Comparison of electrical resistivity by geophysical method and neutron probe logging for soil moisture monitoring in a forested watershed

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Geophysical methods are becoming more popular nowadays in the field of hydrology due to their time and space efficiency. So an attempt has been made here to relate electrical resistivity with soil moisture content in the field. The experiments were carried out in an experimental watershed 'Mulehole' in southern India, which is a forested watershed with approximately 80% red soil. Five auger holes were drilled to perform the soil moisture and electrical resistivity measurements in a toposequence having red and black soils, with sandy weathered soil at the bottom. Soil moisture was measured using neutron probe and electrical resistivity was measured using electrical logging tool. The results indicate that electrical resistivity measurements can be used to measure soil moisture content for red soils only.

Keywords: Electrical resistivity, forested watershed, neutron probe, soil moisture.

THE vadose zone is an unsaturated zone lying between the ground surface and the groundwater table. This zone is of importance as it acts as a link between surface water and groundwater. Knowledge of soil moisture in this zone is essential to understand the meteorological, hydrological and agronomic processes. However, soil moisture is highly variable in space and time because of the nature of the soil topography, land cover, evapotranspiration and precipitation heterogeneity[1,2]. Soil moisture can be measured using classical soil moisture measurement tools such as neutron probe, time domain reflectometry (TDR), etc. However, the use of these tools has certain limitations. Both neutron probe and TDR equipment cannot measure soil moisture directly from the surface. It is required to auger a hole in the soil to put the probe inside to the required depth. Also, the calibration procedure needed for these is time-consuming. Neutron probe and TDR give point measurements and require longer time to cover even a small area.

So we require a tool which can measure soil moisture directly from the surface without disturbing the soil, and which is also fast. Remote sensing can be used to measure soil moisture, but only up to a few centimetres. Also, it is difficult to apply for forested soils due to canopy cover. Use of geophysical methods is also one of the means to predict the soil moisture. Lot of research is being done to link electrical resistivity with soil moisture[3–5]. The electrical resistivity techniques are easy, time efficient, and can be measured from the top surface of the soil. Thus to measure soil moisture from the surface without disturbing the soil, electrical resistivity measurements using electrical resistivity tomography (ERT) by geophysical methods can be employed.

Electrical resistivity is a function of several soil properties, including nature of solid constituents (particle size distribution, mineralogy), arrangement of voids (porosity, pore size distribution, connectivity), degree of water saturation (water content), electrical resistivity of fluids (solute concentration) and temperature[6]. Electrical resistivity exhibits a large range of values, from 1 Ωm for saline soil to 10^5 Ωm for dry soil overlying crystalline rocks, with that of clay ranging from approximately 10 to 100 Ωm (ref. 6). Several studies are available relating electrical resistivity with soil moisture[3–5]. But such studies were limited to agricultural plots and for the root zone (70–80 cm)[7,8]. Some were limited to sandy soils[9] and sandstones[10]. In agricultural plots, addition of fertilizers will change the ionic composition of the soil, thus affecting the electrical resistivity. Also, the coefficient of determination is likely to be greater if comparative measurements of soil moisture content are made for a greater depth and/or a more sophisticated analysis of the resistivity measurements is undertaken[7].

Before using ERT, either laboratory calibration or field calibration of electrical resistivity with soil moisture needs to be done. In the case of laboratory calibration, it is difficult to preserve the soil structure. Many laboratory experiments were conducted on remoulded soil, where the air–void ratio and degree of saturation may not be the same as in the field. The resistivity of clay is a function of moisture content and degree of saturation[11]. At a particular moisture content, an increase in the degree of saturation (or a decrease in the air–void ratio) will indicate a decrease in resistivity[11]. For laboratory calibration, the elementary volume of soil core must be defined because for the same moisture content, an increase in soil core volume is always associated with higher electrical resistivity value[8]. So laboratory calibration may not give the correct relationship between resistivity and soil moisture. In the case of field calibration, electrical resistivity and soil moisture are measured in tandem. This is done to

know if any relationship exists between soil moisture and electrical resistivity for field conditions. The present communication shows the existence of such a relationship.

Thus most of the work done on linking electrical resistivity with soil moisture is limited to agricultural plots, root-zone depth and sandy type of soils[7–10]. Very limited work has been done on clayey type of soils[5,8,11]. In India, the soil structure could be totally different from the rest of the world, that too for a fully forested watershed where there are no anthropogenic activities. The ion chemistry in the water is totally driven by rainwater and minerals present in the soils. So in the present communication, an attempt has been made to link electrical resistivity with soil moisture through field calibration of clayey soils for greater depths in a fully forested watershed. An experimental toposequence has been identified in the experimental watershed 'Mulehole'. The toposequence consists of red and black soils (clayey type), with sandy weathered soil at the bottom.

The soil moisture was measured by neutron probe and electrical resistivity was measured by electrical logging tool. Both were point measurements. If the soil has more moisture content, it will become electrically conductive and will have less electrical resistivity, and vice versa. So electrical resistivity is linked with soil moisture.

The present communication provides detailed information about the study site, procedural set-up, soil moisture and electrical resistivity measurements, and results and discussion.

The study area is located in the experimental watershed 'Mulehole', which is a sub-watershed of the Cauvery/ Kabini/Nuguhole/Soredahalla basin in Bandipur National Park, Chamrajnagar District, Karnataka, in the southern part of India. The watershed is located in the climatic semi-humid transition area[12]. The Mulehole watershed has an area of 4.52 sq. km spreading between 11°43′41″N–11°44′45″N lat. and 76°25′55″E–76°27′40″E long. The elevation varies from 820 to 910 m amsl and the area has an average annual rainfall of 1120 mm for 20 years. The watershed is a moist deciduous forest. The area is mostly undulating with gentle slopes and consists of red soil covering approximately 80% of the watershed, and black soil and loose saprolite covering the rest (Figure 1).

In order to study the moisture dynamics of red and black soils together, an experimental toposequence 'T1' had been identified in the watershed[12]. The toposequence consists of organic soil layer at the top followed by three layers of red soil with black soil intruding into the red soil layers from the stream and with sandy weathered soil (saprolite) forming the bottom layer. The detailed cross-section of the toposequence is shown in Figure 2.

Five auger holes were drilled to different depths in the trench by augering manually. The auger holes were preserved with the help of inflating rubber tube to prevent any preferential flow into them. Of the five auger holes,

A1, A3 and A8 are in the red soil, A2 is in the black soil and A4 is in the transition zone between the red and black soils.

Five boreholes were drilled down to the saprolite in the red soil, black soil and transition area, along a line parallelly located to T1 (Figure 2). The distance between A8 and A3 is 10 m, and it is 5 m for A3 to A1, A1 to A4 and A4 to A2. The different horizons of the boreholes were identified and compared to the description from the trench T1 in order to map the layout of the red soil–black soil system.

Soil moisture was monitored during all the seasons in 2004 and 2005 through neutron probe measurements (soil moisture probe type I.H. II, Didcot Instrument Co Ltd, Abingdon Oxon, England). The working principle of neutron probe is that it emits relatively high-energy neutrons into the medium from a radioactive source, with a detector provided to observe the resulting number of slow neutrons that are backscattered. The high-energy neutrons
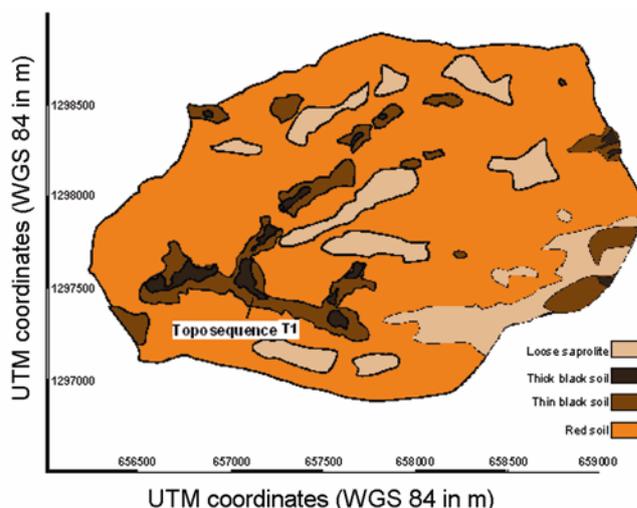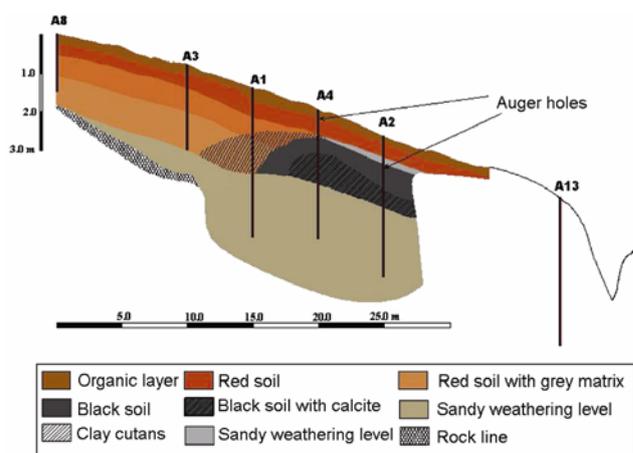

Figure 1. Soil map of Mulehole watershed.

Figure 2. Detailed cross-section of toposequence T1.

then collide with various atoms in the soil. The loss of energy that occurs upon each collision is far greater when the collision with an object of mass similar to neutron. For instance, in a single collision the loss of energy from a neutron to hydrogen is 4000 times that of collision with oxygen. So the presence of hydrogen is closely related to the production of low thermalized neutrons. Because the dominant source of hydrogen in most vadose zone materials is water, the rate of thermalized neutron production can be calibrated to volumetric soil-water content. Site calibration is required to account for local effects of mineral and organic components and structurally bound water in the soil, which also contributes to neutron thermalization[13].

Measurements were carried out at every 10 cm depth. Figure 3 shows the rainfall versus neutron probe and electrical resistivity measurements dates. All measurements taken using neutron probe were 64 s measurements. Between two successive neutron probe measurement periods, the boreholes were preserved with the help of inflatable rubber tubes that were inserted into the holes to prevent any preferential infiltration along the holes and run-off from the top soil during rainfall.

For each soil horizon, a linear relationship was established between the neutron probe measurements and volumetric water content. For this purpose, bulk soil samples were collected while drilling holes (at the end of the dry season, just before the monsoon) and immediately placed and sealed in metallic boxes. Simultaneously, the neutron probe measurements were carried out at the corresponding depth. Gravimetric water content was determined in the laboratory by weighing the samples before and after oven-drying for 24 h at 105°C. The same procedure was carried out at the end of the monsoon season (wet state) in new holes drilled about 50 cm away from the previous ones. The bulk density was measured using the paraffin method on aggregates collected along the trench T1 in each horizon[14]. The volumetric water content in the boreholes was calculated by multiplying the gravimetric water content by the bulk density of the corresponding soil horizon.
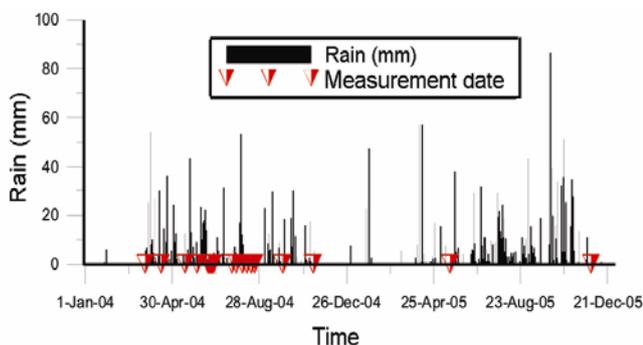

Figure 3. Rainfall versus neutron probe and electrical resistivity measurement dates.

The calibration was established for each horizon using linear regression between the volumetric water content against the R/R_w ratio, where R denotes the number of counts per second of neutron probe in soil and R_w denotes the incident neutron flux. The calibration was established on a volumetric water content range of 16–31% in red soil, 21–35% in black soil, 12–30% in organic topsoil horizon, and 13–29% in sandy weathered soil. The neutron probe calibration results for red and sandy weathered soils are shown in Figure 4.

For field calibration, we need to measure electrical resistivity at the same point where soil moisture was measured. So 1D point measurements of electrical resistivity are required. Hence electrical resistivity is measured here using the inflatable electrical logging tool. The electrical logging tool for the vadose zone is based on an inflating packer with strip electrodes[15]. This tool has been successfully used for thick vadose-zone logging[16]. The set-up is shown in Figure 5. The logging tool is made with a PVC pipe covered with a rubber inflating tube which can be inflated using an air pump externally. An elastic metal contact is placed on the rubber tube. When the device is put inside the auger hole and inflated, the metal contacts come in contact with the soil matrix around them. The acquisition was done using the 'normal' pole–pole array. This quadripole involves two inner electrodes, A and M and two remote surface electrodes, B and N at much greater distance from the auger hole. The AM spacing was 0.28 m. These contacts (A and M) are connected to the resistivity-meter. Two other electrodes N and B which are far away (as shown in Figure 5) are also connected to the resistivity-meter. Current is passed between A and B, and voltage is measured between M and N. The electrical resistivity is calculated as

$$\rho = k\left(\frac{\Delta V}{I}\right),$$

where ρ is the electrical resistivity in Ohm-m, ΔV the potential measured across M and N, I the current induced between A and B and k is the geometric constant.

The geometric constant k depends on the electrode array configuration. For the pole–pole electrode array configuration for half space[6], $k = 2\pi a$. Since the measurements are inside the ground in the auger hole, they are not in half space but in whole space. For the pole–pole electrode array configuration in whole space

$$k = 4\pi a,$$

where a is the distance between electrodes A and M (Figure 5). Electrical resistivity measurements were done simultaneously with soil moisture measurements at the same depths.

Soil moisture was measured by neutron probe and electrical resistivity was measured by electrical logging tool.
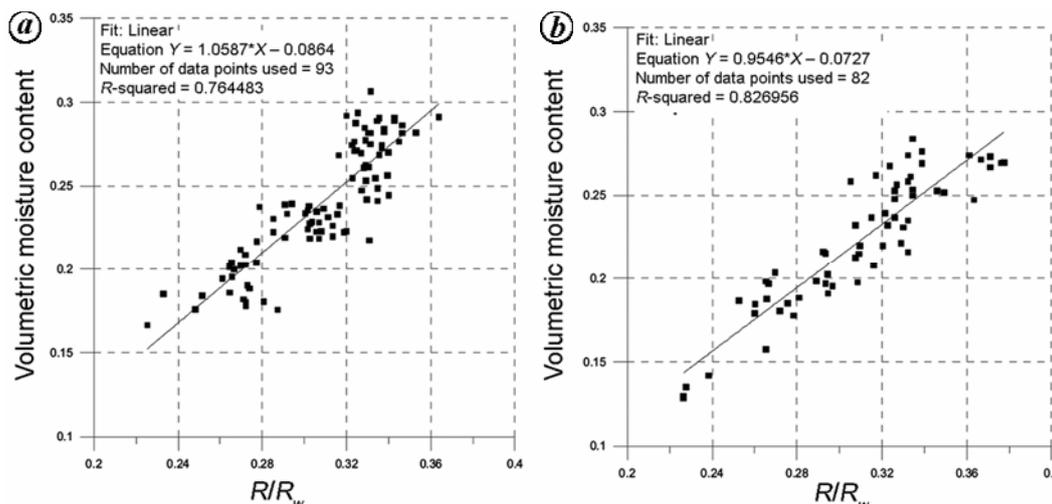
Figure 4. Neutron probe calibration results for red and sandy weathered soils. (*a*) Red soil and (*b*) sandy weathered soil.
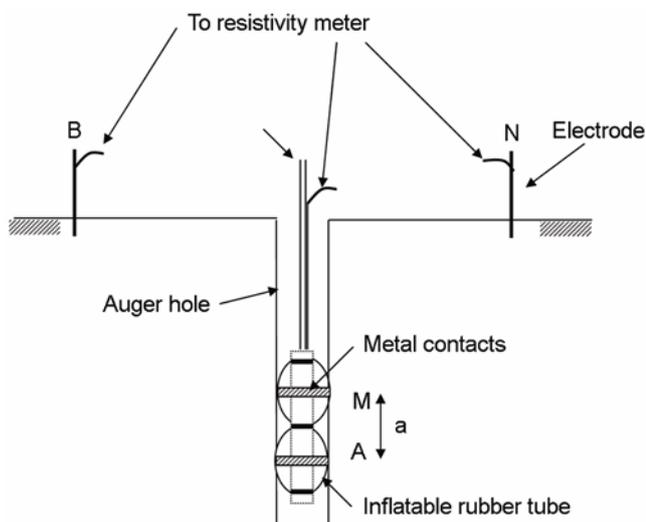

Figure 5. Experimental set-up for electrical resistivity measurement.

In 2004, measurements were frequent (Figure 3) and thus a large number of datasets were gathered. In 2005 only two measurements were made, one in the dry period before the monsoon and the other in wet period just after the monsoon. The data were separated with respect to date, auger hole and soil layer. The data separation with respect to soil layers was done by separating the data for red, black and sandy weathered soils. In the red soil, the data were again separated in accordance with the red soil horizons (Figure 2).

The power relationship given below was used to relate soil moisture with electrical resistivity[4].

$$\theta = a \cdot \rho^{b},$$

where θ is the soil moisture, ρ the electrical resistivity and a and b are fitting parameters.

In the first step, the data with respect to soil types combined from all auger holes were analysed. The data were separated for red, black and sandy weathered soils. The data were plotted to see how they behaved and also for the existence of any relationship (Figure 6). It is clear from Figure 6 that the data are scattered for black and sandy weathered soils. This could be due to chemical composition of the soil affecting the electrical resistivity apart from the presence of water and also due to changes in the air–void ratio, as black soil has the tendency of swelling and shrinking. But for the red soil there is hint of relationship existence. So in the second step, data for each red soil horizon of all the auger holes were combined and analysed (Figure 7). Here for the top red soil horizon the data range was high compared to middle red soil horizon data and bottom red soil horizon data. So the relationship for the top red soil horizon seems satisfactory. For the middle red soil horizon data, the relationship was good compared to bottom red soil data. After comparing the trendlines of each red soil horizon, the trendlines of the middle and bottom red soil horizons were found to be parallel, with some shift. The regression coefficient (R-squared) varied from 0.5 to 0.65, which is not impressive.

So to further improve the relationship, in the third step, since in 2005 the number of data available was only two, one in the dry period before the monsoon and another in the wet period just after the monsoon, for 2004 also it was decided to use data similarly, one in the dry period before the monsoon and another in the wet period just after the monsoon, instead of using all the data, and using the relationship to predict the data for the intermediate period for 2004 and compare them with the measured soil moisture. Figure 8 shows the relationship for different red soil horizons considering only two measurements as mentioned above. From Figure 8, it is clear that there is significant improvement in the relationship for all three red
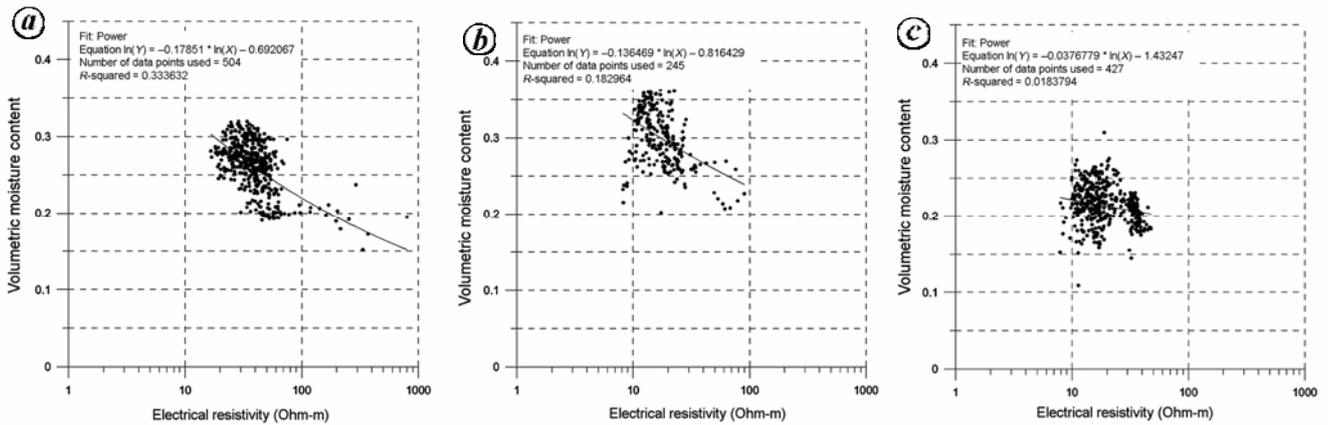
Figure 6. Relationship between soil moisture and electrical resistivity for 2004–2005. (*a*) Red soil, (*b*) Black soil and (*c*) Sandy weathered soil.
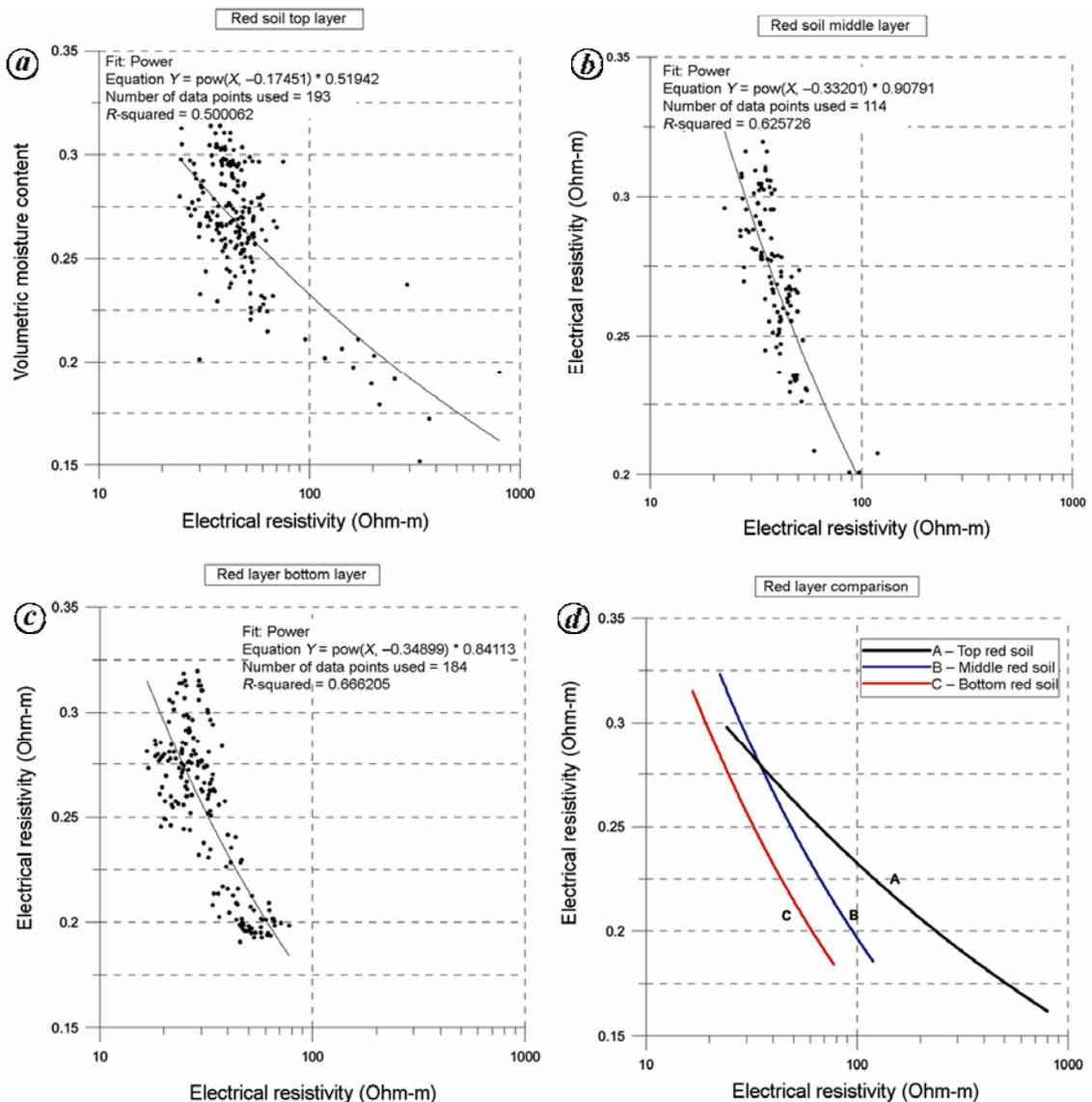

Figure 7. Different red soil horizon plots for all data for 2004 and 2005 for (*a*) top red soil, (*b*) middle red soil, (*c*) bottom red soil and (*d*) combined trendlines.
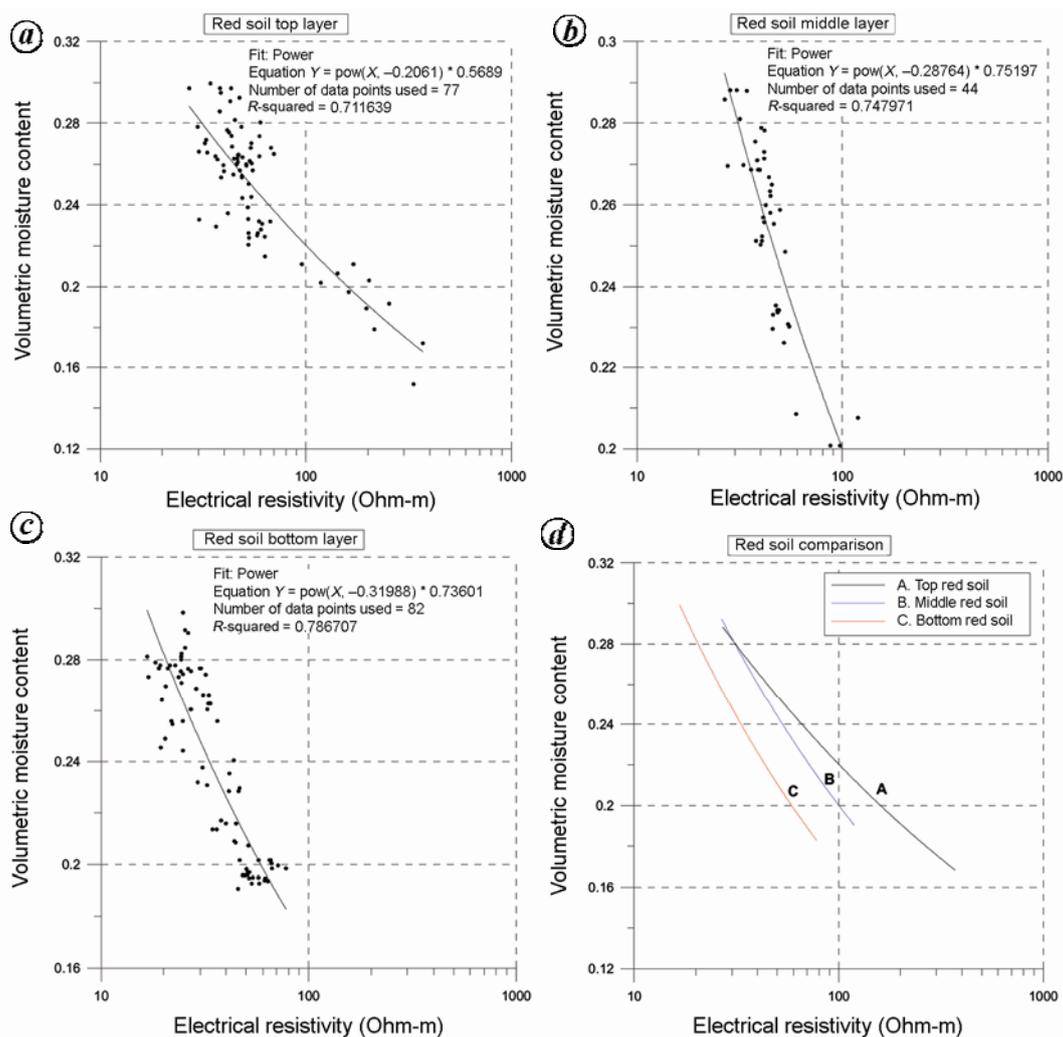
Figure 8. Different red soil horizon plots for data, one in the dry period before monsoon and another in the wet period after monsoon for 2004 and 2005 for (***a***) top red soil, (***b***) middle red soil, (***c***) bottom red soil and (***d***) combined trendlines.

soil horizons, with the regression coefficient varying from 0.71 to 0.78.

These relationships were used to predict soil moisture for the intermediate period, where soil moisture and electrical resistivity measurements were taken in tandem. The predicted soil moisture values were compared with the actual soil moisture for all the red soil horizons (Figure 9). The error between the predicted and measured soil moisture contents was calculated and averaged out for each red soil horizon. For the top red soil horizon, the average error was 7.47%. For the middle red soil horizon, it was 6.18% and for the bottom red soil horizon 8.95%. All the errors in predicting soil moisture were below 10%, which is considered as good prediction.

About 504 data points were used for red soil, 245 for black soil and 428 for sandy weathered soil. By just looking at the plots it is difficult to predict any field calibration relationship for red, black and sandy weathered soils. However, the red soil data provide a hint towards the possibility of existence of a relationship, which needs to be further analysed. For black and sandy weathered soils, the data are mostly scattered and it is difficult to find any trend between them. For the red soil plot, it can be seen that majority of the data lies in the range 0.2–0.33 of soil moisture and 20–80 Ωm of electrical resistivity. Further, for the red soils, when the data for each of the red soil horizon were separated and plotted, the relationship between soil moisture and electrical resistivity was found to improve to a satisfactory level. While using only two datasets, one in the dry period before the monsoon and another in the wet period just after the monsoon for 2004 and 2005, the relationship was found to be more than satisfactory, with average error between predicted and measured soil moisture being below 10% for the data between dry and wet periods, where soil moisture and electrical resistivity measurements were taken in tandem. For the top red soil horizon, where the soil moisture dynamics is higher, the relationship was much better and the range
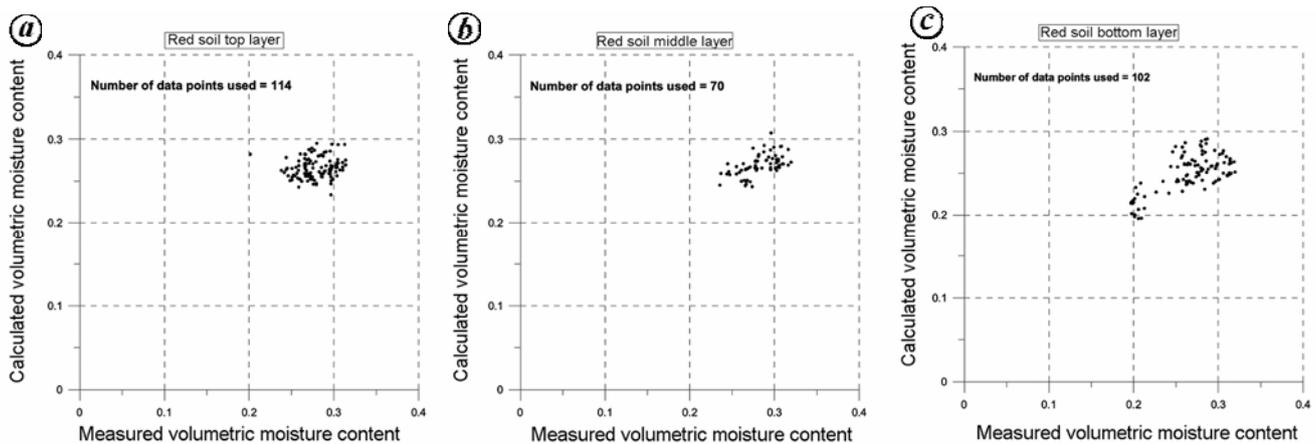
Figure 9. Measured versus predicted soil moisture plots for (***a***) top red soil, (***b***) middle red soil and (***c***) bottom red soil horizons.

of data availability was also higher. These field calibration relationships can be further improved, especially in the case of the red soil, if the range of data availability is more. Most of the data were for the wet period, with very few available for the dry period. Moreover, the middle and bottom horizons are less prone to larger changes in the soil moisture. Also, the temperature effect on electrical resistivity is not taken into consideration due to lack of temperature data. The electrical resistivity decreases when the temperature increases[6]. So the data need to be corrected to a standard referenced temperature. By conducting laboratory experiments on 30 samples of saline and alkaline soils, it was shown that conductivity (inverse of resistivity) increased by 2.02% per °C between 15°C and 35°C (ref. 17). Since the experimental site lies in the climatic semi-humid transition area, the seasonal temperature variation is quite high. So the consideration of temperature effect would have definitely benefitted the results. Also, it is difficult to ensure that the diameter of the auger holes remains the same throughout the measurement period, as the soils have the tendency to go seasonal changes. Variation in the auger hole diameter would have a definite impact on the results of soil moisture and electrical resistivity measurements.

The field calibration relationships for red soils, when only using two datasets, one in the dry period before the monsoon and another in the wet period just after the monsoon for 2004 and 2005, and when considered separately for each red soil horizon were found to be satisfactory, with average error between predicted and measured soil moisture contents being less than 10%. The methodology can be applied in similar environments where similar types of red soil are available. There is further scope for improving the relationship by collecting enough data in both wet and dry states and also bringing in temperature effects in the datasets.

The following conclusions can be made from the above analysis.

• For the red soil, initial field calibration relationship taking into account data for all the red soil horizons is not good, but after separating out the data for each red soil horizon the field calibration relationship improves to a satisfactory level.

• Further, for red soils, when using only two datasets, one in the dry period before the monsoon and another in the wet period just after the monsoon for 2004 and 2005, the relationship improves significantly with R-squared being more than 0.7 and average error between predicted and measured soil moisture contents being below 10%, when predicted for all intermediate periods where soil moisture and electrical resistivity measurements were taken in tandem. These relationships could be applied to areas where similar types of soil are available.

• The volumetric moisture content and electric resistivity relationship for the sandy weathering soil (saprolite) and for the black soil is not satisfactory, and it is difficult to predict any relationship for these soils from field measurements.

• This study shows that water is not the only factor which affects resistivity, but chemical composition of the soil and soil temperature also affect electrical resistivity.

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Soil respiration under different forest species in the riparian buffer of the semi-arid region of northwest India

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Soil temperature and soil moisture are the most important environmental factors controlling soil respiration (SR) in ecosystems. However, SR and associated edaphic factors have not been widely studied in semi-arid regions. In this study, SR was measured in a riparian zone and the effect of soil temperature and soil moisture on SR was examined under five forest species of the semi-arid region. The mean daily SR rate was 1.82, 2.08, 2.35, 2.27 and 2.07 g C m^{-2} d^{-1} in *Jatropha curcas*, *Leucaena leucocephala*, *Acacia nilotica*, *Azadirachta indica* and *Prosopis juliflora* sites respectively. It was found that SR was significantly and positively correlated with soil moisture. A univariate model of sub-surface soil moisture could explain 77% of temporal variation in soil CO_2 efflux, irrespective of species and sites. The logarithmic model could best explain the relationship between SR and soil moisture at 10–20 cm of soil depth ($P < 0.001$). There were negative correlations between SR and soil temperature under majority of species. Overall, across all species, soil temperature poorly explained 26% variation in SR as independent variable. For SR rate–temperature relationship, a bell-shaped function gave the best fit in this ecosystem. Under all the species, SR increases with increase in soil temperature up to 33°C (± 2); thereafter it decreases gradually under all species. There was strong evidence that deficit of soil moisture rather than soil temperature was the main regulating factor of SR under the semi-arid ecosystems.

SOIL respiration (SR) is a major process affecting the global carbon cycle and nutrient flux in the terrestrial ecosystem. It is the major pathway for exchange of gases from soil to atmosphere, influencing atmospheric temperature and ultimately contributing to global warming. Soil carbon is returned from the soil to the atmosphere through SR, which represents one of the largest fluxes in the terrestrial C cycle[1–3]. The main sources of terrestrial flux of CO_2 are decomposing soil organic matter, respiration from heterotrophic soil organisms and autotrophic

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