     

Design, Construction and Testing of 3D Borehole Resistivity Tomography Equipment to Measure Deep Drainage and Soil Moisture Changes

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1. Introduction

Due to their high nutrient content and water holding capacity, cracking soils offer favourable conditions for agriculture. It is therefore not surprising that the majority of irrigated crops in Australia are grown in these fine-grained cracking soils. Due to their high clay content irrigation of these soils was long assumed to be very efficient and water losses due to deep drainage were assumed negligible (Hearn 1998). In recent years evidence of deep drainage in cracking clay soils became widely accepted, yet estimates of its magnitude still vary (Smith et al. 2005). For sustainable management of water and soils in irrigation areas a better understanding of the hydrology of cracking soils as well as tools to apply this understanding are of central importance.

To provide this, the Connected Waters Initiative (CWI) team is presently developing 3D borehole resistivity tomography (3D BRT) to monitor water movement and soil moisture changes in cracking soils. 3D BRT will provide both a tool for on farm use to implement best management practices as well as a tool for research purposes to provide a better understanding of the hydrology of cracking soils.

2. Theory

Bulk electrical resistivity is commonly measured in 2D lines from the soil surface (Fig. 1). For this method a line of electrodes is laid out and current is passed between one pair of current electrodes (A & B) while the potential is measured between another pair of electrodes (M & N). Sequentially measurements with different electrodes and different spacings are carried out to construct a resistivity image of the subsurface. An example of such images can be seen in figure 2. 2D resistivity imaging from the surface is widely applied and off the shelf equipment and measurement routines exist (Acworth 1999).

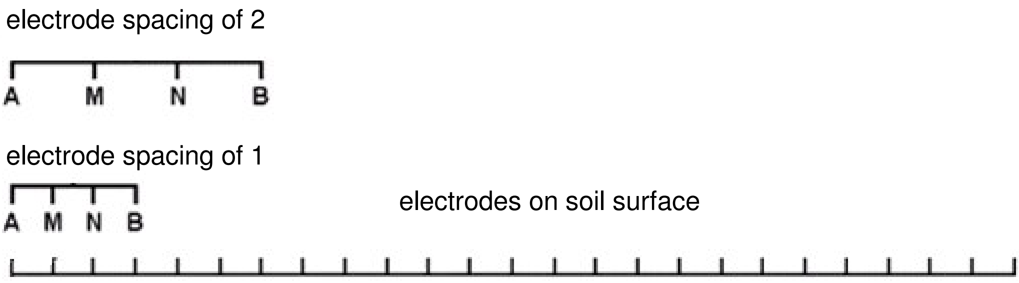


Figure 1: typical electrode setup for electrical resistivity work from the soil surface

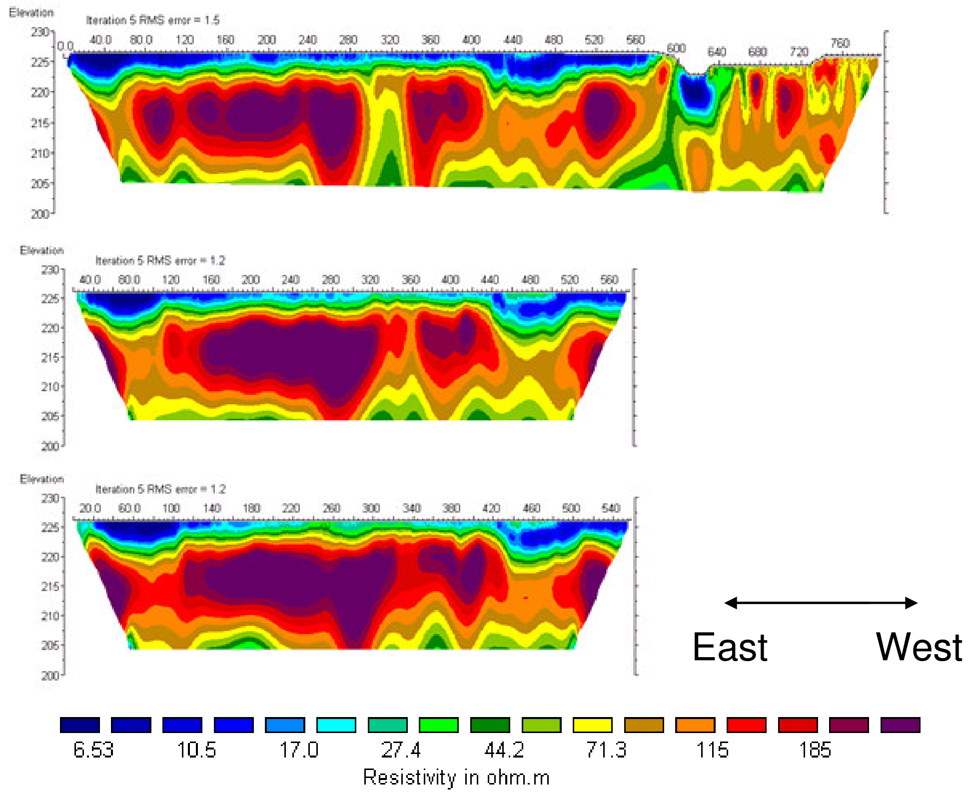


Figure 2: Surface resistivity profiles 1, 2 and 3 taken in August 2007 at the CWI field site near Narrabri

If resistivity measurements are carried out from the surface the image resolution decreases with depth. To maintain constant resolution throughout the soil profile and allow capturing of a 3D resistivity image 3D BRT is carried out with electrodes located in 4 boreholes as shown in figure 3. As there are no off the shelf resistivity probes and measurement routines for borehole measurements, these will have to be designed and tested as part of the development of 3D BRT.

The electrode setup in figure 3 allows for a variety of arrangements of the two current and two potential electrodes, every arrangement being sensitive to distinctive areas of the surrounding soil. Each electrode arrangement takes up time in a measurement routine while the ideal measurement routine is a snap shot in time. The most favourable measurement routine takes the least time, gives the most information about the area of interest and has the lowest signal-noise ration.

Next to probe and measurement routines there is a need to develop calibration procedures that relate the resistivity distribution in the soil back to soil moisture content. Bulk electrical resistivity of a soil is influenced by properties of the soil matrix as well as by the properties of the soil solution (Greve and Kelly 2008).

In general, the properties of the soil solution show higher variation with time than the properties of the soil matrix. It is therefore possible to relate short term temporal changes in bulk electrical resistivity to changes in the soil solution or the soil moisture content. It needs to be noted at this point though, that in cracking soils changes in soil moisture also influence properties of the soil matrix through crack opening and closing. To successfully apply 3D BRT in cracking soils the influence of soil cracking on the soil moisture – resistivity relationship needs to be investigated.

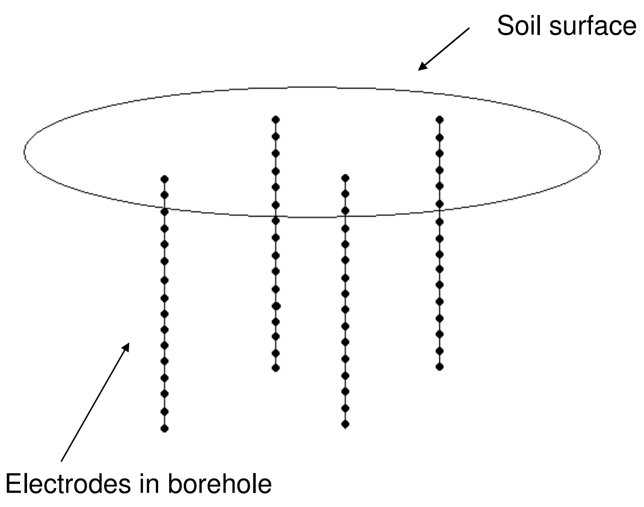


Figure 3: Location of electrodes in four boreholes (oblique view)

3. Fieldwork and Laboratory Methods

The following activities can be separated into two parts, firstly the development and testing of 3D BRT and secondly the collection of complementary data for calibration and validation of the 3D BRT measurements.

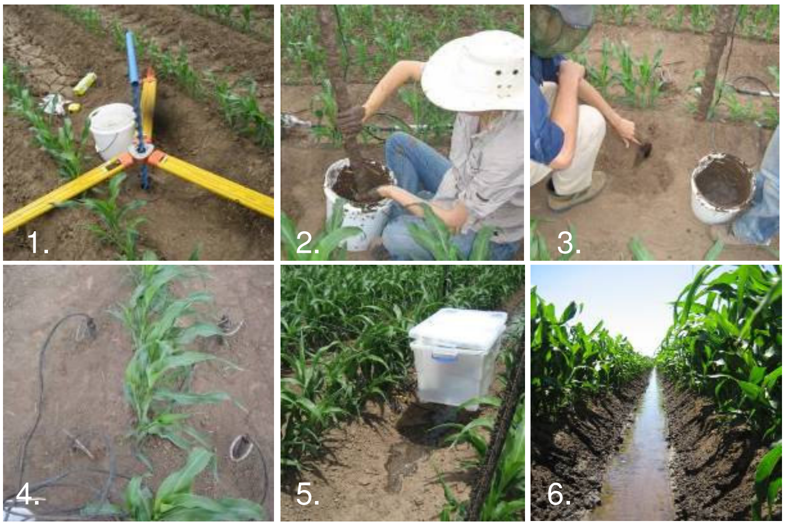
Design and operation of 3D BRT

Several designs of borehole resistivity probes have been build at the Water Research Laboratory (WRL) and were tested in two weighing lysimeters, which were filled with sand and cracking soil (Fig. 4). To develop measurement routines the sensitivity distribution for a variety of possible electrode configurations was modelled theoretically. Next 4 measurement routines with acquisition times ranging from 3 to 45 minutes were programmed and tested in the two weighing lysimeters.

In November 2007 one set of four resistivity probes was installed at a CWI field site near Narrabri, NSW (Fig. 5). In the growing season 2007/08 changes in bulk resistivity during irrigation events and in drying periods were monitored by 3D BRT. Simultaneously several gravimetrical moisture measurements were taken at dry and moist soil conditions to investigate the soil moisture-resistivity relationship.

1. Testing of borehole resistivity probes and measurement routines weighing lysimeter filled with sand
2. Testing of borehole resistivity probes and measurement routines in a weighing lysimeter filled with cracking clay soil
3. Monitoring of effluent from weighing lysimeter during artificial irrigation events

Figure 4: testing of borehole resistivity probes and 3D borehole measurement routines in a weighing lysimeters at the WRL



1. Augering boreholes for probe installation
2. Preparing probes for installation
3. Installation of probes in borehole
4. Readily inserted set of 4 resistivity probes for 3D tomography
5. Elevated box with resistivity instruments next to the inserted probes at the start of an irrigation event
6. Furrow irrigation at the CWI field site

Figure 5: installation and operation of 3D borehole tomography probes at the CWI field site

Investigation of crack dynamics and water flow in cracking soils

Closing and opening of surface cracks was monitored with time lab photography during four irrigation and drying periods in the weighing lysimeter shown in figure 4. The observed changes in cracking intensity, together with the results of the simultaneously carried out 3D BRT and the recorded moisture/weight changes in the weighing lysimeter are presently being analysed to investigate the influence of soil cracking on the soil moisture resistivity relationship. A time lab series of cracks closing, opening and reappearing can be seen at:
http://www.connectedwaters.unsw.edu.au//resources/articles/videocracking.html

To investigate preferential flow in cracked soil a Bromide tracer was applied with the irrigation water of the last irrigation event. The Bromide breakthrough at the bottom of the weighing lysimeter provides a test for the accuracy of the water movement indicated by the 3D BRT.

Installation of mini-lysimeters

To assist with calibration of the electrical resistivity work, measurements of actual deep drainage at the CWI field site near Narrabri were made throughout the growing season 2007/08. Deep drainage was measured with mini-lysimeters, which were installed in August 2007 (Fig. 6).

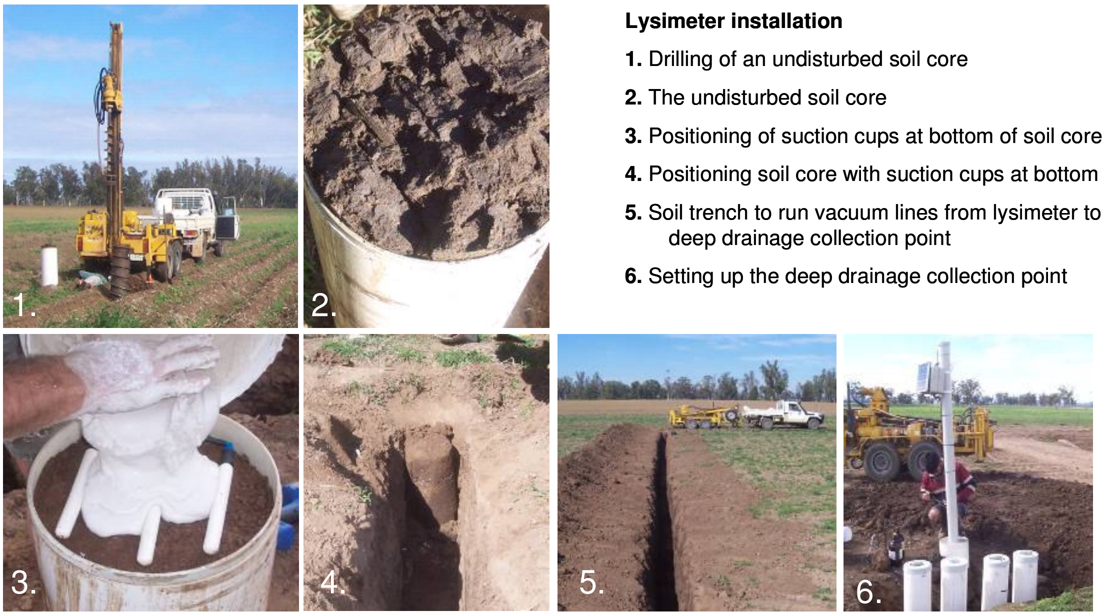


Figure 6: Installation of the three lysimeters at the CWI field site near Narrabri, NSW

During the lysimeter installation a 1.5 m deep undisturbed soil core with a diameter of 0.3 m was taken. Three suction cups were positioned at the bottom of the soil core and sludge from silica flour was applied as contact material between the soil and the suction cups. The soil core was then reinserted into its original location in the soil profile. A trench was dug to lead the vacuum lines from the suction cups to a deep drainage collection point. At the collection point a vacuum pump constantly applies suction to move the water from the suction cups in the three lysimeters through three tipping buckets and finally into separate glass bottles. The tipping buckets record quantity and arrival time of the deep drainage water before the water is collected and stored in the three glass bottles.

Figure 7 shows the location of the three mini-lysimeters as well as the location of 3 2D surface resistivity images that were taken in August 2007. The 2D surface resistivity images itself, which show the heterogeneity of the subsurface at the field site, can be found in figure 2.

The mini lysimeters provide both, a direct measure of deep drainage for comparison with the indirect measurements by 3D BRT, as well as information about the ion concentration of the mobile soil solution at a depth of 1.2m, which aids in the interpretation of the 3D resistivity profiles.

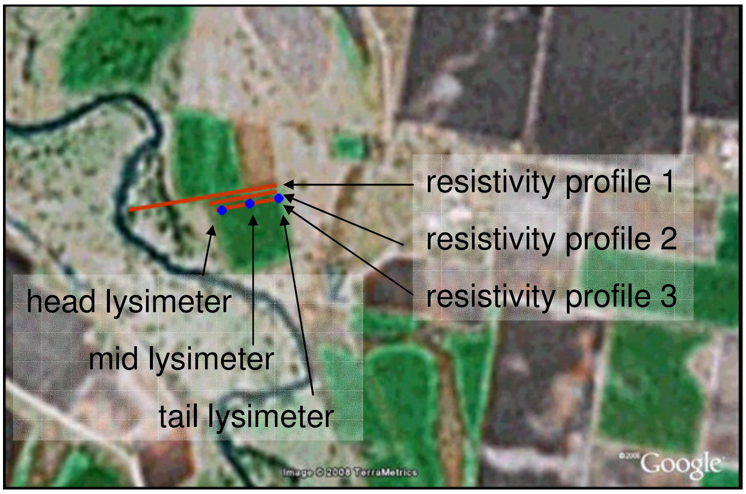


Figure 7: Location of three mini-lysimeters and three 2D resistivity image lines at the CWI field site near Narrabri, NSW

3. Results and Discussion

For the two irrigation events of the growing season 2007/08, deep drainage water was collected in the head and tail lysimeter, while no deep drainage was recorded in the mid lysimeter. Figure 8 and 9 show the recorded deep drainage against time for the two irrigation events. First arrival of deep drainage water in the head lysimeter was recorded 1.5 and 2.5 hours after the start of the irrigation for irrigation 1 and 2 respectively, while arrival of deep drainage in the tail lysimeter was recorded after 5.5 and 5 hours. The rapid drainage may be an artefact of temporary soil disturbance caused during the installation process. For further investigation the work will be continued next growing season.

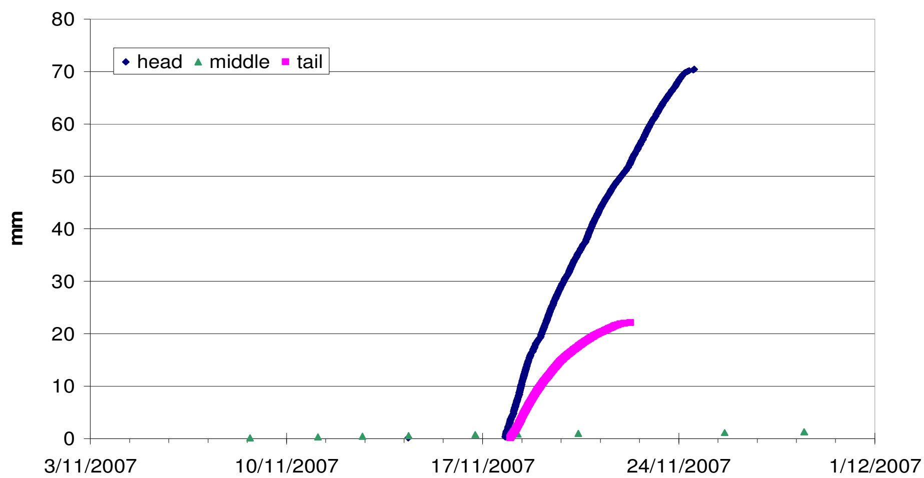


Figure 8: Deep drainage water collected in the mini lysimeters at the CWI field site after the first irrigation event.

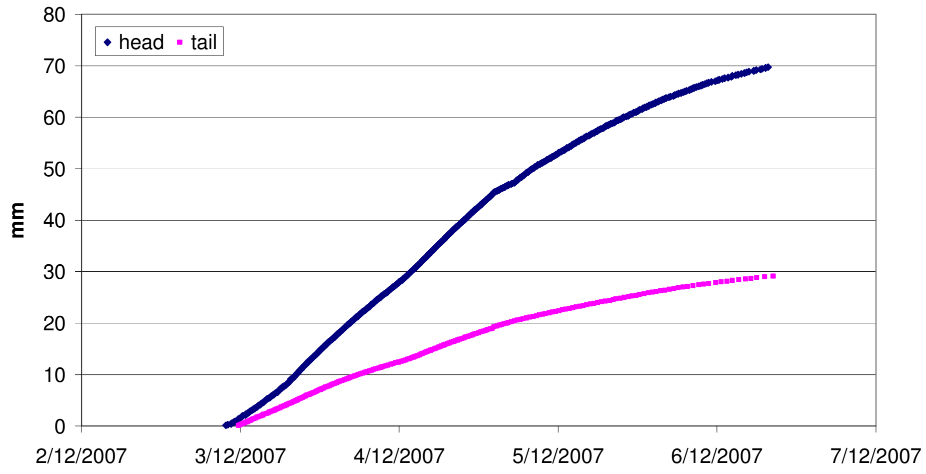


Figure 9: Deep drainage water collected in the mini lysimeters at the CWI field site after the second irrigation event.

The fluid EC of drainage water collected from the tail lysimeter was considerably greater than that from the head lysimeter. Figure 10 shows the location and depth of the three mini-lysimeters on the resistivity image taken in August 2007. It can be seen that the tail lysimeter is located in lower resistivity material, which could be the reason for the higher fluid EC in the deep drainage water from this location.

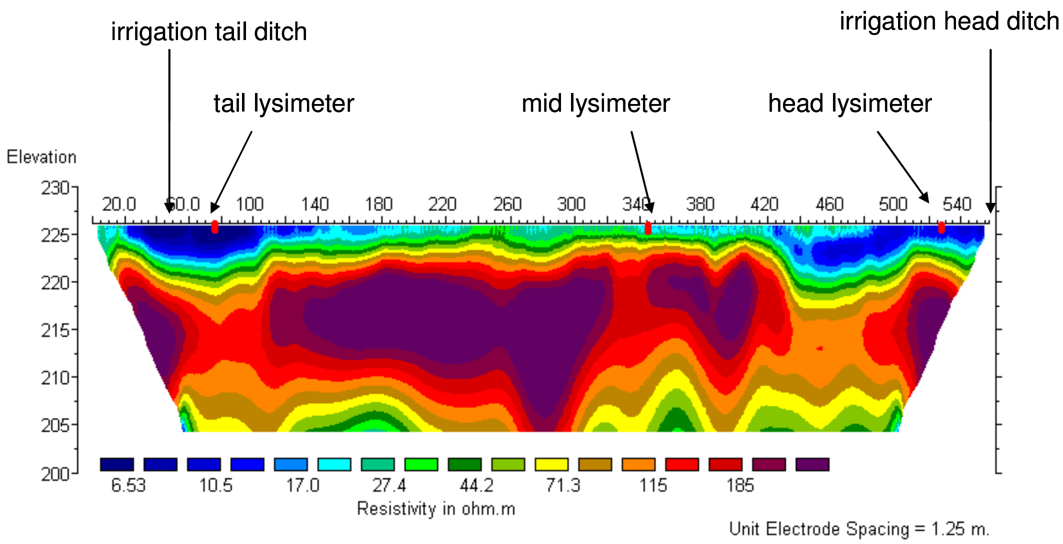


Figure 10: Location and depth of the three lysimeter installations as well as the irrigation head and tail ditch in the resistivity image taken in August 2007

Figure 11 shows the bulk resistivity distribution in the Sorghum field at different drying stages. The images show significant variation in bulk electrical resistivity, which as these changes occur over a short time period are most likely related to soil moisture changes. We thus relate low electrical resistivities in the image to moist soil and higher resistivities to drier soil.

In figure 12 the bulk electrical resistivity distribution before and after the first irrigation event is shown. The fact that the electrical resistivity at a depth of 1.2 m shows only small changes indicates no or only minor occurrence of deep drainage at this location. This result matches the absence of recorded deep drainage water in the adjacent mid lysimeter.

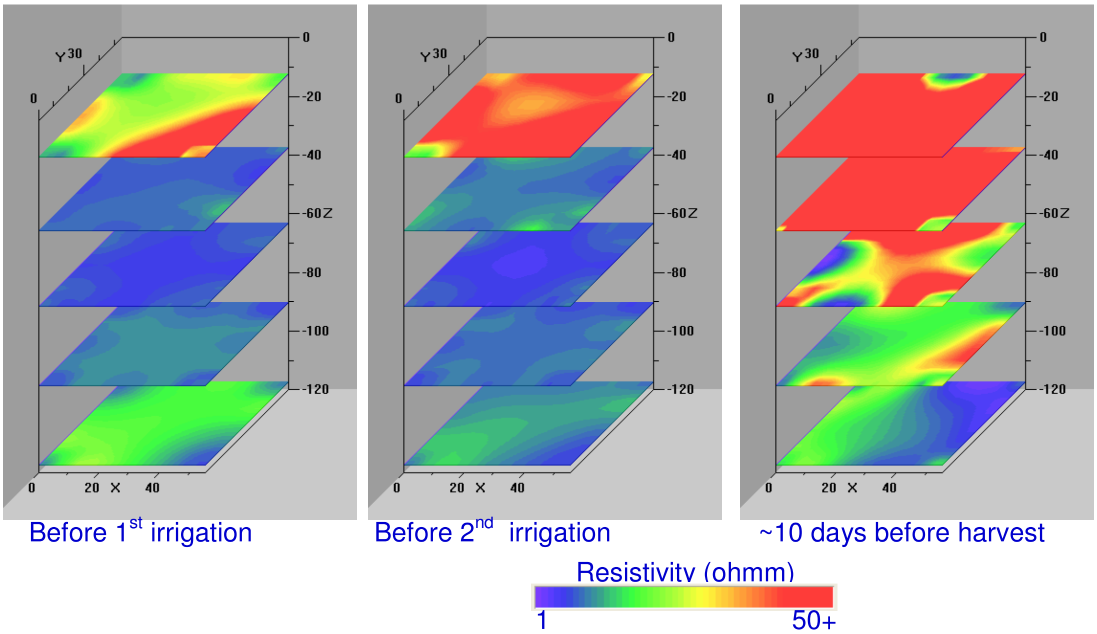


Figure 11: 3D soil electrical resistivity profile beneath a Sorghum crop at different drying stages

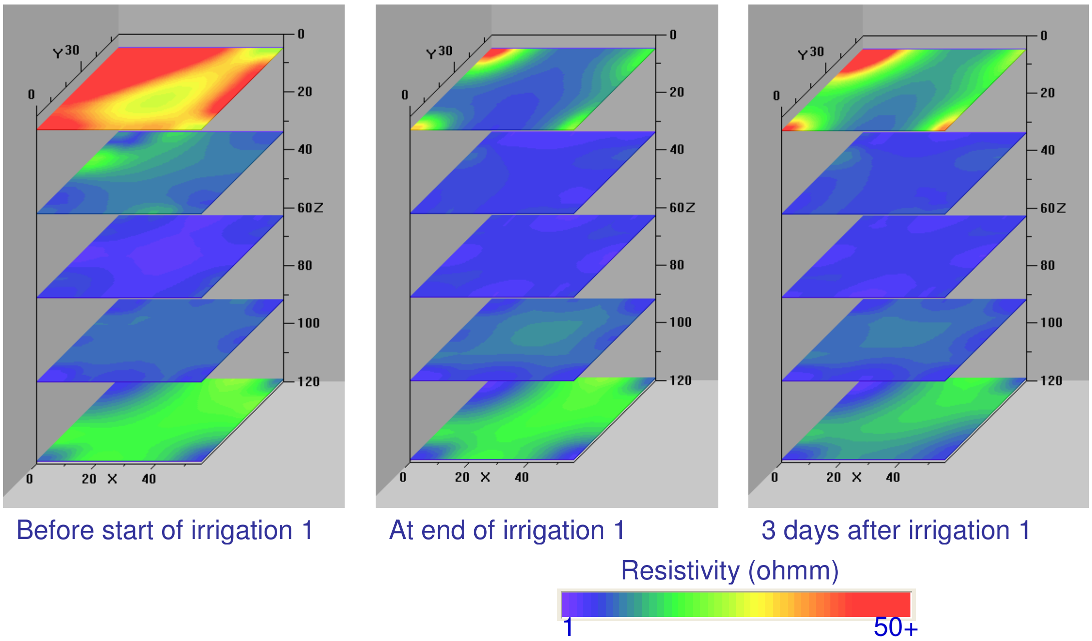


Figure 12: 3D soil electrical resistivity profile beneath a Sorghum crop before and after the first irrigation event of the growing season 2007/08.

4. Conclusions and Future work

The high variation of recorded deep drainage within one field emphasises the high spatial variability of hydrological processes and the need for measuring methods that give spatial resolution. 3D BRT offers exactly this and the results of the 3D resistivity work from the growing season 2007/08 show that the theoretical concepts could successfully be applied in the field.

For successful on farm use of 3D BRT easy and widely applicable calibration methods for resistivity-soil moisture relationships in cracking clays are needed. Further analysis of the collected data from the weighing lysimeters and the CWI field site is presently being carried out to provide such calibration methods and to further verify the usability of 3D BRT to monitor deep drainage and soil moisture changes.

Further data collection and optimisation of the probe design and measurement routines will be carried out in the growing season 2008/09. Additional to the present CWI field site borehole resistivity probes will also be installed at the ACRI field site in Narrabri.

Acknowledgements

The authors would like to thank the Cotton Catchment Community CRC for providing funding, as well as Des McGarry and Thusitha Gunawardena (DNR&W QLD) for installing the mini lysimeters.

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