Time Lapse Imaging in Studying the Unsaturated Zone and the Variographic Analysis of Resulting Resistivity Values.

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Summary

In order to translate the geophysical data into knowledge on hydrological parameters, various magnitudes are correlated empirically or otherwise. The flow characteristics of the moisture through the unsaturated zone remain an enigma for the scientific understanding and groundwater management as process are comparatively complex. Prediction of moisture movement through the unsaturated medium is an important issue in hydrology as it helps in estimating recharge to ground water system. However, the variability of moisture in the unsaturated zone is not easy for determining by simple experiments. Thus the indirect methods such as determining the electrical resistivity of the unsaturated zone are studied with every moisture change. The variability of moisture content is conditioned by the variability of electrical resistivity measurements through Electrical Resistivity Tomography (ERT) and calculated their variability. In the present work the influence of natural recharge on the correlation structure of resistivity data is been documented by the variogram analysis of the electrical resistivity imaging data. The study clearly shows the non-uniform distribution of the moisture in the verical profile following the rainfall infiltration.

Introduction

Some of the most important hydrogeological parameters includes hydraulic head, transmissivity, aquifer thickness, storage coefficient, rainfall, and effective recharge for ground water management. They all are functions of space and are very often highly variable (Ahmed, 1985). However, this variability is, in general, not purely random. If measurements are made at two different locations, the closer the points of measurement, the closer are the measured values. In other words there is some kind of correlation in the spatial distribution of these parameters. Matheron (1963) has given the name “regionalized variable” to these types of parameters. The autocorrelation of these parameters depends highly on the continuity of the system and hence is affected by the geological structures, which control the movement of groundwater.

The primary method for monitoring the timing and spatial pattern of recharge in the unsaturated zone is Electrical Resistivity Tomography (ERT) using a 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 Daily et al., 1992, Zhou et al., 2001 experimented 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. Tanvi et al, 2005, have used the time lapse electrical resistivity tomography to monitor the variations in resistivity tomograms for short duration recharge. Barker et al., 2000, 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., 2004 have used the resistivity imaging data of the hard rock terrain and also processed it to obtain a 3D variation of resistivity in the grainitic 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 for this critical component of the watershed system.

The variability of moisture content is determined by the variability of electrical resistivity measurements through Electrical Resistivity Tomography (ERT). In the present work the influence of natural recharge on the correlation structure of resistivity data is been documented by analyzing the variogram of the electrical resistivity imaging data. This analysis provides the condition or the extent of saturation of moisture in the unsaturated zone.

Variographic analysis of ERT data

The variogram is a function of distance and the successive difference between the variogram shows the variability of the parameter. Hydrogeological parameters often show random variations. However, as they are the result of certain physical processes, correlations of varying degree are obvious. Essentially, estimation of a regionalized variable is to calculate the variability of the parameter. The variogram is however, calculated based on a less restrictive hypothesis and hence is applicable for most of the hydrogeological parameters.

The basic equation to calculate a simple variogram of a variable Z is;

$$\gamma^{zz}(d)=\frac{1}{2}E\,[z(x+d)-z(x)]^2 \quad \text{.................(1)}$$

where $\gamma^{zz}(d)$ is the variogram between the two points, d distance apart; z(x) and z(x+d) are the pair of field values of the parameter Z at x and x+d respectively. E [.] represents the expected value.

Ahmed (1989) proposed the calculation of an experimental variogram as follows:

$$\gamma(\underline{d},\underline{\theta})=\frac{1}{2N_d}\sum_{i=1}^{N_d}[z(\chi_i+\hat{d},\hat{\theta})-z(\chi_i,\hat{\theta})]^2 \quad \text{...(2)}$$

with

$$d-\Delta d \le \hat{d} \le d+\Delta d \quad \text{..(3)}$$

$$\underline{d}=\frac{1}{N_d}\sum_{i=1}^{N_d}\hat{d}_i, \qquad \underline{\theta}=\frac{1}{N_d}\sum_{i=1}^{N_d}\hat{\theta}_i \quad \text{.......(4)}$$

Where d and q are the chosen lag and direction of the variogram respectively. Dd and Dq are tolerance on lag and direction respectively. d̲ and q̲ are actual lag and direction for the corre-sponding calculated variogram. N_d is the number of pairs for a particular lag and direction.

The curve of ã (d) is plotted against 1151 and is called the variogram plot. At the origin i.e. at d=0, the variogram is also zero. The plot generally increases with increasing distance. It rises to a certain distance (called *sill*) and then becomes constant. The increase of the variogram with sill shows the existence of correlation between the parameters. The distance up to which the correlation exists is called the '*range*'. Before using the variogram for the estimation purposes, a mathematical model has to be fitted to it, may be spherical, gaussian, linear, power etc. The discontinuity of the variogram at the origin is called a *nugget effect* and exists because of measurement errors (in case of erroneous data) and small-scale variability. Ahmed and Marsily (1987) have clarified that the nugget effect is a combined result of small-scale variability and the erroneous data and since we do not know the variance of the data error, we simply cannot remove it. Cross-validation approach could be employed.

The electrical and hydraulic measurements of the unsaturated zone.

In the present study we obtained the resistivity values from the time-lapse monitoring of the unsaturated zone in the hard rock areas of a micro watershed in Southern India using electrical resistivity imaging.

The variation in the ERT datasets has been observed for time prior, during and after the rainfall. In this

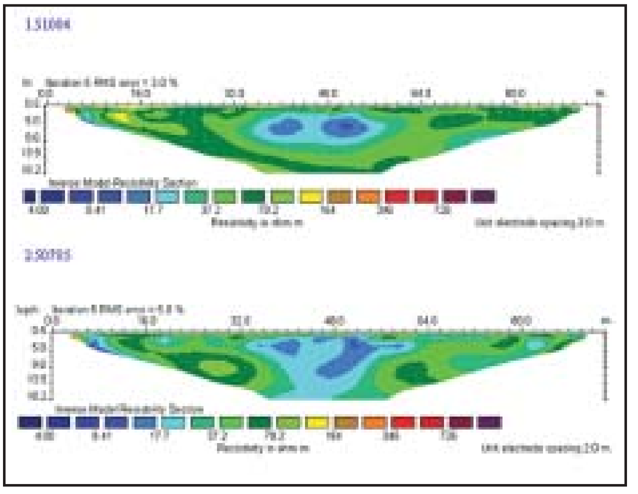

Fig. 1: showing the tomograms showing the changes in the Resistivity on Site S1

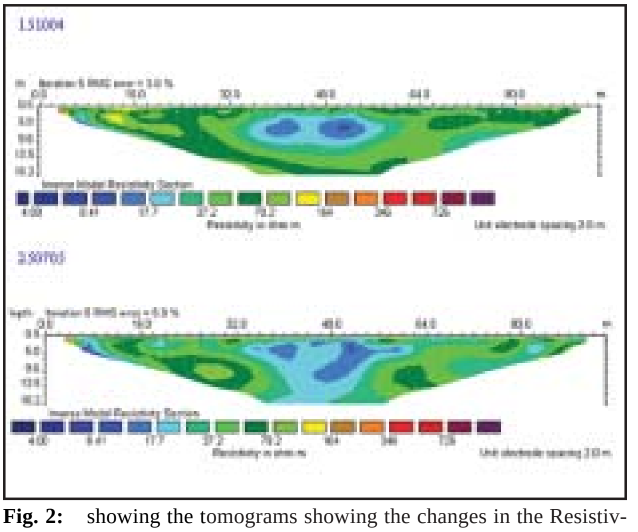

Fig. 2: showing the tomograms showing the changes in the Resistivity on Site S2

work the results of electrical resistivity imaging have been used for time-lapse monitoring of the unsaturated zone in a granitic micro watershed of Southern India to trace the natural recharge in the vadose zone. The natural recharge due to infiltration is variable and also influences the correlation structure of geophysical data with respect to time. The water movement influences the correlation structure based on the electrical measurements because the electrical conductivity of the medium depends upon the water saturation. This spatial variation of the electrical resistivity has been documented by the tomogram analysis of the 2D electrical resistivity imaging data. The tomograms added importance to analyze the moisture movement, as it is more accurate and rigorous at spatial imaging of electrical resistivity data. The long duration imaging surveys with a frequency of 14 days were carried out at two sites S1 and S2 (approximately 300 m apart) along two profiles of length 96 m and 72 m and electrode spacing of 2 m and 1.5 respectively. The subsurface has been mapped up to a depth of 12 meters. Two tomograms of the data acquired on 15th October 2004 (post monsoon of 2004) and 25th July 2005 (during the monsoon period of 2005) at two different sites have been analysed and shown in figure 2 and figure 3, respectively. The resistivity data has been processed and interpreted with the help of RES2DINV software developed by Loke and Barker in 1995.

The spatial correlation among the resistivity data values is calculated using the variogram functions. Resistivity at the site S1, before the rainfall, shows the nugget effect of 200 (ohm-m)^2 with sill value of 1200 (ohm-m)^2 and range of 700 cm. But after the rainfall the variogram of the resistivity at the same site and along the same profile shows a nugget effect of 140 (ohm-m)^2 with the total sill value to 350 (ohm-m)^2 and the range leading to 2500 cm. The coefficient of variation changes from 0.69 (before rainfall) to 0.589 (after rainfall). Similar observations are been reported at yet another site S2 i.e. the decrease in the nugget effect and decrease in the coefficient of variation. The subsequent variography and further absence of nugget effect provided the time lag for the rainfall and recharge process. The variograms of the post monsoon data of resistivity (on 15th October, 2004) at two sites S1 and S2 have been compared with the resistivity data acquired during the monsoon period (on 25th July 2005) at the two sites, respectively, shown in figure 3 and figure 4.

Discussiona and conclusions

At site S1 (refer figure 1) the resistivity values lies in the range of 6 ohm-m to 300 ohm-m at site S1 and the

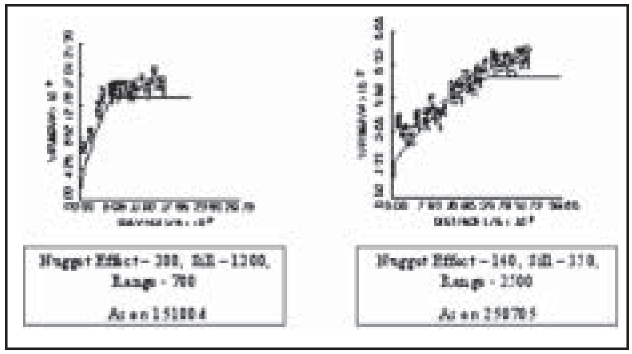

Fig. 3: Variograms showing the extent of variability of Resistivity on Site S1igure 4 Variograms showing the extent of variability of Resistivity on Site S2

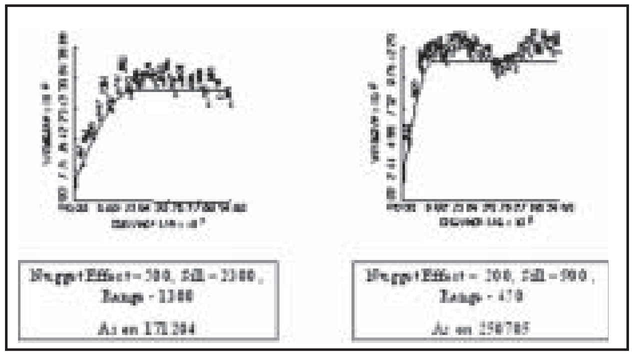

Fig. 4: Variograms showing the extent of variability of Resistivity on Site S2

values are higher on 15/10/04 when compared to that obtained on 25/07/05 but this high value reflects only up to a depth of 5 m. At deeper levels beyond 5 m the value of resistivity decreases between an anomalous zone of 40 m to 50 m along the profile direction. When we move further to deeper levels the resistivity value (on 15/10/04) is lower between the zone of 25 m and 65 m along the profile. When we observe values at further deeper levels beyond 9.5 m the value on 15/10/04 is lower than that on 25/07/05 but between the zone of 40 m and 50 m (horizontal distance along the profile) the observed values during the monsoon of 2005 decreases at compared to that after the post monsoon of 2004. More we tend towards the saturated zone say near about 13 m the resistivity on 25/07/05 is overall low as compared to that on 15/10/04. A detailed description is shown in table 1.

From the variographic analysis of the resistivity datasets, obtained after the time lapse electrical monitoring of the unsaturated zone, it may be concluded that

1. The decrease in the Nugget effect is observed. At site S1 the nugget effect decreases to 30% and at site S2

Table 1: Showing the depth-wise resistivity variation at site S1

Depth UPTO 5m	Horizontal Distance Complete Profile	15/10/04 High	25/07/05 Low
5 m to 9.5 m	40 m to 50 m	Low	High
9.5 m to 11 m	40 m to 50 m	Low	High
11 m to 13 m	Complete Profile	High	Low

the nugget effect shows a decrease of 60 % finally after comparing the two data sets with a gap of 8 months.

2. There is decrease in the variance percentage also, at S1 the variance decreases by 67 % and at another site S2 the variance decreases by 78%.
3. Prior to recharge there is no continuity of moisture, but after the rainfall there exists the continuity.
4. Presence of nugget effect shows that the distribution of moisture, as observed with the resistivity and moisture profiles, is not continuous with depth. There exists some gaps and moisture exists in patches.
5. But after the rainfall and the infiltration the gaps are filled and the distribution of the moisture becomes continuous.

The first finding of the present study shows clearly that the assumption of piston flow for the recharge process is not valid in such aquifer condition. Although the negligible change in the total sill indicates the high variability of formation parameter, reduction in the nugget effect signals the increase in the continuity of moisture present that was more random before the rainfall. Secondly the repeated ERT could support estimation of rainfall recharge at least qualitatively.

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