MAPPING DEEP DRAINAGE RISK AT FIELD AND DISTRICT LEVELS IN THE LOWER GWYDIR VALLEY

J. Triantafilis, I.O.A. Odeh, A.I. Huckel, M. Short and M.F. Ahmed
Australian Cotton Cooperative Research Centre, The University of Sydney, NSW 2006, Australia.

Introduction

The arid and semi-arid regions of the world are being relied upon to provide increasing amounts of agricultural products. This is being facilitated by the increasing dependence on irrigation. In many cases irrigation inefficiency has led to water loss through deep drainage (*DD*) and groundwater recharge. In the irrigated cotton-growing areas of southeast Queensland and northwestern New South Wales, irrigation efficiency is increasingly becoming an important natural resource management issue because of the increasing number of instances where perched water tables are causing problems with respect to water logging and in isolated instances soil salinisation (Triantafilis *et al.*, 2002).

Traditionally, estimates of *DD* have been based on soil hydraulic properties, which whether measured directly or correlated with soil morphological properties, is difficult, time-consuming and expensive to determine. What seems appropriate is a simple methodology that is capable of identifying where irrigation management at the field and district scale requires improvements in water delivery and use. The application of salt/water balance models, which include the Salt and Leaching Fraction-SaLF (Shaw and Thorburn, 1985; shaw, 1988), and Solute Dynamics in Irrigated Clay Soils-SODICS (Thorburne *et al.*, 1990) is therefore appropriate. This is because the models can provide reasonable estimates of *DD* from existing soil databases. This was the approach of McKenzie (1992), Willis and Black (1996) and Willis *et al.* (1997), in the lower Macquarie valley of New South Wales.

Despite the apparent advantage in using a soil/water balance model the information generated at each sampling site is difficult to interpolate. Geostatistical methods such as ordinary kriging may be useful but large data sets are required for increased precision. This is particularly true because of the relatively large spatial variation. Electromagnetic (EM) Induction instruments have been used extensively to map the spatial distribution of soil attributes related to *DD* and groundwater recharge and as such can be used to provide large amounts of information relatively quickly. Soil attributes such as clay content (Triantafilis *et al.*, 2001a), depth to clay (Doolittle *et al.*, 1994), moisture (Kachanoski *et al.*, 1988) and salinity (Triantafilis *et al.*, 2000 and 2001b) have been measured using EM. This is because EM instruments measure bulk soil electrical conductivity (EC_a), which is or related to these properties (McNeil, 1986).

EM instruments have also been used directly to estimate rates of leaching (Slavich and Yang, 1990) and groundwater recharge (Cook *et al.*, 1989a; Cook *et al.*, 1992). Cook *et al.*, (1989b) used a relationship between EC_a and groundwater recharge rate to map and understand the spatial distribution of groundwater recharge rate in a semi-arid area of southern Australia. In this paper we explain the use of an EM38 to characterize the spatial distribution of soil at the field and district levels, respectively, in the lower Gwydir valley, northeast of Moree. First, the EC_a data measured with the EM38 was used to determine suitable soil sampling sites where soil information such as clay content and exchangeable cations were determined to a depth of 1.2 m. The soil information was inputted along with water quality information into the SaLF model to estimate *DD* rate (mm/year). A relationship between EC_a measured with the EM38 at the field and district scales was developed. Using the geostatistical approach of indicator kriging, maps of conditional probability of *DD* exceeding a critical cut-off value (i.e. 50, 75, 100 mm) were produced. The areas of highest risk were consistant with anecdotal evidence where water use inefficiencies (i.e. *DD*) caused the creation of perched water tables and water logged soil conditions at the field and district scale.

Materials and methods

Study area

The Gwydir valley is located in northern New South Wales of Australia. The lower Gwydir valley is defined by the boundary of gently undulating land at the longitude of Pallamallawa and extends west to the Barwon River. Moree is the largest township in the valley and is located 600 km north-northwest of Sydney. The study area is centered on the township of Ashley, situated approximately 15 km north of Moree. The Gwydir and Mehi Rivers, which flow through the valley, are tributaries of the Darling River. The Gwydir River tributaries of Carole Creek and Marshall Ponds Creek traverse the area. As shown in Fig. 1, the primary agricultural industry is irrigated-cotton farming. The largest farms include *"Auscott Midkin"* and *"Midkin South"*, which are located in the northwestern part of the study area and *"Milo"* in the east. Smaller landholdings include *"Norwood"*, *"Glen Prairie"*, *"Caroale"*, *"Kern"*, *"Sappa"*, *"Beela"*, *"Santis"* and *"Listowel"*. *"Ingle Plains"*, which is located between the Canarvon Highway and Rosedale Road, is the largest block of pastoral country.

The field selected for detailed study, is Field 11, on *'Auscott Midkin."* Typically it has a crop rotation of two seasons of furrow-irrigated cotton, one non-irrigated winter crop of wheat followed by a fallow period (12-18 months) to the next cotton crop. It was selected due to the long history of problems associated with a perched watertable that causes waterlogged soil conditions. This is particularly the case in the southern parts of the field where sandy soil types, associated with a prior stream formation are predominant

(Triantafilis *et al.*, 2001a). Geodetically, the area is located at approximately $29^{0}18'$N and $149^{0}45'$E, which is equivalent to the Australian National Grid Reference of 6755660mN and 767020mE. Geologically, unconsolidated alluvial sediments of Recent to Tertiary age, which can extend to a depth of 60 m, underlie "*Auscott Midkin*" (Blandford *et al.,* 1977). As described by Butler *et al.* (1983), the lower Gwydir River valley is part of the Darling Riverine Plain of southeastern Australia; a broad region characterised by coalescent alluvial fans of clay floodplains and prior-stream river ridges.

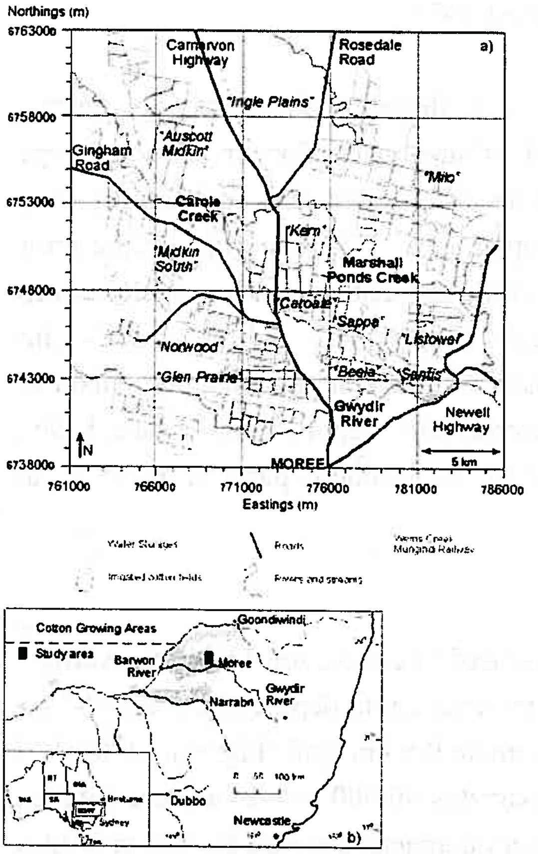

Fig. 1: Location of lower Gwydir River valley and detailed infrastructure of the study area northeast of Moree. Note: Location of *"Auscott Midkin"* Field 11, in northwest corner of the district.

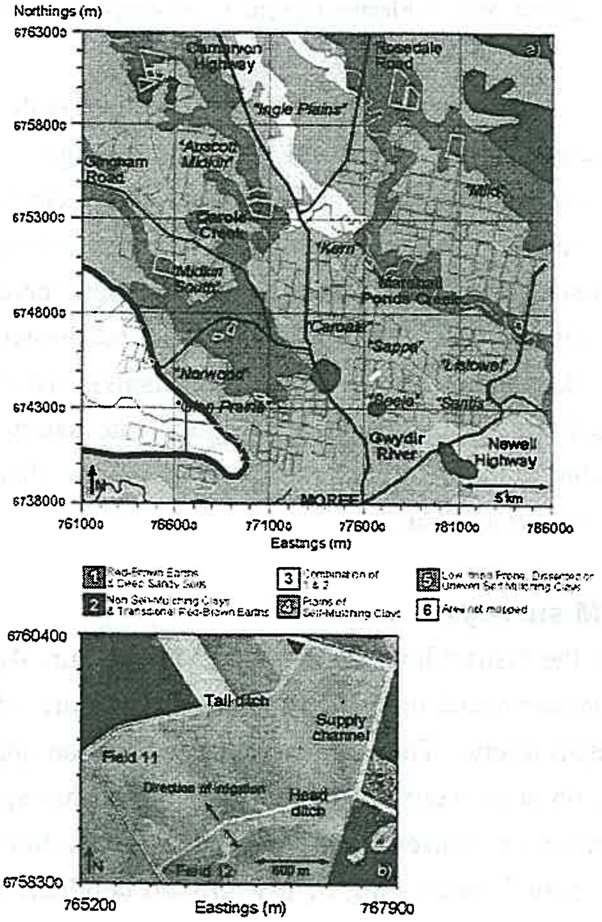

Fig. 2: a) Soil mapping units of the lower Gwydir valley (Stannard and Kelly (1968); and, b) aerial photo of *"Auscott Midkin"* Field 11. Note: location of various irrigation structures.

Stannard and Kelly (1968) identified three distinct surface depositional systems in the lower Gwydir valley: (i) clay floodplains, (ii) prior stream formations, and (iii) levee deposits of present day watercourses. These are shown in Fig. 2. In the process of examining the clay plains on the alluvial floodplains they identified three classes, namely the dark grey to grey brown self-mulching clays (Vertisols), the similar but weakly self-mulching clays (Vertisols), and the non self-mulching brown clays that are characterised by a thin dispersed surface crust (Entisols).

Figure 3. Mobile Electromagnetic Sensing System

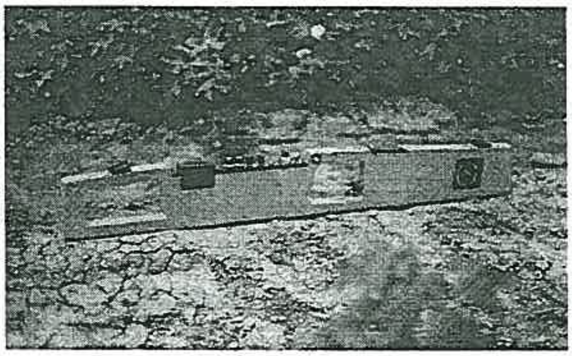

Figure 4. EM38

Prior stream formations, together with the levee deposits of present day streams, occupy only a relatively small percentage (15%) of the lower Gwydir soil landscape (Needham, 1991). They are slightly elevated in relation to the surrounding clay floodplains and are gently undulating in surface topography. The soil types of the prior stream formations are variable and change rapidly over short distances. They include deep sands (Entisols), shallow transitional red brown earths (Inceptisols), and brown soils with marked textural boundaries (Inceptisols). The subsoil of the prior streams may remain of medium to heavy texture or grade into sandy material with depth (Stannard and Kelly, 1968). Figure 2b shows a prior stream channel in the southern parts of Field 11 at *"Auscott Midkin."*

EM surveys

At the district level a Geonics EM38 (Figure 4) was used to collect soil EC_a in the vertical and horizontal modes of operation. This provides information to depths of 0-2 and 0-1 m, respectively. The survey was carried on an approximate 0.5 km grid (Fig 5a). A total of 1,108 sites were visited, across an area that approximates 40,000 ha. In a more detailed survey on *"Auscott Midkin"* Field 11, a Mobile Electromagnetic Sensing System or MESS (Figure 3)-consisting of two ground conductivity meters (i.e. Geonics EM38 and EM31) and a Global Positioning System (i.e. Trimble® FieldGuide and Trimble® AgGPS132), was used to obtain 27,646 measurements of EC_a as measured by the EM38 and EM31 in the vertical mode of operation (Fig. 5b). In this mode of operation, and at a height of 1 m above the ground surface, the EM31 measures to a depth of approximately 6 m. Controlled traffic lanes have been established in Field 11, with farm equipment designed for 12-row cultivation/planting. Therefore, the 55 transects were spaced at 48m intervals that ensured the MESS was aligned in the appropriate furrows to avoid compacted soil.

Soil and water data

At the field level, 105 soil sample locations were selected based on low intermediate and high EM34/38 survey data. In addition and to ensure good representation across the area the sites were spread as evenly as possible. Additional sample locations were drilled in the area during a larger reconnaissance soil survey of the valley. This added an additional 40 sampling sites to the data set. An EM38 measurement was recorded at each site. A detailed description of the sampling design collected at the field level can be found in Triantafilis *et al.* (2001a). Briefly, 81 soil sample locations were selected in Field 11 based on low, intermediate and high values of soil EC_a, which were spaced as evenly as possible across the field.

At each site an intact soil core was recovered and sampled for laboratory analysis at depth increments of 0.0-0.3 and 0.9-1.2m at the district level and 0.0-0.3, 0.3-0.6, 0.6-0.9 and 0.9-1.2m at the field level. The samples were air-dried and ground to pass a 2-mm sieve. Additionally, the soil was analysed for exchangeable cations (mmol(+)/kg) based on Tucker's (1974) method using a mechanical leaching device (Holmgren *et al.*, 1977). Clay percentage was determined using the pipette method of particle size analysis (Coventry and Fett, 1979). Water samples were also collected from Carole Creek, a major tributary of the Gwydir River (Fig. 1), which is used to irrigate Field 11. The electrical conductivity of the water (EC_{iw}) was 0.393 dS/m. This value was used in all simulations.

SaLF simulations

The soil properties collected at the district and field scale were inputted to the SaLF program. This included clay content (%) and CEC (mmol(+)/kg) at the various depths 0-1.2 m. In addition, exchangeable sodium at a depth of 0.9-1.2 m, the EC_{iw} value for Carole Creek (i.e. 0.393 dS/m), and Moree's mean annual rainfall (i.e. 597mm) were entered. Four different applied water simulations were then carried out: (a) 300mm-half the industry standard for irrigated cotton production, (b) 600mm-industry standard for irrigated cotton production, (c) 1200mm-head ditches and industry standard for rice production, and (d) 1,500 and 1,800 mm for supply channels and shallow storage's. The average annual rainfall ($R = 584$ mm) of Moree was also inputted.

Results

Spatial distribution of EC_a

Figure 6a shows the spatial distribution of EC_a (as measured by the EM38 in the vertical mode of operation). It is evident that low values of EC_a (i.e. $\leq$ 50-100 mS/m) mostly coincide with the location of the various streams that pass through the area. This is particularly the case with Marshalls Ponds Creek, which enters the district in the southeast corner at a Northing of 6742000 and joins Carole Creek 6758000. It evident that the major infrastructure constructed through the area (Canarvon Highway and Gingham Road) are found in these areas. This is also the case with the Werris Creek-Mungindi Railway line.

The higher values of EC_a (i.e. > 100 mS/m) are consistent with the clay plains shown in Figure 2a and as described by Stannard and Kelly (1968). This is the case at *"Auscott Midkin"*, *"Sappa"*, *"Caroale"*, *"Listowell"* and *"Milo"*. It is also worth noting that the area about 2.5 km northeast of and parallel with the Carnarvon Highway, and located on *"Ingle Plains"*, has values of EC_a larger than 100 mS/m. In general, most of the fields developed for irrigation are located in these areas. It is worth noting, however, that several of the storages and some of the irrigated farms are located in areas where EC_a is less than 100 mS/m but greater than 50 mS/m. This is the case in the southeastern areas and in particular south of Gingham Road.

Figure 6b shows the spatial distribution of EC_a (as measured by the EM38 in the vertical mode of operation). Most of the field has an EC_a value greater than 100 mS/m. The exceptions are the southeast corner, central southern part and also along the eastern part of the field. Here low values of EC_a (i.e. $\leq$ 100 mS/m) were consistent with the known prior stream channel shown in Figure 2b. It should also be noted that these areas coincide with the location of the head ditch and significantly along the eastern boundary it coincides with the location of a large supply channel.

Estimates of deep drainage

The estimates of *DD* obtained using the SaLF model are comparable with results of Douglas *et al.* (1998) who investigated the various components of the water balance equation in an adjacent irrigated cotton field. By measuring components of the water balance (i.e. precipitation, irrigation, runoff, evapotranspiration and change in soil moisture content) *DD* was estimated by difference for several irrigation events and a couple of different soil types.

For a field located mostly on grey clay alluvial soil (i.e. vertosols), *DD* was estimated to be 12.3 mm after two irrigation events, where 175.9 mm of water was applied and 6.6 mm of water fell as precipitation. Extrapolating this estimate by a multiplication factor of three to estimate *DD* over the entire irrigation season a value of 36.9 mm was obtained. This is similar to the values of *DD* achieved on the clay plains as predicted by the SaLF model. This was the case at *"Auscott Midkin"* Field 11, where *DD* was estimated to be between 34 and 54 mm/year (I = 600 mm of irrigation and R = 597 mm rainfall) for soil profiles with clay content between 45 to 60 %.

Similarly, Douglas *et al.* (1998) estimated *DD* on a red-alluvial soil, equivalent to the prior stream area identified in Field 11. Here *DD* was estimated to be 64.2 mm after 248 mm was applied by irrigation and 14.8 mm fell as precipitation. Extrapolating these results by a factor of 2.4 (equivalent to 600 mm of applied irrigation water) *DD* over the cotton-growing season would approximately be 154 mm. This result is similar to that achieved here, whereby soil profiles collected in prior stream areas with clay contents < 40 % had *DD* values ranging between 100 to 230 mm.

Relationship between *DD* and EC_a

Figure 7a shows the plot of EC_a (as measured by the EM34) versus *DD* (mm/year) as estimated using SaLF at each of the 145 sites collected at the district scale. At low values of EC_a, *DD* is high and with increasing EC_a *DD* diminishes. The relationship is approximated by an exponential function. Figure 7b shows a similar relationship exists for the EM38 and estimates of *DD* at the fieldscale. The fit is shown in Fig 6b. The exponential decay curves shown in Fig. 7 are analogous to analytical models used by Cook *et al.*, (1989a and b) to derive a theoretical relationship between EC_a and groundwater recharge rates in a semiarid region of South Australia. In both cases, they suggest that the sandier soil types will be more prone to larger amounts of deep drainage as compared to the clayier soil types.

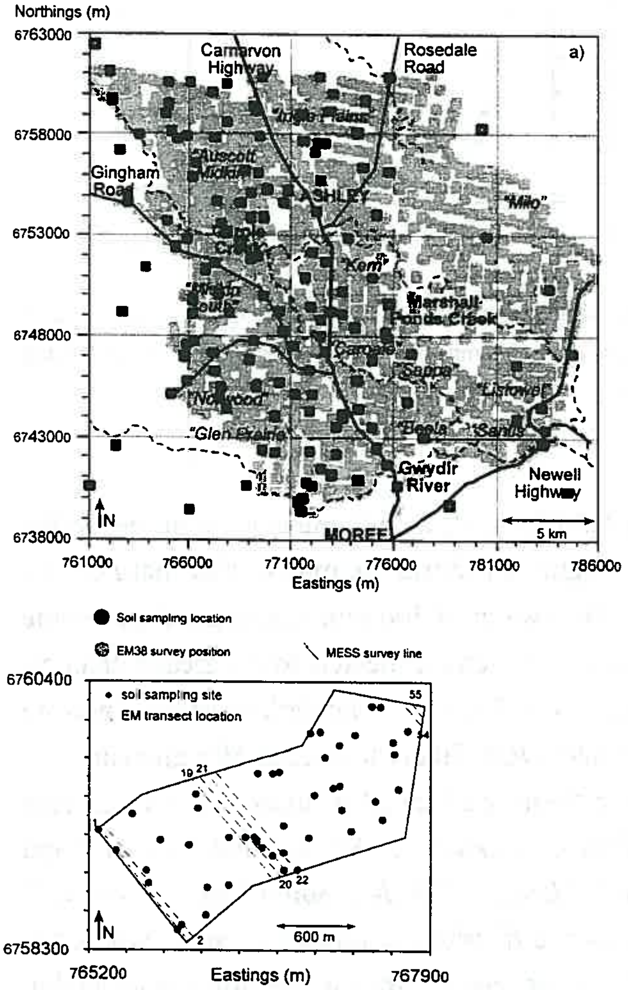

Fig. 5: Location of a) EM38 survey and soil sampling locations at the district level, and b) Mobile Electromagnetic Sensing System transects and soil sample locations in *"Auscott Midkin"* Field 11.

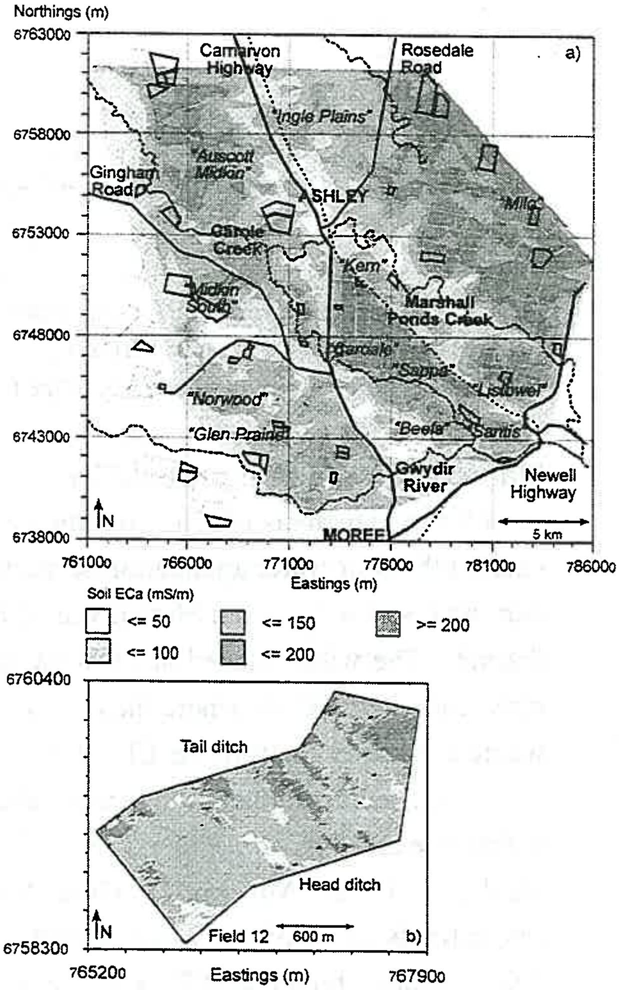

Fig. 6: Contour plots of EC_a (mS/m) as generated by at a) district scale, and b) field scale.

It is evident that in the heavier clay areas (EC_a > 125 mS/m) deep drainage is generally less than 50 mm/year. In these areas few problems of water logging are apparent. Conversely where deep drainage exceeds 50 mm/year the soil is generally sandier in nature and water logging is apparent, especially near earthen storages. In the following section we map where the risk (conditional probability) of deep drainage exceeds 50 mm or more for the various water application scenarios (i.e. $I = 300$, 600, 1,200 and 1,800 mm/year).

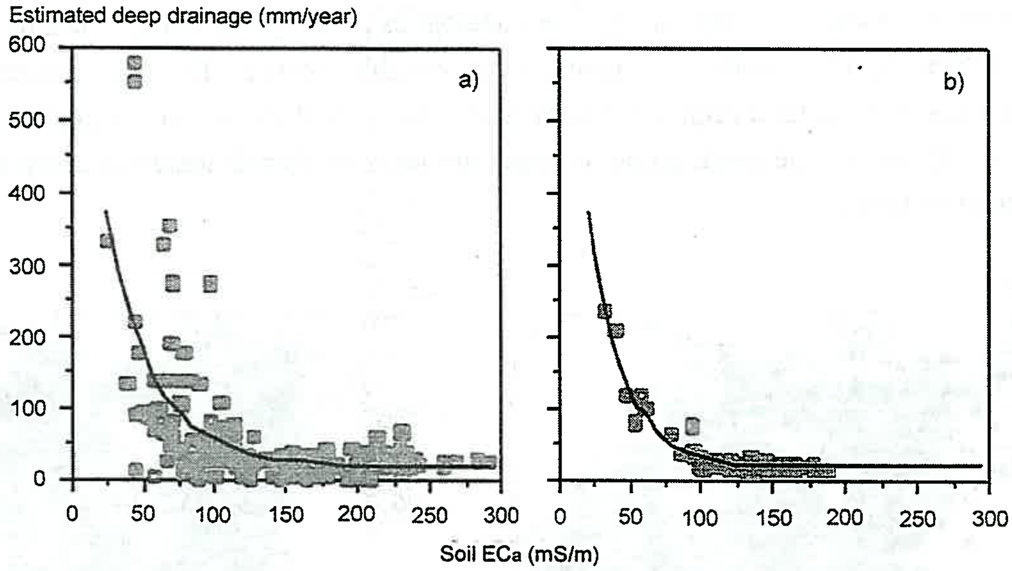

Fig. 7: Relationship between EC_a (mS/m) and estimated deep drainage (*DD*) at a) the district scale, and b) field scale, if 600 mm of irrigation (*I*) water is applied and 584 mm of rainfall is assumed. Note: Fitted models are 3-paramter exponential decay of the form $a.e^{(-b \times EM34)} + c$.

Maps of conditional probability

In order to map areas of risk, conditional probability (CP) or risk maps were produced for each of the four water application scenarios. Figure 8a shows the map of risk that *DD* at a particular site will exceed 50 mm/year if irrigation water of 300 mm was applied across the district. The white shaded areas show where *DD* is least expected to be greater than 50 mm/year and therefore where the risk is lowest (i.e. $CP \leq 0.5$). The darkest shades indicate where the risk is greatest (i.e. $CP > 0.9$) and where *DD* is likely to exceed 50 mm/year.

It is evident most of the irrigated cotton fields are located in areas of low risk. This is the case at *"Auscott Midkin"*, *"Milo"*, *"Kern"*, *"Caroale"*, *"Santis"* and *"Sappa,"* and for the most part *"Norwood"*, *"Glen Prairie"*, *"Beela"*, *"Midkin South"* and *"Listowel"*. Interestingly some of the water storages across the district are located in areas where the risk is medium high (i.e. $0.7 < CP \leq 0.9$). This is the case for the largest storages located in the western part of the district and Northings of 6748000 and 6753000.

With respect to Field 11 at *"Auscott Midkin,"* the district scale map of conditional probability indicates low risk (< 0.5) across the entire field. The fieldscale map also indicates low risk apart from a narrow band of higher CP located in the southern and central parts of the field. As shown in Figure 2b, sandy loams associated with a prior stream channel that has its origins in Field 12 dominate this part of the Field 11.

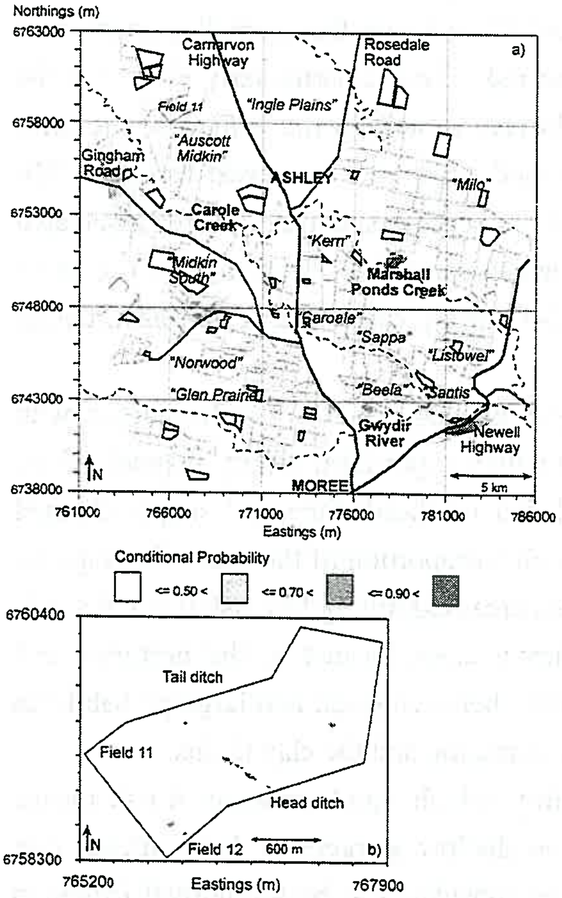

Fig. 8: Maps showing the conditional probability (risk) that soil at a particular site will exceed a deep drainage value of 50 mm/year a) at the district scale, and b) field scale if 600 mm of irrigation water was applied and 584 mm of rainfall is assumed.

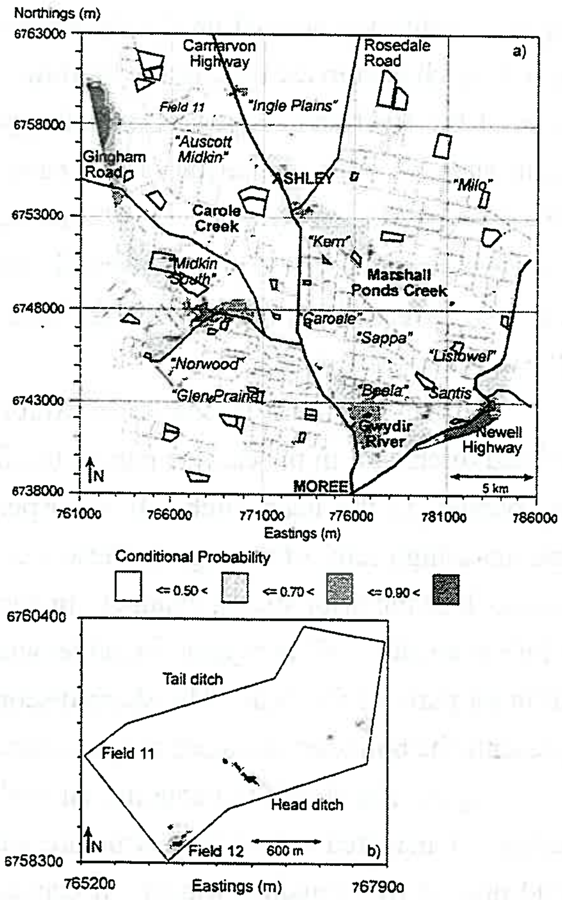

Fig. 9: Maps showing the conditional probability (risk) that soil at a particular site will exceed a deep drainage value of 50 mm/year a) at the district scale, and b) field scale if 600 mm of irrigation water was applied and 584 mm of rainfall is assumed.

Figure 9a shows the risk that *DD* at a particular site will exceed 50 mm/year if irrigation water of 600 mm was applied across the district. It is evident that most fields at *"Auscott Midkin"*, *"Milo"*, *Caroale"*, *"Glen Prairie"* and *"Santis"* are located in low risk areas (i.e. conditional probability < 0.5). This is similarly the case for *"Norwood"*, *Midkin South"*, *"Sappa"*, *"Listowell"*, *"Beela"* and *"Glen Prairie"*. In terms of areas, which could be considered for future irrigated development, it is apparent that the area to the northeast of the Canarvon Highway and on *"Ingle Plains"* would be the most suitable location. It is also increasingly evident that many of the storages are located in areas where the risk (i.e. $0.5 < CP \leq 0.7$) suggests DD might exceed 50 mm/year if water to a depth of 600 mm (i.e. 0.6 m) was stored in these structures. This is particularly the case for many storages located adjacent to Marshalls Ponds Creek and the Gingham Road.

Figure 9a also suggests that on the district scale *"Auscott Midkin"* Field 11 would not experience problems with *DD*. However, Figure 9b, which shows the conditional probability that a *DD* value at a particular site will exceed 50 mm/year if 600 mm of irrigation water was applied uniformly across Field 11, indicates that a small proportion of the field is characterised by areas exhibiting larger risk. This is particularly evident in the center of the field and suggests that soil types located in and on the fringes of the prior stream channel, such as the red brown earths, would experience increased levels of *DD*. *DD* values are also likely to exceed 50 mm/year in the southwest corner: an area associated with the main body of the prior stream channel, which approaches from the east (i.e. from Field 12). Areas along the eastern head ditch, also display slightly larger probabilities of *DD* exceeding 50 mm/year.

Of major concern is that areas exhibiting larger risk (i.e. CP ≥ 0.7) intersect with the head ditch, and in the eastern part of the field with a major farm supply channel, which runs parallel to the head ditch. It is suspected that the head ditch and supply channel experience high rates of seepage in these areas, with a proportion of the water flowing into the branch of the prior stream channel. In contrast, areas exhibiting low risk (i.e. CP ≤ 0.5) of *DD* exceeding 50 mm/year coincide with heavy clays located in the northeast and northwest parts of the field. The sharp discontinuity between small and large probabilities represents the boundary between the prior stream formation and the clay plains.

Figure 10a shows the conditional probability, which simulates areas of risk for the location of irrigated cotton infrastructure such as shallow storages or head ditches (i.e. 1,200 mm of free standing water). It can also be considered to be the normal irrigation requirement for rice production. It is evident from the map that most of the irrigation fields at *"Auscott Midkin"*, *"Milo"* and *"Listowel"* are unlikely to be susceptible to too many problems of excessive deep drainage, since most are located in areas where the risk is low (i.e. CP ≤ 0.5). It is also evident that some of the northern fields of *"Kern"* and *"Sappa"*, which lie adjacent to Marshalls Ponds Creek, may experience water application inefficiencies since the conditional probability is between 0.5-0.7. This is similarly the case with some of the southern fields located on *"Beela"*, *"Santis"* and *"Listowel"*.

Interestingly, many of the irrigated fields located south of Gingham Road, would not be considered appropriate for development for irrigated rice production. There also may be some issues associated with the location of head ditches in these areas, however more detailed work is required to ascertain the efficiency in the delivery of water in these fields. Figure 10b shows *DD* risk map that represents the cutoff values of 50 mm/year under 1,200 mm/year of water applied across *"Auscott Midkin"* Field 11. In the rice growing areas of southern NSW, groundwater recharge is a major problem due to soil heterogeneity and the requirement of permanent flooding of the soil for periods of up to 130-150 days (Beecher and Hume, 1996). Over the growing season, the depth of ponded water required for maximum rice yield ranges from 50 to 250 mm. Obviously, drainage losses would occur in isolated areas of Field 11, associated with the prior stream channel, if water were ponded for extensive periods for rice production.

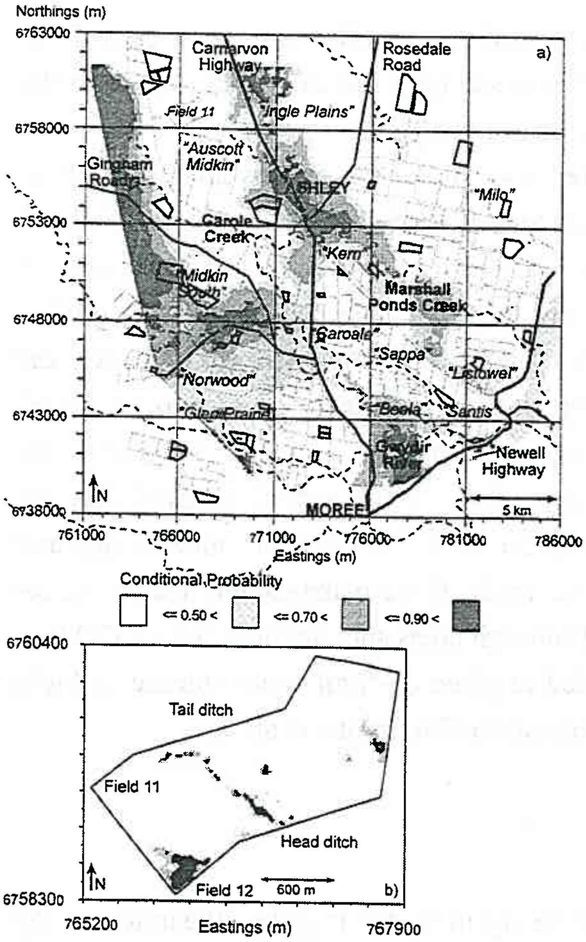

Fig. 10: Maps showing the conditional probability (risk) that deep drainage will exceed a value of 50 mm/year a) at the district scale, and b) field scale if 1,200 mm of irrigation water was applied and 584 mm of rainfall is assumed.

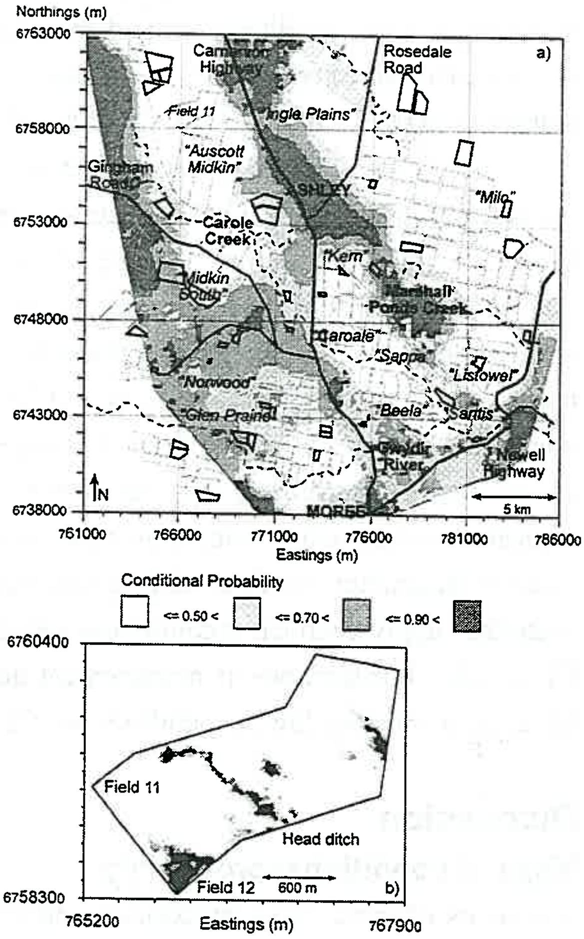

Fig. 11: Maps showing the conditional probability (risk) that deep drainage will exceed a value of 100 mm/year a) at district scale if 1,800 mm of irrigation water was applied, and b) at field scale if 1,500 mm of irrigation water was applied and 584 mm of rainfall is assumed.

Figure 11a shows the most suitable areas to locate large supply channels and shallow storages. Two areas stand out as being most suitable: *"Auscott Midkin"* and *"Milo"*. Most of *"Listowel"* could also be considered. It is apparent, however, that some caution would be required around *"Auscott Midkin"* Field 11. It is also evident that some of the districts irrigated infrastructure is located in areas where water loss may be great and indicates where efficiencies in water delivery and storage could be improved. This is mostly the case in the areas around Gingham Road. Here the risk was consistently high (i.e. conditional probability > 0.9) for this simulation. It is worth noting that of the storages located here, two are known to experience some problems with leakage. This includes the dual-cell storage located at a Northing of 6753000 and Easting 771000. The southern cell is located predominantly in the medium risk zone (i.e. $0.5 < CP \leq 0.7$) although the northeast corner along with the northern cell lies exclusively in the intermediate to high-risk area (i.e. $0.7 < CP \leq 0.9$). The northern cell is known to have water logged soil conditions around the perimeter and suggests the simulation carried out is consistent with the farmer's experiences. This is similarly the case with respect to the storage located at a Northing of 6751000 and Easting of 766000.

However, and in order to get a better idea of where improvements to these structures can be made a MESS survey similar to that carried out at *"Auscott Midkin"* Field 11 would be required. Figure 11b shows the results achieved at a cut-off value of 100 under 1,500 mm of water application. This map simulates the areas where *DD* is anticipated in soil profiles located under a supply channel or shallow storage. As such, the risk map enables a strategic approach to be adopted by management of *"Auscott Midkin"* when considering options to reduce channel seepage into Field 11. For example, water losses may be minimised by clay-lining those regions of the supply channel that are adjacent to areas exhibiting large risks of excessive *DD*. In addition, unnecessary and costly infrastructure work would be reduced. Similarly, if the management decided to re-route the supply channel, it could be positioned through areas showing low risk of *DD* (i.e. CP ≤ 0.5). Furthermore, if management decided to place on-farm water storage in Field 11, areas displaying low probabilities would be most suitable for its location.

Discussion

Maps of conditional probability

The maps of conditional probability, produced using indicator kriging, illustrated at the field scale areas where problems with deep drainage are most likely to be occurring. Those exhibiting the largest risk of excessive *DD* (i.e. > 50 mm/year) using the various water application volumes (i.e. I = 600 – 1,500 mm), corresponded to permeable soil types associated with the prior stream channel evident in the southeast, central and eastern parts of *"Auscott Midkin"* Field 11. In these areas of the field water logging is most evident. As a result the methodology developed indicates where a more strategic approach may need to be implemented by management of *"Auscott Midkin"* when considering options to improve irrigation efficiencies in Field 11 and water delivery in the northern part of this landholding. This is particularly the case along the head ditch and supply channel, which are located on top of the prior stream channel.

At the district level, the results were similarly consistent with anecdotal information about where water storage inefficiencies are evident. This was particularly the case with two of the larger storage located in the western part of the study area. The conditional probability maps also highlighted where storages and major supply channels could be moved in order to improve water storage and delivery across the district. In addition, areas not currently developed for irrigation were also delineated (i.e. northeast of the Canarvon Highway) although some caution will be required in order to find suitable sites to locate water storages.

Cause of perched water tables and water logged soil conditions

The distribution of past and present stream courses within the lower Gwydir River valley has over time produced a complexity of inter-mixing of the various gravel, sand, silt and clay fractions of the surface deposits. Stannard and Kelly (1968) investigated the shallow stratigraphy of the lower Gwydir valley. In general the prior stream formations are similar with those in the lower Namoi valley (Stannard and Kelly, 1977) and consist of sands and gravelly sands or gravelly clays, which generally extend from the surface to over 6 m in some locations. At depths beyond this heavy clays are often found (see Figure 12).

This is similarly the case for the minor terminal branch prior streams, although in this case the coarser to medium textured soil extends to depths of around 1.5 to 2 m. On the clay plains, both close to and at a distance from the present day stream courses, clay is most likely to extend in most cases to at least 6 m and in many instances a much greater thickness before courser textured sediments are encountered (Blandford *et al.*, 1977).

As a consequence and where infrastructure has been located atop the prior or current stream channels, *DD* will be high because of the permeable nature of the soil. This was evidenced during SaLF modeling. In Field 11, where a minor terminal branch prior stream is evident along the head ditch, *DD* is large (i.e. > 50 mm) beyond a depth of 1.2 m. As a result it usually takes about 2-3 times longer to irrigate the central portion of the field: this is most evident after a dry fallow. Somewhere beyond a depth of 1.2 m, the water is impeded from further vertical movement by an impermeable layer, which is most likely of a heavy clay nature. This creates a perched water table that causes water logging near the head ditch. This was evident during the sampling of the central-southern parts of Field 11, despite the fact that the field was in fallow. The water table was created as a result of the irrigation, and hence hydraulic pressure, being undertaken in Field 12. This was similarly the case along the eastern boundary of the field where a supply channel runs in parallel with the head ditch in Field 12. In both cases, however, the perched water table does not create any problems with respect to soil salinisation.

In order to improve water delivery to this part of the farm, a number of options are available. The first is lining the head ditches and supply channel with bentonite in the areas where the prior stream channel occurs. Another option is rerouting the supply channel via clayier areas. As a first approximation the district scale map could be used as a guide (Figure 11a). This is also the case for determining storage relocations. MESS surveys should be undertaken to ensure no prior stream channels are evident.

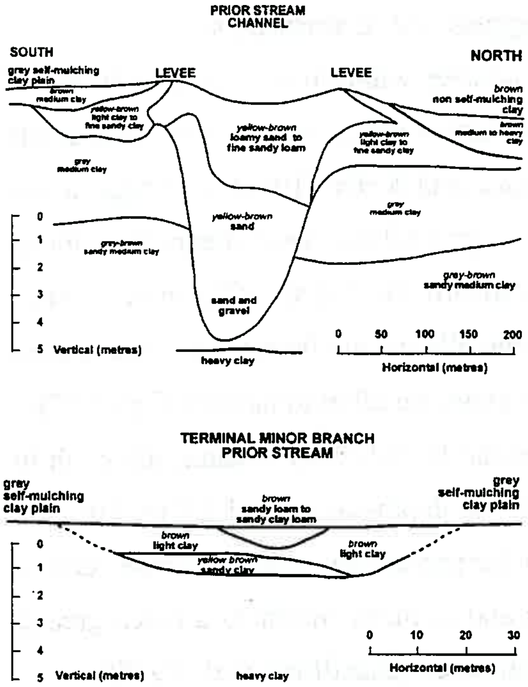

Fig. 12: General shallow stratigraphy near prior streams of the lower Namoi valley (after Stannard and Kelly, 1977).

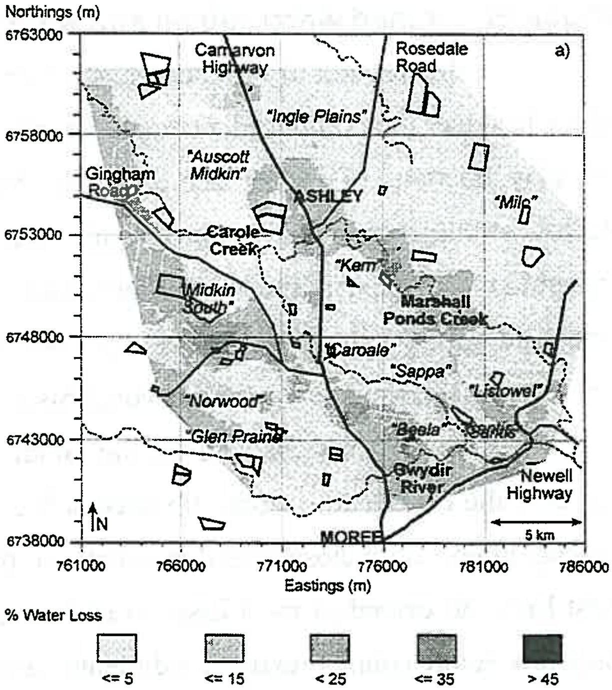

Fig. 13: Map of percentage loss to deep drainage if 1,800 mm of irrigation water was applied (i.e. simulates storage or supply channel) and 584 mm of rainfall is assumed.

Percentage loss of applied water:supply channels and water storages

Figure 13 shows a map of the percentage loss of water beneath storages at the district level. It was calculated by dividing the estimated deep drainage (when I = 1,800 and R = 584 mm) by the amount of water applied (i.e. 1,800 + 584 mm) and multiplied by 100. The darkest shaded area represents where DD would be less than 5 % of total water applied (i.e. < 119 mm/year) and suggests that most storages across the district are for the most part located in suitable areas. It is evident that the storages, which currently experience problems with water logging and leakage, are found in the area where percentage loss as a function of deep drainage is 5-15 % (i.e. between 119 – 358 mm/year). It would appear that for each of these storages the best management option would be the relocation to more suitable areas (i.e. < 5%).

Conclusions

The use of an EM38 instrument allowed in the first instance the establishment of a soil-sampling scheme, which would account for the collection of soil samples that would characterize the various soil types evident at the field and district levels in the lower Gwydir valley. The input of the subsequent soil information collected into the SaLF model enabled estimates of DD to be obtained for various water application scenarios (i.e. I = 300-1,800 mm/year). These estimates of DD were related to measurements made with the EM38 using non-linear (exponential decay models). The use of indicator kriging enabled conditional probability (i.e. risk) maps of DD to be generated in Field 11 and across the district. The results clearly identified areas exhibiting the largest probability (i.e. risk) of excessive *DD* and which corresponded to permeable soil types associated with a prior stream channels. At the field level the risk maps provided a strategic approach to be implemented by the management of "*Auscott Midkin*" Field 11 and across the district when considering options to improve irrigation efficiencies. For example, at the district scale the loss of water from storage or conveyance structures could be minimised by repositioning them in areas exhibiting low risks of excessive *DD*.

Acknowledgements

The results contained in this paper were generated as part of two concurrent Cotton Research and Development Corporation (CRDC) funded and Australian Cotton Cooperative Research Centre (Australian Cotton CRC) administered projects, entitled *"Understanding the salinity threat in the irrigated cotton growing areas of Australia: Phase II – Methods and techniques; and, Phase III – Implementation and Management."* Additional funds were received from the Natural Heritage Trust (NHT) in collaboration with the Gwydir Valley Irrigators Association (GVIA). In this regard we thank Mr Wal Murray (Executive Officer) and Mrs Toni Hunt (Executive Assistant). The research carried out was conducted in close consultation with the GVIA executive including, Mr Richard Browne (*"Auscott Midkin"*), Mr John Seery (*"Kooroogamma"*) and Mr Will Kirkby (*"Glen Prairie"*). We extend our thanks to these growers, as well as the large number of growers in the district for allowing unrestricted access to their properties.

References

Beecher HG, Hume IH (1996) Rice suitability assessment. Final Report. Rural Industries Research and Development Corporation and New South Wales Agriculture, Australia.

Blandford D, Douglas I, Maye B, Pigram JJ (1977) Irrigation development in the lower Gwydir valley. Department of National Resources, Australian Water Resources Council. Technical Paper No. 30. Research Project No. 74/65. Australian Government Publishing Service, Canberra.

Butler BE, Blackburn G, Hubble G (1983) Chapter 18, Murray_Darling Plains (VII) In Soil: an Australian viewpoint. CSIRO Division of Soils. pp 231-239. Academic Press, Melbourne.

Cook PG, Hughes MW, Walker GR, Allison GB (1989a) The calibration of frequency-domain electromagnetic induction meters and their possible use in recharge studies. J Hydrol. 107:251-265.

Cook PG, Walker GR, Jolly ID (1989b). Spatial variability of groundwater recharge in a semiarid region. J. Hydrol. 111, 195-212.

Cook PG, Walker GR, Buselli G, Potts I, Dodds AR (1992) The application of electromagnetic techniques to groundwater recharge investigations. J Hydrol. 130, 201-229.

Coventry RJ, Fett DER (1979) A pipette and sieve method of particle size analysis and some observations on its efficacy. CSIRO Australia Divison of Soils. Divisional Report, No, 38. (CSIRO, Australia).

Doolitlle JA, Sudduth KA, Kitchen NR, Indorante SJ (1994) Estimating depths to clay pans using electromagnetic induction methods. J. Soil Water Cons. 49, 572-575.

Douglas J, Faulkner R, McLeod DH (1998) Managing the hydrologic cycle in relation to cotton. In: Meeting of Program 1, Cooperative Research Centre for Sustainable Cotton Production. May 1998. The University of Sydney, New South Wales, Australia.

Holmgren GGS, Juve RL, Geschwender RC (1977) A mechanically controlled variable rate leaching device. Soil Sci. Soc. Am. J. 41, 1207-1208.

Kachanoski RG, Gregorich EG, van Wesenbeeck IJ (1988) Estimating spatial variations of soil water content using noncontacting electromagnetic inductance methods. Can. J. Soil Sci. 6, 715-722.

McKenzie NJ (1992) Soils of the lower Macquarie valley, New South Wales. CSIRO Division of Soils, Divisional Report No 117. Canberra, ACT.

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

Needham P (1991) The extent of degraded heavy clays and associated soils in north-western New South Wales. Department of Conservation and Land Management, Soil Conservation Service, Inverell Research Service Centre, New South Wales, Australia.

Shaw RJ (1988) Predicting deep drainage in the soil from soil properties and rainfall. Soil Use Mngt. 4:120-123.

Shaw RJ, Thorburn PJ (1985) Prediction of leaching fraction from soil properties, irrigation water and rainfall. Irrig. Sci. 6, 73-83.

Slavich PG, Yang J (1990) Estimation of field scale leaching rates from chloride mass balance and electromagnetic induction measurements. Irrig. Sci. 11, 7-14.

Stannard ME, Kelly ID (1968) Irrigation potential of the lower Gwydir valley. Water Conservation and Irrigation Commission, New South Wales, Australia.

Stannard ME, Kelly ID (1977) Irrigation potential of the lower Namoi valley. Water Resources Commission, New South Wales, Australia.

Thorburn PJ, Rose CW, Shaw RJ, Yule DF (1990) Interpretation of solute profile dynamics in irrigated soils. I. Mass balance approaches. Irrig. Sci. 11, 199-207.

Triantafilis J Laslett GM, McBratney AB (2000). Calibrating an electromagnetic induction instrument to measure salinity in soil under irrigated cotton. Soil Sci. Soc. Am. J. 64:1008-1017.

Triantafilis J Huckel IA, Odeh IOA (2001a). Comparison of statistical prediction methods for estimating field-scale clay content using different combinations of ancillary variables. Soil Sci. 166:415-427.

Triantafilis J Odeh IOA, McBratney AB (2001b). Five geostatistical methods to predict soil salinity from electromagnetic induction data across irrigated cotton. Soil Sci. Soc. Am. J. 65:869-978.

Triantafilis J, Ahmed MF, Huckel AI, Odeh IOA (2002) Application of a mobile electromagnetic sensing system (MESS) to assess cause and management of soil salinity in an irrigated cotton-growing field. Soil Use Mngt. 18, 1-10.

Tucker BM (1974). Laboratory procedure for cation exchange measurements in soils. CSIRO Div. of Soils, Tech. Paper No 23. (CSIRO, Australia).

Willis TM, Black AS (1996) Irrigation increases groundwater recharge in the Macquarie valley. Aust. J. Soil Res. 34, 837-847.

Willis TM, Black AS, Meyer WS (1997) Estimates of deep percolation beneath cotton in the Macquarie valley. Irrig. Sci. 17, 141-150.