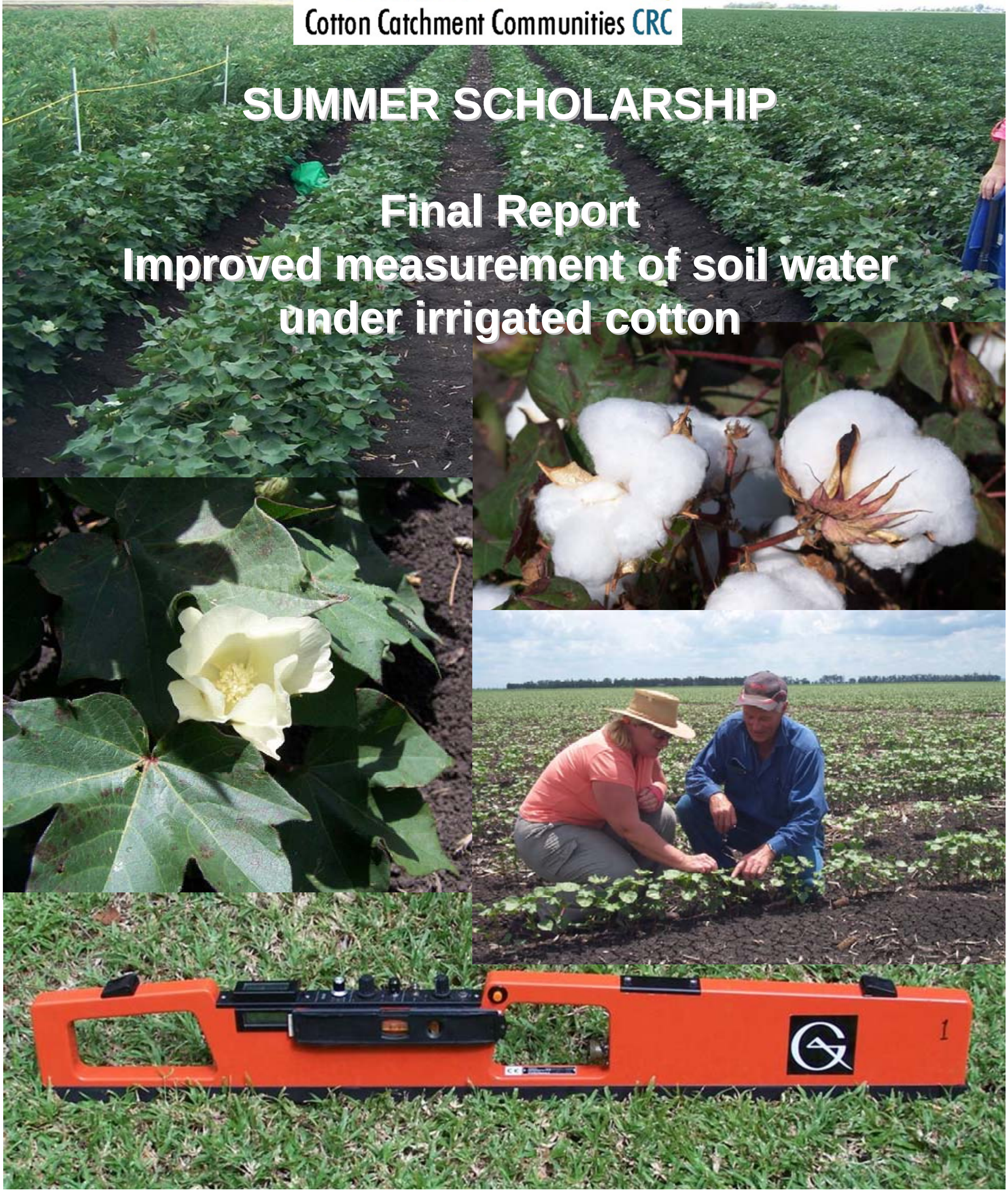
Cotton Catchment Communities CRC

SUMMER SCHOLARSHIP

Final Report
Improved measurement of soil water under irrigated cotton



Queensland Government
Natural Resources and Water

USQ UNIVERSITY OF SOUTHERN QUEENSLAND

Condamine Alliance
COMPLETE CATCHMENT CARE

Cotton Catchment Communities CRC

SUMMER SCHOLARSHIP
Final Report

Project Number 5.10.03.17

Project title “Improved measurement of soil water under irrigated cotton”

Aims and milestones

This project aims to provide detailed measurements of soil water and distribution of irrigation water and changes to the water balance of an irrigated cotton system, during a summer growing season.

Infiltration of irrigation water, and soil water extraction by plants, are key components of the water balance of cotton crops. They are difficult to measure because measurements need to be repeated over time and made at a range of depths in the soil, and because access is difficult when fields are wet. Because our modelling studies of the water balance of cotton crops require this basic information, we wished to trial measuring infiltration and extraction throughout an irrigation season using electromagnetic induction methods (using an EM38 device) to track water content changes across a paddock where spatially variability occurs due to furrow irrigation. That is, soil water may vary from the head to the tail ditch and between furrows. An important innovation will be to use the depth response function of the EM38, in conjunction with measurements of the soil water profile obtained from soil coring, to give depth discrete soil water profiles (‘depth slicing’ as done for airborne EM).

The summer scholarship student was required to calibrate the EM38 at an established study site in SE Qld and monitor water changes during consecutive irrigation sequences in the summer growing period.

Staff

Tami Mills (BSc), Masters in Engineering Technology– Agriculture
University of Southern Queensland, Toowoomba, Qld 4350.
Tel: 07 46966054; Fax: 07 46966054; Email: tami.mills@nrw.qld.gov.au or sharika@aapt.net.au

Jenny Foley, Scientist (Soil Hydrology)
Cotton Catchments Communities CRC
Natural Resources and Water, PO Box 318, Toowoomba, Qld, 4350.
Tel: 07 46881435; Fax: 07 46881193; Email: jenny.foley@nrw.qld.gov.au

Dr Brett Robinson, Scientist
Cotton Catchments Communities CRC
Natural Resources and Water, PO Box 318, Toowoomba, Qld, 4350.
Tel: 07 46881343; Fax: 07 46881193; Email: brett.robinson@nrw.qld.gov.au

Dr Mark Silburn, Senior Soil Conservationist
Cotton Catchments Communities CRC
Natural Resources and Water, PO Box 318, Toowoomba, Qld, 4350.
Tel: 07 46881281; Fax: 07 46881193; Email: mark.silburn@nrw.qld.gov.au

Dr Rabi Misra, Faculty of engineering and Surveying
CRC for Irrigation Futures
University of southern Queensland, Toowoomba, Qld, 4350.
Tel: 07 4631 2805; Fax: 07 4631 2526; Email: misrar@usq.edu.au

Technical assistance

Maria Harris, Scientific Assistant
Natural Resources and Water, PO Box 318, Toowoomba, Qld, 4350.
Tel: 07 46881262; Fax: 07 46881193; Email: maria.harris@nrw.qld.gov.au

Denis Orange, Senior Technician
Natural Resources and Water, PO Box 318, Toowoomba, Qld, 4350.
Tel: 07 46881269; Fax: 07 46881193; Email: denis.orange@nrw.qld.gov.au

Perry Poulton, Farming Systems Research
CSIRO Sustainable Research, PO Box 102, Toowoomba, Qld, 4350.
Tel: 07 46881202; Fax: 07 46881193; Email: perry.poulton@csiro.au

Neil Huth, Farming Systems Research
CSIRO Sustainable Research, PO Box 102, Toowoomba, Qld, 4350.
Tel: 07 46881202; Fax: 07 46881193; Email: neil.huth@csiro.au

Our thanks go to Stewart Leadbetter, Manager of “Melrose” property, Pampas, for generously giving permission for the study to be carried out on Melrose, and to Michael Hegarty who provided field support throughout the sampling period.

The property is also one of the drainage lysimeter sites of Dr. Des McGarry (NRW). Some calibration measurements were made in that field, however the main study was in a field to the north, so that a cotton crop could be monitored.

Project Summary

The summer scholarship project was awarded to Tami Mills (BSc), currently enrolled in Masters in Engineering Technology – Agriculture, at the University of Southern Queensland, Toowoomba. The scholarship commenced on 20th November, 2007 and was completed on 20th April 2008. Scholarships funds were administered through The Condamine Alliance.

This project was in collaboration with CRC Project 2.1.02 "Capturing our understanding of soil water balance and deep drainage under irrigation in models", a project funded in partnership with Cotton Catchment Communities CRC, CRDC, Condamine Alliance and QMDC (led by Dr Mark Silburn).

Background

Cotton growing on the Darling Downs has declined in plantings due to drought and lack of irrigation water, therefore the sustainable use of available water is imperative for the viability of the industry. The strategies required to produce maximum cotton yields are dependent in part on irrigation scheduling. Over-watering can cause water logging, deep drainage and poor crop yield, or on the other hand excessive leaf growth that alters light conditions, leading to poor spray penetration and increased water demand (Milroy *et al.* 2002). Therefore, an efficient way to monitor crop water use and plant available water (PAW) in the soil profile throughout the growing season is essential so that informed management decisions can be made in the application and conservation of irrigation water. Such data is also needed to test water balance models that are used to extrapolate to other seasons, management scenarios and locations. Without models of the water balance, a great deal more experimentation would be required, at high cost, before we could make predictions about the economic and environmental performance of crops and farming systems.

One method of measuring soil water is to use electromagnetic induction devices such as the EM38 (Geonics Ltd., Ontario, Canada). These devices are easy to use, lightweight, and provide rapid measurements over large areas without the need for ground installations or destructive sampling. They measure electric currents, induced at depth in response to an external magnetic field. The strength of the induced current is determined by the apparent electrical conductivity (EC_a) of the soil (a depth-weighted average of the soil electrical conductivity) (Hossain *et al.* 2008). The EC_a is mainly a function of the water, clay, cation exchange capacity (CEC) and salt content of the soil. A site specific calibration is necessary to differentiate the effects of each of these variables on the measured EC_a (O'Leary 2004). For the purposes of tracking water movement and re-distribution throughout the cotton season, repeated measures at the same locations within the paddock (with salt and clay remaining constant) allow for any temporal change of the EC_a to be attributed to changes in soil water content (Akbar *et al.* 2005; Hossain *et al.* 2008; Huth and Poulton 2007; Topp and Ferre' 2003; Wilson *et al.* 2003). EC_a readings are converted to bulk soil water contents through a site/soil specific calibration equation.

In this study, to gain a more accurate description of the soil water contents at various depth within the profile, the EM38 was used in both vertical and horizontal dipole modes, and readings were taken at ground level and at 0.1 and 0.4 m heights above-ground, for the purpose of depth slicing the data to determine soil water contents to various soil depths. This technique has been previously used or recommended by Rhoades and Corwin (1981) and Cook and Walker (1992) who suggested using simultaneous multiple measurements to create a better interpretation of the EC depth distribution. Multi-height measurements were also used to successfully predict soil water in the root zone by Hossain *et al*. (2008).

The research undertaken in this project seeks to improve our understanding and modelling of water use and re-distribution within the cotton growing environment, and investigates the use of depth slicing with an EM38 to quantify the soil water profile at different soil depths.

Methodology

This study was conducted at "Melrose" near Pampas, Darling Downs, Queensland, on a black Vertosol (Isbell 1996) planted to (irrigated) cotton in late November 2007.

An EM38 (Geonics Ltd, Ontario, Canada) was used to measure the apparent electrical conductivity (EC_a) of the soil profile (see cover photo). This device can be operated in both vertical and horizontal dipole modes (i.e. by placing it either upright or sideways on the ground), which allows EC_a to be measured at different depths in the soil. The vertical mode response is most sensitive to the deeper soil bulk conductivity, peaking in response at 0.4 m and declining exponentially to approximately 1.5 m depth, while the horizontal mode is most sensitive to depths at the surface, declining exponentially to approximately 0.75 m.

EM38 readings were taken the day before irrigation was scheduled, soon after irrigation had ceased (within 72 hrs of water-on) and then frequently throughout the drying period, for two scheduled irrigations during the course of the growing season. Readings were continued until crop maturity. Measurement locations in the paddock were chosen to include a spatial representation of the variation in irrigation flow from the head channel to the tail drain (Figure 1), with readings taken at head, mid and tail positions in the paddock. Separate readings were also taken for plant rows and irrigation furrows, to capture small scale wetting/water uptake variability. At each paddock position, 16 readings were taken in furrows and 16 in plant rows, in an 8 m x 8 m grid (Figure 1). Readings were taken in vertical and horizontal modes at the ground surface, and 0.1 m and 0.4 m above the surface (i.e. 6 height/mode readings at each of the 16 positions for furrows and 16 positions for rows, at each H/M/T position). The paddock was sampled a total of 14 times during two periods of soil drying, from Jan-April 2008. These periods followed the second and third (final) irrigations in the field.

Two different EM38's were used for simultaneous data recording at one sampling date in March, to test for consistency between devices. In addition, the effects of large soil cracks, plant foliage, high ambient temperatures and light rainfall on EC_a and instrument drift were checked. Other field observations recorded were ambient temperature, vegetative growth stage of the cotton plants, and a visual description of the extent of soil cracking. Climate data from a nearby weather station (500 m) and town (Pampas, ~10 km) were used in a simulation model.

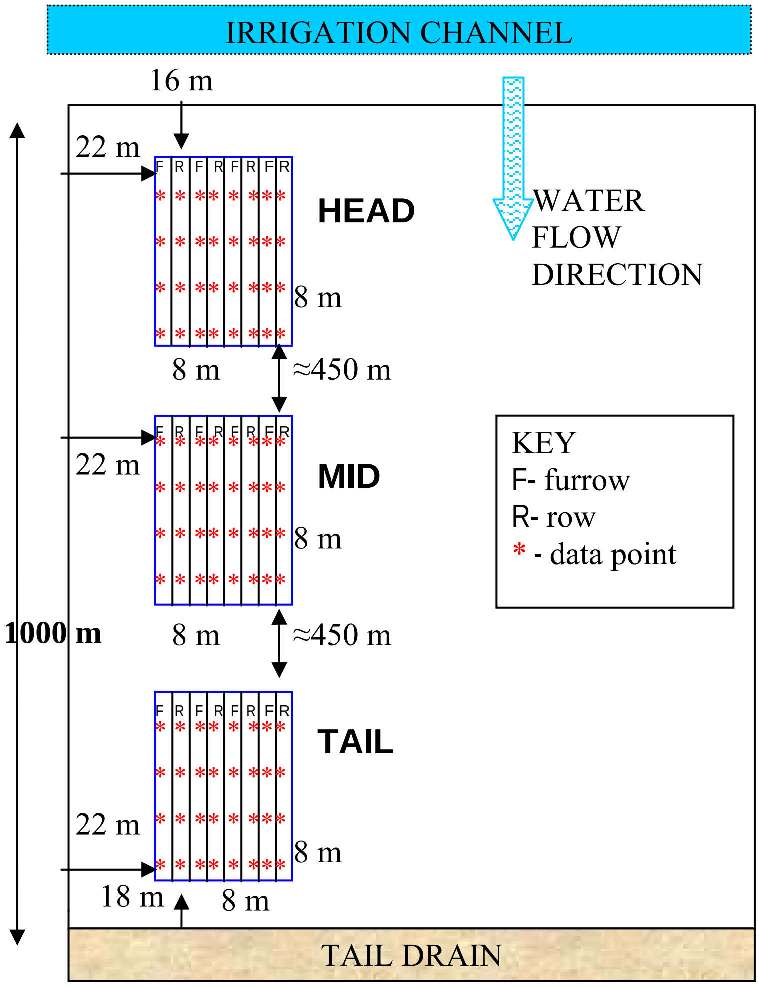


Figure 1. Field experimental layout showing the position of EM38 readings

Calibration

EC_a (mS/m) measurements from the EM38 were converted to mm of water by regression of the EC_a readings against volumetric water contents (for discrete soil depths), for a range of wet to dry field conditions. Initially, an NRW owned EM38 was used to measure EC_a after sorghum harvest and also where soil had been artificially wet to drained upper limit (DUL), in a paddock (the drainage lysimeter field) beside the cotton-study paddock. Two replicated cores and matching EM38 readings were taken at head, mid and tail positions for both 'dry' and' wet' soils. Soil water content and bulk density were sampled to 3 m (in 0.2 m depth increments) using a soil coring rig. EM38 readings were taken in vertical and horizontal dipole modes at ground level, and at 0.1 and 0.4 m above ground.

Due to the unavailability of the NWR EM38 for the rest of the study, a CSIRO owned EM38 was used for further calibrations (and during cotton crop measurements). Head and mid positions in the cotton crop were sampled for calibration purposes soon after the second irrigation, while soil was still above DUL. In addition, core samples and EC_a readings were taken in a second sorghum paddock after harvest, and in nearby native vegetation, to obtain 'very dry' soil-water profiles.

In the vertical position, the EM38 effectively measures EC_a to 1.5 m, while in the horizontal position, to 0.75 m. Raising the device above the ground is equivalent to 'shunting' the EC_a profile lower down the EM38 depth response function (Hossain *et al.* 2008) i.e. in the vertical mode, a reading 0.1 m above ground now measures to a bulk depth of 1.4 m (1.5 m minus 0.1 m), and at 0.4 m above ground to a bulk depth of 1.1 m. Therefore, to determine calibration equations for 6 depths in the soil profile, mm of soil water were calculated from volumetric water contents and summed to each depth (0.35, 0.65, 0.75, 1.1, 1.4 and 1.5 m), then compared by regression with the EC_a measurements.

Modelling methods

In order to predict water use in a range of situations, we are building a simulation model (HowLeaky?, Rattray *et al*. 2004) that can hopefully reproduce the water use of crops in those few situations where we accurately measure water use. This project gave us a rare opportunity to measure water use and compare it with our model's predictions.

Because weather data was not available from the site for the whole period, a composite weather file was "spliced" together from site data for the period 1 Jan 2008 to 29 Feb 2008, and data from Pampas for 1 Jan 2007 to 31 Dec 2007 and 1 Mar 2008 to 19 May 2008. The rainfall totals for the site and Pampas were similar for the period from 1 Jan to 1 Mar at 127 mm and 142 mm, respectively. To further check whether the rainfall and temperature data for the site and Pampas are similar, daily values were also compared statistically by linear regression and the main difference was that the site had slightly lower minimum temperatures than Pampas. So the composite weather file should provide valid results.

The other data used to run the HowLeaky? model (Rattray *et al.* 2004) were a soil parameter file and a crop parameter file. Most soil parameters were derived from data collected by field sampling and laboratory analysis. For example, DUL and bulk density (BD) were obtained from PAWC studies (coinciding with the initial set of NRW EM38 calibrations). Saturated moisture content was estimated from BD measurements. Other parameters were similarly obtained by estimation or extrapolation from experimental or laboratory data.

The crop parameters determine the rate and amount of development of leaf area index (LAI), root depth and other parameters that affect soil water extraction and crop transpiration.

Results

There was no significant difference between the slopes of regression equations of the two EM38 devices (both in vertical and horizontal modes) and so all 18 cores and corresponding readings were used to determine calibration equations (Figure 2).

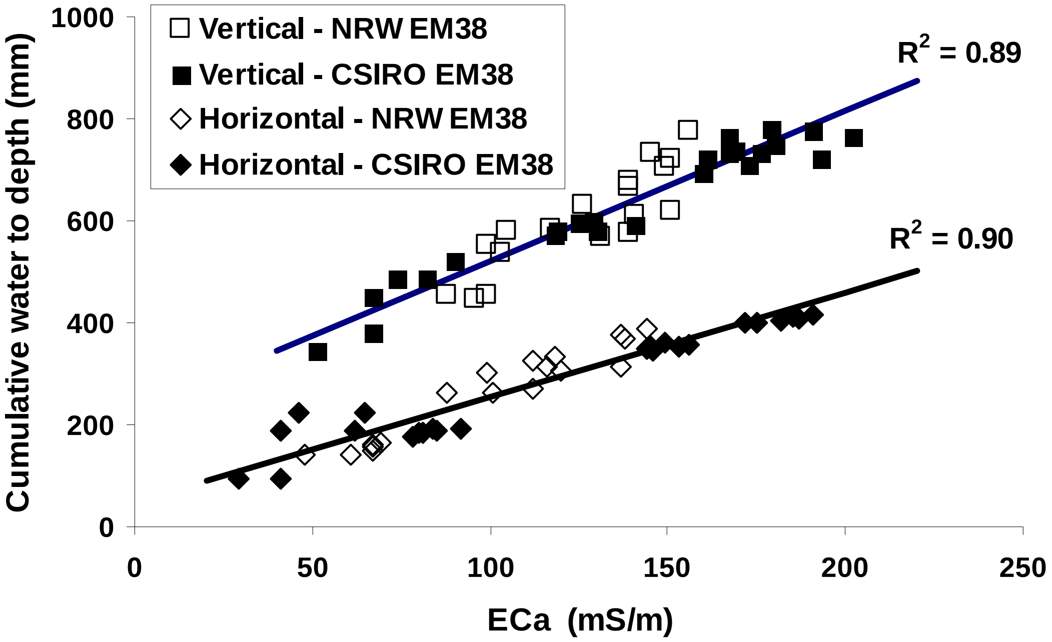


Figure 2. A comparison of EC_a and cumulative water (mm) for discrete depth profiles, taken in vertical and horizontal dipole modes, and using two EM38 devices

The relationship between EC$_a$ and cumulative volumetric soil water content was highly significant (F pr. <0.001) and strongly linear for vertical and horizontal modes (R2=0.9) (Figure 3). As there were slight differences in the slopes of the individual calibration regressions, 6 separate calibrations were used to convert all the data into mm of water (Figure 3). The calibration was highly sensitive to cumulative soil water depth, indicating the need for precise sampling and accurate calculation of soil water.

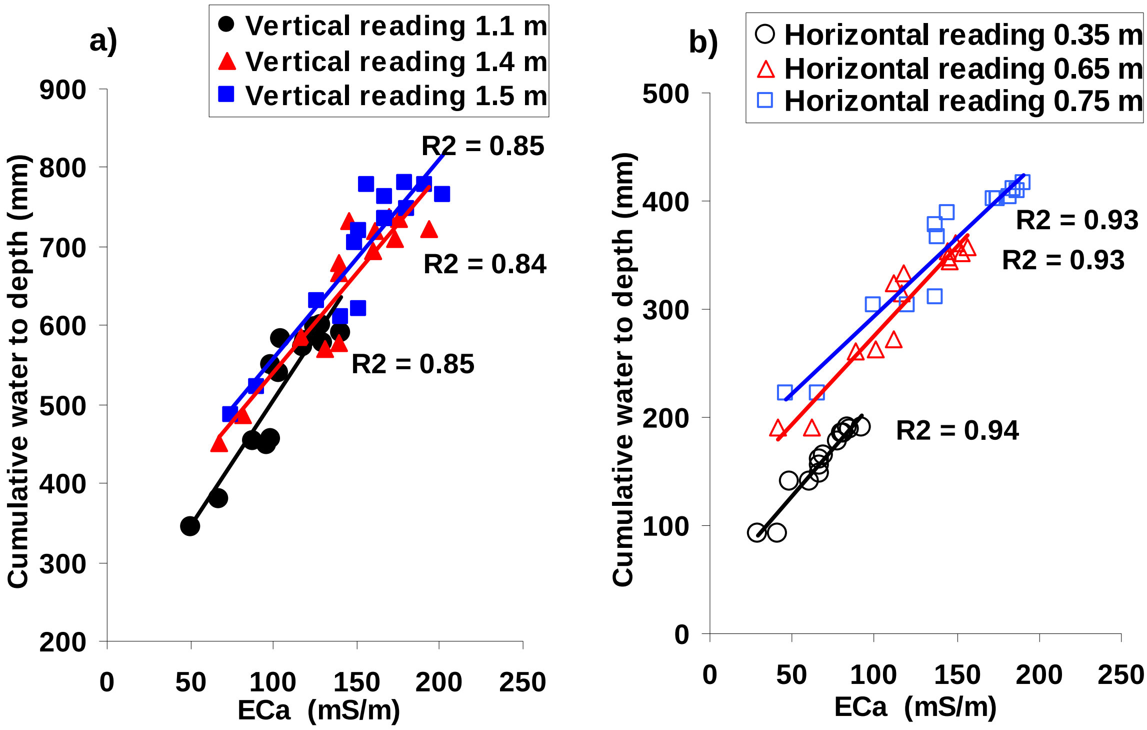


Figure 3. Individual calibration curves for ground and above ground reading depths in a) vertical mode, and b) horizontal mode

The individual regression curves gave a better fit of data in the horizontal dipole mode (Figure 3). These results agree with those of Hossain *et al.* (2008), who also found the horizontal mode consistently provided a better fit. The effective soil depth measured in the horizontal mode is only 0.75 m and the contribution (to the reading) is not uniform with depth, but rather decreases exponentially, with the surface layers contributing more to the bulk reading than the lower layers. Therefore, the surface EM38 readings would be expected to be a little more strongly related to soil water because there is less bulking, or “dulling”, of EC$_a$ responses to temporal changes in water content, most of which occur in the surface layers. This sensitivity to surface conditions leads to a slightly different calibration curve for the surface soil (Figure 3b, 0.35 m depth).

Monitoring field soil moisture content with the EM38

As shown in Figure 4, the RMSE (Root Mean Square Error) from the calibration is small in relation to the estimated changes in soil moisture. It is encouraging to note in this figure that the maximum measured water contents with the EM38 are similar to the soil water contents at saturation, as calculated from the soil measurements of bulk density. The small discrepancy may be due in part to the lack of calibration data for soil near saturation.

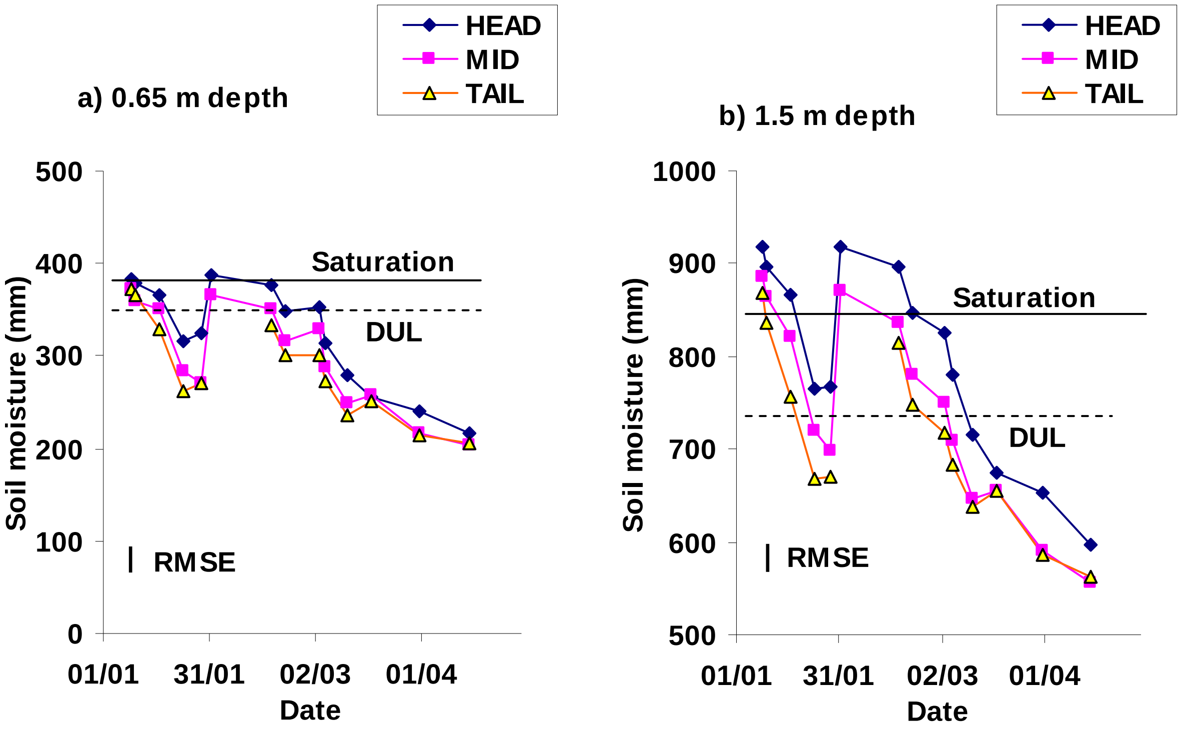


Figure 4. Estimated changes in total soil moisture over time. Two depths and three field positions are shown. RMSE is the root mean square error of the calibration equation, a measure of the accuracy of all of the data.

Figure 4 gives us a detailed picture of the water balance in this paddock, and has several features, including:

- The soil was above DUL for much of the time (i.e. it was probably draining much of the time)
- The soil was saturated to considerable depth at each irrigation, especially near the head ditch
- Despite being wetter, the soil at the head ditch end of the paddock lost water at a similar rate to the mid and tail
- The mid and tail appear fully watered (or wetter) while the soil near the head ditch is too wet for too long. This is consistent with the unhealthy plants that were seen in some areas near the head ditch that were probably affected by waterlogging, despite the high tolerance of cotton plants to waterlogging)
- About half of the irrigation water applied at the end January appears in the 0.65 m to 1.5 m zone (i.e. the rise in the graph to 1.5 m is about

double the rise in the graph to 0.65 m). This is a concern, as there are not as many roots at this depth as there are close to the surface, and water added to this depth is more likely to drain from the profile rather than be used by the crop.

Modelling soil moisture content

One of the main reasons why we are interested in making soil moisture measurements with the EM38 is to check whether our computer models of water use by cotton crops are valid. Of the three possible fates of rainfall and irrigation (runoff, deep drainage and evapotranspiration), evapotranspiration is by far the largest amount. Therefore, if we wish to understand the system, evapotranspiration must be monitored and understood.

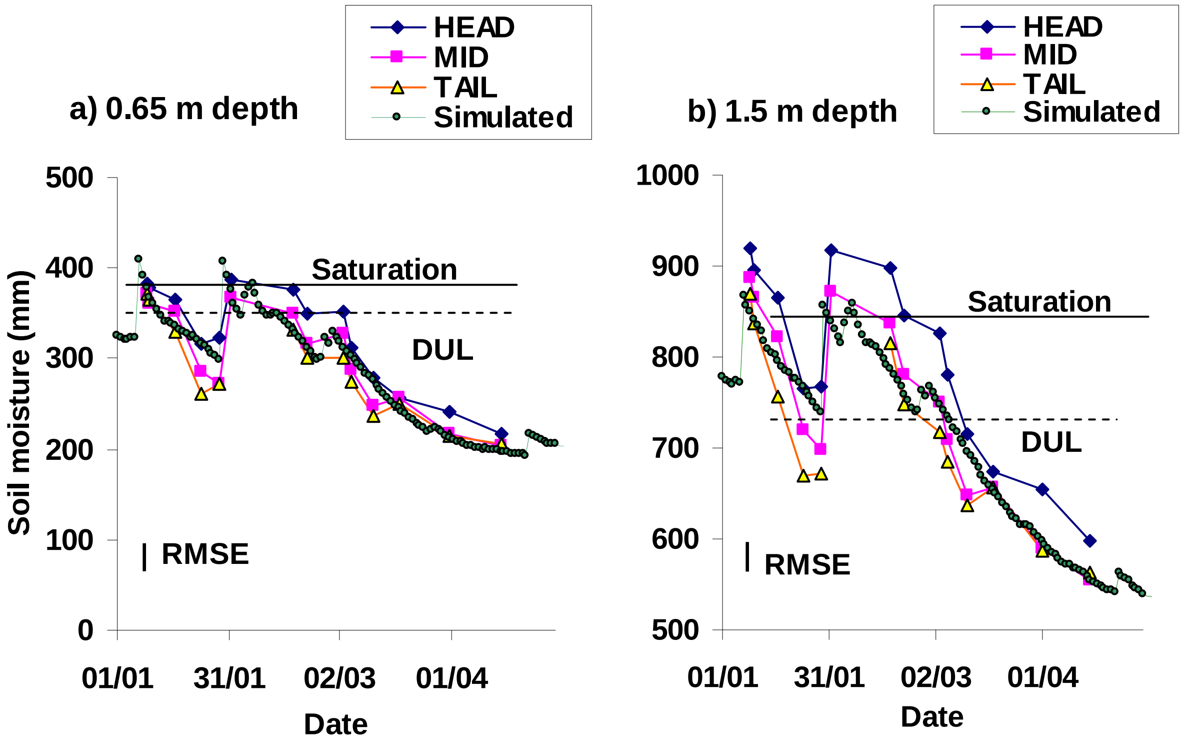


Figure 5. Estimated and simulated total soil moisture for two soil depths. Crop parameters representing a fast-developing crop were used.

The soil water balance model did a good job of simulating the changes in soil moisture. From the end of January to the end of the measurements, the results were excellent, but during January, the measured rate of loss of soil moisture is quite a lot higher than the simulated rate of loss. Therefore, the crop parameters were changed so that more soil water was extracted during the January period. In this simulation, the roots grow more rapidly and the crop cover develops more rapidly, intercepting more radiation and using more water. However, as shown in Figure 5, the amount of simulated water use was still less than the amount implied by the measurements from the EM38. The reasons for this are unclear, but it is worth noting that the EM38 was not calibrated in fully saturated soil. The monitoring measurements included readings much higher than the calibration range, so there is extra uncertainty concerning the interpretation of these highest readings. Also, it is possible that potential evapotranspiration experienced by the crop was higher than in the climate data due to advection from surrounding fields without crops and due to wind, as measurements were made near the edge of the field.

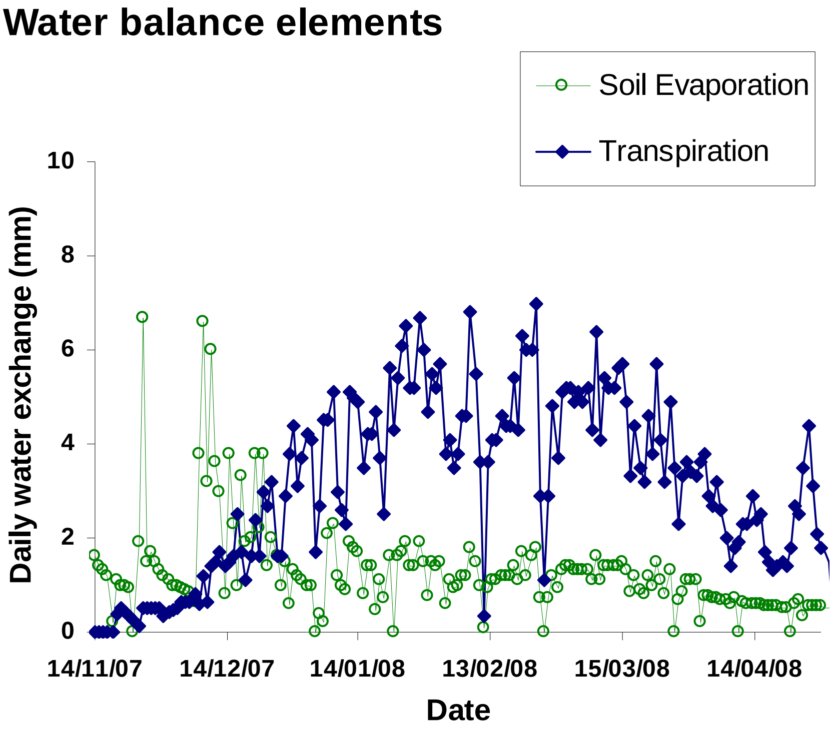


Figure 6. Simulated soil evaporation and transpiration for the monitored crop, using the HowLeaky? model.

Overall, the results from both simulations are good enough to give us considerable confidence in the model. Given the overall validity, the detail of the model's results can be examined to increase understanding of the water balance. Graphs of three elements of the water balance are shown in Figures 6 and 7. As well as examining the detail of these results, we can estimate total soil evaporation, transpiration and deep drainage from planting to maturity. *These are 225 mm, 540 mm and 100 mm, respectively, for this crop.*

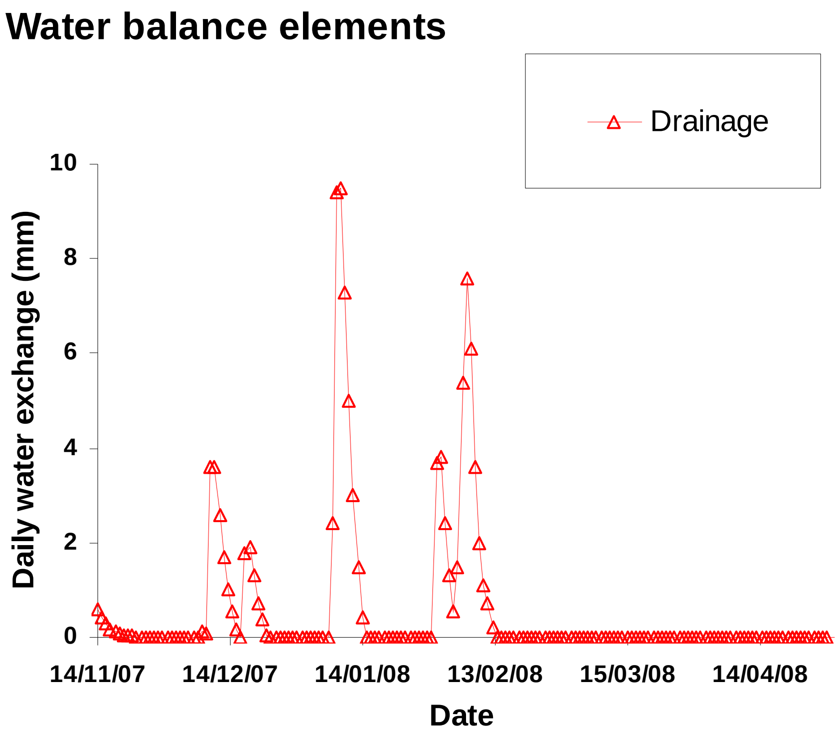


Figure 7. Simulated deep drainage for the monitored crop, using the HowLeaky? model. The total simulated deep drainage between planting and mid May was 100 mm.

Conclusion

The EM38 was easy to use and gave results that were highly correlated with soil moisture contents to a range of depths. Although multiple measurements are required to account for spatial variability, the measurements are quite easy to make. The collection of 192 EC_a measurements (32 points at 3 heights in 2 modes in one location) took approximately half of one hour.

Our data indicate that for each situation (head, mid, tail, row, ditch) 4 measurements are typically required in vertical mode to get an average that is within 5 mS/m of the true mean. In horizontal mode, 15 measurements are typically required for the same accuracy. The greater number of samples required in horizontal mode is presumably because the surface soil has more variability due to cracking and roughness. In larger areas, it will be important to consider the spatial distribution of water, salt and clay in the soil when sampling.

When the soil is close to saturated with water, the accuracy of the results may be less than at other times. Because we only had calibration data from drained upper limit and drier, the accuracy is not known. However, similar calibration problems would exist regardless of the sensor or method used.

Collecting data near saturation is extremely difficult because of problems such as vehicle access and physically removing soil samples from soil coring tubes.

Raising the EM38 to sample to a range of depths was very effective. Good correlation was obtained for both orientations and all heights. Interestingly, at 0.4 m height, the variability of measurements in the horizontal mode was less than at the soil surface, so there appears to be considerable potential for using the EM38 in horizontal mode at 0.3 to 0.5 m height to measure the water content of shallow surface layers of soil.

Temperature, time of day, size of the cotton plants, and other potential effects on the readings from the EM38 were non-significant.

The EM38 monitoring highlighted how wet the soil was until late March. Some of this was due to rainfall soon after the irrigation in late January, but it appears that the irrigation was going to be somewhat earlier than necessary. The soil moisture deficit in late January was small when compared with later in the season.

The data collected by the EM38 agreed to a large degree with the predictions from the HowLeaky? Model, which estimated that during two periods in the season, a significant amount of deep drainage occurred (100 mm). This is of concern both in terms of water wastage and the potential for it to contribute to the rise of salty groundwater and surface salinity.

Presentations and public relations

Results from the study were presented to CSIRO, DPI&F and NRW staff at an Irrigated Farming Systems meeting on 13th May 2008. Detailed method/results descriptions have also been presented to Fernanda Dreccer (CSIRO Plant Industry, Gatton) and Greg McLean (Agricultural Systems Modelling, DPI&F, Toowoomba) for future implementation in their research.

References

Akbar MA, Kenimer AL, Searcy SW, Torbert HA (2005) Soil water estimation using electromagnetic induction. American Society of Agricultural Engineers 48, 129-135.

Cook PG, Walker GR (1992) Depth profiles of electrical conductivity from linear combinations of electromagnetic induction measurements. Soil Science Society American Journal 56, 1015-1022.

Geonics Ltd (2003) EM38 Ground conductivity meter operating manual. Mississauga, Ontario. Canada.

Hossain MB, Lamb D, Lockwood PV, Frazier P (2008) Field determination of soil moisture in the root zone by multi-height EM38 measurements. Precision Agriculture Research Group. UNE Armidale NSW.

Huth NI, Poulton PL (2007) An electromagnetic induction method for monitoring variation in soil moisture in agroforestry systems. Australian Journal of Soil Research 45, 63-72.

Isbell RF (1996) The Australian Soil Classification. CSIRO publishing. Collingwood, Australia.

Milroy S, Goyne P, Larsen D (2002) Irrigation scheduling of Cotton. Cotton Information Sheet. Australian Cotton co-operative Research Centre.

O'Leary G (2004) Standards for electromagnetic induction mapping in the grains industry.

Rattray DJ, Freebairn DM, McClymont, D, Silburn DM, Owens J, Robinson JB (2004) HOWLEAKY? - the journey to demystifying simple technology. Conserving Soil and Water for Society: Sharing Solutions ISCO 2004, the 13th International Soil Conservation Organisation Conference. Brisbane, July 2004.

Rhoades JD, Corwin DL (1981) Determining soil electrical-depth relations using an inductive electromagnetic soil conductivity meter. Soil Science Society American Journal. 45, 255-260.

Topp G, Ferre' TP (2003) Measuring soil water content in Encylopedia of hydrological sciences. (ed Anderson MG) Minister of Public Works and Government Services. US.

Wilson RC, Freeland RS, Wilderson JB, Yoder RE (2003) Inferring subsurface morphology from transient soil moisture patterns using electrical conductivity. American Society of Agricultural Engineers. 46, 1435-1441.