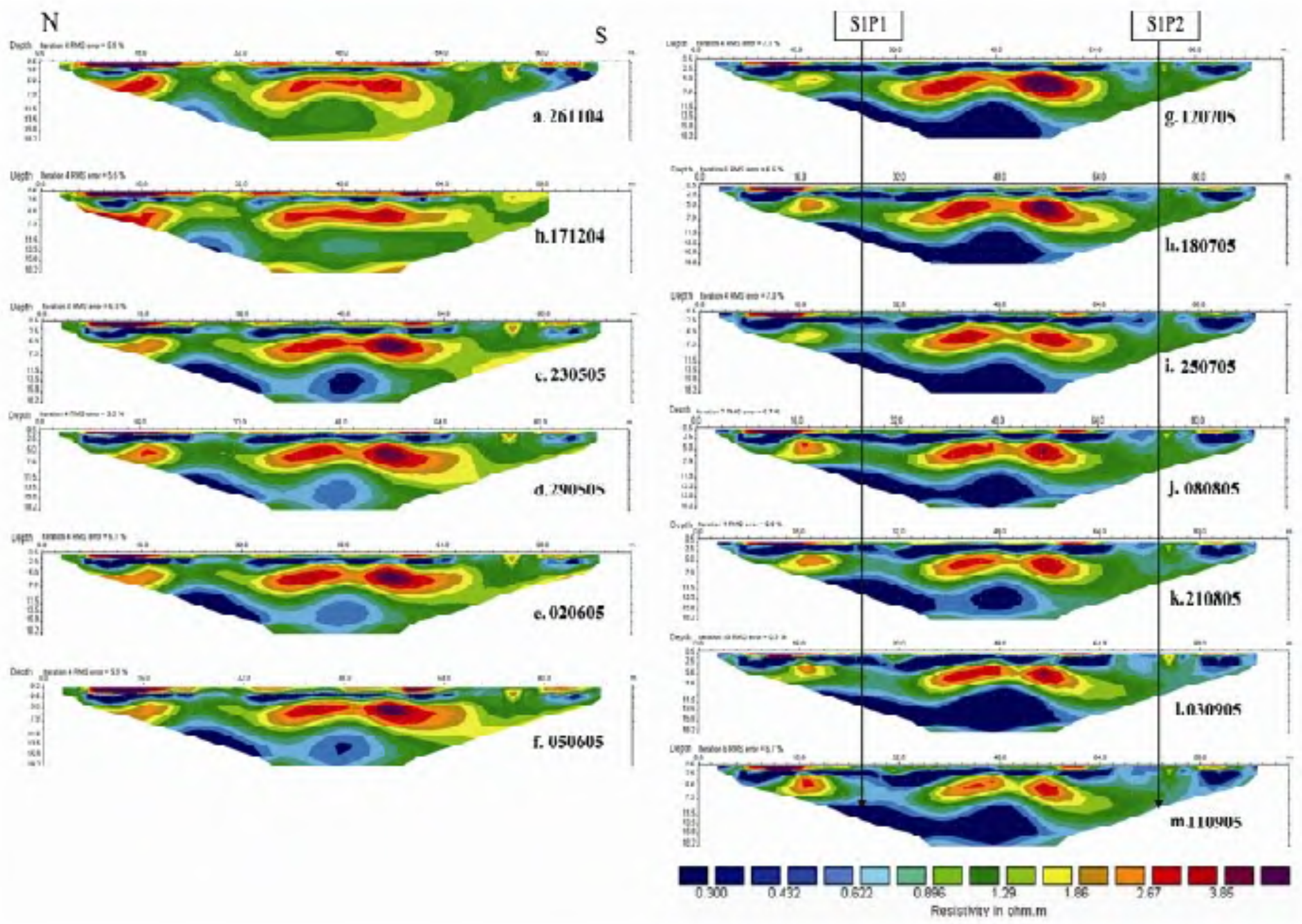

Figure 2. Tomograms after the rainfall events at site S1.

horizontally and vertically. This may be confirmed with the soil moisture profile, shown in Figure 3. The highest resistivity is in the centre of the profile between 35 and 63 m located vertically at a depth of 3 m. This may be indicative of the locally thicker dry sediments above the aquifer or the presence of a resistive body like a boulder that is a common feature. The resistive body appearing at a depth of 3–8 m may either be a 3D artifact due to the small relief or the actual presence of more resistivity at the depth such as solid matrix. It can also be due to the absence of minor fractures for recharge or due to the lack of connecting porosity.

Figure 2 shows the tomograms for site S1 which are the differenced absolute inversion rather than the difference inversions[20,21]. The difference inversions would appear somewhat different because systematic errors from the field and discretization errors in the forward modelling tend to cancel out. The same approach is being followed to obtain the pseudosection at the other representative places.

Quantitatively, the percentage differences in electrical resistivities associated with the arrival of the recharge match the recharge measurement fairly well both in time and space. The match is the scorer for the upper layers of the pseudosection because the fluid or rainfall measurements only indicate mobile recharge (soil moisture/rainfall), whereas the ERT measures mobile and immobile salts.

At the passage S1P1 existing between 20 and 42 m resistivity shows the vertical variations. Non-uniform distribution of the moisture exists in the vertical profile following the rainfall infiltration. The passage of recharge flow is clear in Figure 4.

Farther away on the line, the resistivity highs and lows exist in patches. At the indicative passage S1P2, between the profile lengths of 68–76 m, the resistivity shows noticeable variations. These variations may probably exist because of the small scale variability of the geological material. Due to high porosity, the porosity is well connected to the depth of 12 m ultimately merging into the aquifer. But this part is not being studied as there is not much control of data at this part of the profile.

The zone between 20 and 42 m shows the vertical and horizontal infiltration of the natural recharge. The pathways of the moisture could be deciphered.

The relative percentage change in the electrical resistivity is clear from the comparable pseudosections.

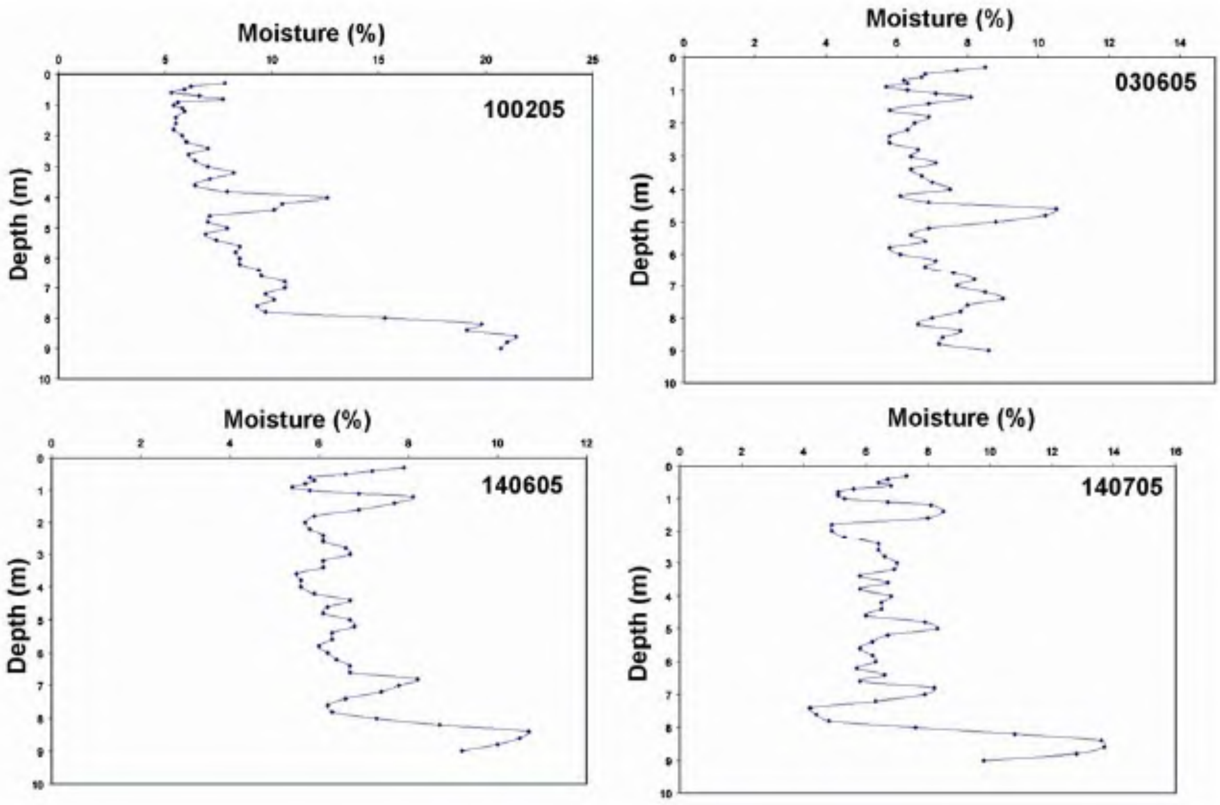

Figure 3. Soil moisture profiles at site S1.

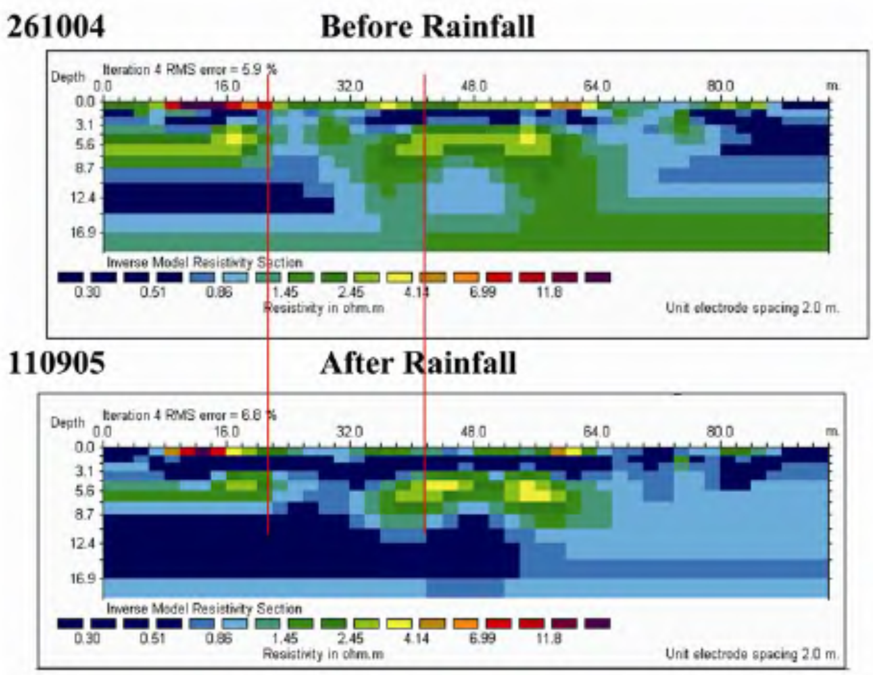

Figure 4. Electrical resistivity tomography model sections, before rainfall and after rainfall at S1.

This clearly brings out the respective zone of preferential recharge, shown in the zone between the two red lines, along the profile length of 21–42 m.

TLERT shows that the resistivity is constant with time and is reliable and sufficient to represent the profile (Figure 2). This also confirms and justifies the most common application of electrical resistivity methods applied for groundwater prospecting as the resistivities do not change in time, the medium being saturated.

1. Unsaturated zone of the granitic terrain is studied and analysed using a comparatively simpler approach; for example, geophysical analytical methods like TLERT and soil moisture measurements as neutron probe. The surface geophysical methods are non-invasive and it is easy to carry out repetitive measurement as well as at many locations while measurement of soil moisture through neutron probe requires complicated procedures of drilling slim holes, sealing it with aluminum tubes and calibration using the known conditions.

2. Prior to recharge there is no continuity of moisture, but after the rainfall continuity exists.

3. The repeated ERT/TLERT could support estimation of rainfall recharge qualitatively.

The present work shows the effect of rainfall recharge on the resistivity and maps the moisture movement through the unsaturated zone leading to the water table by a series of experiments for a longer period. Barker and Moore[9] discussed this in an experiment carried out at Birmingham, England. It is clear from the tomograms that there is a decrease in the resistivity values at the deeper depth levels due to the migration of water from the near surface zone. This work is also an attempt for the 4D studies of the unsaturated zone where time factor acts as an important aspect for the recharge flow and its movement through the unsaturated zone. The results are estimated to yield realistic values under field conditions when studied collectively with the hydrological information.

The analyses of the pseudosection with time indicate that the assumption of the piston flow of the moisture front is not valid in hard rocks. The results of this study provide some indirect parameters to the well-known Richard's equation while studying the unsaturated zone.

1. Sheets, K. R. and Hendricks, J. M. H., Non-invasive soil water content measurement using electromagnetic induction. *Water Resour. Res.*, 1995, **31**, 2401–2409.
2. Barraud, J. P., Dieulin, A., Ledoux, E. and de Marsily, G., Relation entre mesures gé ophysiques et flux de l'eau dans les sols non saturés, Rapp. LHM/RD/79/3, Ecole Natl. Supé rieure des Mines de Paris, Paris, 1979.
3. Cosentino, P., Cimino, A. and Riggio, A. M., Time variations of the resistivity in a layered structure with unconfined aquifer. *Geoexploration*, 1979, **17**, 11–17.
4. White, P. A., Electrode arrays for measuring groundwater flow direction and velocity. *Geophysics*, 1994, **59**, 192–201.
5. Griffiths, D. H. and Turnbull, J., A multi-electrode array for resistivity surveying. *First Break*, 1985, **3**, 16–20.
6. Griffiths, D. H., Turnbull, J. and Olayinka, A. I., Two-dimensional resistivity mapping with a computer controlled array. *First Break*, 1990, **8**, 121–129.
7. Shima, H., Two dimensional automatic resistivity inversion technique using alpha centers. *Geophysics*, 1990, **55**, 682–694.
8. Griffiths, D. H. and Barker, R. D., Two-dimensional resistivity imaging and modelling in areas of complex geology. *J. Appl. Geophys.*, 1993, **29**, 211–226.
9. Barker, R. and Moore, J., The application of time lapse electrical tomography in groundwater studies. *Leading Edge*, 1998, **17**, 1454–1458.
10. Benderitter, Y. and Schott, J. J., Short time variation of the resistivity in an unsaturated soil: the relationship with rainfall. *Eur. J. Environ. Eng. Geophys.*, 1999, **4**, 37–49.
11. Binley, A., Winship, P., Middleton, R., Pokar, M. and West, J., Observations of seasonal dynamics in the vadose zone using borehole radar and resistivity, paper presented at the Annual Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Environ. and Eng. Geophys. Soc., Denver, Colo., 2001.
12. Michot, D., Dorigny, A. and Benderitter, Y., Mise en evidence par resistivite electrique des ecoulements preferentiels et de l'assechement par le mais d'un Calcisol de Beauce irrigue. *C.R. Acad. Sc. Paris, Serie lia*, 2001, **332**, 29–36.
13. Michot, D., Benderitter, Y., Dorigny, A., Nicoullaud, B., King, D. and Tabbagh, A., Spatial and temporal monitoring of soilwater content with an irrigated corn crop cover using surface electrical resistivity tomography. *Water Resour. Res.*, 2003, **39**(5), 1138.
14. Park, S., Fluid migration in the vadose zone from 3-D inversion of resistivtiy monitoring data. *Geophysics*, 1998, **63**, 41–51.
15. Zhou, Q. Y., Shimada, J. and Sato, A., Three-dimensional spatial and temporal monitoring of soil water content using electrical resistivity tomography. *Water Resour. Res.*, 2001, **37**, 273–285.
16. Daily, W., Ramirez, A., Labrecque, D. and Nitao, J., Electrical resistivity tomography of vadose water movement. *Water Resour. Res.*, 1992, **28**, 1429–1442.
17. Arora, T., Krishnamurthy, N. S. and Ahmed, S., TLERT to decipher the unsaturated zone. Published and presented in the International Conference on Hydrological Perspectives for Sustainable Development, IIT, Roorkee, Allied Publishers Pvt Ltd, 2005, vol. II, pp. 846–852.
18. Barker, R. D., Hatzichristodulu, V. C. and Tellam, J. H., High resolution electrical monitoring of fluid flow through the unsaturated zone, 2000; www.envdiag.ceh.ac.uk/documents/Rbarker_final4~1.doc
19. Dutta, S., Krishnamurthy, N. S., Arora, T., Rao, V. A. and Ahmed, S., Application of 2D resistivity imaging as a potential geophysical tool for groundwater investigation, Presented at 29th Annual Convention of AEG, Guwahati, 2004.
20. LaBrecque, D. J. and Yang, X., Difference inversion of ERT data; a fast inversion method for 3-D *in situ* monitoring, Presented at Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Environ. and Eng. Geophys. Soc., Arlington, VA, 2000.
21. Singha, K., Binley, A. M., Lane Jr, J. W. and Gorelick, S. M., Electrical imaging of tracer migration at the Massachusetts Military Reservation, Cape Code. In Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), 6–10 April 2003, San Antonio, Texas, Proceedings: Denver, Colorado, Environmental and Engineering Geophysical Society, CD-ROM, 2003, p. 11.

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