Estimating deep drainage on the field scale using a Mobile EM Sensing System and Sodium-SaLF

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Introduction

Knowledge of the quantity of water draining below the root-zone is necessary in order to maximise and ensure sustainable water use, particularly when surface water is applied for irrigated agricultural production. Traditionally, this has been based on soil hydraulic properties which whether measured directly or correlated with soil morphological properties, is difficult, time-consuming and expensive to determine (Shaw, 1988). Shaw and Thorburn (1985) indicated that soil leaching is closely related to hydraulic conductivity (*K*) and that important soil properties that influence *K*, including; clay content, clay mineralogy (*Cation Exchange Capacity*/Clay % Ratio, *CCR*) and exchangeable sodium percentage (ESP), can be used to predict leaching fraction (*LF*) and deep drainage (*DD*). As a consequence an empirical model was developed into a program called Sodium-SaLF, which provides estimates of *LF*, *DD* and average root zone EC_e, at steady-state, based on these laboratory measured soil properties that are generally collected during soil surveys (ie. *CEC* and clay content). A small number of water quality parameters, such as EC_w, depth of irrigation water applied and annual rainfall, as well as the crop being grown is also required by the model.

Estimating deep drainage on the field-scale is complicated because of the relatively large spatial variation of soil. Over the last decade clay content (Williams and Hoey, 1987); depth to clay (Doolittle *et al.*, 1994) and leaching fraction (Slavich and Yang, 1987) have been estimated using Electromagnetic instruments. Here we demonstrate the use of a Mobile Electromagnetic Sensing System developed by Triantafilis and McBratney (1998) and its potential in estimating deep drainage and average soil EC_e at steady state using EC_a data and soil information coupled to a salt and leaching fraction model or Sodium-SaLF (Shaw and Thorburn, 1995). The research was carried out in a irrigated cotton field in the lower Gwydir valley, Australia.

Materials and methods

Auscott Midkin is a large cotton growing farm located in the lower Gwydir valley in northern NSW, Australia. The field selected for study, Field 11, covers 244 ha and has a long history of problems associated with shallow water tables and water logging. This is particularly the case in the middle parts of the field where sandy soil types are apparent. In order to map the spatial variability of soil types, estimate *DD* and average EC_e at steady state, and hence determine the cause of the water table, an EM survey was conducted using a Mobile EM Sensing System (Triantafilis and McBratney, 1998). It consisted of generating

EC_a measurements from the EM31 and EM38 in both modes of operation with the EM38 positioned 0.20 m above the ground. In total, 55 transects were traversed every 48 m, as illustrated in Figure 1. This was done to align the MESS in the appropriate traffic lanes and so avoid compacted or controlled traffic furrows which would result in non-representative EC_a measurements.

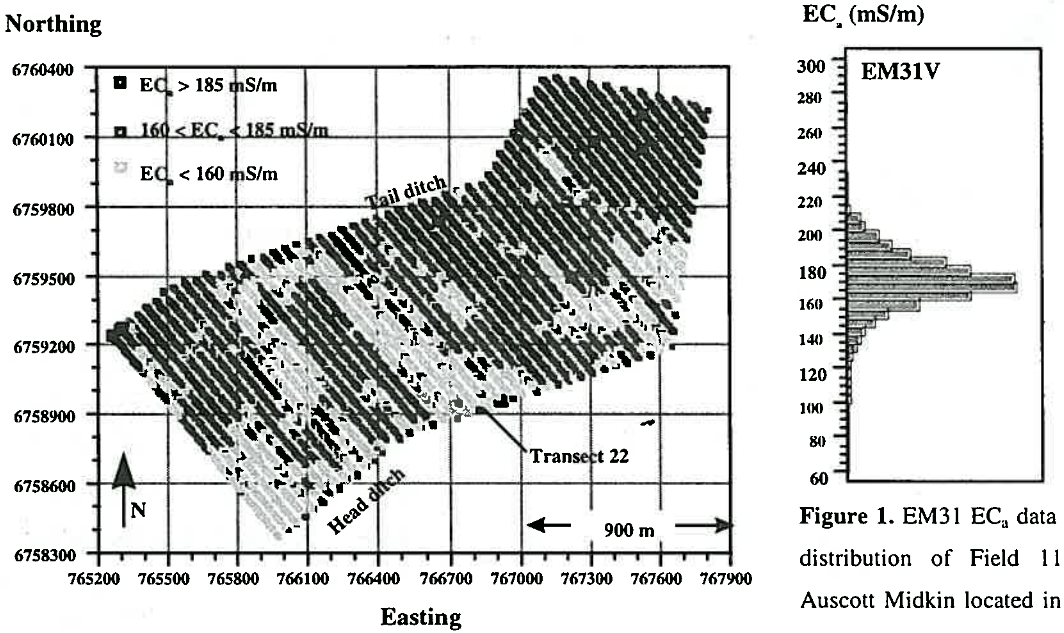

Figure 1. EM31 EC_a data and distribution of Field 11 at Auscott Midkin located in the lower Gwydir valley.

Soil sampling sites for calibration of soil EC_a to *DD* were selected by dividing the vertical EM38 and EM31 EC_a data into odd and even transect numbers. From each half we selected 23 sites ranging from low, medium and high EC_a measurements. An additional 23 samples were collected in places where no EM measurements were made, in order to validate our estimates. At all sites an intact soil core to a depth of 1.5 m was collected and bulked into 0.30 m increments. EM measurements were also taken directly above each calibration site. Laboratory analysis of soil included, *CEC* and particle size analysis at 0-0.3; 0.3-0.6; 0.6-0.9; and, 0.9-1.2 m depths, which are required for the Sodium-SaLF model as well as exchangeable sodium at 1.2 m.

Water samples were collected from nearby Carole Creek, which supplies the water required for irrigated cotton production. The EC_w was 0.393 dS/m. To run the model we assumed that 600 mm of this good quality irrigation water is applied annually and the farm receives an average annual rainfall of 584 mm.

Results and discussion

Figure 2 also indicates low, intermediate and high soil EC_a as generated by the EM31 in the vertical mode of operation. The lighter shaded areas (EC_a < 160 mS/m) indicate parts of the field where a prior stream travelled and where sandier soil types are apparent. In the north-eastern part of the field, larger values of EC_a (>185 mS/m) were generally obtained and reflects an area where heavy clay profiles exist. Similar EC_a patterns were obtained with the EM31 in the horizontal mode and the EM38 in both modes of operation. This suggests the instruments are primarily responding to clay content and soil mineralogy and hence strongly reflect the geology and geomorphology. This is confirmed in the right hand panel of Figure 1 which shows the distribution of EC_a, from the EM31 instrument, is normally distributed. If soil salinity or a shallow saline water table existed, the distribution would have a log-distribution with a high tail, because soil EC_a in those areas would be significantly higher.

Figure 2 shows the spatial distribution of EC_a along a single EM transect, transect 22, located in the middle of Field 11. The upper panel of Figure 2 shows soil EC_a as measured using the EM31 in the vertical mode. The second panel similarly shows EC_a as measured by the EM38 in the vertical mode. It is apparent from these two panels that the pattern of EC_a generated is similar, although the measurements as obtained using the EM31 appear slightly larger than those of the EM38. The last panel of Figure 2 illustrates this clearly and shows the ratio of EM31 and EM38. The reason for the larger ratio (ie., near the head ditch and within the prior stream channel), is that the EM38 is sensing the relatively sandy and less conductive topsoil, associated with this part of the field, which extends to depths of approximately 3-4 m. Beyond this depth a slightly more conductive and clay layer probably exists, which the EM31 is sensing. Deeper sampling should confirm this and elucidate the depth at which this heavy clay subsoil layer exists.

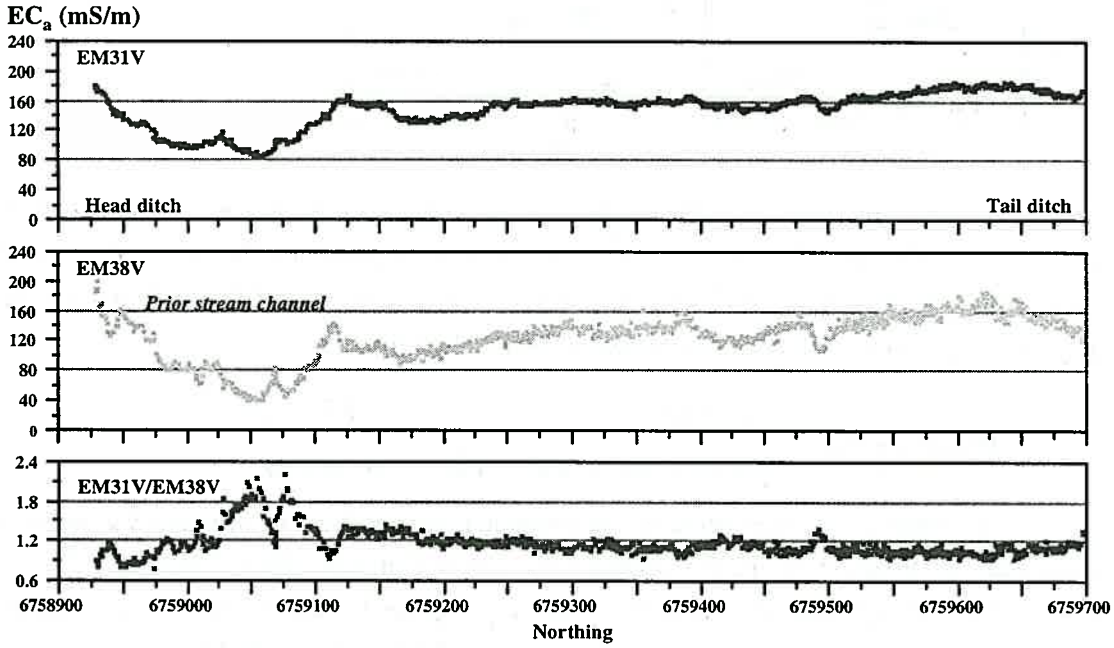

Figure 2. EC_a measurements and ratio of EM31 and EM38 of transect 22 located in Field 11.

The existence of this clay-rich subsoil layer is consistent with Stannard and Kelly (1977), who found in the nearby lower Namoi valley that sandy loams and sandy clay loams characterise the prior stream channels, whereas light and heavy clays are generally found further away from and underlying the channel, as illustrated in Figure 3.

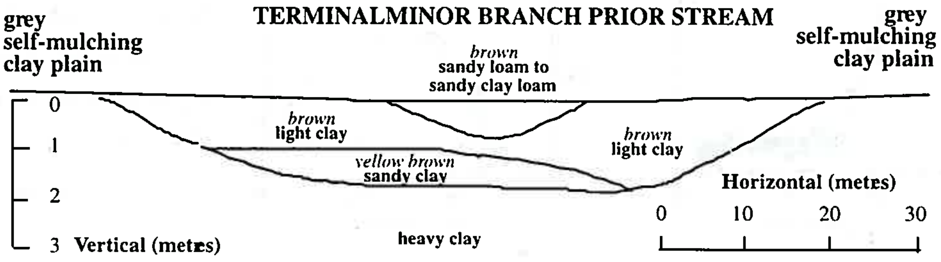

Figure 3. Cross section of a prior stream channel in lower Namoi valley, (Stannard and Kelly, 1977).

Various authors have attempted to calibrate soil EC$_a$ to clay content (Williams and Hoey, 1987) or depth to clay (Doolittle *et al.*, 1994 and Brus *et al.*, 1992). The success in these studies was due to lack of significant salinity or differences in moisture. As a result EC$_a$ was strongly related to clay content. This was similarly the case here with high correlations obtained between soil EC$_a$ and average clay content to 1.20 m. Figure 4, shows this relationship as measured by the EM38. The EM38 was selected despite the fact the EM31 showed greater correlation with clay content and *CEC* (results not shown). The reason the EM31 was not chosen for further analysis was because the instrument measures larger and deeper volumes of subsoil and hence is not as directly representative of soil variability and processes involved in *DD* and average salinity within the root-zone (ie., 1.20 m).

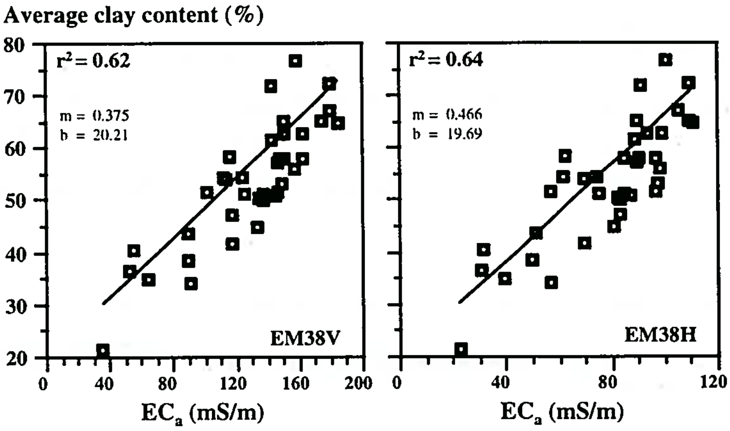

Figure 4. Regression relationship between soil EC$_a$ for EM38 in vertical and horizontal mode of operation and average clay content (%) to 1.20 m.

Owing to the reliance of the empirically based SaLF model to *CEC* and clay content, we found a rather novel but reasonable relationship exists between EC$_a$ and *DD* at steady state as estimated using SaLF. This is shown in the left hand panel of Figure 5 along with a fitted 4-parameter broken-stick model which was of the form:

$$DD\ (\text{mm/year}) = \begin{cases} a + b(EC_a), & if EC_a \le c \\ a + b \times c + d \times (EC_a - c), & otherwise \end{cases}$$

A similar model was fitted to the estimated average EC$_e$, as illustrated in the right hand panel of Figure 5. Using the Akaike Information Criterion (AIC), (Akaike, 1973), the EM38 in the horizontal mode was found to produce a better fit than in the vertical mode and was therefore used in preference to provide estimates of *DD* and average EC$_e$.

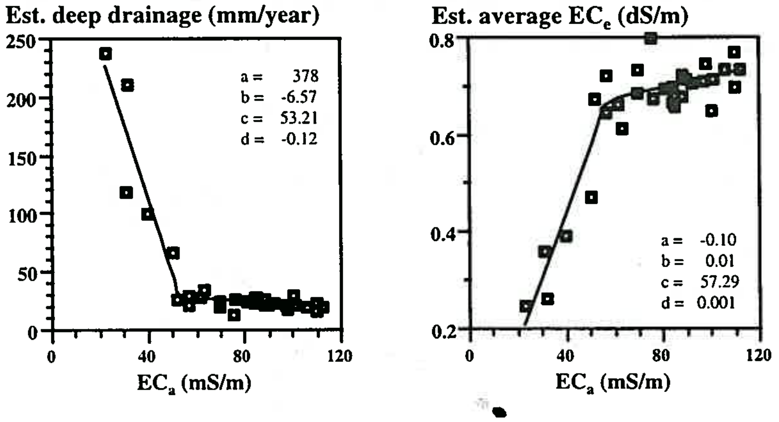

Figure 5. 4-parameter broken-stick model fitted to soil EC$_a$, as obtained with the EM38 in horizontal mode of operation, with estimated deep drainage beyond 1.20 m and average soil EC$_e$ at steady state, as estimated using SaLF.

Although the models fitted were not of an exponential form, which would theoretically be expected (Cook *et al.*, 1989), they do provide reasonable fits between soil EC_a and estimated *DD* and average soil EC_e at steady state. The reason for the abrupt change or lack of continuity between EC_a, *DD* and average root-zone EC_e, is attributable to the way Sodium-SaLF computes these estimates. Initially, the program calculates average clay content for each profile. The profile is then classed into one of eight clay ranges of 10%, and according to *CCR* a linear function is applied. As a result, *DD* or average soil EC_e can be over or underestimated if a profile lies near a class boundary.

Despite this, these relationships were used to predict *DD*, *LF* and average root-zone EC_e in transect 22, at steady state using 600 mm of irrigation water and assuming an annual average rainfall of 584 mm. The top panel in Figure 6 shows estimates of *DD* and *LF* (*DD*/1184 mm X 100) whilst the bottom panel shows the average EC_e at steady state as predicted by the relationships established in Figure 5.

It is apparent from Figure 6 that the majority of transect 22 has a *DD* of 25 mm/year and a *LF* of around 2 %. These estimates are comparable to those obtained by Douglas (1997) who determined *DD* using a soil water balance model for a similar soil in the lower Namoi valley. As for the area associated with the prior stream channel, *DD* ranges from 34-227 mm/year. The average estimated *LF* was 9.5 % in this area. As a result average soil EC_e would be low and indicative of a strongly leached profile. Soil EC_e determined here was similar to the estimates of average EC_e shown in Figure 6.

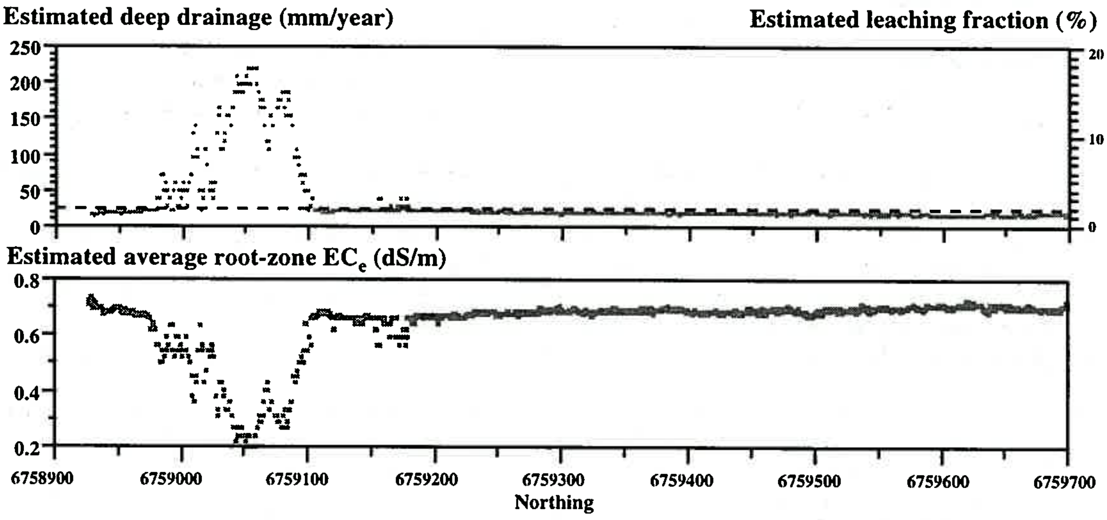

Figure 6. Deep drainage, leaching fraction and average root-zone EC_e as estimated along Transect 22.

These results seem consistent with the farmers perceptions and experience in irrigating the field near Transect 22. Typically it takes approximately 2-3 times longer than the rest of the field. This is particularly the case after a fallow period. Owing to the location of permeable soil near the head ditch and due to the presence of a subsoil clay layer, the excessive *DD* leads to the creation of the shallow water table or at least exacerbates the condition, causing excessive water logging. Fortunately, the perched water table is not interacting with a saline subsoil clay layer and no soil salinity is apparent.

Conclusions

The MESS developed by the University of Sydney provides rapid and reliable measurements for mapping the spatial distribution of soil EC_a on the field scale. The use of a salt and leaching fraction (Sodium-SaLF) model and soil samples, coupled to the EC_a data, enabled estimates of *DD* and average EC_e to be made across the field. These estimates were similar to comparable soil types and measured soil variables, respectively. As a result the reason for the existence of a shallow water table within the field investigated was elucidated. In order to manage this area, the grower would may need to remove the more permeable soil types from irrigated cotton production or alter the method of water application from furrow to sprinkler irrigation in these areas.

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References

Akaike, H. (1973). Information theory and an extension of maximum likelihood principle. In *Second International Symposium on Information Theory* (eds B.N. Petrov & F. Csaki), pp.267-281. Akademia Kiado, Budapest.

Brus, D.J., Knotters, M., van Dooremolen, P., van Kernebeek, P. & van Seeters, R.J.M. (1992). The use of electromagnetic measurements of apparent soil electrical conductivity to predict the boulder clay depth. *Geod.* 55:79-84.

Cannon, M.E., McKenzie, R.C. & Lachapelle, GP. (1994). Soil salinity mapping with electromagnetic induction and satellite-based navigation methods. *Can. J. Soil Sci.* 74: 335-343.

Cook, P.G., Hughes, M.W., Walker, G.R. & Allison, G.B. (1989). The calibration of frequency-domain electromagnetic induction meters and their possible use in recharge studies. *J. of Hydrol.* 107:251-265.

Doolitlle, J.A., Dudduth, K.A., Kitchen, N.R. & Indorante, S.J. (1994). Estimating depths to clay pans using electromagnetic induction methods. *J. Soil and Water Cons.* 49:572-575.

Douglas, J. (1997). Managing the hydrological cycle in relation to cotton. CRC for Sustainable Cotton Production annual report 1996-97, pp 32-33.

Kachanoski, R.G., Gregorich, E.G. & Van Wesenbeeck, I.J. (1988). Estimating spatial variations of soil water content using noncontacting electromagnetic inductive methods. *Can. J. Soil Sci.* 68: 715-722.

Lesch, S.M., Strauss, D.J. & Rhoades, J.D. (1995). Spatial prediction of soil salinity using EM induction techniques 1. Statistical prediction models: A comparison of multiple linear regression and cokriging. *Water Resour. Res.* 31: 373-386.

McNeill, J.D. (1986). Rapid, accurate mapping of soil salinity using electromagnetic ground conductivity meters. Tech. Note TN-18. Geonics Limited, Ontario, Canada.

Rhoades, J. D. (1992). Instrumental field methods of salinity appraisal. In 'Advances in Measurement of Soil Physical Properties: Bringing theory into Practice', pp 231-248. (SSSA Special Publication No. 30).

Shaw, R.J. (1988). Predicting deep drainage in soil from soil properties and rainfall. *Soil Use & Man.* 4:120-123.

Shaw, R.J. & Thorburne, P.J. (1985). Prediction of leaching fraction from soil properties, irrigation water and rainfall. *Irrig. Sci.* 6:73-83.

Slavich, P.G. & Yang, J. (1990). Estimation of field scale leaching rates from chloride mass balance and electromagnetic induction measurements. *Irrigation Science* **11,** 7-14.

Stannard M.E. & Kelly, I.D. (1977). 'The irrigation potential of the lower Namoi valley.' Water Res. Comm., NSW.

Sudduth, K.A., Kitchen, N.R., Hughes, D.F. & Drummond, S.T. (1995). Electromagnetic induction sensing as an indicator of productivity on claypan soils. Proceedings of the Second International Conference on Site Specific Management for Agricultural Systems. (Eds. Probert, P.G., Rust, R.I.H. & Larson, W.E.). pp 671-681.

Williams, B.G. & Hoey, D. (1987). The use of electromagnetic induction to detect the spatial variability of the salt and clay contents of soil. *Aust. J. Soil Res.* 25: 21-28.